SYMPOSIUM J

Semiconductor Quantum Dots

November 27 – 30, 2000

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**Proceedings published as Volume 642
of the Materials Research Society
Symposium Proceedings Series.**

* Invited paper

SESSION J1: THEORY, MODELING, AND SIMULATIONS
Chairs: Laurence Eaves and Simon Fafard
Monday Morning, November 27, 2000
Room 207 (Hynes)

8:30 AM J1.1
DANGLING BOND MAGNETIC POLARON IN CdSe NANOCRYSTAL QUANTUM DOTS. Al. L. Efros, M. Rosen, Naval Research Laboratory, Washington, DC; E. Johnston-Halperin, D.D. Awshalom, Univ of California, Dept of Physics, Santa Barbara, CA; S.A. Crooker, National High Magnetic Field Lab, Los Alamos, NM; X. Peng, A.P. Alivisatos, Univ of California, Dept of Chemistry, Berkley, CA.

Although the major specific properties of the resonant PL of CdSe nanocrystals have been described within the Dark/Bright Exciton model the temperature dependence of the ratio of the intensity of the zero-phonon to the phonon assisted line, as well as the temperature dependence of the PL Stokes shift [1] has not been explained. Also surprising are results seen in measurements of the PL polarization at high magnetic fields -up to 60 T. The temperature dependence of the magnetic field dependent polarization reveals a transition in the g-factor at $\sim$ 4 K [2]. Taken together, all these data suggest a common magnetic origin for the observed effects, which we have identified as the exciton interaction with the spin of dangling bonds at the nanocrystal surface. We have developed a theoretical description of this interaction. At low temperature the exciton/dangling bond spin-spin interaction aligns the spins of the dangling bonds along the CdSe hexagonal axis. The resultant alignment decreases the total energy of the exciton/dangling bond system and forms a dangling bond magnetic polaron. The effect is seen in the temperature dependent Stokes shift and in the changing of the exciton g-factor. At high temperature the spins of the dangling bonds are randomly oriented which allows a direct spin-flip assisted recombination of the Dark exciton. This explains the rapid rise of the zero-phonon line intensity with increasing temperature. The theory describes the experimental data very well.
[1] M. Nirmal, C.B. Murray and M.G. Bawendi, Phys. Rev. B **50**, 2293 (1994)
[2] E. Johnston-Halperin, D.D. Awschalom, S.A. Crooker, Al. L. Efros, M. Rosen, X. Peng and A.P. Alivisatos, to be published.

8:45 AM J1.2
PSEUDOPOTENTIAL CALCULATIONS OF ADDITION ENERGIES AND OPTICAL TRANSITIONS IN CHARGED InAs AND CdSe QUANTUM DOTS. Alberto Franceschetti, Alex Zunger.

Recent single-dot STM experiments [U. Banin *et al.*, Nature **400**, 542 (1999)] have allowed for the first time the observation of atomic-like electronic states in strongly-confined semiconductor quantum dots. The tunneling conductance shows, as a function of the applied voltage, a series of narrow peaks corresponding to the electron and hole charging energies. The energy required to add an electron or a hole to a quantum dot can be manipulated by altering the dielectric constant of the surrounding environment. To quantify this effect, we have calculated the electron and hole addition energies of InAs and CdSe quantum dots as a function of the dielectric constant of the surrounding material. Atomistic pseudopotential wave functions are used as input to the many-body expansion of the total energy of the charged dots, and surface-polarization effects due to the dielectric mismatch at the surface of the dot are fully included in the calculation. We show how the addition energies, the quasi-particle gap, and the optical gap of the quantum dot depend on the dielectric constant of the surrounding material, and provide scaling lows for these quantities as a function of the dot size. Our results are in excellent agreement with STM experiments, and provide a microscopic interpretation of the measured addition energies. We have also calculated the interband emission and absorption spectra of *charged* CdSe quantum dots. We find that: (i) When a charge Q is added to the dot the absorption lines are shifted in energy by an amount approximately proportional to Q. This is a consequence of the different spatial extent of the electron and hole wave functions. (ii) The lowest-energy emission line is strongly red shifted with respect to the lowest allowed absorption line. For $Q > 2$ electrons the red shift results from Pauli blocking of the lowest absorption transition.

9:00 AM J1.3
DENSITY-FUNCTIONAL THEORY STUDY OF CO_2 ADSORPTION ON CdSe(10$\bar{1}$0). L.G. Wang[1], S.T. Pantelides[1,2] and S.J. Pennycook[1]. [1]Solid State Division, Oak Ridge National Laboratory, Oak Ridge, TN; [2]Department of Physics and Astronomy, Vanderbilt University, Nashville, TN.

Intense interest has been raised in the use of semiconducting nanocrystals by recent experimental demonstration of their efficiency for photocatalytic fixation of CO_2. An understanding of CO_2 fixation processes is not only of considerable importance for technological issues but also for the issues like "global climate change" and making use of one of the largest carbon stocks on earth. In the present work, we have investigated CO_2 adsorption on CdSe(10$\bar{1}$0) with and without a surface vacancy employing a pseudopotential plane-wave method. This surface has been identified experimentally on the CdSe nanocrystal. We have found a number of configurations that are energetically metastable both on the perfect surface and at a Se vacancy. Configurations during photoexcitation have been investigated by adding electrons or holes, and a possible route for the reaction is proposed.

9:15 AM J1.4
A SINGLE-BAND CONSTANT-CONFINING-POTENTIAL MODEL FOR SELF-ASSEMBLED InAs/GaAs QUANTUM DOTS. Marco Califano and Paul Harrison, Institute of Microwaves and Photonics, School of Electronic and Electrical Engineering, University of Leeds, UNITED KINGDOM.

We present a simple and versatile approach to calculate the energy eigenvalues and transition energies of self-assembled InAs/GaAs pyramidal dots. In this numerical method we expand the envelope function of a pyramidal quantum dot using a complete orthonormal set of periodic functions, which are solutions for a cuboid with an infinite barrier height and suitably chosen dimensions. The two main features of this approach are: (i) there being no need to explicitly match the wave functions across the boundary between barrier and dot region, it can be applied to arbitrary confining potentials and thus to structures of arbitrary shape; (ii) all the integrals are performed analitycally. In the envelope function calculations we treat the electrons and holes with separate one-band Hamiltonians and take account of the strain effects both on the confining potentials and effective masses *on average* (i.e. we assume constant average strained values for confining potentials and effective masses throughout the dot for both electrons and holes). This single-band constant-confining-potential model is then applied to self-assembled InAs/GaAs pyramidal dots in order to determine their electronic structure. Despite the simplicity of our approach, the calculated energy eigenvalues and transition energies agree well with those of more sophisticated theoretical treatments (Grundmann *et al.*, Phys. Rev. **B 52**, 11969, (1995), and Cusack *et al.*, Phys. Rev. **54**, R2300, (1996)), which take into account the microscopic effects of the strain distribution on band mixing, confining potentials and effective masses. The predictions of the model are compared with several spectra reported in the literature by different authors. Very good agreement with both position and number of experimental peaks in such photoluminescence (PL) spectra is obtained (even where other, more complex models fail to reproduce these features). Furthermore the hole energy splitting between ground and first excited state deduced from capacitance and PL measurements is in excellent agreement with our calculated values.

9:30 AM J1.5
SEMICLASSICAL THEORY OF COULOMB BLOCKADE PEAK HEIGHTS IN CHAOTIC QUATNUM DOTS. Evgenii Narimanov, Bell Laboratories; Harold Baranger, Duke University, Dept. of Physics; Nicholas Cerruti and Steven Tomsovic, Washington State University, Dept. of Physics.

The electostatic energy of an additional electron on a quantum dot blocks the flow of current, an effect known as Coulomb blockade. We develop a semiclassical theory of the Coulomb blockade peak heights in chaotic quantum dots. Using Berry's conjecture that the wavefunctions of a classically chaotic system can be characterized as random variables, we calculate the peak height distributions and the correlation functions. We demonstrate that the corrections to the corresponding results of the standard statistical theory are non-universal and can be expressed in terms of the classical periodic orbits of the dot that are well coupled to the leads. The effect is substantial for both symmetric and asymmetric lead placement.

10:15 AM J1.6
ELECTRONIC STRUCTURE THEORY OF NANOSCALE SEMICONDUCTOR QUANTUM DOTS. Alex Zunger, National Renewable Energy Laboratory, Golden, CO.

Previously, the electronic structure of nanostructure has been almost universally addressed by the standard model of effective-mass k•p envelope function approach. While eminently successful for quantum wells, this model breaks down for small nanostructures, in particular for small dots and wires. Until recently, it was impractical to test the "standard model" against more general approaches that allow many-band, as well as multi-valley, (Γ-X-L) coupling. However, it is now possible due to special mathematical tricks [1, 2], to apply the plane-wave pseudopotential method to 10^3-10^6 atom nanostructures. This shows: (i) How the 'standard model' fails, for thin superlattices [3], and isolated dots [4, 5]; (ii) How quantum size effect leads to a

reduction in dielectric constants [6]; (iii) How 'electron addition spectra' can be predicted [6] for Si, InP, CdSe dots; (iv) How the multi-excitonic spectra can be modelled [7]; (v) How the spectra dots of Si [8], InAs [9], CdSe [10] compare with experiment; (vi) How the use of pseudopotential wavefunctions leads to very different electron-hole Coulomb and exchange energies relative to the 'standard model' [11]; (vii) What is the electronic structure of 'self assembled' InAs/GaAs [12, 13] and InP/GaP [14]. 1. L.W. Wang and A. Zunger, J. Chem. Phys., 100, 2394-1297 (1994); ibid, J. Phys. Chem., 98, 2158-2165 (1994). 2. L.W. Wang and A. Zunger, Phys. Rev. B. 59, 15806-15818 (1999). 3. D.M. Wood, A. Zunger and D. Gershoni, Europhys. Lett., 33, 383 (1996); ibid, Phys. Rev. B, 53, 7949 (1996). 4. H. Fu, L.W. Wang and A. Zunger, Phys. Rev. B, 57, 9971 (1998); ibid, Appl. Phys. Lett., 71, 3433 (1997). 5. H. Fu, L.W. Wang and A. Zunger, Appl. Phys. Lett. 71, 3433-3435 (1997); H. Fu, L.W. Wang and A. Zunger, Appl. Phys Lett 73, 115 (1998). 6. A. Franceschetti and A. Zunger, Appl. Phys. Lett., 76, 1731 (2000). 7. A.J. Williamson, A. Franceschetti and A. Zunger, submitted to Physical Review B. 8. F. Reboredo, A. Franceschetti and A. Zunger, Appl. Phys. Lett., 75, 2972 (1999). 9. A.J. Williamson and A. Zunger, Phys. Rev. B, 61, 1978-1991 (2000). 10. A. Franceschetti, H. Fu, L.W. Wang and A. Zunger, Phys. Rev. B. 59, 5678-5687 (1999). 11. A. Franceschetti and A. Zunger, Phys. Rev. Lett. 78, 915 (1997). 12. L.W. Wang, J. Kim and A. Zunger, Phys. Rev. B 59, 5678-5687 (1999). 13. J. Kim, L.W. Wang and A. Zunger, Phys. Rev. B Rapid Commun., 57, R9408 (1998). 14. A. Williamson, A. Zunger and A. Canning, Phys. Rev. B Rapid Commun., 57, R4258 (1998).

10:30 AM J1.7
AN ANALYTICAL APPROACH FOR COMPUTING THE ENERGY STRUCTURE OF (In,Ga)As QUANTUM DOTS. V.G. Stoleru, D. Pal and E. Towe, Department of Electrical Engineering, University of Virginia, Charlottesville, VA.

The experimental and theoretical results of the electronic structure of self-assembled (In,Ga)As/GaAs quantum dots are presented. We performed analytical calculations to obtain the spatial strain distribution and carrier confinement potential in pyramidal-shaped (In,Ga)As quantum dots grown on (001)GaAs substrates by molecular beam epitaxy. These calculations assume that there is an (In,Ga)As wetting layer before the on-set of the self-assembly of the dots, which makes a contribution to the ϵ_{zz} strain component. The hydrostatic and biaxial strain components are calculated, respectively, from the relations ϵ_h=ϵ_{xx} ϵ_{yy} ϵ_{zz} and ϵ_b=2ϵ_{zz}-ϵ_{xx}-ϵ_{yy}. We further take into account the microscopic effects of the spatial strain distribution on carrier confinement potentials. Although our approach is simple in structure and only of modest computational complexity, the method yields a model whose results are in good agreement with values reported by other authors who use models that require complex computational algorithms. The effects of piezoelectricity have been neglected in our calculations since they are known to minimally affect the energy levels involved in optical transition. The dots considered here are assumed to be in the strong confinement regime; so Coulomb interaction is neglected.
The bound states of the quantum dots are found by numerically solving the Schrödinger equation. Our calculations of the peak luminescence energies are in good agreement with our experimental results and those of others. The ground state energy levels, as well as the first two excited energy levels are calculated as functions of the pyramid base for electrons and heavy-holes. The mixing of the light- and heavy-holes has been ignored in the calculations; instead, only the dominant behavior of the heavy-hole in the valence band is considered. The calculated energy separation between the ground and first/second excited state for electrons and for heavy-holes is in very good agreement with the available experimental photoluminescence, capacitance, and far-infrared absorption data.
A preliminary model, which accounts for indium composition variations in $In_xGa_{1-x}As$ (x=0.1-0.4) due to segregation, is developed. The model reproduces our cross-sectional HRTEM observations very well.

10:45 AM J1.8
IMPORTANCE OF THE WETTING PHENOMENON IN HETEROEPITAXIAL GROWTH. L.G. Wang, P. Kratzer, M. Scheffler, Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin-Dahlem, GERMANY.

Self-assembled InAs islands on the GaAs substrate formed in Stranski-Krastanow growth have attracted intense interest for use as quantum dots structures due to promising applications in optoelectronic devices. However, it is crucial that these islands are homogeneous in size and shape. In the present work, we have investigated the energetics of island growth with a parameter-free approach combining density-functional calculations and elasticity theory. We present two examples to show the importance of the wetting phenomenon in heteroepitaxial growth: one is that the island size is determined by a constrained equilibrium between islands and the wetting layer; another example is formation of a second wetting layer on top of a capping layer, which is the main driving force for the dissociation of partially covered islands. The latter has an important application to eliminate unwanted large islands by introducing an interruption during the growth of the capping layer. Therefore, we emphasize in the present work that to understand better surface morphology in heteroepitaxail growth it is important to take the wetting phenomenon into account.

11:00 AM J1.9
SIMULATIONS OF QUANTUM CONFINEMENT IN SELF-ASSEMBLED InAs/GaAs ISLAND QUANTUM DOT ARRAYS. H.T. Johnson, V. Nguyen, Boston University, Dept of Aerospace & Mechanical Engineering, Boston, MA; A.F. Bower, Brown University, Division of Engineering, Providence, RI.

The self-assembly and electronic properties of nanometer scale InAs island quantum dots on GaAs substrates has been a recent topic of interest in optoelectronics. The uniformity and ordering of arrays of the dots, the size and shape of individual dots, and the highly nonuniform lattice mismatch induced strain fields all strongly affect the experimentally measurable device properties of the arrays. Theoretical work on realistic arrays of island quantum dots has been limited. Here, a finite element approach is used to compute wavefunctions and energies of confined electron and hole states in arrays of InAs island quantum dots on GaAs substrates. Arrays for the calculations are taken from the output of a separate finite element morphology calculation, which has previously been shown to predict island shape and size distributions accurately relative to experimental observations. Arrays of 10-50 islands of varying size, shape, and spatial arrangement, due to varying growth times and conditions, are investigated. Spectra of confinement energies and the associated wavefunctions are calculated. The quantum mechanics calculation relies on a single charge carrier, multiple energy subband $\mathbf{k}\cdot\mathbf{p}$ Hamiltonian formulation and includes the effects of nonuniform lattice mismatch strain. Results include the effects of varying wetting and capping layer thicknesses and the consequences of island size and shape uniformity. Comparisons to experimental photoluminescence data are reported.

11:15 AM J1.10
QUANTUM CHEMICAL CONFINEMENT OF SMALL CdS AND CdSe NANOCRYSTALS. Christos Flytzanis, Laboratoire de Physique de la Matiere Condensee de l'ENS, Paris, FRANCE; Daniel Ricard, Laboratoire Aime Cotton, Universite Paris-Sud, Orsay, FRANCE; Erik Westin, Department of Physics, Chalmers University of Technology, Goteborg, SWEDEN.

Notwithstanding the success of the effective mass approximation (EMA) to describe the quantum confined "electron/hole" states in semiconductor nanocrystals there are several key features and issues there that cannot be addressed within this approach. Issues such as the rate at which the different electronic bulk properties emerge and stabilize as a few atom agregate evolves into a nano- or microcrystal as well as the relevance of different growth paths and the competition between "volume" and "interface" features and other physicochemical aspects are beyond the validity of EMA. To this purpose other descriptions borrowing from quantum chemical approaches are needed. Here we adopt such an approach and address such problems using a linear combination of atomic orbitals (LCAO-MO) modeling within the local density approximation and also including exchange-correlation to compare some ground state properties of a II-VI semiconductor cluster in a way similar to the one used for large molecular assemblies. We apply this approach to spherical clusters of CdS and CdSe. All clusters have a central Cd atom and clusters with 29, 47, 87 and 123 constituents have an outer shell of S (Se) atoms while clusters with 35, 71, 99, 147 and 381 constituents have an outermost shell of Cd atoms. Using a Mullikan projection analysis one can disentangle "band" and "surface" states and follow the stabilization of a clearly visible band gap for clusters beyond 123 atoms. The impact of "dangling bonds" is also analyzed. We also compute the Fermi level and find that this strongly depends on the outer shell constituents and can be related to a size dependent electron/hole affinity. We also calculate optical spectra and oscillator strengths within this approach and we obtain size dependent features and the appearance of resonances whose position is also size dependent.

11:30 AM J1.11
UNIVERSAL GAP FLUCTUATIONS IN THE SUPERCONDUCTOR PROXIMITY EFFECT. M. G. Vavilov, P.W. Brouwer and V. Ambegaokar, Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, NY; C.W.J. Beenakker, Instituut-Lorentz, Universiteit Leiden, Leiden, THE NETHERLANDS.

Random matrix theory is used to study the mesoscopic fluctuations of the excitation gap in a metal grain or quantum dot induced by the

proximity to a superconductor. We propose that the probability distribution of the gap is a universal function in rescaled units. Our analytical prediction for the gap distribution agrees well with exact diagonalization of a model Hamiltonian.

11:45 AM J1.12
DECOHERENCE EFFECTS IN ARRAYS OF COUPLED QUANTUM DOTS. Ernesto Cota, Fernando Rojas, Centro de Ciencias de la Materia Condensada - UNAM, Ensenada, MEXICO; Sergio E. Ulloa, Department of Physics and Astronomy and Condensed Matter and Surface Sciences Program, Ohio University, Athens, OH.

We study the effects of electron-phonon interactions on the distribution of charge (*polarization*) in arrays of four quantum dots located on the corners of a square, with two electrons added. This problem is relevant in the eventual use of these systems as basic cells for Quantum Cellular Automata (QCA) where the influence of the environment needs to be evaluated. A Hamiltonian that takes into account Coulomb interactions and tunneling between quantum dots in the occupation number representation is considered, with the addition of an interaction term where a phonon is emitted or absorbed by the presence of electrons in each site. By standard methods used to describe open systems based on second order perturbation theory, we derive the master equation for the reduced density operator and evaluate decoherence effects on the polarization properties of the cell. The influence of asymmetry in the electron-phonon coupling is also considered. We compare our results with other phenomenological treatments of the relaxation and discuss how this formalism may be generally useful in mapping the effective electron-phonon coupling in other quantum dot systems, where one or many electrons (and/or holes) may be excited in a single self-assembled dot.

SESSION J2: NANOCRYSTALS, COLLOIDAL DOTS, AND BIOLOGICAL APPLICATIONS
Chairs: Ulrike K. Woggon and Richard Noetzel
Monday Afternoon, November 27, 2000
Room 207 (Hynes)

1:30 PM *J2.1
OPTICAL GAIN AND STIMULATED EMISSION IN COLLOIDAL QUANTUM DOTS. V.I. Klimov, A.A. Mikhailovsky, Su Xu, A. Malko, J. Hollingsworth, Chemistry Division, Los Alamos National Laboratory, Los Alamos, NM; C.A. Leatherdale, M.G. Bawendi, Department of Chemistry and Center for MS&E, Massachusetts Institute of Technology, Cambridge, MA.

We investigate dynamical processes relevant to optical amplification and lasing in CdSe colloidal nanoparticles (colloidal quantum dots). Samples studied include quantum dot solutions, dispersions in polymers, and closely packed solid-state films (quantum dot solids). Depending on the matrix material, we observe either optical gain or excited-state absorption at the position of the emitting transition. In quantum dot films, at pump levels of one to two electron-hole pairs per dot on average, a narrow band stimulated emission with a pronounced threshold-type pump intensity dependence is detected [1]. In small-size quantum dots, intrinsic Auger recombination is the most important nonradiative process leading to fast density dependent decay of multiparticle states [2]. A dominant contribution to the band-edge optical gain is provided by doubly excited quantum dots. Therefore, the Auger time of the two-pair decay imposes an intrinsic limit on the lifetime of the optical gain in strongly confined nanoparticles. In this work, we apply different femtosecond spectroscopic techniques to study competition between nonradiative Auger recombination and the build-up of optical gain and stimulated emission. We also use these techniques to study matrix-dependent interplay between optical gain and excited-state absorption in different types of quantum dot samples. The studies performed provide a proof of principle for lasing in strongly confined quantum dots and point the way to new and exciting applications such as compact solid-state lasers and fiber amplifiers. 1. V.I. Klimov, A.A. Mikhailovsky, Su Xu, A. Malko, J. Hollingsworth, C.A. Leatherdale, and M.G. Bawendi, Science (submitted, June 2000). 2. V.I. Klimov, A.A. Mikhailovsky, D.W. McBranch, C.A. Leatherdale, and M.G. Bawendi, Science, vol. 287, 1011 (2000).

2:00 PM J2.2
PHOTO-ACTIVATION DEPENDENCE AND ENERGY TRANSFER IN ORDERED CdSe QUANTUM DOT ARRAYS. Steven R. Cordero, Paul J. Carson, Geoffrey F. Strouse, Steven K. Buratto, University of California Santa Barbara, Dept of Chemistry and Biochemistry, Santa Barbara, CA.

The optical properties of ordered 2-D and 3-D arrays of passivated CdSe quantum dots have been studied. We have observed photo-activation of the luminescence of these materials that is both reversible and environmentally sensitive. The luminescence quantum yield of the ordered assemblies increases by more then a factor of ten during the first 100 seconds of illumination presumably due to enhanced surface passivation by water molecules. We will discuss the many influences on the photo-activation, such as nanocrystal size, passivating layer, excitation power, film thickness, temperature, and relative humidity. Finally, because the increase in luminescence over time is photo-activated, we have used near-field scanning optical microscopy (NSOM) to measure the excited state diffusion length and pattern the CdSe quantum dot arrays.

2:15 PM J2.3
THE ASSEMBLY OF METALLIC AND SEMICONDUCTING NANOCRYSTALS USING BIOLOGICAL AND ORGANIC OLIGOMERS. Chol Steven Yun, Jody Major, Casey M. Hernandez, Stephen M. Woessner, Gregory A. Khitrov, Geoffrey F. Strouse, University of California, Department of Chemistry and Biochemistry, Santa Barbara, CA.

The two- and three-dimensional assembly of metallic and semi conducting nano-crystals, such as CdSe and gold, using both biological and organic oligomers hold potential as archetypical structure for nano-electronics as well as biological sensors. The application of biological oligomers to the assembly of nano-materials are pursued due to their natural characteristic to self organize. This attribute is imparted to nano-materials by means of attaching said biomolecules to the surfaces of the metallic or semi conducting crystals. The application of an organic conjugated oligomers; homo or hetero functional polyphenylacetylenes, to the surface of the materials permits nano-crystals to self assemble or assemble with the assistance of a metal ion. All of the aforementioned attributes of the bio/organic linkers are used to apply the techniques of crystal engineering to the assembly of nano-crystals.

2:30 PM J2.4
PHOTON-ANTIBUNCHING FROM SINGLE SEMICONDUCTOR QUANTUM DOTS AT ROOM TEMPERATURE. Michael D. Mason, Peter Michler, Donald J. Sirbuly, Paul J. Carson, Geoffrey F. Strouse, Atac Imamoglu, Steven K. Buratto, University of California, Dept of Chemistry and Biochemistry, and Dept of Electrical and Computer Engineering, Santa Barbara, CA.

Maxwell's equations successfully describe the statistical properties of fluorescence from an ensemble of atoms or an $n \geq 1$ dimensional semiconductor. In contrast, quantization of the radiation field is required to explain the correlations of light generated by a single two-level quantum emitter, such as an atom, ion or a single molecule. Here we report the experimental observation of photon anti-bunching from single semiconductor quantum dots of CdSe. Apart from providing a direct evidence for a solid state nonclassical light source, this result proves that a single QD acts like an artificial atom, with a discrete anharmonic spectrum. In addition, the relative size of the anti-bunching signature is used to determine the number (n = 1,2 or 3) of emitting species present in an individual nanoparticle or an aggregate of nanoparticles. We also compare the anti-bunching results to luminescence intensity histograms for a large distribution of single nanoparticles providing further insight into the luminescence properties of these interesting materials.

3:15 PM J2.5
QUANTUM-CONFINED ELECTRON TRANSITIONS IN CdSe NANOCRYSTALS. D.S. Ginger, A.S. Dhoot, C.E. Finlayson and N.C. Greenham, Cavendish Laboratory, University of Cambridge, UNITED KINGDOM.

We present quasi-steady-state photoinduced absorption measurements on thin films of colloidal CdSe nanocrystals. We observe an intense, size-dependent absorption peaking in the mid-infrared when the samples are irradiated with visible light. The absorption is accompanied by a bleach in the visible near the position of the first excitonic absorption and persists with a lifetime of milliseconds at room temperature. We characterize the lifetime of the electron state, its cross-section, and its sensitivity to surface chemistry. We attribute this feature to the 1S-1P transition of a delocalized electron.

3:30 PM J2.6
Abstract Withdrawn.

3:45 PM J2.7
LARGE BLUE SHIFT OF BAND GAP PHOTOLUMINESCENCE FROM ZnO QUANTUM DOTS EMBEDDED IN AlN MATRICES. C.W. Teng, J.F. Muth, R.M. Kolbas, North Carolina State University, Department of Electrical and Computer Engineering, Raleigh, NC; A.K. Sharma, A. Kvit, and J. Narayan, North Carolina State University, Department of Materials Science and Engineering, Raleigh, NC.

ZnO is a wide band gap semiconductor (~3.40 eV) with a high exciton binding energy of approximately 60 meV. While most of the existing reports on ZnO nanoparticles focused on the defect luminescence in the visible spectral range for phosphor applications, we have measured the influence of the quantum size effect on the emission energy of ZnO nanostructures. In the present report, five alternating layers of crystalline ZnO quantum dots embedded in an amorphous AlN matrix were deposited on sapphire (0001) substrates by pulsed laser deposition. The structural properties were investigated by high-resolution transmission electron microscopy and atomic force microscopy. The photoluminescence (PL) spectra were excited by the third harmonic output of a mode-locked Ti:sapphire tunable laser (~270 nm). A bright PL peak was observed at ~328 nm, about 0.45 eV blue shifted relative to the band gap of bulk ZnO. Almost no green emission, which is very common in the existing literature, was detected. PL spectra were also measured on similar structures without quantum dots and commercial ZnO nanoparticles not embedded in a dielectric matrix. Experimental data will be presented to demonstrate the physical origin and potential device applications of the blue-shifted luminescence peak from the nanostructures.

4:00 PM J2.8
BIOCONJUGATION OF LUMINESCENT CdSe-ZnS QUANTUM DOTS TO ENGINEERED RECOMBINANT PROTEINS USING SELF-ASSEMBLY: A NOVEL TOOL FOR BIOSENSING.
H. Mattoussi, G.P. Anderson, J.M. Mauro, and E.R. Goldman, US Naval Research Laboratory, Washington, DC, Optical Sciences Division and Center for Bio/Molecular Science and Engineering; V.C. Sundar, F.V. Mikulec, and M.G. Bawendi, MIT, Center for Materials Science and Engineering, Cambridge, MA.

Colloidal semiconductor quantum dots (QDs) are highly luminescent nanoparticles with a size regime and properties that make them ideal for use in biological tagging. Their size-dependent spectroscopic properties, namely absorption and photoluminescence allow the possibility of generating luminescence emission that spans a wide range of radiations in the visible and near IR regions of the optical spectrum with a single excitation wavelength, thus making them ideal for multiplexing studies. These properties combined with the superior resistance to chemical and photo-degradation and a high photo-bleaching threshold compared to organic labels make them suitable for online studies and increase the detection sensitivity. In this presentation, we discuss the use of a novel approach, driven by electrostatic self-assembly, for conjugating highly luminescent colloidal CdSe-ZnS nanocrystals with engineered two-domain recombinant proteins to form conjugates that have a potential use in biosensing and diagnostics applications. Aggregation-free aqueous dispersions of QD-bioconjugates with high quantum yield and improved stability have been prepared and tested. We describe the design and preparation of these hybrid conjugates as well as characterization studies, and discuss the use of these conjugates to detect various biological entities in displacement as well as sandwich assays. Aspects of making quantum dots with various recognition properties will be discussed.

4:15 PM J2.9
n-TYPE COLLOIDAL SEMICONDUCTOR NANOCRYSTALS.
Moonsub Shim, Philippe Guyot-Sionnest, University of Chicago, James Franck Institute, Chicago, IL.

Controlling the electron occupation with n- or p-type nanocrystals will play a crucial role in both electrical and optical properties and create more opportunities for device applications. However, conventional n- or p-doping by introducing impurity atoms has so far been unsuccessful and presents fundamental difficulties in the nanometer-size semiconductors. First, impurities tend to be expelled from the small crystalline cores as observed for magnetic impurities. Second, thermal ionization of the impurities to provide free carriers is hindered by the strong confinement. The difficulty of making n-type nanocrystals can be solved by an approach commonly used in the field of organic conducting polymers, namely, via electron transfer. We present infrared, optical and transport studies that provide an unambiguous evidence for preparation of n-type CdSe, CdS and ZnO nanocrystals.

4:30 PM J2.10
CdSe CLUSTER MOLECULES: MOLECULAR LIMIT OF A BULK SEMICONDUCTOR.
Andreas Eichhoefer, Forschungszentrum Karlsruhe, Institut fuer Nanotechnologie; Victor Soloview, Uri Banin, The Hebrew University Jerusalem, Department of Physical Chemistry; Dieter Fenske, Universität Karlsruhe, Institut fuer Anorganische Chemie.

CdSe nanocrystals serve as a prototypical system for the investigation of the evolution of properties by changing the size of the particles. We have extended these investigations down to the molecular regime and report on an investigation of the chemistry, structure, and electronic properties of a series of CdSe cluster molecules [1]. We have studied the structural pathway of the reaction forming small CdSe cluster-molecules and found that they display structure characteristics of both the zinc blende and the wurzite motif. The cluster compounds were prepared using the organometallic reaction of $CdCl_2$ with silylated chalcogenide compounds $RSeSiMe_3$/$Se(SiMe_{3\,2}$ (R = organic group) in the prescence of tertiary phosphine ligands. The driving force of the reaction is the cleavage of $ClSiMe_3$. Depending on the reaction conditions (solvent, temperature, stoichometricy) we were able to isolate and crystallize several cluster compounds $[Cd_4(SePh)_6Cl_4]^{2-}$, $[Cd_8Se(SePh)_{13}Cl_4]^{2-}$, $[Cd_{10}Se_4(SePh)_{12}(P^nPr_3)]$, $[Cd_{17}Se_4(SePh)_{24}(PPh_2^nPr)_4]^2$ and $[Cd_{32}Se_{14}(SePh)_{36}(PPh_3)_4]$. Their molecular structures were determined using single crystal Xray crystallography. The largest cluster molecule $[Cd_{32}Se_{14}(SePh)_{36}(PPh_3)_4]$ overlaps in size with the smallest CdSe nanoparticles of 1.7 nm in diameter. This is also evident from the comparison of the UV-VIS absorption spectra and the powder diffraction patterns of both compounds. Room temperature absorption and low temperature spectroscopy (PL, PLE) show that the absorption onset shifts considerably from 3.3 eV for the largest cluster to 4.2 eV for the smallest compound $[Cd_4(SePh)_6Cl_4]^{2-}$. Emission is only observed as a broad line at low temperatures and is shifted by 1 to 2 eV to the red of the absorption onset. This is fully consistent with the characteristics of the deep trapped emission in nanocrystal QDs. The systematic blue shift of the band gap for cluster molecules with reduced size, continues the trend observed for larger CdSe nanocrystals. This allows for a complete mapping of the band gap from the bulk semiconductor to the molecular regime. [1] V.N. Soloviev, A. Eichhöfer, D. Fenske, U. Banin, J. Am. Chem. Soc. (2000), 122, 2673

4:45 PM J2.11
SYNTHESIS OF SELF-ASSEMBLED METAL-OXIDE NANOSTRUCTURES IN A DIBLOCK COPOLYMER MATRIX AND INTEGRATION ONTO SEMICONDUCTOR SURFACES.
R.F. Mulligan[1], A.A. Iliadis[2], P. Kofinas[1], A. Lappasi[2], U. Lee[3]. [1]Materials and Nuclear Engineering Department, University of Maryland, College Park, MD; [2]Electrical and Computer Engineering Department, University of Maryland, College Park, MD; [3]Army Research Laboratory, Adelphi, MD.

The next generation of nanoscale electronic devices and circuits require the development of novel engineered materials that can be successfully integrated in the existing technology, and the synthesis and selective application of such engineered materials is of critical importance to the development of functional nano-devices. Nanocomposites, such as metal oxide nanoclusters within a polymer matrix, are expected to be an important class of materials in the area of nano-device fabrication. The synthesis of self-assembled ZnO nanoclusters within microphase separated diblock copolymer templates is reported for the first time. The properties of the nanoscale material are investigated and compared to bulk material behavior. Block copolymers of poly(norbornene) and poly(norbornene-dicarboxylic acid) were synthesized by Ring Opening Metathesis Polymerization (ROMP). This technique allows the polymerization of monomers with a variety of functional groups and results in a narrow molecular weight distribution. Polymer solutions were doped with $ZnCl_2$, from which smooth uniform films were cast. Treatment of these films by wet chemical methods at room temperature allowed the conversion to ZnO. GPC was used to determine the molecular weight and molecular weight distribution of the synthesized polymers. XPS was employed to verify the ZnO synthesis, and the morphology of the metal oxide containing microdomains was investigated by TEM and AFM. The electrical evaluation of the system and the selective application of the self-assembled nanostructures on semiconductor surfaces for functional nano-devices will also be reported. Acknowledgements: This work is supported by NSF grant #9980794.

SESSION J3: POSTER SESSION
SEMICONDUCTOR QUANTUM DOTS
Chairs: Diana Huffaker, Richard Noetzel, Rosa Leon and Simon Fafard
Monday Evening, November 27, 2000
8:00 PM
Exhibition Hall D (Hynes)

J3.1
QUANTUM DOT CELL COUPLED TO A SINGLE MODE QUANTUM CAVITY.
Fernando Rojas, Ernesto Cota, Centro de Ciencias de la Materia Condensada-UNAM, Ensenada, MEXICO; Sergio E. Ulloa, Dept. of Physics and Astronomy and Condensed Matter and Surface Sciences Program, Ohio University, Athens, OH.

We study the properties of the charge distribution (polarization) of a square cell with 4-quantum dots with two electrons, induced or modified by the coupling to a single quantized mode field (cavity). The cells are proposed as basic elements of quantum cellular automata (QCA). In the model, the electrons in the cell can tunnel from dot to dot and Coulomb interaction is included. The quantum cavity is modeled with a harmonic field and its coupling to the cell modulates the electrons' on-site energy. The effect of the relevant parameters (tunneling of electrons between dots, amplitude of the electron-cavity interaction, cavity frequency) is investigated in the properties of polarization of the two-electron fundamental states. We further investigate the asymmetry effect in the electron-cavity interaction in each dot and evaluate the modifications in the dynamic evolution of the polarization. We specifically separate the contribution of each quantum of energy of the cavity to evaluate its contribution to the electronic properties of the cell, and find that there is a range of values of the asymmetry for which the polarization is improved. This suggests that an optimization of the QCA interaction with its environment may yield more reliable and stable operation.

J3.2
ATOMISTIC STUDY OF STRAIN PROFILES IN SEMICONDUCTOR QUANTUM DOT STRUCTURES. K. Shintani, H. Sugii, Y. Kikuchi, M. Kobayashi, Dept of Mechanical Engineering and Intelligent Systems, University of Electro-Communications, Tokyo, JAPAN.

The stable atomic structures of Ge/Si and InAs/GaAs quantum dots are calculated by the conjugate gradient minimizations of the potential energies of the systems. As for Ge/Si dots, the Ge island is assumed to be covered or uncovered by a Si capping layer and is assumed to be of pyramidal shape. The two empirical potentials, the Keating and Stillinger-Weber potentials, are used. The strain profiles along the three paths within the dot structure and along the surface of the capping layer are presented. While the profiles of the normal strain in the direction parallel to the island base obtained by using the two potentials agree with each other except within the substrate and at the edges of the island in the covered structures, the two profiles of the normal strain in the direction perpendicular to the island base show a considerable difference in their magnitudes, and it is found that the result of the Stillinger-Weber potential is valid from the physical point of view. The strain profile along the surface of the Si capping layer is discussed in relation to the vertical ordering of stacked islands. As for InAs/GaAs dots, the three- and five-layer stacked structures are considered, and only the Stillinger-Weber potential is used. The InAs islands are assumed to be of pyramidal and truncated pyramidal shapes. The normal strains exhibit the stepwise up-and-down profiles along the vertical center lines of the islands and intermediate layers. The normal strain in the direction perpendicular to the island base in the five-layer structure consisting of truncated pyramidal islands changes its sign within the second and third stacked islands. On the other hand, there appear no such sign inversions of the normal strains in the stacked islands of pyramidal shape.

J3.3
MANY BODY EFFECTS IN PHOTO-CONDUCTIVITY IN SELF-ASSEMBLED InAs/GaAs QUAMTUM DOTS. Mitsuru Inada, Kazuhiro Ohnishi, Ikurou Umezu, Akira Sugimura, High Technology Research Center, Konan University, Kobe, JAPAN; Pablo O. Vaccaro, ATR Adaptive Communications Research Laboratories, Kyoto, JAPAN.

We report photo-conductivity measurements of inter-dot tunneling in self-assembled InAs quantum dots with illumination from a Ti-sapphire laser light, and the wavelength of which is 800nm. We observed resonance-like peaks only high dot density samples and the resonance peak shifts to a higher voltage when carriers generated by increasing the laser power or temperature. These results indicate that the observed peaks can be attributed to the current originated from inter-dot tunneling and many body effects play some role on the transport properties in these samples. We thus consider that the present quantum dot samples may provide a novel system with strong correlation to study electron transport under the influence of many-body effects.

J3.4
TIME RESOLVED MICROSCOPIC PHOTOLUMINESCENCE SPECTROSCOPY OF SELF-ASSEMBLED QUANTUM DOTS. Zhiheng Liu, G.E. Bunea, H. Robinson, B.B. Goldberg, Boston Univeristy, Physics Department, Boston, MA; S. Farard, Institute of Microstructral Science, NRC, Ottawa, CANADA.

Experimental and theoretical investigations of the physics of self-assembled quantum dots(QD) have been focused on the nature of the individual dots independent of the surroundings or the neighboring dots. However, the coupling of dots to each other, an external cavity or nearby localized states, is an important area of investigation. For example, it has been found that the carriers may tunnel through the potential barrier of one QD to another QD via the localized states of the wetting layer(WL) [1]. We employ scanning confocal microscopy combined with time resolved photoluminescence spectroscopy to study small ensembles of InGaAs/GaAs self-assembled quantum dots at low temperatures. Due to high throughput of our experimental set-up we were able to observe state filling of individual dots. We explored the interaction between QDs and WL as well as the dynamics of the interband radiative recombination and intersublevel thermalization by determining the lifetimes of carriers in QDs and WL and then studying the relationship between these lifetimes. [1] H.D. Robinson, B.B. Goldberg, Physica E.6, 444 (2000)

J3.5
STUDY OF SELF-ORGANIZED InAs/GaAs QUANTUM DOTS BY PHOTOLUMINESCENCE AND PHOTOREFLECTANCE. J.S. Hwang, W.C. Hwang and W.Y. Chou, Department of Physics, National Cheng Kung University, Tainan, TAIWAN

Using photoluminescence and photoreflectance ranging from 8 to 300K, this study investigates transition energies in InAs/GaAs quantum dot (QD) samples grown on (100) misoriented 7° toward (110) GaAs substrates using gas source molecular beam epitaxy with various V/III ratios. Only exciton transition appears in the PL spectra of all samples. The decrease of the FWHM of the PL peak as the temperature increases can be attributed to the effective suppression of non-predominant size QD emissions due to carrier tunneling between nearby dots. Signals from all the relevant portions of the samples have been observed in the PR spectra. One to three transition energies in QDs, depending on the dot size, are observed in the PR spectra. Furthermore, the binding energies of excitons and thus the QD size are estimated from the temperature dependence of the exciton energies and the first transition energies of QDs.

J3.6
DETAILED STUDIES OF SPATIAL ORDERING OF In(Ga)As QUANTUM DOTS IN MULTILAYER In(Ga)As-GaAs QDS STRUCTURES. N. Faleev, L. Grave de Peralta, and H. Temkin, Texas Tech Univ, Dept of Electrical Engineering, Lubbock, TX; Yu. Musikhin, A. Suvorova, and V. Ustinov, Ioffe Physical-Technical Institute, St. Petersburg, RUSSIA; M. Tabuchi, Y. Takeda, Nagoya Univ, Dept of Materials Science & Engineering, Nagoya, JAPAN; T. Kawamura, Y. Watanabe, NTT Basic Research Laboratories, Atsugi, Kanagawa, JAPAN.

Heterostructures with QDs are very interesting physical and structural objects, which have unique physical properties and high potential for device application. They are very attractive for structural investigations because there is a strong correlation between their structural and physical properties. X-ray diffraction and TEM experiments prior to our study have shown the presence of vertical and lateral ordering of QDs and a relief of crystalline planes around QDs and in the upper layers [1,2]. We used x-ray and synchrotron diffraction, x-ray reflectivity and synchrotron grazing incidence diffraction, and transmission electron microscopy for detailed studies of spatial ordering of In(Ga)As Quantum Dots (QDs) in In(Ga)As-GaAs multilayer structures. We have studied heterostructures containing 3-15 QD layers of In(Ga)As, each two monolayers of InAs thick, separated by layers of GaAs, each 5 nm thick. In such structures spatial ordering of QDs is essentially anisotropic relative to [110] and [1-10] directions and is the result of relaxation of elastic strain caused by QDs. The anisotropy ordering of QDs leads to corrugated relief of crystalline planes. Spatially ordered QDs form rows of quasi-Quantum Wires, oriented along the [1-10] direction, without long-range ordering of QDs within rows. Additional lateral long-range ordering was found between rows of QDs in the perpendicular [110] direction. The corrugation of crystalline planes perseveres by upper layers without QDs. It slowly diminishes under optimum epitaxial growth conditions with increasing of the layer thickness. [1]. N. Faleev, K. Pavlov, M. Tabuchi, Y. Takeda, Jpn. J. Appl. Phys. 38, 818 (1999). [2]. N.N. Faleev, A.Yu. Egorov, A.E. Zhukov, et al., Semiconductors 33, 1229 (1999).

J3.7
OPTICAL INVESTIGATION OF ALMBE GROWN InAs SELF-ASSEMBLED QUANTUM DOTS EMBEDDED IN $In_xGa_{1-x}As$ MATRIX. M. Geddo, INFM-UdR Pavia and Dept of Physics Univ. Parma, ITALY; G. Guizzetti, M. Patrini, R. Pezzuto, INFM-Dept. Physics, Pavia, ITALY; S. Franchi, P. Frigeri, CNR-MASPEC Institute, Parma, ITALY.

The achievement of tunability of quantum dots (QDs) properties and in particular of their characteristic emission energy would significantly widen the application field of nanostructures. Concerning InAs/GaAs self-assembled QDs, typically emitting at RT in the 1.05-1.18 μm range, by varying the growth conditions and/or by using opportunely

spaced structures, one can expect to drive the emission wavelength towards the 1.3 μm window of interest for silica fiber communications. Recently it has been shown that InAs/GaAs self-assembled QDs grown by Atomic- Layer MBE (ALMBE) emit, at room temperature, at energies close to 1.3 mm [1-2]. In this work systematic photoreflectance (PR) measurements of the ground state transition energy of InAs QDs embedded in $In_xGa_{1-x}As$ matrix (with x from 0 to 0.28) are presented, demonstrating the possibility of tuning the QD optical response. The samples consist of a 100 nm thick GaAs buffer layer grown by MBE on (100) GaAs substrates. A single layer of self-assembled InAs QDs embedded in a $In_xGa_{1-x}As$ layer 5-10 nm thick and a 10 nm thick GaAs cap layer were grown by ALMBE. The InAs coverage was 3 ML. The samples have been characterized by photoluminescence and spectroscopic ellipsometry. The QD mean sizes were determined by Atomic Force Microscopy. Photoreflectance measurements were performed in the 0.8-1.5 eV energy range. The optical spectra were analyzed by using PR lineshape models characterizing electromodulated signals in bound states of confined semiconductor systems. Room temperature QD spectral features were located at 1.27-1.36 μm, depending on the In content of the embedding matrix, and exhibited a temperature behavior similar to that of the InAs band gap. The evolution of the ground state transition energy and of the In segregation length vs. x is discussed. [1] A. Bosacchi et al. J. Crystal Growth 175/176, 771 (1997) [2] M. Geddo et al. European Physical Journal B, in press.

J3.8
ELECTRON MICROSCOPY STUDY OF ZnTe/CdTe SUPER-LATTTICE WITH HIGH DENSITY OF QUANTUM DOTS. S. Kret, P. Dluzewski, A. Szczepanska, S. Mackowski, T. Wojtowicz, G. Karczewski, J. Kossut, Institute of Physics, Polish Academy of Sciences, Warszawa, POLAND; P. Dluzewski, P. Traczykowski, Institute of Fundamental Technological Research, Polish Academy of Sciences, Warszawa, POLAND; Pierre Ruterana, ISMRA, Caen, FRANCE.

ZnTe/CdTe superlattices containing a high density of quantum dots prepared by using MBE were examined by TEM methods. The HRTEM cross-sectional specimens showed superlattice period of 15 ML (13ML of ZnTe and 2 ML of CdTe) and the density of QD 4.0E6 for one cube micrometer. The diameter of this Cd rich island varies from 4 to 8 nm and the island heights do not exceed one nm. The mean distance between islands centre is about twice their diameter. The Cd concentration in the superlattice structure was estimated from measurement of local lattice parameter and digital processing of experimental and simulated HRTEM images. Computer simulation was performed by using 3D lattice deformation model derived from finite elements calculation of strain distribution of superlattice cross -section for different foil thicknesses. Various models of Cd atoms distribution as well as different shapes of island were examined. Finally, it was found that the concentration of Cd outside islands drops to near zero and reach more than 50% at the island centre. Regions with multilayer ordering of QD was observed and the anticorrelation configuration was found as the dominant form. Our electron microscopy investigations reveal very good separation of individual QDs and their high morphological homogeneity as well as absence of structural defects which is in agreement with relatively good photoluminescence properties of such structures.

J3.9
NOVEL MOLYBDENIUM SULFIDE MATERIALS. Gregory A. Khitrov, Stephen M. Woessner, Chosu Nwe, Jennifer Keyani, Geoffrey F. Strouse, Department of Chemistry, University of California, Santa Barbara, CA.

Molybdenum sulfide materials have been intensively studied for the last 15 years primarily because of their numerous applications in catalysis of hydrodesulfurization, hydrogenation, and other processes. These materials also have potential applications as electrodes in photoelectrochemical solar cells due to their stability to photo oxidation. Nano-sized molybdenum sulfide materials were recently reported to have unique and potentially useful optical and electronic properties. We will discuss the preparation of a novel molybdenum sulfide material and its characterization by electronic and vibrational spectroscopies as well as elemental analysis, TEM and XRD.

J3.10
SYNTHESIS AND CHARACTERIZATION OF NOVEL MAGNETIC SEMICONDUCTOR NANOCRYSTALS. Stephanie Chaney, Gary Braun, Geoffrey Strouse, University of California, Santa Barbara, Dept of Chemistry, Santa Barbara, CA.

Nanomaterials offer an opportunity to probe intermediate phase materials exhibiting unique magnetic structures. A series of novel magnetic semiconducting nanocrystals, based on europium and iron chalcogenides, offer insight into the effects of confinement on magnetic materials. Probing the optical band gap, electronic structural changes upon application of a magnetic field can be studied. By examining the magnetic phase transitions occurring in each series, questions about magnetic ordering in nanoscale materials can be addressed. The synthesis and preliminary magnetic characterization of these materials will be shown.

J3.11
InGaAs QUANTUM DOTS EMBEDDED IN P-N JUNCTION ON GaAs(311)B SUBSTRATE. Kouichi Akahane, Haizhi Song, Yoshitaka Okada and Mitsuo Kawabe, University of Tsukuba, Inst. of Applied Physics, Tsukuba, JAPAN.

Our research has been focused on the fabrication of self-organized InGaAs quantum dots (QDs) on GaAs(311)B substrates by atomic hydrogen-assisted molecular beam epitaxy. Previously, we have successfully demonstrated a high-density, uniform and well-ordered QDs array, which showed a strong photoluminescence (PL) emission and narrow linewidth. For device applications such as QDs lasers, one needs to bury the QDs in an optimally designed device structure. To this end, we have evaluated the properties of QDs embedded in a p-n junction on GaAs(311)B and were compared with the identical structure grown on GaAs(001). The samples were fabricated as follows: a 300nm-thick n-type GaAs buffer layer was first grown at 580°C. Then, an 100nm-thick n-type AlGaAs barrier layer followed by a 40nm-thick GaAs spacer layer were grown at 610°C. After lowering the substrate temperature to 500°C, a 8.8 monolayer (ML) InGaAs QD layer was deposited. On the QDs layer, a 40nm-thick GaAs spacer layer was grown at 500°C, followed by a 100nm-thick p-type AlGaAs then a 5nm-thick p-type GaAs cap layer grown at 600°C. First, we evaluated the excitation power dependence of QDs PL spectra at 4.2K. The PL emission from the QDs grown on GaAs(311)B decreased monotonically with decreasing excitation power. A clear PL emission was observable even at a low excitation power of $0.1W/cm^2$. On the other hand, the PL emission from the QDs grown on GaAs(001) rapidly disappeared when the excitation power was decreased below $0.4W/cm^2$. This suggests that the amount of carriers which contribute to the radiative process at a given excitation power is greatly reduced in the QDs grown on GaAs(001) compared to the self-organized QDs on GaAs(311)B. The possible reasons responsible for the reduction of PL are thought to be due to the differences in the recombination rates through a non-radiative process and/or the escape rate of carriers out to the GaAs through a tunneling process.

J3.12
CdS NANOSTRUCTURES GROWN BY PULSED LASER DEPOSITION. Carlos Manzano, Román Castro, Iván Oliva, Applied Physics Department, CINVESTAV-IPN Mérida, Mérida, Yucatán, MÉXICO; Juan L. Peña, CICAT-IPN, Irrigación, México, MÉXICO.

The growth of nanoscale islands of CdS on glass by pulsed laser deposition is reported. Atomic force microscopy measurement revealed the formation of elliptical islands with typical heights of 9.18 ± 4.70 nm and lengths of the major axis of 82.21 ± 18.34 nm. These results are in agreement with reports in III-V and II-VI islands grown by MBE. The adequated parameters to get this kind of nanostructures are determined. X-ray photoelectron spectroscopy analysis were realized to determine the superficial composition.

J3.13
ENERGY TRANSFER DYNAMICS IN CdSe NANOCRYSTALS. Stephen M. Woessner, Chol Steven Yun, Geoffrey F. Strouse, Dept of Chemistry, University of California, Santa Barbara, CA.

The photophysical properties of CdSe quantum dots (QD) have been extensively studied in the past 10 years. Energy transfer dynamics between the quantum dot and selected dye molecules using photoluminescence quenching could possibly be a new direction in studying the photophysical properties of these materials. Judicious choice of quantum dots and dye molecules will allow for QD ← dye; dye ← QD; or even QD1 ← QD2 energy transfer studies. A logical extension of these energy transfer studies would be to append the quantum dot to the dye molecule using an organic bridge capable of passivating the quantum dot surface. The results of these energy transfer studies will be presented.

J3.14
QUANTUM DOT INTERMIXING IN InAs/AlGaAs AND InAs/GaAs. C. Nì Allen[a], University of Ottawa, Physics Department, Ottawa, CANADA; J.J. Dubowski, P.G. Piva, and S. Fafard, Institute for Microstructural Sciences, National Research Council, Ottawa, CANADA. [a]Also at: Institute for Microstructural Sciences, National Research Council, Ottawa, CANADA.

Photoluminescence (PL) was used to investigate the interdiffusion of self-assembled InAs/GaAs quantum dots (QDs) treated by rapid thermal annealing (RTA) and laser annealing. The observation of intense and sharp shell structures confirmed that the QDs retained

their zero-dimensional density of states. In addition, three main effects of alloy intermixing were demonstrated in QDs having different intersublevel spacings. The emission has been strongly blue-shifted, up to ~200 meV for RTA samples and ~298 meV for the laser annealed ones. The intersublevel spacing was tuned between ~60 meV to ~25 meV in the RTA case, but down to ~12 meV in the case of laser-induced intermixing. Finally the inhomogeneous broadening linearly decreased from a FWHM of ~46 meV down to smaller than 15 meV for RTA and 8 meV in the most extreme case of laser annealing. For samples annealed at the highest temperatures, the most energetic shells of QDs become unbound. Across varying samples, the result of the intermixing was to increase the uniformity of their PL spectra. A one-dimensional model of Fickian diffusion for the growth direction was used to model their PL emission. In order to complete this investigation, the behaviour of the QDs PL intensity was studied to determine if the intermixing induces non-radiative defects. Furthermore, the binary-ternary QD system InAs/AlGaAs was also subjected to intermixing. Rapid thermal annealing and laser annealing provide two additional ways of manipulating the energy levels of self-assembled QD ensembles by tuning the intersublevel energy-spacing and the number of confined states.

J3.15
MAGNETO-PHOTOLUMINESCENCE OF INTERMIXED SELF-ASSEMBLED InAs/GaAs QUANTUM DOTS. Samuel Menard, Jean Beerens, Denis Morris, Centre de Recherche sur les Proprietes Electroniques de Materiaux Avances, Departement de physique, Universite de Sherbrooke, Sherbrooke, Quebec, CANADA; Simon Fafard, Institute of Microstructural Sciences, National Research Council of Canada, Ottawa, Ontario, CANADA.

The electronic structure of InAs/GaAs self-assembled quantum dots (QDs) and the carrier capture dynamic in these dots, have been studied by using a magneto-photoluminescence (PL) experiment at 4.5K. The emission spectra of a large ensemble of dots are obtained for different excitation densities, in magnetic fields up to 16 Tesla with the field oriented perpendicular to plane of the dot. At sufficiently high laser excitation density, the PL spectra reveal the shell structure (s, p, d and f states) of the lens-shaped quantum dots together with the GaAs barrier and the wetting layer (WL) emission bands. We have studied a series of intermixed samples obtained by rapid thermal annealing at 850°C at different times. This intermixing causes strong blueshifts and a pronounced narrowing of the inhomogeneously broadened QD emission. The better-resolved QD PL peaks observed for the intermixed samples allow us to study the behavior of each electronic level in magnetic field. The magneto-PL spectra show the diamagnetic shift of each state and a clear Zeeman splitting of the p-shell. For the higher excited levels the splitting is less obvious since we observe some broadening of the QD emission with increasing magnetic field and laser excitation density. This behavior will be discussed in term of multi-excitonic states. It is also found, that the ratio of the WL peak intensity over the QD emission intensity increases with the magnetic field. This behavior can be explained by looking at the influence of the magnetic field on the carrier capture efficiency when the cyclotron orbit becomes comparable to the carrier diffusion length and to the mean distance between the dots.

J3.16
PROBING RADIATIVE AND SPIN DYNAMICS IN SEMICONDUCTOR NANOCRYSTALS WITH CAVITY QUANTUM ELECTRODYNAMICS. Hailin Wang, Xudong Fan, University of Oregon, Department of Physics, Eugene, OR; Mark C. Lonergan, University of Oregon, Department of Chemistry, Eugene, OR.

We probe radiative and spin dynamics in core/shell semiconductor nanocrystals by modifying spontaneous emission rates of nanocrystals using an optical microcavity. Embedding core/shell CdSe/ZnS nanocrystals in a polystyrene sphere, we have singled out from the complex time-resolved photoluminescence a decay component that exhibits enhanced spontaneous emission rates when the photoluminescence is resonant with a whispering gallery mode. We attribute this component, which has a radiative lifetime of order 15 ns, to optical emissions of the lowest dipole-allowed excitonic transition in the nanocrystals.

J3.17
A TWO-DOMAIN RECOMBINANT PROTEIN FOR CONJUGATION OF LUMINESCENT QUANTUM DOTS WITH ANTIBODIES FOR USE IN IMMUNO-ASSAYS. E.R. Goldman, J.M. Mauro, H. Mattoussi, and G.P. Anderson, US Naval Research Laboratory, Washington, DC, Center for Bio/Molecular Science and Engineering and Optical Sciences Divison.

We have shown that charged semiconductor quantum dots (QDs) can be strongly but non-covalently conjugated with a chimeric version of E. coli maltose binding protein engineered with a high density of opposite charges at its C-terminus. Following success with this model system, an analogous approach was developed for rapid and simple attachment of antibodies to quantum dots. The charged C-terminal segment of an engineered β_2 IgG binding domain of streptococcal protein G (P-G) strongly interacts with quantum dots while carrying a domain that permits specific binding to the Fc region of immmunoglobulin G (IgG) antibodies. The recombinant two-domain protein G derivative was expressed, purified, and tested for IgG binding, activity, and confirmed to associate with charged colloidal quantum dots. QD/P-G conjugate was then modified with selected IgG antibodies forming QD/P-G/IgG bioconjugates. We describe the design, synthesis, and characterization of the P-G recombinant protein. We then discuss non-covalent conjugation of this P-G derivative with CdSe-ZnS QDs, and subsequent development of protocols for sandwich-type fluoroimmoassays using the antibody-coated QDs for detection.

J3.18
THE ENHANCEMENT OF BAND EDGE EMISSION FROM ZnS/Zn(OH)2 QUANTUM DOTS. Hatim Mohamed El-Khair, Ling Xu, Xinfan Huang, Minghai Li and Kunji Chen, State Key Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing, CHINA.

In this work we report, for the first time, the synthesis and enhancement of band edge emission of highly monodispersed ZnS quantum dots (QDs) coated with wider band gap Zn(OH)2 shell. The QDs structure analysis has been investigated by electron transmission microscopy (TEM) and electron diffraction pattern (ED). The diameter of the colloidal particles is ranging from 1 nm to 5 nm and the electron diffraction results reflect wutzite structure of our ZnS QDs. The photoluminescence (PL) spectrum for ZnS QDs prepared from precursors dispersed in water, display a broad emission band ranging from 400 to 476 nm, which seems to be far red shifted from the absorption edge 350 nm. This PL is attributed to the recombination of the charge carriers in surface traps due to S vacancies in water. When the precursors were dispersed in ethanol and reacted in ethanol to form ZnS QDs. Their PL properties show a broad emission band ranging from 350 to 400 nm with the absorption edge near 350 nm. This PL is attributed to the mixing of the near band edge emission and the surface traps states. Due to the SH-group radiationless recombination of carriers occurred, and hence degrades the surface emissiion. Therefore, the solvents match strongly influence PL properties of ZnS QDs. These effects are due to the action of polarities difference for solvents. Hence to attain high quantum yields, we apply wider band gap coating using Zn(OH)2 to develop core/shell structure of ZnS/Zn(OH)2 quantum dots in ethanil. The addition of OH- converts HS- into S2- forming S2—Zn2 –OH2- structure and hence reducing the S vacancancies. The PL properties of this structure display narrowed band emission near 350 nm near to the absorption edge. This PL is attributed to the band edge emission of ZnS QDs, hence from the features of the PL and absorption spectrum of ZnS/Zn(OH)2 QDs indicates that, The surface of ZnS QDs has been perfectly passivated.

J3.19
SYNTHESIS, SURFACE MODIFICATION OF CdSe, CdSe/ZnS AND CdSe/CdS CORE/SHELL SEMICONDUCTOR QUANTUM DOTS AND THEIR USE AS LUMINESCENT PROBES IN BIOLOGICAL APPLICATION. Srikant Pathak, Mark Thompson, Dept of Chemistry, Univ of Southern California, Los Angeles, CA; Soo-Kyung Choi, Norman Arnheim, Dept of Molecular Biology, Univ of Southern California, Los Angeles, CA.

High temperature synthesis of luminescent multicolor (500-650 nm) CdSe semiconductor quantum dots of different sizes (2-5 nm) is done using a known literature procedure. The core CdSe dots are then capped by either ZnS or CdS (~2 nm) shell to enhance their luminescence efficiency. The core and core shell dot (QDs) surface was then modified with different functional groups i.e., -NH_2, -COOH etc., using a series of bifunctional linkers i.e., mercaptoacetic acid, mercaptopropionic acid, mercaptobenzoic acid etc., to render it water soluble and their relative stability with respect to hydrolysis under pH range 7.0-8.0 has been studied. To make functional dots, we covalently attach them to an amine group at the $5'$ end of oligonucleotide sequences using standard DIC (1-ethyl-3-(3-methylaminopropyl) carbodiimide hydrochloride) coupling. The resulting QD-oligonucleotide conjugates were then studied for their stability against hydrolysis and binding efficiency by (a) dye labeled oligonucleotides and (b) desorption of dye tagged oligonucleotides after a period of time. The conjugates were found to be stable for at least two months under hybridization conditions. Our purpose is to use multicolor QD-oligonucleotide conjugates as luminescent probes and to detect chromosomal abnormalities and/or gene mutations using FISH (fluorescence in situ hybridization) procedures. The ability to detect chromosomal DNA sequences in side cells was tested using human alphoid repeated sequences specific to the X or Y chromosomes. Random sequences were used as a control. The oligonucleotide

derivatized quantum dots were hybridized either with human sperm cells or lymphocytes. Specific binding of the probes could be observed in many cases after FISH. The advantage of these QD-conjugate probes include their high luminescece, resistance to photobleaching and stability for months.

J3.20
OBSERVATION OF CdSe COLLOIDAL NANODOT FILMS BY SCANNING PROBE MICROSCOPY. Ichiro Tanaka, Eri Kawasaki, Osamu. Ohtsuki, Wakayama Univ, Dept of Mat Sci & Chem, Wakayama, JAPAN; Soichiro Saita, Itaru Kamiya, Mitsubishi Chemical Corp, Yokohama, JAPAN.

Fabrication of colloidal nanodot films has been of interest both from the fundamental and the applicational point of views because they exhibit nano-size or quantum effects. In order to prepare structures that function as optoelectronic devices, it is indispensable to characterize and control their dimensions on nanometer scale. However, their morphological investigation require special care since colloidal nanodots prepared by wet chemistry are covered by organic surfactants, and consequently, the thin films prepared are composites of inorganic dots and organic matrix. Here, we report the atomic force microscopy (AFM) observation of thin films of CdSe nanodots embedded in tri-n-octylphospine oxide (TOPO). We find that images obtained from such films are extremely sensitive to the parameters employed in the cyclic contact-mode AFM, such as the amplitude or frequency of the oscillation of the cantilever. When the probe is not adsorbed onto the surface, the force curves exhibit normal behavior, and clear corrugations around structures that are ca. few nm are observed. We assign these structures as individual CdSe nanodots, which will then allow us to investigate electronic properties of each dots by tunneling spectroscopy, for instance.

J3.21
EFFECTS OF SPACER THICKNESS ON THE PERFORMANCE OF InGaAs/GaAs QUANTUM DOT LASERS. Nien-Tze Yeh, Wei-Sheng Liu, Shu-Han Chen, Jen-Inn Chyi, Department of Electrical Engineering, National Central University Chung-Li, TAIWAN, R.O.C.

Due to the atomic like energy level, semiconductor quantum dot (QD) lasers were proposed to be a promising device exhibiting high differential gain, low threshold current, and high characteristic temperature. One of the key design parameters for QD lasers is the thickness of the spacer separating the QD layers. However, the influence of the spacer thickness on the performance of QD lasers has hardly been investigated. In this work, the effects of the spacer thickness on the threshold current, thermal stability, quantum efficiency, and internal loss of InGaAs QD lasers are analyzed and discussed. The lasers studied in this work are linear graded-index separate confinement heterostructure lasers. The active region consists of 5 stacks of 5-monolayer InGaAs QDs separated by 10, 20, 25 and 30 nm GaAs spacers, respectively. The quantum dot active region is sandwiched by two 150 nm-thick undoped AlGaAs guiding layers. Both the n- and p-type cladding layers are 1500 nm-thick AlGaAs. Room temperature photoluminescence spectra show that the linewidth of the 5-stacks QD samples increases from 40 to 52 meV as the spacer thickness increases. The lasing wavelengths of these lasers are about 978 nm and independent of the spacer thickness. This indicates that inhomogeneous broadening due to dot size fluctuation with spacer thickness dominates the emission spectra. The threshold current density is 792 A/cm^2 for the laser with a spacer thickness of 10 nm. As the spacer thickness is increased to 30 nm, a steep increase in threshold current to 1260 A/cm^2 is observed. This increase in threshold current is attributed to the decrease in gain as evidenced by larger PL linewidth with thicker spacer. The characteristic temperature decreases from 112 K to 79 K and the internal quantum efficiency deteriorates from 89% to 19% when the spacer thickness is increased from 10 nm to 30 nm.

J3.22
InAs QUANTUM DOTS GROWN ON AN AlGaAsSb METAMORPHIC BUFFER. Y. Lin, A. Stintz, L.R. Dawson, Y.-C. Xin, A.L. Gray, and L.F. Lester, Center for High Technology Materials, University of New Mexico.

Quantum dot (QD) lasers grown on a GaAs substrate are currently a subject of strong interest with 1.3-mm emission from InGaAs QDs having been reported by various groups. To extend the emission wavelength of InAs QDs on GaAs to 1.55-mm, larger QDs with reduced strain are required. Since the lattice mismatch is the driving force for the formation of compressively strained dots, reducing the mismatch leads to a greater thickness of the initial 2D wetting layer that grows before strain energy accumulates and dots form. As the QDs enlarge, part or all of the wetting layer is consumed, leading to larger dots. Thus, the reduced strained ultimately leads to the opportunity to grow larger dots. To reduce the lattice mismatch between the InAs dots and their surrounding material, we provided a growth platform with a lattice constant significantly greater than that of GaAs by using an AlGaAsSb metamorphic buffer on a GaAs substrate. We have found that these layers leave only a light crosshatching feature on the surface of the wafer. The structures studied were grown by solid-source MBE, and the metamorphic buffer consists of 5 layers of AlGaASb whose Sb content is step-graded from 0 to 24%. The last AlGaAsSb layer is almost totally relaxed as determined from x-ray diffraction data. The overall layer structure is intended for a laser diode with an active region consisting of InAs QDs inserted into a 41% InGaAs QW. The growth temperature is maintained at 510°C during the growth of the QD/QW active region. Room temperature photoluminescence (PL) shows a strong PL spectrum with a peak wavelength at 1.46mm. LEDs have been fabricated from this material showing the feasibility of the metamorphic technique for realizing long wavelength QD light emitters on GaAs.

J3.23
THEORETICAL INVESTIGATION OF FERROMAGNETISM APPEARED IN SEMICONDUCTOR DOT ARRAY. Kenji Shiraishi, Hiroyuki Tamura, Hideaki Takayanagi, NTT Basic Research Laboratories, Atsugi-shi, Kanagawa, JAPAN.

The fabrication techniques for semiconductor dot-structures have been under intensive study. The dot size, inter-dot distance, and the inter-dot interactions can now be controlled. However, the key principles of operation of conventional dot applications such as dot-lasers and dot-memories are based on single-dot structures and not arrays of dot structures. Thus, we need a theory that can predict the physical properties of semiconductor dot arrays based on inter-dot interactions. In this paper, we use semiconductor dot arrays to design an artificial ferromagnetic material. We examine the dot array structures and find half-filled flat band structures. Our structure contains triangular units of quantum dots, and these triangular units are aligned periodically in a two-dimensional plane. We use the local spin density functional formalism (LSD) to describe the electronic structures of the quantum dot arrays. The calculated results show that the third lowest band has flat band characteristics when the dot size is around 2 nm. The ground state of this quantum dot system becomes ferromagnetic when the flat band is half filled (5 electrons occupy each triangular unit). The ferromagnetic state is destroyed as the electron number deviates from the half-filled value. This finding indicates that ferromagnetism should occur semiconductor dot-arrays, and that it can easily be controlled by applying the gate voltage.

J3.24
THE THREE ENERGETIC FORCES THAT DICTATE THE QUANTUM DOT MORPHOLOGY. Cheng-hsin Chiu, Institute of Materials Research and Engineering, Singapore, SINGAPORE.

The quantum dot morphology in a Stranski-Krastanow (SK) system has attracted the attention of many researchers recently. Experimental observations of different quantum dot shapes were reported in the literature, including huts, domes, and a mixture of both types of dots. Stability of these structures against island coarsening was also investigated. It was commonly accepted that the morphology of the quantum dots is controlled by two energetic forces in the system: the mismatch strains between the film and the substrate and the film surface energy which is anisotropic. The two energetic forces can explain the formation of dots; however, the two forces alone are not sufficient to describe some key features in the SK system. Examples include the morphological transition from a flat surface to a rough one at a critical thickness and the existence of a wetting layer beneath the quantum dot arrays. To explain these features, it is necessary to consider the film-substrate interaction in the SK system. This motivates us to include the interaction as the third driving force for the quantum dot morphology and to explore how the three energetic forces affect the quantum dot structures. We find that the effects of the forces can be fully represented by the surface energy anisotropy and a non-dimensional parameter that characterizes the remaining combined effects of the three forces. The parameter is called the STABILITY NUMBER of quantum dots. Varying the stability number leads to different characteristics of quantum dot structures. For example, when the stability number is small, the morphological evolution of the quantum dots is dictated by island coarsening, irrespective of the dot shapes. By increasing the stability number, the SK system can develop into an array of huts that is stable against coarsening. At even higher values, the stable dot structure can be huts, domes, or a mixture of huts and domes. These different characteristics of quantum dot structures are demonstrated by three-dimensional simulation for the morphological evolution of an SK system. Implications of the results on the growth of uniform and stable quantum dot arrays are addressed.

J3.25
THEORETICAL ANALYSIS OF OPTICAL TRANSITIONS IN

GaN-BASED QUANTUM DOT STRUCTURES. A.D. Andreev[1] and E.P. O'Reilly[2]; [1]A.F. Ioffe Institute, St.-Petersburg, RUSSIA; [2]Physics Department, University of Surrey, UNITED KINGDOM.

We present the results of the calculated variation with dot size of the optical transition energy and transition matrix elements in GaN/AlN and related quantum dot (QD) structures. The QD carrier spectra and wave functions are calculated using a plane-wave expansion method we have developed, and a multi-band $\mathbf{k}\cdot\mathbf{P}$ model. The method used is very efficient, because the strain and built-in electric fields can be included analytically through their Fourier transforms. We consider both truncated-pyramid-shaped dots, similar to these analysed experimentally in [1], and also cylindrical dots, for which some analytical results are presented. As for quantum well structures, for the QDs the piezoelectric field pushes electrons and holes apart, with the electrons localised at the top of the dot, and the holes at the dot base. In addition, a further effect occurs in the QD case, namely the built-in potential leads to strong lateral confinement of the electron and hole states, so that both can have an effective lateral extend considerably smaller than the overall dot dimensions. The calculated ground state transition energy decreases with increasing dot height in agreement with experimental data. However the calculated electron-hole overlap and optical transition matrix element also decrease very rapidly and become negligible with increasing do height. The results are in good agreement with experimental data for the truncated pyramid dots and with a simple theoretical analysis for the cylindrical dots. [1] F. Widmann, J. Simon, D. Daudin, G. Feuillet, J.L. Rouviere, N.T. Pelekanos, G. Fishman, Phys. Rev. B **58**, 15989 (1998

J3.26
THEORY OF THE ELECTRONIC STRUCTURE OF InAs QDS COVERED BY InGaAs QWS IN GaAs MATRIX. A.D. Andreev, A.F. Ioffe Physico-Technical Institute, St. Petersburg, RUSSIA.

The electronic structure of the nanostructures in InAs/InGaAs/GaAs heterosystem is studied theoretically. The structure consists of several periods of InAs QDs covered by InGaAs QWs and separated by 300 A of GaAs buffer. The QD carrier spectra and wave functions are calculated using a plane-wave expansion method [1], and a multi-band $\mathbf{k}\cdot\mathbf{P}$ model. The method used is very efficient, because the strain and built-in electric fields can be included analytically through their Fourier transforms in full degree. The calculations include 3D strain distribution, piezo-electric effects, pyramidal QD shape and have been carried out in 8x8 Kane model [1]. The calculated optical transition energies are found in reasonably good agreement with recent optical absorption measurements on similar structures [2] [1] A.D. Andreev, E.P. O'Reilly, in "Excitonic Processes in Condensed Matter," R.T. Williams and W.M. Yen, Editors, PV 98-25, p. 271-280, Pennington, NJ(1998). [2] R. Seisyan, S. Kokhanovskii, Yu. Makushenko, A. Andreev, S. Rutkovskii, V. Ustinov, presented at ICPS-2000, Japan, September, 2000

J3.27
PREDICTION OF THE PROPERTIES OF ANNEALED InAs/GaAs QUANTUM DOTS SAMPLES ASSUMING CONSERVATION OF INDIUM ATOMS. Eric Le Ru, Surama Malik, David Childs, Ray Murray, Centre for Electronic Materials and Devices, Imperial College, London, UNITED KINGDOM.

Annealing is known to induce In/Ga inderdiffusion and intermixing in InAs/GaAs quantum dots. It results in a blueshift of the emission energy and a decrease in the intersublevel spacing. We claim that the conservation of Indium within each dot leads to a very tight link between these two effects. To illustrate this, we use a simple 3D harmonic oscillator model to describe the energy levels in the dots. We can then derive analytical expressions linking the optical properties, the structural parameters and the Indium content of each dot. The indium conservation then leads to an almost linear dependence between the emission energy and the intersublevel spacing for any samples derived by annealing a given as-grown sample. These predictions fit very well with our experimental results and other published results. We furthermore show that the same arguments can be used to understand changes in the inhomogeneous broadening upon annealing. Annealing is often cited as a method of tuning the energy emission or the intersublevel spacing in quantum dot devices. By linking theoretically the properties of annealed samples to the as-grown sample, we claim that annealing a sample can also be a useful probe to determine its structural properties.

J3.28
SUPERLINEAR DEPENDENCE OF THE PHOTOLUMINESCENCE FROM InAs/GaAs SELF-ASSEMBLED QUANTUM DOTS. Eric Le Ru, Juliette Fack, Ray Murray, Centre for Electronic Materials and Devices, Imperial College, London, UNITED KINGDOM.

The threshold current of lasers with InAs/GaAs quantum dot active regions is found to increase significantly above 250 K in contradiction to their expected "ideal" behaviour. This would appear to be related to the loss of carriers due to thermal emission into the barrier or wetting layer. We have investigated the excitation density dependence of the photoluminescence at different temperatures in low growth rate quantum dots that emit close to 1.3μm at room temperature. Similar experiments were performed on annealed samples where the barrier height is smaller and these demonstrate that the results are quite general. At low temperatures the photoluminescence signal increases linearly with the incident laser power. However, at higher temperatures where there is significant carrier escape a superlinear dependence is observed. We attribute this effect to saturation of non-radiative centres in the GaAs barrier adjacent to the dots. Similar results are obtained for InGaAs quantum wells with GaAs barriers grown at relatively low temperatures. Finally we describe a model for carrier escape from the quantum dot structures that takes into account saturation of non-radiative centres and subsequent recapture by the dots.

J3.29
MODEL FOR ENERGY RELAXATION IN QUANTUM DOTS: EFFECTS OF A NON-UNIFORM POPULATION OF CARRIERS. Nathalie Perret, Denis Morris, Centre de Recherche sur les Propriétés Electroniques de Matériaux Avancés, Département de physique, Université de Sherbrooke, Sherbrooke, Quebec, CANADA; Simon Fafard, Institute of Microstructural Sciences, National Research Council of Canada, Ottawa, Ontario, CANADA.

When investigating InAs/GaAs self-assembled quantum dots by time-resolved photoluminescence, it is observed that the maximum emission intensity (in the state-filling limit) of each quantun dot transitions can increase, even when higher energy states become more populated than the lower ones. Moreover at very high excitation densities, the higher energy states show the strongest emission intensity. These observations made in the uniform excitation regime (we use an up-conversion technique for signal collection) can not be explained by existing models. We propose a new model based on the fact that the population of carriers does vary from dot to dot. We assume that the number of quantun dots having a number n of carriers follows a Gaussian distribution centered on the average number of carriers per dot. This non-uniform distribution of photocarriers over the excited dot ensemble can be of great importance for describing dot filling effects at low excitation, when energy levels are not saturated yet in all QDs. We have used a modified rate equation model to reproduce the photoluminescence transients observed. The maximum intensity of each QD state has been determined under similar conditions. This model is based on an original approach, different from the existing models (random population model, conventional rate equations). Different relaxation mechanisms (Auger and multiphonon processes) can be taken into account in the calculations.

J3.30
VERTICALLY COUPLED InAs QUANTUM DOTS EMBEDDED INTO SHORT-PERIOD AlAs/GaAs SUPERLATTICE. Serge Oktyabrsky, V. Tokranov, M. Yakimov, L. Senapati and K. Dovidenko. Center for Advanced Thin Film Technology, University at Albany - SUNY, Albany, NY.

Vertical stacks of coherent InAs quantum dots (QDs) embedded into GaAs/AlAs short-period superlattice were grown by molecular beam epitaxy at 475°C. In-situ reflection high energy electron diffraction, low temperature photoluminescence (PL) and high resolution transmission electron microscopy were used to analyze the structure and optical properties of QDs as a function of spacer thickness, superlattice average composition and number of stacked layers. Well-aligned vertical stacks of QDs were observed for the spacing up to 12 nm, though the electronic coupling was low at large spacings as measured by the shift of the PL band. Use of 2 ML thick cladding AlAs layers adjacent to the InAs QD sheets allowed us to compensate for the red shift of the PL emission band due to energy relaxation of excitations in the coupled QD media. Due to reduction of the critical thickness for QD formation with the layer number, we have optimized the InAs coverage for the top layers to obtain the lowest bandwidth and the highest luminescence efficiency at high excitation levels. This approach allowed us to obtain a multiple-plane QD active media with the emission band centered below 1000 nm.

J3.31
InAs QUANTUM DOTS HETEROSTRUCTURES MBE GROWN ON THE VICINAL GaAs(001) SURFACES MISORIENTED TO THE [010] DIRECTION. V.P. Evtikhiev, I.V. Kudryashov, E.Yu. Kotel'nikov, A.S. Shkolnik, A.N. Titkov Ioffe Institute, St. Petersburg, RUSSIA.

Atomic-force microscopy and the photoluminescence (PL) are used to study InAs quantum dot (QD) single sheet array MBE grown on the

vicinal GaAs (001) surfaces misoriented to the [010] direction by 1, 2, 4, and 6 degrees. For a chosen misorientation direction, it is shown that the vicinal GaAs (001) surface is covered with a net of stepped terraces. This specific patterning of the surface suppress the surface diffusion of adatoms between the terraces and makes it possible to achieve higher densities and better uniformity of quantum dots arrays. The increase of misorientation angle leads to the blue shift and narrowing of InAs QD PL lines and makes the PL efficiency higher. With the use of misoriented substrates, single sheet InAs QD laser diodes was realized. The increase of misorientation angle improve LD characteristics. For the stripe laser diodes misoriented by 4 degree the threshold current density of 100 A per square centimeter was realized. This value is limited by internal quantum efficiency of 30. The detailed investigations of the InAs QD PL efficiency shows the principal difference of their dependecies on level of excitation and temperature from measured one for the InGaAs/GaAs quantum well heterostructures. The possible processes of nonradiative recombination are discussed.

J3.32
STRAIN RELAXATION AND SHAPE OF BURIED PbSe QUANTUM DOTS IN PbSe/PbEuTe SUPERLATTICES GROWN ON PbTe/BaF_2 (111) BY MBE. H.H. Kang, L. Salamanca-Riba, Materials and Nuclear Engineering Department, University of Maryland, College Park, MD; M. Pinczolits, G. Springholz, P. Mayer, and G. Bauer, Institut für Halbleiter- und Festkörperphysik, Johannes Kepler Universität, Linz, AUSTRIA.

We have studied the strain relaxation and shape of PbSe buried dots using dark field and high resolution imaging in a TEM. We compare the percent of strain relaxation in dome shape dots with pyramidal dots. Dome shape dots are obtained when the thickness of the PbEuTe spacer layer is below 35 nm while the pyramid-like dots are obtained when the spacer layer thickness is above 35 nm. For the pyramid-like dots we have obtained an estimate for the strain relaxation in each dot of 0.174% along the $\mathbf{g}=(2\bar{4}2)$ direction indicating that the dots are almost fully strained. This result is in agreement with our observation of no misfit dislocations in both dark field images in plan view and high-resolution lattice images in cross section. We compare our experimental estimates of the strain in the dots along different directions with calculations from finite element modeling. We have also observed no appreciable change in the shape of the buried dots compared to the surface dots indicating that any interdifussion between the dots and the spacer layer is negligible.

J3.33
SELF-ASSEMBLED GaInNAs/GaAs QUANTUM DOTS: THE ROLE OF NITROGEN INCORPORATION. P. Ballet, P. Gilet, P. Duvaut, A. Million, LETI/DOPT/CEA-G, Grenoble, FRANCE; L. Grenouillet, LPM-INSA-CNRS, Villeurbanne, FRANCE; G. Feuillet, DRFMC/SP2M/CEA-G, Grenoble, FRANCE.

We report on the realization of self-assembled GaInNAs/GaAs quantum dot heterostructures by molecular beam epitaxy using a RF plasma source for nitrogen. The incorporation of nitrogen into the GaInAs layers leads to a significant decrease in the lattice constant of the alloy and thus directly impacts the formation of quantum dots through the modification of the strain. The influence of nitrogen on strain relaxation and quantum dot formation is investigated by in-situ reflexion high energy electron diffraction while the structural details are obtained by ex-situ atomic force microscopy measurements. The effect of nitrogen on the electronic states of the quantum dots is studied by photoluminescence spectroscopy. The presence of nitrogen induces a strong red-shift of the quantum dot emission, due to the drastic reduction of the alloy band-gap energy, and allows for the emission of light in the technologically important 1.3 and 1.5 micron windows. Finally, we discuss the potential applications of the quantum dot structures by comparing their optical properties with GaInNAs/GaAs quantum well structures.

J3.34
STRONG NANO-SCALE PHASE SEPARATION EFFECTS IN THE OPTICAL SPECTRA OF SEMICONDUCTOR ALLOYS. A.M. Mintairov, J.L. Merz, Dept. of Electrical Engineering, Univ. of Notre Dame, Notre Dame, IN; A.S. Vlasov, V.P. Khvostikov, Yu. G. Musikhin, A.F. Ioffe Physical-Technical Institute, St. Petersburg, RUSSIA; S. Raymond, NRC, Ottawa, CANADA.

We present optical (Raman and time-resolved photoluminescence) and structural (transmission electron microscopy) measurements of $GaAs_{0.88}Sb_{0.12}$ epilayers grown by liquid phase epitaxy on GaAs substrates. The results demonstrate a decomposition of the epilayer into x$\sim$0 (GaAs) and x$\sim$0.5 (Ga_2AsSb) phases having a characteristic length scale of $\sim$10 nm, which allows consideration of the alloy as a high-density quantum dot layer. The evidence of the strong decomposition is the Raman observation of the three-mode behavior of the $GaAs_{0.88}Sb_{0.12}$ optical phonons. Analysis of frequencies and intensities of the Raman bands shows transverse optical phonons having frequencies of 236 and 260 cm^{-1}, related to vibrations of the Ga_2AsSb phase, while a transverse optical phonon has a frequency of 267 cm^{-1}, related to the vibration of the GaAs phase. The Raman observation of the decomposition in $GaAs_{0.88}Sb_{0.12}$ epilayers agrees well with transmission electron microscopy measurements, which give the average size of the phases of $\sim$10 nm. Further confirmation of the strong decomposition was obtained from the measurements of the photoluminescence decay time. The decay times at T=5 K had values of 5-10 nsec, which is typical for the radiative recombination involving spatially separated electrons and holes. The separation of the electrons and holes is a consequence of the type II band alignment expected for the GaAs/Ga_2AsSb interface. It should be noted that a similar type of decomposition was observed by us previously in relaxed $In_{0.12}Ga_{0.88}As$ grown by MOVCD [1]. The common feature of both alloys is a strong lattice mismatch (0.07) of the binary components, which can be a driving force for the observed nanoscale phase separation. [1] A.M. Mintairov, and D.M. Mazurenko Int. J. Electronics 47(4) (1994)

J3.35
MOCVD GaSb/GaAs QUANTUM DOTS. Motlan Motlan, Ewa M. Goldys, Trevor L. Tansley, Macquarie University, Semiconductor Science and Technology Laboratories, Division of Information and Communication Sciences Sydney, AUSTRALIA.

The microstructure and morphology of self-assembled dots(SADs) are important factors in controlling the optical properties of quantum dot semiconductor materials. While growth is primarily driven by strain due to lattice misfit, other factors also play a significant role. Reports on GaSb quantum dots have been sporadic, without a thorough growth evolution study. We report the structural and optical properties of metalorganic chemical vapour deposited (MOCVD) straimed GaSb three-dimensional (3D islands on GaAs as a function of growth time. A study was carried out by atomic force, scanning and transmision microscopes for structural properties. Optical properties were studied by cathodoluminescence. The metalorganic flow rates and the growth temperature were kept constant consecutively at 10/10 sccm for both metalorganic precursors and 540°C. To observe the dot evolution the growth time was varied from 1 second to 8 seconds. The evolution of the dots depends on the total deposited volume, rather than on the growth rate or temperature as generally expected. Growth times between 1 and 3 seconds show a 3D dot areal density increasing slightly from about $1.26\times10^{14}m^{-2}$ to around $1.27\times10^{14}m^{-2}$ with considerable increase in the dot width from 2.9±7 nm to 41±13 nm and with a broader size distribution. Remarkably, further growth up to 5 seconds increases dot densities to 1.29×10^{14}m with the width distribution again narrowing and the average dot size decreasing. At longer growth times the process continues towards areal saturation and the onset of coalescence. The cathodolumiscence study shows the confinement spectra in which the peak shift to a higher band as the growth time consecutively change from 3 seconds to 7 seconds.

J3.36
PHOTOLUMINESCENCE EXCITATION STUDIES OF ANNEALED InAs/GaAs QUANTUM DOTS. David Childs, Surama Malik, Eric Le Ru, Ray Murray, Centre for Electronic Materials and Devices, Imperial College, London, UNITED KINGDOM.

The issue of carrier relaxation in self-assembled quantum dots is not resolved. Several studies have demonstrated phonon and not excited state resonances in photoluminescence excitation (PLE) measurements. The logical implication of these results is that the intensity of the emission from quantum dot structures will be greatly enhanced if the separation of the electronic states, ΔE, can be tuned to be a multiple of the LO phonon energy. By subjecting low growth rate InAs/GaAs quantum dots to anneals at different temperatures ΔE can be varied from 68 meV to 21 meV. Photoluminescence (PL) measurements made under conditions of high excitation show clear excited state emission and confirm that the dot-like nature of the samples is retained after the anneals. The PLE spectra exhibit a strong continuum background which has also been reported in near field spectra of single dots. PLE spectra obtained from these samples exhibit clear excited state resonances, especially in samples where ΔE is much less than the LO phonon energy and we conclude that phonon generation is not the dominant relaxation process in QDs. Resonant PL measurements confirm the PLE results and we find no evidence for virtual states in any of our samples.

J3.37
FABRICATION OF ZnO BASED NANOCRYSTALS AND HETEROSTRUCTURES FOR ULTRAVOLET LIGHT EMITTING DEVICE APPLICATIONS. Masashi Kawasaki, Hideomi Koinuma, Tokyo Inst. of Tech., Yokohama, JAPAN; Akira Ohtomo, and Harold Y. Hwang, Bell Laboratories, Lucent Technologies, Murray Hill, NJ.

Wide gap semiconductor heterostructures have garnered much attention for applications as light emitting devices and high-power/high-frequency electronics. We have developed oxide semiconductor structures based on ZnO, where the band-gap can be tuned from 3 to 4 eV by alloying with Mg and Cd. Control of nanocrystalline size and grain boundary structures enables the design of unique cavities with different substrate materials. ZnO based nanostructures were grown by laser molecular-beam epitaxy, and room temperature ultraviolet excitonic lasing was observed in nanocrystalline films grown on lattice-mismatched substrates using hexagonally assembled grain boundaries as cavities. Highly efficient lasing characteristics have been achieved in ZnO/(Mg,Zn)O quantum wells grown on lattice-matched oxide substrates.

J3.38
EVOLUTION OF ANISOTROPIC THIN FILMS DURING HETEROEPITAXY. J.J. Eggleston and P.W. Voorhees, Northwestern Univ, Dept of Materials Science and Engineering, Evanston, IL.

The importance of surface energy anisotropy has become a principal subject in the study of island growth during heteroepitaxy. Self-assembly and growth of semiconductor quantum dots often results in strongly anisotropic island morphologies. As a result, a fully numerical solution of the equations governing surface energy and elastic energy driven surface diffusion is required to follow the island formation process. A phase-field model for thin film growth has been developed with which the evolution of an elastically stressed film with anisotropic surface energy can be determined. The calculations show the formation and evolution of nearly faceted islands and the critical role played by anisotropy. Fourier analysis of these results allow for a direct comparison with experiments and LEEM results from the literature. The implications of these results on quantum dot formation will be given.

J3.39
EFFECTS of ANNEALING on SELF-ASSEMBLED InAs QUANTUM DOTS and WETTING LAYER IN GaAs MATRIX. J. Jasinski, Materials Science Division, Lawrence Berkeley Lab, Berkeley, CA; A. Babinski, R. Bozek, J.M. Baranowski Inst of Experimental Physics, Warsaw Univ, Warsaw, POLAND.

An effect of post-growth thermal annealing of the InAs/GaAs quantum dots (QDs) is investigated in this work. Self-assembled QDs of average size 7-10 nm were grown by metalorganic vapour phase epitaxy. The photoluminescence (PL) due to emission from QDs as well as two peaks due to emission from the strained InAs wetting layer were observed in as-grown sample. Bimodal structure of the WL PL was attributed to the WL regions of different thickness. Thinner WL presumably surrounds QDs whereas thicker WL covers regions between the QDs. Thermal annealing (30s) at temperatures up to 950 deg C results in quenching of the PL from QDs and thinner WL. The PL peak from thicker WL blue-shifts and narrows with increasing annealing temperature. This behavior is in agreement with cross-section transmission electron microscopy images of annealed samples. We observe complete dissolution of QDs and substantial broadening of the WL. Our results show that the thermally induced modification of the WL rather than ODs can be responsible for blue-shift and narrowing of the PL peaks in structures containing InAs QDs.

J3.40
FABRICATION OF ALL-SOLID-STATE, LOW-COST, AND LARGE-AREA NANOCRYSTALLINE TITANIUM DIOXIDE - POLYMER SOLAR CELLS. Krishna C. Mandal, Bryce K. Dille, D. Peramunage and R. David Rauh, EIC Laboratories, Inc., Norwood, MA.

Recently, dye - sensitized nanocrystalline TiO_2 solar cells have emerged as a promising low-cost photovoltaic (PV) alternative. However, considerable problems remain with regard to liquid redox electrolytes that are toxic, unstable, and difficult to seal and maintain for the lifetime required for large-scale economic power production. This paper describes various critical fabrication steps to develop low-cost, large-area, and stable all-solid-state TiO_2 solar cells based on highly conducting polymer electrolytes. A novel polymer laminated electrolyte and spin casted nanocrystalline TiO_2 layer formation on TCO glass substrates have been demonstrated as valuable active components, which enhanced cost-effective productions. The PV performance presented in this paper show the fabricated solar cells of 5 and 25 cm^2 area with reproducible AM1 efficiencies of 6-7%. A thoroughly characterized 10 x 8 cm^2 prototype solar cell with AM1 efficiency $\geq$5% will also be presented.

J3.41
FORMATION OF COPPER(I) HALIDE NANOCRYSTALLINE IN GLASS SURFACES BY ION-EXCHANGE METOD AND THEIR OPTICAL PROPERTIES. Kohei Kadono, Dept of Optical Materials, Osaka National Research Institute, AIST, Osaka, JAPAN; Tatsuya Suetsugu, Toshihiko Einishi, Takashi Tarumi, Isuzu Glass Co., LTD, Osaka, JAPAN; Maria del Rosario Martinez Rozo, Tetsuo Yazawa, Dept of Optical Materials, Osaka National Research Institute, AIST, Osaka, JAPAN.

Glasses doped with copper(I) halide nanocrystalline have received much attention and intensively studied from the viewpoints of the quantum size effect and third order nonlinear optical properties of the semiconductor quantum dots. Nanocrystalline-doped glasses are conventionally prepared by the melting-quenching-annealing method, in which glass melts containing precursors of the nanocrystalline are quickly cooled and the glasses are annealed to precipitate nanocrystalline. The precipitation or formation of the nanocrystalline from glass matrices is much affected not only by the annealing condition but also by the composition of the glass matrix. The copper(I) halide nanocrystalline-doped glasses are also prepared by introduction of copper(I) ions using ion-exchange method in the surface of glasses containing halide ions. Since the ion-exchange is one of the most important methods for fabrication of waveguide, this technique for preparation of copper(I) halide nanocrystalline-doped glasses is interest for application to photonics devices. In this paper, we prepared cooper(I) halide nanocrystalline in the surfaces of sodium borosilicate glasses containing chloride or bromide ions by ion-exchange method. The relationship between the formation of copper(I) halide nanocrystalline and the composition of glasses was investigated. It has been found that the formation of copper(I) halide nanocrystalline is closely related to the phase-separation of the glass matrices. We have also investigated the optical properties of the copper(I) halide nanocrystalline and interaction of the nanocrystalline semiconductors and the other fluorescent ions.

J3.42
PREPARATION OF NANOCRYSTALLINE TIN DIOXIDE BY A NEW METHOD STARTING FROM DIVALENT TIN: POTENTIAL FOR MODIFIED PROPERTIES. Georges Denes, Arnaud Gueune, Ali Kanaan, Eva Laou, Stephane Le Huerou, Abdualhafeed Muntasar and Frederic Nicolas, Concordia University, Dept of Chemistry and Biochemistry, Laboratory of Solid State Chemistry and Mossbauer Spectroscopy, and Laboratories for Inorganic Materials, Montreal, Quebec, CANADA.

Nanophasic SnO_2 is usually prepared by the sol-gel method. This method involves the precipitation of a stannic gel by hydrolysis of a tin(IV) compound containing labile tin-ligand bonds. We have designed a new method that consists in oxidizing tin(II) to tin(IV) and simultaneously hydrolyzing the tin-ligand bonds in the same reaction process. The new method consists in oxidizing tin(II) to tin(IV) by addition of hydrogen peroxide to an aqueous solution of SnF_2. This results in a substitution of fluorine by oxygen, and a precipitate of hydrated tin(IV) oxide $SnO_2.nH_2O$ (n = ca. 2) is obtained. This phase is nanophasic and can be subsequently dehydrated without recrystallization under mild heating. Recrystallization takes place slowly at higher temperatures, due to the ceramic properties of SnO_2, which make it thermally very stable, and the slow recrystallization makes it possible to tailor the desired average particle size. In addition, control of its properties might be possible by modifying its chemical properties. It can be made to contain tin(II) or tin(IV) fluorides/oxide fluorides by modifying the preparation conditions, mainly the H_2O_2/SnF_2 ratio.

J3.43
SYNTHESIS OF *M*S/LDH (*M* = Pb, Cd, Zn) NANOCOMPOSITES USING LAYERED DOUBLE HYDROXIDES AS NANOREACTORS. Alexei V. Lukashin, Alexey A. Vertegel, N.G. Juravleva, Yuri D. Tretyakov, Dept. of Materials Science, Moscow State University, Moscow, RUSSIA; O.I. Lebedev, G. Van Tendeloo, EMAT, University of Antwerpen (RUCA), Antwerpen, BELGIUM.

In the present work, a novel method for the preparation of semiconductor nanostructured materials is discussed. The method is based on chemical modification of anion-substituted layered double hydroxides (LDH). It combines the simplicity of chemical methods and the possibility to prepare two-, one-, or zero-dimensional nanoparticles in hydroxide matrices. LDHs have a general formula $M'_{1-x}M''_x(OH)_2[(anion)^{x+}_{x/n}\bullet mH_2O]$, where M′ and M″ are metals in the oxidation state +2 and +3, respectively, and $anion^{n-}$ is virtually any anion, which does not form a stable complex with M′ or M″. A structure of an LDH consists of positively charged hydroxide layers $[M'_{1-x}M''_x(OH)_2]^{x+}$ bonded with negatively charged anions, which occupy the interlayer space. Aforementioned peculiarities of the LDH structure suggest their possible application for the preparation of nanomaterials. During chemical reactions of anions in the interlayer space, reaction zone is spatially constrained by the hydroxide layers, giving rise to the conditions similar to those in 2D nanoreactors, such as Langmuir-Blodgett films and self-assembling monolayers. Here we used LDH precursors for the preparation of the *M*S (*M* =

Pb, Cd, Zn) nanocomposites. In order to perform synthesis of MS in the interlayer space of LDH, one should choose such an anionic complex, which would undergo decomposition giving metals sulfide as the only solid state product of the reaction. One compound, which matches the above condition is thiosulfate complex $[M(S_2O_3)_2]^{2-}$ or thiocyanate complex $[M(SCN)_3]^-$. The formation of nanoparticles incorporated into LDH matrix was confirmed by high resolution transmission electron microscopy (HREM) and by other methods.
This work is supported by RFBR (grant 00-03-32579).

SESSION J4: QUANTUM DOT BASED DEVICES AND TRANSPORT STUDIES
Chairs: Simon Fafard and Diana Huffaker
Tuesday Morning, November 28, 2000
Room 207 (Hynes)

8:30 AM *J4.1
TEMPERATURE DEPENDENCE AND DYNAMIC RESPONSE OF SELF-ORGANIZED QUANTUM DOTS FOR 1.3 MICRON GaAs-BASED LASERS. D.G. Deppe, G. Park, O. Shchekin, The University of Texas at Austin; T.F. Boggess and L. Zhang, University of Iowa.

In this talk we present experimental and modeling data characterizing the size and temperature dependence of the dynamic response of InAs and InGaAs quantum dots. We find that large InGaAs dots have low temperature relaxation times from the wetting layer to the ground state of ~1 psec. Smaller InAs dots with more widely separated transverse energy levels exhibit a relaxation time of ~7 psec under similar excitation conditions. The temperature dependence of the relaxation is also opposite for the larger dots versus the smaller dots. The larger dots become slower with increasing temperature, while the smaller dots become faster. Both temperature dependencies are explained through entropy effects that govern relaxation from the wetting layer to the upper discrete dot levels, and a bottleneck in the spontaneous phonon emission.
We find the data measured experimentally is explained using rate equation models based on thermal reservoir coupling to the phonon field. The entropy effect is brought about due to the large disparity in level density between the wetting layer and upper discrete dot levels, and observed for dots with fast relaxation times. Relaxation in the smaller InAs dots is apparently limited by spontaneous phonon emission due to more widely separated energy levels. The rise time is decreased with increasing temperature due to stimulated phonon emission. The impact of the dynamic response on quantum dot lasers is modeled using a six energy level system, and will be briefly discussed.

9:00 AM *J4.2
QUANTUM DOT SEMICONDUCTOR OPTICAL AMPLIFIERS. Richard Mirin and Kevin Silverman, Optoelectronics Manufacturing Group, National Institute of Standards and Technology, Boulder, CO.

Semiconductor optical amplifiers (SOAs) are an important component for the rapidly emerging area of wavelength division multiplexing (WDM), especially for metro networks. One major problem with SOAs based on quantum wells or bulk active regions is crossgain modulation, in which the gain at some wavelength, l1, is affected by a co-propagating wavelength, l2. However, a quantum dot SOA (QDSOA) could eliminate this problem if the quantum dots are uncoupled. In this paper, we will discuss cross gain modulation and wavelength conversion using QDSOAs.

9:30 AM J4.3
TWO-COLOR VERTICAL CAVITY SURFACE EMITTING PbSe QUANTUM DOT LASER FOR THE MID-INFRARED. G. Springholz, T. Schwarzl, W. Heiss, M. Aigle[a] and H. Pascher[a], Johannes Kepler Universitaet, Linz, AUSTRIA. [a]Experimentalphysik, Universitaet Bayreuth, Bayreuth, GERMANY.

The fabrication of the first vertical cavity surface emitting PbSe quantum dot laser using molecular beam epitaxy is presented. The VCSEL structure consists of two high-reflectivity EuTe/PbEuTe Bragg mirrors with a 10 μm thick self-organized PbSe quantum dot superlattice as active cavity region. Because of the very high refractive index contrast of the mirror materials, the microcavity exhibits a very wide stop band region with many sharp cavity resonance peaks (1). FTIR measurements show that at 80 K the absorption of the PbSe quantum dots sets in above a cut-off wavelength of 4 μm, which is about 150 meV above the bulk PbSe band gap. Optical pumping of the laser structure was achieved by a 1064 nm pulsed Nd:YAG laser with a maximum pulse energy of 450 μJ, a pulse length 20 ns and a spot diameter on the sample of about 800 μm. Narrow stimulated laser emission was observed at temperatures up to 90 K at spectral positions matching the cavity modes. The emission line width is below 0.6 meV and the output power linearly increases with pump power. Below 40 K, two color simultaneous emission at 4.237 μm (295 meV) and 4.090 μm (305 meV) is observed, whereas above 50 K the low energy line is replaced by an emission line at 3.93 μm (317 meV). This effect is due to the strong increase of the energy band gap of the IV-VI compounds and is a typical feature for lead salt VCSEL lasers(1). The fact that at any temperature only two emission lines are observed and that the separation of the cavity modes is only 10 meV indicates that the width of the PbSe dot gain spectrum is less than 20 meV. These results open promising perspectives for realization of mid-infrared quantum dot lasers with high operation temperatures.
1. G. Springholz, et al., Appl. Phys. Lett. 76, 1807 (2000).

10:15 AM *J4.4
INFRARED PHOTODETECTION BY SEMICONDUCTOR QUANTUM-DOT NANOSTRUCTURES. E. Towe and D. Pan, Laboratory for Optics and Quantum Electronics, University of Virginia, Charlottesville, VA.

Self-organized quantum-dot nanostructures are emerging as important objects for fundamental as well as practical reasons. In their pristine form, the structures represent ideal objects for studying basic characteristics and properties of charge carriers confined in all three dimensions. Such nanostructures are expected to exhibit unusual properties with potential for technological applications. This paper will review progress in infrared photodetection by (In,Ga)As-on-GaAs quantum dots. Detection of infrared (5-15 um) radiation has generally been accomplished through band-to-band carrier transitions in narrow gap semiconductors such as (Hg,Cd)Te or through use of inter-subband carrier transitions in quantum wells prepared from (Al,In,Ga)As/GaAs heterostructures. The use of quantum dots for infrared photodetection is a recent innovation. These nanostructures are essentially artificial atoms; and as such, the electronic transitions that are important for photodetection are inter-sublevel transitions. The energy level spacing, and hence the absorption wavelengths, can be controlled via the size of the dot or the composition and matrix material surrounding the dot. We will discuss results from multi-periodic (In,Ga)As/GaAs quantum-dot photodetector structures that operate in both the photoconductive and photovoltaic modes. These are unipolar carrier devices. A typical structure is comprised of a superlattice active region sandwiched between silicon-doped GaAs contact layers. A single period of the active region consists of an array of (In,Ga)As quantum dots formed on top of a thin wetting layer of InGaAs; this, in turn, is grown on top of a GaAs barrier layer. The nominal barrier layer is about 50 nm thick; the average height of the dots is about 7 nm, with a lateral extent of 30-50 nm. Although the performance of the state-of-the-art quantum-dot photodetectors is not yet at par with that of quantum-well devices, there are a number advantages that potentially make the quantum-dot device very attractive. These advantages include the ability to sense normal-incidence radiation, ease of fabrication, flexibility in spectral tuning, and an intrinsic capability to operate in the photovoltaic mode.

10:45 AM J4.5
CHARACTERISTICS OF InGaAs/InGaP QUANTUM DOT INFRARED PHOTODETECTOR GROWN BY METAL ORGANIC CHEMICAL VAPOR DEPOSITION. Seongsin Kim, Samsung Electronics, KOREA; M. Razeghi, Northwestern Univ, Dept of Electrical and Computer Engineering, Evanston, IL.

Strain induced InGaAs self-assembled quantum dots grown on GaAs substrate in S-K growth mode have been revealed their physical characteristics and several significant device results were reported. For any III-V compound semiconductor for optoelectronic devices, it is necessary to dope materials for electrical and optical properties, however, detailed doping effects on physical properties of quantum dots have not been reported. Here, we report an investigation of effect on formation of dots when it is doped with Zn and Si, which are conventional p-and n-type dopants respectively. The InGaAs quantum dots were grown on InGaP matrix that is lattice matched to GaAs substrate by metal organic chemical vapor deposition. The surface energy difference between GaAs and InGaP causes strong effect on forming dots with different wetting layer thickness before it starts to form islands. The atomic force microscopy revealed shape deformation, change of densities and distribution, which indicate Zn and Si can be used as surfactants. The optical properties were measured by photoluminescence and thermal activation energy difference can be as large as 30meV for samples with Zn and Si. The intersubband infrared absorption and photocurrent response were observed from fabricated quantum dot infrared photodetector structure, which composed of InGaAs/InGaP quantum dot active region using these dopants. Peak wavelength was observed 5.5 um and 10um, respectively with a peak detectivity of 3.01 x 10^8cmHz$^{1/2}$/W at 77K. Photo-generated carrier life time was determined indirectly from a photoconductive gain derived as measuring spectral noise current density. Photoconductive gain as high as 7.6×10^3 gives us a extended carrier lifetime of 1.4 ns of quantum dot intersubband transition.

11:00 AM J4.6
FIELD EFFECT STRUCTURE WITH DOUBLE LAYER OF InGaAs/GaAs QUANTUM DOTS - A NEW CONCEPT OF ELECTRON TUNNELING DEVICE. A. Babinski, J.M. Baranowski, Inst. of Exp. Physics, Warsaw University, Warsaw, POLAND; R. Leon, C. Jagadish, Electronic Materials Engr. Dept, RS Phys SE, The Australian National University, Canberra, AUSTRALIA.

Self-assembled quantum dots of InGaAs/GaAs have drawn considerable interest in recent years. The results of capacitance measurements on the field-effect structure consisting of two layers of InGaAs/GaAs self-organized quantum dots (QDs) of average diameter ~55 nm will be presented. One layer of QDs was embedded within the standard field-effect structure, the other was placed at the top of the structure. Characteristic peaks in the capacitance spectrum of our device can be seen at low temperature, which were attributed to the QDs charging with subsequent electrons. The Coulomb blockade in the charging of the s- and p-like electron shells was observed. Coulomb charging energy deduced from our measurements was equal to 6 meV for s-like electrons and 3 meV for p-like electrons, which is in agreement with theoretical predictions for relatively large QDs present in our structure. The fine structure was observed in the tunneling spectrum of our QD structures, which was previously reported only in a very small tunneling device [1]. The results of measurements in high magnetic field will be also presented, which confirm our attribution of observed features to the tunneling through QDs states. A discussion of experimental data in terms of previously published reports [2] will be presented. We will also discuss the peculiar properties of our device, which enable the observation of tunneling effects in our structure. [1] B.T. Miller et al. Physica B, 249-251, 257 (1998) [2] B.T. Miller et al. Phys. Rev B 56, 6764 (1996)

11:15 AM J4.7
PROBING THE PROPERTIES OF SELF-ORGANIZED InGaAs QUANTUM DOTS ON GaAs (311)B BY USING CONDUCTIVE ATOMIC FORCE MICROSCOPE TIP. Yoshitaka Okada, Kouichi Akahane, Yoshimasa Iuchi, Mitsuo Kawabe, University of Tsukuba, Inst. Applied Physics, Tsukuba, JAPAN.

Recently, the electronic and optical properties of semiconductor quantum dots (QDs) have been studied extensively. Though the common techniques such as photoluminescence and capacitance spectroscopy can be used to probe the local properties containing many QDs, scanning probe techniques are useful for investigating the properties of individual QD. On the other, we have shown that InGaAs QDs self-organized on GaAs (311)B exhibit an remarkably different characteristics compared to the QDs grown on (100) substrate, and that a complex phase separation and strain-relief mechanism are responsible for the formation of a high-density and well-ordered QDs array on (311)B surface [cf. Appl. Phys. Lett. 73, 3411 (1999)]. To this end, we attempted to probe the properties of InGaAs QDs on GaAs (311)B by using conductive atomic force microscope (AFM) tips. The QDs were formed by depositing an 8ML-thick $In_{0.4}Ga_{0.6}As$ at 500°C on a n-type GaAs buffer layer by atomic H-assisted molecular beam epitaxy. Highly doped Si AFM tips coated with metal such as Au and Ti were used to measure the I-V curves through QDs of varying sizes and positions. In the case of QDs on (100) substrate, it was found that the local surface potentials on larger QDs were smaller than the small QDs possibly due to the effect of surface states. On the other hand, noticeable differences were not observed for QDs on (311)B with various sizes, which suggested that the local surface potential was nearly identical for each QD. Furthermore, a resonant tunneling behavior through an confined quantum energy state was also observed through a QD with 50nm in diameter and 4.5nm in height.

11:30 AM J4.8
OPTICAL PROPERTIES OF InP SINGLE QUANTUM DOT IN EXTERNAL FIELDS. Mitsuru Sugisaki[1], Hong-Wen Ren[1], Selvakumar V. Nair[1], Kenichi Nishi[1,2], Shigeo Sugo[1,2], and Yasuaki Masumoto[1,3]; [1]Single Quantum Dot Project, ERATO, JST, Tsukuba, Ibaraki, JAPAN; [2]Photonic and Wireless Devices Research Laboratories, NEC Corporation, Tsukuba, Ibaraki, JAPAN; [3]Institute of Physics, University of Tsukuba, Tsukuba, Ibaraki, JAPAN.

We report the μ-PL study of a single InP self-assembled quantum dot (QD) embedded in $Ga_{0.5}In_{0.5}P$ matrix in the presence of external electric and magnetic fields. A very sharp μ-PL line due to the radiative decay of the confined excitons was clearly observed at 4 K under the weak excitation, which reflects the δ-function-like density of states of the zero-dimensional semiconductor. With the increase of an applied bias with positive at the top of the sample, a distinct red shift of the μ-PL line was observed. The ground state shows an almost quadratic Stark shift of 3 $\mu eV/kV^2$. Further, we found that some spectral lines appear a few meV below the confined exciton line when the electric field is applied. One of them are assigned to be the multi-exciton line from the excitation power dependence. Others are considered to be negatively charged exciton, that the excess carriers are supplied from the Si doped GaAs substrate. We also studied the size dependence of the diamagnetic shift in a magnetic field. When the μ-PL is measured in the Voigt configuration ($B \perp k \parallel$ growth axis [100]), these peaks show diamagnetic shifts of ~ 2 $\mu eV/T^2$, which does not depend on the QD size because the quantum confinement is dominant. On the other hand, clear size dependence of the diamagnetic shift in the Faraday configuration ($B \parallel k \parallel$ [100]) is observed. The diamagnetic coefficient of small quantum dots is almost same as that measured in the Voigt configuration, but with the increase of the QD size, it increases lineally up to 7 $\mu eV/T^2$. This reflects the competition between lateral and magnetic confinement. Optical anisotropy induced by the anisotropic stress applied from the $Ga_{0.5}In_{0.5}P$ matrix which causes a fine splitting of the μ-PL lines, will be also reported.

11:45 AM J4.9
SINGLE ELECTRON TRANSPORT OF A QUANTUM DOT FORMED BY THE SURFACE ACOUSTIC WAVE IN A NARROW CHANNEL IN A PERPENDICULAR MAGNETIC FIELD. Godfrey Gumbs, Department of Physics, Hunter College of CUNY.

The effect of a perpendicular magnetic field on the quantized current induced by a surface acoustic wave in a quasi-1D channel is studied. The channel has been produced experimentally in a GaAs heterostructure by shallow etching techniques and by the application of a negative gate voltage to Schottky split gates. Commensurability oscillations of the quantized current in this constriction have been observed in the interval of current between quantized plateaus when there is no magnetic field present. The results can be understood in terms of a moving quantum dot with the electron in the dot tunneling into the adjacent 2D region. The dynamics of inserting an electron into the dot forming at the entrance of the channel is not considered in this work. The goal is to explain the mechanism for the step-like nature of the acoustoelectric current as a function of gate voltage and the oscillations when a magnetic field is applied. A transfer Hamiltonian formalism is employed. Applications to a single photon device will be discussed.

SESSION J5: CARRIER DYNAMICS AND INTERACTIONS, ENERGY RELAXATION, AND SINGLE DOT SPECTROSCOPY
Chairs: Dennis G. Deppe and Richard Noetzel
Tuesday Afternoon, November 28, 2000
Room 207 (Hynes)

1:30 PM *J5.1
EXCITON COMPLEXES IN SELF-ASSEMBLED QUANTUM DOTS AND QUANTUM DOT MOLECULES. Manfred Bayer, Alfred Forchel, Physikalisches Institut der Universität Würzburg, Am Hubland, Würzburg, GERMANY; Pawel Hawrylak, Simon Fafard, Institute for Microstructural Science, National Research Council of Canada, Ottawa, CANADA.

We have studied the principles that govern the electronic structure of excitons in semiconductor quantum dots by performing single dot optical spectroscopy. The exciton density of states varies considerably with the number of shells in the dots. For example, in the energy range corresponding to p-p shell transitions only a single absorption line is observed for dots with only a s- and a p-shell confined, while two absorption lines are observed for dots with an additionally confined d-shell. For these dots an optically inactive exciton state exists in form of a coherent superposition of an electron in the s- and a hole in the d-shell and vice versa. This state is in resonance with the optically active p-shell exciton resulting in a mixing of the two states. For the emission of multiexciton complexes in the quantum dots two characteristic features are noted: (1) The emission due to s-shell recombination shows strong variations with the exciton number. (2) The energy of the p-shell emission is approximately independent of the dot occupation. The rules that determine the multiexciton ground states are identified with hidden symmetries in the Hamilton operator, which cause a condensation of electron-hole pairs in degenerate shells. Due to these symmetries the energy to add or to subtract an exciton to a given shell is independent of the number of excitons in the shell. This explains the behavior of the p-shell emission involving only multiexciton ground states. In contrast, excited multiexciton states become involved in the s-shell emission leading to its strong variations. Finally we present studies of single electron-hole pairs in quantum dot molecules. We clearly resolve the energy splitting of the single dot states arising from the coupling of the two quantum dots. This splitting depends strongly on the separation of the dots.

2:00 PM *J5.2
DYNAMICS OF PHOTOEXCITED CARRIERS IN SELF-ASSEMBLED InAs/GaAs QUANTUM DOTS. Denis Morris, Nathalie

Perret, Daria Riabinina, Centre de Recherche sur les Proprietes Electroniques de Materiaux Avances, Departement de physique, Universite de Sherbrooke, Sherbrooke, Quebec, CANADA; Simon Fafard, Institute of Microstructural Sciences, National Research Council of Canada, Ottawa, Ontario, CANADA.

Carrier dynamics in InAs/GaAs self-assembled quantum dots have been studied by using time-resolved photoluminescence (PL) experiment. The nature of the dominant relaxation mechanisms and the possible involvement of multi-particle states were investigated in several doped and undoped quantum dot structures by varying experimental conditions such as the interlevel energy spacing, the laser excitation density, the excitation wavelength and the temperature. The relaxation times are deduced from the rise times of the s state PL signal. Comparison of the relative emission intensities coming from the barriers (GaAs and wetting layer) and the quantum dots gives additional information on carrier capture time. Our results show that, for all samples, Auger relaxation processes play an increasing role at high excitation densities. Under low excitation densities, the carrier relaxation time depends on the dopant type, the interlevel energy spacing and the temperature. Our results are compared with the behaviour expected from different phonon-assisted relaxation models. Further investigations of the time-resolved spectra in the initial stage of the relaxation also show that state-filling effects take place on ultrafast time-scale (about 5 ps). We will discuss the effects of these multi-particules states on the carrier dynamics.

2:30 PM J5.3
EFFECTS OF INTERLEVEL SPACINGS ON CARRIER RELAXATION IN QUANTUM DOTS. Saulius Marcinkevicius, Dept of Physics-Optics, Royal Inst of Technology, Stockholm, SWEDEN; Rosa Leon, Jet Propulsion Lab, California Inst of Technology, Pasadena, CA.

Carrier energy relaxation in self-assembled quantum dots is being widely discussed due to its implications on the performance of the quantum dot lasers. At high carrier densities, short carrier relaxation times have been ascribed to carrier-carrier scattering processes. At low carrier densities, phonon-related processes should dominate the relaxation, however, electron relaxation by LO-phonon emission is only efficient if interlevel distances in the conduction band match the phonon energy. In this work we test the efficiency of LO-phonon related relaxation channel by investigating a set of InGaAs/GaAs quantum dot samples in which the interlevel distances are tuned by intermixing. The photoluminescence spectra of all samples show well-resolved four-peak structure with interlevel transition energies ranging from 25 to 50 meV. The carrier transfer into quantum dots is studied by time-resolved photoluminescence with 3 ps temporal resolution at 80 K. At lowest photoexcitation intensities (corresponding to about one electron-hole pair per dot), the photoluminescence rise time for the ground level is 8-10 ps for the samples with 45-50 meV interlevel transition energies, and 17-20 ps for the samples with smaller interlevel transition energy separation. Since the main difference between the samples is the interlevel separation in the quantum dots, the difference in rise times should be ascribed to a more efficient carrier relaxation in the first group of samples. Assuming that the interlevel distances for the electrons are about twice as large as for the holes, the interlevel distances for the conduction band levels in the first group of samples is close to LO phonon energies for GaAs and InAs. The difference in rise times for the two groups of samples provides thus a direct evidence of efficient electron relaxation via LO phonon emission in quantum dots.

3:15 PM *J5.4
IMAGING THE ELECTRON EIGENFUNCTIONS OF SELF-ASSEMBLED QUANTUM DOTS. L. Eaves, A. Patanè, A. Levin, P.C. Main, E.E. Vdovin, Yu.V. Dubrovskii, M. Henini, School of Physics and Astronomy, University of Nottingham, UNITED KINGDOM; Yu. N. Khanin, Institute of Microelectronics Technology RAS, Chernogolovka, RUSSIA; G. Hill, Dept. of Electronic and Electrical Engineering, University of Sheffield, UNITED KINGDOM.

We report an experimental study of the distribution of the probability density of the electron eigenfunctions in InAs/GaAs self-assembled quantum dots (QDs). We probe the carrier wavefunction using magnetotunnelling spectroscopy, which has previously proved to be a powerful technique for mapping out the energy dispersion curves of bound states in quantum wells [1] and the form of the wavefunctions of confined states in quantum wires [2]. The structure used is an n-i-n, double-barrier GaAs/(AlGa)As resonant tunnelling diode in which a layer of InAs QDs is incorporated in the centre of the GaAs quantum well. We observe features in the low-temperature current-voltage characteristics, $I(V)$, of the diode, corresponding to carrier tunnelling into 0-dimensional states due to individual QDs. The shape of the current resonances is studied as a function of temperature in the range 0.3 to 4.2 K. As discussed below, three successive features correspond to tunnelling through dot states displaying the symmetry of the ground state and first and second excited state, respectively. We investigate the magnetic-field dependence of the current resonances associated with the dot states. In the experiment, carriers tunnel through a barrier into the dots in the presence of a magnetic field, B, perpendicular to the current, I. If x and z indicate the directions of B and I, respectively, then when carriers move from the emitter into the dot, they acquire an in-plane momentum $\Delta k_y = eB\Delta s/\hbar$, where Δs is the effective distance tunnelled along z [1,2]. This has pronounced effects on the tunnelling process. The intensity of the current resonances changes with increasing B and we relate this variation to the square of the Fourier transform of the electron probability density [2]. The $I(B)$ plots provide a means of probing the characteristic form of the wavefunction probability density of the electron confined in the dot as a function of k_y and hence of the corresponding spatial coordinate, y. By rotating the magnetic field in the growth plane, (x, y), we derive full two-dimensional maps of the electron wavefunction probability densities. These reveal clearly the circular symmetry of the dot ground state (000), and the characteristic lobes of the higher energy states (100) and (200) [3].
References
[1] R.K. Hayden *et al.*, Phys. Rev. Lett. **66**, 1749 (1991).
[2] P.H. Beton *et al.*, Phys. Rev. Lett. **75**, 1996 (1995).
[3] O. Stier *et al.*, Phys. Rev. B **59**, 5688 (1999).

3:45 PM J5.5
EFFECT OF INTER-DOT ELECTRONIC COUPLING ON LASER GAIN IN InAs/GaAs QUANTUM DOT ENSEMBLE. Akira Sugimura, Itushi Tadamasa, Ikurou Umezu, Konan Univ, Dept of Applied Physics, Kobe, JAPAN.

Quantum dots have attracted interest due to their potential applicability to optical devices. In order to achieve highly luminescent devices, high dot-density is necessary. However, as it becomes higher, inter-dot electronic coupling increases (A. Sugimura et al., Proc. 24th ICPS, 1998), which will limit the device performance to some extent. In this paper we theoretically study the effect of the electronic coupling on gain coefficient in InAs/GaAs quantum dot lasers. We assume, for simplicity, spherical dot structures. Energy levels and wave functions for each isolated dot are calculated by using envelope function approximation. Inter-dot coupling coefficients are obtained by the overlap integral of wave functions. Coupled electronic states are calculated by the direct diagonalization of the coupled equation for the dot system having 900 quantum dots. Gain coefficient is obtained by the overlap integral of envelope wave functions for electron and hole states. We calculate the gain spectrum for regularly distributed and randomly distributed InAs/GaAs quantum dot systems. It is found that the peak gain coefficient increases first steeply and then gradually as a function of the dot density. Wider dot systems show decrease in the peak gain when the dot density is high enough. These behaviors can be understood by considering the two competing factors determining the peak gain; the increase of the number of oscillators and the gain spectrum broadening. It is also found that the gain spectrum is sensitive to the dot structure; the spectrum for the random system is broader than that for the regular system. Finally, we discuss optimum designing of the quantum dot structures for the high gain laser operation.

4:00 PM J5.6
SPECTROSCOPY OF MULTI-EXCITONS IN SINGLE AlInAs/AlGaAs QUANTUM DOTS. K. Hinzer, Physics Department, University of Ottawa, Ottawa, CANADA; M. Bayer, O. Stern, A. Gorbunov, A. Forchel, Technische Physik, Universitaet Wuerzburg, Wuerzburg, GERMANY; P. Hawrylak, J. Lapointe, Z.R. Wasilewski, S. Fafard, Institute for Microstructural Sciences, National Research Council, Ottawa, CANADA.

We report on single dot photoluminescence studies of AlInAs/AlGaAs self-assembled quantum dots [1]. When probing a large number of quantum dots in this ternary system, broadened emission spectra prevents the observation of a resolved shell structure. This broadening is suppressed by probing for the first time a single AlInAs quantum dot. This is achieved by lithography of as-grown samples, in which mesa structures with lateral sizes down to 100 nm are fabricated. Single dots in these mesa structures can be studied using conventional far-field spectroscopy at T = 1.5 K in an external magnetic field. Photoluminescence spectra at very low optical excitation power on several of these mesas consist of a single emission line associated with the recombination of an electron-hole pair in the lowest state of the quantum dot. At higher excitation intensities, emission from the biexciton state is observed, for which we find a binding energy of 5 meV, a factor five larger than in GaAs-based quantum wells. As well, larger multi-exciton complexes are observed at higher excitation intensities. These artificial atoms are found to have an intersublevel spacing of $\sim$70 meV. In magnetic field, we observe Zeeman splitting of the exciton and biexciton spectral lines confirming the spin degeneracy of the lowest energy level. The diamagnetic shift is less than 0.1 meV in the range of 0 to 8 T, clearly indicating strong

three-dimensional confinement of the carriers. [1] R. Leon, P.M. Petroff, D. Leonard, S. Fafard, Science 267, 1966 (1995).

4:15 PM J5.7
STRUCTURE OF EXCITED STATES AND QUANTUM DE-COHERENCE IN SELF-ASSEMBLED SEMICONDUCTOR QUANTUM DOTS. H. Htoon, D. Kulik, W. Wasicek, C.K. Shih, Department of Physics University of Texas at Austin; O. Baklenov, A.L. Holmes Jr., Department of Electrical and Computer Engineering, University of Texas at Austin.

One of the most important properties of SAQDs is their electronic level structure. Although there have been a considerable number of measurements on the electronic structure, most of them have been performed on a large ensemble of QDs. Another issue of fundamental interest is the quantum coherence/de-coherence of optically excited carriers within QDs. Measurements of quantum coherence of the excitonic wave function have been demonstrated in weakly confined QD systems formed from layer fluctuation in a quantum well. Here, we report studies of the structure of excited states and their quantum de-coherence in SAQDs grown using molecular beam epitaxy. First we determined the excited states of hundreds of individual SAQDs with nanometer spatial precision by combining PLE spectroscopy with cross-sectional nano-PL technique. Then we determined the quantum de-coherence time (dephasing time) of each excited state of individual QDs. PLE spectra of hundreds of QDs revealed (1) A majority ($\approx$ 90%) of the QDs have the first sharp absorption peak at $E_{rel} \approx$ 30 meV (E_{rel}=$E_{excitation}$-$E_{emission}$) and additional 2-3 peaks with $E_{rel} \approx$ 40-50meV. (2) At $E_{rel} >$ 50 meV, there are many sharp PLE peaks riding on the continuum like absorbtion band (3) Some QDs (<10%) have one or two sharp absorption peaks with E_{rel} below 30 meV. Dephasing time measurements revealed: (1) The first excited states with E_{rel} below 30 meV have a dephasing time of 15-30 ps. This long dephasing time could be the result of weak acoustic phonon coupling between the first excited state and the ground state. (2) Nearly all absorption peaks with $E_{rel} \approx$ 30 meV have a dephasing time shorter than 5ps (pulse width of excitation laser). Since E_{rel} matched the GaAs optical phonon energy in this case, an efficinet energy relaxation might lead to the short dephasing time.

4:30 PM J5.8
TIME RESOLVED STUDIES OF ANNEALED SELF-ASSEMBLED InAs/GaAs QUANTUM DOTS. Surama Malik, Eric Le Ru, David Childs, Ray Murray, Centre for Electronic Materials and Devices, Imperial College, London, UNITED KINGDOM.

InAs/GaAs quantum dot structures have been grown at a low growth rate and subjected to post-growth rapid thermal anneals. The object of this treatment is to create a series of samples with different dot sizes and compositions that arise from the interdiffusion of In and Ga atoms whilst maintaining a constant island density. We have then studied the effects of size and composition on the optical properties, particularly the carrier dynamics. The decay transients for each sample can be fitted using a model that incorporates state blocking effects. The extracted lifetimes decrease with annealing and this can be attributed to two effects: changes in the electron and hole wavefunctions and the emission energy. Annealing also reduces the excited state energy level spacings, ΔE, and this allows us to study the time dependent behaviour of the emission from ground and excited states as ΔE is tuned through the LO phonon energies. We find no evidence for slower carrier relaxation when the state separation is significantly different from an LO phonon energy and time resolved photoluminescence clearly shows the presence of ground state emission 100 ps after the laser pulse in all samples. These results are consistent with a fast relaxation that is independent of the separation of the energy levels.

4:45 PM J5.9
RADIATION EFFECTS IN InGaAs/GaAs QUANTUM DOTS: IS THERE A PHONON BOTTLENECK AFTER ALL? R. Leon and G.M. Swift, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA; B. Magness and W.A. Taylor, Department of Physics and Astronomy, California State University, Los Angeles, CA; Y.S. Tang and K.L. Wang, Department of Electrical Engineering, University of California, Los Angeles, CA; P. Dowd and Y.H. Zhang, Department of Electrical Engineering and Center for Solid State Electronics Research, Arizona State University, Tempe, AZ.

The photoluminescence (PL) emission from InGaAs/GaAs quantum-well and quantum-dot (QD) structures were compared after controlled irradiation with 1.5 MeV proton fluxes. Our results show two orders of magnitude enhancement in radiation tolerance with three-dimensional quantum confinement. Some additional radiation-induced changes in photocarrier recombination from QDs, which include an increase in PL emission with low and intermediate proton doses, are also examined.

SESSION J6: GROWTH ON PATTERNED SURFACES, ORDERING, AND ALIGNMENT
Chairs: Glenn S. Solomon and Simon Fafard
Wednesday Morning, November 29, 2000
Room 207 (Hynes)

8:30 AM *J6.1
QUANTUM DOTS AS SENSITIVE PROBES OF THEIR SOLID-STATE ENVIRONMENT. Amo Hartmann, Yann Ducommun and Eli Kapon, Department of Physics, Swiss Federal Institute of Technology, Lausanne, SWITZERLAND.

Spatial or temporal fluctuations in the solid-state environment of semiconductor quantum dots (QDs) can be undesirable sources of inhomogeneous broadening of their predicted discrete, atomic-like density of states. In order to exploit the advantages of the three-dimensional confinement in future QD-based optoelectronic devices, a good understanding of the QD-environment interactions is of fundamental importance.
Here, we summarize some properties of single QDs in the presence of an impurity background. The QDs are fabricated using epitaxial growth of GaAs/AlGaAs heterostructures on substrates patterned with inverted pyramids. The estimated donor density is n $\sim 10^{17}$ cm^{-3}. Individual QDs are optically probed using a micro-photoluminescence (μPL) setup. By means of a photo-depletion mechanism induced by the above-barrier optical excitation, the impurity background is used to efficiently control the number of excess electrons in the QD. Recombination of up to five-fold charged excitons is identified in the μPL spectra of single QDs. By comparing different structurally identical QDs, we demonstrate that the dynamics of these charged states is strongly dependent on the exact distribution of donors around each dot. The influence of fluctuating local electric fields at the QD position, produced by the ionized impurities, on the PL linewidths and on the optical selection rules, is discussed.
The comparison between above-barrier and selective excitation μPL spectra of a given QD allows the identification of a p-type minority doping in our structures, estimated to p $\sim 2x10^{16}$ cm^{-3}. Our analysis gives us the number and type of all the impurities in the surroundings of the dot (typically more than six for n-type and less than two for p-type). Our results show that a good control over the QD environment is necessary to efficiently engineer QD energy levels.

9:00 AM J6.2
IMPROVED UNIFORMITY AND LATERAL CARRIER CONFINEMENT OF LATERAL DOT-LIKE NANOSTRUCTURES FORMED IN TRIANGULAR-SHAPED HOLE ARRAYS ON PATTERNED GaAs (311)A SUBSTRATES UPON PATTERN SIZE REDUCTION BY ELECTRON BEAM LITHOGRAPHY. Richard Nötzel, COBRA Inter-University Research Institute, Eindhoven University of Technology, THE NETHERLANDS; Uwe Jahn, Hans-Peter Schönherr, Klaus H. Ploog, Paul Drude Institute for Solid State Electronics, Berlin, GERMANY.

Triangular-shaped GaAs/(AlGa)As dot-like nanostructures are formed by molecular beam epitaxy (MBE) on GaAs (311)A substrates patterned with arrays of triangular-shaped holes by optical lithography. The ridge-type dot arrays on these micrometer-sized patterns reveal three dimensional carrier confinement by cathodoluminescence (CL) mapping in the triangular tips due to migration of Ga atoms from the sidewalls of the holes to the top surface. The overall structure, however, exhibits rather complex CL emission due to parasitic quantum wells on the slow-growing (111)A - and opposite fast-growing sidewall of the holes. This evolution of the fast-growing sidewall which has been utilized for the formation of novel quantum wire arrays with excellent optical properties, on the other hand, leads to very uniform lateral dot-like nanostructures in the corners of the holes when their side lengths, periodicity, and depths are reduced to the sub-micrometer range to 500 and 40 nm by electron beam lithography. The ridge-like structures on the top surface and the slow-growing (111) sidewall in the holes completely smear out and the overall structure is characterized by a CL spectrum composed of only two lines from the quantum-well layers and the fast-growing sidewalls of the holes which they surround. Their CL linewidths are comparable to that of the quantum well in unpatterned areas and their energy separation, i.e., the lateral confinement energy in the dots exceeds 100 meV. Thus, very uniform and dense dot-like nanostructures with large confinement energy are formed by pattern size reduction based on the unique formation of a fast growing mesa sidewall on patterned GaAs (311)A.

9:15 AM J6.3
SELF-ORDERING IN (Zn,Mn)Se/(Zn,Mn)Se, In,As/In,Sb/In,As, In,Sb/GaSb AND GaSb/GaAs QUANTUM DOT STRUCTURES. P. Moeck, T. Topuria, N.D. Browning, Dept of Physics, Univ of Illinois at Chicago, Chicago, IL; S. Lee, M. Dobrowolska, J.K. Furdyna, Dept of Physics, Univ of Notre Dame, Notre Dame, IN; N. Mason, R.J. Nicholas, Dept of Physics, Clarendon Laboratory,

University of Oxford, Oxford, UNITED KINGDOM; G.R. Booker, Dept of Materials, University of Oxford, Oxford, UNITED KINGDOM.

A sufficiently high size uniformity of self-assembled quantum dots is thought to be achievable by means of self-ordering processes and is one of the conditions that have to be met in order to make QDs useful in optoelectronic devices [1]. Vertical self-ordering of QDs was observed in cross section geometry by means of high resolution transmission electron microscopy (HRTEM) in a molecular beam epitaxy grown (Zn,Mn)Se/CdSe/(Zn,Mn)Se multilayer structure. Z-contrast imaging in a STEM/TEM on the same specimen indicated that there is a self-ordered compositional modulation of Cd atoms on (111)A planes, and (Zn,Mn) atoms on the following (111)A planes (i.e. periodicity $\approx$ 1 nm) within the individual QDs. The QD were of the order of magnitude 100 nm wide and 50 nm high an usually free of structural defects. We assume that the high crystalline perfection of these comparably large QDs may be due to the self-ordered compositional modulation within the individual QDs. A much smaller domain of self-ordered compositional modulation (QDs) was also observed on a symmetry related (111)A plane. A phenomenological similar self-ordered compositional modulation was observed by atomic resolution Z-contrast imaging in plan-view and cross-section geometry in a single layer InAs/InSb/InAs QDs structure which was grown by metal organic vapour deposition (MOCVD). The periodicity of the self-ordered compositional modulation, however, varied from QDs to QDs. Domains with different crystallographic orientations of the self-ordered compositional modulation (QDs) were also present. Horizontal self-ordering was observed by means of atomic force microscopy on MOCVD grown InSb islands on GaSb and GaSb islands on GaAs. The phenomenological classification scheme by Bimberg et al. [1] has been employed to correlate the growth conditions with the achieved levels of self-organization. The general trend observed was the lower the ^{III} / $_{V}$ ratio and growth rate, the higher the level of self-ordering of the islands. [1] Bimberg D., M. Grundmann, N.N. Ledentsov, Quantum Dot Heterostructures, John Wiley & Sons, 1999, Chichester, New York, Weinheim, Brisbane, Singapore, Toronto

9:30 AM J6.4
A NOVEL GaAs QUANTUM DOT-WIRE COUPLED ARRAY FORMED BY SELECTIVE AREA MOVPE. Fumito Nakajima, Yuu Ogasawara, Junichi Motohisa, Takashi Fukui, Research Center for Interface Quantum Electronics (RCIQE), Hokkaido University, Sapporo, JAPAN.

We report a novel GaAs quantum dot-wire coupled arrays by using selective area MOVPE on a GaAs substrate partially masked by SiON. GaAs/AlGaAs was selectively grown at 700°C in wire-like opening areas which have a periodic width modulation to form two types of sidewall facets, {110} and {111}B, during the growth. As the growth proceeded, top (001) terrace were naturally squeezed by both {111}B and {110} facet sidewalls The (001) top terrace region was finally pinched-off partially at the narrowest width wire region because of the self-limited growth mode, which formed ridge regions. At the same time, diamond shaped narrow (001) terraces were formed periodically at the wider wire regions. Thus growing AlGaAs/GaAs/AlGaAs quantum well structures, it is possible to form GaAs dots at the (001) terrace regions which are coupled with ridge wires. We have confirmed the formation of such QD-wire coupled array by spectrally and spatially resolved cathodoluminescence (CL) measurement at 6.8K. For structures with GaAs well width corresponding to 2.3 nm thickness on a planer substrate, strong luminescence at 1.67 eV was clearly observed from the dot region in the CL images. They also indicated the luminescence of the ridge region at 1.83 eV and sidewall facet region and 1.85 eV, respectively. The peak shift is mainly explained by the growth thickness change at each region, which is caused by the difference of surface diffusion of Ga atoms from sidewalls. In the present structure, GaAs QDs are almost completely buried three-dimensionally in AlGaAs. In addition, the wire at the ridge region is formed close to the QDs simultaneously during MOVPE growth and have larger potential height. Therefore, our QD-wire coupled array is very promising for the application to single electron devices with strong confinement and large tunneling barrier heights.

10:15 AM *J6.5
TUNABLE LATERAL AND VERTICAL ORDER IN SELF-ORGANIZED PbSe QUANTUM DOT SUPERLATTICES. G. Springholz, M. Pinczolits, V. Holy, P. Mayer, G. Bauer, H. Kang[a], and L. Salamanca-Riba[a], Johannes Kepler Universitaet, Linz, AUSTRIA. [a]University of Maryland at College Park, MD.

The formation of vertical and lateral correlations in self-organized PbSe/PbEuTe quantum dot superlattices is investigated. From cross sectional TEM, AFM and x-ray diffraction studies we find the occurrence of several different ordered dot phases due to abrupt changes in the vertical correlations at certain spacer layer thicknesses. In particular, it is found that for small spacer thicknesses (d < 350 A), the dots are vertical aligned similar as in Si/Ge or InAs/GaAs dot superlattices, with a weak hexagonal ordering tendency in the lateral direction. For intermediate spacer thicknesses in the range of 350 - 560 A, nearly perfectly ordered trigonal dot lattices are formed with a fcc-like ABCABC stacking sequence and with an inclined layer-to-layer dot correlation direction. In addition, a completely different scaling behavior of the lateral dot spacings versus spacer thickness is observed. Whereas for superlattices with fcc-stacking, the in-plane dot spacing is directly proportional to the spacer thickness, the in-plane dot spacing increases abruptly by a factor of three when the spacer thickness decreases below 350 A. Also, the different vertical correlations result in a completely dif-fe-rent evo-lution of dot sizes and shapes as a function of the number of superlattice periods. The unique tunability of the different 3D dot arrangements is explained by finite element calculations of the elastic strain fields when taking into account not only the elastic anisotropy of the materials but also the finite size of the dots and the spacer layer. The obtained critical thicknesses for the transitions between the different dot phases are in good agreement with the experiments. Our results provide new insights in the ordering mechanism in self-organized quantum dot superlattices and provide a route for extending the tunability range of the ordered dot structures.
1. G. Springholz, et al., Phys. Rev. Lett. 84, 4669 (2000).

10:45 AM J6.6
SPATIAL POSITIONING CONTROL AND OPTICAL PROPERTIES OF SELF-ASSEMBLED InAs QUANTUM DOTS ON GaAs PATTERNED SUBSTRATES. Haiyan An, Junichi Motohisa and Takashi Fukui, Research Center for Interface Quantum Electronics (RCIQE), Hokkaido University, Sapporo, JAPAN.

In this report, the carrier relaxation process and excited states of InAs quantum dots (QDs) selectively self-assembled on the top of high density (4.4×10^9 cm^{-2}) GaAs pyramidal structures have been studied in detail by micro-photoluminescence (micro-PL), micro-photoluminescence excitation (micro-PLE) measurements compared with that of reference planar sample. The symmetry of the electronic states of these selective formed InAs QDs will also be discussed based on the experimental results of ploarization dependent micro-PL and micro-PLE measurements. Furthermore, in order to study the single and double lateral couple InAs QDs, the patterns for selective area MOVPE growth were designed specially with low density (1×10^4 cm^{-2}) on GaAs (001) substrates covered with 40 nm SiON film. The spatial position and number of InAs QDs can be controlled from randomly distributed multiple to three, double and single QD by changing the growth times of underlying GaAs. For QDs less than three, they are well aligned along the [$\bar{1}$10] direction. We observed that the corners of the top facet, that is the inter-facet conjunctions, along [$\bar{1}$10] direction are preferred sites for formation of InAs QDs. This offers a possibility to control the distance between the double QDs, and to in-situ form InAs 'artificial molecules' at designed position. Especially, the double and single dot can be formed on the top of GaAs pyramids when planar InAs layer thickness is 1.3 ML which is far below the critical thickness of InAs QDs formed on planar GaAs substrate. These results will be discussed based on the intra-facet and inter-facet adatoms migration as well as InAs layer strain relaxation on the top facet. The optical characteristics of these double and single InAs QD will be discussed.

11:00 AM J6.7
SELF-ASSEMBLED InAs QUANTUM DOTS ON PATTERNED InP SUBSTRATES. Jacques Lefebvre, Philip Poole, Geof Aers, Boris Lamontagne, and Robin Williams, National Research Council Canada, Institute for Microstructural Sciences, Ottawa, CANADA.

The inhomogeneous linewidth in the photoluminescence (PL) spectra of self-assembled quantum dots (SADs) can be narrowed down when interdot spatial correlations are introduced. Substrate patterning is proven to be one method to achieve spatial correlation, and is tested on InAs SADs grown on InP substrates. The PL spectra from SADs grown on sub-micron patterns are compared with spectra from unpatterned samples.

11:15 AM J6.8
STRAIN AND SPATIAL CORRELATIONS OF InP QUANTUM DOTS. Martin Schmidbauer, Fariba Hatami, Michael Hanke, Thomas Wiebach, Helmut Raidt, Rolf Köhler, W. Ted Masselink, Institut für Physik, Humboldt-Universität zu Berlin, Berlin, GERMANY.

In the last few years self-organizing epitaxial growth mechanisms have been developed for the fabrication of semiconductor quantum dots (QD). In the present paper we describe multilayer structures where the strain field of the buried dots may influence the island nucleation in subsequent layers during growth. This situation may lead to vertical correlation of the dot position which is accompanied by an improved narrow size distribution. Coherently strained InP/$In_{0.48}Ga_{0.52}P$ QDs

have been grown on (001) GaAs by gas source molecular beam epitaxy (GSMBE). Island formation begins after the deposition of about 3 monolayers of InP, after which ordered arrays of islands build up with typical sizes of the QDs of about 30 nm base width and 4 nm height, respectively. All samples show a high degree of lateral ordering which is most pronounced along the < 100 > directions. The multilayered samples typically consist of 10 layers of InP QDs which are embedded in 15 nm thick InP/$In_{0.48}Ga_{0.52}P$ which is latticed-matched to GaAs. Various x-ray diffuse scattering techniques - using intense synchrotron radiation - have been applied which are sensitive to the strain field and/or electron density fluctuations inside and in the vicinity of the InP QDs. We present results of a systematic depth-resolved analysis of both strain and lateral correlation of the InP dot positions. The experimental data are evaluated by a combined approach of finite element calculations along with brute-force x-ray simulations.

11:30 AM J6.9
INTERLAYER SPATIAL CORRELATIONS IN SELF-ASSEMBLED InGaAs QUANTUM DOTS: A SCANNING PROBE MICROSCOPY STUDY. X.-D. Wang, N. Liu, and C.K. Shih, Dept of Physics, The Univ of Texas, Austin, TX; S. Govindaraju, Texas Materials Inst, The Univ of Texas, Austin, TX; A.L. Holmes Jr., Dept of Electrical and Computer Engineering, The Univ of Texas, Austin, TX.

Spatial correlation of the quantum dots (QDs) plays a central role in the formation of ordered QDs arrays. In III-V QD systems such as InGaAs QDs it is generally observed that the QDs in the multi-stacking arrays are either vertically aligned (at smaller spacer thicknes) or uncorrelated (at larger spacer thickness). However, by using cross-sectional scanning probe microscopy, we found that there existed a clear transition from correlation to anticorrelation with increase of spacer thickness. The multi-stacking $In_{0.5}Ga_{0.5}As$ QDs were grown on GaAs substrate by migration enhanced epitaxy (MEE) technique. As a function of the spacer layer thickness, the QDs between the neighboring layers are either vertically correlated (at small spacer thickness) or anti-correlated (at larger spacer thickness), implying a very abrupt correlation/anticorrelation transition. Furthermore, compared with that of correlated QDs, the size distribution of individually anticorrelated QDs is more uniform under the identical growth conditions. Under the assumption that the QDs were formed near the equilibrium condition, we further deduced the effect interlayer QD-QD interaction as a function of spacer layer thickness. The implications in fundamental understanding of the underlying mechanisms for self-organized growth of QDs and the technological applications will be discussed.

11:45 AM J6.10
ELECTRIC FIELD EFFECTS DURING THE ASSEMBLY OF CdSe NANOPARTICLE ARRAYS AS PROBED BY SECOND HARMONIC GENERATION AND ATOMIC FORCE MICROSCOPY. Mohammad A. Islam, Jonathan E. Spanier, Bosang S. Kim, Dalia G. Yablon, Jerry I. Dadap, George W. Flynn, Tony F. Heinz, Irving P. Herman; Columbia University, Materials Research Science and Engineering Center and Columbia Radiation Laboratory, New York, NY.

The effect of static electric fields during the self-assembly of CdSe nanoparticle arrays from solution was investigated. A pair of Au-on-Si electrodes was submerged in a solution of CdSe nanoparticles in hexane solvent and voltages of the order of 1000 V were applied to the electrodes. Two kinds of electrodes were used: flat electrodes and electrodes with micromachined sharp ridges. Sharp ridges were used to enhance the electric fields and to create field gradients. Atomic Force Microscopy (AFM) was used to determine the thickness and long range order of the resulting arrays. AFM images show that the nanoparticle array thickness, lateral dimension and morphology depend on the local direction of the electric fields. Electric Field Induced Second Harmonic (EFISH) was examined in this solution. The effect was largest near the electrodes, presumably due to the enhanced density of the nanoparticles. In addition to profiling the density, the EFISH signal also reflects the degree of alignment of the crystallographic axes of the CdSe nanoparticles. Results obtained for the flat electrodes and ridged electrodes will be discussed in terms of local electric fields and their effect on nanoparticle density and alignment. This work was supported by the MRSEC program of the National Science Foundation, Award No. DMR-9809687.

SESSION J7: NOVEL MATERIALS, STRUCTURE, AND CHARACTERIZATION TECHNIQUES
Chairs: Manfred Bayer and Diana Huffaker
Wednesday Afternoon, November 29, 2000
Room 207 (Hynes)

1:30 PM *J7.1
COUPLING BETWEEN QUANTUM DOT AND PHOTONIC DOT STATES. U. Woggon, University of Dortmund, FB Physik, GERMANY.

We report on spectroscopic studies of two types of coupling in semiconductor quantum dot structures: (i) the coupling between electronic states within a dense ensemble of CdSe quantum dots and (ii) the coupling of electronic states of CdSe quantum dots to the confined photonic states of a spherical polymeric microcavity. First, we compare room- and low-temperature optical spectra of isolated and close-packed CdSe quantum dots and show the existence of delocalized electronic states for a dense ensemble of ultrasmall quantum dots. The presence of collective states results in a red shift and broadening of the optical transitions [1] and in the loss of the detection energy-dependence of the photoluminescence excitation spectra. Using electroabsorption we demonstrate that collective subminibands in close-packed ensembles can collaps and primary localization of electronic states can be restored under strong electric fields. The "Quantum Dot/Photonic Dot"-structure has been created by introducing highly luminescent CdSe nanocrystals into a micrometer-sized spherical, polymeric microcavity [2]. The emission of light of the embedded quantum dots in the microcavity is studied for single polymethylmetacrylate (PMMA) spheres of a few micrometer size doped with CdSe by using a microphotoluminescence set-up at room temperature. A sharp oscillating structure appears in the CdSe photoluminescence band for single isolated PMMA spheres. The evidence of whispering gallery modes inside the spherical microcavity reflects the modification of the quantum dot emission, i.e. the coupling of quantum-confined electronic states with cavity modes. When only a few quantum dots are incorporated in hollow microspheres and placed closed to the surface of the microcavity, a quality factor of 2000 is achieved for the ratio between energy and linewidth (T=300K). [1] M.V. Artemyev et al. Phys. Rev. B 60, 1505 (1999). [2] M.V. Artemyev and U. Woggon, Appl. Phys. Lett. 76, 1353 (2000).

2:00 PM J7.2
OBSERVATION OF RESONANT TUNNELING THROUGH InP QUANTUM DOTS USING BALLISTIC ELECTRON EMISSION MICROSCOPY. C.V. Reddy, V. Narayanamurti, Gordon McKay Laboratory of Applied Science, Harvard University, Cambridge, MA; J.H. Ryou, U. Chowdhury, R.D. Dupuis, Microelectronics Research Center, The University of Texas at Austin, Austin, TX.

Recently, there has been an increasing interest in employing self-assembled quantum dots (SAQDs) as the active layer in building LEDs and lasers, which are expected to display superior performance in terms of low threshold current density and higher characteristic temperatures, in comparison with the conventional multi-quantum well active regions. In the phosphide-based optoelectronics, active regions consisting of InP quantum dots with AlInP as the barrier layers, could be a potential system to investigate. In this paper, we report the successful growth and characterization of quantum-confinement related effects on the current transport mechanism through the self-assembled InP quantum dots on AlInP, grown on GaAs matrix. The excellent microscopic and spectroscopic capabilities of the ballistic electron emission microscopy (BEEM/BEES) technique are utilized to inject electrons into a selective single dot, and to investigate the current transport mechanism by performing spectroscopy on and off the dot. The epitaxial structures were grown by low-pressure metal-organic chemical vapor deposition. The growth was initiated with 5nm AlInP cladding layer on n GaAs substrate, followed by self-assembled InP QDs by depositing 40 monolayers of InP at ~650°C. The QDs were covered with 5nm AlInP, followed by a final 6nm GaAs cap layer. Finally, Schottky contact was prepared by depositing 6nm of gold on the front side. Thus, off the dot, the band profile of our experimental device looks like a single AlInP barrier (GaAs/AlInP/GaAs), and on the dot, it looks like a double barrier heterostructure (DBH) with an embedded InP-QD. Second derivative BEEM is used to measure the relevant heterojunction band-offsets and to see a direct spectroscopic signature of resonant tunneling through the quantum dot. The BEEM spectra taken on and off the dot revealed the presence of a localized state at around 0.1±0.02 eV in the DBH.

2:15 PM J7.3
InAs-InP COUPLED QUANTUM DOT SYSTEMS. G. Medeiros-Ribeiro, A.A. Bernussi, W. de Carvalho Jr., Laboratório Nacional de Luz Síncrotron, Campinas, SP, BRAZIL.

Self-assembled heteroepitaxial quantum dots (QDs) systems have received in the past years a great amount of attention as a relatively simple route of nanostructuring solids with unique electronic properties. One key aspect in this area has been the ability of vertical positioning of QDs through stacking of 2D QD layers. By varying the distance between the layers, one can tune the amount of strain interaction as well as the electronic coupling between QDs. Stacks of InAs in GaAs, and InP in InGaP have been studied over the years, and the corresponding coupling interactions have been modeled and

inferred through optical and magneto-optical experiments. Nevertheless, the stacking of alternated QD layers of different materials, for instance, InAs and InP QD layers, has not received a great deal of attention yet. In this work we present results aimed at the understanding of the interaction between coupled layers of near surface InAs-InP QDs systems. InAs QDs were grown by MOCVD on InGaP layers, being later covered by GaAs spacers with varying thickness, ranging from 2 to 10 nm. InP QDs were then grown over the spacer, and the QD structural properties were investigated through AFM. We found that density, size, and shape of the InP QDs were strongly influenced by the GaAs spacer thickness, with their corresponding effect on the electronic properties of both InAs and InP QDs. With these results we were able to assess the degree of quantum and strain coupling of InAs-InP QD hetero-stacks.

2:30 PM J7.4
A NOVEL STABLE QUANTUM DOT SYSTEM FOR ELECTRON-HOLE PAIR SEPARATION: SELF-ASSEMBLED Cu_2O QUANTUM DOTS ON $SrTiO_3$(001). Yong Liang, Dave McCready, Scott Lea, Scott Chambers, Shupan Gan, Environmental Molecular Sciences Laboratory, Pacific Northwest National Laboratory Richland, WA.

Self-assembled quantum dots have attracted a great deal of attention recently due to their artificial atom-like electronic and optical properties. Two technical challenges in the development of quantum dots applications are the structural stability and property controllability. Since conventional semiconductor quantum dots often exhibit less desirable chemical and thermal stability, we address these issues using oxide-based materials. We have successfully synthesized Cu_2O quantum dots on $SrTiO_3$(001) substrates using oxygen-plasma assisted molecular beam epitaxy. It was found that the initial formation of the quantum dots occurred after a few monolayers of Cu_2O deposition due to the large compressive lattice mismatch between Cu_2O and $SrTiO_3$(001). The chemical structure and composition of the Cu_2O quantum dots were characterized using reflection high-energy electron diffraction (RHEED), x-ray photoelectron spectroscopy (XPS), x-ray diffraction (XRD), high-resolution scanning Auger microscopy (SAM), and atomic force microscopy (AFM). SAM revealed that the amount of interdiffusion between the Cu_2O quantum dots and $SrTiO_3$(001) substrates is significantly less than several semiconductor-based quantum-dots systems we have investigated. Four types of quantum-dot related structures were found under different synthesis conditions: elongated huts, square pyramids, multifaceted domes and corral-like rings. While the first three kinds resemble the morphology observed for SiGe quantum dots, the ring structure mimics that of CdTe/ZnSe. Furthermore, XPS measurement on band offsets shows that $Cu_2O/SrTiO_3$(001) exhibits a type-II heterojunction with both the valance and conduction bands of Cu_2O are higher than that of $SrTiO_3$(001), i.e quantum dot for electrons but anti-quantum dot for holes. Consequently the photo-excited electrons and holes are spatially separated with holes being confined to Cu_2O quantum dots and electrons confined to $SrTiO_3$(001), a property important for photocatalysis and other applications.
Pacific Northwest Laboratory is a multiprogram national laboratory operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

3:15 PM *J7.5
OPTICAL PROPERTIES OF InAs-BASED QUANTUM DOTS IN MICROCAVITIES. G.S. Solomon, Department of Electrical Engineering, Stanford University Stanford, CA.

Lithography-free nanostructures have been proposed as both revolutionary and evolutionary components in solid state devices. Proposed applications vary from molecular self-assembled circuits to light emission at previously inaccessible wavelengths. In this talk, I will discuss a particular nanostructure system, an ensemble of semiconductor strain-induced quantum dots (QDs) of InAs in a host matrix of GaAs. These QDs are inserted in several optical structures to investigate the QDs spontaneous and stimulated emission properties. A QD ensemble can be placed in a 1-D photonic bandgap structure, called a planar microcavity, where the QD spontaneous emission properties can be modified. By processing these planar microcavities into post, discrete optical modes develop and are investigated using the broad QD ensemble emission. When the post diameter is small individual QDs can be isolated; the single QD spontaneous emission lifetime and the coupling efficiency to the fundamental cavity mode can be significantly altered. In a different type of microcavity structure, InAs QDs are inserted into the active region of a microdisk whispering gallery mode cavity. Using optical pumping, and the broad QD spontaneous emission from the ensemble, stimulated emission can be observed from several cavity modes.

3:45 PM J7.6
PHOTOLUMINESCENCE PROPERTIES OF UNIFORM InGaAs QUANTUM DOTS FABRICATED BY HETEROGENEOUS DROPLET EPITAXY. Takaaki Mano, Shiro Tsukamoto, Nobuyuki Koguchi, National Research Institute for Metals, Tsukuba, JAPAN; Kanta Ono, Masaharu Oshima, Univ Tokyo, Dept of Applied Chemistry, Tokyo, JAPAN.

Recently, we have developed a new self-organized fabrication method for InGaAs concave disk shaped quantum dots (QDs), termed Heterogeneous Droplet Epitaxy (HDE) [1,2]. These QDs showed narrow photoluminescence (PL) peaks (full width at half maximum: 21 meV) due to the high uniformity of the QDs. In this paper we investigated the detailed PL properties of the QDs in order to clarify the electronic structure of the QDs. The detailed fabrication process and structure of the InGaAs QDs are described elsewhere [2]. The PL spectra at 20 K were detected using InGaAs photodetector through a spectrometer. An Ar^+-ion laser light excited the samples at 512 nm. To restrict the number of excited QDs, a gold mask with 60 μm circle hole (slit) was fabricated by lithography and sputtering technique. The total number of the QDs measured through the slit was 2×10^5. By increasing the excitation power intensity, new peaks appear at 922 nm and 911 nm in addition to the peak at 946 nm. The intensity of these three peaks was increased until the excitation intensity reached 150 W/cm^2. Above this region, the intensities of these peaks were saturated and no other PL signal was observed. These results suggest that these three peaks are attributed not to ground state (n = 1), first (n = 2) and second (n = 3) excited states, respectively, but to split hole states due to the anisotropic confined potential [3]. References [1] T. Mano et al., Jpn J. Appl. Phys. 38, L1009 (1999). [2] T. Mano et al., Appl. Phys. Lett. 76, 3543 (2000). [3] T. Tanaka et al., Appl. Phys. Lett. 62, 756 (1993).

4:00 PM J7.7
OPTICAL SPECTROSCOPY OF SELF-ASSEMBLED InP QUANTUM DOTS GROWN ON GaP USING GAS-SOURCE MOLECULAR BEAM EPITAXY. F. Hatami, W.T. Masselink, Humboldt-Universität zu Berlin, Dept. of Physics, Berlin, GERMANY; L. Schrottke, Paul-Drude-Institut, Berlin, GERMANY.

This paper describes the growth of and optical emission from InP quantum dots (QD's) grown on (100) GaP using gas-source molecular beam epitaxy. Under the proper growth conditions, the 7.7% lattice mismatch between the strained InP and the GaP buffer drives self-organized island formation through the Stranski-Krastanov mechanism after a critical deposition of InP of approximately 1.8 monolayers (ML's) is exceeded. Atomic force microscopy studies indicate that unburied dots are approximately 100×100 nm^2 in lateral extent and about 20 nm high, with dot densities in the range of $2–6 \times 10^8$ cm^{-2} for InP coverage between 1.9 and 5.8 MLs. Structures prepared for optical investigations contain multiple InP layers and are capped with 10–15 nm of GaP. The photoluminescence (PL) emission from structures with sub-critical InP coverage and, therefore, no QD's consists of two closely spaced, intense, and relatively narrow PL lines in the range of 2.15–2.30 eV. The PL from structures containing InP QD's includes an additional strong emission peak at about 2.0 eV (λ = 620 nm) attributed to radiative recombination of heavy-holes and electrons in the quantum dots. The PL emission energy from the InP QD's is about 0.6 eV higher than the bulk InP bandgap, a shift which is constant over a wide temperature range and is due to strain, quantum confinement, and probably also Ga interdiffusion. Time-resolved measurements indicate characteristic times of several nanoseconds. We believe this is the first report of strong emission from self-organized quantum dots prepared in the (100) GaP system.

4:15 PM J7.8
SYNTHESIS AND CHARACTERIZATION OF METAL-SEMICONDUCTOR NANO-COMPOSITES. Scott L. Cumberland, Geoffrey F. Strouse, University of Califonia, Dept. of Chemistry and Biochemistry, Santa Barbara, CA.

Nano-materials such as CdSe nanocrystals and gold and silver nanoparticles are of great interest in sensing and electronic technologies due to their unique size dependent optical and electronic properties. The proximity of the band gap energy of CdSe nanocrystals and the excitation energy of metal nanoparticle surface plasmon offers the opportunity to produce nano-composite materials with novel optical and electronic properties as well as an enhancement of the nonlinear optical response. It is believed that the organization of these materials into 2- and 3-dimensional structures could provide structural paradigms for nano-electronic architectures. Here we present the synthesis and characterization of CdSe-Ag and CdSe-Au nano-composite materials formed by ligand directed self-assembly of the nano-components into 2- and 3-D architectures.

4:30 PM J7.9
SPECTROSCOPIC PROPERTIES OF ORGANIC MOLECULAR-WIRE/SEMICONDUCTOR NCs HYBRID STRUCTURES. Marina Sirota, Edith Minkin, Efrat Lifshitz, Department of Chemistry and Solid State Institute, Technion-Israel

Institute of Technology, Haifa, ISRAEL; Volker Hensel, Meir Lahav, Department of Materials and Interfaces, Weizmann Institute of Science, Rehovot, ISRAEL.

The present study concentrates on the design, synthesis and spectroscopic characterization of advantageous nanoscaled semiconductor crystals (NCs) arrays, consisting of an organic molecular-wire/NCs hybrid materials, ordered in the form of 3-D crystals. The indicated NCs arrays are prepared by the transformation of 3-D crystals of fully conjugated organic salts into organic/inorganic hybrids, using a topotactic gas/solid reaction. NCs arrays show new collective effects resulting from the inter-NC or matrix-NC interactions in addition to the properties of individual NCs. The present work examines the contribution of the fully conjugated organic matrix to the optical properties of the exhibit electronic coupling between the organic and inorganic constituents, leading to an energy transfer. In addition, the fully conjugated chains may enhance inter-NCs coupling across the chain. Semiconductor NCs arrays may supply a sufficient gain in opto-electronic devices, assembled either on a substrate, an electrode, or embedded in composite structures. We present the characterization of the electronic and optical properties of the molecular-wire/NCs hybrid structures, accomplished by the use of photoluminescence (PL), PL-excitation(PLE) and time-resolved PL.

SESSION J8: STRUCTURAL CHARACTERIZATION
Chairs: Gunther Springholz and Rosa Leon
Thursday Morning, November 30, 2000
Room 207 (Hynes)

8:30 AM *J8.1
CHARACTERISATION OF THE MICROSTRUCTURES OF SEMICONDUCTOR QUANTUM DOTS USING TRANSMISSION ELECTRON MICROSCOPY AND IMAGE SIMULATIONS.
Xiaozhou Liao, Jin Zou, The University of Sydney, Australian Key Centre for Microscopy and Microanalysis, NSW, AUSTRALIA; David J.H. Cockayne, University of Oxford, Department of Materials, Parks Road, Oxford, ENGLAND; Rosa Leon, California Institute of Technology, Jet Propulsion Laboratory, Pasadena, CA; Zuimin Jiang, Xun Wang, Fudan University, Surface Physics Laboratory, Shanghai, CHINA.

The opto-electronic properties of semconductor quantum dots (QDs) are very sensitive to the shape, size, and composition of the QDs. A correct determination of the geometric structure and chemical composition of QDs is a prerequisite for modelling the physical proterties of the QDs. However, because of the small size of QDs, an accurate experimental determination of the QD microstructures has proved to be very difficult and the results have been controversial. Many techniques have been used to study the structures of QDs. Among them, transmission electron mictroscopy (TEM) is one of the most frequently used. Because TEM dynamical diffraction contrast images of QDs arise largely from the strain field of the QDs, rather than from the QD shape and size directly, QD shape and size cannot be interpreted directly from the diffraction contrast images without image simulation. However, because the QD strain field is sensitive to the QD composition, it may be possible to extract composition information of QDs through comparison of simulated and experimental images. We will discuss our results of TEM investigation of the microstructures of InGaAs/GaAs(001) and Ge(Si)/Si(001) QDs. Dynamical diffraction contrast imaging technique with image simulations and other TEM techniques including energy filtering imaging and X-ray energy dispersive spectrometry have been used in the investigation. Results on QD shapes and composition distribution within QDs will be presented.

9:00 AM J8.2
ATOMICALLY RESOLVED SHAPE OF InAs QUANTUM DOTS ON GaAs(001).
J. Márquez, L. Geelhaar, K. Jacobi, Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, GERMANY.

InAs was grown by molecular beam epitaxy (MBE) on GaAs(001) until self-assembled three dimensional islands were formed. At this point the growth was interrupted and the sample was quenched rapidly to room temperature. The shape of the islands, which had the same dimensions known for self-assembled InAs quantum dots, was investigated in situ by ultra-high vacuum scanning tunneling microscopy (UHV-STM). Atomically resolved STM images revealed that the dominating bounding facets of the islands were of high-Miller-indices, instead of low-index planes (i.e. {110}, {111} and {100}). With the help of a comparative study on planar surfaces of (2 5 11) oriented GaAs Wafers we have been able to assign unambiguously the main facets of the islands to be of {137} orientation, which is only 2.3° off from (2 5 11). Moreover, the experiments on the GaAs(2 5 11) surface, a so far unknown stable GaAs surface, indicated that the (137) surface should be energetically unfavorable. As a result, it appears that the dot formation is more complex than suggested by the classical Stranski-Krastanov growth mode.

9:15 AM J8.3
DIRECT OBSERVATION OF SELF-ORDERED COMPOSITIONAL MODULATION IN CdSe QUANTUM DOTS IN (Zn,Mn)Se MATRIX.
T. Topuria, P. Moeck, N.D. Browning, Dept of Physics, Univ of Illinois at Chicago, Chicago, IL; M. Dobrowolska, S. Lee, J.K. Furdyna, Dept of Physics, Univ of Notre Dame, Notre Dame, IN.

In this paper we present the application of the atomic resolution Z-contrast imaging technique in a scanning transmission electron microscope (STEM) to the investigation of self-assembled CdSe quantum dot (QDs) in a (Zn,Mn)Se matrix. For the atomic resolution Z-contrast imaging, we used a sub 0.2 nm electron probe obtainable under routine conditions at the 200 kV JEOL JEM 2010F Schottky field emission STEM of the University of Illinois at Chicago [1]. Since the Z-contrast technique produces an incoherent image which shows a high sensitivity to the mean square of the atomic number (Z) [3], bright features in atomic resolution images can be directly interpreted as atomic columns. The relative brightness of individual atomic columns, on the other hand, depends on the average atomic number of the constituting atoms. By comparing intensity profiles and atomic column spacing in parallel directions within the QD and the surrounding matrix, it is possible to estimate the elemental distribution on an atomic level. The multilayer QDs structure we analyzed was grown by means of molecular beam epitaxy on a ZnSe/GaAs pseudo-substrate [2]. It was found that the QD were of the order of magnitude 100 nm. While one QDs was bound by distinct (001), $(1\bar{1}1)$, $(1\bar{1}\bar{1})$, $(00\bar{1})$, $(\bar{1}1\bar{1})$ and $(1\bar{1}1)$ facets and contained a small angle grain boundary, the other QDs did not show distinct facets and were free of structural defects. The Z-contrast image revealed further that there is a compositional modulation on alternating (111)A planes, suggesting that about 50% of the cation places of the structure are occupied by Cd atoms. This estimation compares well with the results of earlier photoluminescence measurements [2]. We assume that this compositional modulation is due to self-ordering processes and may be responsible for the observed high crystalline perfection of the QDs. [1]] E.M. James and N.D. Browning Ultramicroscopy 78 (1999) 125- 139 [2] M. Kim, C.S. Kim, S. Lee, J.K. Furdyna, and M. Dobrowolska (unpublished) [3] 139P.D. Nellist and S.J. Pennycook, Ultramicroscopy 78 (1999) 111-124

9:30 AM J8.4
SHAPE TRANSITION OF NANOWIRES INTO 3D ISLANDS.
Haeyeon Yang, Gregory J. Salamo, Physics Department, University of Arkansas, Fayetteville, AR.

Basic issues regarding the shape transition in self-assembled nanostructures that are created by strained epilayers are currently the focus of much attention. We explore the stability of InAs nanowires formed on an InP(001) surface and its shape transition into 3D islands using in situ scanning tunneling microscopy (STM). Three major factors affecting the shape are strain energy, surface energy and edge energy of a 3D island. During 3D island formation, an equilibrium is reached between these energies resulting in a 3D island shape. During annealing, however, changes in this energy balance can alter shape. For example, the strain energy of a 3D island due to lattice mismatch changes with intermixing between the substrate material and the island material. In addition, the surface energy changes with a change in surface reconstruction or facets. As a result, during annealing the competition between the surface energy cost, edge energy cost and strain relaxation may alter the island equilibrium shape. Our STM results suggest that the surface energy change is the leading cause in the shape transition from nanowires into 3D islands. Issues regarding the shape transition will be discussed by comparison with other systems.

10:15 AM *J8.5
STRUCTURAL CHARACTERIZATION OF InAs/GaAs AND InAs/InP QUANTUM DOTS BY TRANSMISSION ELECTRON MICROSCOPY.
John P. McCaffrey, Phillip Poole, Zbig Wasilewski, Simon Fafard, Institute for Microstructural Sciences, National Research Council of Canada, Ottawa, CANADA; Michael D. Robertson, JDS Uniphase, Nepean, CANADA.

Comparisons of InAs/GaAs and InAs/InP quantum dots (QDs) utilizing transmission electron microscopy (TEM) show interesting parallels and differences between the two systems. The higher 7.2% misfit in the InAs/GaAs system produces small (~20 nm diameter) QDs with a predominately round shape, while the lower 3.2% misfit in the InAs/InP system produces larger (~35 nm width) QDs with a predominately diamond shape. Small differences in crystal growth procedures between different laboratories and the ambiguous TEM images resulting from a small amount of InAs producing a relatively

high degree of local crystal lattice strain have produced some controversy regarding the actual sizes and shapes of QDs. In this presentation, plan-view and cross-sectional TEM images of QDs are used to monitor changes in QD shapes and dimensions with variations in crystal growth parameters. The sizes and shapes are determined through the interpretation of the observed (primarily atomic number) contrast in cross-sectional images and the observed (primarily strain) contrast in plan-view. The contrast reversals in the center of QD images in cross-section and the variations in apparent shape of QDs in plan-view are discussed and supported by modeling using the many-beam Bloch-wave approach, including strain. Variations in QD size and shape can be controlled by a variety of crystal growth strategies, and are reflected in the optical spectrum of these structures. In both the InAs/GaAs and InAs/InP systems, a growth evolution can be observed with varied growth interrupt time to allow for the formation and growth of the QDs. The observed tendency is for the initial smaller, rounded QDs to evolve towards larger, more facetted QDs with increasing growth interrupt time. An optimum QD formation strategy can be determined by observation of photoluminescence in conjunction with TEM.

10:45 AM J8.6
WAVELENGTH TUNING OF InAs/InP QUANTUM DOTS BY GROWTH INTERRUPTION. Sukho Yoon, Heedon Hwang, Kwang-Sik Cho, Euijoon Yoon, Seoul National Univ, School of Materials Science and Engineering, Seoul, KOREA; Hyeonsik M. Cheong, Sogang Univ, Dept of Physics, Seoul, KOREA; Uk-Hyun Lee, Donghan Lee, Chungnam National Univ, Dept of Physics, Taejon, KOREA.

Quantum dots (QDs) are promising for high-performance optoelectronic devices. It was reported that the material transport from wetting layers and/or by the island decomposition during growth interruption (GI) affected the evolution of QD, resulting in the changes in optical properties. Recently, we also observed that excess InAs formation was caused by As/P exchange reaction and subsequent strain-driven In migration. Therefore, the As/P exchange reaction may affect the InAs/InP QD evolution during GI, consequently optical properties of QDs. In this study, we present the wavelength tuning by the development and dissociation processes of InAs QDs on InP during various GI sequences. InAs/InP QD sample capped with InP after 2-sec GI under AsH_3 atmosphere showed a few PL peaks other than a QD peak at 0.82 eV, presumably from the thickness fluctuation of wetting layers before the complete evolution to QDs. However, the fully developed InAs/InP QD sample with 30-sec AsH_3 GI showed a PL peak at 0.73 eV. Also, the PL peak from the sample with GI under higher AsH_3 partial pressure shifted to 0.64 eV, showing the increased average size. On the contrary, when GI was introduced under PH_3 atmosphere for 10-sec after the 30-sec AsH_3 GI, the PL peak position shifted to the higher energy of 0.68 eV. The blue shift is presumed to be due to the dissociation of QD by the P/As exchange reaction under PH_3 atmosphere. Moreover, the 30-sec PH_3 GI decomposed InAs islands drastically, resulting in quantum wells with thickness fluctuations as confirmed by several PL emissions between 0.77 and 0.95 eV (corresponding to 4 - 9 monolayer thick InAs QWs). It was also observed that the H_2 GI frozen the QD sizes and the PL peak positions did not change. The evolution and dissociation of InAs/InP QDs could be controlled and the emission wavelength could be tailored intentionally for various applications by proper control of the GI sequences with different atmospheres and times.

11:00 AM J8.7
SCANNING TUNNELING MICROSCOPY STUDY OF InAs ISLANDING AND DISSOLVING ON GaAs(001) SURFACES. Shigehiko Hasegawa, Katsuhito Arakawa, Masakazu Tanaka, Osamu Suekane, Toshiko Okui, and Hisao Nakashima, The Institute of Scientific and Industrial Research, Osaka University, Osaka, JAPAN.

Self-assembled quantum dots (QDs) by utilizing islanding in a Stranski-Krastanov mode, *e.g.* InAs islands on GaAs(001), are expected to have tremendous potential for electronic and optical applications. Controlling sizes, densities and spatial arrangement of QDs are the key to realizing electronic and optical devices. In order to manipulate spatial positioning of InAs QDs, detailed knowledge about the mechanism of InAs island formation on GaAs is needed. STM connected to MBE has been used to investigate initial stages of InAs growth on GaAs(001). In this paper, we report on the nucleation sites of InAs islands, step structures of wetting layers, and annealing effects on InAs islands formed on the surfaces. For this purpose, we focus on the time evolution of surface morphologies of GaAs(001) covered with InAs islands after the growth. All STM experiments were carried out at room temperature. InAs islands were grown on GaAs(001)c(4x4) surfaces at 450°C. The formation of InAs islands was confirmed by the appearance of facet-related streaks in RHEED patterns. After that, the samples were immediately transferred to the STM chamber. For STM images taken at 1 hour after InAs growth, most of islands are observed on or nearby steps, which run in zigzags on an atomic scale. In contrast, for STM images taken at 4 hours after the growth, islands are frequently observed on the middle of terraces. Simultaneously, steps come to have round shapes and meander macroscopically. We, therefore, conclude that islands initially nucleate at steps of a wetting layer and that the steps move around even at room temperature. This confirms that the growth of InAs on vicinal GaAs(001) inclined toward $[1\bar{1}0]$ leads to the formation of islands aligned along $[1\bar{1}0]$. Together with annealing effects on InAs islands, we will discuss the possibility of manipulating spatial positioning of InAs QDs.

11:15 AM J8.8
HIGH RESOLUTION ANALYSIS OF EMBEDDED QUANTUM DOTS. Alan Harvey, UMIST, Dept of Physics, Manchester, UNITED KINGDOM; Helen Davock, Peter J Goodhew, University of Liverpool, MS&E, Liverpool, UNITED KINGDOM.

A key piece of information in the understanding of quantum dot behaviour is the composition of the dot after any capping and/or annealing processes. It is important to know the composition and uniformity of the dots after they have been embedded in a semiconducting matrix, which usually contains one or more of the elements in the dot. This is a classically difficult analytical problem for any TEM technique. Recent published models [1] predict the shape of an analytical X-ray linescan produced by the interaction between the electron probe and any dot/wetting-layer/matrix combination. Previously this approach has only been applied to a cross-sectional configuration, but the model has now been extended to include plan view samples. By considering both perspectives, a clearer understanding of the size and composition of buried dots can be achieved. Different compositional variations within the dots (for example, as proposed by Liu et.al. [2]) have also been included in the model and are compared to experimental data in STEM analyses of InAs dots in a GaAs matrix. [1] Alan Harvey, Helen Davock and Peter Goodhew, MRS Fall Meeting 1999, Vol 583 [2] N. Liu, J. Tersoff, O. Baklenov, A. L. Holmes, Jr., and C. K. Shih, Physical Review Letters (2000) 84, 334-337

11:30 AM J8.9
MORPHOLOGY CHANGES OF InAs 3D ISLANDS ON GaAs(001) AS A RESULT OF ANNEALING. C.L. Workman, H. Yang, J.B. Smathers, V.R. Yazdanpanah, G.J. Salamo Department of Physics, University of Arkansas, Fayetteville, AR.

Self assembled 3D islands grown using strained layer heteroepitaxy offer potential advantages for the engineering of electronic and photonic devices. Commercialized devices based on these structures, however, have not been realized due to problems associated with the growth of the 3D islands. Among these problems is the relatively large distribution in size of the islands that result in a broader linewidth than desired. To solve problems such as these, studies of the 3D island growth mechanisms must be done. In this paper, we report on growth and annealing studies of InAs 3D islands on GaAs(001) using a combined molecular beam epitaxy (MBE) and scanning tunneling microscopy (STM) facility. The studies reveal how the island volume, shape, and intermixing with the substrate relate to ripening as the annealing time is increased. STM studies indicate two distinct island shapes, one for small volumes (type-I) and one for large island volumes (type-II). In addition, we have also observed a substantial fraction of a hybrid shape for islands falling roughly in the middle of the volume distribution. With increasing ripening, the islands are observed to transform from a type-I shape to a type-II shape and then back to a type-I shape. Eventually, all islands are of the type-I shape. We will show the benefit of this shape transition to photonic devices based on these structures.

11:45 AM J8.10
NANOMETER-SCALE STUDIES OF QUANTUM DOT FORMATION IN LOW INDIUM CONTENT InGaAsN/GaAs SUPERLATTICES. A.W.H. Lin, B. Lita, and R.S. Goldman, Department of Materials Science and Engineering, University of Michigan, Ann Arbor, MI; D. Mars, Agilent Technologies.

Mixed anion nitride-arsenide alloys offer a promising new avenue for lattice-matched growth of light emitters and detectors operating in the entire near infrared range. However, experiments have presented conflicting results concerning the formation and stability of these alloys. Furthermore, alloy phase separation resulting in apparent quantum dot formation has been reported in both GaAsN/GaAs [1] and relatively high indium content InGaAsN/GaAs [2] superlattices. We have investigated the nanometer-scale structure and electronic properties of a series of low indium content InGaAsN/GaAs superlattices grown by reactive molecular beam epitaxy. Using ultra high vacuum cross-sectional scanning tunneling microscopy and spectroscopy, we have observed lateral compositional variations on the group V sublattice, which have apparently led to the formation of nitrogen-rich quantum dots. These nitrogen-rich quantum dots appear to be randomly distributed within the InGaAsN "layer", with typical

diameters ranging from ~3 to 8 nm. After rapid thermal annealing, the density of quantum dots has nearly doubled, suggesting that additional nitrogen has precipitated out of the InGaAsN "layer". In addition, many of the dots appear to have agglomerated both vertically and laterally, resulting in larger dots, with lateral and vertical extents ranging from ~3 to 10 nm. We will discuss the mechanisms of the formation and coarsening of these nitrogen-rich quantum dots, as well as the impact of their sizes and shapes on the optical properties of the low indium content InGaAsN/GaAs superlattices. [1] R.S. Goldman, R.M. Feenstra, B.G. Briner, M.L. O'Steen, and R.J. Hauenstein, Appl. Phys. Lett. 69, 3698 (1996). [2] H.P. Xin, K.L. Kavanagh, Z.Q. Zhu, and C.W. Tu, Appl. Phys. Lett. 74, 2337 (1999).

SESSION J9: GROWTH STUDIES AND POST-GROWTH PROCESSING

Chairs: Rosa Leon and Simon Fafard
Thursday Afternoon, November 30, 2000
Room 207 (Hynes)

1:30 PM *J9.1
EFFECTS OF GaAs OVERGROWTH ON THE SHAPE, SIZE AND COMPOSITION OF InAs/GaAs QUANTUM DOTS. Tim Jones, Imperial College, London, UNITED KINGDOM.

The growth by molecular beam epitaxy of InAs/GaAs quantum dots (QDs) is a very complex process due to the significant alloying that occurs even in uncapped QD structures. Encapsulation with GaAs is an essential component for optoelectronic device applications and the overgrowth process leads to additional complexities regarding the size, shape and composition of the QDs, and the morphology of the evolving surface. In this paper we will present a detailed discussion of the overgrowth process based on our extensive studies using scanning tunnelling microscopy (STM), reflection high energy electron diffraction (RHEED), atomic force microscopy (AFM), transmission electron microscopy (TEM) and scanning transmission electron microscopy (STEM). STM, RHEED and AFM results show that significant changes in shape and morphology occur during the initial stages of overgrowth. The QDs broaden and collapse very quickly, suggesting that the surface species are very mobile and a considerable amount of mass transport occurs across the surface. Overgrowth leads to additional changes in composition and species intermixing. Energy dispersive X-ray (EDX) measurements using STEM have allowed us to quantify the indium composition of both the dots and the confining layer. Finally, information regarding the strain state of the evolving QD structure is provided by in-plane lattice parameter measurements using RHEED. The results suggest that the strain state of the QDs is constantly evolving during growth. The implication of these results for the optical properties of QD structures will be discussed.

2:00 PM J9.2
EFFECT OF GROWTH RATE ON THE COMPOSITION AND OPTICAL PROPERTIES OF InAs/GaAs SELF-ASSEMBLED QUANTUM DOTS. Peter Joyce, Tomasz Krzyzewski, Gavin Bell, Surama Malik, David Childs, Eric Le Ru, Ray Murray, Tim Jones, Centre for Electronic Materials and Devices, Imperial College, London, UNITED KINGDOM.

The growth of self-assembled InAs/GaAs quantum dots (QDs) has been studied extensively in recent years and offers the prospect of temperature independent ultra-low threshold lasers. One of the most exciting developments is the extension of the emission wavelength, which offers the possibility of producing GaAs based devices that operate at 1.3 μm. Although several methods have been used to control the wavelength, perhaps the most straightforward from a growth perspective involves using very low InAs deposition rates. In this paper, we present a detailed study of the effect of the InAs deposition rate on the properties of InAs/GaAs QDs grown on GaAs(001) substrates at 500°C by conventional solid source molecular beam epitaxy (MBE). Low temperature photoluminescence (PL) measurements of GaAs capped QD structures grown at different rates between 0.13 and 0.006 MLs^{-1} show an increase in the emission wavelength to 1.2 μm (which corresponds to 1.3 μm at room temperature) with decreasing growth rate, and there is a concomitant narrowing of the linewidth to ~27 meV. The growth of uncapped QDs grown at the same rates has been studied in-situ by reflection high energy electron diffraction (RHEED) and scanning tunnelling microscopy (STM). STM measurements show significant changes in the number density and total volume of the dots, with both decreasing substantially as the InAs growth rate is reduced. Our STM measurements allow us to estimate the indium composition of the QDs at different growth rates and it is clear that significant changes occur in the QD composition. The indium fraction increases as the growth rate is reduced and emission at the longest wavelengths occurs from the most indium rich dots. The kinetics of QD formation clearly play an important role in determining the size, composition and optical properties of InAs/GaAs QD structures.

2:15 PM J9.3
MODIFICATION OF SELF-ASSEMBLED QUANTUM DOT PROPERTIES VIA ANION EXCHANGE. Jeng-Jung Shen, April S. Brown, Georgia Institute of Technology, School of Electrical and Computer Engineering, Atlanta, GA; Yongqian Wang, Zhong L. Wang, Georgia Institute of Technology, School of Materials Science and Engineering, Atlanta, GA.

We are investigating the modification of quantum dot size, composition and strain via changes in growth conditions and the use of dissimilar anion anneals. Surface exchange occurs during the anneal and, depending on the temperature during the anneal, can be used to induce drastic morphological changes - for example a 3d to 2d surface morphology - or can modify dot size, density, and composition. The control samples consist of five layers of InAs separated by 10 nm GaAs grown by molecular beam epitaxy (MBE). InAs quantum dots (two and three ML deposition thicknesses) were grown at a temperature of 450°C. Three-minute P_2 anneals were performed for some of the samples. Low temperature anneals, 300°C and 350°C, were used. The control samples and the 450°C growth and 300°C anneal samples showed quantum dot formation on the surface by atomic force microscopy (AFM). The control sample with 3 ML InAs deposition showed a more uniform dot size distribution compared to the other control sample with 2 ML InAs, and therefore, a narrower FWHM was observed by 77K photoluminescence (PL). The standard deviation of the dot size distribution was improved from 509 nm^2 to 285 nm^2 and the PL FWHM decreased from 113 meV to 43 meV. Compared to the control sample with 2 ML InAs, the P_2 annealed sample also showed improved standard deviation (305 nm^2) and FWHM (79 meV), with a concurrent decrease in the dot density from 1.74×10^{10} dots/cm^2 to 0.94×10^{10} dots/cm^2. Due to surface exchange, the composition of the annealed samples are assumed to change to $InAs_xP_{1-x}$. Therefore annealed samples show shifts to higher energy optical transitions. TEM is used to examine the modification in the structural properties resulting from the anneals and make conclusions on the modifications. Ultimately, we hope to observe position dependent exchange and compositional modifications that may be used to form new types of templates for dot nucleation and structures with modified electronic properties.

2:30 PM J9.4
LUMINESCENCE ENHANCEMENT BY HYDROGEN PASSIVATION IN InAs/GaAs SELF-ASSEMBLED QUANTUM DOTS. Eric Le Ru, Philip Siverns, Ray Murray, Centre for Electronic Materials and Devices, Imperial College, London, UNITED KINGDOM.

There is a consensus that point defects may be present in quantum dots and these may influence the efficiency of light emitting devices with quantum dot active regions. In addition the design of these structures requires growth of GaAs cladding layers at substrate temperatures that are less than optimum thus increasing the possibility of incorporating non-radiative centres close to the dots. It is well known that atomic hydrogen passivates shallow and deep defects in bulk and quantum well material, and therefore may be beneficial in quantum dot structures. Hydrogen was introduced into the samples via an inductively coupled plasma and the emission compared with a control sample across the temperature range 10-330 K. The passivation treatment appears to be benign and there is no significant change in the emission energy or the linewidth. Relatively small enhancements in the emission intensity (×2) are measured at low temperatures but this increases by an order of magnitude at ambient temperatures. The enhancement is attributed to passivation of non-radiative defects in the surrounding GaAs barrier and wetting layer. Annealing at temperatures above 600°C results in out-diffusion of the hydrogen and a loss of the enhancement. In principle, by improving the spontaneous radiative efficiency in quantum dot structures, hydrogen passivation offers the prospect for ultra-low laser thresholds.

3:15 PM J9.5
POST-ANNEAL EFFECTS ON PHOTOLUMINESCENCE PROPERTIES OF GaAs QUANTUM DOTS GROWN BY DROPLET EPITAXY. Katsuyuki Watanabe[1,2], Shiro Tsukamoto[1], Yoshihiko Gotoh[2], Nobuyuki Koguchi[1,2]. [1]National Research Institute for Metals, [2]Science University of Tokyo.

Droplet epitaxy method enabled a growth of self-assembled GaAs/AlGaAs quantum dot (QD) structures, which is a lattice-matched semiconductor system and is impossible to fabricate by ordinary S-K mode.[1)]In this paper, we investigated post-anneal effects of the QDs fabricated by this technique. The density and typical base size of the QDs were $1.2 \times 10^{10} cm^{-2}$ and 16nm × 20nm,

respectively. The shape was pyramidal with mainly {111} facets. The samples were annealed under As4 flux in the MBE chamber at the temperatures ranged from 520°C to 760°C for 1 hr. Photoluminescence (PL) spectra of the QDs were measured under indirect excitation conditions in the temperature range from 20K to 300K. The annealing temperature dependence of the integrated PL intensities and peak energies were observed at 20K. The intensity after the anneal of 760°C was enhanced by two orders of magnitude as compared to that of before post-anneal. Additionally, in the case of this sample, the strong emission of the QDs was successfully observed even at room temperature. With the increasing of anneal temperatures, the peak energy shifted from 1.646 eV to 1.749 eV, continuously. It seems that the blue shifts indicate the decrease of size of QDs, due to the interdiffusion of Al and Ga. In this droplet epitaxy, the QDs layer was grown at 180°C, resulting in the incorporation of excess As. By this excess As, the interdiffusion was easily promoted under post-anneal processes, improving the crystallinity of the QD structures and reducing its size. It was confirmed that the droplet epitaxy with the post-anneal process promises the fabrication of high quality GaAs QD structure. [1] K. Watanabe, N. Koguchi and Y. Gotoh, Jpn. J. Appl. Phys. **39**, L79 (2000).

3:30 PM J9.6
TUNING OF THE ELECTRONIC PROPERTIES OF InAs/InP QUANTUM DOTS USING RAPID THERMAL ANNEALING. D. Labrie, Department of Physics, Dalhousie University, Halifax, Nova Scotia, CANADA; S. Raymond, S. Awirothananon, S. Fafard, G.C. Aers, Institute for Microstructural Sciences, National Research Council of Canada, Ottawa, Ontario, CANADA; H. Marchand, L. Isnard, P. Desjardins, S. Guillon, R.A. Masut, Groupe de recherche en physique et technologie des couches minces (GCM), Ecole Polytechnique de Montreal, Departement de genie physique et de genie des materiaux, Montreal, Quebec, CANADA.

We have examined the effect of post growth rapid thermal annealing on the low temperature (5.0 K) photoluminescence (PL) spectrum of MOCVD grown self-assembled InAs/InP quantum dots (QD) for annealing temperatures ranging from 675 to 800°C and times from 30 to 90 s. Low-temperature PL of the as-grown material reveals two main transitions, a broad emission peak with FWHM ~90 meV centered around 850 meV which is attributed to the e1-hh1 transition of an ensemble of QDs, and a narrower peak (~30 meV) centered around 1100 meV attributed to radiative recombination in the wetting layer (WL). The results show that a blueshift of the QD transition is obtained upon annealing, mainly due to interchange of P atoms from the barrier with As atoms from the QDs, thus raising the bandgap of the material inside the dots. This effect increases for higher temperatures and longer anneal times and blueshifts of up to130 meV are obtained for anneal times of 90s at 800°C. However, the FWHM of the QD PL emission remained constant for all blueshifts, In stark contrast to the case of InAs/GaAs self-assembled dots. This difference is discussed in terms of the nature of the inhomogeneous broadening for InAs dots grown on InP versus GaAs. We performed calculations based on Fickian diffusion in order to investigate the relative effect of intermixing on InAs/InP dots of different thickness. The results reveal that the energy difference between dots of different thickness remains approximately constant for all amounts of interdiffusion observed in our experiments. The invariant FWHM observed is therefore consistent with an interpretation in terms of inhomogeneous broadening dominated by monolayer height fluctuations in InAs/InP dots.

3:45 PM J9.7
EFFECTS OF RESIDUAL STRAIN ON INTERDIFFUSION AND SEGREGATION IN InAs/GaAs QUANTUM DOT SUPER-LATTICES. B. Lita and R.S. Goldman, Univ of Michigan, Dept of Materials Science and Engineering, Ann Arbor, MI; S. Krishna, J.D. Phillips, and P.K. Bhattacharya, Univ of Michigan, Dept of Electrical Engineering and Computer Science, Ann Arbor, MI.

Interdiffusion and segregation are fundamental processes of critical importance for the control of island sizes and positions within semiconductor quantum dot structures and devices. Furthermore, residual strain is expected to significantly affect these processes. We have employed InAs/GaAs quantum dot superlattices, consisting of regular arrays of InAs islands embedded in GaAs, to study the effects of residual strain on interdiffusion and segregation in the InAs/GaAs system. Using large-scale and high-resolution cross-sectional scanning tunneling microscopy, we have mapped out the spatial distribution of the island arrays and the position of indium atoms located both vertically and laterally *between* island arrays. Both *in situ* and *ex situ* annealing induce vertical and lateral dissolution of the islands, which in turn significantly affect the organization of the island arrays. Annealing-induced variations in the positions of the indium atoms between the island arrays have enabled us to directly measure In-Ga interdiffusion and In vertical segregation lengths. We will discuss the effects of residual strain on these fundamental parameters, and possibilities for using these processes to produce ideal 3D arrays of InAs islands.

4:00 PM J9.8
MEE-GROWN InGaAs QUANTUM DOTS EMBEDDED IN AN $In_xGa_{1-x}As$ ($x \leq 0.2$) MATRIX FOR 1.3 μm EMISSION. Sridhar Govindaraju, Rubin Sidhu, Archie L. Holmes Jr.

Self-organized InGaAs quantum dots are desired for optoelectronic devices operating at 1.3 μm emission on GaAs substrates. In order to improve their optical properties, these quantum dots have been embedded inside a GaInAs layer, which provide strain relief for the quantum dots. However, this results in a red-shift of the emission wavelength[1]. In this talk, we present a systematic study of the optical properties of InGaAs QDs embedded into a GaInAs matrix for 1.3 μm emission. Changes in the emission wavelength as a function of the In composition and the thickness above and below the QDs in the GaInAs matrix are measured by room and low-temperature photoluminescence. Our results show that 1.3 μm emission could be achieved for 12 monolayer $In_{0.5}Ga_{0.5}As$ quantum dot surrounded by $In_{0.2}Ga_{0.8}As$ quantum wells, which is 6 ML and 10 ML thick for bottom and top quantum well respectively. The effects of changes in the GaInAs matrix, quantum dot deposition conditions, and stacking on the optical properties of these embedded quantum dots will also be discussed. References 1. Nakata, Y., K. Mukai, et al. (2000). "Molecular beam epitaxial growth of InAs self-assembled quantum dots with light-emission at 1.3 μm." Journal of Crystal Growth 208: 93-99.

4:15 PM J9.9
PHOTOLUMINESCENCE TEMPERATURE AND POLARISATION DEPENDANT STUDIES OF InAs QUANTUM DOTS GROWN ON InP (001) BY MBE. Jose Olivares, Bassem Salem, Taha Benyattou, Georges Bremond, Insa de Lyon, Material Physics Laboratory (UMR 5511 CNRS), Villeurbanne, FRANCE; Julien Brault, Michel Gendry, Guy Hollinger, Ecole Centrale de Lyon, LEOM, Ecully, FRANCE; Olivier Marty, Michel Pitaval, Univ Lyon 1, DPM, Villeurbanne, FRANCE.

Low dimensional semiconductor nanostructure such as InAs quantum dots (QD), have been extensively studied due to their theoretical and technological potentiality, making them very interesting for optoelectonic devices applications such as low threshold lasers at room temperature. However, InAs QD on GaAs only covers the 1-1.3μm wavelength range. To reach to the 1.55μm wavelength range, InAs QD on InP is expected to be a good candidate but we still need to better understand and better control the growth of such nanostructures. This work report on the complete study of Photoluminescence (PL) properties performed on InAs self-assembled QD's grown on InP(001) substrate by molecular beam epiatxy (MBE). Different buffer layers like AlInAs and InP on witch the InAs QDs are deposited, have been investigated in order to obtain elongated dots or round shaped dots with smaller and less dispersion size. Temperature dependant PL study reveals a strong maintain of the luminescence intensity around 0.9 eV of the QD up to the room temperature that we correlate to a strong quantum size effect due to a better control of the QD size. This result is well confirmed by the strong PL polarisation (PPL) dependence effect in the case of elongated QD as compared to isotropic dots. These PL results demonstrate the possibility to obtain a more uniform and quantum size dots by controlling the buffer layer surface.

4:30 PM *J9.10
PHOTOLUMINESCENCE INVESTIGATIONS OF INDIVIDUAL SEMICONDUCTOR QUANTUM DOTS. M-E. Pistol, L. Landin, N. Panev, J. Persson, V. Zwiller, L. Samuelson and W. Seifert, Lund University, Lund, SWEDEN.

We have investigated individual quantum dots of InAs in GaAs as well as quantum dots of InP in GaInP, using photoluminescence spctroscopy sometimes in combination with electic fields. We find that the spectra of InAs quantum dots can be explained by neutral exciton complexes but that the spectra of InP quantum dots are dominated by highly negatively charged excitons. This difference can be attributed to the different sizes of these quantum dots with InP dots being larger than InAs quantum dots. We have also studied InP of different sizes where we can follow the evolution from neutral quantum dots to charged quantum dots. The spectra of the charged quantum dots are very complicated and some tentative hypotheses for this complexity will be given.