SYMPOSIUM F
Group IV Semiconductor Nanostructures
November 29 - December 2, 2004

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Symposium Support
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Proceedings to be published in both
book form and online
(see ONLINE PUBLICATIONS at www.mrs.org)
as volume 832
of the Materials Research Society
Symposium Proceedings Series.

* Invited paper
where all we wish partic~r: power in complex photonic structures like quasicrystals and 
finite element method calculations. The stress induced index change spectrometers for sensing and chemical analysis stability and portability are essential. Many other posslblhtes for switches that rely on such resonators have been demonstrated. Size to the wavelength of light or smaller. These microphotonic components can facilitate the penetration of integrated optics from the telecommunications domain to all areas where optical analysis and diagnostics are used. Microphotonic waveguide spectrometers based on designs originally intended for WDM systems can have both bandwidth and resolution comparable to laboratory monochromators. These integrated devices can replace present day bulk optic spectrometers for sensing and chemical analysis wherever small size, stability and portability are essential. Many other possibilities for photonic devices may emerge when the ability to make microphotonic devices is combined with new concepts using photonic crystals and microresonators. Intense interest has also arisen in microphotronics to address the increasing bottleneck in data transmission over the busses connecting electronic chips. As microphotonic devices become a viable technology, several challenges must be overcome. The three most fundamental issues are waveguide loss, input and output coupling of light, and the control of polarization sensitivity. Enhanced coupling becomes increasingly difficult as the waveguide dimension approaches the wavelength of light (e.g. 1 um). Furthermore, the fabrication processes used should be the same as, or modest extensions of, those used today in silicon foundries. In addition to applications of Si-based microphotronics, we will review our work and those of others in these three areas. Mechanisms leading to high waveguide loss, and means to mitigate this loss will be explored. A new input coupling scheme based on depositing graded index (GRIN) films on top of the microphotonic waveguide layer will be described. This coupled design can be applied to SOI or Si3N4 waveguides by using a-Si or silicon nitride films. The coupler is formed by film deposition, photolithography and etching, with no need for high-resolution e-beam lithography or three-dimensional machining. Numerical simulations show that the GRIN coupler remains effective for films composed of discrete index steps. Finally, we describe a unique solution to the problem of polarization birefringence in SOI waveguides using stress induced by an SiO2 cladding. Experimental measurements are in good agreement with theoretical results using integrated mechanical and electromagnetic finite element method calculations. The stress induced index change can fully correct the polarization sensitivity of waveguides over a wide range of dimensions and shapes. This simple approach eliminates need to design waveguides with carefully tailored dimensions and aspect ratios for the purpose of birefringence control.

Silicon Self-Assembled Photonic Band Gap Crystals.
Jacob Thomas Robinson 1, Christina Manolatou 1, Michal Lipson 1 and Hod Lipson 2, Electrical and Computer Engineering, Cornell University, Ithaca, New York; 2Mechanical and Aerospace Engineering, Cornell University, Ithaca, New York.

Si photonic provides a platform for monolithic integration of optics and microelectronics. The challenge in building active Si-based photonic devices compatible with conventional Si electronics is the weak dependence of the index and absorption on the photo-induced free-carrier effect. This weak dependence creates the need for very high power control signals in order to create all-optical switches and modulators. In order to alleviate this problem and develop all-optical devices which are tunable at reasonable power levels, light must be confined and enhanced to create stronger photo-induced effects. This light enhancement is usually achieved with resonators defined by simple geometric shapes in high index material or photonic crystals. Microphotonic devices including sensors, filters, and switches that rely on such resonators have been demonstrated. Alternate methods of confining and enhancing light provide the opportunity to develop novel devices with reduced dimensions, power consumption, and footprint. In this paper we explore a highly light-confining structure with sub-wavelength dimensions. The mechanism of light confinement is based on interference effects from multiple scatterings (Anderson Localization). Anderson Localization can be achieved in a Si/SiO2 composite when the distance between scattering interfaces is on the order of a wavelength. This can be achieved with standard Si nanostructure techniques simply incorporated into integrated devices. To achieve a structure with both strong confinement and enhancement the scattering composite must be arranged such that the interference effects limit localization to a small local optical cavity as well as enable efficient input and output coupling. To accomplish this, the structure was designed using an Evolutionary Algorithm which optimized the intimacy enhancement. The optimized structure consists of a single mode input waveguide and a region of Si and SiO2 rods which form the scattering interface. Finite-Difference Time-Domain (FDTD) method with an excitation wavelength of 1550 nm reveals confinement to about a 100 by 100 nm region in Si. We also demonstrate a corresponding intensity enhancement of over 300 times the input intensity. The resonance in this structure has a Q of over 400. This strong light-confining structure can be used to achieve ultra-fast all-optical modulation in Si with low power. We show that using free-carrier injection from two-photon absorption (TPA) a modulator based on this structure could have a few ps lifetime and a 30-50% modulation depth with an in-plane pump power of about 1 pJ.
Silicon, the dominant material in the microelectronic industry, is highly desirable as the platform for photonic chips. Photonic crystal structures that bend, split, couple and filter light have recently been demonstrated. Here we test the flow of light in these structures as predicted by the structure design and cannot be modified.

Photonic crystal structures are a popular topic due to their lack of non-linear optical properties. We propose and demonstrate the all-optical modulation of a photonic crystal microcavity embedded in a silicon waveguide. The resonance of the cavity is tuned by injecting free carriers into the nanocavity region using an optical pump beam. By strongly confining light in the photonic crystal nanocavity the effective index of light to small refractive index changes is enhanced. The small cavity volume (0.1 μm) and unpassivated sidewalls enable ultra-fast switching speeds with low pulse energies.

Silicon-on-insulator (SOI) waveguides are a promising material for fabrication one-dimensional PBG nano-cavities. Fabrication of porous silicon one-dimensional photonic crystals having 20 to 30 coupled microcavities (up to 200 layers) have been made. The photonic bandgap up to 1000 nm and photoluminescence in the range 700-850 nm has been observed. Here we present a fabrication, structural, and optical characterization of such structures which may be promising for vehicle application. [V. Agarwal et al. Phys. Rev. Lett. 93 (2004) 054001]

Silicon based optoelectronic and photonic devices and circuits are attractive due to their fabrication compatibility with the CMOS process. The main methods to alter the refractive index in Si are the thermo-optic effect and the electro-optic effect. The thermal change of the real refractive index is n ∝ T. However, the thermo-optic effect is slow and can be used up to 1 MHz modulation frequencies. For higher modulation frequencies, electro-optic devices are required. Refractive index change using free carrier injection is a very fast process and is, therefore, used to change both the real refractive index and optical absorption coefficient. However, the index change mechanism due to free carriers is weak in Silicon and usually requires long structures for modulation. The shortcomings of the weak electro-optic effect can be overcome using a resonant cavity and high-index contrast waveguides. The resonant cavity increases the optical path length of the modulator and maximizes the interaction between the optical mode and transmission medium, without increasing the physical device length. As a result, the transmission near resonance of a ring resonator cavity is very sensitive to small refractive index changes, making it very appropriate for modulation. The resonance condition of the ring resonator is given by f = 2π/λ, c/2n, where c is the speed of light in free space, n = effective refractive index of the ring, R = radius of the ring, K = integer corresponding to the multiple resonant wavelengths. By changing the refractive index under carrier injection, the resonant frequency of the cavity can be changed. We fabricated and characterized a tunable electro-optic modulator using high-index contrast Si-SiO2 ring resonators on silicon-on-insulator (SOI) substrate. The devices were fabricated using standard CMOS compatible process technology. A high-index contrast Si-SiO2 waveguide structure is defined on a SOI substrate using e-beam lithography followed by reactive ion plasma etching (RIE). Low-resistance doping regions were defined around the rings using ion-implantation. The waveguides were passivated and planarized by a combination of growth and deposition of oxide. Finally, ohmic metal contacts (Ti) and probe pads (Ti/Au) were deposited. The refractive index of the ring was changed by applying voltage across anode and cathode. Resonant modulation was achieved using an optical dispersion effect due to current injection under forward bias of the p-n junction. The resonance of the ring resonators shows a clear blue-shift under carrier injection. A modulation depth up to 50% is measured for a probe wavelength of 1540 nm. The device features a bias voltage of 0.87V and a power consumption of 1.53μW. Transient analysis of the modulator indicates that the device is rise and fall times are 1.5ns which corresponds to a bandwidth modulation of 775MHz.

There is a growing need for the development of integrated biosensors. Many current systems for bio-detection are either large, or lack the desired level of sensitivity. We demonstrate a micron-size silicon photonic structure for use in a highly sensitive integrated biosensor having a very long optical pathlength of 40 μm enabling highly sensitive molecule detection. The sensor uses the high field confinement inside a Fabry-Perot micro-cavity to enhance the effective absorption cross-section of metal nano-particles that are used as tags for analyte biomolecules of interest. The micro-cavity was designed and fabricated on a high refractive index contrast silicon waveguide on Silicon-On-Insulator platform. The device is 450 nm wide and less than 5 microns in length, allowing for a high density of devices on a single chip. Experimental results show that such a device is sensitive enough to detect the presence of a discrete number of 10 nm diameter gold nanoparticles. The detection is achieved by measuring the decrease in optical transmission due to the absorption losses of the metallic particles at a wavelength of 1.5 microns. These results are in agreement with 3-D Finite-Difference Time-Domain simulations of the micro-cavity structure. The simulations predict a 7-9% loss in transmission through the structure for each nano-particle in the sensing area. The transmission changes less than 2% due to a change in the location of the particles within the sensing area.

Detection of various concentrations of DNA was performed using the device. Concentrations ranged in value from 10^5 to 10^8 copies/mL with sample volumes between 10^-12 and 10^-9 L. A polymer lift-off technique was used to place small areas (40-100 nm in diameter) of DNA biorecognition elements on top of the micro-cavity. This DNA layer was used to specifically bind and detect the presence of a discrete number of c-DNA molecules tagged with 10 nm gold particles. Such a structure allows for on-chip integration of biosensor components with high sensitivity and low limits of detection, approaching single molecule detection for various analytes such as DNA, RNA, proteins, and antigens.

We present a fabrication, structural, and optical characterization of such structures which may be promising for vehicle application. [V. Agarwal et al. Phys. Rev. Lett. 93 (2004) 054001]
structures. Photonic crystals formed from mesoporous silicon are made by the electrochemical etching of silicon by means of periodic vacation of chemical reaction parameters during the etching process. This paper presents fabrication and characterization of superstructures coupled microcavities (CMC's) and "photonic molecules" (PM's) based on porous silicon. Coupled microcavities consist of two identical microcavities with different porosity arranged in series. Photonic molecules are PBG structures consisted of two identical microcavities separated by thick layer (spacer). The CMC's and PM's are made by the electrochemical etching of heavily doped Si (100) in HF/CH3OH solutions. The pore size is controlled by the variation of the current flowing through the wafer perpendicular to its surface. The thickness of this layer is controlled by etching time. Studied CMC's samples have two identical half-wavelength-thick cavity spacers surrounded by Bragg reflectors. These photonic crystal consist of several periods of porous silicon bilayers, which are quarter-wavelength-thick porous silicon layer with different porosities. The thickness of intermediate Bragg reflector is varied from 0.5 to 4.5 bilayers. The center of photonic band gap (190 nm) of CMC's is 900 nm (3). The spectrum has a plateau with high reflectivity. The modes of coupled microcavities are split with spectral (angular) gap between them determining by intermediate Bragg reflector transmittance. The photonic molecules consist of two identical microcavities with 5 periods of porous silicon bilayers in each Bragg reflector separated by thick layer. The thickness of this layer is changed in series from A to 2A with step of A/4. The linear spectrum of photonic molecule has one or three modes, which are determined by the thickness of the space between microcavities. Microcavities separated by spacer with thickness divisible by even numbers of A/4 possess three resonance state. On the contrary PM's with spacer thickness divisible by odd number of A/4 have only one resonance state.1 The second- and third-harmonic generation spectroscopy in wave-vector domain is performed to characterize the fine structure of complex spectrum of porous silicon crystals. Nonlinear power dependence of nonlinear-optical response on electric field of fundamental radiation provides unique information about local field distribution across this complex layered structures.

SESSION F2: Si/SiGe Heterostructures and Devices
Chairs: E.A. Fitzgerald and Leonid Tyekabov
Monday Afternoon, November 29, 2004
Constitution B (Sheraton)

1:30 PM *F2.1
Formation of High Quality SiGe Hetero-Structures and their New Device Applications, Yasuhito Shiraiki, Advanced Research Laboratories, Musashi Institute of Technology, Tokyo, Japan.

Since advanced crystal growth techniques such as molecular beam epitaxy (MBE) and UHV-CVD were well established, it has become possible to introduce hetero- and quantum-structures into silicon (Si). These structures enable us to develop advanced Si devices based on new concepts which were mainly established in the field of compound semiconductors. These concepts have been introduced into various semiconductor devices like hetero bipolar transistors (HBTs). The cut-off frequency of HBTs exceeds 300 GHz and they are now in the mass production phase. Another hopeful semiconductor effect transistor (FETs), particularly based on strained silicon and germanium and modulation-doping (MOD) structures, can provide extremely high mobility and therefore high performances, much better than conventional Si MOSFETs. The mobility of n-channel MOD structures, for instance, reaches almost one million cm2/Vs, while the hole mobility of strained Ge layers exceeds the mobility of bulk Ge. Another interesting application of SiGe hetero-structures is light emission. Although the materials are indirect band-gap semiconductors, luminescence efficiency was found to be significantly improved by introducing new quantum structures. Light emitting diodes (LEDs) and micro-cavities were fabricated to demonstrate their high potential as low-electronic devices, particularly optical interconnection and parallel processing in VLSI circuits. It is obvious that these device applications are strongly dependent on the material qualities of SiGe hetero-structures. In this talk, the development in the material growth which makes new device applications of SiGe hetero-structures, particularly quantum structures, possible is reviewed and the future prospect is discussed.

2:15 PM F2.2

The strain in silicon/silicon-germanium quantum wells reduces the usual six-fold degeneracy of the silicon conduction band, leaving a pair of degenerate bands in the growth direction. Quantum confinement in the silicon well further splits this degeneracy, leading to a five-fold degeneracy (with two gaps). The valley splitting between these lowest two levels. We show that microwave spectroscopy can be performed between these two states. Transport measurements at 0.25K in a silicon/silicon-germanium two dimensional electron gas enable us to detect microwave absorption at the valley splitting energy. The observed lineshapes are similar to those observed in electrically detected spin resonance signals. The valley splitting is found to increase linear with an applied perpendicular magnetic field. The valley splitting peak shows a dramatic (7-fold) increase in width as the temperature is increased from 0.25 K to 0.4K. These results indicate that in moderate magnetic fields the silicon valley degeneracy can be completely removed in low temperature quantum devices.

2:30 PM F2.3
Formation of Ge Nanostructures by Phase Separation During MOVPE of (III-V)-x(Ge2)x Alloys, Andrew Gordon Norman, Jerry M. Olson, Manuel J. Romero, Pat Dippo and Mowafak Al-Jassim; National Renewable Energy Laboratory, Golden, Colorado.

We report a new method of forming single crystal Ge nanowires and nanocrystals. The Ge nanostructures are produced by the phase separation of (III-V)-x(Ge2)x alloys during metal organic vapor phase epitaxy (MOVPE). For the (GanP)x-(Ge2)x alloy system, by adjusting the growth conditions, we have formed Ge nanowires of up to 2 μm length, with controlled diameters ranging from 5 nm to greater than 50 nm, embedded in a high band gap GaP matrix. By changing the (GanP)x-(Ge2)x alloy composition, we control the density of the nanostructures. Restricting the epitaxial layer thickness results in the formation of Ge nanocrystals. These Ge nanostructures have been studied structurally and chemically by transmission electron microscopy; Optical properties have been measured by a combination of photoluminescence, optical absorption, and cathodoluminescence. Room temperature photoluminescence has been observed from these samples, with broad peaks centered at about 1 eV. The onset of optical absorption at room temperature in these phase-separated (GanP)x-(Ge2)x alloy layers containing Ge nanostructures is observed at energies between 0.7 and 0.8 eV.

2:45 PM F2.4
High Mobility SiGe Heterostructures, Eugene Arthur Fitzgerald, Materials Science and Engineering, MIT, Cambridge, Massachusetts.

We have shown that thin layers of tensile Si and compressed SiGe can be layered on the nanometer-scale in the vertical direction (growth direction) of a MOSFET structure and drastically increase the lateral mobility of electrons and holes. Such vertical engineering using thin layers and strain can also be used to design fields at the desired vertical field. Unlike Si which has fewer degrees of freedom, the SiGe system allows for the interchange of band offset, layer thickness, and vertical field in material design. At high fields, we have shown that a tensile SiGe quantum well grown at the Si/SiGe interface can yield an electron mobility enhancement of 2x and a hole enhancement of 10x. Materials engineering offers a continual evolution in lattice-constant engineering, potentially leading to other promising heterostructures in the future.

3:30 PM F2.5
Towards Heterogeneous Integration of Semiconductor Nanostructures - SiGe on Si, Kang L. Wang, Hyungjun Kim, Song Tong and Fei Liu; Electrical Engineering Department, University of California-Los Angeles, Los Angeles, California.

There has been tremendous progress in SiGe microelectronics. High performance HBT and other devices as well as their integration on Si CMOS platform have been demonstrated. In addition to the use of SiGe HBT for high frequency mixed signal applications, integration with optoelectronics devices will enable a major cost reduction in optical communications, in which Si-based efficient light sources and fast detectors are critical. This talk will address the use of self-assembled Ge quantum dots grown on Si for this potential application. We will discuss the challenges associated with the strain field to provide the registration of dots is used to illustrate the possible means of guided assembly. Optical properties both in interband and intersubband transitions will be reported. The above successful demonstration of the growth of Ge on Si in nano-structural forms suggests a general technique to extend the growth of other
lattice mismatched materials in nano forms on Si CMOS. Indeed, all kinds of III-V dots, nanowires, and nanotubes have been produced, such as carbon dots, SiGe nanowires, ZnO nanowires, and GaN nanowires. Based on the latter nanowires, PN junctions and CMOS like devices have been demonstrated. These results suggest a general approach to achieve emerging heterogeneous integration of nanoostructures and devices from different nanomaterials for nanosystems.

4:00 PM F2.6

Structural and Optical Properties of SnₓGe₁₋ₓ Quantum Dots and Quantum Wires, Jordana Bandara, Douglas Bell and Shouleh Nikzad; Jet Propulsion Laboratory, Pasadena, California.

SnₓGe₁₋ₓ layers and quantum dots (QDs) are of great interest as materials that could provide tunable direct band gaps, allowing completely group IV-based optoelectronic devices. These materials could be used in a wide range of applications such as emitters, infrared detectors, and thermophotovoltaics. However, substantial challenges remain in the growth and processing of these materials. We have grown SnₓGe₁₋ₓ films by low temperature Molecular Beam Epitaxy (MBE), using low growth annealing (<200°C) in order to grow fully strained layers. X-ray diffraction, transmission electron microscopy, and Rutherford backscattering spectroscopy data indicate high-quality epitaxial films. Post-growth annealing was used to form QDs. Either QDs or quantum wires may be formed depending on annealing parameters. The effects of varying substrate temperature between 400°C (wires) and 750°C (QDs) on size and distribution of quantum structures were explored and will be discussed. Sn concentration (5-10%) and film thickness (200 nm - 2 μm) were also varied. In addition, varying the annealing of samples with Ge cap layers was compared to that of uncapped samples. A Ge cap was used in order to limit Sn surface segregation and to control dislocation formation in the SnₓGe₁₋ₓ layer during the annealing process. Optical properties probed by Fourier transform infrared spectroscopy (FTIR) will be presented. FTIR spectra clearly show the decrease in band gap of SnₓGe₁₋ₓ layers with increasing Sn fraction up to 10%.

4:15 PM F2.7

Time-Resolved Photoluminescence in Si/SiGe Nanostructures, Boris Kamenetsky¹, Jean-Marie Barbier², David Lockwood³ and Leonid Tsybeskov⁴; ¹Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, New Jersey; ²Institute for Microstructural Sciences, National Research Council, Ottawa, Ontario, Canada.

We present comprehensive studies of spectrally and time-resolved photoluminescence (PL) in Si/SiGe nanostructures with Ge content controllably varied from 10 to 60%. Using a pulsed laser excitation source, which was adjusted to match the PL peak time, we show that time several components and their ratio strongly depends on the excitation conditions such as pulse intensity, duration, etc. We present a model where different PL bands originate within a near pure Ge clusters and/or Si-SiGe interfaces.

4:30 PM F2.8

Top-gated Quantum Dots in Silicon/Silicon-Germanium Two-Dimensional Electron Gases, K.M. Lewis¹, C.C. Haselby², Levente J. Klein³, J.L. Triott⁴, Snijt Goswami⁵, D.E. Savage⁶, M.G. Lagally⁷, D.W. van der Weide⁸, J.O. Chu⁹, P.M. Mooney², Susan N. Coppersmith² and Mark A. Erikson¹; ¹University of Wisconsin - Madison, Madison, Wisconsin; ²IBM Watson Research Center, Yorktown Heights, New York; ³IBM TJ Watson Research Center, Yorktown Heights, New York; ⁴Department of Materials Science and Engineering, University of Virginia, Charlottesville, Virginia.

Novel microelectronic devices such as quantum dot cellular automata and photonic waveguides require nanoscale control of quantum dot positions. This can present a challenge in fabrication since the quantum dots are typically formed by strain-driven self-assembly, leading to random nucleation positions. In this presentation we will show that low-dose implantation of Ga using a focused ion beam (FIB) can be used to control the nucleation sites of Ge islands grown on the Si(001) surface, allowing us to fabricate arbitrary patterns of quantum dots without creating significant surface topography. The experiments were carried out in a UHV system incorporating a FIB, a transmission electron microscope with gas handling capabilities enabling CVD growth to take place in the polepiece, and an electron beam evaporator in a side chamber. By using this system we can pattern a thin specimen using the FIB, anneal it in the TEM and then observe surface time the self assembly of islands as Ga is deposited onto the specimen, all without breaking vacuum. We find that with suitable implantation and annealing conditions this patterning technique slightly modifies the surface roughness and possibly the subsurface strain field. This increases the island nucleation probability on irradiated areas and therefore allows the control of island positions on the nanometer scale. Furthermore, we find that the islands nucleated on implanted areas have a different shape from Ge islands grown on unmodified Si(001) surfaces, and exhibit a lower wetting layer thickness and a smaller critical size for dislocation nucleation. We will describe the kinetics of island growth, which can be extracted from video recordings during deposition onto FIB-patterned surfaces. We will also describe the structural and properties of the islands produced. Furthermore, by comparing UHV-CVD with MBE deposition of Ge, we will show that gas reactivity is not the principal factor allowing the island nucleation barrier is modified on irradiated areas. Finally, we will discuss the optimum conditions for forming arbitrary patterns of islands and the possibilities of using this technique during fabrication of quantum dot-engineered devices.
Transport properties of semiconductor nanostructures are characterized by a complex interplay between quantum confinement effects and self-organized quantum dot formation. The quantum dot formation depends on the dopant concentration and the growth conditions. Here, we consider the effects of dopant concentration and growth conditions on the quantum dot formation. The quantum dot formation can be described by the Poisson-Fermi statistical model, which takes into account the quantum confinement effects and the electron-electron interactions. The model is based on the assumption that the quantum dots are formed by the self-organization of the dopant atoms in the semiconductor film. The model predicts that the quantum dot size and the donor density are correlated.

F3.3 Computer Simulation of Charging/Erasing Transients of a Ge/Si Hetero-Nanocrystal-Based Flash Memory. Dengtao Zhao, Yan Zhu, Ruigang Li and Jianlin Liu; ECE Department, University of California, Riverside, Riverside, California.

The transient process of the programming/erasing is very important for a nanocrystal-floating-gate flash memory. In this work, a computer simulation was carried out to investigate the charging, retention and erasing processes of our proposed Ge/Si hetero-nanocrystal floating gate flash memory. The simulation was based on the Poisson equation and by using the donor concentration and the average charge in one dot were simulated respectively.

Evident hysteresis features can be observed in the transient processes in a voltage-sweeping mode. The hysteresis strongly depends on the dot density. The presence of electron states in the Ge/Si dot can enhance the hysteresis process which suggests the enhanced data storage. While measuring the transient process in a constant voltage, the time decay of transient current and charge are weakened if Ge is used on Si dot, indicating a longer retention time for Ge/Si-floating-gate flash memory.

F3.4 Threshold Voltage Shift in Hetero-nanocrystal Floating Gate Flash Memory, Yan Zhu, Dengtao Zhao, Ruigang Li and Jianlin Liu, ECE department, University of California, Riverside, Riverside, California.

Owing to the band offset at the interface of hetero-nanocrystal, flash memory using hetero-nanocrystals as floating gate can have a longer retention time while keeping almost the same programming speed. As an index of memory window, the threshold voltage shift that results from the charge stored in the floating gate is one of the most important parameters for the flash memory. In this presentation, we show our simulation results of the threshold voltage shift of our proposed Ge/Si hetero-nanocrystal floating gate memory device. First, numerical investigations were carried out by solving 3-D Poisson-Boltzmann equation. The simulation shows that the presence of the Ge on Si dot can remarkably prolong the retention time, indicated by the time decay behavior of the threshold voltage shift. It also shows that increase of thickness of either Si or Ge dot will introduce a reduction of the threshold voltage shift. The shift also strongly depends on the dot density. However, only a weak dependence of threshold voltage shift on the tunneling oxide thickness was found. A capacitor model was also proposed to explain the dependence of threshold voltage shift on variable parameters, which agrees well with the results of 2-D Poisson-Boltzmann numerical method.

F3.5 Source-Drain Engineering Challenges in FinFET Fabrication, Daniel Phan+, Hong-Jih Li++, Billy Nguyen, Gabriel Gebara, Dana Larison, Barry Sassman, Larry Larson. International SEMATECH, Austin, Texas.

Daniel Pham+, Hong-Jih Li++, Billy Nguyen, Gabriel Gebara, Dana Larison, Barry Sassman, Larry Larson. International SEMATECH, Austin, Texas.

The nanocrystalline silicon (nc-Si) based asymmetric double-barrier structure with the principle of direct tunneling and charge storage have attracted great interest due to its potential application in nano-electronic devices, such as single electron memory. In such structure, the operation with a small number of stored electrons can be realized which is based on quantum confinement and Coulomb blockade principle in the nc-Si. In this work, we fabricated the nc-Si/nc-Si/nc-Si asymmetric double-barrier structures (with the nc-Si size of 2 nm, 4 nm, and 7 nm, respectively) on Si substrates by plasma-enhanced chemical vapor deposition (PECVD) technique and laser frequently furnace annealing. In planar and cross-section transmission electron microscopy (TEM) photographs, we observed separate nc-Si granules almost of the same size as the as-deposited nc-Si layers due to the constrained crystallization phenomenon. The nc-Si is of the order of 1011 cm-2. By Raman scattering spectroscopy, we further verified the existence of nc-Si in the structures. By using capacitance-voltage (C-V) measurements, we studied the electrical properties of the structures. As the temperature increases, two capacitance peaks were observed due to resonant tunneling and Coulomb blockade in low frequency C-V curves of both samples with 2 nm- and 4 nm-thick nc-Si layers, respectively. From the interval between the two peaks, the Coulomb charging energy of nc-Si dot was estimated. By using 7 nm-thick nc-Si layers, we estimated that the Coulomb charging energy of nc-Si dot was estimated to be 175 meV and 102 meV respectively, which are in good agreement with the results obtained by theoretical calculation (180 meV and 90 meV respectively). While in the C-V curves of the sample with 7 nm-thick nc-Si layer, three peaks were observed. The frequency dependence of the resonant tunneling of electron was also investigated, which demonstrated that each capacitance peak in C-V curves was caused by injecting a single electron into each nc-Si. We estimated the density of nc-Si grains to be about 1011 cm-2 based on that, which is in agreement with the result of TEM photographs. This nc-Si/nc-Si/nc-Si asymmetric double-barrier structure is one of the basic units of nc-Si floating gate FET, which could be used for future room temperature nano-electronic devices such as nanomemory.
determined. (4) As the contrast in the elastic constant between the two nc-PS layers is increased, the stop band frequency tends to decrease. (5) The devices are composed of many stacked nc-PS layer pairs with low (20%) and high (90%) porosities (the pitch of the two layers and their proportion are 10 μm and 0.5, respectively, in this case) the minimum frequency of the acoustic band gap is about 40 MHz. The above results show a new possibility of nc-PS layer for the ABC device applications. In appropriate combination between the ABC operation with the thermally induced ultrasound emission [6] and with the optoelectronic characteristics, some applications will be opened towards integrated devices. Takeda et al. [8] fabricated silicon micro/nanotips in the SiO2. Koshida, J. Appl. Phys. 86, 5274 (1999). 2. B. Jusserrand et al., Phys. Rev. B, 33, 2897 (1986). 3. D. Bellet, in Properties of Porous Silicon, Chapt 4, ed. L. Canham (IEE, 1997) pp.127-131. 4. H. Shinoda, T. Nakajima, M. Yoshiyama and N. Koshida, Nature 400, 853 (1999).


Porous silicon, well known as a visible luminescent material, has been revealed to be an attractive candidate for the application to ultrasonic emitter recently. Since the ultrasonic emission is induced thermally it is important to evaluate thermal properties of porous silicon. We are investigating the evaluation of thermal conductivity of porous silicon using phase delation in photoacoustic signals. We report the dependence of thermal conductivity on anodization time during forming porous silicon.

F3.9 Extreme Aspect Ratio Semiconductor Structures. A. Amezcua', P. Sazio', H. Fang2, D.-J. Won2, T. Schiedematel2, B. Jackson2, F. F. Barri1, J. Badding1 and V. Gopalan1; 1Optoelectronics Research Center, University of Southampton, Southampton, United Kingdom; 2Materials Research Institute, Pennsylvania State University, University Park, Pennsylvania.

We have succeeded in synthesizing semiconductors (Si and Ge) inside a highly ordered array of nanometric holes in over centimeters length scales. These high-index contrast, extreme aspect ratio structures have fascinating optical properties, such as optical modulation, and a convenient way of forming two and three dimensional photonic crystal structures without lithography. The synthesis and optical guiding properties of these structures will be presented. This development also opens up new avenues for highly ordered semiconductor nanowires research from quantum confined effects to optical lasing.

F3.10 On-chip Silicon based Waveguide with 1D Photonic Crystal Cladding. Yasha Yi, Peter Bernal, Shoji Akiyama, Xiaoxuan Duan and Lionel C. Kimerling; DMSE, M.I.T, Cambridge, Massachusetts.

We developed a new type of on-chip silicon waveguide - the Photonic Crystal (PC) Cladding waveguide, in which the cladding layers are comprised of high index contrast dielectric layers (e.g., Si/SiO2 or Si/Si3N4). A unique feature of this waveguide is that the refractive index in the new PC cladding waveguide core has a large flexibility, low index core (e.g. SiO2) or hollow core waveguide can be realized on silicon chip. In parallel to the conventional index guiding waveguide, the PC cladding waveguide can be designed as slab waveguide, ridge waveguide, and channel waveguide, which have low index core (SiO2 or air) and high index contrast dielectric cladding pairs (Si/SiO2 or Si/Si3N4). Besides, our fabrication process is entirely Si-CMOS-compatible. The mode dispersion and field profiles of these waveguides are studied and found to be very similar to that of metallic waveguides. To demonstrate the PBG guiding mechanism, we performed (elliptically) focused probe beam propagation experiment. The effective index of the propagation mode is measured directly. The measured effective index is less than that of indices in both Si and Si3N4 cladding layers, which is a clear demonstration of the photonic band gap guiding principle. The slab waveguide loss measurement shows low loss of 0.5 dB/cm for both TE and TM modes at 1550 nm. We have also fabricated and measured PC cladding channel waveguide, light is demonstrated to guide in the low index core materials, the waveguide loss measurement shows low loss and analyzed, which form the foundation for future integration on Si chips. The future challenge on the film stress control due to multilayer stacking is also discussed. Potential applications include high power transmission, low dispersion, thin film thickness, novel properties engineering, and biomaterials sensor on silicon chip.

F3.13 Structure and Field Emission Properties of SiC Nanotip Arrays by Using ECR-CVD as Self-Masked Dry Etching Technique. Hung-Chun Lo, Chih-Ish Chen, Chih-Hsun Hsu, Jih-Shiang Hwang, Li-Chyong Chen and Kuei-Hsien Chen; 1Department of Materials Science and Engineering, National Chiao Tung University, Hsinchu, Taiwan, 2Center for Condensed Matter Sciences, National Taiwan University, Taipei, Taiwan, 3Institute of Ocean and Electronic Sciences, National Taiwan Ocean University, Keelung, Taiwan; 4Institute of Atomic and Molecular Science, Academia Sinica, Taipei, Taiwan.

We report here arrays of SiC/Si nanotips with high aspect ratio (100) and sharp apexes (1 nm) by direct etching from Si substrates. Well-aligned nanotip arrays were fabricated by single-step electron cyclotron resonance (ECR) plasma process using gas mixtures of silicon tetrachloride, argon and hydrogen plasma. The nanotip arrays using high resolution transmission electron microscopy (HR-TEM) revealed that the process is a self-mask etching process in that, accompanying the etching of Si, deposition of SiC nanoclusters occurred simultaneously, therefore, forming protective caps on the...
tips. The nanotip arrays so produced showed magnificent field emission property with typical field emission current of 0.5 mA/cm² at an applied field of 0.8 V/µm. The nanotip arrays also exhibited excellent stability, as evident by temporal evolution of the emission current at a constant applied voltage measurement which showed less than 5% fluctuation in one hour. Formation of Si nanotip arrays with controlled Si nanotip arrays pattern have also been demonstrated. The SiC nanotip arrays produced by ECR-plasma process of monolithic Si wafer offers a Si process compatible, reliable and economic field emission source alternative to carbon nanotubes.

F3.14 A Low Temperature Inverse Micelle Solvothermal Approach for Shape-Controlled Synthesis of Germanium Nanocrystals. Wenzhong Wang, Jianyu Huang, Dezhi Wang, Shankar Kunwar and Zhifeng Ren; Physics, Boston College, Chestnut Hill, Massachusetts.

We report a simple low temperature inverse micelle solvothermal route to synthesize large quantity single crystal germanium (Ge) nanocrystals. By adjusting the growth parameters, such as the concentration and type of the surfactant, nanocrystals with different morphology, including nanospheres, nanocubes, etc, have been successfully prepared. The as-prepared nanocrystals were characterized by X-ray diffraction, transmission electron microscopy, high resolution transmission electron microscopy and energy dispersive X-ray spectrometry. The X-ray powder diffraction patterns show that the as-prepared nanocrystals are diamond-type cubic pure Ge. The Ge nanocrystals prepared using surfactant pentadecyl alcohol monooctadecyl ether (C12E5) as capping agent at high concentration of the surfactant exhibit few different low-index planes, such as (100), (110), (111). Pure Ge nanospheres were prepared using low concentration surfactant C12E5 as capping agent. The nanospheres have an average diameter of 20 nm. Using surfactant heptadecyl alcohol monooctadecyl ether (C17E5) and sodium octylsulfate as a capping agent, the Ge nanocrystals are as small as 5 nm. The size of the nanospheres can be controlled by tuning the deposition conditions. In this work, we demonstrate the formation of Ge nanocubes with edge length of about 100 nm. The preparation of Ge nanocrystals was performed in a 125 mL Parr reactor (Model 4750, Parr Company, Moline, IL). A typical preparation procedure of Ge nanocrystals is as follows: 80 mL hexane, 0.6 mL GeH4, 0.6 mL phenyl-GeCl3, 1.8 mL C12E5, and 5.6 mL Na (25 wt% dispersion in toluene) were added to a 200 mL flask. Then the mixtures were stirred in a magnetic stirrer for 30 min before being transferred to a Parr reactor. The Parr reactor was kept at 280 °C for 72 h without any stirring and shaking, and then cooled to room temperature. A black powder was collected and washed with excess amount of hexane, alcohol, and distilled water to remove any NaCl byproduct and hydrocarbon residue, and then dried at 60 °C for 12 h in an oven.

F3.15 Ge and Si Nanostructures Deposited by PLD. Daria Ribinina, Federico Rosci and Mohammed Chaker; INRS-EMT, University of Quebec, Varennes, Quebec, Canada.

Semiconductor nanostructures are of great interest because of their numerous potential applications. Indeed, quantum dots (QD) as the active gain medium in semiconductor lasers may be one of the early applications of nanotechnology within active devices of commercial use. Ge or Si nanolayers and nanocubes are the key system for the integration and development of optoelectronic devices in the existing silicon-based industry [1,2]. Pulsed laser deposition (PLD) has established itself as a very versatile method for thin film growth of almost any kind of materials. During PLD, the interaction between an intense laser and a target material results in the creation of a plasma that contains several species including atoms, ions, electrons and small clusters. This plasma is highly directional and allows the transfer of matter from the target to the substrate. It is known that highly nanocrystalline and cluster-assembled films can be prepared by single beam PLD when deposition is performed into a moderate pressure gas [3]. Recent studies were performed on the size of Si nanoclusters deposited by PLD which show that the size of deposited nanoclusters can be controlled by tuning the deposition conditions. In this work, we study the size correlation of Ge and Si nanoclusters with the deposition conditions such as gas pressure, target-substrate distance and laser fluence. The fabrication of the semiconductor nanostructures was performed by ex situ atomic force microscopy (AFM). The pressure of inert gas (He) was varied from 1 to 10 Torr. For an increase of He pressure it was observed that size of Ge nanoclusters decreases. Decreasing the He pressure from 5 to 0.5 Torr resulted in increase in the size of Ge nanoparticles. Furthermore, we demonstrated in this work that Si nanoparticles dimensions as a function of deposition conditions do not have similar trends as in the case of Ge. This may be explained by the relatively smaller size of Ge nanoparticles at room temperature is a major advantage of PLD technique. Usually semiconductors nanostructures are grown by molecular beam epitaxy or chemical vapour deposition. The major problems of these techniques are the limited control over the size and shape of zero-dimensional nanostructures. PLD is an alternative technique of the growth of semiconductors nanostructures with a good control of their size distribution. 1. N. Motta, J. Phys. - Cond. Matt. 14 (2002) 5853. 2. F. Ribinina, J. Phys. - Cond. Matt. 17 (2005) 7423. 3. D.H. Loendes, D.B. Geohegan, A.A. Puretsky, D.P. Norton, C.M. Rouleau, Science 273 (1996) 808. 4. L. Patrone, D. Nelson, V.I. Safarov, M. Senia, W. Marne, J. Appl. Phys. 87 (2000) 3829. 5. A.V. Kukhtin, R.P. Sylvestre, S. Patskovsky, M. Meunier, J. Appl. Phys. 91 (2002) 5248.


Si and Ge nanocrystals (NC) embedded in oxide matrix have attracted much attention due to their potential optoelectronic and photocative applications. They could combine efficient and tunable light emission at room temperature together with full compatibility with standard complementary metal-oxide-semiconductor technology. Moreover, a major interest in small-size group-IV NCs relies in the fact that they can have direct optical transitions. Yet, a generalized standard way to grow and produce high quality Si1-xGex NC embedded in oxide matrix, with a good control over size and distribution is not available.

In the present contribution we report about the formation of NC in an oxide matrix after polycrystalline Si0.7Ge0.3 oxidation. For it, we have performed oxidations at 650 °C and dry oxidations at 800 °C. High Resolution Transmission Electron Microscopy (HRTEM), Electron Energy Loss Spectroscopy (EELS) and Energy Filtered Transmission Electron Microscopy (EFTEm) have been used to characterize the NC after wet and dry oxidations. EFTEm images and EELS analysis show the evolution of the oxidation of polycrystalline Si0.7Ge0.3 layer, leading to the formation of a polycrystalline Si1-xGex NC embedded in the thermal oxide. We have found that the polycrystalline layer is gradually consumed during oxidation, first homogeneously both in wet and dry oxidation and later more irregularly. Significant differences arise from wet and dry oxidation. In dry oxidation, initial polycrystalline Si0.7Ge0.3 layer leads to silicon oxide while Ge is segregation. Once the silicon is completely oxidized, we observe the presence of unoxidized Ge clusters as EFTEm images clearly show. However, it is difficult to assess the presence of Ge clusters in the oxide by means of EFTEm, although infrared spectroscopy (FTIR) shows fingerprints of it. On the contrary, wet oxidation leads to a progressive oxidation of the layer, both of Ge and Si, that maintain island of material which form like NC in the oxide. These NC can be detected even when the layer is completely oxidized, showing a more homogeneous size distribution than dry oxidations. These NC are also Ge-richer in comparison with wet oxidation. In conclusion, wet oxidation is preferable to oxidize polycrystalline Si1-xGex to obtain Ge-rich NC embedded in the oxide matrix, as both Ge and Si are oxidized, in contrast to dry oxidation, where Ge is mainly segregated.


Rapid growth of Ge quantum dots (QD) is a desirable and preferable approach to produce quantum dots due to its technological importance. The fabrication of quantum dots is almost exclusively accomplished by molecular-beam epitaxy (MBE) technique. Recently an e-beam evaporation process was also attempted. In this study, a new approach using high-vacuum ion-beam sputtering deposition technique was investigated for the fabrication of high-density of nanocrystalline Ge quantum dots (QD). The new approach eliminates the need of expensive MBE equipment. As received (100) silicon wafers and surface modified (100) silicon wafers were used as the substrates. Various substrate temperatures, ranging from 100 °C to 800 °C, were used. The ion beam was mass filtered and used to deposit Ge quantum dots. The ion beam energy was varied through adjusting the incident gas flow rate and the electron cyclotron resonance (ECR) voltage, respectively. In selected experiments, an assisting ion source was used to enhance the incident ion flux to obtain high-density QD. The ion beam energy was varied from 5 to 100 eV. The dot size varied from 5 to 100 nm, all with an aspect ratio of 1/10, approximately. The as-grown samples were characterized using atomic force microscopy (AFM) for surface morphology, high resolution transmission electron microscopy (HRTEM), micro-Raman spectroscopy for microstructure, and photoluminescence (PL) for quantum confinement effect. Among the result, a unique PL peak at 971 nm was observed.
The interest in tin quantum dots (QDs) in crystalline silicon is motivated by possible applications for optical components. A predicted direct band gap for Si$_{1-x}$Sn$_x$ (0.9 < x < 1.0) [1] and an increase in the band gap energy (from 0.98 eV for a-Sn) when forming QDs is the basis for this interest. In this paper we present a method to form a two-dimensional layer of Sn nanocrystals in an epitaxial Si layer grown on a n+ (001) Si crystal. This causes additional islands have a diamond-like structure, with a lattice parameter roughly 2Ell cm$^{-2}$. The optical properties will be discussed where a comparison between different ways of creating the Sn QDs will be made. [1] A. Richard, Soref and Clive H. Perry, J. Appl. Phys. 69 (1991) 539 [2] E. Sundqvist, P. Hauke, C. Cheyssac, A. Stella, Surf. Sci. 364 (1996) 467 [3] Y. Lei, P. M. Ajayan, T. Kwon, J. Phys. Chem., D. Buironi, R. R. Raman, R. K. Agarwal, K. S. Ramanathan, F. Banhart, and H. A. Atwater, Appl. Phys. Lett., 82 (2003) 4262

F3.20 Abstract Withdrawn

F3.21 Epitaxial Sn-Si Islands Formed at the SiO$_2$/Si Interface by Sn Implantation and Annealing. J. M. Lopes, Paulo F. P. Fichtner,1,2 Fernando Claudio Zawislak,1 Ricardo M. Papaleo,1,2 Francisco Lovey,1,2 A. Condé and A. Tolley,1 Departamento de Física, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil; 2Faculdade de Física, PUC-RS, Porto Alegre, RS, Brazil; 3Departamento de Materiales, Centro Atómico Bariloche, Bariloche, Argentina.

Thin films of SiO$_2$ on Si (100) were implanted with 120 keV Sn ions at a fluence of 1.5E16 cm$^{-2}$. After high temperature (900-1100 °C) thermal annealing, an array of Sn-Si islands were observed at the SiO$_2$/Si(100) interfaces due to migration of the implanted Sn ions (initially located at around the middle of the oxide layer). The island system was characterized by transmission electron microscopy (TEM), scanning force microscopy (SFM) and Rutherford Backscattering Spectrometry under channeling conditions (RBS/C). TEM observations on cross-section samples showed either trapezoidal or diamond-like islands (about 1-2 nm high and with a 4-7 nm wide base) epitaxially attached to the Si matrix. SFM images of the Si surface, obtained after oxide removal, revealed also 1-2 nm high protrusions, packed in a relatively ordered arrangement at an area density of roughly 2Ell cm$^{-2}$. TEM images of the lattice suggest that the islands have a diamond-like structure, with a lattice parameter slightly larger than that for pure Si crystals. This causes additional strain contrast and plane misalignment with respect to the Si matrix. In fact, the presence of Sn atoms in substitutional positions was demonstrated by RBS/C. The breakdown of the planar SiO$_2$/Si interface and the appearance of the island system is discussed in terms of elastic strain energy accumulation due to the lattice misfit. The influence of the damage produced by Si and O recoils on the stability of the SiO$_2$/Si interface and on the island formation is also discussed.

F3.32 Gated SiGe Single and Double Quantum Dots for Quantum Computation. Levente J. Klein1, S. Goswami2, R. K. Sliker1, K.L.M. Lewis1, Robert Blick1, J.O. Chu1, P.M. Mooney2, Susan N. Coppersmith1, and M.A. Eriksson1, 1Department of Physics, University of Wisconsin Madison, Madison, Wisconsin; 2IBM T.J. Watson Research Center, Yorktown Heights, New York.

Spins of localized electrons in quantum dots are promising candidates for quantum information processing. Here we present Coulomb blockade measurements of quantum dots formed in the two-dimensional electron gas of a silicon/silicon-germanium heterostructure. The quantum dots are formed by electron beam lithography and subsequent reactive ion etching. Lateral side gates fabricated from the two-dimensional electron gas itself nearby the dot [1] allow to tune the charging of the quantum dot potential. Energy level plots of the conductance through the quantum dots acquired at low temperature (0.2 K) show stable single electron charging. Recent advances show low charge noise, with no switching events observed over hours of continuous measurement. A large extraction time is expected in Si due to small spin orbit coupling. A fundamental goal of these experiments is the observation of electron spin resonance in an individual quantum dot. As a step towards this goal, we observed electrically detected electron spin resonance in Hall bars fabricated from silicon/silicon-germanium two-dimensional electron gas. Finally, for tunnel coupled quantum dots, we present well defined stability plot of the conductance as a function of the gate voltage on each dot. Single electron charging of each quantum dot will be discussed. [1] C. J. Crowell, B. G. Rein, and J. A. Cooper, "Blockade in a Si/SiGe Two-Dimensional Electron Gas Quantum Dot," L. J. Klein et al. Appl. Phys. Lett. 84, 4047 (2004).

SESSION F4: Si/SiGe THz Devices
Chair: Jean-Marc Baribeau
Tuesday Morning, November 30, 2004
Constitution B (Sheraton)

8:30 AM *F4.1 Towards a Si/SiGe Quantum Cascade Laser for Terahertz Applications. D. Santori, J. M. Fromherz, P. H. Pikhart, F. Capasso, J. H. English, and M. Sorel, Department of Physics, University of Cambridge, Cambridge, Cambridgeshire, United Kingdom.

There are many potential applications of terahertz radiation including medical and dental imaging, remote chemical imaging, biosensing, molecule detection, molecular spectroscopy and pollution monitoring. Terahertz applications have been slow to develop due to the lack of any practical and cheap source of radiation. Recently a GaAs quantum cascade laser has been demonstrated to operate at low temperatures without the terahertz with power outputs up to 80 mW. While the indirect bandgap of silicon has precluded the development of a silicon-based laser due to the inefficient recombination of electrons and holes, the unipolar quantum cascade laser concept should allow a Si-based laser to be produced. Below the optical photon energy (62 meV or 14.9 THz in silicon), group IV materials have the significant advantage over III-V materials of no polar optical phonon scattering potentially allowing higher operational temperatures. Progress in developing a Si/SiGe quantum cascade laser will be presented including evidence of population inversion along with waveguide designs and measurements. Strain symmetrised Si/SiGe quantum cascade interwell structures with up to 600 active periods will be presented demonstrating tunable terahertz electroluminescence around 2 THz. The experimental results have excellent agreement with theoretical spectra calculated using a soft-consistent 6 band kp band structure solver. The use of buried silicide layers produced using a technique similar to bond and etch back silicon-on-insulator will be shown to aid the vertical confinement of the optical mode allowing modal overlap and waveguide losses comparable to demonstrated GaAs terahertz quantum cascade lasers. Electroluminescence above 3 THz will be demonstrated from quantum cascade devices fabricated from Si/SiGe heterostructures grown on buried silicide wafers. Potential problems relating to impurity electroluminescence, high current densities, diode fabrication and waveguide fabrication will be discussed. Pump-probe measurements using a free electron laser have extracted a non-radiative lifetime of 25 ps from a 95 micron wavelength (3.2 THz) quantum cascade emitter. Monte Carlo modelling of the subband scattering mechanisms and dynamics produce a comparable value of 14 ps. The near temperature independence up to 300 K of the non-radiative lifetimes will also be presented.

9:00 AM *F4.2 Recent Results on the Road to a Si/SiGe Quantum Cascade Laser. Ulf Gennser1, Alex Borisov2, Maxi Scheiner3, Laurent Diehl4, Soichiro Tsujiro5, Chaudi Falub3, Hans Sigg2, Elisabeth Mueller2, Detlev Gruenzucker2, Yves Camydel1, Olivier Kernarvo2, Isabelle Sagnes1, Daniel Benshal1 and Jerome Faist4; 1LPN-CNRS, Marcoussis, France; 2Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland; 3ST Microelectronics, F-38092 Crolles-Cedex, France; 4Universite de Neuchatel, CH-2000 Neuchatel, Switzerland.

Quantum cascade (QC) lasers emitting in the mid or far infrared, with continuous wave room temperature operation, are very interesting devices for niche applications such as chemical sensors or medical imaging. Of particular interest, the QC laser design, exploiting intersubband transitions instead of band-to-band recombination, does not require prior itself to direct bandgap material, and the possibility of realizing a silicon based intersubband laser has recently attracted serious interest. Pseudomorphic Si/SiGe QC structures have been realized, exhibiting electroluminescence in the 9 μm range, with non-radiative lifetimes around 0.5 ps. Using
SiGe pseudo-substrates, strain compensated Si/Ge QC structures grown at low T (≤800 °C) and containing up to 30 cascades have been reported to yield interface roughness as low as 0.2 nm. Using a "bound-to-continuum" (B-C) design to enable the rapid extraction of carriers via a superlattice miniband, electroluminescence in the 7 μm range has been demonstrated at current densities of up to 8 kA/cm², though with a reduced quantum efficiency compared to the pseudomorphic case. A major complication is the use of the valence band, where the Si/Ge heterostructures have their maximum band offset. Hence, a B-C design based on heavy hole states will have interspersed light hole states that may reduce the photodiode lifetime. However, studies of simple tunneling structures show that the scattering in these structures is sufficiently low, so that the total angular momentum is conserved during tunneling. As a consequence, the minibands between the light hole states can effectively transport, even in the presence of light hole states. Achieving lasing with these highly strained valence band heterostructures requires the solution of a host of problems in terms of the material, the laser design, and the interband physics of the valence band. Current research is focused on developing high conductivity, low optical loss contact structures and new waveguide designs; increasing the quantum efficiency of the strained compensated cascade structures; and understanding the effect of the interspersed light hole states.

**SESSION F5: Si/Ge Three-Dimensional Nanostructures**

**Chair:** J. Kolodzy
**Tuesday Morning, November 30, 2004**

**Constitution B (Sberston)**

**10:15 AM **F5.1** Progress in the Growth and Characterization of Ge Quantum Dots at Interfaces on Si Islands. Joseph Marc Baribeau**

Self-assembled quantum dots have the potential to become the building blocks of the next generation of microelectronic, optoelectronic and photonic devices. SiGe alloyed layers grown on Si (001) are among the best-studied semiconductor systems in which, under appropriate growth conditions, a one-dimensional self-organization takes place at the nanometer scale [1]. In this talk, we review progress in the understanding of SiGe alloy island growth and dot formation on Si (001). We discuss the evolution of the island morphology with SiGe coverage, look at the various growth parameters or post-growth treatments on the shape of the islands and dots. We describe the structural, vibrational and optical properties of SiGe islands and review recent progress in the determination of their composition and strain distribution. The spatial distribution of the three-dimensional islands and their vertical correlation in multi-layer stacks is also reviewed. We discuss various growth techniques that have been examined to grow SiGe quantum dots and in particular control their size, density and spatial distribution. For example, we show how C pre-deposition on Si (001) can influence nucleation and growth conditions. We also discuss the conditions that lead to the formation of surface cusps on Si (001) and show how surface features can promote nucleation of dots. Finally, we briefly review recent progress in the use of SiGe islands and superlattices in device applications. [1] J.-M. Baribeau, L. Rowell and D.J. Lockwood, Self-Assembled SiGe Dots and Islands, in Self-Organized Nanoscale Materials, edited by M. Hidachi and D.J. Lockwood (Kluwer/Plenum, New York, 2005).

**10:45 AM **F5.2** 1D Alignment of Nanoscale Ge Islands on Grooved Si(001) Surfaces. Takeshi Kitajima**, Bing Liu** and Stephen R. Leone**

1Electrical and Electronic Engineering, National Defense Academy of Japan, Yokosuka, Kanagawa, Japan; 2Department of Engineering Physics, and Lawrence Berkeley National Laboratory, University of California Berkeley, Berkeley, California.

Positioning of size controlled quantum dot arrays is one of the main issues of nanoscale surface design and materialization. The combination of lithographic patterning and self-assembly of nanoscale 3D islands via the Stranski-Krastanov growth mode of lattice-mismatched Ge/Si heteroepitaxy can provide ordered dot arrays. Here we present 1D alignment of size-controlled Ge 3D islands on electron beam patterned Si surfaces with V-grooves. The Si(001) surface is patterned into lines using electron beam lithography and subsequent chlorine plasma etching. The typical width and depth of the groove is 100 nm and 20 nm, respectively. The sample is grown in a MBE chamber, which also has an ion gun and a heater for the sample. After the surface cleaning, 6 ML of Ge is supplied at the rate of 1 ML/min and the sample temperature is kept at 850 K. Surface morphology of the grown sample is measured by ex situ atomic force microscopy (AFM). Two patterns of types are prepared for the growth. One is a line pattern with <100> directed grooves and the other has <110> directed grooves. On the <100> line pattern, both of top Si(001) surface atoms between the grooves and Si(103) vicinal side facet atoms of the V-grooves accommodate Ge islands. On the <110> line pattern, only top Si(001) atoms have islands and the Si(113) vicinal side facet atoms are free of islands. The absence is most likely due to the lower surface free energy of the (113) facet. Islands on the top (001) surface atoms of both the <110> and <100> line patterns are dome-type islands of 50 nm width and 4 nm height on average when the line width is more than 100 nm. When the line width is less than 100 nm, islands on the top surface of the <110> line pattern is extended in the <110> direction. This shows that the islands grow faster in the <110> direction due to a bias for Ge dimer diffusion on the modified surface morphology. On the <100> line pattern, the island shape shows no change. Islands on the (103) vicinal facet in grooves of the <100> line pattern are pyramid-type islands of 55 nm width and 2 nm height on average. The islands are directed toward the <110> direction and shows similarity to the pyramid-type islands on the (001) surface. The density of these islands are about twice the island density on the top surface and islands form one dimensional arrays because of the limited width of the side facet. The nucleation of pyramid islands on the side facets of the grooves might be due to the high surface free energy of the (103) surface, which have one dangling bond for each step. During growth, the Ge wetting layer on the Si surface should minimize its energy via diffusion of Ge toward the grooves by covering the dangling bonds with excess Ge. Preferential nucleation of islands in the groove on a 4 ML sample support this hypothesis. We believe this is the first example of an artificial 1D regimented array of pyramid-type islands of less than 50 nm size.

**SESSION F5: Si/Ge Three-Dimensional Nanostructures**

**Chair:** J. Kolodzy
**Tuesday Morning, November 30, 2004**

**Constitution B (Sberston)**

**11:00 AM **F5.3** Formation of Ultrahigh Density β-FeSi 2 Nanodots by Codeposition of Fe and Si on Oxidized Si(111) Surfaces. Yoshiaki Nakamura**, Yasushi Nagadomi** and Masayuki Ichikawa**

1Dept. of Applied Physics, The Univ. of Tokyo, Tokyo, Japan; 2CREST, Japan Science and Technology Agency, Tokyo, Japan.

Semiconducting β-FeSi 2 is attractive as a promising material for a Si-based light emitter with a wavelength (≥1.5μm) of optical fiber communication. It has been reported that N(111) can be a direct-gap semiconductor [1]. Therefore we expect that β-FeSi 2 nanodots on Si (111) have high light-emitting efficiency because coherent nanodots preserve strain caused by the lattice mismatch and a nanodot has almost no impurities due to its small size. In this work, we report formation of β-FeSi 2 nanodots with ultrahigh density by codeposition of Fe and Si on oxidized Si (111) surfaces. Samples cut from an n-type Si (111) wafer were introduced into the ultrahigh vacuum (UHV) chamber at the base pressure of
The Si(001) surface is intrinsically unstable against kinetic step bunching during Si deposition on SiGe heteroepitaxy [1]. While this phenomenon has for some time been associated with a strain-driven equilibrium mechanism [2], it is now clear that it is purely kinetic in origin. Recent kinetic Monte Carlo (KMC) simulations in connection with a basic physical model provide unequivocal evidence for step bunching being caused by the interplay between the adsorption/desorption kinetics at atomic height steps and the pronounced diffusion anisotropy on the reconstructed Si(001) surface [3]. The simulations take into account that multilayer SiGe dots are nucleated and grow through several growth modes, including adsorption/desorption at atomic height steps, the pronounced diffusion anisotropy on the reconstructed Si(001) surface, and the pronounced temperature dependence of the step bunching phenomena [4].

The detailed understanding of step bunching on Si(001) allowed us to tailor the period and height of the bunches by controlling substrate miscut, growth temperature, deposition rate and layer thickness. Using vicinal Si(001) substrates with 4° miscut along [110], homoepitaxial layers with ripple periods of \( \pm 100 \) nm were prepared. These were then employed as templates for the ordering of SiGe or Ge dots grown in the direct attachment mode. When the period lengths of the template coincide with the mean spacing of the dots, only one dot row fits into one period. We could show that the dots then nucleate at the step bunches, where the energetically favorable (105) facets of the dots are mostly created. This way 1D ordering of SiGe dots on a nanometer scale can be achieved in an entirely self-organized manner, regardless of their density. Combined with vertical ordering that allows the topmost dot layer to be exploited as a sacrificial, self-aligned mask for selective ion implantation, electric contacts to individual dots become now feasible [5].

In this paper, we fabricate the EL devices using HF treated and oxidized SiGe or SiGe dots in 2D and 3D, we used arrays of p-systems that were defined by lithography and reactive ion etching. For small enough periods, only one dot per unit cell is created, which nucleates at the lowest point of the pit.

Self-assembled formation of quantum dots is of increasing interest for application in optical, nanoelectronic, biological, and quantum computing systems. From fabrication technology point of view, there can be great advantage if it all could be made on Si substrate. Furthermore, SiGe is also a model semiconductor system for fundamental studies of the growth and their properties. In practice, as the MBE growth of heterostructures is an inherently non-equilibrium process, the resultant of the formation of self-assembled nanostructures are extremely complex and very sensitive to their growth and overgrowth conditions. The morphology, structure, and composition of the QDs can all be changed during the growth; therefore it will be very crucial to understand their structures of different stages. In this presentation, our efforts are focused on characterizing and understanding the quantum dot growth phenomena by high-resolution HAADF-STEM imaging. The formation of uncapped QD and the effect of encapsulation process were investigated by means of the direct imaging. The morphological and compositional evolution of the QDs and wetting layers was directly observed at atomic scale for the first time. The results show that during the encapsulation, Ge content in the centre of QD keeps unchanged (100%), despite of significant intermixing, lateral spreading, and lateral inhomogeneous Ge distribution inside a Ge QD. Initially non-uniform wetting layer for the uncapped Ge QD becomes uniform after encapsulation, and a 3-monolayer-thick core with 60% Ge was performed in the 2-period wetting layer with an average Ge content of 30%. Moreover, the above results were obtained by direct Z-contrast STEM imaging without involving complex image simulation procedures.

The Si(001) surface is intrinsically unstable against kinetic step bunching during Si deposition on SiGe heteroepitaxy [1]. While this phenomenon has for some time been associated with a strain-driven equilibrium mechanism [2], it is now clear that it is purely kinetic in origin. Recent kinetic Monte Carlo (KMC) simulations in connection with a basic physical model provide unequivocal evidence for step bunching being caused by the interplay between the adsorption/desorption kinetics at atomic height steps and the pronounced diffusion anisotropy on the reconstructed Si(001) surface [3]. The simulations take into account that multilayer SiGe dots are nucleated and grow through several growth modes, including adsorption/desorption at atomic height steps, the pronounced diffusion anisotropy on the reconstructed Si(001) surface, and the pronounced temperature dependence of the step bunching phenomena [4].

The detailed understanding of step bunching on Si(001) allowed us to tailor the period and height of the bunches by controlling substrate miscut, growth temperature, deposition rate and layer thickness. Using vicinal Si(001) substrates with 4° miscut along [110], homoepitaxial layers with ripple periods of \( \pm 100 \) nm were prepared. These were then employed as templates for the ordering of SiGe or Ge dots grown in the direct attachment mode. When the period lengths of the template coincide with the mean spacing of the dots, only one dot row fits into one period. We could show that the dots then nucleate at the step bunches, where the energetically favorable (105) facets of the dots are mostly created. This way 1D ordering of SiGe dots on a nanometer scale can be achieved in an entirely self-organized manner, regardless of their density. Combined with vertical ordering that allows the topmost dot layer to be exploited as a sacrificial, self-aligned mask for selective ion implantation, electric contacts to individual dots become now feasible [5].
Light-emitting silicon nanocrystals (nc-Si) have attracted much interest due to their importance for optoelectronic devices. Electron hole recombination in a quantum-confined system is generally considered as the theoretical frame explaining the photoluminescence (PL) origin. However, there is still a living debate about the PL properties. This is particularly true for the temporal PL behavior. The decay is exponential or non-exponential, with the former being described by a stretched exponential law and the latter, a stretched exponential law. In the case of silicon nanoparticles, the origin of the stretched exponential decay is often attributed to interactions between the nanocrystals, with excitation transfer from the smaller particles to the bigger ones. In contrast to these approaches, the absence of carrier hopping has been demonstrated experimentally in porous silicon (Mihalcescu 1998). In order to elucidate this question, time-resolved photoluminescence measurements on films made from gas phase grown silicon nanocrystals (Ehbrecht 1999; Ledoux 2000) have been carried out. The gas-phase synthesized nanoparticles are extracted as a supersonic beam, size-selected, and deposited downstream as films of variable densities. The nanoparticle number densities were determined by atomic force microscopy. The PL spectroscopy was carefully studied, as a function of the film density. Incident UV excitation intensity was recorded, the sample absorption measured and the PL yield determined. PL decay dynamics were recorded at different PL wavelengths. The photoluminescence properties appear independent of the film density. Even in the very low density film (4700 particles/cm^2) where nanoparticles are completely isolated from each other, the decay kinetic corresponds to a stretched exponential law (Guillois 2004). This means that carrier hopping alone cannot explain the stretched exponential decay. The origin of the stretched exponential decay must be linked to an intrinsic characteristic of the nc-Si. In this talk, the experimental results will be described in details and compared to the theoretical predictions available in the frame of the quantum confinement model. Then, the possible origins of the multiphonon character of the decay dynamics will be discussed, and the particular properties of the PL in indirect band-gap semiconductors emphasized. [Ehbrecht 1999] M. Ehbrecht, F. Huisken, Phys. Rev. B 59, 2975 (1999) [Guillois 2004] O. Guillois, N. Herlin-Boime, C. Reynaud, G. Ledoux, F. Huisken, J. Appl. Phys. 95, 3677 (2004) [Ledoux 2000] G. Ledoux, O. Guillois, F. Huisken, B. Kohn, V. Paillard, D. Portier, C. Reynaud, Phys. Rev. B 62, 1542 (2000). [Mihalcescu 1998] I. Mihalcescu, J. C. Vial, R. Romestain, Phys. Rev. Lett. 80, 3392 (1998)

2:30 PM *F6.3 *F6.4
Center for Computational Material Science, NRL, Washington DC, District of Columbia.

The strong photoluminescence of Si nanocrystals and porous Si, which can be considered as an ensemble of Si nanocrystals, has stimulated great interest in optical properties for one of the most attractive systems. The major experimental results on the linear and nonlinear optical properties of Si nanocrystals and will analyze these results in the framework of existing theoretical models. At the end I will discuss the potential application of ensembles of Si nanocrystals.

3:15 PM *F6.4 *F6.5
First Principles Simulations of Group IV Semiconductor Nanomaterials. Alexei J. Williams, Physics, Lawrence Livermore National Laboratory, Livermore, California.

The results of recent first-principles calculations of the structural, electronic and optical properties of group IV semiconductor nanomaterials will be presented. At the nanoscale, the surface to volume ratio increases dramatically and new phenomena, such as quantum confinement, arise. Accurate description of these phenomena requires ab initio calculations with atomic detail and efficient treatment of electron correlation. I will describe some of our recent algorithmic improvements to density functional and quantum Monte Carlo electronic structure calculations which enable these techniques to be applied to exotic nanoscale semiconductors and nanostructures. Using these techniques we are able to accurately predict the size dependence of the structural and optical properties of silicon, germanium and carbon nanoparticles. Calculations used to interpret optical and X-ray absorption and photoemission measurements and subsequently predict atomic surface reconstructions, chemical surface doping and structural phase transformations will be discussed.

3:45 PM F6.5
Foerster Effect between Semiconductor Nanoparticles. Christoph Delerue and Guy Allan; ISEN, IEMN, Lille, France.

The Foerster resonance energy transfer between molecules has been studied for more than fifty years. It has been recently observed in quantum dot arrays [1] and could be a loss mechanism for quantum dot lasers. This effect can also be used to transfer excitations in a controlled way. Using the tight-binding approximation, we calculate the transition rate between two semiconductor nanocrystals as a function of their distance and their size. We consider intra- and inter-band transitions and show the differences between direct (InAs) and indirect (Si) gap semiconductor with the simple Foerster theory of dipole-dipole interaction and with the radiative lifetime. [1] S.A. Crooker et al., Phys. Rev. Lett. 89, 186802 (2002)

4:00 PM *F6.6 *F6.7
Optical Gain in Silicon Nanocrystals. Lorenzo Pace.
Physics, University of Trento, Povo (Trento), Italy.

Optical gain in Si nanocrystals grown by a wealth of different techniques has been observed. The material gain value has been extracted from the modal gain measured with the time-resolved-variable-stripe-length (TRVSL) technique by taking into account the propagation losses and the modal confinement factors of the embedding waveguide structure. Further pump-probe measurements have confirmed the presence of net optical gain. A four level model of this phenomenon has been proposed where the interface between the Si nanocrystals and the embedding matrix is playing a critical role. An interesting dependence on the silicon nanocrystal mean radius as well as on the optical confinement factor and active material refractive index has been observed. A critical balance between stimulated emission and loss mechanisms such as Auger non-radiative recombination or excited state absorption or propagation losses emerges from our data. We acknowledge University of Catania, CNR-IMM of Catania, University of Modena, Technical University of Munich, Rochester University, Max Plank Institute of Halle, Research Institute in Prague, University of Barcelona, University of Helsinki, where the samples reviewed here have been produced.

4:30 PM *F6.7
Physics Department, Technical University of Munich, Garching, Germany.

The energy transfer of electronic excitation plays an essential role in numerous scientific branches such as photophysics and biochemistry. To elucidate the fundamental physical effects occurring during energy transfer processes semiconductor nanostructures are viewed as a promising systems. Oxygen molecules in the electronic ground state are chemically inert due to their spin-triplet characteristic. The transition from the ground triplet state to one of the excited singlet states and vice versa requires the change of electron spin state (spin-flip process) and direct states conversion via absorption/emission of photons is spin-forbidden in the first approximation. However, excitation of an intermediate substance (photosensitizer, usually dye molecule) and subsequent transfer of energy to oxygen activates the molecule to an excited singlet state. We demonstrate that the efficiency of photosensitization of oxygen molecules mediated by excitons confined in silicon nanocrystals is extremely high: 100% at cryogenic and 75% at room temperature. The remarkable photosensitizing properties of silicon nanocrystal assemblies result from a binned energy spectrum of photoexcited excitons, a long triplet exciton lifetime and a highly developed surface area. We present experimental proof for the efficient generation of singlet oxygen molecules. We show that energy transfer proceeds via direct electron exchange and is accompanied by photon emission cascade. From time-resolved measurements the characteristic time of energy transfer is found to be in the range of microseconds. Magneto-optical experiments reveal the importance of the spin orientation of the exchanged electrons for the energy transfer rate. Room temperature photooxidation of silicon nanocrystals evidences the direct chemical action of photosensitized oxygen molecules.

F7.1
Elec.&Elec Eng., Tokyo Univ. A&T, Tokyo, Japan; Quantum14 Co., Tokyo, Japan.

Nanocrystalline porous silicon (PS) is a promising material for achieving various optoelectronic device applications, such as...
light-emitting diodes, waveguides, lab-on-chip, potential lasing capabilities, etc [1]. However, its luminescence quantum efficiency remains rather low. Best values to date are about 3% [2] for the photoluminescence (PL) and 1.1 % [3] for the electroluminescence (EL). The luminescence stability of nanocrystalline PS for a long-term operation is also a critical issue which needs to be solved before any applications can be considered. Complete surface passivation is especially important to suppress the generation of non-radiative recombination centers. A possible solution to this problem is to cover the nanocrystalline Si surface with a high quality SiO2 layer with minimized interfacial defects. In order to achieve this high quality surface passivation, a high-pressure H2O vapor annealing technique that is useful for improving the electrical properties of polycrystalline silicon TFT devices [4] has been applied to nanocrystalline PS. The annealing effects on various optoelectronic properties of PS prepared under various conditions have been studied as a function of the annealing pressure (1 to 3 MPa), temperature (150 to 300 °C), and treatment time (1 to 3 h). The microscopic characterization of the high-pressure annealed samples has been carried out, and XPS and AFM studies on complimentary effects of electrochemical oxidation. It has been observed that the PL of PS is drastically enhanced by the high-pressure anneal under relatively low temperatures, while the emission wavelength remains unchanged. This treatment is very effective to quench non-radiative defects at the nanocrystalline Si surfaces by decreasing the interfacial mechanical stresses, to enhance the carrier localization in Si nanocrystals, and consequently to improve both the luminescence efficiency and stability. The improvement in the optical properties produces desirable effects on the electrical properties as well. Due to a significant decrease in the carrier recombination at the interfacial oxides, for instance, ballistic electron emission from the PS diodes that were previously significantly stabilized. In addition, EL characteristics should be improved, since carrier injection efficiency into luminescent silicon nanocrystals should also be increased.B. Gelloz and N. Koshida, Handbook of Electroluminescent Materials, Chap. 10, 203, edited by D.R. Vij, Institute of Physics Publishing, Bristol and Philadelphia. (2004); [3] J.C. Vial et al. Phys. Rev. B 45,14171 (1992) [3] B. Gelloz and N. Koshida, J. Appl. Phys. 88 (7), 3519 (2000); [5] T. Samehahina, M. Satoh, K. Sakamoto, K. Otsuki and K. Sakai, Jpn. J. Appl. Phys. 37 L1452 (1998).


The heteroepitaxial growth of group IV semiconductors represents a field of enormous interest, due to the possibility it offers to engineer the optoelectronic properties of the resulting structures with vast flexibility [1]. In particular, the Stranski-Krautkranov (SK) growth mode of Ge on Si surfaces may yield a real breakthrough in the semiconductor industry. Indeed, the self-assembled Si/Ge 3D islands may act as quantum dots, whose luminescence properties could be used to develop new optoelectronic devices compatible with the existing Si-based technology. For these reasons, the growth of Ge on Si substrates has been the subject of numerous theoretical and experimental reports during the past two decades [2]. Nevertheless, several critical issues, such as the adoption of SiGe nanostructures for device fabrication, have not been fully resolved. One of the points of major concern regards the actual stoichiometry inside individual 3D islands. Mixtures of Ge and Si may be present at the early stages of growth of Ge on Si surfaces. A detailed description of the chemical composition gradient inside single dots is necessary to model the potential barriers which cause carrier confinement inside the system. Further, mapping the Si/Ge concentration inside self-assembled islands could cast some light on the nature of the main diffusion mechanisms that produce the alloying itself, thus eventually leading to their control. Our results on the growth of Ge on Si(111) are obtained by Low Energy Electron Microscopy (LEEM) and X-Ray Photoemission Electron Microscopy (XPEEM). The former has been used to map the chemical composition of a single island with a high lateral resolution, thus allowing mapping the Si/Ge concentration in the topmost layers of the system. Ge was deposited by MBE on Si(111) substrates kept at temperatures ranging from 400 to 600 °C. The surface morphology was analyzed by LEEM and XPEEM. XPEEM core level spectra and related images were acquired on individual islands. An analytical methodology developed ad hoc allowed us to obtain an unprecedent mapping of the surface stoichiometry with a 30 nm spatial resolution. One of the islands investigated is shown in Fig. 1. The borders seem to be consistent with diffusion mechanisms which are mainly mediated through surface mobility. Our analysis represents a fundamental step towards a more accurate understanding of the chemical composition gradient inside single dots, which could provide the necessary spatial resolution. 1) P. Chottare, A. Portavoce, J. Phys.: Condens. Matter 16 4162 (2004); 2) C. Tschor, J. Phys. Rep. 365, 335 (2002); 3) J. Berbezier, A. Bonf, A. Portavoce, J. Phys.: Condens. Matter 14 8285 (2002); 4) P.C. Kelnines, J. Phys.: Condens. Matter 16 1485 (2004) 5) F. Ratto, F. Rosati, A. Locatelli, S. Cheri, S. Fontann, S. Heun, P.D. Szukub, A. Sgarlata, M. De Crescenzi, N. Motta, Appl. Phys. Lett. 84, 4326 (2004). 6) F. Ratto, F. Rosati, A. Locatelli, S. Cheri, S. Fontann, S. Heun, P.D. Szukub, A. Sgarlata, M. De Crescenzi, N. Motta, in preparation.

**F7.3 Uniform dome-shaped self-assembled Ge islands by UHV/ CVD after boron pre-deposition.** Ningqin Heung, Wentao Huang and Peiyi Chen; Institute of Microelectronics, Beijing, China.

The effects of pre-deposition of boron with different B2H6 flux on the self-assembly growth of Ge islands on Si(100) substrate by UHV/ CVD are studied by atomic force microscopy (AFM). Proportion of dome-shaped Ge islands increases with the increasing of flux of B2H6 [Fig. 1]. Quantum dome-shaped Ge quantum dots with size and height distribution of less than 4.3%; which is much more narrow than the size distribution of typical self-assembled Ge dots, are obtained after appropriate boron pre-deposition [Fig. 2]. The lateral size and height of these dots are 60 and 10 nm respectively and the density is about 8 × 10^12 cm^-2. Based on the shape transition model we proposed elsewhere, the uniform size and shape distribution after boron pre-deposition was explained. During the growth, boron atoms will diffuse into Ge island. The reduced lattice mismatch results in a larger critical size for shape transition from pyramids to domes, then uniform dome-shaped Ge islands can be obtained. The results show that method of boron pre-deposition can be used to fabricate quite uniform Ge quantum dots to meet the requirements of opto-electronic devices.

**F7.4 Classical Versus First-Principles Structural Relaxation:**

**Calculated Electronic Excitations and Optical Properties of Ge Nanocrystals Embedded in a SiC Matrix.**

Giancarlo Cappellini; Hans-Christian Weikker, Davide De Salvador, Jurgen Futamura, Friedrich Bechtstedt, Guido Sudbrock, Luciano Colombo, Padova, Italy. & 162


Ariana R. Rodrigues1, Giovanni Zanelatto1, Adelson Jose Chiquito1, Alexander I. Milekin3 and Jose Claudio Galperin3; 1Physics, Universidade Federal de Sao Carlos (SP), SP, Brazil, 2Institute of Semiconductor Physics, Novosibirsk, Russian Federation.

The three-dimensional confinement of charge carriers in quantum dots is responsible for their electronic and optical properties, which differ substantially from those of bulk materials. The interesting properties of the quantum dots qualify them as promising materials for the design of microelectronic and optoelectronic devices with improved characteristics. Among them, the multilayer nanostructures, such as Ge/Si are of special interest due to their possible application in various devices and integration with modern silicon technology. In this work, the vibration spectra of self-assembled structures with germanium quantum dots were studied using Raman scattering; capacitance measurements were also accomplished. The structures were prepared by molecular-beam epitaxy of germanium and silicon layers on Si (001) substrates, based on the Stranski-Krautkranov growth mechanism. After a 500 Å buffer Si layer, ten monolayers of germanium was grown, followed by a 500 Å silicon layer. The process was repeated five times. The growth temperature of germanium was set at 300, 400, 500 and 600 °C. Resonant Raman scattering was accomplished with excitation energies provided by Ar+, Kr+ lasers. The spectra were acquired at the temperature 8 K. The longitudinal optical phonon confined in the dots was monitored, revealing that the dots are sustained in these structures; the intensity and the frequency position of this Raman line are analyzed as a function of the excitation energy for each sample. The resonance maximum at 2.4 eV observed in the case of the sample grown at 300 °C is attributed to the E1 exciton (1) in the strained Ge dots. For 400 °C, however, the E2 resonance was...
also detected, around 2.55 eV. The amplitude of the resonance curve falls to a half as compared to the former, as an indication that the size of the quantum dots. When the SiGe films are oxidized in steam, the oxide falls to a half as compared to the former, as an indication that the substrates. An epitaxial Si cap, which is partially consumed during each stage of the oxidation.

An electronic memories or photonic devices. Up to date, there are only a few reports about the synthesis of nanoparticles of SiGe by oxidation and/or annealing of SiGe films, though the oxidation of SiGe has been studied in the past. In this work, a comparative analysis of the two oxidation processes in SiGe layers using Raman and FTIR spectroscopies is presented. When SiGe films are oxidized in a pure oxygen ambient, Ge is segregated from the growing silicon oxide and a UV band at 4 eV. To clarify the origin of the luminescence spectrum during the dry and steam oxidation of SiGe Films, Andres Rodríguez, 1 Jesus Sangrador 1, Tomas Rodríguez 1, Angel Cuncllo Prieto 1, Manuel Ávila 2 and Juan Jimenez 2, 1 Tecnología Electrónica, E.T.S.I. de Telecomunicación, Universidad Politécnica de Madrid, Madrid, Spain; 2 Física de la Materia Condensada, E.T.S.I. Industriales, Universidad de Valladolid, Valladolid, Valladolid, Spain.

Nanoparticles embedded in a dielectric medium can be used for either electronic or photonic devices. To date, there are few reports about the synthesis of nanoparticles of SiGe by oxidation and/or annealing of SiGe films, though the oxidation of SiGe has been studied in the past. In this work, a comparative analysis of the two oxidation processes in SiGe layers using Raman and FTIR spectroscopies is presented. When SiGe films are oxidized in a pure oxygen ambient, Ge is segregated from the growing silicon oxide and a UV band at 4 eV. To clarify the origin of the luminescence spectrum during the dry and steam oxidation of SiGe Films, Andres Rodríguez, Jesus Sangrador, Tomas Rodríguez, Angel Cuncllo Prieto, Manuel Ávila and Juan Jimenez.

The large-scale calculation method can provide process simulations of silicon with the size of up to more than ten million atoms. The large-scale calculation method can provide process simulations of silicon with the size of up to more than ten million atoms. The method is applied to cleavage process [3, 4], a non-equilibrium process. Cleavage dynamics is simulated with external loads. Bond-breaking and surface rebonding occur, when the bulk (sp3) wavefunctions change their character, locally, into surface (sp3) wavefunctions. As a remarkable feature of 10 nm scale simulations, step formations are observed. We focus on the unstable cleavage with (001) plane and the stable (experimentally observed) cleavage with (111)-2×1 plane. First, the cleavage process under [001] external load is investigated. In smaller samples, with the size of 4×4, a (001) cleavage plane is obtained, in which the symmetric surface dimers appear. In larger samples, with the size of 10×20 nm, however, the (001) cleavage plane becomes unstable with many step formations. The result is consistent to the experimental fact that no (001) plane appears on clean surface. Second, the cleavage process with [111] external load is simulated. During the cleavage propagation, the pi-bonded (Pandey) (2 x 1) structures are formed, as elementary process. An anisotropic surface strain is induced by forming the pi-bonded structure, which enhances the stress relaxation in the SiGe layers of the sample grown at 1100°C in N2 ambient. The Si and the Ge layers were intermixed and the strain-relaxed SiGe with the high-pi-edge dislocation plane, formed on the SiGe/SOI interface could be formed. Furthermore, by increasing the annealing duration, enhanced solid-phase intermixing of Ge and Si resulted in the SiGe buffer layer directly formed on the insulator. Although residual threading dislocations were seen in this type of samples, XRD-2DSRM clearly revealed that the SiGe layer formed by this process exhibited much smaller mosaicity compared to those prepared by the Ge-condensation method. This work was partly supported by NEDO [1]. T. Tsuchiya et al., Materials Science and Engineering B88 360 (2002) [2]. N. Tsuchiya et al., Material Science in Semiconductor Processing, submitted.
as the elementary (2 x 1) structure, different types of step formations are observed and compared to experiments [5-7]. In a case, a well-defined (2 x 1) structure is observed after annealing at 300°C. The cleavage surface is defective before the step formation. Moreover, in several cleavage simulations, the cleavage path is bent from the (001) plane into the (111)-2x1 plane. This result implies the (relatively) stability of the (111)-2x1 cleavage mode. A common theoretical viewpoint among the above nanostructures is the competition of two anisotropic strain mechanisms; (i) strain due to the global (crack) shape and (ii) strain due to the local atomic or electronic structure. This implies that fabrication is the combination of silicon monoxide evaporation with the possibility of enhanced growth control. Full preparation; The current list of our works is seen in our web page: http://fujimac.t.u-tokyo.ac.jp/hoshi/ [5] Feenan and Scrogo. Phys. Rev. Lett. 59, 2173 (1987) [6] Tokunaga et al., J. Vac. Sci. Technol. B9, 598 (1991) [7] Ers et al., Ultramicroscopy 42-44, 619 (1992)

P7.10

Growth and Properties of Core/Shell Silicon Nanowires.

Florian M. Kolb, Herbert Hofmeister, Eckard Pippel, Margit Zacharias and Ulrich Gosele; MPI of Microstructure Physics, Halle (Saale), Germany.

Semiconductor nanowires are potential building blocks for future nanotechnological applications. A method for silicon nanowire fabrication is the combination of silicon monoxide vapor deposition with gold island formation on a silicon substrate [1]. Similar to the vapor-liquid-solid (VLS) mechanism, this method combines the simplicity of silicon monoxide evaporation with the possibility of enhanced growth control. The resulting wires have a core diameter of down to 10 nm. With this contribution we present several cleavage simulations of the growth of these nanowires and their structural properties. Post-treatment of the wires by etching and post-oxidation offers a way for further decreasing the size of the nanowires. As result we will present a model for the growth process as well as an experimentally supported explanation for nanowire diameter oscillations during the growth. The nanowires fabricated with this method consist of a crystalline silicon core and a thick amorphous oxide shell. Analyzing the oxide shell using electron energy-loss spectroscopy (EELS) including the energy-loss near-edge fine structure (ELNES) revealed that the shell consists of silicon dioxide without any silicon suboxides. The nanowires and the gold droplets on their tips were analyzed seperately using electron diffraction and high-resolution transmission electron microscopy (HRTEM). For size control we investigated the effect of gold colloid nanocrystals as starting points for the growth of the silicon/silicon dioxide nanowires. It will be demonstrated how the size of the gold is correlated to the thickness of the nanowires grown by our method. [1] F.M. Kolb, H. Hofmeister, R. Scholz, M. Zacharias, U. Gosele, D.D. Ma, S.-T. Lee, Journal of the Electrochemical Society, 151 (7) G472, (2004)

P7.11

Metal-Free Growth of Si Nanowires by Annealing SiOx (x<2) Films Deposited by PECVD, Xiaowei Wang, Jianguo Zhang and Qiming Wang, Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China.

The Si nanowire (SiNW) is an important material for nano-electronic and optoelectronic devices. Currently, SiNWs are usually fabricated with the catalysis of metals, most of which are deep level recombination centers in Si and can deteriorate the performance of the devices based on the Si nanowires fabricated. In this paper, we present a new SiNW growth method free from metal catalysis by high temperature annealing of SiOx (x<2) films deposited by plasma-enhanced chemical vapor deposition (PECVD). The influence of the stoichiometry (x value) and the thickness of SiOx films, the annealing temperature and the annealing atmosphere on the SiNW growth was studied in detail. The results indicated that the SiOx film with x equal to 1 was the most favorable stoichiometry for SiNWs growth after annealing at 1000-1100°C. Thinner SiOx films below 300 nm in thickness were easier for the growth of SiNWs at lower annealing temperatures. A relatively large N2 flow rate of greater than 10 sccm during the furnace annealing was of importance for the SiNW growth, and SiNWs could be sharpened and elongated with the aid of H2 in (2x1) diamond steps after annealing at 1100°C. Silicon micrometers in length can be fabricated in this way. The formation mechanism is also discussed and is likely to be related to oxide-assisted growth (OAG) mechanism, with SiOx films serving as the Si source. Silicon nanowires and furnace annealing processes are also compatible with the current Si CMOS technology, this metal-free SiNW growth method has promising applications in fabricating high quality Si nanodevices based on SiNWs.

F7.12


We report on a rich variety of nanostructures which can be synthesized by varying the pressure and temperature in a Vapor-Liquid-Solid epitaxy on Si, on their growth kinetics, and on the novel surface energy properties of these materials. In these studies the CVD growth of Si and Ge nanowires is seeded by metallic nanodots on (111) and (100) oriented Si. Experiments are carried out for diodes and system in a UVH system for pressures from 10-6 to 10-2 Torr and temperatures between 300 and 800°C. The growth kinetics and morphology are observed to depend strongly on pressure for Si, with the growth of layered heteropentasil islands at lower pressures and at higher pressures with a transition to rapid <111> axial nanowire growth with a growth rate that scales linearly with pressure. Growth kinetics are quantitatively compared with that for VLS growth and are contrasted to Si nanowire growth. We also report first measurements of the nucleation time for nanowire growth. Examples of the dramatic superhydrophobic and superhydrophilic behavior of functionalized Si nanowire surfaces will be presented. We combine monolayer surface chemistry with silicon nanowire substrates to create a lotus leaf like surface, and for the first time demonstrate the amplification of light-induced water contact angle switching. Measurements of the contact angle for water on both the smooth and nanostructured surfaces allow direct comparison of the effects of surface morphology on hydrophobicity. These results, based on a biomimetic approach to nanotechnology, have new implications for the design of microfluidic systems.

F7.14


Arrays of uniform, Si nanospikes and flat top nanopillars were fabricated using nanosphere lithography and subsequent plasma etching and high-resolution electron microscopy (HRTEM). For size control we investigated the effect of gold colloidal nanocrystals as starting points for the growth of the silicon/silicon dioxide nanowires. It will be demonstrated how the size of the gold is correlated to the thickness of the nanowires grown by our method. [1] F.M. Kolb, H. Hofmeister, R. Scholz, M. Zacharias, U. Gosele, D.D. Ma, S.-T. Lee, Journal of the Electrochemical Society, 151 (7) G472, (2004)

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in detail.

F7.15 Fabrication of a Regular Array of Atomic Silicon Wires on Silicon, Takaharu Sekiguchi, Shunjii Yoshida and Kohei M. Itoh, Department of Applied Physics and CREST-JST, Keio University, Yokohama, Japan.

In recent years nanotechnology towards realization of quantum information processing has been extensively studied. As a candidate for quantum computing, we present the so-called "atomic quantum computer" [1], which utilizes nuclear spins (I) of Si isotopes. We will use a vicinal surface of $^{28}$Si isotope (l=0) as a template for linear chains of $^{29}$Si (l=1/2). In the present study we report successful fabrication of atomic $^{29}$Si chains along a regular array of a uniform step structure on a vicinal $^{28}$Si(111) substrate. The experiments were performed in a UHV chamber, and the surface structure was observed by high resolution scanning tunneling microscopy. At first, we fabricated an array of atomic 7x7 steps on a Si(111) surface with about 8° miscut toward [1-1-2]. By modifying the thermal annealing process proposed by Viernet et al [2], the density of kinks smaller than 7x7 unit cell was reduced and the atomic structure of the step edges were unified. This step edge structure is classified as U(2,0) according to the lateral shift of the 7x7 structure on the lower terrace with respect to that on the adjacent upper terrace. While the step-parallel component of this shift was absent (0), the step-normal shift was (2a/3b) = 0.89 nm, where a = 0.33 nm is the distance between the adjacent [1-10] rows in the ideal 1x1 lattice and (2/3)b is the intrinsic shift due to (111) layer stacking. Indeed, a partial 7x7 structure of 2b width was observed just below the step edge and contained four adatoms in each unit cell. Furthermore, we deposited Si atoms on the surface with this uniform step structure from a Knudsen cell. By optimizing the deposition amount and the substrate temperature during the growth, a single-adatom-row growth was achieved up to the lower terrace. The single-adatom-row growth was allowed in the 2b wide region just below the step edge where there was no stacking fault. In contrast, such a growth was inhibited in the remaining terrace containing the stacking fault and the temperature was not high enough to relieve it. Excess Si deposition resulted in subsequent formation of ill-ordered 7x7 structures along the single adatom row. Above the optimal temperature highly-ordered 7x7 structure was formed along each step edge without the single adatom row, while below this temperature, Si clusters were formed just above the step edge. Details such as the structure model and the growth mechanism will be discussed in the symposium. [1] T.D. Laughlin et al., Phys. Rev. Lett. 89, 017901 (2002). [2] J. Viernet et al., Appl. Phys. Lett. 72, 548 (1998); J.-L. Liu et al., J. Appl. Phys. 84, 255 (1998). [3] W. Shimda and H. Tofchihara, Surf. Sci. 311, 107 (1994).

F7.16 Characterization of SiC Nanowire Grown by APCVD Using Single Precursors, Rho Dae Ho1,2, Kim Jae-Soo2, Byun Dong-Jin1, Yang Jae-Woong1, Lee Jae-Hoon1 and Kim Na-Ri3; 1Materials Science and Engineering, Korea University, Seoul, South Korea; 2Metal Processing Center, Korea Institute of Science and Technology, Seoul, South Korea; 3Advanced Materials Engineering, Daejin University, Pochon, South Korea.

Nanowires were studied as a candidate for vertical nanodevices in recent years, especially SiC nanowires due to their high carrier mobility and high thermal stability. SiC nanowire was grown on Si directly. Grown nanowires were thoroughly characterized by optical and electrical properties. Recent report of the SiC nanowires' optical properties shows much lower threshold voltages about 2.5 - 3.5 V/um. These results were lower than that of carbon nanotubes. Mo, Si and C. But most of SiC nanowire growth methods produce a particle like shape. To resolve this problem, CVD method was used. And growth process was improved using single precursors (HMDS, TMS and TPS) than other reports. By this growth, SiC nanowire was grown. Measured threshold voltage was about 2.5 - 3.5 V/um. These data were varied with kind of catalyst and growth conditions. High blue emission peak was observed in the grown SiC nanowires by PL measurements. Acknowledgments: This research was supported by a grant (code #: 04K1501-03110) from ‘Center for Nanostructured Materials Technology’ under ‘21st Century Frontier R&D Programs’ of the Ministry of Science and Technology, Korea.

F7.17 Growth and Characterization of SIOx Nanowires by VLS and SLS Growth Mechanism, Bho Dae Ho1,2, Kim Jae-Soo2, Byun Dong-Jin1, Yang Jae-Woong1, Lee Jae-Hoon1 and Kim Na-Ri3; 1Materials Science and Engineering, Korea University, Seoul, South Korea; 2Metal Processing Center, Korea Institute of Science and Technology, Seoul, South Korea; 3Advanced Materials Engineering, Daejin University, Pochon, South Korea.

CVD was used in this research. And growth temperature was lower by using SiOx nanowire. At first, ideal 1x1 lattice and uniform step structure from a Knudsen cell. By optimizing the deposition amount and the substrate temperature during the growth, a single-adatom-row growth was achieved up to the lower terrace. The single-adatom-row growth was allowed in the 2b wide region just below the step edge where there was no stacking fault. In contrast, such a growth was inhibited in the remaining terrace containing the stacking fault and the temperature was not high enough to relieve it. Excess Si deposition resulted in subsequent formation of ill-ordered 7x7 structures along the single adatom row. Above the optimal temperature highly-ordered 7x7 structure was formed along each step edge without the single adatom row, while below this temperature, Si clusters were formed just above the step edge. Details such as the structure model and the growth mechanism will be discussed in the symposium. [1] T.D. Laughlin et al., Phys. Rev. Lett. 89, 017901 (2002). [2] J. Viernet et al., Appl. Phys. Lett. 72, 548 (1998); J.-L. Liu et al., J. Appl. Phys. 84, 255 (1998). [3] W. Shimda and H. Tofchihara, Surf. Sci. 311, 107 (1994).

F7.18 Germanium Nanowires Growth via Vapor Transport, Yi Ma, Xiaocai Wang, Jianyu Huang, Dzehi Wang and Zhifen Ren; Physics, Boston College, Brighton, Massachusetts.

Germanium nanowires were synthesized from the mixture of germanium oxide and graphite powder with or without Au catalyst. EDS, SAED, SEM, TEM were used to characterize the structure of the germanium nanowires. When no catalyst was used, big wires were obtained with the diameter of around 180 nm. When Au catalyst was used, the diameter of the wire was modulated by the size of gold nanoparticles. We will also discuss the growth mechanism of the nanowires.

F7.19 Synthesis and Characterization of ZnS/Si Wire Heterostructures, Chunsheng Du and Ning Pan; University of California at Davis, Davis, California.

Semiconductor heterostructures with modulated composition enable the generation of devices with diverse functions. In this regard, the capability of heterostructures formation through carefully controlled interfacing in nanoscale building blocks with high surface area will be increasingly important in the assembly of electronic and photonic devices. Here we report the synthesis of silicon (Si) and zinc sulfide (ZnS) nanowire heterostructures via the solid-liquid-solid (SLS) and vapor-liquid-vapor (VLS) processes using cobalt as a metal catalyst. Si powder and ZnS powder were used as raw source materials for the growth of heterostructures. The fabrication process involved the growth of Si nanowires via VLS process followed by the growth of ZnS nanowire from the end of Si nanowire by way of a VLS process via thermal evaporation of ZnS powder in a quartz tube furnace at 10007 C, while hydrogen was introduced into the furnace at a flow rate of 50 sccm. The growth time was 15 min to 1 h. The heterostructures were thoroughly characterized by scanning electron microscopy (SEM) and transmission electron microscopy (TEM) (Philips CM 12). Electron microscope equipped with energy dispersive x-ray spectroscopy (EDS) system. Our synthesis of axial heterostructures, including heterojunctions between ZnS and Si within a single wire, indicates the general potential of axial heterostructures for the development of nanodevice devices. This method may be applicable to the preparation of other sulfide-silicon.
heterostructures or other zinc-blende semiconductors.

**F7.20** Optical Properties of Ge Nanowires Grown on Silicon (111) and (100) Substrates. Boris Kamenev1, Varun Sharma1, Ted I. Kamins2, R. Stanley Williams2 and Leonid Tsybeskov2; 1Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, New Jersey; 2Quantum Science Research, Hewlett-Packard Laboratories, Palo Alto, California.

We report Raman scattering and photoluminescence (PL) measurements in Ge nanowires (NWs) grown by chemical vapor deposition on silicon substrates with (100) and (111) crystallographic orientations. A sharp and narrow Raman peak at 380 inverse centimeters indicates the single-crystal quality of Ge NWs 40 nanometers in diameter and approximately a micrometer in length. The absence of Si-Ge vibrations in Raman spectra shows that SiGe interdiffusion is insignificant for most of the NW volume. Low temperature PL spectra and the PL intensity temperature dependence strongly indicates that the observed emission originates mostly at Ge NW/Si substrate interfaces, where Si-Ge intermixing has been detected. We found that such interfaces are formed differently for (111) and (100) oriented Si substrates. In this study, nanowires were strongly oriented (111) preferential growth direction of Ge NWs.

**F7.21** Carrier Transport in One-dimensional Ge Nanowire - Si Substrate Heterojunctions. Boris Kamenev1, Eunkyu K. Lee1, Pavel A. Forsh2, Ted I. Kamins2, R. Stanley Williams2 and Leonid Tsybeskov2; 1Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, New Jersey; 2Quantum Science Research, Hewlett-Packard Laboratories, Palo Alto, California.

We present detailed ac and dc measurements on electrical and photophysical properties of one-dimensional heterojunctions formed between VLS-grown Ge nanowires and crystalline Si substrates. We show that at the region of nanowire-substrate interfaces these junctions exhibit nearly ideal properties while at the nanowire end, where Au clusters are located, carrier transport is controlled by structural defects, most likely dislocations.

**F7.22** Generation of Silicon Nanowhiskers by Molecular Beam Epitaxy. Luis Schubert1,2,3, Nikolai D. Zakharov1, Gerhard Gerth1, Hartmut S. Leipner4, Peter Werner5 and Ulrich Goesele6; 1Max Planck Institute of Microstructure Physics, Halle, Germany; 2Department of Physics, Martin-Luther University, Halle, Germany.

Silicon nanowhiskers are frequently grown by chemical vapor deposition (CVD) and gas-source molecular beam epitaxy (GS-MBE). These techniques are using small droplets of metals, such as gold, as a seed for the nanowhisker growth. The silicon is preferentially incorporated via the liquid silicon-metal droplet, a mechanism referred to as the vapor-liquid-solid mechanism (VLS). At the present time, there is little information on the growth of Si nanowhiskers by molecular beam epitaxy (MBE). The purpose of this paper is to present our first results on a more detailed analysis of the MBE-specific VLS mechanism. All growth steps were performed in an ultra-high vacuum (UHV). The whiskers were generated as seeds, whose size (diameter: 50 nm to 150 nm) depends on the amount of deposited Au and the substrate temperature. During the subsequent Si deposition (substrate temperature between 400°C and 550°C), nanowhiskers were formed with a diameter ranging from 50 nm to 200 nm. The length (maximum 1 µm) depends on the substrate temperature and the size of the Au droplets. The relation between length and diameter of the nanowhiskers is opposite to what is reported in literature for growth via CVD. The experiments were discussed on the base of a model including not only the conventional VLS mechanism, but also a strong surface diffusion component.

**F7.23** Auger Electron Spectroscopy of Contacts to Si Nanowires. Bangshui Liu1, Soham Dey1, Theresa S. Mayer2, Joan M. Redwing1 and Suzanne E. Mohney1; 1Department of Materials Science and Engineering, The Pennsylvania State University, University Park, Pennsylvania; 2Department of Electrical Engineering, The Pennsylvania State University, University Park, Pennsylvania.

Silicon nanowires (SiNWs) have drawn considerable attention recently due to their potential applications in new electronic, photonic, and mechanical devices, as well as chemical and biological sensors. The development of low-resistance, stable ohmic contacts to these nanowires is necessary for optimal performance of some of these devices. In this study, a Physical Electronics Model 670 scanning Auger nanprobe is used to characterize the diffusion of metals along SiNWs before and after annealing. Special challenges are encountered in the small size of the nanostructure and the geometry of the samples. These challenges include shadowing, edge effects, and substrate backscattering effects, which are affected by beam energy and sample orientation. The effects are evaluated first and the integration is used to extract useful information from Auger electron spectroscopy of nanowires. Finally, the reactions between the contacts and nanowires are discussed in light of the changes in the contact resistance upon annealing, with special emphasis given to the contacts for which favorable annealing conditions have been identified for reduced contact resistance.

**F7.24** Formation of Hydrogen-Passivated Silicon Nanochains by Pulsed Laser Ablation without Thermal Annealing. Mitsuhiro Inada1, Riuoru Umezawa1, Shuichi Tanaka1, Shinro Mashiko1 and Akira Sugimura2; 1National Institute of Information and Communications Technology, Kobe, Japan; 2Department of Physics, Konan University, Kobe 658-8501, Japan.

We have formed silicon nanochains covered with hydrogen by pulsed laser ablation of silicon target in pure hydrogen gas without annealing process. When the hydrogen gas pressure was higher than 670 Pa, silicon nanowhiskers with 4-10 nm width and length of up to several microns were formed. Transmission electron microscopy shows the nanowhisker consists of many links of crystalline silicon nanoparticles. Micro-Raman spectra from the nanowhiskers show an evident downshift of silicon peak and asymmetric broadening. These results also indicate that the nanowhiskers have crystalline silicon core with amorphous shell. It is a particular attention that the silicon nanowhiskers have crystalline core without any intentionally annealing process. Fourier transform infrared absorption shows that hydrogen content in the silicon nanowhiskers is 10-30% with Si-H23 configurations. Since the nanowhisker has silicon core, Si-H bond is dominantly located on the surface of nanowhiskers. This suggests the surface of nanowhiskers is ideally passivated by hydrogen. In the micro-photoluminescence measurements, we observed bright visible luminescence at around 1.6 eV. This result suggests that crystalline structure and hydrogen-passivation suppress non-radiative recombination process and increase the PL intensity of nanowhiskers.

**F7.25** Growth Rate of Silicon Nanowires. Jun Kikkohno1, Yutaka Ohno2 and Seiji Takeda3; 1Department of Physics, Osaka University, Toyonaka, Osaka, Japan.

We have measured the growth rate of silicon nanowires (SiNWs) in the temperature range between 355 and 500°C. The SiNWs were grown by a vapor-liquid-solid (VLS) growth method using Au-Si liquid droplets as catalysts and monosilane (SiH4) as a vapor phase reactant, and were post-growth observed by means of transmission electron microscopy (TEM). The growth rate increases exponentially as the temperature increases. The physical meaning of this activation energy for the growth of SiNWs, which may be composed of an energy needed to remove Si atoms from a vapor-liquid interface to a liquid-solid interface and that for the decomposition of SiH4 will be discussed. It is also found that SiNWs grown at the temperatures higher than about 400°C are more straight: most SiNWs grown below 400°C are rather twisted. This can be accounted for by the growth rate of SiNWs. In addition, SiNWs with smaller diameters are likely to grow more rapidly. These basic data is useful to understand the initial stage of the growth of SiNWs.

**F7.26** Modification of nc-Si/SiO2 Nanostructures by Selective Laser Induced Heating. Boris Kamenev1, Haim Grebel1, Viktor Timoshenko2 and Leonid Tsybeskov2; 1Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, New Jersey; 2Physics Department, Moscow State University, Moscow, Russian Federation.

We report a modification of nc-Si/SiO2 nanostructures by selective laser induced heating. The nc-Si/SiO2 nanostructures were heated using a nanosecond laser pulse with energy density of 30-40 mJ/cm². This amorphization is found for structures with relatively thick SiO2 separating layers and, most likely, caused by the strain relaxation. The amorphization of the amorphous phase results in increasing of photoluminescence efficiency. The data indicate the presence of at least two luminescence origins in the nc-Si/SiO2 nanostructures.

**F7.27** Si nanocrystals in PECVD silicon oxides and comparison of its luminescence efficiency with implanted and annealed samples. Mariano Peralvarez1,2, M. Lopez1, R. Stanley Williams1 and Leonid Tsybeskov2; 1Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, New Jersey; 2Physics Department, Moscow State University, Moscow, Russian Federation.

We report a modification of nc-Si/SiO2 nanostructures by selective laser-induced heating of Si nanocrystals. Using Raman spectroscopy, we found amorphization of Si nanocrystals after irradiation by nanosecond laser pulse with energy density of 30-40 mJ/cm². This amorphization is found for structures with relatively thick SiO2 separating layers and, most likely, caused by the strain relaxation. The amorphization of the amorphous phase results in increasing of photoluminescence efficiency. The data indicate the presence of at least two luminescence origins in the nc-Si/SiO2 nanostructures.
Si nanocrystals (Si-nc) embedded in SiO2 present outstanding photo and electroluminescent emission in the visible and are the materials of choice for the realization of efficient light sources integrated with Si technology. Several Si compatible approaches have been used to synthesize Si-nc embedded in SiO2, being ion implantation one of the most frequently reported. Some authors have reported Si-nc formation from PECVD SiO2 still with the problem of Si excess and the detailed matrix composition -presence of N and H- affect the precipitation and growth of the Si-nc and the photoluminescence (PL) efficiency. We report in this work a thorough study on the structural properties and PL efficiencies of a series of Si-nc/SiO2 composites fabricated by this method in a wide range of Si excess up to 50 atomic percent (which corresponds to x in SiOx down to 0.5). For reference, the same study has been performed in Si-nc/SiO2 materials synthesized by ion implantation and annealing. The SiOx PECVD deposited samples have a thickness between 50 and 100 nm and the phase separation, precipitation and growth of the Si-nc have been achieved by high temperature annealing at 1250 degrees C. Refractive index and thickness have been measured by ellipsometry and correlated with compositional measurements. The detailed composition profile has been determined by XPS, SIMS and FTIR analyses. H has completely disappeared in annealed samples while the N concentration is found between 5 and 10%. EFTEM demonstrates that isolated Si-nc are formed for Si excess up to 20% while for higher Si concentration a continuous Si phase is observed. The PL efficiency in PECVD samples is maximized for a Si excess of 17% which is much lower than the maximum efficiency found in implanted samples for the 15% of Si excess. We have measured absorption cross-section and lifetimes of Si-nc in both deposited and implanted samples and have found that they depend only on Si excess in both samples which have undergone a complete phase separation. No dependence of PL efficiency has been found on the presence of N in the matrix. We will present a detailed study and modelization of PL emission as a function of pumping power in which we have taken into account excited state absorption and Auger quenching effects. We will also report at the conference the making and characterization of LEDs fabricated from deposited samples.

SESSION F8: Si Nanocrystals and Porous Si: Light-Emitting and Other Properties II

8:15 AM *F8.1 Electric Force Microscopy of Individually Charged Silicon Nanoparticles. Thierry Melin1, Heinrich Diesinger1, Dominique Deremos2, Thierry Baron2, Sophie Barbet3 and Didier Steivenard3;

1IEMN-CNRS UMR 8520, Dpt ISEN, Villeneuve d Ascq, France; 2LTM - CNRS UMR 5129, CEA, Leti DTS, Grenoble, France.


8:45 AM *F8.2 Silicon Nanocrystals: From Coulomb Blockade To Memory

Arrays, Rajesh A. Rao, Ramachandr Murudhir, Robert F. Steinle, Sherry Straub, Bruce Hradsky, Jane Yater, Steve Anderson, Erwin Prinz, Craig Swift, Tushar Merchant, Matt Stoker, Michael Sadd and Bruce E. White; APRDL, Technology Solutions Organization, Freescale Semiconductor, Inc., Austin, Texas.

Non-volatile memory devices using discrete charge storage nodes - such as silicon nanocrystals or traps in silicon nitride (SONOS) - offer potential to lower the operating voltages compared to continuous floating gate flash due to their immunity to charge loss via isolated channel tunneling in the tunnel oxides results in scaling and scaling of the charge storage size by up to 50% at the 90nm technology node. Furthermore, discrete charge storage memory devices can be integrated with high voltage periphery and logic devices using only 4 non-critical mask adds over conventional CMOS process flow. The superior Fowler-Nordheim tunneling erase characteristics of nanocrystal memory compared to SONOS permit HCI/FN operation capability at tunnel oxide thicknesses needed to mitigate read disturb, rendering Si nanocrystal embedded NOR type applications. New aspects in silicon nanocrystal memory technology include Coulomb blockade or charge confinement effects, atomic nucleus, and nanocrystal passivation to preserve them during subsequent processing and program/erase endurance characteristics. The paper will discuss the above aspects and focus on the effect of Coulomb blockade as nanocrystal size is reduced, which manifests in faster erase and larger gate disturb of unselected bits during program and read. 4Mb NOR memory arrays have been fabricated using 90nm CMOS technology. Excellent memory characteristics including tight VT distributions are obtained using a tunnel oxide thickness of 5nm and a 6V power supply.

9:15 AM *F8.3 Enhanced Silicon Nanocrystal Photoluminescence via Au Near-Field Energy Transfer Processes. Julie Suzanne Biceen, Isaac Garcia-Munoz, Nathan S. Lewis and Hatice Yuceer; IEMN-CNRS UMR 8520, Dpt ISEN, Villeneuve d Ascq, France; 2LTM - CNRS UMR 5129, CEA, Leti DTS, Grenoble, France; 3California Institute of Technology, Pasadena, California.

We report two approaches to increase the luminescence emission intensity from Si nanocrystals (nc-Si) under optical pumping via: 1) the use of nanostructured Au as a sensitizer for nc-Si emission, and 2) near-field coupling of nc-Si emission to localized surface plasmons on rough Au surfaces to increase the radiative emission rate relative to conventional nc-Si emission. We have observed a ten-fold enhancement in photoluminescence intensity from nc-Si coupled to Au nanostructures emitting at 1.7 eV. We also observe a decrease in the radiative lifetime, and we will present data showing this effect. The emission energy is unchanged during this enhancement process. By placing nc-Si embedded in silicon dioxide in proximity to a 100-nm thick nanoporous gold (npg) film with surface roughness and voids on the order of 10 nm, we have designed a system that takes advantage of both the enhanced absorption and the enhanced radiative rate. We will discuss our results in the context of models for energy transfer from nc-Si to localized plasmons in the npg film. Energy transfer from nc-Si to Au takes advantage of the large absorption cross-section (10-10 cm2 for Au vs. 10-3 cm2 for Si) to sensitize the nanocrystals, and we will present data showing the increase in absorption cross-section of nc-Si upon coupling to npg. Energy transfer from the nc-Si to the Au leads to an increase in the radiative emission rate, but does not quench PL as the rough surface of the npg film enables radiative emission from the metal. We will present data showing a decrease in lifetime, and support it with data showing that coupling to Au suppresses the saturation of PL intensity that otherwise occurs as pump power is increased. Since the efficiency of the near-field energy transfers, which are consistent with Förster (dipole-dipole) processes, depends on separation distance, we will report trends in PL intensity and lifetime upon systematic variations of the nc-Si/Au separation distance from 0.5 to 50 nm.

9:45 AM *F8.4 Coupling Si Quantum Dots to Surface Plasmons. Jerem Kalkman and Albert Polman; FOM-Institute AMOLF, Amsterdam, Netherlands.

We present a new way to enhance the effective emission rate and efficiency of Si quantum dots. The quantum dots are placed near a metal-dielectric interface and decay by the generation of surface plasmons. While this in itself constitutes a loss process, the plasmons can currently be coupled to the field of the quantum dot by focusing the electric field over a nanoscale length. The effective emission rate of the quantum dot-plasmon system is then determined by the sum of the quantum dot's intrinsic radiative rate and the plasmon coupling rate, and -as we will demonstrate- can thus be enhanced by several orders of magnitude. Surface plasmons are electromagnetic modes that propagate at the interface between a metal and a dielectric. When an excited Si quantum dot is placed close to such an interface, a near-field interaction between the quantum dot, dipole and the metal occurs leading to the excitation of a surface plasmon at the dipole's frequency. We describe this interaction
in terms of a semi-classical model, also taking into account distance-dependent variations in the local density of states and coupling to low-energy surface modes. The surface plasmon, propagating along the metal-dielectric interface, can subsequently be coupled out into the far field using a properly engineered grating that relaxes the momentum mismatch between the plasmon and a far-field photon. We show that in well-engineered structures the plasmon propagation losses are small and the efficiency of converting the plasmon to light can be close to unity. We provide direct experimental evidence of enhanced decay rates of Si quantum dots by energy transfer to surface plasmon polaritons at the metal-dielectric interface. Quantum dots in different depths using ion implantation, whereupon the sample was covered with an optically thick silver film. For quantum dots placed d=40 nm away from the SiO₂-Ag interface, a two-fold increase in decay rate is observed at A=750 nm, while no effect is observed at d=100 nm, both in agreement with our calculations. Strong stretched exponential decay characteristics are observed for quantum dots very close to the metal, also in agreement with our model that takes into account the surface and the depth dependent homogeneous broadenings. With our model supported by experiments, we performed calculations on systems that will show much larger enhancements e.g. using Au rather than Ag. Very large effects are expected for coupling to metal films with finite thickness, where complex plasmon coupling behavior between the two metallo-dielectric interfaces causes a 1000-fold enhanced coupling rate from Si quantum dots to the surface plasmons. By using this plasmon coupling concept, the saturation output power of LEDs based on Si quantum dots can be enhanced by orders of magnitude. Efficient coupling to surface plasmons also circumvents non-radiative quenching processes in Si quantum dots, thus leading to an enhanced effective emission quantum efficiency.

10:30 AM F8.5 Influence of the Strain, Surface Structure and Particle-Particle Interaction on the Occupied and Empty Density of States in Group-IV Nanostructures. Anthony van Buuren, Christoph Bostedt, Trevor Willey, R. W. Meulenberg and Losi Terminello, Chemistry and Materials Science Department, Lawrence Livermore National Laboratory, Livermore, California.

The observed size dependence in the optical properties in semiconductor quantum dots has been generally explained in terms of a quantum confinement argument. Until recently the effect of the strain, surface reconstruction and particle-particle interaction on the electronic and structural properties of quantum dots has been neglected due to the inherent difficulty in measuring these properties. Traditional analysis techniques of nanostructures, such as optical spectroscopy of the band gap transitions in semiconductors, provide useful, but lack surface and element specific information about the electronic structure. Synchrotron radiation has been used to study quantum dots possible, with superior potentials in achieving longer decoherence of quantum information processing, in hot-carrier solar cells, and for better control of the amplitude and phase of electron waves. In principle, one can construct semiconductor quasicrystals out of the IQDs. The icosahedral symmetry also provides a natural bridge between the IQDs and capped carbon nanotubes, from which one can build rich nano-architectures including perfect lattices. Experimental feasibility of fabricating the IQDs will also be discussed. [1] Zhao, Kim, Du, and Zhang, Phys. Rev. Lett. (in press).

11:15 AM F8.7 Electron Exchange Interaction in Electronically Confined Si Quantum Dots. Seungwon Lee¹, Paul von Allmen², Susan N. Coppersmith³ and Mark Friesen³; ¹Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, ²Department of Physics, University of Wisconsin, Madison, Wisconsin.

Electron exchange interactions in electronically confined Si quantum dots are modeled with an splusp* empirical tight-binding model. Previous work has shown that the exchange energies for electrons confined by P donors in bulk Si display a fast oscillatory behavior with respect to the inter-donor distance [1]. This result implies that P donors need to be position with atomic-scale precision in order to implement a Si:P based quantum computer architecture. In contrast to the Si:P architecture, electronically confined Si quantum dots show a simple exponential decay of the exchange energy with the increase of the inter-dot distance. The exponential behavior is attributed to tensile biaxial strain in the Si quantum well, which is epitaxially grown on top of a relaxed Si1-xSex layer. The tensile biaxial strain lifts the degeneracy of six valleys in the Si band structure, with the Z valley lower than the X and Y valays. The lowest electron wave function originates from the Z valley, and hence Bloch oscillations are present in the Z direction only. As a result, when the inter-dot distance changes along the X and Y directions, the exchange energy, which is determined by the overlap between the two electron wave functions, does not oscillate. [1] B. Koiller, X. Hu, and S. Das Sarma, Phys. Rev. Lett. 88, 276803 (2002).

11:30 AM F8.8 Quasiballistic Electron Emission from Planarized Nano-crystalline-Si Surface Emitting Devices. Yoshishige Tsujiya¹, Takuya Nakatsuka², Hiroshi Mizuta³, Shunri Oda¹,¹ Akira Kojima¹ and Nobuyoshi Koshiba¹; ¹Quantum Nanoelectronics Research Center, Tokyo Institute of Technology, Tokyo, Japan; ²Department of Physical Electronics, Tokyo Institute of Technology, Tokyo, Japan; ³Department of Electrical and Electronic Engineering, Tokyo University of Agriculture and Technology, Koganei, Japan.

Planar-type cold cathode surface emitting devices based on Si nano-fabrication technologies attract much attention because they have many advantages such as low vacuum requirement, toleration of low operation voltage, and easy fabrication. We have developed a cold cathode electron emitter based on nanocrystalline-Si (nc-Si) formed in the gas phase by VHF plasma decomposition of SiH₄, and its efficiency has been improved by the planarization of the nc-Si layer by the reflow technique [1]. However, electron transport through the nc-Si layer is still unclear. In this paper, the transport mechanism through the nc-Si layer in the nc-Si surface emitting devices is discussed based on the results of energy distribution of emitted electrons. Fabrication processes of the nc-Si-SiO₂-SiO₂ nano-architectures were as follows. The nc-Si dots were deposited onto the planarized Si substrates by VHF plasma process. Subsequent oxidation, phosphorus diffusion, and annealing processes were carried out. With these process a planarization of nc-Si layer was achieved. An Al ohmic electrode on the backside of the Si substrates and a 20 nm-thick Au film on front surface were formed by evaporation and then the diode structure is completed. Electron emission characteristics are measured in vacuum with a base pressure of 10⁻⁶ Torr. An electrode is grounded and a negative extraction voltage is applied to the Al electrode. A metal collector plate with the applied voltage of 100 V was placed in front of the surface of the sample, and a distance between the sample and the collector is about 5 mm.
Energy distribution of emitted electrons was measured using a conventional ac-retarding-field analyzer [2]. The emission current was observed using external voltage at 5 V and when 5 V was applied rapidly. A pulse period of 1 s for the 5 V was applied, and the maximum number of electrons is higher than the case of Maxwellian. Similar results were obtained in the porous Si diode [2], and according to Ref. [2], this behavior strongly suggests that electrons are emitted quasi-ballistically from the device. The energy that provides the planarized nc-Si layer play an important role in this high efficiency cold cathode emitter. [K.Nishiguchi, X.Zhao, S.Katsuki, J.Appl. Phys. 92 (2002) 2757, T.Komoda, Y.Shibayama, and N.Koshida, J.Vac.Sci. Technol. B 17, (1999) 1776].

Due to the complete carrier depletion associated with strong quantum confinement, both the thermal conductivity and heat capacity per unit volume of nanocrystalline porous silicon (nc-PS) are extremely low in comparison to those of single-crystalline silicon (c-Si). Previously [1], we reported this high contrast of thermal properties makes it possible to use nc-PS device as a thermally induced ultrasonic emitter (TUE) by efficient heat transfer at the device surface without any mechanical vibrations. We now report detailed experimental study for intensifying the sound pressure output by the control of nc-PS structure and driving mode. As the sound pressure is proportional to input power, a TUE device can be driven at high power output by a TEM device. To obtain a large acoustic output, major limiting factors for the electrical input power need to be clarified. Taking into account that the key component of the device is a patterned thin metal electrode deposited onto the nc-PS surface, we can assume that the most important determining factor for a maximum electrical input power is a mechanical stress at the interface induced by a rapid interfacial temperature raise rather than an electronic heating. In a fundamental study, the thermal conductivity and heat capacity per unit volume of nc-PS layer are significantly increased with decreasing its thickness. The planarized nc-Si layer play an important role in this high efficiency cold cathode emitter.

Semiconductor nanowires are versatile building blocks for fundamental studies in nanoscience, and have the potential to open up many exciting opportunities in nanoelectronics and nanophotonics in the future. Yet to push these fundamental and application areas forward requires increasing control of, and more generally modulation of the dopant within nanowire structures. To this end we describe the first monocrystalline synthesis of modulation-doped silicon nanowires. These nanowires were fabricated using nanocrystals-catalyzed vapor-liquid-solid growth process, where micro-Raman measurements. The slight downshift of the optical phonon and the peak broadening is much more dependent on the size and period of the differentially doped regions. In addition, two applications of these new nanostructures will be demonstrated. First, a lithography approach for addressing based on modulation doped silicon nanowire field-effect transistor arrays has been developed, and results for the assembly and demonstration of a 2x2 address decoder circuits will be discussed. Second, low temperature transport studies of modulation doped silicon nanowire, where modulation doping is used to define potential barriers, will be discussed. Significantly, these investigations show coulomb blockade and single electron tunneling behavior with quantum structure defined by modulation doped barriers during synthesis. Prospects and future directions will be discussed.

2-15 PM F9.3
Size Control and Phonon Confinement of Silicon Nanowires Synthesized by Laser Ablation. Nobuki Fujita, Takashi Oshima, Kouichi Murakami, Institute of Applied Physics, University of Tsukuba, Tsukuba, Japan. The size control of SiNWs has not yet been investigated in the former method. In order to achieve the size control of SiNWs for laser absorption method, we have synthesized SiNWs under various conditions and investigated the dependence on the condition of catalyst, the laser power, the gas phase temperature and the gas phase temperature using a frequency-doubled Nd:YAG laser. SiNWs were synthesized by laser ablation of a target which was placed in a quartz tube heated at 1000-1200°C in a flowing Ar gas. The diameter of SiNWs was found to significantly depend on above-mentioned parameters, i.e., it decreased with decreasing them. Thus, it is found that the diameter of SiNWs can be controlled by the synthesis parameters even for laser ablation method. Furthermore, the effect of phonon confinement depending on the diameter of SiNWs was investigated by micro-Raman measurements. The right shift of the optical phonon and asymmetric broadening were observed in the Raman spectra for SiNWs. The Si optical phonon peak shifted towards lower wavenumber with the decrease in diameter of the SiNWs. The relation between the shift of the optical phonon peak and the diameter of SiNWs was in agreement with the phonon confinement model. The degree of the shift of the optical phonon and the peak broadening is much more dependent on the size of SiNWs with increasing excitation power, which is due to local thermal effects. These results indicate that the most important determining factor for a maximum electrical input power is a mechanical stress at the interface induced by a rapid interfacial temperature raise rather than an electronic heating. In a fundamental study, the thermal conductivity and heat capacity per unit volume of nc-PS layer are significantly increased with decreasing its thickness. The planarized nc-Si layer play an important role in this high efficiency cold cathode emitter.
heating. This is caused by the difference in the thermal conductivity among SiNWs with different diameters. Hence, it is found that the effect of local heating gives useful information about SiNWs with different diameters. Electron spin measurements and photoluminescence measurements are in now progress to investigate doping effects of P donor in one-dimensional SiNWs.

2:30 PM F9.4

Self organized Ge nanostuctures on high index Si substrates have been the subject of intense research because of their promise for novel devices. We have grown Ge layers on Si(124) surfaces, which upon annealing form a surface composed of alternating (113) and (157) facets. This faceting behavior results in an extended and uniform hill-and-valley structure along [210], providing a natural template for nanowire formation. Ge layers were grown at 600 °C by gas-source molecular beam epitaxy (GS-MBE). Surface and cross-sectional morphologies were observed by atomic force microscopy and transmission electron microscopy. Average film thickness of Ge layers was measured by Rutherford backscattering spectroscopy. Initial growth of Ge is faster on (113) resulting in an asymmetric cross-sectional geometry due to differences in the interface energy between Ge and Si on two facets. At a Ge thickness of 8.7 monolayers (MLs), we observe a well-ordered array of Ge nanowires which are nearly symmetric cross section. The Ge nanowires are typically 40 nm wide, 7 nm high, and 1 µm in length, with a lateral period of 80 nm. MLs grown on Ge wires started to open irregularly. The growth rate of Ge on Si(124) was 4.3 times slower than that on Si(001) substrates at 600 °C. Nanowire-related photoluminescence peaks were observed at around 0.8 eV for Si-capped samples. Morphological and nanowire-related photoluminescence will be discussed along with observed photoluminescence.

2:45 PM F9.5
Complex Diameter Modulations in Silicon Carbide Nanowire Growth. Hideo Kohno, Hitode Yoshida and Seiji Takeda. Physics, Osaka University, Toyonaka, Osaka, Japan.

Some of semiconductor nanowires grown via self-organized processes exhibit diameter modulations. Not only periodic, but also non-periodic complex modulations have been observed. Nevertheless, such complex diameter modulations have never been investigated from the viewpoint of random walk and fractality so far. In this study we fabricated SiC nanowires with non-periodic diameter modulation and investigated the modulations in terms of scaling. SiC nanowires were grown by heating a Si substrate on which Au of 7.5 nm thick was deposited and a SiC powder in an evacuated silica container at 1200 °C for 2 hours. Numerous SiC nanowires with diameters of several tens of nanometer were grown on the Si substrate. By processing transmission electron microscopy (TEM) images of the SiC nanowires, the digitized diameter data were obtained. It was found that the increments of the diameter modulations were power-law distributed. This means that the modulations are not Brownian motion. By calculating the height-height correlation functions of the modulations, we found multifractality in the modulations. We note that experimental observation of multifractality in actual physical systems is very rare. Furthermore, it is interesting that such complex fractality appears in nanoscale scale. The growth mechanism and degree of determinism will be also discussed.

3:15 PM F9.6

Nanowires are of both fundamental and technological interest. They represent the critical components in the potential nanoscale electronic and photonic device applications. In this regard, heterojunction and superlattice nanowires are especially important. In this talk, we will present our recent work on the growth of these semiconductor nanowires and superlattice nanowires. Their precise size, position and orientational control of these nanowires will be discussed. We will then discuss the interesting thermoelastic properties of these Si/Ge nanowires and their relationship with the phonon confinement.

3:45 PM F9.7
Quantum Confinement and the Vibrational and Electronic Properties of Group IV and III-V Nanowires. Xinyuan Zhao, Li Yang, C. M. Wei and Mei Yin. School of Physics, Georgia Institute of Technology, Atlanta, Georgia; 2Institute of Physics, Academia Sinica, Taipei, Taiwan.

We have investigated the structural, electronic, vibrational, and optical properties of hydrogen-passivated silicon nanowires along [110] and [111] directions with diameter d up to 4.2 nm using first-principles density-functional theory. Information about SiNWs with different diameters. Electron spin measurements and photoluminescence measurements are in now progress to investigate doping effects of P donor in one-dimensional SiNWs.

4:00 PM F9.8
Coherent Single Charge Transport in Molecular-Scale Silicon Nanowire Transistors. Zhaohui Zhong, Ying Fang, Wei Lu and Charles M. Lieber. 1Department of Chemistry and Chemical Biology, Harvard University, Cambridge, Massachusetts; 2Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts.

We have investigated the low-temperature electrical transport properties of single-crystal silicon nanowires with diameters as small as several nanometers. Coulomb blockade oscillations are observed with a periodic addition of charge over a large temperature range. Analysis of data recorded on nanowire devices with varying source-drain separations suggests that nanowires behave as single quantum dots for lengths up to several hundred nanometers. Detailed studies of the conductance vs. source-drain and gate voltages provided evidence for resonant tunneling through individual quantized energy levels of the molecular scale silicon nanowires. These results differ from those obtained for nanofabricated planar silicon devices, which show localization on much shorter length scales. This is caused by the difference in the thermal conductivity among SiNWs with different diameters. Hence, it is found that the effect of local heating gives useful information about SiNWs with different diameters. Electron spin measurements and photoluminescence measurements are in now progress to investigate doping effects of P donor in one-dimensional SiNWs.

4:15 PM F9.9

One-dimensional nanostructures such as silicon nanowires (SiNWs) are promising materials for nano-scale sensors and photo-detectors. Moreover, the electrical and optoelectronic properties of silicon nanowires (SiNWs) can be tailored by quantum confinements for diameters of order 5nm or less. In this work, we studied the electrical transport properties of SiNWs grown by Fe-catalyzed pulsed laser vaporization (R. J. Barsotti, J. E. Fischer, C. M. Lieber, C. K. W. Au and P. C. Ecklund, Appl. Phys. Letters 81, 2866, 2002). Previous AFM and TEM studies showed that the average diameter is 7 nm including 1-2 nm native oxide. E-beam lithography was used to make 2 and 4 terminal devices with back gate, and gold was used as electrodes to give low contact resistance. As-grown devices showed p-type behavior with high resistivity. To modify conductivity and majority carrier type, spin-on glass or FIH (focused ion beam) were used to dope with phosphorous or gallium respectively. I-V and gate response were compared before and after doping; with P-glass we found that the FET behavior changed from p- to n-type. Furthermore, photoresonse of 2-terminal devices was investigated under UV illumination using a low pressure mercury pencil lamp with strong 254 nm emission and 2 mW/cm² power. We found that the electrical properties of SiNW devices are very sensitive to UV. The conductance increased significantly when SiNW devices were exposed to UV, much more strongly than with room light or 0.5 mW HeNe laser. The possible mechanisms will be discussed.

4:30 PM F9.10
Fabrication and Electrical Characterization of Silicon Nanowire Arrays. Sarah M. Ditto, Ahmad Mohammad, Kok-Keong Low, Suzanne E. Moloney and Joan M. Redwing. Department of Materials Science and Engineering. Materials Research Institute, Penn State University, University Park, Pennsylvania.

Resistivity measurements of individual nanowires are challenging, requiring techniques to assemble the nanowires and lithographically define electrical contacts at each end. Furthermore, contact resistance often dominates nanowire resistance measurements carried out using a simple two-point geometry. In this study, resistivity measurements were carried out on high-density vertical arrays of boron-doped silicon
nanowires (SiNWs) synthesized by vapor-liquid-solid growth within the pores of unidoped alumina membranes. The membrane provides a support structure for the SiNWs and acts as an insulating layer to passivate the formation of electrical contacts via the top and bottom membrane surfaces. The alumina membranes used in this study were nominally 0.6 μm thick with 200 nm diameter pores. To prepare the nanowire structures, a thin layer of silver was initially sputtered on the back-side of the membrane followed by sequential electrodeposition of 5 μm of silver, 28-42 μm of cobalt and 0.25 μm of gold within the pores. Vapor-liquid-solid growth of SiNWs within the pores was performed in an atmosphere of 5% H2 and trimethylboron (TMB) as the silicon and boron-dopant sources, respectively. Cobalt silicide, which forms during nanowire growth at the cobalt-silicon interface served as the back-side contact to the nanowires. Circular Al dots, deposited by e-beam evaporation, were used to form top-side electrical contacts to the nanowire arrays. For measurements of nanowire resistivity and contact resistance, a series of samples were prepared in which the length of the SiNW was varied from 12 to 27 μm using a constant gas flow of 5% H2 and 0.5% SiH4. Preliminary measurements yield an average resistivity of 35 ± 6.14 Ω cm for the boron-doped SiNWs measured using this technique. The effect of dopant concentration on nanowire resistivity will also be reported.

F10.1 Nano-Bridging: An Effective Solution to Interconnecting Nano-Scale Devices. M. Safi Islam1, 2, Shashank Sharma1, 2, Ted I. Kamins1 and R. Stanley Williams1, 2, 1Quantum Science Research, Hewlett-Packard Laboratories, Palo Alto, California; 2Electrical and Computer Engineering, University of California, Davis, California.

Interconnecting nanoscale devices made of one dimensional nanowires (NWs) with current densities and switching challenges since NWs were first contemplated as device components. The research-based approach of sequentially connecting electrodes to individual NWs has contributed to understanding the characteristics of the NWs and exploring novel device applications, but provides no path to mass-fabrication nor to circuit integration. A method for high density integration along with a massively parallel, self-assembly technique for interconnecting these building blocks of nano-electronics is critical for practical application of NWs. We report a novel technique of growing a high density of highly oriented interlaced silicon NWs between two electrically isolated Si electrodes defined by conventional optical lithography. A metal-catalyzed chemical vapor deposition (CVD) process was used to grow NWs and form robust "nano-bridges" on a silicon-on-insulator (SOI) substrate. Current-voltage measurements of p-type boron-doped NWs demonstrate highly linear I-V characteristics, confirming excellent ohmic contacts for suitably doped nanowires. An approximate correlation between the resistivity and the dopant gas flow has also been observed. Our VLSI compatible, self-assembly technique of connecting NWs between two electrodes needs only relatively coarse lithography and offers the high surface-to-volume ratio needed for nanoelectronic applications. This novel bridging technique has the potential for solving the long-standing issue of interconnecting nanoscale devices in many material systems.

F10.2 Hydrogen Passivation of Er and Si Nanocrystallites in Er-doped SiO2 - Increase in Photoluminescence, Nace Fulata1, 2, Changqing Li1, Hiroshi Uematsu1, Takamichi Aral1, Tetsuya Maekam1 and Kouchi Murakami1, 2, 1Institute of Applied Physics, University of Tsukuba, Tsukuba, Japan; 2Special Research Project on Nanoscience, University of Tsukuba, Tsukuba, Japan.

Hydrogen passivation effect of the photoluminescence (PL) from Er ions and Si nanocrystallites (nc-Si) has been investigated in Er-doped SiO2. We show the PL at RT from Er ions in nc-Si. Enhanced PL from Er ions in the presence of nc-Si is due to the intermixing of Er ions with nc-Si which act as nonradiative recombination centers. The crystallinity of nc-Si is important to further enhance the efficiency of the energy transfer from nc-Si to Er ions since residual defects at the interface between nc-Si and the surrounding SiO2 and in the nc-Si act as nonradiative recombination centers, resulting in quenching the PL of both the Er and nc-Si. In order to passivate the residual defects, hydrogen gas treatments were done at 300-550°C for Er-doped SiO2 films with nc-Si fabricated by laser ablation. Enhancement of PL was successfully obtained for Er ions by hydrogen gas treatment. The PL intensity of Er ions in as-grown nc-Si increased by a factor of 2-3, respectively, depending on the hydrogenation conditions. Electron spin resonance (ESR) measurements showed a decrease in residual defects performed by hydrogen gas treatment. Based on g-factors of the ESR signal, the temperature dependence of passivation and dissociation of the defects, the defects probably exist at the interface between nc-Si and the surrounding SiO2, namely, P3 type defects. These results strongly indicate that the optical excitation energy of nc-Si is more effectively transferred to Er ions by hydrogen passivation of P3 type defects which act as nonradiative recombination centers.

F10.3 Characterization and Modelling of the Emission at 1540 nm from Silicate Glasses Co-doped with Si and Er Ions, Yousef Lesbour1, Paolo Pellegrino1, Jose Moreno1, Cristina Garcia1, Joan Ramon Morante1, Blas Garrido2 and Michel Frassoni2, 1Electronics, University of Barcelona, Barcelona, Spain; 2Fontainebleau Research Centre, Corning S.A., Avon, France.

We have characterized and modelled the mechanism of energy transfer from Si nanoparticles to Er, in different silicate glasses, namely soda-lime and aluminium silicates, in comparison with pure silica. The interest in such composite glasses is their wide optical bandwidth at 1540 nm and large Er solubility. By means of ion implantation and thermal treatment a set of glasses with 12% Er at 500°C were obtained. From a multi-implantation scheme we have prepared a 380 nm thick glass layer with a uniform Si excess (5% or 15% atomic excess) and an Er-rich distribution. Several Er doses were chosen so that the resulting Er peak concentration is located at a distance of up to 6×1019 cm-3. Fused silica wafers implanted in the same conditions were used as a reference material in order to compare the different efficiency and mechanisms of Er emission as the host silicate is changed. Systematic photoluminescence (PL) measurements (both for
Luminescence of Rare Earth Doped Si/Al/SiO\textsubscript{2} Co-sputtered Films. Luis F. Fonseca, Carlos Rizzo, Oscar Resto and S. Zvi Weiss; Physics, University of Puerto Rico, San Juan, Puerto Rico.

Er\textsuperscript{3+} and Nd\textsuperscript{3+} doped Si/Al/SiO\textsubscript{2} thin films have been prepared by rf co-sputtering. Some of these films were annealed at 700°C. Erbium doped Si/Al/SiO\textsubscript{2} films were prepared with different configurations: one configuration with a large quantity of Al and a second configuration with a smaller quantity of Al. The configuration with large quantity of Al shows a diminished luminescence at 1.53 μm, but this emission is increased by substrate heating. The configuration with smaller quantity of Al shows emission at 1.53 μm similar in intensity to the Er-doped Si/SiO\textsubscript{2} film. The spectral shape of the 1\textsubscript{5}D\textsubscript{2} → 1\textsubscript{5}I\textsubscript{7/2} emission is broader than for an analogous Er\textsuperscript{3+} doped Si/Al/SiO\textsubscript{2} film with a smaller quantity of Al due to the configuration of the absorbing Si/SiO\textsubscript{2} film. Erbium clusters are formed in Si/SiO\textsubscript{2} films and changes the spectral shape of the 1\textsubscript{5}D\textsubscript{2} → 1\textsubscript{5}I\textsubscript{7/2} emission with respect to the Nd\textsuperscript{3+} doped Si/SiO\textsubscript{2} films.

Optical activation of Erbium by Si nanowires using sol-gel derived Er-doped silica. Kiseok Suh', Jung H. Shin', Oun-Ho Park2, Byeong-Soo Bae3, Heon-Jin Choi3 and Jung-Chul Lee3;

Efficient Si-based light emitting material has been attracting much interest because of its potential application in photonics with Si technology. In particular, Er-doping of Si material has great importance due to their Er\textsuperscript{3+} intra-4f emission at 1.54 μm, a standard wavelength for telecommunications. Er-doped Si light emitting diodes (LED) operated at room temperature were demonstrated with good electrical properties. However, the luminescence efficiencies were quite poor due to their intrinsic Auger and temperature quenching of Er\textsuperscript{3+} luminescence. On the other hand, excellent optical properties were obtained by using silicon-rich-silicon-oxide (SiRSO), which consists of nanocluster Si (nc-Si) embedded inside an SiO\textsubscript{2} matrix. Although optical gain as well as efficient LED have been demonstrated, SiO\textsubscript{2} matrix makes the size and shape of the Si clusters difficult in requirement high voltages or thin SiRSO layers to operate LEDs. Such problems may be solved by using Si nanowires (Si-NWs) instead. We report in the results of such optical activation of Si-NWs using sol-gel derived Er-doped silica. Silicon nanowires (Si-NWs) were grown by typical VLS method using SiC\textsubscript{4} as a source gas. The diameter of Si-NWs is about 100nm and the length is 10μm. Er doped silica film was spin coated on Si-NWs. The starting solution was prepared by hydrolyzing tetraethoxysilane (TEOS) in 0.05 M HCl aqueous solution with ethanol as a cosolvent and adding the ErCl\textsubscript{3} \textsubscript{6}H\textsubscript{2}O to the solution. The mixture was then stirred at RT for 1 day and spin coated on Si-NWs and annealed at 450°C for 1h, 500°C for 1min in a flowing N\textsubscript{2}/O\textsubscript{2} environment for comparison. The spin-coated spin-coated silica film was coated on pure Si wafer without Si-NWs. We measured the Er\textsuperscript{3+} photoluminescence (PL) properties of Er-doped silica with Si-NWs and pure Er-doped silica. The PL intensity of the pure Er-doped silica pumped with 473 nm laser was negligible since the photoluminescence cannot excite the Er\textsuperscript{3+} ions resonantly. However, that of the Er-doped silica with Si-NWs pumped with the wavelength of 473 nm is enhanced by an order of magnitude. The enhanced PL is caused by a generated carrier in Si-NWs which can transfer their energy to Er\textsuperscript{3+}. Also, the temperature dependence of the PL and Er\textsuperscript{3+} lifetime (6.9 msec at RT) of Er-doped silica with Si-NWs shows complete suppression of thermal quenching which means good luminescence efficiency comparable to pure Er-doped silica. The electronic devices using Si-NWs allow us to apply operating voltages of less than 5V were demonstrated already. Therefore, easy current injection and efficient Er\textsuperscript{3+} luminescence can be acquired by sol-gel derived Er-doped silica with Si-NWs.
near-infrared spectral region where a narrow line due to radiative 
relaxation of the lowest excited singlet state to the ground triplet 
state of oxygen is detected. However, because of the 
restriction of spin and angular momentum conservation rules, the 
oscillator strength of the transition is extremely small; the intrinsic 
lifetime of the state is very long (2.7×10^10 s) resulting in very weak PL 
intensity. Therefore, it was so far detected only at very low 
temperatures when oxygen molecules are condensed on the surface of 
Si nanocrystals. Although the intrinsic lifetime is extremely long, 
intermolecular interactions lead to an enhancement of the transition 
rate. The radiative transition rate is three to four orders of magnitude 
larger in solution than in diluted gas phase. However, in most 
solvents, deactivation of O_2^· is radiationless by collisional 
electronic to vibrational energy transfer from O_2^· to a solvent molecule. 

Therefore, to obtain luminescence, a solvent consisting of poor quenchers should be chosen. The second important requirement 
on the solvent is that it should not quench luminescence of Si 
nanocrystals. As a solvent which satisfies these requirements, we 
employed hexafluorobenzene (C_6F_6). The singlet oxygen lifetime 
in the solution is about 25 msec, which is about three orders of 
magnitude longer than that in benzene (C_6H_6). In this work, we 
study PL from porous Si powder dispersed in C_6F_6. From the PL 
study, we demonstrate that singlet oxygen can be generated by the 
energy transfer from Si nanocrystals at room temperature.

**F10.10** 
Control of Photoluminescence Properties of Si Nanocrystals by Simultaneously Doping n and p Type Impurities. 
Minoru Fujii, Yasuhiro Yanaguchi, Keiichii Ninomiya and Shinji Hayashi; Department of Electronic & Electronics Engineering, Kobe University, Kobe, Japan.

Si nanocrystals (nc-Si) show strong luminescence in the visible range. The luminescence is considered to arise from the recombination of excitons near the red bandgap of nc-Si. The luminescence property is expected to be modified by controlling impurities in nc-Si. However, shallow impurity doping in nc-Si results in radiationless Auger recombination, in which the energy released by the recombination of an exciton is consumed by giving kinetic energy to an electron (hole) supplied by doping. The Auger recombination could be avoided if isoelectronic impurities are doped or carriers in nc-Si are perfectly compensated by simultaneously doping n and p type impurities. In nc-Si, an exciton is confined in a space comparable to or smaller than the Bohr radius, and the wavelength of excitons as well as shallow impurities are extended in a whole nanocrystal. If for example one P atom and one B atom are doped simultaneously in a nanocrystal a few nanometer in diameter, it could be treated as a perfectly compensated single system with no excess carriers, and thus the exciton could enjoy the enhancement of oscillator strength due to further localization by impurity doping without being afraid of the Auger recombination. Therefore, impurity control of nc-Si may add new optical properties on nc-Si which can not be realized by pure nc-Si. In this work, we have prepared B and/or P doped nc-Si embedded in glasses by co-rolling and/or co-precipitation in a wide range, and studied the PL properties. We will demonstrate that proper control of shallow impurities allows us to extend the tunable range of luminescence energy at room temperature below the bulk bandgap (till near-infrared luminescence below 1.2 eV).

The near-infrared luminescence at room temperature may open up new application of nc-Si based materials on an optical telecommunications field.

**F10.11** 
Pump-probe experiments on low loss silica waveguides containing Si nanocrystals. Daniel Navarro1, Nicolo Daludo1, Mirko Melchiorri2, Lorenzo Paolin3, Cristiana Garcia1, Paolo Pelleg fifino1, Eila Garrido1, J.R. Morante1, F. Schich1 and G. Sarrabayrouse3. 
1Physics, University of Trento, Povo (Trento), Italy; 2Electronica, Universitat de Barcelona, Barcelona, Spain; 3Laboratory for Analysis and Architecture of Systems of C.N.R.S., Toulouse, France.

Rib-loaded silica waveguides containing Si nanocrystals were grown by quadruple implantation of Si ions into a 2 μm-thick thermally-grown SO_2 layer. The resulting rib-loaded waveguides active region was about 300 nm, with Si excess ranging from 7% to 15% (determined by X-ray photoelectron spectroscopy). Complete phase separation and nanocrystal formation was assured by annealing at 1100 °C, and studied by means of optical tools such as Raman, optical absorption and luminescence. The rib-loaded structure of the waveguide was fabricated by photolithographic and reactive ion etching processes, with patterned rib widths ranging from 1 to 6 μm. Efficient light propagation was observed when end-fire coupling a probe signal both at 633 nm and 780 nm into the waveguides, with attenuation losses as low as 11 dB/cm in the red. An increase of losses has been observed and explained as a function of the rib width and the mechanism involved in the light coupling and absorption has been evaluated and discussed. Pump and probe experiments under CW and time resolved conditions at 780 nm are underway to look for optical gain in these structures. The results of the experiments will be presented and discussed at the conference.

**F10.12** 
Multi-color Luminescence from nanocrystalline silicon. Hiroshi Kimura1, Katsue Sato1, Kenji Hirakuri1, Mitsuwa Iwase1 and Tomio Izumi2. 
1Electronic and Computer Engineering, Tokyo Denki University, Saitama, Japan; 2Electronics, Tokai University, Hiratsuka, Kanagawa, Japan.

The nanocrystalline silicon (nc-Si) is extremely attractive material for luminescent color. Luminescent color from the nc-Si shifts from red light to blue light by varying the size. We previously studied that the size was dependent on quantum yield of Si atoms introduced into amorphous SiO_x (a-SiO_x) film. In this study, we report the correlation between the luminescent color and the Si concentration in the a-SiO_x film. The a-SiO_x film including the Si atoms was prepared by sputtering method. The Si concentration of the samples was varied by changing the sputtering condition. The nc-Si was formed by the coagulation of Si atoms at annealing temperature of about 1000 °C. The Si concentration and the luminescent properties were estimated by using X-ray photoelectron spectroscopy (XPS), scanning electron microscopy (SEM), and photoluminescence (PL) measurements. Red luminescence was obtained from the nc-Si formed at the Si concentration of 9%. When the Si concentration was decreased from 9% to 2%, the luminescent color blue-shifted from red to blue light, because the decrease of the Si concentration leads to the reduction of the size. Moreover, the intensity of their luminescence was very strong.

**F10.13** 
Improvement of Operating Voltage and Luminescent Properties in Nanocrystalline Silicon Electroluminescent Device. Katsuke Sato1, Kenji Hirakuri1, Mitsuwa Iwase1 and Tomio Izumi2. 
1Dept. of Electronic and Computer Engineering, Tokyo Denki University, Saitama, Japan; 2Dept. of Applied Science, Tokai University, Hiratsuka, Kanagawa, Japan; 3Dept. of Materials Science, Tokai University, Hiratsuka, Japan; 4Dept. of Electronics, Tokai University, Hiratsuka, Japan.

Nanocrystalline silicon (nc-Si) is useful candidate materials for development of new flat panel displays including electroluminescent (EL) display and field emission display. However, the EL device using nc-Si has a poor performance under luminance and operating voltage. In this paper, we fabricated the EL device using hydrofluoric acid (HF) treated nc-Si to realize high brightness and low operating voltage. Moreover, we report luminescence and electrical properties from the EL device. The luminescent layer was prepared on p-type Si wafer. The nc-Si, which used for the luminescent layer, was formed in a silicon dioxide (SiO_2) layer by co-sputtering of Si/SiO_2 targets and subsequently annealing at high temperature. Therefore, the EL device using nc-Si with the SiO_2 layer showed luminescence with a peak of 650 nm by applying the operating voltage above 5 V. When the SiO_2 layer in the EL device was removed by the HF treatment, the operating voltage decreased from 5.0 V to 2.5 V. Moreover, the luminescence of the EL device was also increased more than one order of magnitude by the HF treatment, because the carrier was efficiently injected into the nc-Si by the removal of SiO_2 layer. The red luminescence from the EL device could be seen with naked eye under illumination at the operating voltage of 3.0 V.
electron diffraction (TED) data is consistent with the formation of c-Si QDs in silicon nitride matrix. Especially, the crystalline plane of the Si QDs was well aligned, suggesting an exact crystallinity of Si QDs in silicon nitride matrix. This result suggests that the size of c-Si QDs can be controlled in a silicon nitride film using PECVD without post annealing. An effective mass theory with an adjustable potential barrier model predicts that band gap of c-Si QDs is very different from that of amorphous silicon quantum dots (a-Si QDs). It has been reported that the quantum confinement effect is less remarkable in a-Si QDs than that of c-Si QDs [1, 2]. This study showed that quantum confinement parameter of c-Si QDs is larger than that of a-Si QDs, indicating that c-Si QDs have strong quantum confinement effect compared to a-Si QDs. It has been reported that the quantum confinement effect is in the size of c-Si QDs in silicon nitride matrix. This result suggests that the surface area, size and morphology is determined by high resolution transmission electron microscopy and nitrogen adsorption measurements. The surfaces of the nanoparticles are decisive for the properties of semiconductor nanocrystals. The surfaces and that dot nucleation is enhanced in the vicinity of surface terminations of group IV nanocrystals as the particle shape is changed (i.e. from a sphere to a rod). Finally, we will show that synchrotron radiation techniques are an ideal tool to study the chemical environment, such as 2D or 3D metal dots. This work was supported by the Division of Materials Sciences, Office of Basic Energy Science, and performed under the auspices of the U. S. DOE by LLNL under contract No. W-7405-ENG-48. Part W of program listing.

The surfaces of the nanoparticles are decisive for the properties of electronic devices made from nanocrystals. In this work, we present an investigation of the influence of different chemical surface modifications on the band edge shifts and effect of surface termination of group IV nanocrystals as the particle shape is changed (i.e. from a sphere to a rod). Finally, we will show that synchrotron radiation techniques are an ideal tool to study the chemical environment, such as 2D or 3D metal dots. This work was supported by the Division of Materials Sciences, Office of Basic Energy Science, and performed under the auspices of the U. S. DOE by LLNL under contract No. W-7405-ENG-48. Part W of program listing.
Energy Transfer from Si Nanocrystals to Er Ions - Different Mechanisms Depending on Er Concentration.

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Silicon nanocrystals (nc-Si) act not as an efficient photo-sensitizer for energy transfer from Er ions (Er$^{3+}$). The presence of nc-Si in Er-doped SiO$_2$ enhances the effective absorption cross-section of Er$^{3+}$ by more than four orders of magnitude. This enhancement is due to the efficient energy transfer from nc-Si to Er$^{3+}$. Since the absorption band of nc-Si covers all the visible range, Er$^{3+}$ can be excited by white light. Furthermore, luminescence from Er$^{3+}$ in this system shows almost no fluorescence quenching. Due to these features, this system is considered to be a key component to realize planar waveguide type compact optical amplifier operating at 1.5$\mu$m. In our previous work on SiO$_2$ thin films containing nc-Si and Er$^{3+}$ (Er-doped SiO$_2$), we reported the mechanism of energy transfer from nc-Si to Er$^{3+}$ by analyzing the time transient of Er$^{3+}$ photoluminescence (PL) at 1.5$\mu$m just after pulsed excitation. The analysis revealed that there are two energy transfer processes occurring simultaneously, i.e., fast and slow processes, and that the ratio of the fast to slow processes increases with increasing the size of nc-Si. This suggests that the mechanism of the fast process is essentially the same as that in Er-doped bulk-Si; an excited electron is transferred to Er$^{3+}$ related center in the bandgap, and then the recombinative energy of a bound exciton is transferred to Er$^{3+}$ by an Auger-like process. In this mechanism, Er$^{3+}$ should be located inside nc-Si or very close to the surface of nc-Si. On the other hands, the slow process is a characteristic process occurring only in Er:nc-Si:SiO$_2$. This is probably the Förster type Coulombic interaction between Er$^{3+}$ and free-excitons in nc-Si, and is considered to occur even if Er$^{3+}$ are located relatively far from nc-Si. In this work, the time transient of Er$^{3+}$ PL is studied as a function of Er concentration. It is shown that the ratio of the fast to slow process increases with increasing Er concentration. In order to analyze quantitatively the observed Er concentration dependence, we introduced a simple model in which the two energy transfer processes are divided into three groups depending on the location relative to nc-Si. We consider three spherical fields around a nanocrystal. Er$^{3+}$ located in the first field, which is the closest to nc-Si is excited by the fast process, and that in the second field by the slow process. Er$^{3+}$ located in the third field do not interact with nc-Si. Under the assumption that Er$^{3+}$ is uniformly distributed in a whole film, the observed Er concentration dependence is well fitted by the model. The fitting reveals that Er$^{3+}$ located within about 1nm from nc-Si surface is excited by the fast process and those located within about 2nm by slow process. Similar values are obtained by fitting the nc-Si size dependence of the ratio with the same model.
The formation of Er and Si clusters doped silica films has been shown as one of the most promising approaches for emission and optical amplification in the infrared. In this contribution we explore the structural properties of different silicate glasses co-implanted with supported by EC through the SINERGIA project. Pump and probe experiments at 1353 nm show two regimes: at intermediate power the excited state absorption of the Si nanoclusters is observed that is overcome by signal amplification by an internal gain of 0.5 dB/cm was observed for a waveguide 1 cm long. A discussion of these results in terms of direct and indirect excitation of Er and a comparison with results reported in the literature will be presented at the conference. This work was supported by EC through the SINERGIA project.

The excitation spectrum has a cutoff at 1.22 eV, well above the bandgap of bulk Si, suggesting that quantum confinement effects play a role in the excitation process. The results suggest that this new material is comprised of a superlattice of Si/cm at 1600 nm. Insertion losses measurement as a function of wavelength in the Er absorption region has permitted to estimate an Er absorption cross section at 1535 nm of 6x10^-17 cm^2. Pump and probe experiments at 1310 nm show intense state absorption of the Si nanoclusters. Pump and probe experiments at 1353 nm show two regimes: at intermediate power the excited state absorption of the Si nanoclusters is observed that is covered by signal amplification by an internal gain of 0.5 dB/cm was observed for a waveguide 1 cm long. A discussion of these results in terms of direct and indirect excitation of Er and a comparison with results reported in the literature will be presented at the conference. This work was supported by EC through the SINERGIA project.
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We have deposited Erbium (Er) doped Silicon-rich SiO$_2$ films where Er emission is activated at low temperatures enabling the fabrication of compact planar light sources and amplifiers with a low thermal budget for integration with standard Si CMOS processes. Silicon-rich SiO$_2$ films containing Er were deposited through reactive rf magnetron co-sputtering and subjected to a single annealing step to simultaneously form Silicon nanocrystals (Si-nc/s) and activate the Er emission. We studied, in detail, the fabrication parameters of Si content, annealing temperature and annealing time to investigate the role of Si-nc density, morphology and crystalline/amorphous quality on the Er energy transfer mechanism. For comparison, Si-nc/s were fabricated in SiO$_2$ through furnace annealing from Silicon-rich oxide films deposited through reactive rf magnetron sputtering. Near infrared emission from the Si-nc/s was optimized by controlling the Si content, annealing temperature and annealing time. By comparing Si-nc and Er coupled Si-nc samples, obtained in a wide range of fabrication parameters, we found that the Er emission enhancement due to the presence of the Si-nc/s increases for samples annealed at temperatures well below the annealing temperature that optimizes the Si-nc emission. In particular, maximum room temperature photoluminescence at 1535 nm has been measured for annealing temperatures between 600 °C and 800 °C and a factor of almost $10^3$ increase in the Er excitation cross section has been measured for samples containing Si-nc relative to the Er excitation cross section in SiO$_2$. In addition, preliminary Variable Stripe Length (VSL) gain measurements show the presence of optical gain in the films. The Er emission cross section derived from the gain measurements is comparable with the cross section of Er in SiO$_2$ and is not affected by the presence of the Si-nc/s.