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

Chairs

Leonid Tsybeskov
ECE Dept.
New Jersey Institute of Technology
University Heights, NJ 7102
973-596-5680

David J. Lockwood
Institute for Microstructural Sciences
National Research Council Canada
Ottawa, Ontario, K1A OR6 Canada
613-993-9614

Christophe Delerue
Dept. ISEN
IEMN
41 Blvd. Vauban
Lille, 59046 France
33-3-2030-4053

Masakazu Ichikawa
Quant.-Phase Electron. Center
University of Tokyo
Tokyo, Japan
81-3-5841-7901

Symposium Support
Freescale Semiconductors
|Hamamatsu Corporation
|2004 Fall Exhibitor

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
Silicon is the most widely used platform for planar waveguide circuits, being the natural substrate for conventional and high index contrast waveguide systems. High index contrast systems such as silicon-on-insulator (SOI) and Si3N4 allow a reduction in structure 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 optical 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 microphotonicics to address the increasing bottleneck in data transmission over the buses connecting computer chips. As microphotonic devices become a viable technology, several challenges must be overcome. The most fundamental issues are waveguide loss, input and output coupling of light, and the control of polarization sensitivity. Even for well-established devices 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 microphotonicics, we will review the 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 coupler design can be applied to SOI or Si3N4 waveguides by using a-Si or silicon oxynitride 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 a 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 compensate for polarization birefringence 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.

Si photonicics 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 at reasonable power levels, light can 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. Microphotonicics using photonic 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 complexity. In this paper we present 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 realized with standard Si nanophotonic techniques and 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 spatial modal cavity as well as provide sufficient light confinement. To accomplish this, the structure was designed using an Evolutionary Algorithm which optimized the intensity enhancement. The optimized structure consists of a single mode input waveguide and a region of Si and SiO2 rods which form the scattering interfaces. Finite-Difference Time-Domain (FDTD) method with an excitation wavelength of 1550 nm reveals confinement to about 100 by 100 nm in Si. We also demonstrate a corresponding intensity enhancement of over 300 times the input intensity. In particular, when light emitting materials are combined with complex photonic structures, this approach can directly lead to realization of novel multifrequency optical devices based on localized light modes and strong field enhancement effects. Here we report on a new material approach based on SiO2 rods and Si-rich SiN4 layers followed by thermal annealing treatments. This approach is nicely suitable for the realization of light emitting complex dielectrics. Efficient broad band light emission and good quality photonic structures have been both demonstrated paving the way to the realization of multifrequency complex structures with enhanced light emission. In particular, we will report on the first fabrication of good quality light emitting Thue-Morse aperiodic structures where strong field enhancement effects and multifrequency response are demonstrated for the first time. In addition, within a fully VLSI-CMOS compatible fabrication window, it was possible to activate broad band (800nm-1700nm) light emission homogeneously from the inside of the complex photonic structure, allowing direct access to the study of light propagation and light states in complex photonic structures like quasicrystals and periodic dielectric materials.


Photonic crystals are structures composed of artificial atoms that are approximately one thousand times larger than in traditional molecular crystals. When photonic crystals are properly tailored, they can exhibit a remarkable optical property, a range of colors for which light is not allowed to exist inside the material. This behavior, known as the photonic band gap, could be utilized to confine, manipulate, and guide light. Thus, these materials offer a route to novel photonic technologies. For this goal, conventional microfabrication techniques have been successfully adapted to obtain photonic band gap crystals. However, here we will address a completely different approach. Namely, what type of photonic band gap structures can be achieved by self-assembly? Can we spontaneously assemble the appropriate complex, ordered structures by manipulating simple building blocks? We will review efforts to use the self-assembly of colloidal particles to obtain high-quality silicon photonic band gap crystals. Despite the simplicity of this approach, experiments have recently shown that these structures can exhibit optical properties consistent with a photonic band gap. Further, since the photonic crystal is grown as a thin coating, it is extremely useful for both fundamental and technologically relevant studies. In this a review we will present our current knowledge of how self-assembly works and how it can be further modified to obtain even more complex structures.
Silicon, the dominant material in the microelectronic industry, is highly desirable as the platform for photonic chips. Photonic crystal structures that bond, split, couple and filter light have recently been demonstrated. The flow of light in these structures is predetermined by the structure design and cannot be modified. All-optical control of light on silicon is challenging due to its lack of non-linear optical properties. Here we propose and demonstrate the all-optical control of light on a nanocavity using a photonic crystal and a high-index contrast waveguide. The resonance condition of the ring resonator is given by $f_o = k/(c/n_{eff})^{1/2}$ where $c$ = speed of light in free space, $n_{eff}$ = 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 nanocavity can be changed. We fabricated and characterized a tunable electro-optic modulator using high-index contrast Si-SiO$_2$ ring resonators on silicon-on-insulator (SOI) substrate. The resonances were obtained using a SOI substrate using electron beam lithography and reactive ion etching. Using a pulse energy of only 40 pJ, a refractive index change of approximately $10^{-2}$ is obtained. This small index change, due to the high confinement nature of the cavity structure, leads to a strong change in transmission spectrum. Consequently, the resonance is shifted by more than its full width at half maximum (8nm), and the transmission of the device is modulated by more than 96%. The free carrier relaxation time in such a compact structure is less than 50 ps, leading to switching speeds on the order of 1GHz. Such a device could open the door to the large-scale integration of ultra-fast modulators and switches.

Photonic crystal structures that bond, split, couple and filter light have recently been demonstrated. The flow of light in these structures is predetermined by the structure design and cannot be modified. All-optical control of light on silicon is challenging due to its lack of non-linear optical properties. Here we propose and demonstrate the all-optical control of light on a nanocavity using a photonic crystal and a high-index contrast waveguide. The resonance condition of the ring resonator is given by $f_o = k/(c/n_{eff})^{1/2}$ where $c$ = speed of light in free space, $n_{eff}$ = 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 nanocavity can be changed. We fabricated and characterized a tunable electro-optic modulator using high-index contrast Si-SiO$_2$ ring resonators on silicon-on-insulator (SOI) substrate. The resonances were obtained using a SOI substrate using electron beam lithography and reactive ion etching. Using a pulse energy of only 40 pJ, a refractive index change of approximately $10^{-2}$ is obtained. This small index change, due to the high confinement nature of the cavity structure, leads to a strong change in transmission spectrum. Consequently, the resonance is shifted by more than its full width at half maximum (8nm), and the transmission of the device is modulated by more than 96%. The free carrier relaxation time in such a compact structure is less than 50 ps, leading to switching speeds on the order of 1GHz. Such a device could open the door to the large-scale integration of ultra-fast modulators and switches.

For modulation. The resonance condition of the ring resonator is given by $f_o = k/(c/n_{eff})^{1/2}$ where $c$ = speed of light in free space, $n_{eff}$ = 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 nanocavity can be changed. We fabricated and characterized a tunable electro-optic modulator using high-index contrast Si-SiO$_2$ ring resonators on silicon-on-insulator (SOI) substrate. The device is fabricated using electron beam lithography and reactive ion etching. Using a pulse energy of only 40 pJ, a refractive index change of approximately $10^{-2}$ is obtained. This small index change, due to the high confinement nature of the cavity structure, leads to a strong change in transmission spectrum. Consequently, the resonance is shifted by more than its full width at half maximum (8nm), and the transmission of the device is modulated by more than 96%. The free carrier relaxation time in such a compact structure is less than 50 ps, leading to switching speeds on the order of 1GHz. Such a device could open the door to the large-scale integration of ultra-fast modulators and switches.
structures. Photonic crystals formed from mesoporous silicon are made by the electrochemical etching of silicon by means of periodic vacuum 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 several photonic crystals with close periods of microcavity layers. 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 (0Ol) wafers. The pore size is controlled by the variation of the current flowing through the wafer perpendicular to its surface. The layer thickness is controlled by etching time. Studied CMC's samples have two identical half-wavelength-thick cavity spacers surrounded by Bragg reflectors. Photonic crystals consist of layers of porous silicon bilayers, which are two quarter-wavelength-thick porous silicon layer with different porosity. The thickness of intermediate Bragg reflector is varied from 0.5 to 4.5 bilayers. The center of photonic crystal band in CMC's is 900 nm (A). The bands have 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 A/4. The linear spectrum of photonic molecule has one or three modes, which are determined by the thickness of the spacer between microcavities. Microcavities separated by spacer with thickness divisible by even number of A/4 possess three resonance state. On the contrary PM's with spacers thickness divisible by odd number of A/4 have only one resonance mode. Photonic crystals consist of a series of diatomic molecules. The second- and third-harmonic generation 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

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 semiconductor devices. These concepts are not sufficient to develop new devices or to improve the properties of the devices. The goal of these devices is hetero-superlattice bipolar transistors (HBTs). The cut-off frequency of HBTs exceeds 300 GHz and they are now in the mass production phase. Another possible new class of high power devices is the electro-refractive devices which make use of the electric field for control of index of refraction. These devices are based on electro-optic effects in periodic structures, particularly based on strained silicon and germanium and modulation-doping (MOD) techniques. These devices can provide extremely high mobility and therefore high performance, much better than conventional Si MOSFETs. The mobility of channel MOD semiconductors, for instance, reaches almost one million cm2/Vs, while the mobility of strained Ge layers exceeds the mobility of bulk Ge. Despite this, the interest in 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 for electro-optic devices, particularly optical interconnection and parallel processing in VLSI circuits. It is obvious that these devices can be 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 the appearance of two valleys. The valley splitting energy between these lowest two levels is a function of the number of quantum wells. We show that microwave spectroscopy can be performed between these two states. Transistor measurements at 0.25K in a silicon/silicon-germanium two dimensional electron gas clearly show the valley splitting. The valley splitting peak shows a dramatic increase in width as the temperature is increased from 0.25K to 0.4K. These results indicate that the valley splitting is found to increase linearly with applied perpendicular magnetic field. The valley splitting peak shows a dramatic increase in width as the temperature is increased from 0.25K 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)-1_x(Ge_x), Alloys. Andrew Gordon Norman, Jerry M. Olson, Manuel J. Romero, Pat Dippo and Mowafik Al-Jassim; National Renewable Energy Laboratory, Golden, Colorado.

We report a new method of forming single crystal Ge nanowires and nanocrystals. The Ge nanowires are produced by the phase separation of III-V(1-x)(Ge_x) alloys during metal organic vapor phase epitaxy (MOVPE). For the (GaInP)(1-x)(Ge_x) alloy system, by adjusting the growth conditions, we have formed Ge nanowires of up to 2um length, with controlled diameters ranging from 5 nm to greater than 50 nm, embedded in a high band gap GaInP matrix. By changing the alloy composition, we can 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 using 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 (GaInP)(1-x)(Ge_x) alloy layers containing Ge nanowires 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 compressive SiGe can be layered at 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 devices 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 Si/compensated SiGe heterostructure is a promising candidate for high mobility devices. Devices with SiGe/SiGeGe.5/Al can achieve an electron mobility enhancement of 2.7 and a hole enhancement of 10x. Materials engineering offers a continuous 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, Kwang-Hyeon 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 this talk we will discuss the use of SiGe HBT for high frequency mixed signal applications. A silicon/silicon-germanium two dimensional electron gas is integrated with optoelectronics devices, enabling 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 of self-assembled Ge quantum dots: control of size and registration or placement of dot arrays. The size control based on the growth parameters, including T, deposition rate, etc. will be addressed. Likewise, mechanisms of registration of dots on Si will be discussed. One critical issue at 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 nanotubes, Si/Ga nanowires, and GaN nanowires. Based on the latter nanowires, FN junctions and CMOS like devices have been demonstrated. These results suggest a general approach to achieve emerging heterogeneous integration of nanostructures and devices from different nanomaterials for nanosystems.

4:00 PM F2.6 Structural and Optical Properties of Sn_xGe_{1-x} Quantum Dots and Quantum Wires, Jordana Bandera, Douglas Bell and Shouleh Nikzad; Jet Propulsion Laboratory, Pasadena, California.

Sn_xGe_{1-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 Sn_xGe_{1-x} films by low temperature Molecular Beam Epitaxy (MBE), using low growth temperatures (<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 (0-10%) and film thicknesses (0.2 - 2.0μm) were also varied. In addition, 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 Sn_xGe_{1-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 Sn_xGe_{1-x} layers with increasing Sn fraction up to 10%.

4:15 PM F2.7 Time-Resolved Photoluminescence in Si/SiGe Nanostructures, Boris Kamenev, Jean-Marc Baribeau, David Lockwood and Leonid Tsybeskov; Electrical 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, we have also studied the effect of PL rise and decay times has 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 nearly pure Ge clusters and/or Si-SiGe interfaces.


Electrons in silicon/silicon-germanium two-dimensional electron gas quantum dots are a promising architecture for spin-based quantum computation. Top-gated quantum dots allow precise tuning of electron shape and interdot coupling. We report the observation of Coulomb blockade in dots defined by a combination of etching and metal top gating. A nanometer channel or mesa is fabricated by electron beam lithography and subsequent reactive ion etching. Metal gates are deposited across the channel to define the leads of the dot. The sides of dot are defined either by surface depletion from the etched sidewalls or by metal plunger gates. Low temperature measurements (1.8K) show a single electron charge energy of about 2μeV. We observe steps in the differential conductance known as the Coulomb staircase with varying source-drain bias. We also report on the use of gate dielectrics to further reduce the leakage current from the top gates.

4:45 PM F2.9 Nanometer-scale control of Ge island nucleation sites on Si(001) using a Ga focused ion beam, Alain Portavoce, Mark C. Chu, P.M. Mooney, Susan N. Coppersmith and Mark A. Eriksson; 1University of Wisconsin - Madison, Madison, Wisconsin; 2IBM Watson Research Center, Yorktown Heights, New York; 3Department 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 fabricating 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. At the same time the self assembly of islands as Ge 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. Further, 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 videos during deposition on to FIB-patterned surfaces. We will also describe the structural properties of the islands produced. Furthermore, by comparing UHV-CVD with MBE deposition of Ge, we will show that gas reactivity is not the primary factor controlling 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.

SESSION F3: Poster Session

Chairs: Christophe Delerue and Masakazu Ichikawa
Monday Evening, November 29, 2004
8:00 PM Exhibition Hall D (Hynes)

F3.1 Charge Transport in Silicon Nanocrystal Arrays, Rishidev Krishnam, Philippe Fauchet, Todd Krauss, Qianghui Xie, Xiang-Dong Wang and Joseph Kulik; 1Electrical and Computer Engineering, University of Rochester, Rochester, New York; 2Department of Chemistry, University of Rochester, Rochester, New York; 3Physical Analysis Lab Arizona, Freescale Semiconductor, Tempe, Arizona.

Single layers of isolated, size-controlled silicon nanocrystals were prepared by thermal crystallization of a thin amorphous silicon layer sandwiched between silicon dioxide layers. A subsequent oxidation step ensured controlled increase in their lateral size with increasing size of the nanocrystals, separation of the nanocrystals (from 1 to 3 nm), stoichiometry of the resulting oxide and surface morphology were monitored with transmission electron microscopy, scanning transmission electron microscopy, atomic force microscopy, x-ray photoelectron spectroscopy, and Raman spectroscopy. Mesoscopic charge transport studies performed with an electrostatic force microscope (EFM) revealed rapid lateral transport of charges when the nanocrystals were tightly packed (~1 nm separation) and interconnected. As the inter-nanocrystal separation was increased, lateral charge transport was rapidly suppressed. Nanocrystals separated by up to 3.6 nm retained the injected charges in a well-defined localized region (275 electrons inside a 62 nm diameter region) for a time of the order of several days. The ability to switch from a very short to a very long retention time using the same structure by simply changing the post-growth processing conditions is attractive for various applications. The ability to obtain a long charge retention time and place the nanocrystals at well-defined depths indicates that our structures may be useful for charge storage applications such as in non-volatile memory devices. We believe that our structures with long retention times could also be used as charge templates for self-assembly applications.

F3.2 Addition Energies of Semiconductor Quantum Dots from First Principles, Alberto Franceschetti; Oak Ridge National Laboratory, Oak Ridge, Tennessee.
Transport properties of semiconductor nanostructures are characterized by a complex interplay between quantum confinement effects and charge transport. The transient dielectric response of quantum dots is particularly intriguing due to the interplay between electronic and excitonic effects. Here, we use density-functional theory in the local-density approximation to calculate the electron and hole add-on energies of Si and InAs quantum dots in the 1-3 nanometer size regime from first principles. The addition allows us to estimate the density of states for different quantum dot sizes, thus providing a pathway to optimize the quantum-dot density on a nanometer scale. Our results provide an accurate description of the surface and the relative importance of single-particle splittings vs. Coulomb interactions in the addition spectra of quantum dots. We also show how the results of our calculations can be used to extract the parameters of a model dielectric function that can be used to predict the addition spectra of quantum dots in different dielectric environments.

F3.2 Computer Simulation of Charging/Erasing Transients of a Ge/Si Hetero-Nanocrystal-Based Flash Memory. Dengtao Zhao, Yan Zhu, Ruigang Li and Jianlin Liu; Electrical Engineering, Quantum Structures Laboratory, 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 Poisson equation and tunneling current. The transient gate current and the average charge in one dot were simulated respectively. Evident hysteretic features can be observed in the transient processes in a voltage-sweeping measurement mode. The hysteresis strongly depends on the sweeping speed due to the non-linear transmission in the gate oxide. Ge/Si dot can enhance the hysteresis process which suggests the enhanced data storage. While measuring the transient process in a constant voltage mode, the time delay of transient current and charge are increased if Ge is used on top of Si dot, indicating a longer retention time for Ge/Si-floating-gate flash memory.

F3.3 Threshold Voltage Shift in Hetero-nanocrystal Floating Gate Flash Memory, Yan Zhu, Dengtao Zhao, Ruigang Li and Jianlin Liu, EE 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 threshold voltage shift of our proposed Ge/Si hetero-nanocrystal floating gate memory device. First, numerical investigations were carried out by solving 2-D Poisson-Boltzmann equation. The simulation shows that the presence of the Ge on Si dot can remarkably prolong the retention time, as indicated by the time delay behavior of the threshold voltage shift. It also shows that increase of thickness of either Si or Ge dot will introduce a retardation of threshold voltage shift. The shift also strongly depends on the doping 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.


Daniel Pham+, Hong-Jyh Li++, Billy Nguyen, Gabriel Gebars, Danna Larison, Barry Sassa, Lynn Larson. International SEMATECH, +Freescale Semiconductor, Austin, Texas. At the first step, it is shown by a theoretical calculation that acoustic stop bands are generated in the periodic nc-PS structures. The acoustic wave propagation in the periodically stacked nc-PS layers was calculated in a simplified onedimensional model of single-atomic elastic layers. The major device parameters are the pitch of two nc-PS layers with different porosities and the respective porosity of the thick layer. The porosity of the thick layer is in the order of 0.101, which is far below the porosity range of the experimental nc-PS layers. (3) Another interesting property of the nc-PS layers by which the elastic constant is estimated is of the order of 1011 cm-2. By Raman scattering spectroscopy, we further verified the existence of the nc-PS in the structures. By using capacitance-voltage (C-V) measurements, we studied the electrical properties of the structures. At room temperature, 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 with the diameter of 2 nm 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 a single electron into every 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 n-Si/nc-Si/nc-Si asymmetric double-barrier structure is one of the basic units of nc-Si floating gate FET, which could be applied for future room temperature nanoelectronic devices such as nanomemories.

F3.5 Structural characterization and Coulomb blockade of a-SiNx/nanocrystalline Si/a-SiNx asymmetric double-barrier structures. Xinfan Huang, Liangcai Wu, Min Dai and Kunji Chen; Fudan University, Shanghai, China.

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 nanoelectronic 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 paper, we fabricated the n-Si/a-SiNx/a-SiNc/nc-Si/a-SiNx double-barrier structures (with the nc-Si size of 2 nm, 4 nm, and 7 nm, respectively) on the p-type Si substrates by plasma-enhanced chemical vapor deposition (PECVD) technique and by high frequency furnace and remote plasma. In planar and cross-section transmission electron microscopy (TEM) photographs, we observed separate nc-Si grains almost of the same size as the as-deposited a-Si layers due to the constrained crystallization process of 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. The nanocrystalline Si/a-SiNx asymmetric double-barrier structure is one of the basic units of nc-Si floating gate FET, which could be applied for future room temperature nanoelectronic devices such as nanomemories.
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 ultrasonic emission [3] and with the optoelectronic characteristics, some applications will be opened toward integrated devices. Takahiko Kishi, Shigeru Ohmukai, Hirokazu Shimizu and Yuasa Tsutsuji, Electrical and Computer Eng., Akashi College of Technology, Akashi, Hyogo, Japan.

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.


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, including 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 Bernel, Shoji Akiyama, Xiaoman Duan and Lionel C. Kimerling; BMSE, 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 composed 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 present a coupled mode theory analysis of the effective index of the propagation mode is measured directly. The measured effective mode index is less than either of 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 cladding loss are also measured 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, high coupling, and high index contrast dielectric waveguide properties, engineering, and biomaterials sensor on silicon chip.

F3.11 High-Speed All-Optical Modulation in Silicon using Two-Photon Absorption and High-Finesse Cavities.

Christina Manolatou and Michal Lipson, ECE, Cornell University, Ithaca, New York.

The ability to control light with light in Silicon in an integrated fashion would enable the integration of a variety of optical and electronic devices in a single CMOS compatible platform. Most integrated passive devices in Silicon (Si) are passives where the light cannot be altered once the structure is fabricated. Achieving active devices in Silicon is a challenge due to its weak nonlinearity and transparency at telecom wavelengths which require large devices and high-power excitation. We report here arrays of SiC/Si nanotips with high aspect ratios (100) and sharp apexes (1 nm) by direct etching from Si substrates. We report here arrays of SiC/Si nanotips with high aspect ratios (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 arsine, argon and hydrogen. 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 protecting 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 voltage as low as 0.8 V. In addition, the SiC 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 3% fluctuation in one hour. Formation of gate-controlled SiC nanotip arrays with well-defined 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.


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 spectroscopy. 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 glycol monododecyle ether (C12E5) as capping agent at high concentration of surfactant show few different low angle reflections from the cubic phase including (111), (200), (220), (311), (222), triangle, hexagon, etc. 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 glycol monododecyle ether (C17E5) as capping agent, 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 for Ge nanocrystals is as follows: 80 mL hexane, 0.6 mL GeCl4, 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 glass flask. Then the mixtures were stirred in a magnetic stirrer for 30 min before being transferred to a Parr reactor, which was kept at 280 °C for 2 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 Rishchina, 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 and Si nanostructures 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, and the size of the 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. In order to evaluate the size of the nanoclusters, the deposition 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. Depositing the Ge target from 5 x 10⁵ cm² to 0.5 J/cm² 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. In conclusion, high resolution scanning transmission electron microscopy and energy dispersive X-ray analysis of AlGaN nanostructures 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 problem of these techniques is the limited control of 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) 26523. 2. F. Mottola, Cond. Matt. 14 (2002) 7007. 3. D.H. Loendes, D.B. Geoghegan, A.A. Puresky, D.P. Norton, C.M. Rouleau, Science 273 (1996) 898. 4. L. Patrone, D. Nelson, V.I. Safarov, M. Senia, W. Marne, J. Appl. Phys. 87 (2000) 3825. 5. A.V. Kuznetsov, J.-P. Sylvestre, S. Patskovsky, M. Muehler, J. Appl. Phys. 91 (2002) 2428.

F3.16 Si1-xGex Nanocrystals Observed by EFTEM: Influence of the Dry and Wet Oxidation Process. Angel Cunídras1, Jordi Arbiol2, Joan Ramon Morante3, Tomas Rodríguez4 and Andres Rodríguez5; 1Electronic Engineering, Universitat Politècnica de Catalunya, Cerdanyola, Barcelona, Scientific and Technical Facilities, Universitat de Barcelona, Barcelona, Barcelona, Spain; 2Electronics, Universitat de Barcelona, Barcelona, Barcelona, Spain; 3Electronic Technology, Universidad Politècnica de Madrid, Madrid, Spain.

Si and Ge nanocrystals (NC) embedded in oxide matrix have attracted much attention due to their potential optoelectronic and photonic 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 advantage in small-size group-IV NCs lies 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 850 °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. HRTEM images and EELS analysis show the evolution of the oxidation of polycrystalline Si0.7Ge0.3 layer, leading to NC embedded with Ge-rich nanoclusters. 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 oxidized Ge clusters as EFTEM images clearly show. However, it is difficult to assess the presence of Ge in the oxide by means of EFTEM, although infrared spectroscopy (FTIR) shows fingerprints of it. On the contrary, wet oxidation lead to a progressive oxidation of the layer, both of Ge and Si, that maintains 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 more preferable to oxidize polycrystalline Si1-xGex to obtain Ge-rich NC embedded in an oxide matrix, as both Ge and Si are oxidized, in contrast to dry oxidation, where Ge is mainly segregated.


Numerous efforts have been made for the research and development of 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 sputter deposition technique was investigated for the fabrication of high-density of nanoheterostructures of Ge 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 300°C to 800°C, were used. The ion beam used was the monochromatic ion gun. A low beam energy was varied through adjusting the inlet gas flow rate and the electron cyclotron resonance (ECR) voltage, respectively. In selected experiments, an as-generated ion source was used to enhance the incident beam. Ge quantum dots obtained have dot diameter from 5 x 108 cm⁻² to 5 x 109 cm⁻². The dot size varied from 80 to 700 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 photo luminescence (PL) for quantum confinement effect. Among the results, a unique PL peak at 971 nm was observed.
Formation of Sn Nanodots on a (001) Si Surface and their Incorporation in an Overgrown Si Layer.

John Laurencelle, Martine Ly-Nguyen-Larsen, Shusaku Hayama and Gordon Davies. Institute of Physics and Astronomy, Aarhus University, Aarhus C, Denmark; Institute of Physics, King’s College London, London, United Kingdom.

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$_x$ ($0.9 < x < 1$) [1] and an increase in the band gap energy (from 0.08 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 (001) (001) Si crystal. Using this method a high degree of freedom to adjust the density and size of the dots since the dots initially created are on the Si surface, that is, lower deposition temperature gives a higher density of dots, and a smaller amount of Sn deposited on the surface gives a decrease in dot size. The formation of Sn dots on the surface can be best described as formation in the Volmer-Weber mode [2]. Incorporation of the Sn dots into the overgrown Si layer will change the form and composition of the Sn dots to a SiSn alloy with a shape elongated in the growth direction. A high temperature treatment of the structure recreates the dot shape and the island size formation [3] occurs. 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) 530 [2] E. Sandberg, R. Hanaor, D. Cheyssac, M. Legoupil, Surf. Sci. 364 (1996) 467 [3] Y. Le, P. Maere, T. Touboul, D. Benhamed, R. Ragan, K. S. Min, and H. A. Atwater. Appl. Phys. Lett., 82 (2003) 4292.
SiGe pseudo-substrates, strain compensated Si/SiGe QC structures grown at low T (≤300 °C) and containing up to 30 cascade layers have been realized. Direct write interface roughness as low as 0.8 nm. Using a "bound-to-continuum" (B-C) design to enable the rapid extraction of carriers via a superlattice miniband, the photocurrent in the 7 μm range has been demonstrated at current densities as high as 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/SiGe heterostructures have their maximum band offset. Hence, a B-C design based on heavy hole states will have interspaced light hole states that may reduce the non-radiative lifetime. However, studies of single 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 heavy hole states can effectively block 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 strain compensated cascade structures, and understanding the effect of the interspersed light hole states.

0:30 AM •F5.3

Recent interest in biological imaging, remote sensing, and biochemical analyses has made nanoscale Terahertz (THz) emitters based on solution of a host of problems in terms of the material, the laser source, the interspersed light hole states that may reduce the non-radiative lifetime. However, studies of single 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 heavy hole states can effectively block 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 strain compensated cascade structures, and understanding the effect of the interspersed light hole states.

SESSION F5: Si/SiGe Three-Dimensional Nanostructures
Chair: J. Kolodzey
Tuesday Morning, November 30, 2004
Constitution B (Sheraton)

10:15 AM •F5.1
Progress in the Growth and Characterization of Ge Quantum Dots on Si(111) Islands. Joshua D. Spence, Robert E. T. Grove, and David J. Lockwood; Dept. of Applied Physics, The Univ. of Tokyo, Tokyo, Japan; and Microsystems and Nanotechnology Laboratory, University of California, Berkeley, California.

Semiconductor SiGe quantum dot and island structures have been realized in a wide variety of growth conditions. These structures have been shown to have a wide range of properties, including high quantum efficiency, high hole mobility, and high carrier optical gain. In this talk, we will discuss recent progress in the growth and characterization of Ge quantum dot and island structures on Si(111) surfaces. We will present results from studies of the growth and optical properties of Ge quantum dot and island structures, as well as measurements of their photoluminescence and electroluminescence properties. We will also discuss the potential applications of these structures in future electronic and optoelectronic devices.

11:00 AM •F5.2
Formation of Ultrahigh Density FeSi2 Nanobots by Codoposition of Fe and Si on Oxidized Si(111) Surfaces. Yoshiaki Nakamura1, Yasushi Nagadomi1 and Masakazu Ichikawa1,2; 1Dept. of Applied Physics, The Univ. of Tokyo, Tokyo, Japan; 2CREST, Japan Science and Technology Agency, Tokyo, Japan.

Semiconductor SiGe is attractive as a promising material for a Si-based light emitter with a wavelength (≤1μm) of optical fiber communication. It has been reported that a SiGe quantum dot (QD) can be a direct-gap semiconductor [1]. Therefore we expect that FeSi2 nanobots on Si (111) have high light-emitting efficiency because coherent nanobots preserve strain caused by the lattice mismatch and a nanobot has almost no impurities due to its small size. In this work, we report formation of FeSi2 nanobots 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 base pressure of
2x10^14 Pa, equipped by scanning tunneling microscopy (STM) and reflection high-energy electron diffraction (RHEED) apparatuses. Clean Si surfaces were prepared by cycles of flashing and slow cooling at 800°C in the UHV chamber. The samples were oxidized at 500°C for 10 min at the oxygen pressure of 2x10^-4 Pa in the chamber to form ultrathin Si oxide films with a thickness of 0.3 nm. Si with an amount of 0.5 bilayer (BL) was deposited on the ultra-thin Si oxide films at 500°C to create nucleation sites before codeposition of Fe and Si. Then Fe and Si were simultaneously deposited on the samples with a stoichiometric ratio of deposition rates (1:2) up to amounts of 4 monolayers (ML) by co-deposition. As-grown FeSi nanodots were then annealed at 500°C within 40-600°C. For the sample grown at 500°C, STM images showed that semipenular nanodots were formed with the average size of 86 nm and the density of 2x10^11 cm^-2. RHEED patterns of this sample indicated that FeSi nanodots were c-FeSi nanodots on Si(111). On the other hand, RHEED patterns showed that the main phase of the nanodots was c-FeSi for the sample grown at 600°C and α-FeSi2 for the sample grown at 400°C. We annealed β-FeSi2 nanodots deposited on Si at 500°C to improve the crystallinity, which was confirmed by RHEED patterns. STM images of annealed samples showed a larger dot size of 27 nm and a smaller dot density of 2x10^12 cm^-2 by coalescence. To investigate the effect of the nucleation sites created by Si predeposition, we made samples without predeposition. For the samples made by codeposition of Fe and Si at 500°C without predeposition, STM images showed similar nanodots in size, density, and shape to the case of samples made with nucleation sites. However, RHEED patterns indicated mixed phases of c-FeSi and α-FeSi2 were formed in nanodots. We could form β-FeSi2 nanodots with ultrahigh density (>5x10^11 cm^-2) by codeposition of Fe and Si at 500°C after the predeposition of Si, proving the crystallinity of β-FeSi2 nanodots by annealing at 550°C. This work was partly supported by JSPS.KAKENHI (15K21056). References [1] L. Miglio, V. Mergegelli, and O. Jepsen, Appl. Phys. Lett. 75, 368 (1999).

11:15 AM F5.4 Growth and Overgrowth of Ge/Si Quantum Dots: An Observation by Atomic Resolved HAADF-STEM Imaging.

D. Zhu1, P. A. Middelbos1, R. E. Dunin-Borkowski1, B. A. Joyce2, D. W. Pashley3, Andrew L. Bleloch4 and P. J. Goodwin5; 1Materials Science and Metallurgy, University of Cambridge, Cambridge, United Kingdom; 2Physics, Imperial College, London, United Kingdom; 3Materials, Imperial College, London, United Kingdom; 4UK SuperSTEM Laboratory, University of Cambridge, United Kingdom; 5Engineering, University of Liverpool, Liverpool, United Kingdom.

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, Si-Ge is also a model semiconductor system for fundamental studies of the growth and their properties. In practice, as the MBE growth of heterostructure is an inherently non-equilibrium process, the resultant of the formation of self-assembled nanostructures is closely dependent on their growth and overgrowth conditions. The morphology, structure, and composition of the QDs can be all changed during the growth; therefore it will be very crucial to understand their structures of different stages of the growth. In this presentation, our efforts are focused on characterizing and understanding the QD growth phenomenon by high-resolution HAADF-STEM imaging. Both the formation of uncapped QD and the effect of encapsulation process were investigated based on the analysis 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 5-monolayer-thick core with 60% of Ge was formed in the 5-monolayer-thick 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.

11:30 AM F5.5 Heteroepitaxial Growth on Vicinal and Nanostructured Si(001): From Kinetic Growth Instabilities to Perfectly Ordered Domains in Silicon Nanostructures.

Monique Schaffner1, Jozef Schneider1, Institut für Halbleiterphysik, Johannes Kepler Universität Linz, Linz, Austria.

The Si(001) surface is intrinsically unstable against kinetic step bunching during Si growth on SiGe heteroepitaxy [1]. While this phenomena has for some time been associated with a strain-driven equilibrium mechanism [2], it is now clear that it is of purely kinetic origin. Recent kinetic Monte Carlo (KMC) simulations in connection with a basic stability analysis provide 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 of pattern formation, nucleation, and growth of QDs are in good agreement with experiments in the low growth temperature regime. The critical phenomena has for some time been associated with a strain-driven equilibrium mechanism [2], it is now clear that it is of purely kinetic origin. Recent kinetic Monte Carlo (KMC) simulations in connection with a basic stability analysis provide 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].
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 often exponential, but non-exponential behaviors can be described by a stretched exponential law systematically reported for all types of nanocrystalline silicon. Such decay kinetics is expected when there are several pathways of deexcitation with different characteristic times, and a genuine disorder in the material. In the case of silicon nanostructures, 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 [Mihalcsov 1998]. In order to elucidate this question, time-resolved photoluminescence measurements on films made from gas-phase 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 (4 7 10^9 particles/cm^2) where nanoparticles are completely isolated from each other, the decay kinetics 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 multipexponential 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-Baime, C. Reynaud, G. Ledoux, F. Huisken, J. Appl. Phys. 95, 3677 (2004) [Ledoux 2000] G. Ledoux, O. Guillois, F. Huisken, B. Kohn, V. Paulillard, D. Porterat, C. Reynaud, Phys. Rev. B 62, 1542 (2000). [Mihalcsov 1998] I. Mihalcsov, J. C. Vial, R. Romestain, Phys. Rev. Lett. 80, 3392 (1998)

3:45 PM F6.6
Optical Gain in Silicon Nanocrystals. Lorenzo Pavesi, 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 (TRVSIL) 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 losses 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 Planck Institute of Halle, Research Institute in Prague, University of Barcellona, University of Helsinki, where the samples reviewed here have been produced.

4:30 PM F6.7
Silicon Nanocrystals: Photosynthesizers for Molecular Oxygen. Dmitri Kovalev, 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 the singlet state. We demonstrate that the efficiency of photosensitization of oxygen molecules meditated 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 broad 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 phonon emission cascade. From time-resolved measurements the characteristic time of energy transfer is found to be in the range of micro-seconds. 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.

SESSION F7: Poster Session
Chairs: Minoru Fujii and Dmitri Kovalev
Tuesday Evening, November 30, 2004
8:00 PM
Exhibition Hall D (Hynes)
light-emitting diodes, waveguides, lab-on-chip, potential lasing capabilities, etc [1]. However, its luminescence quantum efficiency remains rather low [2]. Best values to date are about 3% [3] 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 poly-crystalline 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 characterizations of the high-pressure-annealed samples have been carried out, and the structures exhibit enhanced EL characteristics should be significantly stabilized. In addition, EL characteristics should be improved, since carrier injection efficiency into luminescent silicon nanocrystals depends on the transition dipole moment of the excited states. The use of optical microscopy (LEEM) and X-Ray Photoemission Electron Microscopy (XPEEM) is a suitable technique to analyze both the optical properties and the electron excitations of Ge nanoparticles embedded in a cubic SiC matrix. The combined method is shown to be applicable to embedded nanocrystals in large simulation cells for which the first-principle treatment of the ionic relaxation is presently out of reach, whereas the electronic, optical and excitation properties can already be obtained via first-principles techniques [1] [1].

We discuss and test a combined method to efficiently perform ground-state excited-state calculations for relaxed structures using both a quantum-first-principles approach and a classical molecular-dynamics simulation. We apply this method to calculate the optical and electronic properties of the resulting structures with various geometries. The three-dimensional confinement of charge carriers in quantum dots is of special interest due to their possible application in microelectronic and optoelectronic devices with improved electronic and optical properties, and the electron excitations of Ge nanoparticles embedded in a cubic SiC matrix. The combined method is shown to be applicable to embedded nanocrystals in large simulation cells for which the first-principle treatment of the ionic relaxation is presently out of reach, whereas the electronic, optical and excitation properties can already be obtained via first-principles techniques [1] [1].

The three-dimensional confinement of charge carriers in quantum dots is of special interest due to their possible application in microelectronic and optoelectronic devices with improved electronic and optical properties, and the electron excitations of Ge nanoparticles embedded in a cubic SiC matrix. The combined method is shown to be applicable to embedded nanocrystals in large simulation cells for which the first-principle treatment of the ionic relaxation is presently out of reach, whereas the electronic, optical and excitation properties can already be obtained via first-principles techniques [1] [1].

We discuss and test a combined method to efficiently perform ground-state excited-state calculations for relaxed structures using both a quantum-first-principles approach and a classical molecular-dynamics simulation. We apply this method to calculate the optical and electronic properties of the resulting structures with various geometries. The three-dimensional confinement of charge carriers in quantum dots is of special interest due to their possible application in microelectronic and optoelectronic devices with improved electronic and optical properties, and the electron excitations of Ge nanoparticles embedded in a cubic SiC matrix. The combined method is shown to be applicable to embedded nanocrystals in large simulation cells for which the first-principle treatment of the ionic relaxation is presently out of reach, whereas the electronic, optical and excitation properties can already be obtained via first-principles techniques [1] [1].

We discuss and test a combined method to efficiently perform ground-state excited-state calculations for relaxed structures using both a quantum-first-principles approach and a classical molecular-dynamics simulation. We apply this method to calculate the optical and electronic properties of the resulting structures with various geometries. The three-dimensional confinement of charge carriers in quantum dots is of special interest due to their possible application in microelectronic and optoelectronic devices with improved electronic and optical properties, and the electron excitations of Ge nanoparticles embedded in a cubic SiC matrix. The combined method is shown to be applicable to embedded nanocrystals in large simulation cells for which the first-principle treatment of the ionic relaxation is presently out of reach, whereas the electronic, optical and excitation properties can already be obtained via first-principles techniques [1] [1].

We discuss and test a combined method to efficiently perform ground-state excited-state calculations for relaxed structures using both a quantum-first-principles approach and a classical molecular-dynamics simulation. We apply this method to calculate the optical and electronic properties of the resulting structures with various geometries. The three-dimensional confinement of charge carriers in quantum dots is of special interest due to their possible application in microelectronic and optoelectronic devices with improved electronic and optical properties, and the electron excitations of Ge nanoparticles embedded in a cubic SiC matrix. The combined method is shown to be applicable to embedded nanocrystals in large simulation cells for which the first-principle treatment of the ionic relaxation is presently out of reach, whereas the electronic, optical and excitation properties can already be obtained via first-principles techniques [1] [1].

We discuss and test a combined method to efficiently perform ground-state excited-state calculations for relaxed structures using both a quantum-first-principles approach and a classical molecular-dynamics simulation. We apply this method to calculate the optical and electronic properties of the resulting structures with various geometries. The three-dimensional confinement of charge carriers in quantum dots is of special interest due to their possible application in microelectronic and optoelectronic devices with improved electronic and optical properties, and the electron excitations of Ge nanoparticles embedded in a cubic SiC matrix. The combined method is shown to be applicable to embedded nanocrystals in large simulation cells for which the first-principle treatment of the ionic relaxation is presently out of reach, whereas the electronic, optical and excitation properties can already be obtained via first-principles techniques [1] [1].

We discuss and test a combined method to efficiently perform ground-state excited-state calculations for relaxed structures using both a quantum-first-principles approach and a classical molecular-dynamics simulation. We apply this method to calculate the optical and electronic properties of the resulting structures with various geometries. The three-dimensional confinement of charge carriers in quantum dots is of special interest due to their possible application in microelectronic and optoelectronic devices with improved electronic and optical properties, and the electron excitations of Ge nanoparticles embedded in a cubic SiC matrix. The combined method is shown to be applicable to embedded nanocrystals in large simulation cells for which the first-principle treatment of the ionic relaxation is presently out of reach, whereas the electronic, optical and excitation properties can already be obtained via first-principles techniques [1] [1].

We discuss and test a combined method to efficiently perform ground-state excited-state calculations for relaxed structures using both a quantum-first-principles approach and a classical molecular-dynamics simulation. We apply this method to calculate the optical and electronic properties of the resulting structures with various geometries. The three-dimensional confinement of charge carriers in quantum dots is of special interest due to their possible application in microelectronic and optoelectronic devices with improved electronic and optical properties, and the electron excitations of Ge nanoparticles embedded in a cubic SiC matrix. The combined method is shown to be applicable to embedded nanocrystals in large simulation cells for which the first-principle treatment of the ionic relaxation is presently out of reach, whereas the electronic, optical and excitation properties can already be obtained via first-principles techniques [1] [1].

We discuss and test a combined method to efficiently perform ground-state excited-state calculations for relaxed structures using both a quantum-first-principles approach and a classical molecular-dynamics simulation. We apply this method to calculate the optical and electronic properties of the resulting structures with various geometries. The three-dimensional confinement of charge carriers in quantum dots is of special interest due to their possible application in microelectronic and optoelectronic devices with improved electronic and optical properties, and the electron excitations of Ge nanoparticles embedded in a cubic SiC matrix. The combined method is shown to be applicable to embedded nanocrystals in large simulation cells for which the first-principle treatment of the ionic relaxation is presently out of reach, whereas the electronic, optical and excitation properties can already be obtained via first-principles techniques [1] [1].
also detected, around 2.5 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 dot is diminished. For the sample grown at 560 °C, the amplitudes were almost comparable to the quantum dot sizes, and the phonon frequencies were unchanged. The oxidation energy cannot be unambiguously followed anymore. The analysis of the sample grown at 560 °C is performed. The sample grown at higher temperatures revealed no quantum dot formation. The capacitance versus voltage measurements using standard lock-in techniques monitored the presence of the Ge quantum dots in the 300 and 400 °C samples only. (1) S. H. Kwok, P. Y. Yu, C. H. Tung, Y. H. Zhang, M. F. Li, C. S. Peng and J. M. Zhou, Phys. Rev. B35(7), 4880 (1989).

**E7.6** Measurement of the Concentration-Dependent Si-Ge Interdiffusion During Oxidation Enhanced Interdiffusion in Si-Ge Heterostructures, Nevan Ozguner, Daniel B. Aubertine, and Paul C. McIntyre; Materials Science and Engineering, Stanford University, Stanford, California.

We present a study of the effects of Si surface oxidation, a well-established method for injection of interstitial defects into silicon, on Si-Ge interdiffusion in epitaxial heterostructures. Measurements were performed on single crystal Si$_{1-x}$Ge$_x$/Si$_{1-y}$Ge$_y$ superlattices grown by low-pressure chemical vapor deposition onto Si (001) substrates. An epitaxial Si cap, which is partially consumed during dry O$_2$ post-anneals, is grown on these superlattices for the oxidation experiments. Measuring interdiffusion via x-ray diffraction involves monitoring the decay of x-ray (004) or (004) superlattice satellites as a function of annealing time. In a model system, where the interdiffusivity is concentration independent, the logarithm of the superlattice satellite decay rate is linearly proportional to the interdiffusivity, and a straightforward analysis of the data is not possible with SiGe because the interdiffusivity is a strong function of Ge concentration. In previous work we have shown that by using Si$_{1-x}$Ge$_x$/Si$_{1-y}$Ge$_y$ superlattices with an as-grown composition amplitude of less than 2% Ga we are able to extract the interdiffusivity at a multilayer’s mean composition. In this presentation, we describe an observation of the Si-Ge interdiffusion kinetics for the case of oxidation anneals when compared to the as-grown samples. The x-ray scattering method is used to quantify the effects of nonequilibrium point defect concentrations created during Si oxidation on the interdiffusivity of Si and Ge over the temperature range 770°C to 870°C.

**E7.7** Evolution of the Luminescence Spectrum During the Dry and Steam Oxidation of SiGe Films, Andres Rodriguez, Jesus Sangregor, Tomas Rodriguez, Angel Curbelo Prieto, and Manuel Avella; and Juan Jimenez, Tecnologia Electronica, E.T.S.I. de Telecomunicacion, Universidad Politcnica de Madrid, Madrid, Spain, and Fisica 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 optoelectronic devices. To date, there are 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 progressive Ge enrichment of the remaining layer occurs, ending with the formation of elemental Ge, which is subsequently oxidized. For advanced oxidation, Ge oxides appear and nanoparticles of Ge were found to form. When the SiGe films are oxidized in steam, the oxide layer contains a mixture of SiO$_2$ and GeO$_2$ bonds from the very beginning of the oxidation process. Ge segregation also occurs but it is much less important in this process than in the dry one. The cathodoluminescence of these samples was also studied, showing the existence of blue luminescence at 3.1 eV, which is related to the presence of defects at the interface between Ge nanocrystals and the oxide matrix, and a UV band at 4 eV. To clarify the origin of the luminescence bands, dry and steam oxidation processes were carried out using SiGe films of different thickness. In dry oxidized SiGe, the luminescence appears only when x-ray full oxidation, no matter its original thickness, reaches a maximum and then vanishes when the oxidation is completed. In steam oxidized SiGe layers, however, the luminescence progressively increases in intensity as the oxidation proceeds and reaches a maximum when the layer is fully oxidized. The origin of the luminescence is discussed in terms of the nature of the oxides and the presence of nanoparticles in each stage of the oxidation.

**E7.8** Dislocation and Strain Distribution Analysis for SiGe Buffer Layers Formed on Si-Insulator Substrates, Noriyuki Tsuoka, Akira Sakai, Shogo Mochizuki, Osamu Nakatsuka, Shigeki Zaima, Yukio Yasuda, Masaki Ogawa, Tautumu Takaoka, Norichuki Sugiyama and Shin-ichi Takagi; 1Graduate School of Engineering, Nagoya University, Nagoya, Japan; 2Hyogo Science Institute, Kobe, Japan; 3MIRAI Project, Association of Super-Advanced Electronics Technology, Kawasaki, Japan.

For Si-based electronic devices with high mobility and low power-consumption, technologies which combine advantages of using silicon-on-insulator (SOI) substrates with those of strained lattice channels have been recently developed. Strain-relaxed SiGe layers directly formed on SOI or directly forming candidates for substrates to realize these devices. This paper addresses the analysis for microstructures in SOGI formed by two typical methods and clarifies the relationship between dislocation interconnection and strain distribution in SOGI. One of these samples employed here to form SOGI was a Ge-condensation method in which pseudomorphic SiGe layers epitaxially-grown on SOI substrates were oxidized [1]. Strain of the SiGe layers was almost completely relaxed and low threading dislocation density was obtained. On the other hand, X-ray diffraction two-dimensional reciprocal space mapping (XRD-2DRSM) showed asymmetric diffraction profiles indicating that the SiGe layer had mosaic structures. Furthermore, in plan-view TEM images, contrasts relevant to residual strain-undulation, running approximately along two orthogonal in-plane <110> directions, were clearly observed in SOGI although no misfit dislocations lying parallel to the film surface were seen. This result strongly suggests that 50% misfit dislocations glided out of the SiGe layers during the oxidation process while local strain-undulation caused by the dislocations still remained even after the SiGe layer was totally strain-relaxed. We have tried another process in which the strain relaxation of SiGe layers was accomplished predominantly by introducing pure-edge dislocation networks [2]. After cleaning a SOI (001) substrate surface, a low-temperature Ge layer was epitaxially grown and an amorphous Si (a-Si) cap layer was subsequently deposited; a typical sample structure was a-Si (17nm)/200(C-grown Ge (35nm)/SOI (100nm)). The sample was then annealed at 1100°C in N$_2$ ambient. The a-Si and the Ge layers were intermixed and the strain-relaxed SiGe with the pure-edge dislocation network of the SiGe/COI interface could be formed. Furthermore, by 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-2DRSM 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 B89 360 (2002). [2] N. Tsuoka et al., Material Science in Semiconductor Processing.
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 step appears after applying an axial (111) cleavage. A common trend is that 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. These results imply the (relative) stability of the (111)-2x1 cleavage mode. A common viewpoint among the above nanostructures is the competition of two different strain mechanisms; (i) strain due to the global (crack) shape and (ii) strain due to the local atomic or electronic structure. We speculate that the competition is inherent in all the structural properties on the order of 10 nm. [1] Hoshi and Fujiwara, J. Phys. Soc. Jpn (JPSJ) 69, 3773 (2000). [2] Hoshi and Fujiwara, JPSJ 72, 2429 (2003). [3] Takayama, Hoshi and Fujiwara, JPSJ 72, 1519 (2004). [4] In preparation; The current list of our works is seen in our web page: http://ijm.nu-tokyo.ac.jp/~hoshi/ [5] Feestra and Stricos, Phys. Rev. Lett. 59, 2173 (1987) [6] Tokumoto et al., J. Vac. Sci. Technol. B9, 509(1991) [7] Mers et al., Ultramicroscopy 42-44, 516 (1992)

F7.10 Growth and Properties of Core/Shell Silicon Nanowires.
Florian M. Kolb, Herbert Hofmeister, Eckard Pippel, Margit Zacharias and Ulrich Goesele; 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 condensation 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 diameter of 10 nm. With this contribution we present a detailed investigation of the growth mechanisms 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 processes 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 thin amorphous oxide shell. Analyzing the oxide shell using electron energy-loss spectroscopy (EELS) including the energy-loss near-edge fine structure revealed that the silicon oxide contains no silicon suboxides. The nanowires and the gold droplets on their tips were analyzed separately using electron diffraction and high-resolution transmission 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. Goesele, D.D. Ma, S.-T. Lee, Journal of the Electrochemical Society, 151 (7) G472, (2004)

F7.11 Metal-Free Growth of Si Nanowires by Annealing SiOx (x<2) Films Deposited by PECVD.
Xiaojun Wang, Jinzuo 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, these devices are usually fabricated using the catalysis of metals, mostly of which are deep level recombination centers in Si and can deteriorate the performance of the devices based on the Si nanowires thus 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 1000-1150°C. Thinner SiOx films below 300nm in thickness were easier for the growth of SiNWs at lower annealing temperatures. A relatively large N2 flow rate of greater than 10sccm during the furnace annealing was of importance for the SiNW growth, and SiNWs could be sharpened and elongated with the aid of He (2 x 10−3 Torr) accompanying the SiNW growth. SiNWs 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. This mechanism of oxide and furnace annealing processes are suitable to the current Si CMOS technology, this metal-free SiNW growth method promises applications in fabricating high quality Si nanodevices based on SiNWs.

F7.12 Synthesis and Photoluminescence of Silicon–Germanium Alloy Nanowires.
Xiaojun Wang, Jinzuo Zhang, Qiming Wang, Capasso Federico and Zhiwen Ren, Physics, Boston College, Chestnut Hill, Massachusetts; Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts.

Silicon-germanium alloy nanowires were synthesized by thermal evaporation and condensation of the mixture of silicon monoxide and germanium powder without any catalyst. EDS, SAED, SEM, TEM were used to characterize the structure and chemical composition of the nanowires. Photoluminescence study showed that there is a strong infrared emission. And the emission peak position was determined by the ratio of silicon to germanium.

F7.13 VLS Epitaxy of Si and Ge Nanowires: Morphologies, and Properties.

We report on a rich variety of nanostructures which can be synthesized by varying the pressure and temperature in 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 pressures and temperatures in a UHV system. We 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 Fabrication of Uniform Arrays of Nanopillars, Nanospikes and Nanorings Using Modified Nanosphere Lithography.
Jefferson Earl Rose, Chemistry, UCLA, Los Angeles, California; Chemistry, UCLA, Los Angeles, California.

Arrays of uniform Si nanospikes and flat top nanopillars were fabricated using nanosphere lithography for interconnect gateTEM processes. Using a monolayer of self-assembled 470 nm polystyrene nanoparticles as a mask, processing that sequences physical Ar+ pre-etching followed by SF6 chemical etching results in nanopillars or nanospikes. For the same chemical etching conditions, a low energy physical pre-etch gives nanospikes and high energy pre-etch results in nanopillars. Both nanostructures have nanowire interconnects that are intrinsic to the fabrication process and are therefore convenient means electrical wire for future devices. In addition arrays of uniform Si nanorings with flat tops were fabricated using new nanosphere chemical modification lithography. A self-assembled monolayer of 470 nm polystyrene nanospheres was chemically etched followed by mechanical agitation which resulted in a mask of nanoring patterns. Subsequent etching of Si results in nanorings that have a thickness of 100 nm, an outer diameter of 250 nm and an inner diameter of 150 nm. By varying the solvent used during processing nanorings, Si nanowire interconnects could be made optional. The silicon surfaces were studied using AFM and SEM. Single Ge quantum dots were self-assembled on Si nanopillars. The Ge quantum dots appear to be self-aligned to the center of the pillars. Arrays of Si nanowires were formed by nano-sphere lithography on the surfaces of Si. The template used to form the nanopillars was a monolayer of nominally 470nm polystyrene spheres. The resulting nanopillars were 210nm high and 200nm in diameter as determined by tapping-mode AFM and SEM. The Ge was deposited by molecular beam epitaxy at surface temperature of 600 degrees C. The self-assembled and aligned Ge quantum dots were formed after deposition of 10 ML of Ge, as determined by an in-situ quartz crystal monitor. The size of resulting Ge quantum dots was measured by AFM in the tapping mode and were found to be 8nm in diameter. Ge quantum dots were also formed on nanorings. The nanorings were formed using modified-nanosphere lithography (MNSL) a new technique. These advancements and more recent experimental results will be discussed.
In recent years nanotechnology towards realization of quantum information processing has been extensively studied. As a candidate for quantum information processing the present group has proposed "all-gas phase "quantum computer" [1], which utilizes nuclear spins (I) of Si isotopes. We will use a vicinal surface of $^{28}$Si isotope (i=0) as a template for linear chains of $^{28}$Si (I=1/2). In the present study we report successful fabrication of atomic $^{28}$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. After optimizing the deposition amount and the substrate temperature during the growth, a single adatom row was grown along each lower edge of the steps. The single-adatom-row growth was allowed in the 2b wide region just below the step edge, while stacking faults were present in the remaining part. In contrast, a growth was inhibited in the remaining terrace containing the stacking fault because 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. Ladd, et al., Phys. Rev. Lett. 89, 017901 (2002). [2] J. Viernow, et al., Appl. Phys. Lett. 72, 548 (1998); J.-L. Lin, et al., Surf. Sci. 311, 107 (1994).

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-Hoon2 and Kim Na-Ri'1, 'Materials 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; 4Light Materials Team, Korea Institute of Industrial Technology, Chonan, Chungnam, South Korea.

SiC were the promising materials because of its typical properties like wide bandgap, high electron mobility, chemical stability and superior physical properties. Since the discovery of carbon nanotubes, one-dimensional nanoscale materials have received widespread interest due to its potential applications of electrical and optical nanodevices. Carbon nanotube was used strength materials and hydrogen storage materials and optical device materials like FET (Field Emission Tip). SiC nanowire and nanotubes were considered candidate materials of carbon nanotubes because of SiC's superior physical properties. Specially, SiC nanowire's physical properties and thermal stability was studied to FET application. In this study, we fabricated SiC nanowires via APCVD process. The growth temperature was varied 1000 - 1200 °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 fabrication process involved the growth of Si nanowire via way of VLS process through thermal evaporation of Zn as powder in a quartz tube furnace at 1000 °C. Then, the wires were analyzed using TEM, HRTEM, and EDS. The wire diameter was around 100 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.

Synthesis and Characterization of ZnS/Si Wire Heterostructures, Chunchang 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 coals 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 nanowire via way of VLS process through thermal evaporation of ZnS nanowire from the end of Si nanowire by way of a VLS process via liquid phase epitaxy of ZnS in a quartz tube furnace at 1000 °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 using scanning electron microscopy (SEM) (Philips XL30), transmission electron microscopy (TEM) (Philips CM 12), and high resolution transmission electron microscopy. 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 growth 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 Sharma2, Ted I Kanani3, R. Stanley Williams4 and Leonid Tsybeskov1; 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 ~500 inverse centimeters indicates single-crystal quality of Ge NWs. 40 nm 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 indicate 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. 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. Forsh1, Ted I Kanani3, R. Stanley Williams4 and Leonid Tsybeskov1; 1Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, New Jersey; 2Quantum Science Research, Hewlett-Packard Laboratories, Palo Alto, California.

Silicon nanowires 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 nanowire 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 nanowires by molecular beam epitaxy (MBE). The poster presents 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) chamber. The whiskers were generated as seeds, whose size (diameter: 50nm to 150nm) depends on the amount of deposited Au and the substrate temperature. During the subsequent Si deposition (substrate temperature between 400°C and 560°C), nanowhiskers were formed with a diameter ranging from 50nm to 200nm. The length (maximum 1μm) 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 experimental results are discussed on the base of a model including not only the conventional VLS mechanism, but also a strong source diffusion component.

**F7.22 Auger Electron Spectroscopy of Contacts to Si Nanowires.** Bangshik Liu1, Soham Das2, Theresa S. Mayer3, Joan M. Redwing4, Mariano Peralvarez5, M. Lopez5, J. R. Morante5, 1Department of Materials and Engineering, The Pennsylvania State University, University Park, Pennsylvania; 2Department of Electrical Engineering, The Pennsylvania State University, University Park, Pennsylvania; 3Department 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 new devices. In this study, a Physical Electronics Model 670 scanning Auger nanoprobes is used to characterize the diffusion of metals along SiNWs before and after annealing. Special challenges are encountered in such small structures due to the small size of the nanowires 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纳forists are discussed in further information from Auger electron spectroscopy of nanowires. Finally, the reactions between the contacts and nanowires are discussed in the changes of 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, Kyouko Umezu2, Shuichi Tanaka1, Shinro Mashiko1, I. 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 670Pa, silicon nanochains with 4-10nm wide and length up to several microns were formed. Transmission electron microscopy shows the nanochains consist of many links of crystalline silicon nanoparticles. Micro-Raman spectra from the nanochains show an evident downshift of silicon peak and asymmetric broadening. These results also indicate that the nanochains have crystalline silicon core with confinement effects. It is a particular attention that the silicon nanochains have crystalline core without any intentionally annealing process. Fourier transform infrared absorption shows that hydrogen content in the silicon nanochains is 15-30% with Si-H3 configurations. Since the nanochain has silicon core, Si-Si bond is dominantly located on the surface of nanochains. This suggests the surface of nanochains ideally passivated by hydrogen. In the micro-photoluminescence measurements, we observed bright 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 nanochains.

**F7.25 Growth Rate of Silicon Nanowires.** Jun Kikukawa, Yutaka Ohno and Seiji Takeda; Department 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 has also been found that SiNWs grown at the temperatures higher than about 400°C is 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 Grebel2, Viktor Timoshenko2, and Leonid Tsybeskov1; 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 irradiation of silicon samples. 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 emergence of the amorphous phase results in increasing of luminescence efficiency with implanted and annealed samples. Mariano Peralvarez1, M. Lopez1, J. R. Morante1, 1Department of Materials and Engineering, The Pennsylvania State University, University Park, Pennsylvania; 2Department of Electrical Engineering, The Pennsylvania State University, University Park, Pennsylvania.

Si nanocrystals in PECVD silicon oxides and comparison of its luminescence efficiency with implanted and annealed samples, Mariano Peralvarez1, M. Lopez1, J. R. Morante1, 1Department of Materials and Engineering, The Pennsylvania State University, University Park, Pennsylvania; 2Department of Electrical Engineering, The Pennsylvania State University, University Park, Pennsylvania.

**F7.27 Si nanocrystals in PECVD silicon oxides and comparison of its luminescence efficiency with implanted and annealed samples.** Mariano Peralvarez1, M. Lopez1, J. R. Morante1, 1Department of Materials and Engineering, The Pennsylvania State University, University Park, Pennsylvania; 2Department of Electrical Engineering, The Pennsylvania State University, University Park, Pennsylvania.
SESSION F8: Si Nanocrystals and Porous Si: Light-Emitting and Other Properties II
Chair: Albert Polman and Anthony Van Buuren
Wednesday Morning, December 1, 2004
Constitution B (Sherston)

8:15 AM *F8.1 Electric Force Microscopy of Individually Charged Silicon Nanoparticles. Thierry Melin1, Heinrich Diesinger1, Dominique Deresmes1, Thierry Baron2, Sophie Barbet1 and Didier Stievenard1; 1LIM- CNRS UMR 8260, Matisse, Villeneuve dAscq, France; 2Institut de Microelectronique de Nancy, CNRS, UMR 7198, Vandoeuvre-lès-Nancy, France.

We report on charge injection experiments performed on single silicon nanoparticles[1,2] and their analysis by Electric Force Microscopy (EFM). An analytical model will be presented, enabling a quantitative determination of the charge state of the semiconductor nanoparticles from EFM signals, for arbitrary tip and nanoparticle shapes[3]. Experimentally, we provide an analysis of the capacitive and charge interactions taking place in EFM of silicon nanoparticles deposited on conductive substrates. We demonstrate that the weak image interactions associated with charged nanoparticles - of dipole-dipole type- can be identified from a spectroscopic EFM analysis[4]. Finally, we address the issue of the charge injection mechanisms. From the hysteretic behavior of the charge injection processes, we separate volume versus surface charge effects[5]. We show that charges are mostly injected in the nanoparticle volume, with however residual injection on the nanoparticle surface. Volume charge injection mechanisms are modeled in a regime of successive charge tunnelings through the tip/nanoparticle and nanoparticle/substrate oxide tunnel barriers, taking into account quantum confinement and electrostatic effects by solving the coupled Schrödinger and Poisson equations for the charge wavefunctions confined at the nanoparticle substrate interface. Mechanisms of charge saturation will be discussed from the comparison between experiments and theory.[1-5]

8:45 AM *F8.2 Silicon Nanocrystals: From Coulomb Blockade To Memory Arrays. Rajesh A. Rao, Ramachandran Muralidhar, Robert F. Steineke, Sherry Straub, Bruce Hradsky, Jane Yater, Steve Anderson, Erwin Prinz, Craig Swift, Tedlar Merchant, Matt Stoker, Michael Sadow 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 detrapping. The tunneling oxide thickness results in scaling and scaling technology. 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 nanocrystals very attractive as embedded NOR or NAND applications. New aspects in silicon nanocrystal memory technology include Coulomb blockade or charge confinement effects, atomistic nucleation, 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 tuned oxide thickness of 5nm and a 6V power supply.


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 report a ten-fold enhancement in photoluminescence intensity from nc-Si coupled to Au nanomaterials operating 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 Au-Si takes advantage of the metal's relatively large absorption cross section (10^-10 cm^2 for Au vs. 10^-15 cm^2 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 increased radiative rate, but does not quench PL as 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. Jeroen 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 are only efficiently coupled on field magnitudes. This provides a way to enhance 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 outgoing dipole and the metal occurs, leading to the injection 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 local 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 these structured surfaces are highly lossy and that 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 plasmons at the metal-dielectric interface. Quantum dots in SiO2 at different depths using ion implantation, whereupon the sample was covered with an optically thick silver film. For quantum dots placed d=100 nm away from the SiO2-Ag interface, a two-fold increase in decay rate is observed at ~250 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 quantum dimensions and the deep dielectric aspects of the quantum dots.

Our experimental results show how the bare plasmon coupling behavior between the two metal-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.

11:30 AM F8.8
Quasiballistic Electron Emission from Planarized Nanocrystalline-Si Surface Emitting Devices. Yoshihide Tsujiya\(^{1}\), Takuya Nakatsuka\(^{1}\), Hiroshi Mizuta\(^{1}\), Shunri Oda\(^{1,2}\), Akira Kojima\(^{1}\) and Nobuyoshi Koshiba\(^{1}\)
\(^{1}\)Nanoelectronics Research Center, Tokyo Institute of Technology, Tokyo, Japan; \(^{2}\)Department of Physical Electronics, Tokyo Institute of Technology, Tokyo, Japan; \(^{3}\)Department of Electrical and Electronic Engineering, Tokyo University of Agriculture and Technology, Koganei, Japan.

Planar-type cold cathode surface emitting devices based on Si nanofabrication technologies attract much attention because they have many advantages such as high tolerance of vacuum, low operational 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 SiH\(_4\) and its efficiency has been improved by the planarization of the nc-Si layer by the reactive ion etching \(^{1}\). However, electron transport mechanisms 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 surface emitting devices are as follows. The nc-Si dots were deposited onto the n-Si substrates by VHF plasma process. Subsequent oxidation, phosphorus diffusion and annealing process were carried out. With these processes 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.

11:15 AM F8.7
Electron Exchange Interaction in Electronically Confined Si Quantum Dots. Seungwon Lee\(^{1}\), Paul von Almen\(^{2}\), Susan N. Coppersmith\(^{3}\) and Mark Friesen\(^{4}\)
\(^{1}\)Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California; \(^{2}\)Department of Physics, University of Wisconsin, Madison, Wisconsin.

Electron exchange interactions in electronically confined Si quantum dots are modeled with an s\(^{p3}\)d\(^{5}\)s\(^*\) 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 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 inter-dot distance. The exponential behavior is ascribed to the tensile biaxial strain in the Si quantum well, which is epitaxially grown on top of a relaxed Si\(_{1-x}\)Ge\(_x\) 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 valleys. 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).

10:30 AM F8.6
Solid Fullerenes for Tetravalent Semiconductors: The Most Atomlike Quantum Dots. Yufeng Zhao, Yong-Hyun Kim, Mao-Hua Du and Shengbai Zhang


One of the most fascinating properties of carbon is its bistability both in graphite and fullerene forms. One can thus wrap a graphite sheet into the various forms of (hollow) carbon nanotubes and fullerenes with properties distinctly different from those of diamond. Other tetrahedral semiconductors such as Si and Ge, however, do not have such a stable graphene-type structure. For a long time, a fullerene made of Si or Ge has been considered impossible. On the other hand, at the macroscopic scale, one can cut a crystal almost into any arbitrary shapes, for example to a sphere to minimize surface to bulk ratio. With these two contrasting features, we show that small single crystals of an atomic layer, the shapes it can take will be much limited, especially for semiconductors with highly anisotropic surface energies. Seeking for an optimal shape that could yield both low facet energies and high sphericality has been a daunting challenge in semiconductor based nanosciences. Here, we show \(^{1}\) that the two seemingly unrelated subjects are intimately related. In the size range from upper tens to several thousand atoms, a tetravalent semiconductor quantum dot (IQD) has a unique set of properties that can be largely controlled by the surrounding medium. As an example, the quantum dot here is a solid fullerene constructed by bending a solid belt, via the formation of stacking faults, to a seamless full enclosure. Because the solid fullerenes apply to all tetrahedral elements, this prediction opens up new opportunities for all archetypical semiconductors such as Si and Ge, not just for C.

Calculations on hydrogendoped IQDs reveal significantly increased level spacing and up to fivefold orbital degeneracy. Discrete valence states are also evident. This is because, while a cubic structure has only 48 group operations, an icosahedral quantum dot (IQD) has 120 operations, the highest for any point group. Thus, the IQDs represent the most atomlike quantum dots possible, with superior potentials in achieving longer coherence length for quantum information processing, in hot-carrier solar cells, and for better control of the inter-valley phase of electron wavefunctions.

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 nanoarchitectures including perfect lattices. Experimental feasibility of fabricating the IQDs will also be discussed. \(^{1}\) Zhao, Kim, Du, and Zhang, Phys. Rev. Lett. (in press).
Energy distribution of emitted electrons was measured using a conventional ac-retarding-field analyzer [2]. The emission current was observed with an external voltage of 10 V at a temperature of 25 °C. The emission current increased with the application of a 5 V ac voltage, and it was enhanced twice compared with that of single-crystalline silicon (c-Si). Previously, the power density of the cold cathode emitter. [1] K. Nishiguchi, X. Zhao, and S. Oda, J. Appl. Phys. 92, 2577-2579 (2002) observed that the cold cathode emitter. [1] K. Nishiguchi, X. Zhao, and S. Oda, J. App!. Phys. 92, 2577-2579 (2002) 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 layer structure and driving mode. As the sound pressure is proportional to input power, a TiO2 device showed a high power output due to its low thermal conductivity compared to the SiO2 layer. 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 electrostatic field. According to the proposed hypothesis, the maximum acoustic pressures were measured under a pulsed operation at a pulse-width of 16 μs and a pulse-period of 1 s for two devices with different nc-PS layer thicknesses of 2 μm and 5 μm. It has been confirmed that the sound pressure of 2-μm-thick device is enhanced twice compared with that of 5-μm-thick one at the same input power. The frequency dependence of the acceptable maximum input power also shows the behavior as expected from the theoretical analysis. These are consistent with the result of nano-indentation measurements that the hardness and Young's modulus of the nc-PS layer are significantly increased with decreasing its thickness. The present result provides useful information for further progress of the nc-PS acoustooptics. [1] H. Shinoda, T. Nakajima, K. Ueno, and N. Koshida, Nature 400, 853 (1999).

SESSION F9: Group IV Semiconductor Nanowires

1:30 PM *F9.1

Formation of Nanocatalysts for the Growth of Silicon Nanowires, Seiji Takeda, Jun Kikawaka and Hideo Kohno, Department of Physics, Osaka University, Toyonaka, Osaka, Japan.

Silicon nanowires can be grown spontaneously via nanocatalysts. They usually nucleate at nanocatalysts and then grow in a certain direction under the influence of the formation of a nanocatalyst of a desired size at the desired site on a substrate before the growth of nanowires, one can simply decide the nucleation site and the radius of a one-dimensional structure artificially. Furthermore, impurities added to nanocatalysts occasionally induce the nucleation of silicon nanowires. It is also known that twins and polytype structures are frequently observed in silicon nanowires, modulating the electronic structures in some extent. Despite of accumulated experimental data, the mechanism for the formation of nanocatalysts is not clarified. We have examined the formation process of nanocatalysts by means of ultrahigh vacuum scanning tunneling microscopy and transmission electron microscopy (TEM) at high temperatures. Gold-silicon nanocatalysts that we have examined were thought to form on a hydrogen (H)-terminated (111) silicon surface and to expel silicon nanowires of extremely high aspect-ratio via the vapor-liquid-solid (VLS) mechanism. We have observed that a nanocatalyst, i.e. a droplet of melted gold-silicon alloy of about 5 nm in diameter, is normally formed in a pit on a 5 V-terminated surface when the temperature range around 500°C. Based on the result, we have proposed a method of making a thin template, which facilitates to decide the nucleation sites and the sizes of nanocatalysts, resulting in the size control of the nanowires. As the growth Si nanowires is very fast. We have measured the growth rate of Si nanowires ex-situ by TEM. The rate certainly depends on various growth parameters, especially the growth temperatures. We discuss in more details on the kinetics of the growth of Si nanowires. A lot of applications are possible of an array of one-dimensional silicon nanostructures whose arrangement, morphology and interior structures is well controlled. For instance, we can use for fabricating of nano-sensors, micro-electro-mechanical-systems (MEMS) as well as nanoelectronic devices.

2:00 PM F9.2

Synthesis, Properties, and Applications of Modulation-Doped Silicon Nanowires, Chen Yang1, Zhaohui Zhong1 and Charles M. Lieber1,2; 1Department of Chemistry and Chemical Biology, Harvard University, Cambridge, Massachusetts; 2Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts.

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 demonstration of synthesis of modulation-doped silicon nanowires. The nanowires were prepared using nanoclusters-catalyzed vapor-liquid-solid growth process, where electron microscopy was used to verify that no radial over coating occurs during axial elongation and to determine burst times by the temporal burst electrical input. 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 rise rather than an electrical field. Furthermore, the maximum acoustic pressures were measured under a pulsed operation at a pulse-width of 16 μs and a pulse-period of 1 s for two devices with different nc-PS layer thicknesses of 2 μm and 5 μm. It has been confirmed that the sound pressure of 2-μm-thick device is enhanced twice compared with that of 5-μm-thick one at the same input power. The frequency dependence of the acceptable maximum input power also shows the behavior as expected from the theoretical analysis. These are consistent with the result of nano-indentation measurements that the hardness and Young's modulus of the nc-PS layer are significantly increased with decreasing its thickness. The present result provides useful information for further progress of the nc-PS acoustooptics. [1] H. Shinoda, T. Nakajima, K. Ueno, and N. Koshida, Nature 400, 853 (1999).
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 us 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 nanowires 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 [-2 – 1 – 1], 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 (157) 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 growth of Ge nanowires started to ripen 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. Cross-sectional morphologies of SiNWs will be discussed along with observed photoluminescence.

2:45 PM F9.5
Complex Diameter Modulations in Silicon Carbide Nanowire Growth, Hideo Kohno, Hitoshi Yoshida and Seiji Tauleci; 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. We found that 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 nanowire scale. The growth mechanism and degree of decorrelation will be also discussed.

3:15 PM F9.6
 Elemental Semiconductor Nanowires and their Thermoelectric Properties, P. Yang and Rong Pan; University of California-Berkeley, Berkeley, California.

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 research on the growth of elemental semiconductor nanowires and superlattice nanowires. Their precise size, position, and orientational control of these nanowires will be discussed. We will then discuss the interesting thermoelectric 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 II-VI Nanowires, Xinyuan Zhou1, Li Yang1, C. M. Wei2,3, and Mei-Yin Chou1; School of Physics, Georgia Institute of Technology, Atlanta, Georgia; 1Institute of Physics, Academia Sinica, Taipei, Taiwan.

We have investigated the structural, electronic, vibrational, and optical properties of hydrogen-passivated silicon nanowires along [1 1 0] and [1 1 1] directions with diameter d up to 4.2 nm using first-principles density-functional theory. Quantum confinement 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
Silicon nanowires: doping-dependent n- and p-channel FET behavior and UV photoresponse, Kumhoo Byon1, C. K. W. Adu2, P. C. Ecklund2 and J. E. Fischer1; 1Materials Science and Engineering, University of Pennsylvania, Philadelphia, Pennsylvania; 2Department of Physics, Penn State University, University Park, Pennsylvania.

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. H. Lee, J. Mahmood, C. H. Wong, K. W. Adu and P. C. Eklund, Appl. Phys. Letters 81, 2866, 2002). Previous AFM and TEM studies showed that the average diameter is 7nm including 1-2 nm natively. E-beam lithography was used to make 2 and 4 terminal devices with back gates. The morphologies of titanium and gold were 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 FiB (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, photoresponse 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. Dills, Ahmad Mohammadi, Kok-Keong Low, Suzanne E. Mohney 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
Interconnecting nanoscale devices made of one dimensional nanowires (NWs) with dense arrays of nanowires has presented a grand challenge 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 mass integration along with a massively parallel, self-assembly technique for interconnecting these building blocks of nano-electronics is critical for high density, 10^10/cm^2 nanowire feature height. The average feature height changed from 1.0 micron and widths less than 5 nm can be grown on vicinal Si(OOl) substrates with a miscut of 2.5 degree toward the [110] azimuth. We now demonstrate that platinum passivates the Er disilicide nanowire surfaces during reactive ion etching (RIE) of these Er disilicide and Pt coated Er disilicide nanostructures shows that nanowires without Pt on the surface are significantly etched whereas NWs with Pt are not. AFM images were obtained both before and after etching the nanowires to measure the change in nanowire feature height. The average feature height changed from 1.0 nm to 7.8 nm for Pt coated nanowires and from 1.0 nm to 5.8 nm for the remaining uncoated Er disilicide nanowires. Er disilicide nanowires are on the order of 1 nm tall; thus these self-assembled nanowires act as an etch mask to define Si nanowires. Furthermore, Er disilicide nanowires with a lower coverage of Pt on the surface formed arrays, deposited by dots aligned along Si[110] with a very narrow size distribution after RIE. STM images taken prior to etching show that Pt forms clusters on the nanowire surface when the Pt coverage is incomplete. The cluster size is related to the nanowire width. Thus, the Si quantum wires have a narrow size distribution, a high density, 1010/cm^2, and are aligned along the Si[110] direction due to the original template. The Si-quantum dot size is tunable between 1-3nm (depending on the size of the RES disilicide nanowires), the size regime where strong quantum confinement effects are expected. Using scanning tunneling spectroscopy, we measured current rectification at the RES disilicide/p-type Si junction. Coupled with self-assembled molecular layers, these nanoscale mesa junctions could have current switching and rectifying behavior in large arrays may be used for general computing. The achievement of a high density of ordered self-assembled nanostructures is an important precursor to forming sensing, memory and logic devices with density and features sizes not attainable using conventional lithography.

4:45 PM F0.11
Nano-Bridging: An Effective Solution to Interconnecting Nano-Scale Devices. M. Saf Ismail1,2, Shashank Sharma1,2, Ted I. Kamins1 and R. Stanley Williams1,2; 1Quantum Science Research, Hewlett Packard, Palo Alto, California; 2Electrical and Computer Engineering, University of California, Davis, California.

Interconnecting nanoscale devices made of one dimensional nanowires (NWs) with dense arrays of nanowires has presented a grand challenge 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 mass integration along with a massively parallel, self-assembly technique for interconnecting these building blocks of nano-electronics is critical for high density, 1010/cm^2 nanowire feature height. The average feature height changed from 1.0 micron and widths less than 5 nm can be grown on vicinal Si(OOl) substrates with a miscut of 2.5 degree toward the [110] azimuth. We now demonstrate that platinum passivates the Er disilicide nanowire surfaces during reactive ion etching (RIE) of these Er disilicide and Pt coated Er disilicide nanostructures shows that nanowires without Pt on the surface are significantly etched whereas NWs with Pt are not. AFM images were obtained both before and after etching the nanowires to measure the change in nanowire feature height. The average feature height changed from 1.0 nm to 7.8 nm for Pt coated nanowires and from 1.0 nm to 5.8 nm for the remaining uncoated Er disilicide nanowires. Er disilicide nanowires are on the order of 1 nm tall; thus these self-assembled nanowires act as an etch mask to define Si nanowires. Furthermore, Er disilicide nanowires with a lower coverage of Pt on the surface formed arrays, deposited by dots aligned along Si[110] with a very narrow size distribution after RIE. STM images taken prior to etching show that Pt forms clusters on the nanowire surface when the Pt coverage is incomplete. The cluster size is related to the nanowire width. Thus, the Si quantum wires have a narrow size distribution, a high density, 1010/cm^2, and are aligned along the Si[110] direction due to the original template. The Si-quantum dot size is tunable between 1-3nm (depending on the size of the RES disilicide nanowires), the size regime where strong quantum confinement effects are expected. Using scanning tunneling spectroscopy, we measured current rectification at the RES disilicide/p-type Si junction. Coupled with self-assembled molecular layers, these nanoscale mesa junctions could have current switching and rectifying behavior in large arrays may be used for general computing. The achievement of a high density of ordered self-assembled nanostructures is an important precursor to forming sensing, memory and logic devices with density and features sizes not attainable using conventional lithography.

SESSION F10: Poster Session
Chairs: Siegfried Jainz and C. Reynaud
Wednesday Evening, December 1, 2004
8:00 PM
Exhibition Hall D (Hynes)

F10.1 Nano-meter scale metal/Si nanowire junctions and aligned silicon quantum dot arrays for nanoelectronics fabricated with Bi as spacer during growth. Brad Macke1,2,3 and R. Stanley Williams1,2; 1Quantum Science Research, Hewlett Packard, Palo Alto, California; 2Department of Chemistry, Korea Advanced Institute of Science and Technology, Daejon, South Korea.

Research in semiconductor physics is undergoing a paradigm shift. A bottom up or self-assembly approach is being investigated as an alternative to the current top down lithographic approach. Most significantly, the shift from the exclusive use of lithography for device fabrication opens up the possibility of not only developing novel fabrication schemes but to the incorporation of diverse material systems. Hexagonal rare earth disilicide nanowires self-assemble during epitaxial growth as one-dimensioanl metallic nanostructures on Si(001) substrates due to an anisotropic lattice mismatch with Si[110]. We have demonstrated that dense arrays of parallel RES disilicide (RE= Er, Dy, Sm, Gd) nanowires exhibiting high aspect ratios, having lengths exceeding 1 micron and widths less than 5 nm can be grown on vicinal Si(001) substrates with a miscut of 2.5 degree toward the [110] azimuth. We now demonstrate that platinum passivates the Er disilicide nanowire surface during reactive ion etching (RIE) of these Er disilicide and Pt coated Er disilicide nanostructures shows that nanowires without Pt on the surface are significantly etched whereas NWs with Pt are not. AFM images were obtained both before and after etching the nanowires to measure the change in nanowire feature height. The average feature height changed from 1.0 nm to 7.8 nm for Pt coated nanowires and from 1.0 nm to 5.8 nm for the remaining uncoated Er disilicide nanowires. Er disilicide nanowires are on the order of 1 nm tall; thus these self-assembled nanowires act as an etch mask to define Si nanowires. Furthermore, Er disilicide nanowires with a lower coverage of Pt on the surface formed arrays, deposited by dots aligned along Si[110] with a very narrow size distribution after RIE. STM images taken prior to etching show that Pt forms clusters on the nanowire surface when the Pt coverage is incomplete. The cluster size is related to the nanowire width. Thus, the Si quantum wires have a narrow size distribution, a high density, 1010/cm^2, and are aligned along the Si[110] direction due to the original template. The Si-quantum dot size is tunable between 1-3nm (depending on the size of the RES disilicide nanowires), the size regime where strong quantum confinement effects are expected. Using scanning tunneling spectroscopy, we measured current rectification at the RES disilicide/p-type Si junction. Coupled with self-assembled molecular layers, these nanoscale mesa junctions could have current switching and rectifying behavior in large arrays may be used for general computing. The achievement of a high density of ordered self-assembled nanostructures is an important precursor to forming sensing, memory and logic devices with density and features sizes not attainable using conventional lithography.

F10.10 Characterization and Modelling of the Emission at 1540 nm from Silicate Glasses Co-doped with Si and Er Ions. Yousef Lebour1, Paolo Pellegrino1, Jose Moreno1, Cristina Garcia1, Joan Ramon Morante1, Blas Garrido1 and Michel Prassas2; 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 aluminum 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 glass samples were produced. From a multi-implantation scheme we have prepared a 350 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 varied from 2x10^19 cm^-3 up to 6x10^20 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

carriers in Si-NWs which can transfer their energy to ErCl6.

('Er doped silica film was spin coater in alcohol as a cosolvent and adding the

electrical properties. However, the luminescence efficiencies were quite

order effects have been revealed, such as energy up-conversion among Er atoms and concentration quenching. This exhaustive model makes use of several physical parameters which describe the PL process and which have been experimentally determined for each kind of host glass: lifetime at 1540 nm (from 3 to 12 ns, depending on the Er dose), effective absorption coefficient (of the order of 1×10−17 cm−1), radiative transition rate at 1540 nm, concentration quenching and up-conversion coefficients, coupling constant between Er and Si clusters. Finally, the dependence of the optical behaviour of the different processed glasses and the comparison with the structural characterization will be discussed.

F10.4 Luminescence of Rare Earth Doped Si/Al2O3 Co-sputtered Films, Luis F. Fonseca, Carlos Rozo, Oscar Resto and S. Zvi Weiss; Physics, University of Puerto Rico, San Juan, Puerto Rico.

Er3+ and Nd3+ doped Si/Al2O3 thin films have been prepared by rf co-sputtering. Some of these films were annealed to 700°C. Erbium doped Si/Al2O3 films were prepared with different doping 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/Al2O3. The spectral profile of the 1532 nm emission is broader than for an analogous Er3+ doped Si/Al2O3 and the quantity of the [100] orientation is greater than for the [110] orientation. This change of the solubility of Nd3+ (and luminescence for high Nd3+ concentration) in Si/Al2O3 films and changes the spectral shape of the 1532 nm emission with respect to the Nd3+ doped Si/Al2O3 films.

Porous silicon (PSi), obtained from an electrochemical etching of crystalline silicon (c-Si), has efficient photo- and electroluminescences in the visible at room temperature. Since the beginnings of the last decade it was well established that the pores grow preferentially along the [100] crystallographic directions [1]. During the last years, samples obtained form etching (110)-oriented c-Si, called birefringent PSi, have demonstrated to possess a strong anisotropic structure that provides a sensitive tool to analyze atom and molecular systems in isolation in negligible quantities [2]. Furthermore, packs of birefringent porous silicon layers, alternating their porosity and thickness, act as dichroic microcavities with a transmission dependent on the polarization direction of the incident light [3]. In this work, the density-functional theory (DFT) is utilized to study structural and optical anisotropy in birefringent PSi. The DFT within the local density approximation (LDA) is perhaps the most used ab-initio method to calculate ground-state properties of semiconductors. Unfortunately, this approach underestimates the band gaps which can be overcome by shifting the DFT-LDA conduction-band spectrum to higher energies via a scissors operator. The birefringent PSi model is started from a (110)-oriented c-Si substrate and with the same kind of configurations along [100] and [010] crystallographic directions. All the dangling bonds are saturated by hydrogen atoms, as done in Ref. [4]. Firstly, a full geometry optimization is carried out using Car and Parrinello’s method to find the structural ground state. Then, optical properties are obtained through Fermi’s Golden Rule and Kramers-Kronig transformation [5]. A scissors operator of 0.7 eV is included in order to reproduce the experimental value of the c-Si electronic band gap. In particular, for a [110] incident light, polarized along [1-10] and [001] directions, we observe that the difference of refractive index between these two polarizations decay exponentially with the light wavelength, in good agreement with the experimental data of Ref. [6]. Furthermore, the theoretical absorption spectra follow the same photon-energy dependence as the experimental results [1] for each polarization.

F10.6 Abstract Withdrawn

F10.7 Abstract Withdrawn

F10.8 Anisotropically Nanostructured Silicon: A First-Principle Approach, Yuri Bonder and Chang-Wun Wang; Instituto de Investigaciones en Materiales, Universidad Nacional Autonoma de Mexico, Mexico D.F., Mexico.

Luminescence of Rare Earth Doped Si/Al2O3 Co-sputtered Films, Luis F. Fonseca, Carlos Rozo, Oscar Resto and S. Zvi Weiss; Physics, University of Puerto Rico, San Juan, Puerto Rico.

Efficient Si-based light emitting material has been attracting much interest because of its potential application in photonicics with Si technology. In particular, Er-doping of Si material has great importance due to their Er3+ intra-4f emission at 1.54 μm, a standard wavelength for medical applications. For 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 temperature quenching of Er3+ luminescence. On the other hand, excellent optical properties were obtained by using silicon-rich-silicon-oxide (SRSO), which consists of nanocluster Si (nc-Si) embedded inside an SiO2 matrix. Although optical gain as well as efficient LED have been demonstrated, SiO2 matrix makes the growth difficult requiring high voltages or thin SRSO 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 Er3+ doped silica. Silicon nanowires (Si-NWs) were grown by typical VLS method using SiCl4 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 hydrosilylating tetraethoxysilane (TEOS) in 0.05 M HCl aqueous solution with ethanol as a cosolvent and adding the ErCl3·6H2O 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 7h, 550°C for 5min in a flowing N2/He environment. For comparison, a nanowires silica film was coated on pure Si wafer without Si-NWs. We measured the Er3+ 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 172 nm excitation laser was almost twice since the photon excitation cannot excite the Er3+ 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 an generated carriers in Si-NWs which can transfer their energy to Er3+ ions. Also, the temperature dependence of Er3+ lifetime (6.9 μsec 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 silicon nitride thin films will allow the generation of up to 6 eV photons were demonstrated already. Therefore, current injection and efficient Er3+ luminescence can be acquired by sol-gel derived Er-doped silica with Si-NWs.

F10.9 Generation of Singlet Oxygen at Room Temperature Mediated by Energy Transfer from Si Nanocrystals, Minzar Puri, Shingo Minobe, Shing Hayashi, Egon Gross, Joachim Diener and Dmitri Kovalev; 1Department of Electrical & Electronics Engineering, Kobe University, Kobe, Japan; 2Physik Department, Technische Universität Muenchen, Muenchen, Germany.

The molecule-like electronic structure of Si nanocrystals provides them with noble functions which have been realized so far by organic molecules. Very recently, Si nanocrystal assemblies are found to be an efficient photosensitizer for the formation of singlet oxygen (1O2). Singlet oxygen representing electrically excited states of an oxygen molecule is a very important material in biology and chemistry because it mediates important processes in modification of biological structures. Formation of 1O2 requires the presence of light-absorbing photosensitizer with subsequent energy transfer of electronic excitation to molecular oxygen. For efficient energy transfer photosensitizers must have spin-triplet excited states to satisfy the spin-conservation rule during the energy transfer process. Furthermore, the lifetime of the excited triplet state should be long enough to enhance the probability of energy exchange. Si nanocrystals satisfy all these criteria and triplet excitations in Si nanocrystals play the same role as a triplet-excited state of dye molecules. The formation of 1O2 is evidenced by photoluminescence (PL) measurements in the
near-infrared spectral region where a narrow line due to radiative relaxation of the lowest excited singlet state to the ground triple 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 is extremely long, and the exciton recombination rate is three or four orders of magnitude larger in solution than in diluted gas phase. However, in most solvents, deactivation of $^{13}O_2$ is radiationless by collisional electronic to vibrational energy transfer from $^{13}O_2$ to a solvent molecule. Therefore, to obtain anisotropic luminescence, the 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 hexafluoroethane (CaF$_2$). The singlet oxygen lifetime in the solution is about 25 msec, which is about three orders of magnitude longer than that in benzene (C$_6$H$_6$). In this work, we prepare PL from porous Si powder dispersed in CaF$_2$. From the PL studies, 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 Yamaguchi, Keiichi 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 formed in a red bandgap. 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 iso-electronic impurities are doped or carriers in nc-Si are perfectly compensated by simultaneously doping p and n type impurities. In nc-Si, an exciton is confined in a space comparable to or smaller than the Bohr radius, and the wavefunction 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 ion implantation or by codoping in a wide range of ratio, as studied the PL properties. We will demonstrate that proper control of shallow impurities allow us to extend the tunable range of luminescence energy at room temperature below the bulk bandgap (till 0.9 eV). The near-infrared luminescence at room temperature may open up new application of nc-Si based materials on an optical telecommunication field.

**F10.11**

Pump-probe experiments on low loss silica waveguides containing Si nanocrystals.

Daniel Navarro1, Nicolaid Daldossi1, Mirko Melchiorri2, Lorenzo Paolani1, Cristian Garcia3, Paolo Pellegregos4, Ema Garrido1, J.R. Morante1, C. Scheid2, and G. Sarrabayrouse1. 1Physics, University of Trento, Povo (Trento), Italy; 2Electronica, Universidad 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 SiO2 layer, following the procedure outlined by Yeh et al. The nanocrystals active region was about 300 nm, with Si excess ranging from 7% to 13% (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 ellipsometry, optical absorption and luminescence. The rib-loaded structure of the waveguides was fabricated by photolithographic and reactive ion etching processes, with patterned rib widths ranging from 1 to 8 µm. Efficient light propagation was obtained 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 mechanisms involved in the light coupling (collimation and absorption) have 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.

Hisaaki Kuno1, Kazuo Kide2, and Tomio Izumi2; 1Electronic and Computer Engineering, Tokyo Denki University, Hatoyama, 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 the density of Si atoms introduced into the a-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 size distribution of nc-Si is modified 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 luminescent was obtained from the nc-Si at the Si concentration at 9%. When the Si concentration was decreased from 9% to 2%, the luminescent color blue-shifted from red to blue light, because the increase 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 Luminance Properties in Nanocrystalline Silicon Electroluminescent Device.

Kazutsu Sat01, Kenji Hayakawa1, Mitsuaki Iwase2 and Tomio Izumi4; 1Dept. of Electronic and Computer Engineering, Tokyo Denki University, Saitama, Japan; 2Dept. of Applied Science, Tokai University, Hiratsuka, 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 poor performance under luminescence and operating voltage. In this paper, we fabricate 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 nc-Si 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. The nc-Si then, were dispersed uniformly onto the p-type Si wafer with the removal of SiO$_2$ layer by treating in HF solution. And the electrode was formed at top and bottom of the luminescent layer. The top and bottom electrodes were used as indium tin oxide (ITO) and aluminum (Al), respectively. The EL device using nc-Si with the SiO$_2$ layer showed red luminescence with a peak of 650 nm by applying the operating voltage about 5 V. When the SiO$_2$ layer in the EL device was removed by the HF treatment, the operating voltage decreased about 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.

**F10.14**

Photoluminescence from Crystalline Silicon Quantum Dots Embedded in Silicon Nitriles.

Tae Wook Kim1, Back Hyun Kim1, Chang Hee Cho2, Seong Ju Park2, Nae Man Park2 and Gun Yong Sung2; 1Material Science and Engineering, Gwangju Institute of Science and Technology, Gwangin, South Korea; 2Basic Research Laboratory, Electronics and Telecommunications Research Institute, Daejeon, South Korea.

Even though the electronic and optical properties of silicon quantum dots are expected to be very different from those of bulk material, very few experimental evidences have been reported. In this study, we report on the growth of silicon quantum dots and structural and optical properties of silicon quantum dots with various silicon optoelectronic devices. Well-defined crystalline silicon quantum dots(c-Si QDs) embedded in silicon nitride films were grown by plasma enhanced chemical vapor deposition (PECVD) without post annealing. The wavelength of photoluminescence peak of sample was decreased from 697 nm (1.78 eV) to 454 nm (2.73 eV) with decreasing the dot size. High resolution transmission electron microscopy (HRTEM) analysis showed that the average size of Si QDs was in a range of 4.9 to 2.9 nm. In addition, the ring pattern in transmission
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 used in HRTEM imaging 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 assumed infinite potential barrier 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. 1. N.-M. Park, C.-J. Choi, T.-Y. Sung, and S.-J. Park, Phys. Rev. Lett. 86, 1535 (2001) 2. K. Nishio, J. Koga, T. Yamaguchi, and P. Yonezawa, Phys. Rev. B 69 195304 (2004) * sjpark@gst.ac.kr


Understanding the confinement and surface physics of doped and undoped nanocrystals is currently an important field of research. Quantum confinement effects as well as the impact of surface termination are critical to the design and future utilization of these novel materials in devices. We use soft x-ray probes such as x-ray absorption spectroscopy (XAS), photoelectron spectroscopy (PES), and soft x-ray fluorescence (SXF) experiments to determine the electronic structure of a variety of nanostructured materials. We report the changes in the energy position of doped Si nanocrystals for different 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 chemical environment of dopants in semiconductors, which is very difficult to access by other means.

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

F10.16 Structural, Electronic and Defect Properties of Chemically Modified Silicon Nanoparticles. Andrea Baumer1, Martin Stephan Brandt1, Martin Stutzmann1, Claudia Dahmen1, Joerg Auerheim2, Horst Kessler2, H. Wiggers3, M. Pridoehl4, and F. M. Pietra4.

In this study we report on the preparation and characterization of silicon nanoparticles using silicon nitride substrates as templates for nanostructure formation. Semi-crystalline Si quantum dots (a-Si QDs) with well-defined size and distribution of those surface cusps. Surface cusps are formed in the early stage of epitaxy breakdown and we have observed that Ge self-assembled dots can be grown on these cusps. Surface nitrogens are generally of square shape with sides predominantly oriented along [110] directions and are typically 50 nm in size and at least 5 nm deep. The cusps can be very regular in size and their surface density is typically of the order of 1019 cm-2. The dimensions and distribution of the cusps is comparable to that of self-assembled Ge dots on Si and thus these features may be of interest for tailoring dot synthesis. We have observed that Ge self-assembled dots can be grown on cusped surfaces that dot nucleation is enhanced in the vicinity of surface cusps. Large area AFM reveals that surface cusps are decorated by clusters of large dome-like Ge dots, while a lower density of smaller dome and pyramid shape islands is seen away from the dots. These results are suggestive of preferential nucleation at some points to the other, we perform annealing at 800°C for 10 hours with the current direction parallel to the step-edges. Here we find that the dc current direction climbing up the kinks straightens the step-edge more efficiently than the opposite going-down direction. With the climbing-up direction, the kinks are transported away and concentrate at a certain part of the sample. We propose a mechanism in current direction dependent re-distribution of kinks in analogy of stop-bunching phenomena. [K. Yagi et al., Surf. Sci. Rep. 43, 57 (2001)]. We also find that a long annealing duration of at least 10 hours is important to form step edges of a perfectly straight and unique atomic configuration even for samples with the azimuthal misorientation of 1 degree and less. At the conference, we present high-resolution STM images around the steps and discuss the their structures. The knowledge of these structures will provide ideas of how deposited atoms and/or molecules stick to the step-edges, when these straight-edged Si steps are employed as templates for nanostructure formation.


We report on the successful fabrication of the atomically straight step-edge structures on the surface of the Si (111) wafers with the intentional miscut of about 1 degree towards [-1-1-2] direction. High resolution STM shows clearly that a series of parallel single atomic step-edges with the average separation distance of 10 nm are formed along [-1-1-2] direction. Each step edge is completely straight (without any atomic kinks) for about 104 Si atoms and has the identical atomic step-edge structures which are different from the results reported by Himpsel's group [W.Shimada and H. Tochihara, Surf. Sci. 311, 107(1994)]. The method to prepare such structures developed in this study is an extension of the one developed by the Himpsel's group [Lin et al., J. Appl. Phys. 84, 1105 (1998) and J.Vlasiov et al., Appl. Phys. Lett. 72, 348 (1998)]. The differences are the cooling procedures and new discovery of the step-edge more efficiently than the opposite going-down direction. With the climbing-up direction, the kinks are transported away and concentrate at a certain part of the sample. We propose a mechanism in current direction dependent re-distribution of kinks in analogy of stop-bunching phenomena. [K. Yagi et al., Surf. Sci. Rep. 43, 57 (2001)]. We also find that a long annealing duration of at least 10 hours is important to form step edges of a perfectly straight and unique atomic configuration even for samples with the azimuthal misorientation of 1 degree and less. At the conference, we present high-resolution STM images around the steps and discuss the their structures. The knowledge of these structures will provide ideas of how deposited atoms and/or molecules stick to the step-edges, when these straight-edged Si steps are employed as templates for nanostructure formation.


There is currently a broad interest in the development of deposition of group IV semiconductor nanostructures for selective growth of quantum dots and for surface functionalization. In silicon homoepitaxy, lowering the growth temperature results in breakdown of single crystal growth at a limiting thickness that decreases with decreasing temperature. The loss of crystallinity may initially involve point defect formation or surface roughening, followed by twinning, polycrystalline and finally amorphous growth. We have also observed that at relatively high growth temperatures (400-450 °C) the epitaxy breakdown can be very sluggish and proceed via columnar growth in which surface cusps are formed in the early stage of epitaxy breakdown. We have used atomic force microscopy to study the shape, size and distribution of surface cusps. Surface nitrogens are generally of square shape with sides predominantly oriented along [110] directions and are typically 50 nm in size and at least 5 nm deep. The cusps can be very regular in size and their surface density is typically of the order of 1019 cm-2. The dimensions and distribution of the cusps is comparable to that of self-assembled Ge dots on Si and thus these features may be of interest for tailoring dot synthesis. We have observed that Ge self-assembled dots can be grown on cusped surfaces that dot nucleation is enhanced in the vicinity of surface cusps. Large area AFM reveals that surface cusps are decorated by clusters of large dome-like Ge dots, while a lower density of smaller dome and pyramid shape islands is seen away from the dots. These results are suggestive of preferential nucleation at some points to the other, we perform annealing at 800°C for 10 hours with the current direction parallel to the step-edges. Here we find that the dc current direction climbing up the kinks straightens the step-edge more efficiently than the opposite going-down direction. With the climbing-up direction, the kinks are transported away and concentrate at a certain part of the sample. We propose a mechanism in current direction dependent re-distribution of kinks in analogy of stop-bunching phenomena. [K. Yagi et al., Surf. Sci. Rep. 43, 57 (2001)]. We also find that a long annealing duration of at least 10 hours is important to form step edges of a perfectly straight and unique atomic configuration even for samples with the azimuthal misorientation of 1 degree and less. At the conference, we present high-resolution STM images around the steps and discuss the their structures. The knowledge of these structures will provide ideas of how deposited atoms and/or molecules stick to the step-edges, when these straight-edged Si steps are employed as templates for nanostructure formation.

F10.19 Synthesis of Microcrystalline Silicon Films by Low Energy Electron-Beam-Induced Deposition at Cryogenic Temperatures. Junji Uchida1, Kiyokazu Nakagawa2, Tatsuya Tozuka3, and Shouji Sato3, 1Clean Energy Research Center, University of Yamanashi, Kofu, Yamanashi, Japan; 2Center for Crystal Science and Technology, University of Yamanashi, Kofu, Yamanashi, Japan; 3Miyutou Co., LTD., Uenozuma, Yamanashi, Japan.

[Introduction] We have proposed an advanced method for synthesis of semiconductor thin films at substrates temperatures lower than room temperature. This is based on the electron-beam-induced deposition (EBID) combined with vacuum
Silicon nanocrystals (nc-Si) act as an efficient photo-sensitizer for energy transfer from Er ions (Er⁺). The presence of nc-Si in Er-doped SiO₂ enhances the effective absorption cross section of Er⁺ by more than three orders of magnitudes. This enhancement is due to the efficient energy transfer from nc-Si to Er⁺. Since the absorption band of nc-Si covers all the visible range, Er⁺ can be excited by white light. Furthermore, luminescence from Er⁺ in this system shows the optical transition and dual slow processes, with patterned rib widths ranging from 1 to 8 μm. Pump-probe experiments on Er coupled Si-nanocrystals reveal that Er⁺ located within about 1 nm from nc-Si is excited by the fast process, and that in the second field by the slow process. The recombination energy of a bound exciton is transferred to Er⁺ by an Auger-like process. In this mechanism, Er⁺ should be located inside nc-Si or very close to the surface of nc-Si. On the other hand, the slow process is a characteristic process 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⁺ related center in the bandgap, and then the recombination energy of a bound exciton is transferred to Er⁺ by an Auger-like process. In this mechanism, Er⁺ should be located inside nc-Si or very close to the surface of nc-Si.
pumping rates. Efficient light propagation was observed when end-fire coupling a probe signal in the rib waveguide both at 1310 nm and 1550 nm, which is consistent with the bandgap of bulk Si. The transmission spectra are shown in Figure 1. Insertion losses measurement as a function of wavelength in the Er absorption region has permitted to estimate an Er absorption cross section of 1535 nm 6×10⁻²⁷ cm². Pump and probe experiments at 1530 nm show two regimes: at intermediate power the excited state absorption of the Si nanoclusters is observed that is more pronounced at higher pump power as expected due to the excited 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 more pronounced at higher pump power as expected due to the excited state absorption of the Si nanoclusters.

In a similar way, Si nanocrystals embedded in structural analysis of the resulting structures have been performed by supported by EC through the SINERGIA project. Insertion losses measurement as a function of wavelength in the Er absorption region has permitted to estimate an Er absorption cross section of 1535 nm 6×10⁻²⁷ cm². Pump and probe experiments at 1530 nm show two regimes: at intermediate power the excited state absorption of the Si nanoclusters is observed that is more pronounced at higher pump power as expected due to the excited 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 more pronounced at higher pump power as expected due to the excited state absorption of the Si nanoclusters.

The formation of Er and Si clusters doped silica films has been shown in samples with Er concentration higher than 10⁻²⁰ cm⁻³, the Er atoms are always located outside the Si nanoclusters and at the edges of the Si nanoclusters. This strongly suggests a modification of the microscopic structure of this center (labeled Er-1) is characterized by high symmetry type (orthorhombic) and comprises a single Er³⁺ ion and multiple oxygen ligands, most likely in its direct surrounding. Consequently, emission from that center does not suffer from inhomogeneous broadening typical for Si:Er materials prepared by ion implantation, and exhibits an low temperature is characterized on an ultra-narrow linewidth of 7. 2 × 10⁻¹⁰ eV (at T = 4.2 K). This makes Si:Er multi-nanolayer systems attractive for Si photonics. In the contribution, we will review properties of Er-related optical centers formed in the multi-nanolayer structures as revealed by high-resolution time-resolved photoluminescence, excitation and magneto-optical spectroscopies. In particular, the following issues will be addressed: - Details of microscopic structure of the Er-1 center - Excitation cross-section and its variation upon excitation wavelength (band-to-band vs. subbandgap pumping) and mode (cw vs. pulsed) - The percentage of optically active Er-related centers in comparison to the Er concentration - Fast comparison between the two decay kinetics in high pumping rate and Auger quenching based on the experimental findings, potential of Si:Si nanolayers for silicon photonics will be discussed. [1] N.Q. Vinh et al. Phys. Rev. Lett. 90, 066401 (2003). [2] M.A.J. Klik et al submitted for publication.

The three-dimensional confocal microscopy of ultra-high-Q toroidal microcavities on silicon doped with Er and Si nanocrystals demonstrate, we will review properties of Er-related optical centers formed in the multi-nanolayer structures as revealed by high-resolution time-resolved photoluminescence, excitation and magneto-optical spectroscopies. In particular, the following issues will be addressed: - Details of microscopic structure of the Er-1 center - Excitation cross-section and its variation upon excitation wavelength (band-to-band vs. subbandgap pumping) and mode (cw vs. pulsed) - The percentage of optically active Er-related centers in comparison to the Er concentration - Fast comparison between the two decay kinetics in high pumping rate and Auger quenching based on the experimental findings, potential of Si:Si nanolayers for silicon photonics will be discussed. [1] N.Q. Vinh et al. Phys. Rev. Lett. 90, 066401 (2003). [2] M.A.J. Klik et al submitted for publication.
We have deposited Erbium (Er) doped Silicon-rich SiO₂ 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 SiO₂ 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 SiO₂ 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 10³ increase in the Er excitation cross section has been measured for samples containing Si-nc relative to the Er excitation cross section in SiO₂. 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 SiO₂ and is not affected by the presence of the Si-nc/s.