SYMPOSIUM E

Microphotonics–Materials, Physics, and Applications

November 27 – 29, 2000

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* Invited paper

SESSION E1: MICROPHOTONICS AND LITHOGRAPHIC STRUCTURES
Chairs: Edwin L. Thomas and Thomas F. Krauss
Monday Morning, November 27, 2000
Fairfax A (Sheraton)

8:30 AM *E1.1
THE MATERIALS PHYSICS OF MICROPHOTONICS. Lionel C. Kimerling, MIT, Microphotonics Center, Cambridge, MA.

The communications infrastructure of the globe is being rebuilt for an optical-based Internet Protocol instead of the current central office, circuit architecture. The ultimate optical network architecture is undefined, and is totally dependent on the capability of components that do not yet exist. This new generation of integrated passive and active optical components will emerge from a variety of semiconductor and insulator materials and both linear and nonlinear optical phenomena. This talk will project a roadmap for research in the context of the evolving needs of the new telecommunications network architecture.

9:00 AM *E1.2
3-D SILICON PHOTONIC LATTICES, DESIGN FABRICATION AND PROPERTIES. Shawn-Yu Lin, J.G. Fleming, Sandia National Labs, Albuquerque, NM.

The drive for miniature photonic devices has been hindered by our inability to tightly control and manipulate light. In many ways, the current state of photonics technology is similar to that of electronics before the semiconductor revolution. Microelectronics technologies were enabled by the availability of semiconducting crystals of sufficient purity and perfection. This advance allowed components, which had already been proposed by theorists to be realized. Eli Yablonovitch and Sajeev John first proposed the 3-D photonic lattice, the artificial, photonic analogue of a semiconductor, in 1987. The theory developed predicted that highly symmetric 3-D arrangements of materials of strongly differing refractive index contrast would possess a photonic bandgap. A wide range of energies of light would be forbidden, independent of orientation. Such materials could be employed to change thermal emissivity, and be manipulated to form high Q cavities, prisms and waveguides with 90° bends. Such lattices were fabricated in the millimeter regime by the early 1990's, however, until now, fabrication difficulties have hindered further progress in this area. At Sandia National Laboratories we have been able to overcome these fabrication problems using combinations of advanced Si processing techniques to create silicon based lattices with mid-gaps down to 1.1 microns. This advance opens the way for many potential applications: thermal emissivity modification for military systems; spectroscopy; local optical interconnects; miniature super-prisms; wavelength divisional multiplexing. Eventual applications may include ultrafast optical switches, silicon infrared LED's and lasers and, eventually, entire ultra-fast silicon-based photonic circuits. In this presentation we will discuss novel designs, fabrication and properties of these artificial materials. This work was supported by the United States Department of Energy under contract DE-AC04-94AL85000. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

10:00 AM *E1.3
LINEAR AND NONLINEAR CONTROL OF OPTICAL MICRORESONATORS. Amnon Yariv, California Institute of Technology, Pasadena, CA.

Nonlinear optical effects in optical waveguides and especially in fibers are usually regarded as problematic and leading to signal degradation. There are many situations, however, some old – as in Solitons – where they can be utilized to advantage. In this talk I will describe some of these new configurations and results.

10:30 AM E1.4
THREE-DIMENSIONAL YABLONOVITE-LIKE PHOTONIC CRYSTALS BY FOCUSED ION BEAM ETCHING OF MACROPOROUS SILICON. Sebastian Rowson[1], Kang Wang, Alexei Chelnokov[1], Pierre Garoche, Jean-Michel Lourtioz[1]; [1]Institut d'Electronique Fondamentale, Orsay, FRANCE; Laboratoire de Physique des Solides, Orsay, FRANCE.

We report on fabrication of three-dimensional photonic crystals by focused ion beam etching of macroporous silicon. The fabricated Yablonovite-like structures contain up to 25 by 25 by 5 crystal lattice cells with a period of 0.75 micrometers. Photonic bandgaps at wavelengths close to 3 micrometers are shown from reflection measurements and confirmed by numerical calculations. Further reduction of the period is possible using the same technology.

10:45 AM E1.5
FABRICATION OF THREE DIMENSIONS STRUCTURES WITH TiO_2. Koichi Awazu, Electrotechnical Laboratory.

Three dimension photonic crystals by X-ray lithography toward three dimensions photonic band gap materials were fabricated for infrared and visible wavelength. As x-ray source, synchrotron radiation (SR) facility (TERAS, Electrotechnical Laboratory, Japan) was used. Wavelength of white light from SR was obtained in the region of 0.2nm - 1nm and peaking at 0.5nm with 0.05nm thick Be window. The conventional mask technology (W mask and SiN_x membrane) can be used to fabricate three dimension structures in thick resist layers. Three consecutive expositions under a tilt angle of 35 degree with respect to the normal to the substrate and a rotation angle of 120 degree between each exposure were performed in He atmosphere. A honeycomb lattice of holes is used as a parameter for the x-ray mask. Fabricated sub-micrometer period structures contain up to 10 crystal periods. TiO_2 molding was performed on the patterned resist. Resist was removed selectively from the resist-TiO_2 composite with some techniques. Finally, three dimensions TiO_2 structures were obtained.

11:00 AM E1.6
A NEW PROCESS FOR FABRICATING THREE-DIMENSIONAL PERIODIC STRUCTURES MADE OF PHOTO-RESISTS. Kazumi Matsuda, Takashi Matsuura, Junichi Murota, Tohoku Univ, Res. Inst. Electrical Communication, Sendai, JAPAN.

Three-dimensional periodic structures are currently interested because of their application potential to photonic crystals. But the reported fabrication methods contain difficult and complicated processes. In the present paper, a new simple process is proposed for fabricating three-dimensional periodic structures made of photo-resists at low temperatures. After the first photo-resist layer is coated on the wafer patterned with alignment markers and pre-baked, it is exposed to the lithographic light with the first pattern. At that time, the photo-resist is not developed, but only after we repeat the resist-coating and exposure for the desired cycles to the final goal, we develop the photo-resist. In order to suppress mixing of the upper layer resist with the lower one during coating, an about 20nm thick aluminum layer is vacuum-evaporated before each photo-resist coating. Also, this aluminum layer is effective for suppressing penetration of the lithographic light to the lower layer during exposing the upper layer with a different pattern. By applying the above proposed process method, we fabricated a crossed-rod stack structure prototype with Lines&Spaces. A remarkable difference of the structure from the conventional one is that a space is present at some parts below the resist. The minimum feature size of the present prototype made by our g-line stepper was 0.7-1μm. We will reduce the minimum size of the pattern, increase the number of the layers, and fill the space with subsequent low-temperature deposition of materials such as wet-chemical selectively-deposited SiO_2.

11:15 AM E1.7
SILICON BASED TWO-DIMENSIONAL PHOTONIC CRYSTAL STRUCTURES. M.J.A. de Dood, E. Snoeks, A. Moroz and A. Polman, FOM-Institute AMOLF, Amsterdam, THE NETHERLANDS; T. Zijlstra and E.W.J.M. van der Drift, DIMES, Delft, THE NETHERLANDS.

We have designed and fabricated two-dimensional photonic crystal structures based on silicon. Deep anisotropic etching using a high density SF_6/O_2 plasma was employed to fabricate a square lattice of silicon rods. By optimizing the etching process we were able to fabricate structures with a rod radius of ~100 nm and a lattice spacing of 570 nm. Etching as deep as 5 μm was achieved. Calculations predict that these structures have a photonic bandgap for TM polarization centered around 1.5 μm.
To confine the light in the photonic crystal in the vertical direction two index guiding schemes were considered. First, silicon rods were etched in the top layer of a silicon-on-insulator wafer. Index guiding in the photonic crystal is then expected as the effective index of the photonic crystal is higher than that of the SiO_2 underneath. Second, MeV ion irradiation was used to amorphize the top 1.9 μ of a Si substrate. Thermal annealing at 500°C was used to relax the amorphous Si network structure to minimize absorption losses to less than 50 cm^{-1}. The refractive index of amorphous Si is 3.73 at 1.54 μ, significantly higher than that of crystalline Si (n=3.44).
Next, the rod structure was etched through the amorphous Si/crystal Si double layer. For both the SOI and amorphous/crystal structures, in- and output waveguides were integrated with the photonic crystal. Optical measurements to characterize the waveguides were performed. Characterization of photonic crystal structures using these waveguides will be presented as well.

11:30 AM E1.8
ACCURATE DRY ETCHING WITH FLUORINATED GAS FOR TWO-DIMENSIONAL Si PHOTONIC CRYSTAL. Chiharu

Takahashi, Jun-ichi Takahashi, NTT, Telecommunications Energy Labs, Kanagawa, JAPAN; Masaya Notomi, Itaru Yokohama, NTT, Basic Research Labs, Kanagawa, JAPAN.

Silicon is attracting much attention as a photonic material because of its transparency and high dielectric constant in optical-telecommunications wavelength regions. One of the interesting applications is Si photonic crystal (Si-PhC). When a two-dimensional Si-PhC is fabricated, air holes with less than submicrometer diameters and depths greater than 1 μm need to be periodically and densely arrayed in single-crystal Si (sc-Si). The processing technologies developed for electronic devices such as Si LSIs are applicable to PhC fabrication. However, the dry-etching process should be improved because the pattern features of PhCs bring about severe requirements concerning accuracy and aspect ratio. Chlorinated gas is used for anisotropic Si etching in the LSI process because undercutting caused by Cl radicals is negligible for sc-Si. However, the etched shapes of sc-Si have sidewalls with tapered slopes at the bottom outside of the pattern. Using a profile simulator, we attributed the origin of these slopes to negative sputtering at the sidewalls. The tapered slope makes it difficult to achieve Si etching with high accuracy and aspect ratio. For this reason, we investigated Si etching with fluorinated gases. An ECR etching apparatus was used and carbon-containing gases were added. We confirmed that carbon generated in ECR plasma protects the sidewall from undercutting by F radicals, even for air holes 0.2 μm in diam. Hard etching masks with high Si/mask selectivity are necessary for high-aspect-ratio etching. We found that metallic Ni has a selectivity above 100 in our ECR etching with fluorinated gas, and 2D-Si-PhCs with definite photonic band gaps were fabricated by using Ni mask. In addition, the hard masks with a variety of selectivity were investigated in order to further improve the controllability of the etched shape of the air hole.

11:45 AM E1.9
EPITAXIAL FERROELECTRIC $BaTiO_3$ THIN FILMS ON SILICON(001) FOR MICROPHOTONIC APPLICATIONS. Feng Niu, A.R. Teren, Brent H. Hoerman and Bruce W. Wessels, Dept. of MS&E and Materials Research Center, Northwestern University, Evanston, IL.

Ferroelectric thin films have shown considerable potential for high speed photonic and non-linear optical applications. Efforts are currently underway to integrate these films on silicon. In order to obtain near bulk like non-linear optical and electro-optic properties, epitaxial ferroelectric films are required. In this investigation epitaxial $BaTiO_3$ thin films have been deposited by metalorganic chemical vapor deposition (MOCVD) on (001)MgO grown on silicon (001) substrates. The epitaxial MgO, which serves as the low index optical cladding layer, was grown by metal-organic molecular beam epitaxy (MOMBE). A b-SiC template layer was used to stabilize the epitaxial MgO on Si. X-ray diffraction and transmission electron microscopy indicated that $BaTiO_3$ was epitaxial with an orientational relationship given by $BaTiO_3$ (100)//Si (001) and $BaTiO_3$ [110]/ /Si [110]. Polarization measurements indicate the $BaTiO_3$ epitaxial films on Si are ferroelectric. Preliminary electro-optic and waveguide measurements will be presented.

SESSION E2: THEORY, SIMULATION AND ENHANCED EMISSION

Chairs: Axel Scherer and E. Fred Schubert
Monday Afternoon, November 27, 2000
Fairfax A (Sheraton)

1:30 PM *E2.1
ALL-DIELECTRIC HOLLOW WAVEGUIDES AND COAXIAL CABLES FOR OPTICAL COMMUNICATIONS. M. Ibanescu, Y. Fink, S. Fan, E.L. Thomas, J.D. Joannopoulos, Massachusetts Institute of Technology, Cambridge, MA.

The emergence of a dielectric omnidirectional multilayer structure opens new opportunities for low-loss, broadband, and polarization-insensitive guiding of optical light. We have recently designed, fabricated and tested all-dielectric hollow waveguides that permit transmission of optical light in air and around 90-degree bends with low losses. We have also designed all-dielectric coaxial cables that can support guided modes that are very similar to the classic TEM modes of metallic coaxial cables. These modes are very intriguing in that they can be polarization-rotation insensitive and nearly dispersionless. The generality of the underlying concept of these systems and approach suggests potenial relevance not only throughout telecommunications but in other areas as well, such as high-power laser guiding in medical and industrial applications.

2:00 PM *E2.2
THEORY AND SIMULATIONS OF RANDOM LASERS. Costas M. Soukoulis, Xunya Jiang, Ames Laboratory and Department of Physics, Iowa State University, Ames, IA.

Disordered systems that both scatter and amplify light (the so-called random lasers) have been a fascinating subject to study. Over the last five years, there have been substantial theoretical and experimental efforts to unravel the mechanism that gives rise to this amazing behavior. A model to simulate the phenomenon of random lasing is presented. It couples Maxwell's equations with the rate equations of electronic population in a disordered system. Finite difference time domain methods are used to obtain the field pattern and the spectra of localized lasing modes inside the system. A critical pumping rate exists for the appearance of the lasing peaks. The dependence of on the length of the system and the strength of disorders is obtained. The number of lasing modes increases with the pumping rate and the length of the system. There is a lasing mode repulsion. This property leads to a saturation of the number of modes for a given size system and a relation between the localization length and average mode length. Similar behavior is expected to be seen in photonic crystals, too.

3:00 PM *E2.3
PHOTONIC BAND GAP MATERIALS: A NEW FRONTIER IN QUANTUM AND NONLINEAR OPTICS. Sajeev John, University of Toronto, Department of Physics, Toronto, Ontario, CANADA.

Unlike semiconductors which facilitate the coherent propagation of electrons, photonic band gap (PBG) materials execute their novel functions through the coherent localization of photons. Light localization provides a basis for the creation of integrated all-optical microchips. I discuss the synthesis of certain large scale inverse opal structures with a complete three-dimensional PBG centered at wavelengths of importance for telecommunications. I also discuss the possible synthesis of other materials with a larger PBG. When a PBG material is doped with impurity atoms which have an electronic transition that lies within the gap, spontaneous emission of light from the atom is inhibited. Instead, the photon forms a bound state to the atom. I discuss the application of doped PBG materials for micro-lasers and the realization of nonlinear optical effects which occur at a much lower threshold than in ordinary vacuum. I describe the design of an all optical transistor based on collective switching of two-level atoms near a photonic band edge, by external laser field, from a passive state to one exhibiting population inversion.

3:30 PM E2.4
MONOCRYSTALLINE SILICON AND ERBIUM DOPED SILICON BASED MICROCAVITIES FOR OPTICAL DEVICES. Emmanuel Hadji, David Sotta, Vincent Calvo, Thomas Charvolin, Helene Ulmer, Noel Magnea, CEA/Grenoble, DRFMC/SP2M, FRANCE; Olivier Constantin, Francois Baleras, Hubert Moriceau, Pierre Renard, CEA/Grenoble, LETI/DMITEC, FRANCE; Pascal Besson, Marie-Noelle Semeria, CEA/Grenoble, LETI/DMEL, FRANCE.

We show that the simultaneous confinement of electron-hole pairs and photons can noticeably improve the radiative properties of silicon. Very efficient carrier confinement, up to room temperature, is demonstrated on c-Si thin films sandwiched between SiO_2 barriers. The insertion of these light emitting structures in a vertical microcavity allows to further enhance spontaneous light emission. To investigate the application of these microstructures to Si microphotonics, we have fabricated two types of microcavities with spatially confined carriers: mono-crystalline (c-Si) well and erbium doped c-Si well. We present here the design, fabrication and characterization of these Si based vertical microcavities. The cavity thickness is defined by oxidation and etching of a silicon on insulator (SOI) wafer. Then membranes are fabricated by local substrate etching using the buried oxide as an etch stop layer. Finally, dielectric multilayer stacks are deposited on both sides of the membranes. Both 100 mm and 200 mm wafers are processed by this technique. Moreover an erbium implantation step can be incorporated in the process. Measurements of the microcavity optical transmission are in good agreement with theoretical predictions. The photoluminescence of c-Si and c-Si:Er microcavities will be presented and compared to the photoluminescence of c-Si and c-Si:Er non resonant structures.

3:45 PM E2.5
CMOS COMPATIBLE MICRO-EMITTERS. M. Lipson, K. Chen, S. Saini, L.C. Kimerling, MIT, Dept. of MS&E, Cambridge, MA.

Optically passive components that are Si-based, such as waveguides, splitters and bends with very low loss have been recently demonstrated. The lack of optically active CMOS compatible components in a micro-scale may present a limitation to the on-chip optical interconnect technology. In this work we study light confining structures and analyze their feasibility as optical amplifiers and emitters. The main fundamental limit for the feasibility of micro-scale optically active components is the small ion concentration (or gain) in materials such as Er-doped SiO_2 or Si. This limitation can be overcome by using a strong light confining structures in which the electromagnetic field is enhanced by orders of magnitude. We have fabricated Si/SiO_2 microcavities with Q-500. In the cavity, in the region of maximal light confinement a layer of Erbium Oxide was embedded. The cavity mode was tuned by performing angle-resolved measurements. By analyzing the cavity mode dispersion, we show that the electromagnetic field is indeed strongly localized in the Er_2O_3 layer. We measure the photoluminescence obtained by optically pumping the Erbium using an 1.5 micron light source. An enhancement of the spontaneous emission (relative to a thin Erbium Oxide film) of orders of magnitude was observed. By analyzing these results we show the conditions in which lazing and amplification in these structures can be obtained. These results show the feasibility of emitters based on 1D strong light confining structures on Silicon and open the door to applications such as lazing in CMOS compatible micro-optical components.

4:00 PM E2.6
NARROW BAND EMISSION FROM LITHOGRAPHICALLY DEFINED PHOTONIC BANDGAP STRUCTURES IN SILICON: MATCHING THEORY AND EXPERIMENT. Anton C. Greenwald, James T. Daly, Edward A. Johnson, Ion Optics, Inc., Waltham, MA; Thomas George, Jet Propulsion Laboratory, Pasadena, CA; Rana Biswas, Iowa State University, Dept of Physics, Ames, IA.

The authors previously reported discovery of narrow, thermal emission bands from crosses etched into silicon wafers [1]. Emitted wavelengths corresponded to changes in geometrical scale of the lithographically defined features. We will now show that the wavelength of measured peaks can be accurately predicted by modeling the complete electrodynamic problem on a multi-processor computer. New calculations show changes in the emission pattern as a function of etch depth, and have been used to optimize 2D surface geometry for high power emission in a single, narrow band. We will present calculated and measured results for changes in the geometry of the holes etched into the silicon substrate (square, round, cross), changes in arrangement (square or hexagonal), and for variations with feature size, etch depth, substrate resistance, and rounding of feature corners. This research offers promise for a new class of tunable infrared emitter devices. 1 James T. Daly, et. al., MRS Symp. Proc. v515, (2000). This work is supported in part by the NIST Advanced Technology Program contract no: ATP-99-01-2051

4:15 PM E2.7
MODIFIED SPONTANEOUS EMISSION IN AMORPHOUS SILICON-NITRIDE BASED OPTICAL MICROCAVITIES. F. Giorgis, F. Ferrero, P. Mandracci, C.F. Pirri, INFM and Physics Dep. Polytechnic of Torino, ITALY; M. Cazzanelli, L. Pavesi, INFM and Physics Dep. University of Trento, ITALY.

In the recent past, amorphous multilayers with thickness in the range 50 nm to 300 nm, based on amorphous silicon-carbide, silicon-nitride and silicon-oxide were applied for the fabrication of Distributed Bragg Reflectors (DBR)[1] and Fabry-Pèrot (F-P) interference filters [2]. The interest in this kind of application is basically due to the good homogeneity of the layers obtainable and to the easy modulation of the refractive index, obtained simply changing the composition of the adopted alloys. Exploiting such advantages, amorphous silicon-nitride multilayers were deposited by Plasma Enhanced CVD, preparing Bragg reflectors and planar microcavities by using a F-P structure where the spacer was a luminescent layer with high radiative efficiency. Microcavities with high finesse were investigated through stationary and time resolved photoluminescence measurements. In detail, such structures show tunable narrow emission bands (few nm) and a strong resonant enhancement of the luminescence yield (more than one order of magnitude) [3]. These analysis are backed by a study of the emission properties of silicon-nitride alloys and will be discussed in terms of a modified spontaneous emission rate predicted by Purcell or light intensity spatial redistribution due to the anisotropic phonon density of states in the cavities. [1] A. Convertino, A. Valentini, P.V. Giugno, R. Cingolani, Appl. Phys. Lett. 70, 2799 (1997). [2] R.Y. Tsai, L.C. Kuo, F.C. Ho, Appl. Optics 32, 5561 (1993). [3] F. Giorgis, Appl. Phys. Lett. 77, 522 (2000)

4:30 PM E2.8
ENHANCED EMISSION FROM A LIGHT-EMITTING DIODE MODIFIED BY A PHOTONIC CRYSTAL. Alexei A. Erchak, D.J. Rippin, S. Fan. G.S. Petrich, L.A. Kolodziejski, E.P. Ippen, J.D. Joannopoulos, Center for Materials Science and Engineering, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA.

Enhanced light extraction is observed from a light-emitting diode (LED) structure containing a two-dimensional (2D) photonic crystal. In semiconductor LED structures, the extraction efficiency is reduced by the capture of emitted light into planar waveguide modes. The photonic crystal is used to enhance the extraction efficiency by (i) creating a photonic bandgap (PBG) that eliminates the unwanted waveguide modes at the emission wavelength, or (ii) efficiently coupling the planar waveguide modes into radiation modes. To investigate the effect on emission, a 2D array of holes is etched into the top cladding layer of an asymmetric InGaP/InGaAs quantum well (QW) structure emitting around 980 nm. The 50 x 50 micron, 2D photonic crystal LED mesa consists of an active region, a low refractive index spacer layer of oxidized AlGaAs, and an oxidized AlAs/GaAs distributed Bragg reflector (DBR). To create a PBG that overlaps the 980 nm QW emission wavelength, the lattice constant is 315 nm with a hole diameter of 220 nm. The lattice constant and hole diameter is varied to create various photonic crystals. To minimize carrier recombination, the holes do not penetrate the InGaAs QW; however, the hole depth is still sufficient to create a PBG. The DBR reflects the QW emission and the oxide spacer layer minimizes the coupling to the lateral guided modes in the DBR. Spatially-resolved photoluminescence (PL) images were recorded from uniformly pumped LED mesas and selectively pumped regions (~5 microns in diameter) on the LED mesas. Light extraction enhancements as high as 5x were measured from photonic crystal LEDs as compared to LEDs without a photonic crystal. Increased PL emission is observed in LEDs enhanced from Bragg scattering from guided to radiation modes, from Bragg scattering of the PL pump into guided modes for efficient pumping, and from a random pattern of holes.

4:45 PM E2.9
ELECTROMAGNETIC ENERGY TRANSFER VIA NEAR FIELD COUPLING IN YAGI ARRAYS: A LARGE SCALE ANALOG TO PLASMONIC NANOSCALE DEVICES. Stefan A. Maier, Mark L. Brongersma, and Harry A. Atwater, Thomas J. Watson Laboratory of Applied Physics, California Institute of Technology, Pasadena, CA.

The study of microwave energy propagation in arrays of copper rods with millimeter-scale periodicity can serve as an analog to electromagnetic energy transfer in the nanoscale regime via surface plasmon modes in metal nanoparticle chains which have a similar ratio of structure periodicity to the free space wavelength. For metal nanoparticle structures excited at visible wavelengths, we have shown that routing of energy, signal splitting and the building of active structures is possible. We have also investigated the guiding of electromagnetic surface waves along linear arrays of closely-spaced copper rods in the microwave regime at 8 GHz via full electromagnetic field simulations and experimental measurement. The electromagnetic field is highly confined to the guiding structure due to near field coupling between adjacent rods if the spacing between the rods is much less than the wavelength of the guided radiation. Propagation of electromagnetic energy occurs with little attenuation along straight arrays and radiation into the far field occurs only at discontinuities. Energy can be routed around 90 degree corners with a power loss of about 3-4 dB due to reflection and radiation at the corner. Signal splitting via tee structures with one main and two side arms is possible with a power drop of about 8 dB from the main into one side arm. These routing structures can serve as building blocks for active circuits such as switches that employ the interference of surfaces waves with a phase difference. We anticipate the power loss at discontinuities in nanoscale structures to be less than that measured in the microwave regime due to resonant coupling if the surface plasmon mode is excited. Such nanoparticle structures can serve as building blocks for the smallest structures with optical functionality.

SESSION E3: WAVEGUIDES AND EMITTERS

Chairs: Amnon Yariv and Herman Haus
Tuesday Morning, November 28, 2000
Fairfax A (Sheraton)

8:30 AM *E3.1
TWO-DIMENSIONAL PHOTONIC CRYSTAL CHANNEL WAVEGUIDE STRUCTURES PATTERNED IN A GaAs/AlGaAs HETEROSTRUCTURE WAVEGUIDE. Christopher J.M. Smith, Richard M. De La Rue, Optoelectronics Research Group, Glasgow University, Glasgow, SCOTLAND; Segolene Olivier, Maxime Rattier, Henri Benisty, Laboratoire PMC, Ecole Polytechnique, Palaiseau, FRANCE; Thomas F. Krauss, School of Physics & Astronomy, St. Andrews University, St. Andrews, SCOTLAND; Ursula Oesterle, Romuald Houdre, IMO, Ecole Federal de Lausanne, Lausanne, SWITZERLAND; Claude Weisbuch, Laboratoire PMC, Ecole Polytechnique, Palaiseau, FRANCE.

Photonic crystals are now widely recognised as promising candidates for the realization of compact and highly-functional photonic integrated circuits [1]. Due to difficulties in measurements and to a lesser extent in fabrication, it is only recently that there have been experimental measurements on photonic crystal channel waveguides

[2] and compact bends [3] at optical wavelengths. The spectral properties of the photonic crystal channel waveguide formed by removing a few rows of holes from a uniform 2D array of holes etched into a GaAs/AlGaAs waveguide have already been measured [4] and a good overall transmission level has been found. Here we will revise these experiments and present results on the interaction of a waveguide and a microcavity [5] and show preliminary data on 120° bends where filtering action is provided at the bend corner by the inclusion of a lozenge shaped cavity, similar to the ideas proposed in [6]. [1] J.D. Joannopoulos et al., "Photonic crystals: Molding the flow of light," Princeton University Press, 1995. [2] T. Baba et al., "Observation of light propagation in photonic crystal optical waveguides with bends," Electronics Letters, 35, 654-655, 1999. [3] S.Y. Lin et al., "Experimental demonstration of guiding and bending of electromagnetic waves in a photonic crystal," Science, 282, 274-276, 1998. [4] C.J.M. Smith et al., "Quantitative and qualitative analysis of 2D photonic crystal waveguides," presented at PECS, Sendai, Japan, March 8-10, 2000. [5] H. Benisty et al., "All-photonic-crystal coupled cavity and guide," presented at CLEO 2000, San Francisco, May 7-12, 2000. [6] C. Manolatou et al., "High-density integrated optics," J. Lightwave Tech., 17, 1682-1692, 1999.

9:00 AM *E3.2
OPTICAL PROPERTIES OF DIFFERENT TYPES OF GaAs-BASED PHOTONIC CRYSTAL SLABS AND THEIR APPLICATION TO DEVICES. Kuon Inoue, Hokkaido University, Research Institute for Electronic Science, Sapporo, JAPAN.

Recently, a slab type of photonic crystals (PCs) has attracted an increasing interest, because those have potentials of developing a new type of opto-electronic devices and circuits. I review our recent works on two types of GaAs-based PC slabs with air-rod structure; one is an air-bridge type (AB) and the other with both the core- and cladding layers perforated for the conventional waveguide (PW). We measured the transmittance spectra by using a wavelength-tunable laser and also obtained information about the reflectance with a time-of-flight method. The observed spectra are well explained in terms of the corresponding band structures, *i.e.*, the bands of the guided modes for AB-PCs and those for the quasi-guided (leaky) modes with a finite Q-value for the PW-PCs, respectively. We find that for both cases there is a photonic band gap in the Γ-X direction for both TE-like and TM-like modes, respectively. Concerning the out-of-plane leakage of radiation, the transmittance T for the AB-PCs with the period number $N = 10$ is almost 100%, proving that there exist the guided modes inside the light corn, whereas for the PW-PCs, $T \geq 70\%$ for $N = 5$, but it decreases as N increases from 5 to 50, indicating that the radiation loss becomes serious for $N > 10$. So, it is concluded that the AB type is superior to developing a new type of devices, but the PW type can also be used for $N = 5$, hopefully $N = 10$, with the air-filling factor f smaller than 0.35 or less. I will also report on the characteristics of a few devices such as a sharply-bent waveguide and a laser, fabricated from the above PCs. This work was supported by NEDO within the framework of the Femtosecond Technology Project.

10:00 AM *E3.3
MICROSTRUCTURED POLYMER LIGHT-EMITTING DIODES. I.D.W. Samuel, J.M. Lupton, B.J. Matterson, School of Physics and Astronomy, University of St. Andrews, St. Andrews, Fife, UNITED KINGDOM; M.J. Jory, W.L. Barnes, School of Physics, University of Exeter, Exeter, Devon, UNITED KINGDOM.

Semiconducting polymers are very promising materials for display applications. However, like inorganic semiconductors, the light extraction from light-emitting diodes (LEDs) is a serious problem. We have investigated the use of lateral wavelength scale microstructure to address this issue. We show that waveguided light can be Bragg-scattered out of the polymer film, giving control of the spectrum, polarisation and efficiency of the emitted light. We demonstrate working LEDs in which the efficiency is doubled by microstructure.

10:30 AM E3.4
THE EFFECT OF SIZE AND ROUGHNESS ON LIGHT TRANSMISSION IN A Si/SiO_2 WAVEGUIDE: EXPERIMENTS, MODEL, AND A PROTOTYPE. Kevin K. Lee, Desmond R. Lim, Anuradha Agarwal, Hsin-Chiao Luan, James Foresi, Kazumi Wada, MIT, Dept of Materials Science and Engineering, Cambridge, MA.

In optoelectronic circuits, greater miniaturization and thus higher density can be obtained, when a high index contrast (delta n) exists between the core and cladding of a waveguide system. We have previously demonstrated optical devices consisting of micron-sized bends, splitters, resonators, and switches in a high index contrast (delta n=2.0) system using a silicon/silicon dioxide waveguide. Micrometer/nanometer sized interconnects are imperative for dense (1 million devices/sq. cm) integrated optics in telecommunications, and optical interconnection for ULSI circuits. In this work, we experimentally evaluate the effect of size and surface roughness on transmission losses within a Si/SiO_2 waveguide system, and successfully explain the results using a theoretical model. This model accurately predicts that loss increases as waveguide width decreases. Furthermore, we show that a major source of loss comes from sidewall roughness for a Si/SiO_2 system due to its high delta n. We have constructed a complete contour map showing the interdependence of sidewall roughness and transmission loss, to assist users in their design of an optimal waveguide fabrication process that minimizes loss. Additionally, users can find an effective path to reduce the scattering loss from sidewall roughness. From this analysis, we designed and developed a waveguide smoothing technology that reduces the single-mode transmission loss of SOI waveguides from 30 dB/cm to 0.8 dB/cm.

10:45 AM E3.5
WAVEGUIDING AT 1550nm IN PLANAR PHOTONIC CRYSTAL CIRCUITS. Dusan Nedeljkovic[a], Marko Loncar, Theodor Doll, Axel Scherer, Jurriaan Gerretsen[a], and Thomas P. Pearsall[a]; [a]Centre Europen de Recherche de Fontainebleau, Corning, SA, Avon, FRANCE; Department of Electrical Engineering, Caltech, Pasadena, CA.

Planar photonic crystal waveguides and devices may offer the possibility to build photonic circuits with greater density and new functionality compared to existing waveguide devices that are based on the control of light by refraction. The primary vehicles for this research are the study of microcavity lasers as a path to understanding new functionality, and the propagation of light around sharp bends as the path to increasing the packing density of planar optical circuits. In this paper we report our results on the successful demonstration of coupling and guiding of light in a planar photonic circuit incorporating sharp bends. Planar waveguide circuits were fabricated in silicon on insulator wafers using electron-beam lithography and chemically-assisted ion beam etching. The target ratio between the hole radius and the period was 0.4. Waveguides were formed by omitting a row of holes in the structure during lithography. The waveguide benefits from optical confinement in the plane of propagation by the photonic crystal and confinement perpendicular to the plane by total internal reflection. A tunable semiconductor diode laser (4 mW) was used to characterize optical transmission. Butt-coupling of a single-mode fiber was used to introduce the laser output into the photonic crystal. Coupling is optimized by observing the mode at the exit facet of the guide. Waveguiding can be visualized by imaging the light scattered from the top of the guide. We show such guiding around 2 sharp bends over more than 200 microns long. Simultaneous imaging of the photonic crystal showed clearly that the light is confined to the Si waveguide in the center of the structure. When we optimize coupling, the scattered light intensity at the top surface is so small that guiding can no longer be visualized in this way. Waveguide losses have been measured quantitatively and are less than 8 dB/cm. Transmission of TE-polarized light is preferred over TM-polarization. This is one indication that the characteristics of real planar photonic crystal waveguides with a finite third dimension differ from the predictions calculated for infinite two-dimensional waveguide structures, where TM-polarized modes are forbidden. This measured performance represents significant progress relative to previous efforts to control the flow of 1550nm light by planar photonic crystal waveguides. Losses appear to be modest, but more efficient coupling is an important challenge that needs to be met.

11:00 AM E3.6
PROBING PHOTONIC CRYSTAL WAVEGUIDE USING DIFFRACTION GRATING. Y. Desieres, T. Benyattou, R. Orobtchouk, Laboratoire de Physique de la Matiere, UMR CNRS 5511, INSA, Villeurbanne, FRANCE; C. Seassal, P. Pottier, C. Grillet, X. Letartre, P. Viktorovitch, Laboratoire d'Electronique Optoelectronique et Microsystemes, UMR CNRS 5512, Ecully, FRANCE.

The use of bi-dimensional (2D) photonic crystal waveguide (PCW) on classical planar waveguides should be a key point toward high-density integrated optics, not only because efficient highly-bent corners has been theoretically predicted for such structures [1] but also because they represent a natural way for light coupling to high-Q photonic crystal microcavities. However, reported experimental studies on such PCW are still scarce [2, 3] and, as far as we are concerned, arguable if we consider the reported high coupling losses. To overcome this problem, we have used a technique similar to the one developed by Labilloy et al. [4]. We use guided photoluminescence (G-PL) to investigate the propagation of an air-cladding slab mode through a straight 25 μm-long PCW. The PCW was patterned on an InP air suspended membrane including an InAs quantum dots layer. The dots layer allows investigation of a large spectral range near 1.55 μm with lower reabsorption than quantum wells. A diffraction grating located near the PCW exit is used to extract the guided photoluminescence. We report clear evidences for straight photonic crystal waveguiding. Indeed, a strong PL signal extracted by the diffraction grating is detected when the PL excitation is located at the PCW entrance. We will also present the local analysis of the photoluminescence diffracted along the PCW. Sharp structures are detected. They are attributed to Fabry-Perot resonances due to the PCW finite length. These results are explained using a theoretical analysis based on the finite difference in the time domain (FDTD).

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11:15 AM E3.7

PROPAGATION AND RADIATIVE COUPLING IN PHOTONIC CRYSTAL WAVEGUIDES. Caterina Netti, Jeremy Baumberg, Dept of Physics and Astronomy, Univ of Southampton, UNITED KINGDOM; Martin Charlton, Madj Zoorob, Greg Parker, Dept of Electronics and Computer Science, Univ of Southampton, UNITED KINGDOM; David Whitakker, Toshiba Cambridge Research Lab, Cambridge, UNITED KINGDOM.

We have developed a new experimental technique to systematically investigate in a fully quantitative way photon propagation in SiN photonic crystal (PC) waveguides. For the first time this allows us to strongly challenge PC theories. We fabricated PC structures with lattices producing full PBGs in the visible spectrum for both TE and TM electromagnetic modes. Transmission and reflection experiments allow us to probe both propagating and leaky modes and correlate their mutual coupling. Transmission measurements were performed using a novel high-brightness ultra-broad-band achromatically collimated white-light laser source carefully coupled into the waveguide. Samples having different air filling fraction were investigated. Planar 2D calculations performed using a finite-difference time-domain method give a complete picture of the transmission of light through a $finite-sized$ PC. This analysis also allows us to track the propagation of a laser pulse through the modulated structure, giving a clear description of how band gaps form. The introduction of air pores, transverse to the layers with a pitch on the optical wavelength-scale, produces extreme changes of the external reflection properties of the multilayer waveguide. Besides diffraction effects produced by the wavelength-scale periodicity, we demonstrate experimentally a new birefringence which mixes polarisations along specific symmetry directions. Reflection experiments on small areas were performed by means of the high-brightness white light laser source as a function of the incident angle (Θ), the polarisation of the incident and reflected light and the polar angle (Φ). The reflection spectra for TE and TM polarisation contain information on both the multilayer Fabry-Perot reflectivity and the 3D modes of the PC which access the dispersion of the waveguide leaky modes. Theoretical calculations using scattering-matrix treatment show excellent agreement with the experimental results. They confirm the strong potential for designing PCs which introduce specific birefringent symmetries and distributed feedback reflectors able to control mode energies and polarisations.

11:30 AM E3.8

FABRICATION OF ALL-SILICA INTEGRATED OPTICAL WAVEGUIDES FOR USE IN THE ULTRAVIOLET SPECTRUM. Darren R. Dunphy, Michael B. Sinclair, Alan J. Hurd, Sandia National Laboratories, Albuquerque, NM; Dhaval A. Doshi, Hongyou Fan, Shawn Coffee, University of New Mexico, Dept of Chemical and Nuclear Engineering, Albuquerque, NM; C. Jeffrey Brinker, both Sandia National Laboratories and University of NM.

Integrated optical waveguides (IOW's) capable of guiding light in the ultraviolet portion of the electromagnetic spectrum would be of great interest in chemistry and materials science, not only for use as a chemical sensing transducer but also as a tool for fundamental studies of thin film structure. Unfortunately, most waveguide materials do not possess the necessary transparency in the UV. Pure, undoped silicon dioxide is an exception; the utilization of silica in waveguide structures is limited by the lack of suitable low-index, UV transparent substrates, however. We report here the development of IOW's that incorporate a low-index, UV transparent porous silica buffer layer between a nonporous silica waveguide and a standard soda-lime glass substrate. Our buffer layers are fabricated through the surfactant-templated self assembly of sol-gel silica films. Removal of the surfactant after film formation yields a refractive index in the range of ca. 1.2 to 1.35, depending on the identity and concentration of the surfactant. Importantly, the UV transparency of these films is high, as scattering losses from the resultant mesoporous structure are negligible due the small size (< 10 nm) of the pore cavities. Our studies of these important optical parameters will be presented. In addition to refractive index and transparency, buffer layer thickness is another critical consideration in the fabrication of our all-silica IOW's. We will discuss our efforts at modeling the effect of buffer layer thickness on waveguide loss due to leakage into the substrate. Finally, we will present data on actual devices and compare our results with our theoretical calculations.

11:45 AM E3.9

PHOTONIC QUASICRYSTAL WAVEGUIDES. Madj Zoorob, Martin Charlton, Greg Parker, Dept of Electronics and Computer Science, Univ of Southampton, UNITED KINGDOM; Caterina Netti, Jeremy Baumberg, Dept of Physics and Astronomy, Univ of Southampton, UNITED KINGDOM.

A major drawback of photonic crystal waveguides is the different alignment of the photonic bandgaps (PBGs) in different propagation directions. This has led to the focus on high refractive index materials in which the PBGs at least overlap. We show here a new alternative based on the use of high orientational symmetry quasicrystals, which leads to full PBGs in lower refractive index glasses. Periodically patterned 2D photonic crystals in planar waveguides are a promising technology for mesoscale integrated photonics. However the symmetry of the underlying lattice underpins the photon multiple scattering and the optical bands are thus different in different directions. The triangular lattice has the largest (six-fold) rotational symmetry of any regular planar tiling. To improve the orientational independence of these PBG devices, we have instead adopted a 12-fold-symmetric quasicrystal formed by a random arrangement air pores at the corners of squares and equilateral triangles. Silicon-compatible optical waveguides based on SiN core (n=2.02) and SiO cladding (on Si) are then patterned using high-resolution electron beam lithography. Broadband achromatic transmission measurements using a new high-brightness white-light laser technique are used to show the success of these devices, which have full polarisation-independent bandgaps at the telecommunications-compatible near-IR wavelengths. Theoretical simulations have been developed using a finite difference time domain method (since the lack of periodicity precludes efficient plane wave expansions). This confirms the operation of quasicrystal photonic crystals. Glass quasicrystal devices (which are matched to optical fibre refractive indices) are the first structures that are predicted to show full bandgaps in low refractive materials with filling fractions down to 30%. Thus by modifying diffraction space in order to constrain optical propagation, improved integrated optical components can be realised.

SESSION E4: NOVEL MATERIAL PHOTONIC CRYSTALS

Chairs: Kiyoshi Asakawa and Pierre Wiltzius
Tuesday Afternoon, November 28, 2000
Fairfax A (Sheraton)

1:30 PM *E4.1

PHOTONIC CRYSTAL NANOCAVITIES. Axel Scherer, Oskar Painter, Jelena Vuckovic, Marko Loncar, Ali Husain, Tomoyuki Yoshie, Electrical Engineering, Caltech, Pasadena, CA.

The high resolution of lithography and anisotropic etching permits us to microfabricate two-dimensional Bragg mirrors. When defects are introduced into these photonic bandgap crystals, high Q optical nanocavities with very small mode volumes can be created. We evaluate these optical cavities by observing luminescence and lasing, and characterize the propagation of light between such nanocavities by using photonic crystal waveguides. Not only do photonic crystal cavities and waveguides form some of the important building blocks for integrated nano-photonics, but they also permit the exploration of strong coupling with narrow linewdith sources and may result in ultra-low threshold laser sources.

2:00 PM *E4.2

RECENT PROGRESS OF AUTOMATIC SHAPING TECHNOLOGY FOR PHOTONIC CRYSTALS. Yasuo Ohtera[a], Takashi Sato[a], Takayuki Kawashima[b], Kenta Miura[a], and Shojiro Kawakami[b]. [a]Research Institute of Electrical Communication, Tohoku Univ., Sendai, JAPAN; [b]New Industry Creation Hatchery Center, Tohoku Univ., Sendai, JAPAN.

We have established the autocloning technology, which utilizes the

self-shaping effect of dielectric films in sputtering and sputter-etching processes, and confirmed its effectiveness in the fabrication of multi-dimensional photonic crystals. Several passive devices for the near IR wavelengths or visible wavelengths such as polarization splitters, diffraction gratings, and waveplates are successfully operated on the basis of this technology.
In this talk, we will review some new aspects of the development of photonic crystals based on the combination of autocloning technology and the modulation of lattice structures, and demonstrate several applications.
First, we will explain how to modulate lattice structures in autocloned crystals. By changing the surface geometry on a periodically-patterned substrate or the thickness of each part of multilayers, either gradual or abrupt modification of the lattice to any directions can be introduced. Either the lattice constant or orientation or both can be spatially modulated.
Next, we will demonstrate some applications. One of them is the novel index-guiding waveguides, which can be realized by growing a multilayer on a substrate with modulated lattice constants or orientations. It operates at frequencies near the 1st photonic bandgap. Light is confined in the core by the difference in effective refractive indices. This class of waveguides have not only fascinating dispersion characteristics near the bandgap but also have advantages in the fabrication process, as it does not require additional etching processes to isolate the core region and the cladding as is needed for conventional 2D photonic crystal waveguides. Detailed results of the simulations, fabrications, and characterizations of the waveguides will be addressed in the meeting.
We will also discuss other applications such as multi-channel wavelength selective filters and position-tunable superprisms.

3:00 PM *E4.3
SELF ASSEMBLED BLOCK COPOLYMER STRUCTURES AS PHOTONIC BAND GAP MATERIALS. Yoel Fink, Augustine Urbas, Edwin Thomas, MIT, Department of MS&E; Moungi Bawendi, MIT, Department of Chemistry; John D. Joannopoulos, MIT, Department of Physics; Maria Xenidou, Exxon Research.

In this talk current results of the ongoing program aimed at realizing photonic band gaps in self assembled block copolymer systems will be presented. In order to form useful band gaps in the visible regime, periodic dielectric structures made of typical block copolymers need to be modified to obtain appropriate characteristic distances and dielectric constants. Moreover, the absorption and defect concentration must also be controlled. This affords the opportunity to tap into the large structural repertoire, the flexibility and intrinsic tunability that these self-assembled block copolymer systems offer. A symmetric poly(styrene-b-isoprene) (~400k MW) block copolymer was used to achieve a photonic band gap in the visible regime. By swelling the diblock copolymer with lower molecular weight constituents we have been able to control the location of the stop band across the visible regime. One two and three-dimensional crystals have been formed by changing the volume fraction of the swelling media. Methods for incorporating defects of prescribed dimensions into the self-assembled structures have been explored leading to the construction of a microcavity light-emitting device.

3:30 PM E4.4
BURIED PATTERNED GaAs/AlO_x STRUCTURES FOR 2D PHOTONIC CRYSTALS. J.H. Schmid, M. Adamcyk, A. Cowan, J. Mackenzie, V. Pacradouni, B.J. Ruck, T. Tiedje, J.F. Young, Univ of British Columbia, Dept of Physics and Astronomy, Vancouver, BC, CANADA; V. Fink, K. Kavanagh, Department of Physics, Simon Fraser University, Burnaby, CANADA; Y. Feng, Institute for Microstructural Sciences, National Research Council of Canada, Ottawa, Ontario, CANADA.

We propose a new method for fabricating waveguides on GaAs containing laterally periodic structures with a high index of refraction contrast. These structures are suitable for active and passive devices containing one or two dimensional photonic crystals. The principle idea is to create an optical waveguide by overgrowing GaAs on a 30-50 nm thick patterned AlAs layer by molecular beam epitaxy (MBE) without exposing the AlAs to ion damage or oxidation. After regrowth, the buried AlAs layer is laterally oxidized to create a high index of refraction contrast structure consisting of a semiconductor with an embedded patterned oxide. This structure is fabricated by first patterning the GaAs cap of a uniform layered structure using holographic photolithography and electron cyclotron resonance (ECR) etching. This pattern is transferred to the buried AlAs layer by non-selective etching with Cl_2 gas in an etch chamber attached to the MBE chamber. The non-selectivity of the etch ensures that the original pattern propagates down into the semiconductor heterostructure. The Cl_2 etch is carried out at 300 C and $1x10^{-5}$ mbar at an etch rate of 20 nm/min. Since the thermal Cl_2 etch does not involve a plasma there are no ions present during the process and therefore no ion damage to the substrate. The etched sample is then transferred in UHV to the MBE chamber for regrowth. This process protects the AlAs layer from oxidation by eliminating air exposure prior to regrowth. After regrowth, the patterned AlAs layer can be laterally oxidized in a water vapor saturated ambient to yield a high index contrast grating consisting of GaAs and AlO_x (n=1.6). This method is suitable for the fabrication of one-dimensional gratings for DFB lasers or 2D photonic crystals consisting of a continuous layer of AlO_x with GaAs-filled holes. Secondary ion mass spectroscopy results show that for MBE-grown GaAs homoepitaxial thin films where a typical thermal cleaning process is used to remove the native oxide on the wafer, the substrate-buffer layer interface has carbon and oxygen contamination in the 10^{12} cm^{-2} range. These contaminants have detrimental effects to device performance when found near the active layer of a structure requiring an epitaxial regrowth step. We compare the contamination levels at the GaAs/GaAs growth interface resulting from the use of different methods for pre-growth cleaning: atomic hydrogen etching, thermal desorption and Cl_2 etching. We also present, cross-sectional transmission electron microscopy results showing regrown films on buried AlAs layers patterned using the Cl_2 process. We will present 2D-photonic bandstructure calculations for the proposed structures which are based on a Green's functions method that allows one to model the effect of the thin high-index contrast grating on the waveguide in a non-perturbative way.

3:45 PM E4.5
THIN FILM CHALCOGENIDE GLASS WAVEGUIDES AND GRATINGS. H.Y. Hwang, S. Spaelter, J.A. Rogers, J. Zimmermann, T. Katsufuji, S-W. Cheong, and R.E. Slusher, Bell Laboratories, Lucent Technologies, Murray Hill, NJ.

Chalcogenide glasses are promising materials for photonics applications due to a number of attractive properties, including a large Kerr nonlinear refractive index (~500 times silica), large linear refractive index (~2.5), ability to incorporate optically active rare earth dopants, and ease of integration with a wide range of other materials. Thin films of chalcogenide glass have been grown by pulsed laser deposition, and low-loss (<1 dB/cm) single and multimode waveguides have been defined in three ways: growth on ridge silica waveguides, using the photodarkening effect in chalcogenide glass (a permanent linear index change when exposed to bandgap illumination), and patterning ridge waveguides. Long (10 cm) uniform films have been formed by masking and translating the substrate during growth, allowing for the fabrication of test structures and devices. We have demonstrated record phase shifts (~2π) by self-phase modulation in planar waveguides of $Ge_{0.25}Se_{0.75}$. Strong Bragg gratings were fabricated by growth directly on short period gratings (~280 nm) in polymer films on silicon which were replica molded from holographically generated templates.

4:00 PM E4.6
TUNABLE POROUS SILICON PHOTONIC BAND GAP STRUCTURES. J. Eduardo Lugo, Herman A. Lopez, Sharon M. Weiss, Selena Chan and Philippe M. Fauchet, Univ of Rochester, Dept of E&CE, Rochester, NY.

The tuning of one-dimensional photonic band gap structures based on porous silicon will be presented. The photonic structures are prepared by applying a periodic pulse of current density to form alternating high and low porosity layers. The width and position of the photonic band gap are determined by the dielectric function of each layer, which depends on porosity, and their thickness. In this work we show that by controlling the oxidation of the porous silicon structures, it is possible to tune the photonic band gap towards shorter wavelengths. The formation of silicon dioxide during oxidation causes a reduction of the refractive index, which induces the blue shift. The photonic band gap is determined experimentally by taking the total reflection of the structures. In order to understand the tuning of the photonic band gap, we developed a geometrical model using the effective medium approximation to calculate the dielectric function of each of the oxidized porous silicon layers. The two key parameters are the porosity and the parameter β, defined as the ratio between the silicon dioxide thickness and the pore radius before oxidation. Choosing the parameter β to fit the experimental photonic band gap of the oxidized structures, we extract the fraction of oxide that is present. For example, the measured 240 nm blue shift of a photonic bandgap that was centered at 1.7 microns corresponds to the transformation of 30% of the structure into silicon dioxide. A similar approach can be used for oxidized two-dimensional porous silicon photonic structures.

4:15 PM E4.7
SUBMICRON-SCALE FREQUENCY SELECTIVE SURFACES FOR THERMOPHOTOVOLTAIC SPECTRAL CONTROL. James E. Raynolds, Michael Locascio, Lockheed Martin, Schenectady, NY.

Frequency Selective Surfaces (periodic arrays) containing sub-micron scattering elements for use in Thermophotovoltaic spectral control applications have been designed, fabricated, and analyzed. These filters are promising because of their simplicity (few layers vs. many-layered dielectric stacks) and low sensitivity to angle of incidence effects. The demands of maximum efficiency and power density result in stringent requirements on high transmission in the pass band, high reflectivity in the stop band, a sharp transition from low to high transmission, and low overall absorption. This poses a challenging design problem via trade-offs between desirable pass band transmission, stop band reflection and absorption. Detailed comparisons between theory and measurements will be presented.

4:30 PM E4.8
PECVD SILICON OXIDE-AEROGEL AND POLYMER-AEROGEL WAVEGUIDES. S. Ponoth, Dept of Chemical Engineering, N. Agarwal, ECSE Dept, P.D. Persans, Physics Dept, J. Plawsky, Dept of Chemical Eng, Rensselaer Polytechnic Institute, Troy, NY.

Aerogel (porous silicon oxide) is a good candidate material for cladding of waveguides because of its low and controllable refractive index. The high refractive index contrast that is obtained using aerogels as the cladding material implies smaller single mode waveguides and small bending radii, both of which are important factors for the realization of on-chip waveguides. In this paper we describe the processing steps involved in making PECVD silicon oxide-aerogel and polymer-aerogel waveguides. Optical characterization results of these waveguides are also reported. Oxide deposition is done at temperatures ranging from 100°C to 500°C on aerogel films with porosities ranging from 20% to 80%. Prospective applications of these waveguides are for on-chip optical interconnects and for sensors. The scattering losses in the oxide aerogel waveguide seem to be dependent on the adhesion of the oxide to the aerogel and thus scattering could be used as a non-destructive method to evaluate adhesion of films. Supported by New York State Science and Technology Foundation (Grant No. 98-IT-674) and Microelectronics Advanced Research Corporation (Grant No. SPL-98073).

4:45 PM E4.9
OPTICAL SENSORS FROM BLOCK COPOLYMER BASED PHOTONIC CRYSTALS. Augustine M. Urbas, Yoel Fink, Peter Derege, Timothy Swager, Edwin L. Thomas, MIT, Dept. of Materials Science and Engineering, Cambridge, MA.

Optical properties of self-assembled photonic crystals fabricated from block copolymer based systems will be discussed. These systems provide a useful platform from which a variety of optical sensors can be fabricated. We will demonstrate materials exhibiting an optical response to a variety of environmental stimuli. Specifically, the effects of processing, strain, environment and composition will be discussed, as well as, efforts towards device fabrication.

SESSION E5: POSTER SESSION
Chairs: Kazumi Wada, Edwin L. Thomas, Thomas F. Krauss, Pierre Wiltzius and Kiyoshi Asakawa
Tuesday Evening, November 28, 2000
8:00 PM
Exhibition Hall D (Hynes)

E5.1
LIGHT TRANSMISSION FRACTAL STRUCTURE THROUGH DISORDERED MULTILAYER PHOTONIC SYSTEMS.
Fredy R. Zypman, Yeshiva University, Department of Physics, New York, NY.

In the process of growing multilayer systems, there exist a number of factors that limit the accuracy with which the widths of the single layers and their roughness can be measured. For example, in Molecular Beam Epitaxy, the temperature of the source materials cannot be changed infinitely fast. Likewise, the shutters have a finite response time. Finally, there exist impurities and temperature gradients in the substrate's surface. For these reasons, it is interesting to study the effect of randomness on the properties of layered photonic systems. In this theoretical work, we consider a light beam with non-zero frequency width and calculate its transmission through a disordered high-dielectric-contrast layered structure. We generate deviations away from the perfectly ordered structure: each interface is located around the "perfect" position with a probability distribution with width W. For a given growth process, the number of such positions is N. We then calculate the area, A, of the curve T vs W for a given N. Finally we plot log(T) vs log(N) and find a straight line. The fractal dimension is 1.1. We are currently introducing different probability distribution to study their effect on fractal dimensions.

E5.2
Abstract Withdrawn.

E5.3
PHOTONIC CRYSTALS IN A MAGNETIC FIELD. Qiao Feng, Chun Zhang, Jun Wan and Jian Zi, Surface Physics Laboratory, Fudan University, Shanghai, PR CHINA.

One-dimensinal photonic crystals within a magnetic field are studied theoretically by a transfer matrix method. Photonic band structures are different for the left- and right-circular polarization with the introduction of a magnetic field. Photonic bands are found to be shifted upwards for the right-circular polarization and downwards for the left-circular polarization with respect to those without a magnetic field. Photonic bandgaps for the left- and right-circular polarization may partially overlap or separate depending on the frequency and the magnetic field. The resulting outgoing wave may be linearly, circularly, or elliptically polarized. These features could have potential applications in optical devices.

E5.4
PHOTONIC BAND STRUCTURE OF THREE-DIMENSIONAL DIELECTRIC SUPERLATTICES DEVELOPED BY AUTOCLONING TECHNIQUES. Virginie Lousse and Jean Pol Vigneron, Facultés Universitaires Notre-Dame de la Paix, Namur, BELGIUM.

Autocloning techniques [1-2] have recently been proposed as an alternative route for developing periodic dielectric structures, designed as photonic crystals. These structures are usually rumpled layers of semi-conducting or insulating materials deposited on a periodically corrugated substrate surface. Using plane-wave expansions, the photonic band structures of TiO_2-SiO_2 and Ta_2O_5-SiO_2 autocloned superstructures are computed and studied as a function of the layer thickness. The reported computations include dispersion relations, density of states and displacement field amplitude maps.
[1] S. Kawakami, Electron. Letters, 33, 1260 (1997)
[2] T. Sato, K. Miura, Y. Ohtera, T. Tamamura, and S. Kawakami, presented at the 'International Workshop on Photonic and Electromagnetic Crystal Structures', Sendai, Japan (2000)

E5.5
CALCULATION OF CAVITY ELECTROMAGNETIC MODES IN A PHOTONIC SLAB CRYSTAL. Jean Pol Vigneron and Virginie Lousse, Facultés Universitaires Notre-Dame de la Paix, Namur, BELGIUM.

A photonic slab crystal is essentially designed as a two-dimensional array of finite-size, high-aspect-ratio, micropillars, prepared on a highly reflecting, low dissipation, substrate. Microfabrication allows for a wide variety of guiding patterns to be created in these periodic structures. These serve many purposes: radiation accumulation in microcavities (which may contain radiation sources or detectors), and energy transfer in waveguides (with sharp direction changes). In this communication, we report the development of a transfer-matrix computational method specifically designed to describe the waves mainly propagating inside the slab structure. A special attention is paid to the estimation of radiative losses in the substrate and vacuum on both sides of the slab. The possible use of planar dielectric superlattice buffers isolating the slab from the substrate and the vacuum will be discussed.

E5.6
Ge PHOTODETECTORS FOR Si MICROPHOTONICS.
Hsin-Chiao Luan, Douglas D. Cannon, Kazumi Wada and Lionel C. Kimerling, Department of MS&E, Massachusetts Institute of Technology, Cambridge MA; Lorenzo Colace, Gianlorenzo Masini and Gaetano Assanto, Department of Electronic Engineering & National Institute for the Physics of Matter, Terza University of Rome, Roma, ITALY.

We present a technology for the integration of high performance Ge photodetectors with Si Microphotonic components. This technology involves two key elements: the direct epitaxial growth of Ge on Si and the passivation of Ge by oxidation of Si epilayer grown on Ge. This technology is uncomplicated and can be integrated as part of the front-end Si CMOS process technology. High quality Ge epilayers were grown on Si by a two-step ultrahigh vacuum / chemical-vapor-deposition (UHV/CVD) process. Two-step UHV/CVD allows the epitaxial growth of Ge on Si without islanding. Threading-dislocations in Ge epilayers were reduced by cyclic thermal annealing. PIN Ge photodetectors were fabricated. At 1.3 um, we measured a responsivity of 550 mA/W. With the addition of SiO_2 anti-reflection coating, an external responsivity of 770 mA/W was measured. Response time as short as 650 ps was measured. The passivation of Ge epilayers was done in two steps: Si epitaxy on Ge and thermal oxidation. In the first step, a thin-flat Si epilayer was grown on Ge epilayer in the surface reaction controlled regime. In the second step, the wafer was cleaned by standard RCA clean and then a thin layer of thermal oxide was grown into the Si epilayer by dry oxidation. Thin Si epilayer protected the Ge epilayer during RCA clean. Thin thermal oxide provided passivation for the Ge surface. Capacitance-voltage measurement and analysis demonstrated the high quality of the oxide-epilayer surface. Our processing technology and materials are suitable for the integration of Ge photodetectors with Si CMOS technology. Applications for our technology include Si Microphotonic applications such as detectors for fiber-to-the-home receivers and optical interconnects.

E5.7

DUAL WAVELENGTH LASER SOURCE MONOLITHICALLY INTEGRATED WITH Y-JUNCTION COUPLER AND ISOLATOR USING QUANTUM WELL INTERMIXING. J.H. Teng, S.J. Chua, Z.H. Zhang, Y.H. Huang, G. Li, Z.J. Wang, Institute of Material Research and Engineering, SINGAPORE.

Multi-wavelength laser sources are key elements for a variety of applications such as wavelength division multiplexing (WDM), optical recording, and optical color printing. These laser sources can be realized by growth-etch-regrowth and selective area epitaxy methods that need extensive growth capabilities. Post growth quantum well intermixing can be an easy and effective way for the fabrication of photonic integrated circuit. By monolithic integration of different wavelength lasers with coupler in one chip, the complex optical alignment can be eliminated. In this paper, we report the fabrication of a dual wavelength laser source with monolithically integrated isolator and Y-junction coupler using a novel impurity free quantum well intermixing technique. The dual wavelength laser source contains two laser diodes with different wavelength, one Y-junction coupler to couple the two light into one output port, and one isolator to avoid the cross talks between the two channels. Different band gap regions in the wafer were realized by one step selective area quantum well intermixing. Control of the band gap shift was achieved by varying the area of the wafer covered by the Ge strip arrays buried between the wafer surface and the spin-on silica film. The Y-junction coupler is transparent to the two laser channels. The band gap of Y-junction coupler is 78meV and 52meV larger than that of the laser channel 1 and 2 respectively. The isolator employed can avoid the short wavelength channel 2 optically pumping the long wavelength laser channel 1 because it is transparent to channel 1 but absorptive to channel 2. Two distinct wavelengths of 750nm and 769nm can be emitted either simultaneously or independently from the same output port. The two channels show similar threshold current and external differential quantum efficiency.

E5.8

FREQUENCY-DOUBLED Ti:SAPPHIRE ULTRAFAST LASER MICROMACHINING OF Si-ON-SiO_2 FOR PHOTONIC BANDGAP CRYSTAL FABRICATION. Ming Li and Xinbing Liu Panasonic Technologies, Inc., Boston Laboratory, Cambridge, MA.

Photolithographic fabrication of photonic crystals in semiconductors has already been reported in the literature. A 1-D photonic crystal structure in Si-on-SiO_2 waveguide has been made with X-ray lithography [1], and the spectral transmission of such a device has been measured to show good agreement with theory. Here we report promising progress toward the direct fabrication of photonic crystal structures utilizing femtosecond laser machining.
The amplified Ti:Sapphire laser system (Clark-MXR CPA-2000) was operated at a pulse width of 150 fs, a wavelength of 775 nm, a pulse repetition frequency of 330 Hz, and a pulse energy of 800 microJ. This laser beam was first frequency-doubled to 387 nm with a BBO crystal and then focused by a long working distance microscope objective (100X UV microscope objective, N.A.=0.5, f = 2 mm) on a Si-on-SiO_2 wafer (200 nm-thick Si on 1 micron-thick SiO_2). The wafer was mounted on a computer-controlled motorized XY stage with nm-resolution, which in turn was mounted on another PC-interfaced XYZ stage with micrometer-resolution. A microscope imaging system, which used the focusing lens as the objective, was incorporated into the setup to monitor the sample surface and drilling in real-time. This setup is significantly simpler than lithography. With this setup, we have achieved reproducible results of a 200 nm hole array with center-to-center spacing of 420 nm, using ~60 pulses, each of which produces a fluence of ~1/2 of the single pulse breakdown threshold. The 420 nm meets the requirement for 1-D photonic bandgap.
This work was performed under FESTA, which is supported by the New Energy and Industrial Technology Development Organization (NEDO).
References: [1] J.S. Foresi et al., Nature, 390, 143 (1997).

E5.9

STUDY ON INHOMOGENEOUS RADIAL DISTRIBUTION OF DEFECTS IN AS-GROWN AND ANNEALED CZ-Si CRYSTALS BY MULTI-CHROIC INFRARED LIGHT SCATTERING TOMOGRAPHY. Minya Ma, Toshiharu Irisawa, Tomoya Ogawa, Gakushuin Univ, Computer Center, Dept of Physics, Tokyo, JAPAN; Cesare Frigeri, Istituto CNR-MASPEC, PARMA, ITALY.

Abstract Multi-chroic infrared light scattering tomography (MC-IR-LST) and transmission electron microscopy (TEM) have been used to systematically investigate the inhomogeneous radial distribution of defects in as-grown and annealed CZ-Si crystals. A defect morphology of dark stripes was observed for the first time by MC-IR-LST system in a special region in the as-grown CZ-Si crystal. After annealing the crystal at 1150°C for 16 hours in an O2 atmosphere, the dark stripes, which became scattering in width and deep in contrast, were clearly visible in an OSF-ring area. The location of the dark stripes in the as-grown crystal was well coincident with that in the annealed CZ-Si crystal, in which many stacking faults were revealed by TEM analysis. It means that dark stripes as an original grown-in defect were generated during the crystal growth. The quantitative measurement of the inhomogeneous radial distribution of defects in the crystal was carried out and the character of the defects in the different regions was analytically discussed.

E5.10

FABRICATION AND CHARACTERIZATION OF 2D AlGaAs PHOTONIC CRYSTALS WITH HIGH ASPECT RATIO HOLE PATTERNS BY Cl_2 RIBE. Yoshimasa Sugimoto, Niclas Carlsson, Naoki Ikeda, Kiyoshi Asakawa, The Femtosecond Technology Research Association, Tsukuba, JAPAN; Noriko Kawai, Kuon Inoue, Hokkaido Univ. Research Institute for Electronic Science, Sapporo, JAPAN.

AlGaAs-based two-dimensional photonic band-gap crystal (PBC) slab waveguide devices were fabricated using electron beam lithography (EB) and a reactive ion beam etching (RIBE) technique. Air hole-based triangular lattices with lattice constants ranging from 0.32 to 0.45 μm were fabricated on both semiconductor-clad (SC) and air-bridge (AB) structures. For the SC-type structure, periodic air-hole structures were fabricated in an MBE-grown 0.5-μm-thick $Al_{0.1}Ga_{0.9}As$ waveguide (core) layer and a 2.0-μm-thick $Al_{0.35}Ga_{0.65}As$ cladding layer on a GaAs substrate. The etch depth of the air-holes is 0.9 μm, given an entirely perforated core layer and a partially perforated cladding layer. A series of samples was prepared with air-filling factors ranging from 0.3 to 0.5. On the other hand, an AB-type structure that achieved strong optical confinement was fabricated in a 0.3-μm-thick $Al_{0.1}Ga_{0.9}As$ core and a 2.0-μm-thick $Al_{0.8}Ga_{0.2}As$ cladding layer structure by selective wet chemical etching. A sequential treatment with phosphoric acid and buffered hydrofluoric acid was used to remove the cladding layer below the core layer containing a periodic pattern of dry etched cylindrical holes. After wet etching the air-filling factors measured for different samples ranged from 0.47 to 0.64. Each PBC structure was sandwiched between a pair of 3-μm-wide dry-etched stripe waveguides. In a transmission/reflection spectrum with wavelengths ranging from 0.85 to 1.1 μm on an SC-type device, a band-gap with large attenuation exceeding 30 dB was observed for both E- and H-polarization. This work was supported by NEDO within the framework of the Femtosecond Technology Project.

E5.11

SELECTIVE-AREA EPITAXIAL GROWTH OF GaAs IN DEEP DIELECTRIC WINDOWS USING SOLID SOURCE MOLECULAR BEAM EPITAXY. Loke Wan Khai, Yoon Soon Fatt, Zheng Haiqun, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, SINGAPORE; Clifton G. Fonstad, Dept of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA.

An improved selective-area epitaxial growth process for GaAs in deep dielectric windows (DDW) is reported. The growth was carried out on $< 100 >$-oriented semi-insulating (SI) GaAs substrate at 520°C by solid source molecular beam epitaxy (SSMBE) using a valved arsenic cracker source. Dielectric stacks with 10 periods of alternating silicon nitride (2000$\AA$) and silicon dioxide (1000$\AA$) layers were deposited using plasma enhanced chemical vapor deposition (PECVD) for the formation of deep (3μm) dielectric windows. The alternating dielectric layer stack has been shown to be of higher thermal stability than a single dielectric layer. A process of fabricating the DDW structures, which eliminates possible contamination at the growth area during photoresist patterning and removing, and also etching of the DDW, has resulted in improved epitaxial layer quality. Micro-Raman spectroscopy measurements showed a drastic increase in the longitudinal-optic (LO) to transverse-optic (TO) signal ratio from ~4.0 to ~16.0 of the first-order Raman line of GaAs. Supporting evidence from low temperature photoluminescence (PL) showed a reduction in intensity of the conduction band to neutral carbon acceptor (e, C°) emission by a factor of 4.6. This indicates lower levels of carbon contamination originating from the improved fabrication process of the DDW, and also reduction of PL intensity by a factor of 2.1 from neutral or ionized donor and acceptor bound exciton emission due to unintentionally doped species. Scanning electron microscopy images showed smoother surface morphology of the GaAs inside the DDW area. These results could have important implications on the process of MBE regrowth technique for optoelectronics integration.

E5.12
PHOTONIC CRYSTALS BY CONTROLLED DRYING OF COLLOIDAL CORE-SHELL PARTICLES. Krassimir P. Velikov[a], Alexander Moroz[a], and Alfons van Blaaderen[a,b]. [a]Chemistry and Physics of Condensed Matter, Ornstein Laboratory, Debye Institute, Utrecht University, Princetonplain, Utrecht, THE NETHERLANDS; [b]FOM Institute for Atomic and Molecular Physics, Amsterdam, THE NETHERLANDS.

We report on photonic crystals made via a controlled-drying procedure of specially designed high-dielectric ZnS core and low-dielectric SiO_2-shell colloidal particles. The core-shell morphology allows easy control over the filling fraction of the high dielectric material and placement of dyes. For instance, the ZnS core can be doped, e.g. with manganese (luminescent core), or a fluorescent dye can be incorporated at a well-defined radial position into the silica shell in order to probe the local density of states of the photonic crystal. To create localized modes inside the gap, random defects can be created by dielectric doping. Photonic crystals were fabricated using a controlled-drying process, which relies on capillary forces and other surface tension effects to organize colloidal particles. Using two types of particles with different sizes and applying a layer-by-layer crystal growth, a variety of partially new binary (AB, AB_2, and AB_3) colloidal crystals can be created depending on the particle size ratio and volume fraction of the colloids. Binary colloidal crystals of high dielectric spheres, such as ZnS, are potentially interesting as they might have a complete photonic bandgap. The layer-by-layer crystal growth technique also permits controlled in-plane dielectric and fluorescent doping. We have performed optical transmission measurements on thin planar colloidal crystals grown on glass substrates. Experimental results will be compared with numerical calculation using the KKR method.

E5.13
SEMICONDUCTOR SIEVES AS NOVEL MATERIALS FOR NONLINEAR OPTICAL APPLICATIONS. I.M. Tiginyanu, Technical Univ, Chisinau, MOLDOVA; I.V. Kravetsky, G. Marowsky, Laser-Laboratorium Goettingen e.V., Goettingen, GERMANY; J. Monecke, W. Cordts, Technical Univ, Freiberg, GERMANY; H.L. Hartnagel, Technical Univ, Darmstadt, GERMANY.

Electrochemical etching technique was successfully used to fabricate semiconductor sieves of III-V compounds (GaP, GaAs, InP), i.e., two-dimensionally nanostructured membranes exhibiting extremely high spatial variations of the dielectric properties. Depending on the technological conditions (e.g. anodic etching of samples subjected to a preliminary MeV-ion implantation or illuminated in-situ), the distribution of holes may be quasi-uniform or ordered. Material percolation results in a good mechanical stability and efficient thermal conductivity of nanostructured membranes and makes them resistant to optical damage. The presence of holes modifies the refractive index of the material and, in case of their parallel orientation, induces an optical anisotropy that is of particular importance for nonlinear optical applications. Bulk GaAs, for instance, possesses a second order nonlinear optical coefficient several orders of magnitude higher than that of KDP, ADP and other materials broadly used in upconversion. However, the utilization of large nonlinear susceptibilities of III-V compounds has not been possible due to the lack of birefringence necessary for phase matching. In this work we present results of an optical second harmonic generation (SHG) study in membranes of III-V compounds subjected to nanotexturization. A Q-switched Nd-YAG laser was used as a pump beam source. The SHG rotational and fundamental polarization dependencies are indicative of optical homogeneity and uniaxial symmetry of the membranes. A SHG efficiency at least two orders of magnitude higher than that of bulk materials is reported and the phase matching conditions for membranes with porosity-induced anisotropy are deduced. We show that the artificial anisotropy and the enhanced nonlinear optical response induced by nanotexturization make semiconductor sieves very promising for use in all-optical devices.

E5.14
OBSERVATION OF QUANTIZED PHOTONIC BANDS IN QUANTUM WELL STRUCTURE OF PHOTONIC CRYSTAL. S. Yano, Y. Segawa, Photodynamics Research Center, The Institute of Physical and Chemical Research (RIKEN), Sendai, JAPAN; J.S. Bae, K. Mizuno, Research Institute of Electrical Communication, Tohoku University, Sendai, JAPAN; H. Miyazaki, Dept of Applied Physics, Tohoku University, Sendai, JAPAN; K. Ohtaka and S. Yamaguchi, Dept of Applied Physics, Chiba University, Chiba, JAPAN.

The quantum well structure was fabricated using two kinds of photonic crystals in milli-meter wave region. The photonic crystal are fabricated by layered the 2D lattice made by Si_3N_4 spheres. The transmittance spectra were measured in normal incident for 2D lattice when well crystal is various well thickness. A lot of sharp transmitted peaks were observed in the stop band of barrier crystal. Some of peaks are observed in same frequency for different well number. From the similarity of semiconductor, they are assigned the quantized state of photonic band. To discuss the symmetry of observed fine peaks, the intensity of electrical field was measured in air gap of well crystal. Then, the different patterns of electrical field were observed for each peaks. These structures are well explained the concept of the quantization of photonic band, that is, the transmitted peaks are quantized state of single quantum well. This model is much advanced than the idea of multi mode of impurity state because the number and frequency of the confined fine structure in stop band are easily expected by the photonic band dispersion.

E5.15
OPTICAL PROPERTIES OF FABRY-PEROT MICROCAVITY WITH Er-DOPED HYDROGENATED AMORPHOUS SILICON ACTIVE LAYER. A.B. Pevtsov, A.A. Dukin, N.A. Feoktistov, V.G. Golubev, A.V. Medvedev, Ioffe Physico-Technical Institute RAS, St. Petersburg, RUSSIA; A.V. Sel'kin, Centro de Investigaciones en Dispositivos Semiconductores, Instituto de Ciencias, Univesidad Autonoma de Puebla, MEXICO.

It is well known that cavity systems enable to control the emission properties by confinement of photons in both quantum-size embedded systems and three-dimensional bulk materials. In this work, the room temperature transmission, reflection and spontaneous emission characteristics of the a-Si:H/a-SiO_x:H Fabry-Perot planar microcavity with the a-Si(Er):H active region were studied. The multiple-quarter-wave stack distributed Bragg reflectors (DBR) and the active layer were fabricated by plasma-enhanced chemical vapor deposition technique in a single technological cycle without exposure to air between the intermediate operations. A specially synthesized metalorganic compound was used to incorporate Er in the active a-Si:H layer. The cavity eigenmode was in resonance with the 1.54 μm emission of the 4f electronic transition for Er^3 ions in a-Si:H. The bottom and top reflectors consisted of 3 pairs of a-Si:H ($\lambda/4 = 110$ nm, refractive index n =3.5 at 1.54μm) and a-SiO_x:H ($\lambda/4 = 225$ nm, n =1.7 at 1.54 μm) quarter-wave layers, respectively, the $\lambda/2$ active region thickness being around 220 nm. The high dielectric contrast between a-Si:H and a-SiO_x:H enables to achieve the high quality factor of microcavity ($\approx$ 240) with the small number of layers in DBR. The two order enhancement and selective narrowing (up to 6 nm) of the Er emission line was observed as compared to the case of the single a-Si(Er):H film deposed on a quartz substrate. Angle of incidence behavior of the cavity transmittance, reflectance and emission spectra was studied. Theoretical calculations of the reflection, transmission and photoluminescence spectra based on the actual parameters of the cavity have been performed which show a good agreement with the experimental data obtained.

E5.16
THEORETICAL INVESTIGATION OF IV-VI COMPOUND SEMICONDUCTOR MID-INFRARED VERTICAL CAVITY SURFACE EMITTING LASERS. S. Khosravani and Z. Shi, School of Electrical and Computer Engineering, University of Oklahoma, Norman, OK.

Mid infrared diode lasers are mainly used for trace-gas-sensing applications. Performance requirements that are not yet available include continuous wave (cw) operation at temperatures higher than thermoelectric cooler range, spectral purity, and reasonable output powers with good beam quality. Recently, we have reported IV-VI compound semiconductor mid-infrared VCSELs that operate near room temperature. In this work, theoretical calculations on such VCSELs are made. While Auger processes are the primarily mechanism responsible for the rapid degradation of III-V interband semiconductor laser performance with increasing wavelength, it is well known that the Auger coefficient in IV-VI structures is an order of magnitude less than those in type-II QWs, which are in turn significantly suppressed relative to other III-V and II-VI semiconductors with the same energy gaps. Our calculations show that Auger recombination does not hinder PbSe laser system to have sufficient material gain for above room temperature operation. However, Auger recombination is clearly the dominating loss channel and the major source of heat generation. Compared with the conventional IV-VI lasers on IV-VI substrate heat dissipation with the new VCSEL structure is improved but insufficient heat dissipation still limits the room temperature laser operation in cw mode. For an optically pumped PbSe lambda-cavity active region with PbSrSe/BaF_2 broadband high reflectivity mirrors on BaF_2 substrate the calculated highest cw temperature is about 265K. If the VCSEL structure is optimized for 250K operation, the calculated threshold pump intensity is 50kW/cm^2 and the efficiency is around 3%. While the preliminary vertical-cavity lasing results are quite encouraging, substantial improvements should be possible. Quantum well (QW)

VCSELs are projected to have not only superior gain and differential gain properties but also much lower thresholds and internal losses. Ultimately, electrical injection and single-mode cw emission at thermoelectric cooler temperatures are envisioned.

E5.17
FORMATION MECHANISMS OF DEFECTS IN ERBIUM/ OXYGEN IMPLANTED SILICON. X. Duan, Y. Ohno, J. Michel and L.C. Kimerling, MIT, Dept. of Materials Science and Engineering, Cambridge, MA.

Erbium doped silicon has been used for Light Emitting Diode (LED) devices. An oxygen ligand field is required for optical activation of the erbium. The formation mechanism of defects in erbium/oxygen co-implanted silicon was systematically studied using TEM, HRTEM and SIMS. Our investigation shows that the residual implantation induced damage nucleates defect formation. Implantation of Er/O at 400keV with subsequent annealing did not cause any extended defects in (100) Si. High energy implantation of Er/O at 4.5MeV in (100) Si, however, creates several forms of secondary defects consisting of dislocations, dislocation loops and precipitates after annealing. It was found that oxygen influences the formation of secondary defects. Upon reducing the residual implantation damage in the Si matrix, oxygen tended to segregate into Frank-type dislocation loops where platelet precipitates of Er_2Si_5 formed along habit planes of {111}. Following association of oxygen and erbium, the plate-like Er_2Si_5 with a habit plane of {111} dissociated and Er_2O_3 was generated. A model for the conversion mechanism between the phases Er_2Si_5 and Er_2O_3 is proposed.

E5.18
ANALYSIS OF ELECTROMAGNETIC WAVE PROPAGATION THROUGH PHOTONIC CRYSTALS WITH GAIN AND LOSS. Hideaki Taniyama and Tahito Aida, ATR Adaptive Communications Research Laboratories, Kyoto, JAPAN.

Recently, periodic dielectric structures (photonic crystals) have attracted much attention because of their ability to control the propagation of electromagnetic waves. These structures possesse physical properties such as existence of photonic band gaps and anomalous dispersion relations, which open many exciting possibilities for the applications. Predicted applications include thresholdless operation of lasers based on the inhibition of spontaneous emission, optical waveguides where light propagates along lines of defects and wave length sensitive anomalous refraction caused by the anisotropy of the optical band structures. Control of these characteristics by external input signals such as electric currents or electromagnetic waves as the control signals also require intensive studies for applications such as optical switch or optical modulators. In this paper, we propose photonic crystals in which some lattice points are made of materials with gain or loss embedded in a medium. The characteristics of wave propagation depend on the gain or loss coefficients of those materials. We study theoretically the electromagnetic wave propagation characteristics through several kinds of photonic crystals with gain or loss lattice points. Multiple scattering method is used to calculate electromagnetic wave propagation through the photonic crystals with finite range of periodicity[1,2]. Controlled transmission spectrum and the direction of the transmitted wave by changing the gain coefficient of the materials are investigated in detail. Both two-dimensional and three-dimensional photonic crystal structures are analyzed in this study. References: 1) A.Z. Elsherbeni and A.A. Kishk, IEEE Trans. Antennas Propagat., 40, 96 (1992). 2) N. Stefanou, V. Karathanos, and A. Modinos, J. Phys: Condens. Matter 4, 7389 (1992).

E5.19
NONLINEAR OPTICAL RESPONSES OF SPIN-COATED VANADIUM OXIDE FILMS. Masanori Ando, Kohei Kadono, Kenji Kamada and Koji Ohta, Osaka National Research Institute, AIST, MITI, Dept of Energy and the Environment and Dept of Optical Materials, Ikeda, Osaka, JAPAN; Jean-Francois Delouis, Keitaro Nakatani and Jacques Delaire, Ecole Normale Superieure de Cachan, PPSM, Cachan, FRANCE.

Transition metal oxides attract growing interest as a new class of nonlinear optical materials for two reasons. One reason is that some transition metal oxides are theoretically predicted to show large optical nonlinearity reflecting strong correlation of electrons. Another reason is that many transition metal oxides have good thermal and chemical stability. We investigate the temporal behavior of third-order optical nonlinearity, nonlinear transmission and transient absorption, of V_2O_5 films prepared by pyrolysis of vanadium 2-ethylhexanoate spin-coated on glass substrate. The V_2O_5 film shows a third-order nonlinear susceptibility of $1.2x10^{-8}$ esu at a wavelength of 532 nm by the degenerate four-wave mixing (DFWM) technique using pulsed laser beam with a duration of 35 ps. Temporal behavior of third-order optical nonlinearity of the film was examined by delaying the forward pump beam against the backward pump and the probe beams in the DFWM experiment. In addition to the instantaneous response, fast relaxation with a lifetime of 26 ps and slow relaxation with a lifetime of 153 ps were observed. Nonlinear transmission was observed for the V_2O_5 film using the same laser source. It was found that the transmittance decreases with increasing intensity of the incident light. This behavior suggests that the reverse saturable absorption would contribute to the fast nonlinear optical response of the V_2O_5 film. Transient spectra after excitation of the film with 10 ns-pulsed laser at 355 nm showed a positive change in absorbance immediately at the end of the pulse covering all visible spectrum from 400 to 800 nm, and two decay components: one occuring during the first 50 nanoseconds, and the other one during the first microsecond. These results suggest that the V_2O_5 films have potential applicability to photonic devices such as optical power limiting against ps- and ns-pulsed lasers.

E5.20
OPTICAL SPECTROSCOPY AND MICROSCOPY OF A SINGLE DYE-DOPED MICRODROPLET LEVITATED IN AN ION TRAP. Masahide Tona and Masahiro Kimura, Kochi Univ Tech, Dept of Mechanical Engineering, Kochi, JAPAN.

We have investigated optical properties of a single microdroplet levitated in an ion trap. The isolated droplet is naturally shaped into nearly perfect sphere due to the surface tension and acts as a high Q resonator. Resonant light waves in the spherical cavity are confined near the surface of the droplet by almost total internal reflection. Such microcavity resonances are termed 'morphology dependent resonances' (MDRs). The microdroplet employed in this work was composed of liquid glycerol doped with 10^{-4}M rhodamine 6G and had a radius of several micrometers. To obtain emission spectra, the levitated droplet was irradiated by a green laser (pulsed or cw Nd:YAG SHG). The MDRs were discerned as a ripple structure in the emission spectra of the droplet. Furthermore, in the pulsed laser excitation, the emission peak intensity increased nonlinearly with the pump power in the spectral region where the losses by self-absorption are trivial. It is concluded that the lasing action occurs when the gain around the circumference of the droplet exceeds the loss resulting from reabsorption. We have also obtained photographs of the emission from the microdroplet in the ion trap by using an optical microscope. The drastic change of the image occurred when the pump power exceeded the lasing threshold. Below the threshold, the image was nearly uniform, reflecting the fluorescence from almost entire region of the droplet. Above the threshold, however, the image of the lasing droplet exhibited a distinct rim which was much brighter than the central region, indicating that the resonant waves are confined near the liquid-air boundary by the MDRs. Moreover, it was observed that the rim had a symmetric structure and was not a uniform ring. Details of this novel structure will be presented.

E5.21
FABRICATION OF ONE DIMENSIONAL PHOTONIC STRUCTURES COUPLED TO FIBER. Lu Chen, Y. Suzuki, Dept. of Materials Science and Engineering, Cornell University, Ithaca, NY; Glenn E. Kohnke, Science and Technology Division, Corning Incorporated, Corning, NY.

We have fabricated one dimensional photonic bandgap structures with a bandgap nominally around 1.5 micron according to theoretical modeling. These structures are defined by electron beam lithography. We couple light directly from an optical fiber into the photonic bandgap structures without using planar waveguide structures. Optical measurements of typical structures indicate suppression of light transmission in the 1400 to 1700nm region. Scattering at interfaces due to the direct coupling of light from fiber to the photonic structure gives rise to broadband energy loss. One dimensional photonic structure with defects are also fabricated and their optical characteristics will be discussed.

E5.22
STUDY OF DEEP LEVELS IN Ge DIRECTLY DEPOSITED ON Si. K. Kono, Hsin-Chiao Luan, K. Wada and L.C. Kimerling, Department of Materials Science & Engineering, Massachusetts Institute of Technology, Cambridge, MA.

We report the study of deep levels in Ge grown directly on Si by the DLTS measurement of MOS devices. High quality Ge epilayers grown on Si can be used for the integration of efficient Ge photodetectors on Si for optical communications. High quality Ge was eptaxially grown on Si using ultrahigh vacuum/chemical vapor deposition followed by cyclic thermal annealing. At the end of Ge epitaxy a thin flat layer of Si was grown. Silicon oxide layer was thermally grown into this thin Si layer to create a high quality SiO_2/Si interface. MOS devices were formed by deposition of Al electrodes. DLTS measurement was conducted to understand the defects in Ge layer and the interface states at interfaces in the samples. Three deep levels, one at the midgap and two near valence bands were observed. The depth profile of deep levels were measured. The depth profile showed decrease in total number of deep levels in shallow region. This isconsistent with the reduction of the dislocation observed using TEM. The nature and the effects of the deep levels will be discussed.

E5.23

MATERIALS ENGINEERING FOR OPTIMIZED SILICA PLANAR LIGHTWAVE CIRCUITS IN MICROPHOTONICS. Jessica G. Sandland, Anuradha Agarwal, Caroline A. Ross, Kazumi Wada, L.C. Kimerling, MIT, Dept of Materials Science and Engineering, Cambridge, MA.

The fabrication process for Planar Lightwave Circuits (PLCs) must allow for the creation of multiple layer structures without introducing conformational changes in the underlying layers. This constraint requires that newly deposited layers have a lower T_g than the underlying layers. T_g can be lowered by introducing various dopant atoms into the oxide. However, these dopant atoms also affect the refractive index of the oxide. It is desirable to engineer T_g and the refractive index in designing function into the PLC. As dopant atom polarizability increases, n increases; however, no such clear relationship exists between polarizability and T_g. The structure and composition of various binary and ternary glasses are considered in order to allow for the optimization of n for a large range of required T_gs. The structure of Ge and Ti-doped silicates, borates, phosphates, and their intermediate glasses are investigated, and we demonstrate a methodology for selecting materials to simultaneously design for n and T_g.

E5.24

SYNTHESIS AND PROPERTIES OF MONODISPERSE CONDUCTIVE CORE-SHELL COLLOIDS. Lee Y. Wang, National Taiwan Univ, Center for Condensed Matter Sci; Yi-Jun Lin, Wen-Yen Chiu, Dept of Chemical Engineering, Taipei, TAIWAN.

An efficient synthetic route for the preparation of monodisperse polyaniline-based conductive colloids in core-shell structure was demonstrated. Cationic polystyrene latex, prepared by surfactant-free emulsion polymerization method using azobis(isobutylamidine hydrochloride) as an initiator, with a thin layer adsorption of anionic polyelectrolytes was used as the core particle. Aniline monomer was then polymerized and in situ deposited onto the core surface in ammonium persulfate aqueous solution. The resulting conductive latexes were characterized by a wide range of techniques including light scattering, infra-red and ultraviolet-visible absorption spectroscopy, electron microscopy, zetasizer, and thermogravimetric analysis. Ionic strength, type and chain length of polyelectrolytes, pH value, and aniline concentration were identified as decisive factors affecting particle stability. It is interesting to note that monodisperse latexes of different size can be easily prepared by the use of polymer core with adequate surface charge density during shell formation process. Most importantly, these polymer spheres can self-assembled into two- or three- dimensional ordered arrays. These results suggest their potential use as photonic materials.

E5.25

MULTIPLE SOI LAYERS BY MULTIPLE SMART-CUT® TRANSFERS. C. Maleville; T. Barge; B. Ghyselen and A.J. Auberton SOITEC S.A., Parc Technologique des Fontaines; Bernin, Crolles Cedex, FRANCE.

Silicon On Insulator (SOI) technologies are now entering into mainstream applications, with recent announcements regarding for instance microprocessor applications. One condition for this to happen has been to prove that SOI material manufacturing processes can be compatible with such industrial developments (availability, cost, quality, ..). Among these processes, Smart-cut ® is one based on layer transfer from one substrate to another. Beyond simple SOI wafers that can also be high value added substrates for other applications such as photonics, sensors and other micromaching purposes, we will show and demonstrate in this paper how Smart cut process can be seen as a basic step and how this process can be used to realize multiple SOI wafers (4 SOI levels), allowing different crystalline and/or amorphous layers to be stacked. Realizing multiple SOI layers based on layer transfer process can be achieved in many different ways: repeating a single layer transfer several times onto a SOI wafer initially obtained, transferring onto a single substrate or a SOI wafer whole SOI layers stacks already formed, . In any case, at least one SOI wafer has to be used again in a wafer bonding step. Wafer bonding, without any glue but based on molecular or hydrogen bonds as it is meant generally, requires relatively good substrate surface quality, especially in terms of roughness and surface defect density. Surface roughness on a standard SOI wafer achieved with Smart-Cut (called UNIBOND ® wafer), is similar to standard silicon substrates. Since flatness and surface defects density are also in silicon properties range, wafer bonding can be applied similarly between two SOI wafers. As a result, multiple SOI layer stacks can be easily performed when using SOI wafers as top and base in Smart-Cut technology. Other III-V compounds intermediate layers or substrates, compatible with single Smart-Cut transfer, could then be used in such layer stacks processes.

SESSION E6: FABRICATION OF PHOTONIC CRYSTALS BY SELF-ASSEMBLY

Chairs: Edwin L. Thomas and Thomas P. Pearsall

Wednesday Morning, November 29, 2000

Fairfax A (Sheraton)

8:30 AM *E6.1

STRONG INTERACTION BETWEEN LIGHT AND PHOTONIC CRYSTALS MADE USING SELF-ORGANIZATION. Willem L. Vos, van der Waals-Zeeman Instituut, Universiteit van Amsterdam, Amsterdam, THE NETHERLANDS; Mischa Megens, Princeton Univ, Princeton, NJ.

Photonic crystals are optical materials with an intricate three-dimensional structure that manipulate light in unusual ways thanks to Bragg diffraction. The structure has length scales of the order of the wavelength of light. Photonic crystals are currently under intense investigation because of the predictions that spontaneous emission of an excited atom inside the crystal is completely inhibited or that photons can become spatially localized. We have recently developed a new kind of photonic crystals, consisting of air spheres in a solid matrix, that strongly interact with light. The solid is structured with a template made from self-organizing colloids. Various means to infiltrate the solid are being pursued. We will discuss our optical experiments on these crystals. I gratefully acknowledge the contributions of L. Bechger, F. Koenderink, A. Lagendijk, H. Schriemer, H. van Driel, R. Sprik, J. Wijnhoven, M. Megens.

9:00 AM *E6.2

PHOTONIC BAND GAP MATERIALS FROM SELF-ASSEMBLING BLOCK COPOLYMERS. Samson A. Jenekhe, University of Rochester, Dept. of Chemical Engineering, Rochester, NY and University of Washington, Dept. of Chemical Engineering, Seattle, WA.

We are investigating microporous and nanoporous polymeric materials as periodic dielectric composite structures with potential three-dimensional photonic band gaps in the visible and near infrared regions for the controlled confinement, propagation, or generation of light. One initial approach focuses on self-assembling rod-coil block copolymers which have been found to self-organize into rugged hollow spheres, cylinders, and other geometries. Hierarchical self-assembly of such rod-coil block copolymers have been found to produce highly iridescent periodic microporous films with periodicities in the 200-4000 nm range. The polymer/air dielectric composites have refractive index contrasts of 1.6-1.8. The refractive index contrast and photonic properties can be enhanced by incorporating nanoparticles (fullerenes, metals, semiconductors) into solutions of the block copolymers without hindering the self-assembly of the microporous materials. Initial results on the effects of macromolecular architecture on the self-assembly and photonic properties of microporous PBG block copolymer systems will also be presented.

10:00 AM *E6.3

PHOTONIC MATERIALS USING STRUCTURED COLLOIDS AND EMULSIONS. David J. Pine, Vinothan N. Manoharan, James D. Thorne, Department of Chemical Engineering, University of California, Santa Barbara, CA; Sascha Klein, Fred F. Lange, Materials Department, University of California, Santa Barbara, CA.

We present colloidal and emulsion templating methods for fabricating photonic crystals of close-packed air spheres with diameters on the order of 300 nm in a titania matrix. The emulsion methods differ from their colloidal counterparts in that they are capable of producing the high-refractive-index rutile phase ($n \simeq 2.9$) instead of the more commonly produced low-index anatase phase ($n \simeq 2.4$) thus improving the optical stop-band properties. By contrast, the colloidal templating methods produce better ordering of the pores thus producing a more perfect colloidal crystal. A key problem with both techniques is that they employ uniform spherical particles which seem capable of producing only close packed ordered structures rather than the diamond or other structures which are known to possess far superior optical properties, most notably much wider optical band gaps. We present a new fabrication method which combines both emulsion and colloidal templating techniques to produce photonic crystals capable of ordering in the more open crystal structures which optimize optical band gap properties.

10:30 AM E6.4

OPTICAL SWITCHING RESPONSE OF LIQUID CRYSTALS IN SELF-ASSEMBLED COLLOIDS. P. Mach[1,3], K.H. Lin[1], A.G.

Yodh[1], D. A. Weitz[2], Pierre Wiltzius[3]. [1]Dept. of Physics, Univ. of Pennsylvania, Philadelphia, PA; [2]Dept. of Physics, Harvard University, Cambridge, MA; [3]Bell Laboratories, Lucent Technologies, Murray Hill, NJ.

We have measured the electro-optic switching properties of nematic liquid crystals incorporated into self-assembled colloid materials. The host structures for the liquid crystal are periodic, and are made from colloidal silica or polystyrene suspensions by sedimentation or flow cell methods; we studied structures with lattice constants in the range of approximately 0.5 to 1.5 microns. In one category of our samples, the nematic material is imbibed directly into the interstitial regions of the close-packed colloid. Alternately, the assembled colloid spheres can first be cast with an optically isotropic polymer, and the particles subsequently removed by an appropriate chemical etch. The liquid crystal is then filled into the connected network of colloid-templated cavities within the polymer matrix. Applying an electric field to thin (roughly 15 micron) liquid-crystal/matrix samples reorients the nematic director pattern and changes the scattering behavior. We present experimental results characterizing the optical transmission of these structures in response to applied field for various structural periodicities and material combinations, as well as our observation of switching in diffraction patterns generated from both categories of our samples.
Supported by grants NSF-DMR 96-31279 and MRSEC-DMR 96-32598.

10:45 AM E6.5
INDUCED BIREFRINGENCE IN ELECTROOPTICAL PHOTONIC BI-ORIENTED CRYSTALS. P. Kopperschmidt and U. Gösele, Max-Planck Institute of Microstructure Physics, Halle, GERMANY.

Electrically induced birefringence in Photonic bi-oriented Crystals (PBC) is demonstrated assuming a regular assembly of dielectric anisotropic grains. Regions of alternating high and low optical constants are achieved due to a periodic twist between the grains. The dielectric contrast at the grain boundaries varies according to the directions of light propagation. In directions of large dielectric contrast, modes of the lightflow are confined and photonic bandgaps are generated. In directions of low or zero dielectric contrast, the artificial crystal is optically transparent. The generation of bandgaps in the photonic bandstructure can be induced by imposing external fields to PBC. If a dc electric field is applied to the PBC, the dielectric indexellipsoid of each twisted grain is deformed. For explicit bi-crystalline geometry and direction of lightflow, PBC are optically transparent at no external field. Conversely, at high external fields a periodic dielectric contrast is observed at the grain boundaries. If the electrically induced dielectric contrast is sufficiently large, photonic confinement is observed. Thus, the optical transmission can be directed by the intensity of the imposed electric field. The electrically induced birefringence in one-dimensional PBC may have possible applications for optical switches and modulators. In two-dimensional PBC, the induced birefringence may be applicable to tune the directions in optical waveguides.

11:00 AM E6.6
STRUCTURAL CHARACTERIZATION OF THIN FILM PHOTONIC CRYSTALS. G. Subramania, R. Biswas, Dept. of Physics and Astronomy, Iowa State University, Ames, IA; K. Constant, Department of MS&E; M.M. Sigalas, Agilent Technology, Palo Alto, CA; K.M. Ho, Department of Physics and Astronomy, Iowas State University, Ames, IA.

Recently there has been a tremendous increase in the experimental fabrication of photonic crystals composed of a wide variety of materials and possessing interesting structural morphologies. When these structures are probed for optical properties various assumptions are made regarding the structural details which are based on the synthesis technique. In certain experimental approaches drastic structural changes can occur during the intermediate processing steps. Techniques such as etching, heat treatment that are routinely used in photonic crystal fabrication can alter the chemical nature or change the phase of the material left in the final product. In this paper we have proposed simple, non-destructive techniques for probing structural information of photonic crystals which can in principle be applied to samples made irrespective of processing technique used for fabrication. We demonstrate techniques such as refractive index liquid backfilling and variable angle specular reflectance on thin film inverse opal photonic crystals synthesized by colloidal self organization. We estimate the fill fraction of air, c axis compression as well as index of background material by comparing experimental data with band structure calculations. We find that the thin film photonic crystals can have a very high fill fraction ($92-94\%$) with a considerable compression of c axis ($\sim 25\%$).

11:15 AM E6.7
A SELF-ASSEMBLY APPROACH TO THE FABRICATION OF 3D PHOTONIC CRYSTALS WITH BANDGAPS IN THE OPTICAL REGIME. Byron Gates, Yu Lu, Yadong Yin, Younan Xia, Univ of Washington, Dept of Chemistry, Seattle, WA.

This talk will discuss a self-assembly approach to the formation of 3D photonic crystals with bandgaps in the optical regime. This approach is based on the crystallization of monodispersed colloidal particles (both spehrical and nonspherical). We have demonstrated several effective methods for organizing these building blocks into desired, well-controlled periodic structures under different types of external fields. This presentation will also describe the photonic bandgap properties of these self-assembled structures.

11:30 AM E6.8
SUB-MICRON PATTERNED DEPOSITION OF COLLOIDS FOR THE FABRICATION OF PHOTONIC CRYSTALS. Susanne Friebel, Joanna Aizenberg, Pierre Wiltzius, Lucent Technologies, Bell Laboratories, Murray Hill, NJ.

Patterned self-assembled monolayers (SAMs) with different chemical functionality can be used as a template for high resolution deposition of a wide variety of organic and inorganic materials. We fabricate these patterned, chemically functionalized monolayer surfaces on a sub-micron scale using a UV-lithographique technique which combines high resolution and short exposure times using SAMs as a resist. We show the application of these templates for the deposition of minerals, polymers and colloids to fabricate 2D structures. Large area line, square and triangular patterns with a periodicity of 532nm were generated by exposing SAMs of positively or negatively charged thiols to an UV-laser interference pattern at 193nm for less than a minute followed by the immersion into an oppositely charged thiol. Using these substrates patterned with oppositely charged SAMs, large arrays of charged colloids were fabricated, their deposition being controlled by electrostatic forces. Variation of the geometry and periodicity of the patterns as well as the size of the spheres allows the properties of the fabricated structures to be tuned within a certain range. We plan to exploit this technique further to fabricate colloidal photonic crystals and to study their optical properties using spectroscopy.

11:45 AM E6.9
GROWTH AND LUMINESCENCE OF Er_2O_3 THIN FILMS. Kevin M. Chen, Sajan Saini, Michal Lipson, Xiaoman Duan, and Lionel C. Kimerling, MIT, Dept of Materials Science and Engineering, Cambridge, MA.

We present the first report of room temperature photoluminescence (PL) from erbium oxide (Er_2O_3) thin films fabricated via reactive sputtering and subsequently annealed. Er_2O_3 is a promising material for microphotonic amplifiers and emitters due to its available high concentration of Er^3 atoms. As deposited, the films show an inhomogeneously broadened PL spectrum at 1.55 μm, indicative of their mixed amorphous/polycrystalline microstructure. Post-deposition anneals control nucleation and growth in the films which increase crystallinity as measured by glancing angle xray diffraction (GAXRD) and transmission electron microscopy (TEM). The PL spectra sharpen with annealing and develop maxima at 1541 nm and 1549 nm for films treated at 650°C and 1000°C, respectively. Erbium-rich films, grown at lower plasma deposition powers, show higher PL. A process map summarizes the influence of plasma deposition power and annealing parameters. Highly luminescent Er_2O_3 films have been incorporated into CMOS-compatible microcavity photonic structures.

SESSION E7: PATTERNING AND TEMPLATING OF PHOTONIC CRYSTALS

Chairs: James G. Fleming and Kazumi Wada
Wednesday Afternoon, November 29, 2000
Fairfax A (Sheraton)

1:30 PM *E7.1
PHOTOCHEMICALLY CONTROLLED PHOTONIC CRYSTALS. Sanford A. Asher, Marta Kamenjicki and Igor Lednev, Department of Chemistry, University of Pittsburgh, Pittsburgh, PA.

Photonic crystals can be prepared by polymerizing a hydrogel around a crystalline colloidal array (CCA) to form a polymerized colloidal array (PCCA). The PCCA diffracts light due to the periodic lattice formed by the embedded CCA. We have developed a photochemically controllable PCCA by attachment of an azobenzene derivative to the PCCA. Trans to cis photoisomerization with UV light switches the diffraction to the red, while cis to trans photoisomerization with visible light blueshifts the diffraction back. This material can be used for display devices and optical memories. We will also discuss other novel PCCA materials fabricated from unusual composite materials.

2:00 PM *E7.2

FABRICATION AND OPTICAL PROPERTIES OF HIGH DIELECTRIC CONTRAST THREE-DIMENSIONAL PHOTONIC CRYSTALS. Paul V. Braun, Jennifer A. Lewis, and Valeria Tohver, University of Illinois, Dept. of Materials Science and Engineering, Urbana, IL; Pierre Wiltzius, Robert W. Zehner, Christian Kloc, Marcus K. Weldon, Christopher A. White, Sanjay S. Patel, Bell Labs, Lucent Technologies, Murray Hill, NJ.

The formation of low dielectric contrast three-dimensionally microperiodic structures through colloidal templating is relatively straightforward, but fabrication of high refractive index structures as required for many photonic band gap applications remains quite challenging. To address this problem, we have developed a range of materials chemistry routes which operate within the three dimensional void space of a colloidal template to form essentially infinite, high refractive index contrast three dimensionally periodic structures including imbibing of nanocrystalline titania, melt imbibing of chalcogenide glasses, and electrodeposition of II-VI semiconductors. Several other routes to even higher refractive index materials are currently under exploration. This alone however, does not address the critical need for colloidal templates with small enough periodicities. As the colloidal particles become smaller, it becomes exceedingly more difficult to crystallize them into a defect free colloidal template. Through the addition of nanoparticles to the colloidal particles, we have discovered it is possible to form highly regular colloidal crystals through simple gravity driven sedimentation. This is presumably because the nanoparticles lead to a weak depletion attraction between the colloidal particles. Optical and physical characterization of both the high refractive index photonic crystals and the depletion stabilized colloidal templates will be discussed.

3:00 PM *E7.3

SELF-ORGANIZED PHOTONIC CRYSTALS. D.J. Norris, NEC Research Institute, Princeton, NJ.

Colloidal chemistry has recently been used to make 3D photonic crystals from a variety of materials. A typical approach is to induce sub-micron colloidal spheres to organize on a face-centered cubic lattice. This template, which is periodic on an optical length scale, then serves as a three-dimensional scaffolding into which another material may be infiltrated. Subsequent removal of the template by selective etching yields a 3D photonic crystal, also called an inverted opal. These structures are particularly interesting since they have been predicted to exhibit an omnidirectional photonic band gap and enhanced optical nonlinearities. Here we show how to use colloidal self-organization to make three different materials: 1) semiconductor structures to explore high refractive index contrast, 2) silver structures to explore the behavior of metallo-dielectric photonic crystals, and 3) poly(p-phenylenevinylene) (PPV) structures to explore the intrinsic optical nonlinearities of conjugated polymers. We then discuss the optical properties of our photonic crystals. In particular, we use optical microscopy to probe a single crystalline domain in each of our samples. By measuring spatially resolved reflection and emission spectra, inhomogeneities due to averaging over inherent disorder (always present in self-organized photonic crystals) can be eliminated. "Defect-free" spectra are obtained, from which the intrinsic photonic properties can be extracted.
Work done in collaboration with Yu. A. Vlasov (NEC Research Institute), M. Deutsch (NEC Research Institute), and Nan Yao (Princeton Materials Institute, Princeton University).

3:30 PM E7.4

PHASE BEHAVIOR OF BINARY MIXTURES OF ATTRACTIVE SILICA MICROSPHERES AND REPULSIVE NANOPARTICLES: DEPLETION ENHANCED CRYSTALLIZATION OF PBG TEMPLATES. Jennifer A. Lewis, Valeria Tohver and Paul V. Braun, University of Illinois, Materials Science and Engineering Department, Urbana, IL; Pierre Wiltzius, Bell Labs, Lucent Technologies, NJ.

We have studied the phase behavior of binary mixtures of attractive silica microspheres and repulsive nanoparticles. At low nanoparticle additions, an unstable gel forms that can undergo transient settling depending on its composition. Above a lower critical volume fraction of nanoparticle species, this system undergoes a remarkable transition yielding a homogeneous binary fluid. In this regime, silica microspheres assembly into a crystalline array under gravity-induced sedimentation. Their robust nature is revealed through confocal microscopy, which shows that a touching particle network forms. At higher nanoparticle volume fractions, the binary system is observed to destabilize once again due to depletion attraction. Our observations provide new insight into the phase behavior of binary systems that begin in a nonequilibrium state. Current work focuses on assembling epitaxially grown colloidal crystals from these stable binary fluids to use as templates for microphotonic structures.

3:45 PM E7.5

PHOTONIC CRYSTALS FROM LARGE SILVER COLLOIDAL PARTICLES: TOWARDS A COMPLETE PHOTONIC BAND GAP IN THE VISIBLE. Krassimir P. Velikov[a], Gabby E. Zegers[a], Alexander Moroz[a] and Alfons van Blaaderen[a,b]. [a]Chemistry and Physics of Condensed Matter, Ornstein Laboratory, Debye Institute, Utrecht University, Utrecht, THE NETHERLANDS; [b]FOM Institute for Atomic and Molecular Physics, Kruislaan, Amsterdam, THE NETHERLANDS.

Recently it was shown that simple face-centered-cubic (fcc) structures of both metallic and coated metallic spheres are ideal candidates to achieve a tunable complete photonic bandgap (CPBG) for optical wavelengths [1]. A CPBG can be opened if the crystal is made out of material having a Drude-like behavior of the dielectric function, such as silver [1]. Here we report on synthesis and characterization of large (100 - 1000 nm in radius) monodisperse silver colloidal particles with tunable size using a controlled aggregation procedure [2]. The experimental methods to create metal (Ag) and metallo-dielectric particles and their characterization by electron microscopy will be discussed. The optical properties on a single particle level are studied by means of light scattering and compared to Mie scattering theory. Silver particles in water tend to self-organize in a charge stabilized colloidal crystal, which displays strong Bragg reflection colors. First results on optical properties of dried and charge stabilized colloidal crystals of Ag particles will be presented. [1] A. Moroz, Phys. Rev. Lett. 83, 5274-5277 (1999); Europhys. Lett. 50, 466-472 (2000). [2] D. V. Goia and E. Matijevic, Coll. and Surf. A 146, 139-152 (1999).

4:00 PM E7.6

GROWTH AND CHARACTERIZATION OF LUMINESCENT RARE EARTH DOPED SILICA NANOPARTICLES. Cristin E. Moran, Gregory D. Hale, and Naomi J. Halas.

Silica or silica-based glass doped with rare earth (RE) ions is a commonly used near-IR active material for photonic applications, including lasers and optical fiber amplifiers. Doped silica glass can be made in bulk by any of several methods using either high temperature processing for vapor-phase doping, or solution-phase sol-gel techniques. Currently, however, there are no reported processes for making discrete, doped silica nanoparticles of regular, controllable size and shape. Two methods are used to produce these doped particles. The first is based on a procedure for producing silica microspheres by catalyzing the hydrolysis and condensation of tetraethylorthosilicate (TEOS) with acetic acid. We have grown silica nano- and micro-spheres doped with Nd^3, Pr^3, Gd^3, and Er3 using this method. The particles are spherical and separable, with a particle size distribution that is controllable by variation of reactant concentrations. Once grown, the doped particles are baked at 750°C for 24 hours to promote full condensation of the silica host. We have also used inverse micelles to grow rare earth doped silica nanoparticles ranging in size from approximately 50-200 nm in diameter. After reaction, the particles are cleaned by washing with acetone and water to remove surfactant and residual ions. After baking, the particles retain their size and shape and exhibit room temperature luminescence on a variety of emission wavelengths in both the visible and the near infrared.

4:15 PM E7.7

VACANCY-INDUCED OPTICAL SECOND HARMONIC GENERATION IN LARGE-SIZED SiON NANOCRYSTALLITES. K.J. Pluciòski, Military University of Technology, Warsaw, POLAND; I.V. Kityk, Institute of Physics WSP, Czistochowa, POLAND; S. Benet, Univ. Perpignan, FRANCE.

On the basis of band energy calculations, vacancy induced second - order nonlinear optical effects in large sized SiON nanocrystallites were evaluated. We have shown the possibility of enhancing the optical second harmonic generation in such kinds of nanocrystallites by varying the N/O ratio and the number of I vacancies. We found that there is an optimum concentration of Si vacancies at which the optical second-harmonic generation is maximum. The simulations were verified using the Kurtz-Perry method for SHG measurements of the nanopowders. The second harmonic generation was measured for the pumping wavelength of a YAG:Nd laser. With increasing vacancy concentration, the SHG signal increases and achieves its maximum at a vacancy concentration of about $10^{19}cm^{-3}$. A correlation between the vacancy induced nonlinear optical response and low-frequency Raman intensities was found. The maximum vacancy-induced SHG was observed for nanocrystallite sizes lying between 25 and 30 nm. The SHG tensor coefficients for the system under consideration were larger (at least 10%) than the corresponding parameters for SiON single crystals. In order to understand the phenomena observed, we compared our measurements with ab initio band energy calculations, taking into account anharmonic electron-phonon interactions. The equilibrium positions of the near-the-surface atoms were determined. We discovered that the contribution of near-the-surface defects to the total second-order nonlinear optical susceptibilites was approximately

12%. The total nonlinear optical susceptibility was equal to about 0.6 pm/V. The laser power beams were diffracted in order to obtain light profile nonhomogeneity (usually of a gaussian-like form) not smaller than 92% of the maximum light intensity for power from 0.5 to 0.75 GW/cm^2. Independent measurements of the SHG signals were taken for the oligoetheracrylate matrices. The influence of the photopolymer matrix background as well as those of the linear absorption (245 cm^{-1}, $\lambda = 530$ nm) and Fresnel reflection were eliminated. To exclude the influence of hyper-Raman scattering (superposing on the output SHG), we carried out additional investigations of the scattered light (up to 2600 cm^{-1}), starting from a wavelength of $\lambda = 441$ nm. Hyper-Raman maxima between 1200 cm^{-1} and 1800 cm^{-1} were detected with intensities at least 9 times weaker than the transmitted light intensity. In the case of the Raman and hyper-Raman measurements, we used an argon laser with 441 nm Ar spectral line and SPM-3 spectrometer. A position-sensitive photomultiplier (calibrated using helium-neon gaseous mixture discharge) was applied to detect the integrated scattering background.

4:30 PM E7.8
NOVEL EMISSIVE BEHAVIOR FROM ELECTRICALLY PUMPED, RARE-EARTH-DOPED NANOALUMINA. R.M. Laine, T. Hinklin, S. Rand, and G. Williams, Depts. of Materials Science and Engineering, Chemistry and the Applied Physics Division, University of Michigan, Ann Arbor, MI.

Nanosized delta-alumina powders doped with lathanides can be produced by flame spray pyrolysis (FSP) of very simple, low cost aluminum precursors doped with ceria. This scaleable synthesis route produces single crystal nanopowders at > 100 g/h with surface areas of 50-120 m2/g. Typical powders consist of homogenously doped unaggregated single crystals, with particle sizes ranging from 10-30 nm average diameter. Similar micron sized powders are exploited for their cathodoluminescence behavior. By reducing the size of the particles and thus the interparticle cavity, the scattering regime is changed from diffusive to strong scattering causing photon localization. Lasing occurs due the localization within the gain medium. Details concerning the alkoxide chemistry, flame spray pyrolysis, and the lasing behavior of nanosized doped powders will be discussed.

4:45 PM E7.9
PLASMONICS: ELECTROMAGNETIC ENERGY TRANSFER AND SWITCHING BELOW THE DIFFRACTION LIMIT IN NANOPARTICLE CHAIN-ARRAYS. Mark L. Brongersma, John W. Hartman, Stefan A. Maier, and Harry A. Atwater, Thomas J. Watson Laboratory of Applied Physics, California Institute of Technology, Pasadena, CA.

Integrated optics appears to face the fundamental limitation that structures for guiding and modulation of light must have dimensions comparable to the wavelength of light. Recently however, it was theoretically shown that this problem can be circumvented by "plasmonics", i.e., transport of electromagnetic energy along linear chain-arrays of closely spaced 10-50 nm diameter metal nanoparticles. This transport relies on the coupled near-field electrodynamic interaction between metal particles that sets up coupled plasmon modes. Calculations in the point dipole approximation indicate strong guiding of electromagnetic radiation and electromagnetic dispersion relations are obtained. Coherent propagation with a group velocity exceeding 0.1 c is possible in straight arrays, around sharp corners (bending radius $\ll$ l), and structures of more complex architecture. The transport is dependent on the frequency and polarization direction of the coupled plasmon mode. The factors dictating the choices for particle and host material will be described. Furthermore, the sensitivity of the transport characteristics to fluctuations in particle size, particle shape, and interparticle spacing is quantified. Finally, the operation of a "plasmon switch" that acts as an all-optical inverter is modeled. Recent efforts to fabricate and test nanoscale plasmonic structures will be presented; we note that such "plasmonic devices" potentially are among the smallest structures with optical functionality.