SYMPOSIUM OO

Infrared Applications of Semiconductors III

November 29 – December 2, 1999

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* Invited paper

SESSION OO1: ANTIMONIDE RELATED MATERIALS AND DEVICES I
Chairs: Sylvia Dorato and Andrew Ongstad
Monday Morning, November 29, 1999
Room 206 (H)

8:00 AM OPENING REMARKS

8:15 AM *OO1.1
PROGRESS IN ANTIMONIDE-BASED MID-IR LASERS. G.W. Turner, M.J. Manfra, H.K. Choi, A.K. Goyal, S.C. Buchter, C.C. Cook, A. Sanchez and D.L. Spears Lincoln Laboratory, Massachusetts Institute of Technology Lexington, Lexington, MA.

There is a significant interest in extending the maximum operating wavelength of high-power, room-temperature diode lasers further into the mid-IR region. At the present time, a number of groups have demonstrated room-temperature, CW, Watt-class diodes which operate near 2 μm, but it has not been possible to achieve such performance levels for diode lasers which operate near $\sim$4 μm. Many commercial and military applications would benefit from the availability of room-temperature, high-power, all-diode-laser systems which could cover the entire 2-5 μm mid-IR region. However, the short-term requirements for high-power, quasi-CW lasers operating near 4 μm are being addressed by the development of cryogenically cooled, optically-pumped semiconductor laser (OPSL) systems. In this presentation, we will first review some of the issues that make extending the operating wavelength of room-temperature diode lasers so difficult. We will then discuss the design and characterization of advanced quantum well and superlattice OPSL active regions that we have grown by molecular beam epitaxy (MBE) on GaSb substrates. These active regions, which are based on InAs/GaSb/AlSb and InAs/GaInSb/AlSb type-II combinations, incorporate additional epitaxial layers to increase the efficiency of the absorption of the optical pump radiation. We will present some laser results which are based on these advanced OPSL active regions and compare the performance of such advanced laser structures to more conventional 4 μm InAsSb/AlAsSb double-heterostructure OPSLs using both 1 μm and 2 μm optical pumping. This work was sponsored by the Air Force Research Laboratory under Air Force Contract No. F19628-95-C-0002. The opinions, intrepretations, conclusions and recommendations are those of the authors and are not necessarily endorsed by the United States Air Force.

8:45 AM *OO1.2
PSEUDOPOTENTIAL METHODS FOR SUPERLATTICES: APPLICATIONS TO MID-IR SEMICONDUCTOR LASERS. Gregory C. Dente, GCD Associates, Albuquerque, NM; Michael L. Tilton, Boeing, Albuquerque, NM.

Many mid-infrared semiconductor laser sources are now being developed with superlattice active regions. The common theoretical method for calculating the electronic and optical properties of these heterostructures and superlattices is based on k.P perturbation theory and the envelope function approximation (EFA). Indeed, this approach has been used so extensively that it has been referred to as the Standard Model. Unfortunately, although the Standard Model has considerable intuitive appeal, the theoretical underpinnings are controversial. In particular, the low momentum assumptions of k.P are probably violated in many of the applications, and several options for interface envelope function boundary conditions exist, a situation that can lead to additional uncertainties. These elements of uncertainty become even more pronounced when the Standard Model is applied to the analysis of structures with Type II band offsets, such as GaSb/InAs superlattices. We have recently begun using a solution method based on the Empirical Pseudopotential Method, EPM. This method shows particular strength in analyzing structures with short periods or thin layers, for which the Standard Model may be problematical. We will describe the EPM applied to bulk solids and then demonstrate our direct generalization of the method for applications to superlattice structures. The method differs from other pseudopotential methods in several ways. First, we generate the superlattice pseudopotential from the pseudopotential coefficients of the constituent materials in a particularly simple manner. Second, in the plane-wave expansion for the superlattice Bloch function, we can use a subset of the full reciprocal space for the superlattice; a selection centered on the reciprocal lattice points for the bulk constituents proves to be a particularly useful approximation for longer period superlattices. Third, our method allows for direct incorporation of coherently strained layers. Calculations for recently developed mid-IR semiconductor lasers using type-II superlattice active regions will be used to illustrate the method.

9:15 AM OO1.3
InN_xSb_{1-x} LIGHT EMITTING DIODES GROWN BY MBE. A.D. Johnson, R.H. Bennett, G.J. Pryce, J. Newey, A.M. Keir, and G.M. Williams, Defence & Evaluation Research Agency, Gt Malvern, UK.

We present the first reported MBE growth of light emitting diodes (LEDs) with active regions made up of InSb/ InN_xSb_{1-x} ($0<x<0.02$) superlattices, grown onto InSb(100) substrates. Such dilute alloys of nitrogen in other III-V materials have been shown to exhibit very large bandgap bowing parameters due to differences in atomic size and the electro-negativity of nitrogen. Novel growth techniques have been developed to enable epitaxy of high quality InN_xSb_{1-x}, using an electron cyclotron resonance (ECR) plasma source. Material characterisation was performed by double crystal x-ray diffraction (DXRD) and transmission electron microscopy (TEM), and nitrogen composition has been determined using DXRD and secondary ion mass spectrometry (SIMS). To determine the effect of nitrogen on bandgap, the structures have been fabricated into LEDs with InSb/ InN_xSb_{1-x} superlattice active regions with period $\sim$600ÅFor a nitrogen content of 0.2%, the peak emission of the diodes shifts from $\sim$6μm to $>$7μm at room temperature. The prospects for extending the emission to longer wavelengths and the possibility of such structures use in diode lasers will also be discussed.

9:30 AM OO1.4
ELECTRONIC STRUCTURE ENGINEERING OF THE LINE-WIDTH ENHANCEMENT FACTOR IN MID-INFRARED SEMICONDUCTOR LASER ACTIVE REGIONS. Michael E. Flatté, J. T. Olesberg and Thomas F. Boggess, The University of Iowa, Iowa City, IA.

The linewidth enhancement factor is a fundamental parameter that characterizes the limit of spectral purity and the tendency for filamentation in a semiconductor laser. For either narrow-line or high-power operation, it is generally desirable that the linewidth enhancement factor be minimized. This parameter depends primarily on the magnitude and shape of the differential gain spectrum of the active region material. In mid-infrared laser materials, band structure engineering has been used routinely to minimize the effects of nonradiative recombination. This same approach can be used to tailor the differential gain spectrum in order to minimize the linewidth enhancement factor. Favorable features of the electronic structure of active region materials include 1) band-edge dispersion in the conduction band, which shifts the peak of the gain away from the band edge and 2) intersubband absorption resonances lying above the peak gain in energy. Both of these strategies shift the peak of the differential gain closer to the peak gain, and thus reduce the linewidth enhancement factor. These electronic structure design strategies can be used to reduce the linewidth enhancement factor in type-II InAs/GaInSb systems to almost 1, which is significantly smaller than typical values of 2.5-5 of type-I strained quantum wells. We note that a linewidth enhancement factor close to 1 is much smaller than a typical linewidth enhancement factor in visible or near-infrared semiconductor lasers. Furthermore in some materials the peak of the differential gain lies in a region of positive gain, indicating that a grating could be used to select a mode with negligible linewidth enhancement factor.

9:45 AM OO1.5
RECENT PROGRESS OF MID-IR TYPE-II INTERBAND CASCADE LASERS. Chih-Hsiang Lin*, W.-Y. Hwang, A. Delaney and C. H. Kuo*, Applied Optoelectronics Inc., Sugar Land, TX; Y. Mu, H.Q. Le, Jun Zheng, B.H. Yang and S.S. Pei, SVEC and ECE Dept., Univ. of Houston, TX; *also with SVEC, University of Houston, Houston, TX.

Since the realization of the first type-II interband cascade (IC) laser, we have significantly improved the output power and quantum efficiency of IC lasers at wavelengths from 2.9 to 4.6 um. The 4-um device shows an internal quantum efficiency (IQE) of 220% at 80 K with 5-usec pulses and a duty cycle of 10%. Since the active region is composed of 23 stages, the IQE is only 9.6% per stage. Based on our study, the main reason for such a low IQE is due to the leakage current. After improving the device design and materials quality, we have demonstrated the first two-color type-II IC laser. It shows two lasing wavelengths at 4.488 and 4.568 um. The threshold current density is 125 A/cm2, which is the lowest value for any laser at this wavelength range. The device shows a peak output power per facet of 150 mW with a pulse length of 5 us and a frequency of 1 kHz. The average external quantum efficiency with an output power of 150 mW per facet is 278%, which is the highest value for any laser at this wavelength. The high output power and high efficiency of these devices clearly demonstrated the potential of the type-II IC lasers for high power mid-IR applications. Further reduction in internal loss and threshold current density should significantly improve the performance of the next generation of IC lasers. We will also report the recent progress in type-II IC lasers.

10:30 AM *OO1.6
CW ROOM TEMPERATURE 2.3-2.7 μm AlGaAsSb/InGaAsSb DIODE LASERS WITH HEAVILY STRAINED QUASI-TERNARY

InGaSb(As) QUANTUM WELLS. Dmitri Garbuzov, Hao Lee, Sarnoff Corporation, Princeton, NJ.

InGaAsSb is a unique III-V material which has the potential to cover the wavelength range from 1.7 to 4 μm being grown on binary (GaSb or InAs) substrates. Using AlGaAsSb compositions as a wide band gap copartner, Type I heterostructures can be designed and grown for such device applications as photodiodes, thermophotovoltaic cells and diode lasers. However, analysis of the published data demonstrates a fast degradation of the device performance at wavelength exceeding 2.2 μm. For a long time this wavelength was the upper limit for room temperature CW operation of InGaAsSb-based diode lasers. Recently it has been established that approaching the miscibility gap is the main reason for the performance degradation of the long-wavelength InGaAsSb-based devices. In the case of diode lasers with thin QW active regions the problem can be solved by replacing quaternary compositions with quasi-ternary InGaSb(As) compounds in the QW region. InGaSb (As) compositions with In content from 25% to 40%, located out of the miscibility gap, cover the wavelength range of 2.2-2.7 μm. Compressive strain in the QWs increases with In content and reaches 2.3% at the maximum In content. Despite heavy strain in QWs exceeding the Matthews- Blakeslee limit the diode lasers demonstrate very low threshold and relatively good differential efficiency at room temperature. CW output powers of hundreds of mW and of several mW have been obtained, respectively, for multimode broad-contact and single mode ridge diode lasers operating at record-long wavelengths of 2.2-2.7 μm.

11:00 AM *OO1.7
OPTICALLY-PUMPED W AND W-OPIC LASERS FOR HIGH CW POWER AND HIGH-EFFICIENCY IN THE MID-IRR. W.W. Bewley, C.L. Felix, I. Vurgaftman, L.J. Olafsen, D.W. Stokes, E.H. Aifer, J.R. Meyer, M.J. Yang, Naval Research Laboratory, Washington, DC; H. Lee, R.U. Martinelli, Sarnoff Corp., Princeton, NJ; A.R. Sugg, Sensors Unlimited, Inc., Princeton, NJ.

A diamond pressure bonding (DPB) technique for semiconductor lasers has been developed, in which an excellent heat sink is achieved simply by pressing the flat diamond and epilayer surfaces together in a controlled manner. Besides eliminating the metallization steps along with most other processing, this approach has the further advantage of allowing top optical pumping through the diamond at wavelengths that would be strongly absorbed for bottom pumping through the substrate. When DPB is applied to optically-pumped (λ_{pump} = 1.06 μm) type-II W lasers [InAs/Ga(In)Sb/InAs/Al(As)Sb], cw operation is observed throughout the 3-7 μm wavelength range. For example, T_{max} = 290 K at λ = 3.0 μm and 210 K at λ = 6.1 μm. At T = 77 K, a cw output power of 0.54 W is obtained at λ = 3.2 μm. With a mechanical chopper at 25% duty cycle, the peak quasi-cw power for the same device is 0.75 W at 77 K and 0.27 W at 140 K. We also report a novel W-OPIC approach, which yields significantly lower thresholds and higher efficiencies when optical pumping is by a pulsed 2.1 μm Ho:YAG laser. For a cavity length of 0.5 mm and uncoated facets, a device emitting at λ = 3.4 μm displays an incident threshold of only 8 kW/cm^2 at 300 K, and a characteristic temperature (T_0) of 64 K for the range 77-300 K. The external power conversion efficiency per facet is 9% at 77 K and 4% at 275 K, the latter of which is a factor of 5 higher than any previously reported value for that temperature and $\lambda \geq$ 3 μm.

11:30 AM OO1.8
GaInAsSb/AlGaAsSb QUANTUM WELL DIODE LASERS EMITTING IN THE 2.2 TO 2.3 μm WAVELENGTH RANGE. C. Mermelstein, S. Simanowski, M. Mayer, R. Kiefer, W. Pletschen, J. Schmitz, M. Walther, J. Wagner, Fraunhofer-Institut fuer Angewandte Festkoerperphysik, Freiburg, GERMANY.

There is a rapidly growing demand for efficient semiconductor lasers emitting at mid-IR wavelengths beyond 2 μm for, e.g., chemical process control, leak detection, and atmospheric pollution monitoring. The (AlGaIn)(AsSb) material system is well suited for the realization of diode lasers covering the 2 to 3 μm spectral range. We report on the characteristics of GaInAsSb/AlGaAsSb separate confinement heterostructure quantum well (QW) lasers, grown by molecular beam epitaxy on n-doped (100) GaSb substrates. The active region consisted of three compressively strained 10 nm $Ga_{0.70}In_{0.30}As_{0.06}Sb_{0.94}$ QWs separated by 20 nm wide $Al_{0.28}Ga_{0.72}As_{0.02}Sb_{0.98}$ barriers. The QW region was embedded between 50 nm thick $Al_{0.28}Ga_{0.72}As_{0.02}Sb_{0.98}$ separate confinement layers (structure A) followed by 2 μm wide $Al_{0.85}Ga_{0.15}As_{0.07}Sb_{0.93}$ cladding layers. Structure B was a Large Optical Cavity (LOC) design, differing from the structure A in having 400 nm wide separate confinement layers. Index guided ridge waveguide Fabry-Perot lasers were fabricated by chemically assisted ion beam etching. Cleaved laser bars were In-soldered substrate-side down onto Cu heat sinks. All devices were operated in cw mode. For structure A single mode lasing at 2.35 μm was achieved at 320 K for drive currents not too far above threshold. For the LOC laser structure B the lasing wavelength was 2.24 μm at 280 K. For a ridge width of 64 μm and a cavity length of 600 μm, a threshold current density of 285 A/cm^2 was observed at 280 K, which is significantly lower than that of 755 A/cm^2 observed for structure A. The characteristic temperature for the threshold current density of the LOC laser was T_0=123 K for the 200 to 280 K temperature interval. A differential quantum efficiency of 50% was measured at 280 K, corresponding to an output power of 80 mW per facet at a drive current of 650 mA. The maximum total power efficiency of the LOC diode amounted to 17%.

11:45 AM OO1.9
1.5-μm LUMINESCENCE FROM InGaAs/GaPAsSb TYPE-II QUANTUM WELLS GROWN ON GaAs. Yong-Hang Zhang, Phil Dowd, Shane Johnson, Wolfgang Braun*, Department of Electrical Engineering and Center for Solid State Electronics Research, Arizona State University, Tempe, AZ. * Present address: Paul-Drude-Institut für Festkerperelektronik, Berlin, GERMANY.

1.3 and 1.55 mm Vertical Cavity Surface Emitting Lasers (VCSELs) are highly desirable devices for optical data links, semiconductor chip interconnects, and local area networks. To overcome the thermal and refractive index limitations of the InGaAsP/InP material system, devices grown on GaAs have been proposed. In this talk, we report detailed experimental study of a set of thin InGaAs/GaPAsSb/ InGaAs QW samples grown with MBE. Strong room temperature band-to-band photoluminescence has been observed from these QW structures at wavelengths from 1.2 μm up to 1.5 μm, depending on the composition of the GaPAsSb layer. Room temperature electroluminescence (EL) has also been observed from light emitting diodes at wavelengths close to 1.3 μm. Stronger EL with narrower FWHM was achieved at low temperatures. Temperature dependent measurements down to 20 K have revealed a peak wavelength shift of 3.5A/K. These discoveries indicate that these InGaAs/GaPAsSb/ InGaAs type-II QW structures are suitable for long wavelength VCSEL applications.

SESSION OO2: ANTIMONIDE RELATED MATERIALS AND DEVICES II
Chairs: P. LeVan and Omar Manasreh
Monday Afternoon, November 29, 1999
Room 206 (H)

1:30 PM *OO2.1
GROWTH OF InSb ON GaAs SUBSTRATES USING InAlSb BUFFERS FOR MAGNETIC FIELD SENSOR APPLICATIONS. R.M. Biefeld and J.D. Phillips, Sandia National Laboratories, Albuquerque, NM.

Magnetic field sensors are becoming increasingly important for position sensing in computer controlled automotive applications. Magnetoresistive sensors using high electron mobility InSb are highly suited for these applications and are currently in production. The magnetoresistive sensors require wide bandgap substrates such as GaAs for reasons including electrical isolation at elevated temperatures, cost, and mechanical strength. It is desirable to reduce the film thickness in these devices in order to reduce power consumption and die size. However, due to the large lattice mismatch (14.6%), the growth of InSb on GaAs results in a large number of dislocations at the material interface, reducing the electron mobility. The dislocation density decreases and electron mobility increases significantly for thicker InSb layers. To resolve this problem, it is desirable to grow a highly resistive buffer with a lattice constant similar to InSb that will contain the dislocations. We will present the use of InAlSb as a buffer layer for InSb growth on GaAs by metal-organic chemical vapor. The evolution of the growth of the InSb and InAlSb layers was evaluated using in-situ reflectance monitoring and will be described. Electron mobilities of $\sim$40,000 cm^2/(V.s) were measured at room temperature for layers with $\sim$0.55μm of InSb and $\sim$0.9μm thick InAlSb buffers. The electron mobility dependence on $In_{1-x}Al_xSb$ layer composition for x$\leq$0.22 will be presented and is a result of the tradeoff between the buffer layer lattice mismatch and bandgap energy difference relative to InSb. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

2:00 PM *OO2.2
COMPOUND SEMICONDUCTOR APPLICATIONS FOR AUTOMOTIVE SENSORS. M.W. Pelczynski, J.J. Heremans, Emcore Corporation, Somerset, NJ.

As automotive technology moves into the 21st century, requirements for magnetoresistor and Hall devices for speed and position sensing applications are becoming more demanding. Currently, sensing

technology is split into two areas: silicon based active devices (integrated) and indium antimonide (InSb) based passive components. InSb has been shown to be superior as a sensor material due to increased sensitivity to magnetic field changes as well as increased operating range with respect to temperature. Additionally, devices can be easily tailored to meet a number of product requirements without adding electronic circuitry to compensate for lack of performance. In the present work, we will review the status of InSb based Hall and MR devices, including work on silicon substrates. Next we will present data on the first III/V monolithically integrated sensor that includes an AlGaAs/InGaP based HBT stack integrated to the InSb MR structure. Finally, we will show data for a sensor using an InAs quantum well with AlGaAsSb barriers grown by low pressure MOCVD, that will operate at temperatures exceeding 200 C.

2:30 PM OO2.3
ELECTRO-OPTICAL CHARACTERIZATION OF INFRARED SUPERLATTICE PHOTODIODES FOR THE 8 TO 12 μm WAVELENGTH RANGE. L. Buerkle, F. Fuchs, W. Pletschen, J. Schmitz and M. Walther, Fraunhofer-Institut fuer Angewandte Festkoerperphysik (IAF), Freiburg, GERMANY.

InAs/(GaIn)Sb superlattices (SLs) show a broken-gap type-II band alignment. For short period superlattices with sufficiently thin individual layers, confinement and strain effects result in an effective band gap which is tunable between zero and about 0.3 eV, hence making this material system interesting for IR detector applications. InAs/(GaIn)Sb superlattices were grown by MBE on GaSb substrates. The characterization of these superlattices with high resolution X-ray diffraction, atomic-force microscopy, infrared photoluminescence, and magneto-transport measurements is presented. Furthermore, infrared photodiodes designed for the 8 to 12 μm spectral range consisting of a 150 period superlattice stack were fabricated. These photodiodes exhibit quantum efficiencies around 30%, leading to peak responsivities above 2 A/W. At 77 K diodes with cutoff wavelengths of 8 and 12 μm show a dynamic impedance of $R_0A = 1\ \mathrm{k\Omega\,cm^2}$ and $3\ \Omega\,\mathrm{cm^2}$, respectively, corresponding to detectivities of $D^\star = 5\times10^{10}$ cm$\sqrt{\mathrm{Hz}}$/W and 1×10^{12} cm$\sqrt{\mathrm{Hz}}$/W. Diffusion limited performance is observed down to 90 K. Results of the electro-optical characterization of the photodiodes are discussed along with the investigation of the bias-voltage dependence of the photoluminescence intensity and its correlation to the results of a conventional CV-analysis.

2:45 PM OO2.4
ROLE OF SURFACE STEP STRUCTURE ON PHASE SEPARATION OF GaInAsSb. Christine A. Wang, MIT Lincoln Laboratory, Lexington, MA.

The GaInAsSb alloys, which are of great interest for mid-infrared detectors, lasers, and thermophotovoltaics, are metastable materials that can phase separate. This paper reports the correlation between the surface step structure, as determined by atomic force microscopy, and photoluminescence (PL) properties of lattice-matched GaInAsSb/GaSb grown by organometallic vapor phase epitaxy (OMVPE). The growth temperature is significant in determining the step structure. When the growth temperature is 575°C, 0.58-eV GaInAsSb forms step bunches. For lower-energy gap metastable alloys, the step edges become irregular and the surface roughness increases. The deterioration of the step structure likely results from decomposition of the metastable alloy, and conseqeuntly leads to degraded PL properties. The 4-K PL full width at half-maximum (FWHM) is significantly broadened due to carrier recombination in the lower energy gap InSb-rich quaternary regions. On the other hand, the step structure of epilayers grown at a lower temperature of 525°C is vicinal with step heights of one to two monolayers. Here, the PL FWHM values are considerably smaller. This improvement in material quality is related to lower adatom lifetimes at the lower growth temperature. The importance of surface kinetics as it influences the step structure and thermodynamically driven phase separation is discussed.

3:30 PM *OO2.5
GROUP V GRADED BUFFER LAYER SYSTEMS FOR TPV: DISLOCATION AND SURFACE MORPHOLOGY IN Al0.5 Ga0.5As1-ySby AND GaAs1-xSbx BUFFER LAYER SYSTEMS. Eric Chen, David C. Paine, Brown University, Division of Engineering, Providence, RI; Parvez Uppal, John S. Ahearn and Kirby Nichols, Sanders Lockheed-Martin, Nashua, NH.

In0.75Ga0.25As-based TPV structures grown on an Sb-adjusted step-graded buffer system on GaAs have been investigated. We demonstrate that an important advantage of using Sb-graded buffer layers is the ability to independently adjust the metal (group III) element to optimize growth morphology. In this talk we present a cross sectional TEM and AFM study of strain equivalent structures consisting of a multilayer grading scheme in which the Sb content of Al0.5Ga0.5As1-xSbx and GaAs1-xSbx is successively increased in a twelve step staircase of 100 nm thick layers. It is shown that the addition of Al results in a dramatic improvement in growth surface morphology and reduction in threading dislocation density. For example, AFM analysis of the surface roughness of the two sets of samples shows that the In0.75Ga0.25As TPV devices grown on Al0.5Ga0.5As1-xSbx buffer layers are several orders of magnitude smoother than the equivalent GaAs1-xSbx structure. Cross-sectional and plan view TEM show that the threading defect density is also low in the quaternary compared to the ternary structures. Our results show that surface roughness leads to threading dislocation trapping which, in turn, results in high thread densities. Measurement of device characteristics shows that the lower thread density of the quaternary buffers results in significantly improved device performance.

4:00 PM OO2.6
InGaAsSb THERMOPHOTOVOLTAIC CELLS GROWN BY OMVPE. Nancy Morris, Dmitri Garbuzov, Ramon Martinelli, Hao Lee, Gordon Taylor, John Connolly, Sarnoff Corporation, Princeton, NJ; Zane Shellenbarger, Gary Tompa, Structured Materials Industries, Inc., Piscataway, NJ.

The growth of InGaAsSb thermophotovoltaic (TPV) cells using organometallic vapor-phase epitaxy (OMVPE) is reported. The high throughput, excellent uniformity and reproducibility of OMVPE make it the preferable method for economic production of TPV cells. Growth was conducted in a low-pressure, vertical rotating-disk reactor capable of growing up to three two-inch diameter wafers. Precursors used were trimethylgallium (TMG), trimethylindium (TMI), trimethylantimony (TMSb), and arsine (AsH_3). Doping of the InGaAsSb material was achieved using dimethylzinc (DMZ) for p-type doping and hydrogen selenide (H_2Se) for n-type doping. The InGaAsSb epitaxial layers were grown lattice-matched to GaSb substrates. The composition of the InGaAsSb material was varied corresponding to bandgap energy of the material in the 0.55 to 0.52 eV range. The material properties of InGaAsSb layers were assessed using double-crystal X-ray diffraction, spectroscopic transmission and absorption, photoluminescence, and Van der Pauw measurements. Detailed results on the growth process and device properties are presented. The uniformity of material and device properties across the two-inch wafers was also examined. Several device structures were explored with variations in layer thicknesses and doping levels. A preliminary investigation of a monolithic dual-junction tandem TPV cell was also conducted. The results of quantum efficiency and current-voltage measurements show that these TPV cells are comparable to the best reported results for other growth methods.

4:15 PM OO2.7
ADVANCED GaSb/InGaAsSb/AlGaAsSb 2-2.5 μm PHOTOVOLTAIC DETECTORS. T.T. Piotrowski, A. Piotrowska, E. Kaminska, K. Golaszewska, E. Papis, M. Piskorski, W. Jung, J. Katcki, Institute of Electron Technology; J. Adamczewska, Institute of Physics PAS; J. Piotrowski, Z. Orman, J. Pawluczyk and Z. Nowak, Vigo Systems Ltd., Warsaw, POLAND.

Advanced photovoltaic detectors based on LPE-grown InGaAsSb/AlGaAsSb heterostructures lattice matched to (100) GaSb substrates are reported. The design of devices makes possible to prevent unwanted thermal generation of charge current at the surface, interface and contact areas and to reduce parasitic impedances. Sulfuration of GaSb surface has been used to prepare epiready grade GaSb substrates. SEM, TEM and XRD were used to examine the structural quality of heterostructures; C-V measurements were performed to evaluate carrier concentrations in InGaAsSb epilayers. Sulfuration was shown to enhance greatly the quality of GaSb surface, to improve structural quality of photodiode heterostructures and to decrease the carrier concentration in the active layer to $< 5\times10^{15}$ $\mathrm{cm^{-3}}$. The sulfuration procedure has been also used for passivation of the surface of the devices. The photovoltaic detectors have been characterized by measurements of I-V curves and spectral response. We have measured detectivities of about 10^{10} $\mathrm{cmHz^{1/2}/W}$ for unbiased 2.5 μm cutoff detectors operating at room temperature. Further optimization of device structure by using monolithic optical immersion to microlenses directly formed in the transparent substrate enables improvement of detectivity by one order of magnitude and reducing the capacitance by two orders of magnitude. The detectivities can be improved by one order of magnitude using of epilayers. In addition, the optical immersion reduces capacitance of the device by two orders of magnitude. The performances of the fabricated photodiode heterostructures have been confronted with results of computer simulation. It was found that the practical performance is within one order of magnitude of the theoretical limits set by statistical nature of thermal generation-recombination processes in the material.

4:30 PM OO2.8
HIGH TEMPERATURE W DIODE LASERS EMITTING AT 3.2

μm. L.J. Olafsen, W.W. Bewley, I. Vurgaftman, C.L. Felix, E.H. Aifer, D.W. Stokes, J.R. Meyer, Naval Research Laboratory, Washington, DC; H. Lee, R.J. Menna, R.U. Martinelli, D.Z. Garbuzov, M. Maiorov, J.C. Connolly, Sarnoff Corp., Princeton, NJ; A.R. Sugg, G.H. Olsen, Sensors Unlimited, Inc., Princeton, NJ.

W lasers based on type-II antimonides were recently operated nearly to room temperature under the conditions of cw optical pumping. However, the development of electrically pumped mid-infrared lasers has not yet reached the same level of performance. This is largely related to the more challenging task of simultaneously optimizing the doping/transport and gain/optical properties of the device. Here we report a demonstration of type-II mid-IR diode lasers employing W active quantum wells. Laser structures with 5 active periods sandwiched between broadened-waveguide separate confinement regions and quaternary optical cladding layers were processed into 100-μm-wide stripes, cleaved into 1-mm-long cavities, and mounted junction side down. For 0.5-1 μs pulses at a repetition rate of 200 Hz, lasing was obtained up to a maximum temperature of 265 K, where the emission wavelength was 3.18 μm. The threshold current densities were 140 A/cm^2 and 7.9 kA/cm^2 at 78 and 260 K, respectively. The characteristic temperature, T_0, was 64 K for temperatures between 120 and 200 K. The slope efficiency was 49 mW/A per facet at 78 K, which decreased only gradually to 22 mW/A at 220 K. Significant further improvements in the operating characteristics are expected once the optimization of the designs and fabrication procedures is complete.

4:45 PM OO2.9
HIGH-POWER MID-IR INTERBAND CASCADE LASERS BASED ON TYPE-II HETEROSTRUCTURES. Rui Q. Yang, J.D. Bruno, J.L. Bradshaw, J.T. Pham, D.E. Wortman, U.S. Army Research Laboratory, Adelphi, MD.

Interband cascade (IC) lasers, utilizing optical transitions between the conduction and valence bands in a staircase of Sb-based type-II quantum well (QW) structures, represent a new class of semiconductor mid-IR light source. IC lasers reuse each injected electron by making use of the broken band-gap alignment in type-II QWs to form cascade stages, leading to a quantum efficiency greater than the conventional limit of unity. Thus, mid-IR IC lasers are promising for obtaining high output power because they can circumvent the fast phonon scattering loss in intersubband lasers and suppress Auger recombination through band-structure engineering. Since the first demonstration in early 1997, IC lasers have been improved with encouraging results. However, their potential has been exploited to a much lesser degree. Recently at ARL, we have demonstrated mid-IR (3.8-3.9 micrometer) IC lasers based on InAs/GaInSb heterostructures at temperatures up to 210 K, which is higher than the previous record (182 K) for an IC laser at this wavelength. In this presentation, we will describe the recent results of IC lasers grown in a Varian Gen-II MBE system at ARL, which have exhibited significantly higher differential quantum efficiencies and peak powers than previous IC lasers. We observed from several devices at temperatures above 80 K, a slope greater than 750 mW/A per facet, corresponding to a differential external quantum efficiency exceeding 460%. A peak optical output power exceeding 4 W/facet was observed from one device at 80 K, which is the highest ever reported from any single mid-IR diode laser at emitting wavelengths beyond 3 micrometer. Also, most of devices were able to operate repeatedly without suffering from damage at high currents (>10 kA/cm^2) in contrast to previously reported IC lasers.

SESSION OO3: INNOVATIVE DEVICES I
Chairs: Helen M. Dauplaise and Ian Ferguson
Tuesday Morning, November 30, 1999
Room 206 (H)

8:00 AM *OO3.1
DC to 65 GHz WIDE BANDWIDTH InGaAs PHOTODIODES AND PHOTORECEIVERS. Abhay M Joshi, Discovery Semiconductors, Princeton Jct, NJ.

We have developed DC to 65 GHz Wide Bandwidth InGaAs Photodiodes and Photoreceivers for optical fiber driven telecommunication applications. The Photodiode operates at a nominal reverse bias of -3V and has a minimum responsivity of 0.5 A/W at 1300 and 1550 nm. The Ripple Factor is less than 1 dB for a wide band of frequencies, DC to 65 GHz. The salient feature of the Photodiode is an on-chip co-planar waveguide output for proper impedance matching. We have also designed Ultra Wide Bandwidth Amplifiers using InGaAs p-HEMT technology and monolithically integrated them with InGaAs Photodiodes. These Opto-electronic Integrated Circuits (OEICs) which combine photonics, microwave, and digital functions on the same chip is a technology that has significant potential for commercial applications such as ethernet fiber local area networks and optical communication systems. Important inter-service military applications are optically fed phased array systems and optically controlled microwave networks for airborne and spaceborne systems.

8:30 AM *OO3.2
PROGRESS IN MONOLITHIC PHOTONIC INTEGRATION USING QUANTUM WELL SHAPE MODIFICATION ENHANCED BY ION IMPLANTATION. Emil S. Koteles, Institute for Microstructural Sciences, National Research Council of Canada, Ottawa, Ontario, CANADA.

A review is presented of progress in the development of ion implantation enhanced quantum well shape modification as a technique for monolithically integrating optoelectronic devices of varying functionalities on a single semiconductor wafer. Fundamental issues related to the physics of the technique, both material issues and device issues, are considered and the performance of both discrete and integrated devices is discussed. The main conclusion of this review is that there are no inherent drawbacks to the utilization of this technique and some serendipitous advantages but that more work on reproducibility and reliability is required before commercial viability can be assured.

9:00 AM OO3.3
VERY LONG WAVELENGTH INTERMINIBAND LASERS. Alessandro Tredicucci, Federico Capasso, Claire Gmachl, Deborah L. Sivco, Albert L. Hutchinson, Alfred Y. Cho, Bell Laboratories, Lucent Technologies, Murray Hill, NJ.

Quantum Cascade (QC) lasers have established as the best semiconductor injection lasers operating in the mid-infrared at wavelengths $\lambda \geq 5$ μm. At very long wavelengths ($\lambda \geq 10$ μm) the reduction of radiative and injection efficiency, the high free-carrier and two-phonon absorption losses, and the poor thermal conductivity of thick waveguides result in diminished performances, especially for continuous wave (cw) operation. Semiconductor superlattices (SL), with the large dipole matrix element of interminiband transitions, the intrinsic strong population inversion, and the high current carrying capabilities, offer a natural elegant solution to the necessity of increased material gain. A new graded SL device operating pulsed at $\lambda \sim 11.5$ μm up to 300 K is presented here. The laser displays hundreds of mW of peak power at cryogenic temperatures and is also the first QC laser at wavelengths > 9 μm capable of cw operation at liquid nitrogen temperature with maximum powers of ~ 60 mW at 35 K. The requirement of large confinement factors while minimizing at the same time absorption losses makes metallic waveguides based on surface plasmon modes ideal candidates for very long wavelength devices. Laser emission is demonstrated at $\lambda \sim 16.5$ μm from a QC structure < 4 μm thick with no cladding layers. The maximum operating temperature is 190 K, with 17 mW of peak power at 10 K, better than any previous QC laser of comparable wavelength. The closeness of the active region with the metal contacts in this waveguide geometry is furthermore extremely promising for considerably improving power dissipation of QC lasers operated cw or at high duty-cycles.

9:15 AM OO3.4
AlGaAs/GaAs DISTRIBUTED FEEDBACK QUANTUM CASCADE LASERS. W. Schrenk, S. Gianordoli, L. Hvozdara, N. Finger, G. Strasser, K. Unterrainer, E. Gornik, Solid State Electronics, TU Wien, AUSTRIA.

We report on the first distributed feedback (DFB) quantum cascade lasers (QCL) in the AlGaAs/GaAs material system, showing single mode emission at 10 microns. The active cell of our QCL is based on an intersubband transition. The active region of the device consists of 30 periods, embedded into a plasmon enhanced waveguide. The first order DFB grating is exposed by contact photolithography and etched into the surface of the top cladding layer by reactive ion etching, therefore no regrowth is necessary. Ridge waveguide lasers are processed by ion beam etching. The extended contacts are isolated with a 280 nm thick SiN layer. One micron thick sputtered Au films form the top contact, back contacts consist of a Ge/Au/Ni/Au alloy. The calculated coupling coefficient is in the range of 20 cm^{-1} and the waveguide losses are only a few percent higher than the waveguide losses of a laser without grating. The calculations are based on a rigorous analysis of the waveguide-grating structure for TM polarized light. The laser bars with as cleaved facets are mounted epilayer up on a temperature controlled cold head of a He flow cryostat and are driven in pulsed mode with pulse lengths up to 100 ns and a repetition rate of 5 kHz. The laser spectra are measured with a Fourier transform infrared (FTIR) spectrometer, utilizing a liquid nitrogen cooled MCT detector. These DFB lasers are continuously wavelength tunable by changing the heat sink temperature from 4.2 K to 100 K. The shift in the single mode emission wavelength is 3 Angstrom per Kelvin.

9:30 AM OO3.5
SPACE CHARGE SPECTROSCOPY OF INTEGRATED QUANTUM WELL INFRARED PHOTODETECTOR - LIGHT EMITTING DIODE. M. Ershov, A.G.U. Perera, B. Yaldiz, S. Matsik, Department of Physics and Astronomy, Georgia State University, Atlanta, GA; H.C. Liu, Institute for Microstructural Sciences, National Research Council, Ottawa, CANADA.

Quantum Well Infrared Photodetector - Light Emitting Diode (QWIP-LED) is an integrated optoelectronic device converting mid- or far-infrared radiation into near-infrared or visible radiation which can be easily images by conventional CCDs. QWIP-LED normally operates under the forward bias, when the photocurrent is directly fed into LED to be converted into the output optical signal. Under the reverse bias, the p-n junction of the LED effectively blocks the current in the device, making it suitable for the QW charge spectroscopy, which allows the non-destructive evaluation of the QWIP-LED structural and physical parameters. We present the results of the theoretical and experimental investigations of the capacitance-voltage (CV) and admittance characteristics of QWIP-LEDs. The quasistatic (low-frequency) capacitance displays a series of steps as a function of the reverse voltage, which is due to the discrete extention of the space-charge region caused by the heavily-doped QWs. The parameters of the capacitance steps are related to the width of the QW period and the doping in the QWs. QWIP-LED displays a large negative capacitance under forward bias. The admittance of the QWIP-LED shows a resonance behavior as a function of the temperature (at fixed frequency) or the frequency (at fixed temperature). This helps to extract the ionization energy of the QWs and the capture rate of the carriers to the QWs. The experimental data are in good agreement with the predictions of the numerical and analytical models.

10:15 AM *OO3.6
QUANTUM DOTS IN OPTOELECTRONIC DEVICES. A. Stintz, K.J. Malloy, G.T. Liu, H. Li, T.C. Newell and L.F. Lester, Center for High Technology Materials, University of New Mexico, Albuquerque, NM.

Self-assembled InAs-GaAs quantum dots (QDs) have been used in both sources and detectors. We discuss the optical and electrical cross sections of quantum dots and their relevance to optical detector and emitter device design. Quantum dot laser performance improves upon placing a high density of InAs QDs in an InGaAs quantum well, thus optimizing electrical capture. The threshold current densities of these DWELL (dots-in-a-well) laser diodes are significantly lower than those of any reported quantum-well laser diode. The room temperature threshold current density is 25 A/cm^2 for uncoated facets with lasing wavelength around 1.3 micron. The influence of the InGaAs well and other growth conditions on QD formation will be discussed. In particular, the properties of laser diodes with quantum confined microstructures that deviate significantly from the conventional quantum dot microstructure will be discussed.

10:45 AM OO3.7
MID-INFRARED PHOTODETECTOR USING SELF-ASSEMBLED InAs QUANTUM DOTS EMBEDDED IN MODULATION DOPED GaAs QUANTUM WELLS. S.-W. Lee, K. Hirakawa and Y. Shimada, Institute of Industrial Science, University of Tokyo, Tokyo, JAPAN.

The quantum dot infrared photodetectors (QDIPs) using InAs self-assembled quantum dots (QDs) have been proposed and successful operation in the mid-infrared range has been demonstrated. Most of the structures reported so far utilize a vertical transport through stacked self-assembled QDs. However, because of unavoidable inhomogeneity in size and spatial alignment of the self-assembled QDs, the tunneling transport through multiple self-assembled QDs is strongly affected by the disorder. As a result, it seems to be difficult to obtain high photoconductive gains in the vertical transport structures. In this work, we have designed and fabricated a QDIP which utilizes the bound-to-continuum intersubband transition in the self-assembled InAs QDs and subsequent lateral transport of photoexcited carriers in the modulation-doped AlGaAs/GaAs two-dimensional (2D) channel. In this structure, the electrons are photoexcited from the ground state in the QDs to the virtual excited state above the conduction band of GaAs (bound-to-continuum operation), relax to the heterointerface, and drift laterally along the interface due to the applied electric field, thereby producing a photocurrent. The photocurrent spectra of the QDIP were measured in a single-pass normal incidence geometry by using a Fourier transform spectrometer. A broad photosignal is observed for the normal incidence radiation in a photon energy range of 100-300 meV and even above 400 meV. A peak responsivity as high as 4.7 A/W was obtained at photon energy of 160 meV at T= 10 K. This value is approximately two orders of magnitude larger than the values for the QDIPs reported so far. The high responsivity is realized mainly by a high mobility and a long lifetime of photoexcited carriers in the modulation-doped 2D channels. Furthermore, it is found that the observed photosensitivity survives up to 190 K.

11:00 AM *OO3.8
InGaAsN FOR HIGH EFFICIENCY SOLAR CELLS. A.A. Allerman, Steven R. Kurtz, E.D. Jones, N.R. Modine and R.M. Sieg, Sandia National Laboratories, Albuquerque, NM; S.A. Ringel, D. Kwon and R.J. Kaplar, Department of Electrical Engineering, The Ohio State University, Columbus, OH.

The conversion efficiency of the current generation of multi-junction solar cells would be increased significantly with the addition of a cell with band gap between 1.05 to 1.25eV. The incorporation of 1-3% nitrogen into InGaAs (4-9% In) results in films that can be lattice matched to GaAs with the desired bandgap. The growth by metal-organic chemical vapor deposition and performance of InGaAsN solar cells, with a 1.15eV and 1.05eV bandgap, is described. Alloy composition and bandgap have been found to be very sensitive to growth temperature and N/V ratio. The addition of DMHy significantly reduces growth rate for InGaAs films. The effect of N/V, In/III and V/III gas phase ratios on composition and bandgap will be presented. Initial solar cells relied on $SiCl_4$ for n-type doping but only limited electron concentrations over a narrow range of growth conditions was achieved. However, TESn was used to obtain n-type films over a wide range of growth conditions and film compositions. Post growth thermal annealing was found to significantly improve the photoluminescence from bulk films, reduce trap densities as measured by Deep Level Transient Spectroscopy (DLTS) and improve the internal quantum efficiencies of solar cells. Solar cell internal quantum efficiencies (IQE) $\approx$80% and open circuit voltages (V_{oc}) of $\approx$0.5V are obtained for material with a 15eV bandgap. Cells with a 1.05eV bandgap exhibit lower IQE ($\approx$70%) and V_{oc} ($<$0.35V). The hole diffusion length in annealed, n-type InGaAsN is 0.6-0.8μm, while electron diffusion lengths remain negligible (0.1μm). To date, high quantum efficiencies have only been obtained with cell designs utilizing hole diffusion in n-type material. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Dept. of Energy under contract DE-AC04-94AL85000. Funding was also provided by Air Force Research Laboratory and Lockheed Martin Missile and Space.

11:30 AM OO3.9
TIME-RESOLVED PHOTOLUMINESCENCE STUDIES OF $IN_XGA_{1-X}AS_{1-Y}N_Y$. R.A. Mair, J.Y. Lin and H.X. Jiang, Kansas State University, Department of Physics, Manhattan, KS; E.D. Jones, A.A. Allerman and S.R. Kurtz, Sandia National Laboratories, Albuquerque, NM.

Recently, the quaternary InGaAsN alloy system has attracted a great deal of attention due to its potential application in next-generation multi-junction solar cells as well as in optoelectronic devices for optical communications. To date, reported investigations of the fundamental optical transitions and carrier dynamic processes in the InGaAsN alloy are scarce. In this work, time-resolved photo-luminescence (PL) spectroscopy has been employed to study the mechanism of optical transitions and recombination dynamics in an InGaAsN epilayer grown by metal-organic chemical vapor deposition (MOCVD) on GaAs. The In and N mole fractions of the epilayer are approximately 0.03 and 0.01, respectively, so that the quaternary alloy is nominally lattice matched to GaAs. Picosecond time-resolved PL measurements were acquired under varied excitation intensities and sample temperatures. Our results indicate that localized exciton transitions are dominant in the quaternary alloy at low temperatures. The PL decay at 10 K was measured at different emission energies across the PL spectrum and found to be predominantly single exponential. However, the measured decay time decreases with increasing emission energy, and can be well described by a function describing localized exciton recombination within exponential tail states. PL emission spectra at 10 K exhibited both a blue shift and broadening with increased excitation intensity due to band filling within the exponential tail of the density of states. The PL also exhibited a pronounced blue shift with increasing sample temperature up to 50 K, which is a manifestation of the existence of tail states. Details of the measurements, estimates of the localization energy and the critical energy which separates the localized and extended exciton states (or the mobility edge) in the InGaAsN sample studied here, and implications to material properties and performance will be discussed. – Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

11:45 AM OO3.10
EFFECTIVE MASSES FOR InGaAsN ALLOYS LATTICE MATCHED TO GaAs. E.D. Jones, A.A. Allerman, I.J. Fritz, S.R. Kurtz and N.R. Modine, Sandia National Laboratories, Albuquerque, NM; K.K. Bajaj, Emory University, Atlanta, GA; S.T. Tozer and X. Wei, National High Magnetic Field Laboratory, Tallahassee, FL.

It is now well established that addition of small amounts of nitrogen to GaAs lowers the band gap energy dramatically because of the large negative bowing parameter. The semiconductor alloy system, InGaAsN, has thus been identified as a candidate material system for long wavelength laser systems and high-efficiency multi-junction solar cells. Besides the effect the isoelectronic nitrogen has upon the band gap energy, information regarding the effect on the masses is also important. Here we present conduction-band effective mass determinations for nitrogen concentrations of 1 and 2%. The measurements were made used three different experimental techniques: (1) Low temperature band gap energy dependence as a function of InGaAsN/GaAs quantum-well width. (2) Room temperature photoreflectance measurements of the ground and excited state energies for InGaAsN/GaAs quantum wells. (3) Low temperature magnetoluminescence measurements of the exciton diamagnetic shift in bulk InGaAsN epilayers. The effective masses are found to be approximately 2 to 3 times heavier than the GaAs value of 0.067. Additionally, the mass pressure coefficients for the effective masses were determined between ambient and 100 kbars from the 2-K magnetoluminescence data. The conduction-band effective masses are found to very pressure dependent, approaching values of 0.6 at 100 kbar. Theoretical interpretations of the heavier masses and their strong pressure dependence will be provided using the results of a first-principles band structure calculation for the InGaAsN alloy system. Finally, a new and novel approach for studying pressure dependent masses based upon the interpretation of excitonic linewidths due to alloy fluctuation theory will be presented.

SESSION OO4: INNOVATIVE DEVICES II
Chairs: Jerry R. Meyer and Yong-Hang Zhang
Tuesday Afternoon, November 30, 1999
Room 206 (H)

1:30 PM *OO4.1
QUANTUM CASCADE LASERS AND APPLICATIONS. Claire Gmachl, Federico Capasso, Alessandro Tredicucci, Deborah L. Sivco, James N. Baillargeon, Albert L. Hutchinson, Alfred Y. Cho, Bell Laboratories, Lucent Technologies, Murray Hill, NJ.

Quantum cascade (QC) lasers are a fundamentally different semiconductor laser source based on intersubband transitions. They are designed by methods of bandstructure engineering and realized by molecular beam epitaxy. One characteristic feature is the cascading scheme, where many (N = 1 - 75) active regions are stacked upon each other alternated with electron injection regions, allowing each electron above laser threshold to ideally create N laser-photons as it traverses the cascade. Therefore, QC-lasers have an intrinsic potential for high optical output power. A second feature is the tailorability of the emission wavelength through layer thickness. Wavelengths from 3.5 to 17 micrometer have been demonstrated using the GaInAs/AlInAs/InP material system. Finally, distributed feedback devices provide continuously tunable single mode emission. Here, we focus on 8 micrometer QC-lasers. Pulsed peak output power levels of $>$ 500 mW at room temperature and $>$ 1 W at 200 K have been obtained for Fabry-Perot lasers with 75 active region stages. In continuous wave (cw) operation, 200 mW have been measured from one facet at 80 K and still 60 mW at 110 K, both from lasers with 30 stages. Single-mode tunable QC-distributed feedback (DFB) lasers have been fabricated in the wavelength range between 5 and 17 micrometer. A side-mode suppression ratio of 30 dB and a 140 nm single-mode tuning range have been obtained for a QC-DFB laser emitting around 8.5 micrometer and operated in pulsed mode. QC-DFB lasers driven in cw-mode display a tunability of $\sim$ 70 nm as a result of thermal tuning between 20 K and 120 K. In various collaborations with spectroscopists these QC-DFB lasers have already been used successfully in various gas-sensing applications, involving the detection of ammonia, nitrous oxide, and nitric oxide. This material is based upon work supported in part by DARPA/US ARO under Contract No. DAAG55-98-C-0050.

2:00 PM *OO4.2
MULTI-SPECTRAL CAPABILITY AND BROAD-WAVELENGTH TUNABILITY OF Sb-BASED MID-INFRARED SEMICONDUCTOR LASERS. H.Q. Le, C.-H. Lin, C.H. Kuo, S.J. Murry, J. Zheng, B.H. Yang, and S.S. Pei, Department of Electrical and Computer Engineering and Space Vacuum Epitaxy Center University of Houston, Houston, TX.

Many applications of mid-infrared lasers such as spectrophotometric sensing require a broad-wavelength tunability or multi-spectral capability. The Sb mid-IR laser has a broad spectral gain band thanks to the low effective electron mass. A single wafer can cover a spectral range as large as $\sim$9% of its center wavelength. However a challenge in using this broad band capability is that it also involves a trade-off with the strong internal absorption loss that limits the laser power and temperature. Optimal management of this trade-off is critical from the system application point-of-view. This talk reviews the broad wavelength tunability of 3-5 um GaSb-based and InAs-based semiconductor lasers1 and discusses the optimization problem for multi-spectral applications. The problem requires consideration from material design to device geometry and external configuration. Relative merits of optically pumped laser, electrically pumped laser, edge-emitting, grating-coupled surface emitting, and external cavity will be compared and discussed. Spectral properties of quantum-well lasers,2 interband cascade lasers,3 and superlattice lasers will be presented. Results and semi-empirical extrapolation indicate that high power ($\sim$watt level), high brightness (MW/cm2sterad), elevated temperature ($>$150 K), and multi-spectral capability ($>$ 200 nm) are feasible, but at the expense of very high complexity in the whole laser package.
1. H.Q. Le, G.W. Turner, J.R. Ochoa, M.J. Manfra, C.C. Cook, and Y.-H. Zhang External cavity mid-infrared semiconductor lasers Proceeding of SPIE, Vol. 3001, p. 298 (1997).
2. C.-H. Lin, P.C. Chang, S.J. Murry, D. Zhang, Yucai Zhou, and S.S. Pei at SVEC, J. I. Malin et al. at NRL, Nearly Room-Temperature Type-II Quantum-Well Lasers at 3-4 um, J. Electronic Materials, vol. 26, pp. 440-443, 1997.
3. B.H. Yang, D. Zhang, R.Q. Yang, C.H. Lin, S.J. Murry, and S. S. Pei, Mid-IR Interband Cascade lasers with Quantum Efficiencies $>$ 200%, Appl. Phys. Lett., vol. 72, pp. 2220-2222, 1998.

2:30 PM OO4.3
THE LONGEST WAVELENGTH OPO PUMPED BY A 1 μm LASER. Konstantin Vodopyanov, John Maffetone, Ilya Zwieback and Warren Ruderman, INRAD, Inc., Northvale, NJ.

We report here type-II-phase-matched $AgGaS_2$ SRO OPO which yielded continuously tunable 3.9-11.3 μm idler output with quantum efficiency 22 % and slope efficiency 41%. The OPO had sub-MW/cm^2 threshold intensity and sub-100 μJ threshold energy for nanosecond 1.06μm pump radiation. Chalcopyrite $AgGaS_2$ (AGS) crystal transmits light between 0.5 and 12 μ, has high nonlinear-optical coefficient (d_{36}=12pm/V) and is one of the few crystals which can be pumped by 1 μm lasers -to get phase-matched down conversion into the $\lambda>5$ μm region. Nonetheless the tuning range of existing AGS OPOs did not exceed 4.2 μm so far[1-2]. The AGS crystal was grown at INRAD using Horizontal Gradient Freeze technique. A 2 cm long crystal was cut for type-II phase-matching. Type-II was chosen to achieve narrower OPO linewidths and to maximize the effective nonlinearity. Flat OPO mirrors were spaced apart by 2.7 cm and had high reflectivity for the signal wave and high transmisivity for the idler. By rotating the crystal we achieved an unprecedented tuning range of 3.9 to 11.3 μm with a linewidth of approximately 1 cm^{-1} . Due to its extremely small threshold pump energies the OPO can be pumped by existing laser-diode-pumped Nd-lasers. We will also demonstrate molecular absorption spectra taken with our OPO system. 1. Y.X. Fan, R.L. Eckardt, R.L. Byer, R.K. Route, R.S. Feigelson, Appl. Phys. Lett. 45 , 313 (1984) 2. P.P. Boon, W.R. Fen, C.T. Chong, X.B. Xi, Jpn. J. Appl. Phys. 36, L1661 (1997)

3:15 PM *OO4.4
NARROW-LINEWIDTH TERAHERTZ INTERSUBBAND EMISSION FROM THREE LEVEL SYSTEMS. Benjamin S. Williams, Bin Xu and Qing Hu, Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA; Michael R. Melloch, School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN.

Narrow-linewidth terahertz spontaneous emission resulting from interwell (or diagonal) intersubband transition from an electrically pumped multiple quantum-well (MQW) structure was observed. The center frequency of the emission peak is at 2.57 THz, and its full width at half maximum (FWHM) is 0.47 THz. The emission frequency is in good agreement with the calculated intersubband transition energy of 11.3 meV (corresponding to 2.7 THz) in a three-level system, which was designed to achieve population inversion between two radiative levels.

3:45 PM OO4.5
STRONG 1.5 μM EMISSION FROM Er-DOPED GaN ELECTROLUMINESCENT DEVICES AT 400K OPERATING TEMPERATURE. M. Garter, B.K. Lee, R. Birkhahn, J. Heikenfeld, D.S. Lee and A.J. Steckl, Nanoelectronics Laboratory, University of Cincinnati, Cincinnati, OH.

Erbium doped semiconductors are of interest because of the Er^{3+} luminescence at 1.5 μm which is used in optical fiber communications. Er-doped GaN has received attention recently due to the realization that temperature quenching of the infrared (IR) radiation is reduced as the band gap of the host material increases. In this paper, we report on the temperature dependence of the IR electroluminescence

(EL) for GaN:Er. We feel that this information will help clarify the practicality of Er-doped GaN EL devices as IR light emitters. Research on silicon doped with erbium at levels around $10^{20}/cm^3$ has shown that the IR radiation is generally quenched at temperatures around 150K. The addition of oxygen or reducing the erbium concentration has been shown to improve the temperature quenching in silicon. In contrast, our results with GaN:Er indicate that the onset of temperature quenching of the 1.5 μm radiation does not occur until $\sim$400 K even though the erbium concentration is an order of magnitude higher (around $10^{21}/cm^3$). GaN:Er devices have been fabricated with indium tin oxide (ITO) top-side contacts to an Er-doped GaN layer grown on Si. The GaN was grown by molecular beam epitaxy (MBE) using solid sources for Ga and Er and a plasma source for N_2. The IR EL spectrum shows several peaks clustered around 1550 nm. Intense green peaks at 537 nm and 558 nm are also present. All emission lines correspond to Er^{3+} transitions to the $^4I_{15/2}$ ground level and have narrow linewidths. The IR EL intensity vs. temperature shows a peak between 350 to 370K. From 275 to 410K the signal is at least 90 % of the peak intensity. At 500K, the signal is still 50% of the peak intensity.

4:00 PM OO4.6
PERFORMANCE AND SPECTRAL RESPONSE OF FAR-INFRARED $Pb_{1-x}Sn_xTe$(In) PHOTODETECTORS. Ivan Ivanchik, Dmitriy Khokhlov, Moscow State Univ, Dept of Physics, Moscow, RUSSIA; Judith Pipher, Nick Raines, Dan Watson, Univ of Rochester, Dept of Physics and Astronomy, Rochester, NY.

Direct comparison of performance has been done for a $Pb_{1-x}Sn_xTe$(In) photodetector, a Si(Sb) BIB structure and a state-of the art Ge(Ga) photodetector. The same cryogenic environment and measuring electronics was used for testing of all photodetectors mentioned above. The $Pb_{1-x}Sn_xTe$(In) photodetector shows several orders of magnitude higher responsivity S_I then the Si(Sb) BIB at the wavelength $\lambda = 14$ μm. Persistent photoresponse with $S_I \sim 10^3$ A/W for 1 s accumulation time at the wavelengths $\lambda = 90$ and 116 μm has been observed for the first time for the $Pb_{1-x}Sn_xTe$(In) photodetector. These value of S_I is by two orders of magnitude higher than for Ge(Ga) photodetector operating in the same wavelength region. The energy corresponding to these wavelengths is smaller than the thermal activation energy of the ground impurity state in $Pb_{1-x}Sn_xTe$(In) indicating that optical excitation of electrons from metastable impurity states give most important contribution to the far-infrared photoresponse. The red cutoff energy of this photoresponse may exceed 220 μm - the highest cutoff wavelength observed so far for the photon infrared photodetectors.

4:15 PM OO4.7
TUNED INFRARED EMISSION FROM LITHOGRAPHICALLY-DEFINED SILICON SURFACE STRUCTURES. James T. Daly, Edward A. Johnson, Anton C. Greenwald, John A. Wollam, Ion Optics, Inc., Waltham, MA; Thomas George and Eric W. Jones, Jet Propulsion Laboratory, Pasadena, CA.

Photonic bandgap structures have received much attention as optical and infrared filters with controllable narrow-band absorbance. There is a need, however, for the same kind of control of the thermal emittance of surfaces for applications ranging from control of radiative heat transfer to gas absorption spectroscopy. We report on the fabrication of photonic bandgap structures on silicon surfaces using standard lithographic techniques. Substrate resistivity varied from p- to n+ and in some cases background surface emissivity was suppressed with a high reflectivity coating such as gold. We have measured the infrared reflectance and emittance of these textured surfaces. We demonstrate that peak absorption/emittance wavelength and spectral purity (linewidth) correlate with photonic bandgap feature size and spacing as well as surface conductivity.* This work was supported in part by the National Science Foundation and by NASA.

SESSION OO5: POSTER SESSION
Chairs: Ian Ferguson Omar Manasreh Bethanie J. H. Stadler and Yong-Hang Zhang
Tuesday Evening, November 30, 1999
8:00 P.M.
Exhibition Hall D (H)

OO5.1
MICROSTRUCTURE STUDIES OF THE GaInAsSb/GaSb HETEROSTRUCTURE. Ziyang Zhang, Shuwei Li, Baolin Zhang, Tianming Zhou, Hong Jiang, Yixin Jin, Changchun Institute of Physics, Chinese Academy of Sciences, Changchun, P.R. CHINA.

Abstract In recent years, there has been considerable interest in the quaternary GaInAsSb alloy system. Since the quaternary GaInAsSb alloy system has a direct bandgap adjustable in wavelength from 1.7 to 4.5mm when grown lattice-matched on GaSb or InP substrate, it may provide the basis for emitters and detectors over this entire region. But when the epitaxial layer is lattice mismatch to the substrate, there will be easy to generate misfit dislocations that can degrade the material qualities and device performance. In order to reduce the densities of dislocations for device applications, it is essential to investigate both the formation and motion of these dislocations. First, the quaternary alloy Ga0.88In0.12As0.18Sb0.82 was grown on GaSb substrate by MOCVD. The substrate was n-type GaSb oriented 2 degree-off (001) towards $< 011 >$. Second, we studied the specimen by TEM and AFM. During the experiment, the following phenomena were found: 1. In the TEM image between the interface and the surface, We found that the GaInAsSb epilayer is almost fully relaxed with 60 degree dislocation, 90 degree dislocation. Furthermore these dislocations constitute 'pile-ups' rom some multiplication source. 2. In the AFM surface image of the GaInAsSb epilayer, many ridges were observed. It seems likely that there is a finite residual strain in deposit. These ridges are produced above those 'pile-ups' as growth progresses. With new 'pile-ups'appeared, surface ridges were continually produced. The ridges maintain their profile after the enhancement ceases. 3. In the TEM image of the crossection close to surface, it is observed that only 90 degree dislocations form the ridges, and 60 degree dislocations do not, because lomer 90 degree dislocations are given a locally enhanced growth in situ, and 60 degree dislocations can glide in all epilayer.

OO5.2
OPTIMIZING THE GROWTH OF InAsSn/InAs (001) SUPERLATTICE STRUCTURES. Manoj R. Pillai and Scott A. Barnett, Northwestern University, Dept of Materials Science and Engineering, Evanston, IL; Robert Biefeld, Sandia National Laboratories, Albuquerque, NM.

Antimony segregation in InAsSb/InAs (001) superlattices was studied using x-ray diffraction (XRD) and photoluminescence measurements. InAsSb/InAs samples were grown by metalorganic vapor phase epitaxy (MOVPE) on InAs (001) substrates. The superlattices had a period of $\approx$ 500 $\AA$, with a nominal InAsSb thickness of $\approx$ 50-100 $\AA$. The experimental $\theta - 2\theta$ patterns were simulated using a kinematical calculation with an exponential composition profile as expected for Sb segregation. The interfacial broadening due to the Sb segregation extended over 20-30 $\AA$ for most of the structures. Roughness was simulated by using random fluctuations in the thickness of each layer and defects by random fluctuations in d-spacing. The interface roughness values were of the order of less than 1 $\AA$. Growth conditions such as TMIn flow rate and growth temperature were varied to optimize the final structure in terms of reducing the Sb segregation lengths. We observe that reducing the growth temperature and increasing the TMIn flow reduces the Sb segregation from 25 $\AA$ to less than 10 $\AA$. We will report on the effect of varying the AsH_3 flow rate and TMSb flow rate. Also, photoluminescence measurements from these samples done at 16 K, will be discussed. Initial results suggest an improvement in the PL emission from the samples with lower Sb segregation.

OO5.3
TYPE-II SUPERLATTICES ON COMPLIANT GaAs SUBSTRATES. G.J. Brown, K. Mahalingam, A. Saxler, F. Szmulowicz, Air Force Research Laboratory (AFRL/MLPO), Wright-Patterson AFB, OH; Chih-Hsiang Lin, C.H. Kuo, W.Y. Huang, Applied Optoelectronics Inc., Sugarland, TX.

A limiting factor in the development of infrared imaging arrays utilizing type-II InAs/InGaSb superlattices is the GaSb substrates used for lattice-matched epitaxial growth. These substrates are conductive, limited to two inch diameters, and are highly absorbing at infrared wavelengths greater than 5 microns. This non-transparency in the infrared is incompatible with the standard approach of indium bump bonding arrays to readout circuits and using backside illumination for infrared imaging. An alternative to the GaSb substrates is the use of GaAs substrates with a bonded, thin compliant layer to reduce misfit dislocation formation associated with the large lattice mismatch between GaAs and the superlattice. Type-II superlattices of several different designs have been grown by molecular beam epitaxy on compliant GaAs, as well as GaSb, substrates. The effects of these substrates on the optical, electrical, and structural properties of the superlattices were studied. The superlattices grown on the compliant substrates were found to have low dislocation densities, uniform layers, excellent electrical isolation from the substrate, and improved infrared photoresponse. The development of superlattices on compliant substrates is a more cost effective approach to addressing the GaSb substrate limitations for infrared imaging than a program to improve the bulk crystal growth of GaSb.

OO5.4
MECHANISMS OF INTERSUBBAND TRANSITION IN N-TYPE III-V QUANTUM WELL SUPERLATTICE AND IMPROVEMENT

ON ABSORPTION FOR TE POLARIZED FIELD. C.W. Cheah, R.P.G. Karunasiri, L.S. Tan, Dept of Electrical Engineering, National University of Singapore, SINGAPORE.

An eight-bands k.p model incorporating envelope function approximation has been developed to study intersubband transitions in quantum wells. In this work, the valence band envelope functions were expressed in analytical form in terms of the envelope functions associated to the conduction band edge, and the Schrodinger equations were also derived for the envelope wave- functions. From the equations, closed form energy dependent effective mass for conduction band electron and the effective potential for the envelope wave-functions could be identified easily. The model has been used to study intersubband transition due to TM and TE polarized field in n-type quantum well superlattice. In this work, two main III-V material systems, namely AlGaAs/GaAs and AlGaAs/InGaAs, have been comprehensively compared. The unique differences in the absorption spectra for the two material systems were identified, together with the reasons and mechanisms that result in the differences, with particular emphasis placed on TE polarized field excitation. The material systems were found to influence the absorption spectra through two important parameters: the bulk momentum interband transition matrix element, and the band gaps of the system. Well and barrier regions were also found to play very different roles in the absorption of TE polarized field for the two material systems. This knowledge is crucial to the understanding of the response of quantum well to TE polarized field; and this understanding leads to several possible ways of improving such absorption, through the choice of material and the structure of the quantum well that greatly alters the symmetry of envelope wavefunctions. This work helps to shed some light on the controversial question about the TE absorption in n-type quantum wells, and to provide guidelines for the design of n-type quantum well with better TE polarized field absorption.

OO5.5
HIGH RESOLUTION X-RAY DIFFRACTION ANALYSIS OF P-TYPE STRAINED $InGaAs/AlGaAs$ MULTIPLE QUANTUM WELL STRUCTURES. W. Shi, D.H. Zhang, T. Osotchan, P.H. Zhang, S.F. Yoon, School of Electrical and Electronic Engineering, Nanyang Technological University, SINGAPORE.

Be-doped $InGaAs/AlGaAs$ multiple quantum well (MQW) structures, grown by solid-source molecular beam epitaxy with different doping concentration in the wells, were investigated by x-ray diffraction and transmission electron microscopy (TEM). Some features have been observed from the x-ray measurements. (1) The MQW mean mismatch increases from $1.176 \times 10^{-3} cm^{-3}$ to $1.195 \times 10^{-3} cm^{-3}$ and $1.29 \times 10^{-3} cm^{-3}$ for the structures with doping concentration of $1 \times 10^{17} cm^{-3}$, $1 \times 10^{18} cm^{-3}$ and $2 \times 10^{19} cm^{-3}$ in the wells, respectively. (2) The period of the MQW also increases with doping density. (3) The intensity of the first order satellite in the rocking curve of the x-ray diffraction decreases as the Be concentration is increased, indicating that the diffusion in the heavily doped wells is likely more significant than that in the lightly doped ones. (4) The full width at half maximum of the zero order satellite peak becomes widened as doping concentration increases, indicating that high Be-doping in the well likely deteriorates the quality of the multiple quantum well stacks. Simulation based on the Takagi-Taupin equation is also conducted, with the bandgap shrinkage caused by the Be-doping in the wells being taken into account, and the results are in very good agreement with the experimental values. In addition, TEM measurement is also conducted and clear pictures on well and barrier layers of the structures are observed. The information obtained is of great value for the design of p-doped quantum well infrared photodetectors.

OO5.6
INFRARED-PHOTOVOLTAIC RESPONSES OF ION-BEAM SYNTHESIZED β-$FeSi_2/n$-Si HETEROJUNCTIONS. Yoshihito Maeda, Kenji Umezawa, Dept. of Materials Sciences, Osaka Prefecture University, Sakai, JAPAN; Kiyoshi Miyake, Dept. of Environmental Sci. Human Eng., Saitama University, Urawa, JAPAN; Kenya Ohashi, Hitachi Research Laboratory, Hitachi Ltd. Hitachi, JAPAN.

Ion-beam synthesized (IBS) β-$FeSi_2$ has been regarded as a material with vague photovoltaic responses in spite of its evident optical features such as a direct optical transition and photoluminescence at $\sim$1.5μm. β-$FeSi_2$ has been widely noticed as a promising candidate of Si-based IR-LEDs because of these outstanding optical responses. However, there is few studies on Infrared (IR) or visible photovoltaic responses of IBS β-$FeSi_2$ in order to develop the IR or visible photodetectors. In this study, we present evident photovoltaic responses of IBS polycrystalline p-type β-$FeSi_2/n$-Si(100) heterojunctions in the IR to visible wavelength range. Using a triple ion implantation carried out with the total dose of 1×10^{17}cm^2 at the energies of 100, 80 and 50 keV and subsequent high temperature anneal at 800 °C, we obtained a continuous polycrystalline β-$FeSi_2$ layer on Si(100), which consisted of large grains of $\sim$10 μm and was $\sim$60 nm in the thickness. This continuous layer showed a high hole mobility of 440 cm cm^2/Vs at room temperature though its carrier concentration was more than 10^{18} cm^{-3}. The high temperature and long time anneal above 800 °C improved the IR and visible photovoltaic responses from the heterojunctions. We achieved a maximum open-circuit voltage of 0.4 V and a short-circuit current of 0.8 mA/cm^2 under white light illumination of 100 mW/cm^2. The maximum quantum efficiency was 0.32 %. At the lower anneal temperature $\sim$500 °C, we confirmed that precipitation of the psuedomorphic metallic γ-$FeSi_2$ near the $p-n$ junction is detrimental to both rectification and photovoltaic response. We confirm that IBS continuous β-$FeSi_2$ layer will be a promising material for the IR to visible photodetectors.

OO5.7
EFFECT OF LAYER RELAXATION ON THE INTERNAL PHOTOEMISSION IN $Pt/Si_{1-x}Ge_x$ SCHOTTKY BARRIER TYPE INFRARED DETECTORS. B. Aslan, R. Turan, Department of Physics, Middle East Technical University, Ankara, TURKEY; O. Nur, M. Karlsteen and M. Willander, Department of Physics, MINA, Chalmers University of Technology and Gothenburg University, Gothenburg, SWEDEN.

A Schottky type infrared detector fabricated on a p-type $Si_{1-x}Ge_x$ substrate has a higher cut-off wavelength than that on a pure Si substrate because the barrier height of the Schottky junction on p-type $Si_{1-x}Ge_x$ decreases with the Ge content and the induced strain in the $Si_{1-x}Ge_x$ layer. We have studied the effect of the strain relaxation on the internal photoemission characteristics of a $Pt/Si_{1-x}Ge_x$ Schottky junction with x =0.14 and shown that the cut-off wavelength of the diode made on a strained $Si_{0.86}Ge_{0.14}$ layer is higher than that on a Si substrate as expected. This shows the possibility of tuning the range of these detectors in the mid-infrared region. However, the thermal relaxation in the $Si_{0.86}Ge_{0.14}$ layer is found to reduce the cut-off wavelength to lower values, showing that the difference between the Fermi level of the metal and the valence band edge increases with the layer relaxation. This effect should be taken into the account when a Schottky type infrared detector will be manufactured on a strained $Si_{1-x}Ge_x$ substrate. I-V characteristics of the junctions have also indicated an increase of the barrier height with the relaxation. These results demonstrate the band edge movements in a $Si_{1-x}Ge_x$ layer experimentally in agreement with the expected changes in the band structure of the $Si_{1-x}Ge_x$ layer with the Ge content and the relaxation.

OO5.8
THERMALLY STABLE, SEMI-INSULATING GaAs BY RUTHENIUM DOPING. A. Dadgar, Otto-von-Guericke Universität, Institut für Experimentelle Physik, Magdeburg, GERMANY, Technische Universität Berlin, Institut für Festkörperphysik, Berlin, GERMANY; O. Stenzel, Technische Universität Berlin, Institut für Anorganische und Analytische Chemie, Berlin, GERMANY; M. Kuttler, Technische Universität Berlin, Institut für Festkörperphysik, Berlin, GERMANY; A. Krost, Otto-von-Guericke Universität, Institut für Experimentelle Physik, Magdeburg, GERMANY; D. Bimberg, Technische Universität Berlin, Institut für Festkörperphysik, Berlin, GERMANY; H. Schumann, Technische Universität Berlin, Institut für Anorganische und Analytische Chemie, Berlin, GERMANY.

Semi-insulating GaAs is a prerequisite for high speed electronic and optoelectronic devices. In MOCVD growth GaAs can be compensated by Cr doping. Cr, however, offers poor thermal stability which can lead to device degradation. Ruthenium has recently been shown to be a thermally stable dopant to achieve highly compensated InP [1]. Here we present first results on ruthenium doped semi-insulating GaAs. The samples were grown by LP-MOCVD using bis-(dimethyl-pentadienyl)ruthenium as Ru precursor. In DLTS measurements a deep Ru-correlated level 620 meV above the valence band has been observed. By comparison with Ru-doped InP this deep level can be assigned to the $Ru^{3+/2+}$ acceptor. Current-voltage measurements on Ru doped layers show a resistivity above 10^8 Ω cm under electron injection on GaAs:Si/GaAs:Ru/GaAs:Si structures and above 10^7 Ω cm under hole injection on GaAs:Zn/GaAs:Ru/GaAs:Zn structures. So, as in the case for Ru-doped InP, both n- and p-type conductivity can be compensated. Thus, also low-temperature grown GaAs which usually shows p-type conductivity can be compensated by Ru-doping. Diffusion studies on Ru implanted GaAs reveal an at least two orders of magnitude lower diffusion coefficient in contrast to Cr in GaAs. Consequently, as in the case for semi-insulating InP by Ru-doping, this dopant is a very well suited thermally stable compensator for MOCVD grown semiinsulating GaAs.(1) A. Dadgar, O. Stenzel, A. Niser, M. Zafar Iqbal, D. Bimberg and H. Schumann, Appl. Phys. Lett. 73, 3878 (1998)

OO5.9
PN JUNCTION FORMATION BY DIFFUSING PHOSPHORUS INTO P-TYPE Ge1-xSix BULK CRYSTALS. S.Kato, T.Sato, T.Horikoshi, H.Nemoto, T.Iida and Y.Takano, Department of Materials Science and Technology, Science University of Tokyo, Chiba, JAPAN.

Solar cells with the high conversion efficiency could be obtained by making on Ge0.6Si0.4 crystals. We have studied fabrication processes of the Ge1-xSix solar cells. In this report, we show the results of the Ge1-xSix crystal growth and pn junction formation on the grown crystals. We also demonstrate I-V characteristics of the pn diodes. Ge1-xSix crystals were grown by the vertical Bridgman method. CaCl2 was encapsulated to prevent from the reaction between the molten Ge1-xSix and the quartz ampoules. The grown Ge1-xSix crystals were poly-crystals with about 1-2 mm2 grains, and the composition x of them was varied from o to 0.5. Phosphorus atoms were diffused from P-diffused Si grains to the Ge1-xSix crystals in vacuum ampoules. The SIMS measurements showed that in the case of Ge0.8Si0.2, the diffusion depth was 1.5 um and the surface concentration was 2x1019 cm-3. The depth profile of it was consistent with the one of the complementary error function. The diffusion coefficients were found to change with the composition of Ge1-xSix. For examples, 1.9x10-12 cm2/s was in the Ge pure crystals and 2.2x10-14 cm2/s was Ge0.4Si0.6, respectively. The total carrier concentration dropped abruptly from 1016 /cm2 to 1015 at the point of x=0.15, where the band structure changed from Ge- to Si-like. Mesa structure diodes were made by etching and I/V characteristic was measured. The n factor was determined to be 1.2 from the measurements.

OO5.10
DEFECTS IN CdTe-BASED PHOTODETECTORS. V. Valdna, Tallinn Technical Univ, Institute of Materials Technology, Tallinn, ESTONIA.

CdTe is an important host material for the room temperature photodetectors, infrared optics and solar cells. The optoelectronic properties of CdTe can be widely varied depending on the dopant type and concentration. The aim of this work was to investigate the influence of different dopants and the concentration of dopants onto the defect structure and optoelectronic properties of CdTe. The results show that at a low concentration of halogen dopant and under tellurium vapour pressure high p-type conductivity is formed in CdTe. High photoconductivity can be achieved in CdTe if the concentration of shallow acceptor complexes, formed by the halogen dopant and intrinsic defects, is balanced with the concentration of excess substitutional halogen. If a donor-like codopant is used that substitutes Cd and under Cd vapour pressure the conductivity of CdTe can be converted into n-type.

OO5.11
PHOTORESPONSE OF TELLURIUM RICH Te_xSe_{1-x} NON-LINEAR OPTICAL SEMICONDUCTORS. G.J. Brown, Cindi L. Dennis, M.C. Ohmer, Air Force Research Laboratory, Materials & Manufacturing Directorate (AFRL/MLPO), Wright-Patterson AFB, OH; Jean-Olivier Ndap, Arnold Burger, Fisk University, Nashville, TN.

Elemental Te and Se crystals are non-centrosymmetric seimconductors with band gaps of respectively 0.33 eV and 1.7 eV and substantial birefringence. As a result they have excellent nonlinear optical properties and a broad transparency in the infrared. Te possesses the highest second order nonlinear optical coefficient known for a phase matchable material. However, for some applications its band gap is too small, hence the motivation for our study of Te rich Te_xSe_{1-x} solid solution alloys. The optical properties of Te_xSe_{1-x} were studied for x=0.8, 0.9, and 1.0. The results of variable temperature, polarization sensitive, spectral photoconductivity measurements on oriented single crystals are reported. The band gaps and their temperature dependencies were determined for $Te_{0.8}Se_{0.2}$, $Te_{0.9}Se_{0.1}$, and Te by this method. It was found that the room temperature band gap of $Te_{0.8}Se_{0.2}$ was 0.498 eV, that of $Te_{0.9}Se_{0.1}$ was 0.38 eV, and that of Te was 0.333 eV. In all cases it increases with increasing temperature. Analytical expressions describing these dependencies are reported. Furthermore, for the first time the characteristic two peak spectrum of tellurium was separated into its two components for incident radiation polarized parallel and perpendicular to the c-axis as a function of temperature. However, two distinct peaks were not discernible in the alloys, with or without polarization, although the intensity was slightly polarization dependent. This may indicate that the usual treatment of alloys as crystalline analogs is less than perfect in this instance.

OO5.12
GROWTH, SPECTROSCOPY, AND MID-INFRARED LASER PERFORMANCE OF CHROMIUM (2+) DOPED CADMIUM MANGENESE TELLURIDE. U. Hommerich, J.T. Seo, M. Turner, A. Bluiett, D. Temple, L. Salary, Hampton University, Dept. of Physics, Hampton, VA; S B. Trivedi, H. Zong, S.W. Kutcher, C C. Wang, R.J. Chen, Brimrose Corporation of America, Baltimore, MD.

The demonstration of mid-infrared laser activity from Cr (2+) doped ZnS and ZnSe has stimulated interest in Chromium doped II-VI semiconductors as mid-infrared gain media. The most striking features of these novel laser materials are the large absorption and emission cross-sections, the high luminescence quantum yield, the predicted absence of excited state absorption, and the wide laser tunability ranging from nearly 2000 to 3000nm. A promising new host material for Cr(2+) ions is the ternary compound semiconductor CdMTe. Compared to ZnSe and ZnS, CdMnTe offers the advantages of ease of crystal growth and compositional tuning. In this paper we present latest results on the crystal growth, spectroscopy, and laser performance of Cr doped CdMnTe with 15%, 45%, and 60% Mn content.

OO5.13
INFRARED PHOTOSENSITIVITY DUE TO THE Yb-INDUCED DEFECT STATES IN $Pb_{1-x}Ge_xTe$ ALLOYS. Evgenii P. Skipetrov, Natalia A. Chernova, Elena A. Zvereva, Moscow State University, Physics Department, Moscow, RUSSIA; Evgenii I. Slyn'ko, Institute of Material Science Problems, Chernovtsy Department, Chernovtsy, UKRAINE.

We investigate the galvanomagnetic properties (B $\leq$ 0.1 T, 4.2 $\leq$ T $\leq$ 300 K) of $Pb_{1-x}Ge_xTe$ ($x < 0.04$) alloys doped with ytterbium both in the chamber shielded from the background illumination and under infrared illumination from the heat source (mini-lamp) and GaAs-LED. The alloys exhibit high photosensitivity at $T < T_c \approx 40$ K and the effect of persistent photoconductivity at the liquid helium temperature. The value of photoresponse increases with the increase of the Ge content in the alloy. The photoconductivity kinetics shows two types of relaxation processes: a fast one (characteristic relaxation time $\tau \sim 0.01$ sec) and a long-duration one ($\tau \sim 10$ sec and decreases exponentially with temperature increase). The high photosensitivity is likely provided by a capture of electrons on the Yb-induced states E_{Yb}, the position of that with respect to the valence band top E_v depends upon the Ge content x: $E_{Yb} - E_v \approx (-4 + 680x)$ meV. We suppose, that the charge carrier capture and emission occurs by a multiphonon process and that there is a reconstruction of a crystal lattice. Thus, various charge states of the defect are separated between each other by an energy barrier, that results in a long-duration character of the relaxation processes. The height of this barrier estimated from the temperature dependence of the relaxation time is about 10 meV.

OO5.14
POSITIVE AND NEGATIVE PHOTOCONDUCTIVITY IN LEAD TELLURIDE DOPED WITH GALLIUM EPITAXIAL FILMS. B.A. Akimov, V.A. Bogoyavlenskiy, L.I. Ryabova, Moscow State Univ, Dept of Low Temperature Physics, Moscow, RUSSIA; V.N. Vasil'kov, ORION Center, Moscow, RUSSIA.

We have studied the photoelectric and kinetic properties of n-PbTe(Ga) films in the temperature interval 4.2-300 K. The films were prepared on $< 111 >$ BaF_2 substrates with use of the hot wall technique, the film thickness was 1-6 μm. The photoconductivity (PC) measurements were performed with use of a heat source and GaAs-LED with λ=1 μm. The photoelectric properties of the films are correlated with the substrate temperature T_{sub}. The first group of samples demonstrates a behavior similar to high resistivity bulk n-PbTe(Ga) single crystals. Another group of films obtained at higher T_{sub} is characterized by lower resistivity values and coexistence of positive and negative PC in the temperature range 4.2-100 K. The negative PC dominates at temperatures lower than 30-40 K. Under the continuous illumination the observed negative PC transient is similar in main features to positive one and may be characterized by non-exponential kinetics and persistent effect at the relaxation tail. LED pulses induce only negative photoresponse with a moment relaxation time of about 10^{-5}s. The experimental results are discussed in terms of negative U-potential and mixed valence of Ga in PbTe.

OO5.15
Abstract Withdrawn.

OO5.16
MODE OF ARSENIC INCORPORATION IN MBE HgCdTe. M. Sumstine, T.S. Lee, S. Sivananthan, Dept. of Physics, Chicago, IL.

During the past decade, MBE has evolved as an accurate and flexible manufacturing technology for HgCdTe. Nevertheless p-type doping continued to be an unresolved issue for MBE HgCdTe. As-grown MBE HgCdTe layers are highly compensated n-type and have increase in defect density. During isothermal annealing under Hg flux, As atoms

are nearly fully activated to act as acceptor for arsenic concentration in the range of mid 10^{15} to high 10^{17} cm^{-3}, and its activation ratio decreases rapidly as arsenic doping level increases until it finally goes below 5% at the mid 10^{19} cm^{-3} due to a limitation of arsenic atom solubility in HgCdTe[1,2,3]. Theoretical work has been carried out to understand whether arsenic incorporates as individual arsenic atoms, as dimers, or as tetramers in as-grown and annealed layers. Hall effect data of HgCdTe layer at 80K shows lower donor concentration by around one order than arsenic concentration measured with SIMS. Based on quasi-thermodynamic model [4], arsenic incorporates as arsenic tetramer in as-grown As-doped HgCdTe layers, it is expected that arsenic atoms incorporate as $As_4{}^D$ and $As_4{}^0$ (here $As_4{}^D$ is an arsenic tetramer acting as a donor, which is placed on the lattice in such a manner that two arsenic atoms occupy Hg sites, one occupies a Te site, and the fourth is in interstitial position. $As_4{}^0$ is an electrically neutral arsenic tetramer, which is placed on the lattice in such a manner that one arsenic atom occupies a Hg site, one occupies a Te site, and the other two are in interstitial positions.) During annealing in the range of 300-450°C, it is inferred that one $As_4{}^D$ or $As_4{}^0$ is cracked into four As^A and the concentration of $As_4{}^D$ and $As_4{}^0$ rapidly decreases close to zero (here As^A is an individual arsenic atom acting as an acceptor occupying Te site). Therefore, in the annealed layers, the activation ratio can be close to 100% up to the arsenic concentration of high 10^{17} cm^{-3}. Above this concentration, excess individual arsenic atoms, which can't occupy Te sites, seem to become arsenic cluster. The cluster might consist of $As_4{}^0$ or $As_2{}^0$ made of As^A atoms (here $As_2{}^0$ is a neutral arsenic dimer, which is placed on the lattice in such a manner that one arsenic atom occupies a Hg site, the other a Te site). [1] P. S. Wijewarnasuriya and S. Sivananthan, Appl. Phys. Lett. 72(14), 1694(1998). [2] X. H. Shi, S. Rujirawat, R. Ashokan, C. H. Grein, and S. Sivananthan, Appl. Phys. Lett. 73(5), 638(1998). [3] O. K. Wu, R. D. Rajavel, and J. E. Jensen, Mater. Chem. Phys. 43, 103(1996). [4] J. W. Garland, C. H. Grein, B. Yang, P. S. Wijewarnasuriya, F. Aqariden, and S. Sivananthan, Appl. Phys. Lett. 74(14), 1975(1999).

OO5.17

IMPURITY-INDUCED DEFECT STATES IN $Pb_{1-x}Ge_xTe$ ALLOYS DOPED WITH GALLIUM. Evgenii P. Skipetrov, Elena A. Zvereva, Vladimir V. Belousov, Ludmila A. Skipetrova, Moscow State University, Physics Department, Moscow, RUSSIA.

Galvanomagnetic properties ($B \leq 0.1\mathrm{T}, 4.2 \leq T \leq 300$ K) of n-$Pb_{1-x}Ge_xTe$¡Ga¿ ($0.04 \leq x \leq 0.08$) single crystals have been investigated in the shielded from external background illumination chamber and under controlled illumination from infrared heat source. On the temperature dependencies of the resistivity ρ and the Hall constant, measured in the darkness, the low-temperature activation range of the impurity conductivity has been revealed. In all investigated samples the anomalous high photosensitivity under the illumination at temperatures below $50 \div 60$ K and an effect of persistent photoconductivity at helium temperatures were observed. Obtained experimental results were explained assuming that gallium doping leads to the formation of deep impurity-induced level E_{Ga} in the forbidden band of the alloys. From the slope of the activation range on ρ (1/T) dependencies the activation energy of Ga-induced level was determined. It was shown that with increasing germanium concentration the E_{Ga} level moves almost linearly relative to the bottom of the conduction band E_c with the rate $\mathrm{d}(E_{Ga} - E_c)/\mathrm{d}x \approx 20$ meV/at.%. So, in PbTe it should be resonant with the conduction band locating approximately on 45 meV higher the conduction band bottom. The existence of high photosensitivity and long-duration relaxation processes can be connected with capture of electrons from Ga-induced defect centers to the conduction band under the illumination, when localized and band states are separated from each other with an autolocalization barrier in the configuration space.

OO5.18

SECOND-HARMONIC GENERATION IN ORIENTED CdSe-NANOCRYSTAL-DOPED INDIUM TIN OXIDE FILM AND ITS APPLICATION TO AN INFRARED DETECTOR. Aiko Narazaki, Toshiaki Hirano, Jun Sasai, Katsuhisa Tanaka, Kazuyuki Hirao, Dept of Material Chemistry, Graduate School of Engineering, Kyoto Univ, Kyoto, Japan.

Second-harmonic generation is applicable to a near infrared detector. In this study, the second-harmonic generation has been examined for CdSe nanocrystals doped in indium tin oxide (ITO) films. The thin film samples were prepared by r.f. magnetron sputtering with ITO target on which CdSe chips were placed. The X-ray diffraction pattern of as-prepared film indicates that CdSe crystallites are precipitated in an amorphous ITO matrix, and they are preferentially oriented in the direction of (111) plane of zinc blende structure or (002) plane of wurtzite structure. The mean diameter of CdSe crystallite was estimated to be 5nm using Scherrer's equation, which is in good accordance with transmission electron microscope observation. The incident angular dependence of second-harmonic intensity, i.e., Maker fringe pattern, was measured for both amorphous ITO and CdSe-doped ITO films. The Maker fringe pattern of the latter exhibits a maximum second-harmonic intensity at around 50° and zero value at 0° whereas the former shows no second-harmonic generation. These results lead to a conclusion that the second-harmonic generation in CdSe-doped ITO film is due to the CdSe nanocrystals. Moreover, the CdSe crystallites grew with keeping its initial orientation when a dc voltage of 50V/cm was applied in the direction parallel to the film surface. The application of the electric field effectively enhanced the second-harmonic intensity by two orders of magnitude compared with that of the as-prepared film. The second-order nonlinear coefficient $d^{(2)}$ for the electrically treated specimen obtained on the basis of a modified Maker fringe theory is d_{31} = 30pm/V, which is comparable to d value reported for CdSe single crystal , d_{33} = 76pm/V.

OO5.19

PbTe/PbEuTe MULTI-QUANTUM WELLS: STRUCTURAL AND OPTICAL PROPERTIES. E. Abramof, A.Y. Ueta, P.H.O. Rappl, P. Motisuke, Lab. Associado de Sensores e Materiais, Instituto Nacional de Pesquisas Espaciais, Sao Jose dos Campos-SP, BRAZIL; S.O. Ferreira, Depto de Fisica, Universidade Federal de Viaosa, Viaosa-MG, BRAZIL.

PbTe/PbEuTe heterostructures are of great interest for the fabrication of lasers in the mid-infrared range[1]. In this work, PbTe/$Pb_{1-x}Eu_xTe$ (x 0.04) multi-quantum wells (MQWs) were grown on (111) cleaved BaF_2 substrates by molecular beam epitaxy. $Pb_{1-x}Eu_xTe$ with the same x value as the MQW barrier was used as buffer layers. The samples were characterized structurally in a high-resolution diffractometer in the triple-axis configuration. The ω scans of the (222) Bragg reflection showed very well resolved satellite peaks indicating that sharp interfaces were obtained. Reciprocal space maps around the asymmetric (224) Bragg diffraction point were performed in order to obtain information about the strain state in the MQW. With this strain information, the (222)ω scans were simulated by dynamical theory of x-ray diffraction using Takagi-Taupin equations. By fitting the measured spectra, the period and the individual layer thickness of the MQW structure were precisely obtained. The transmission spectrum of the MQW's was measured in a Fourrier transform infrared spectrometer from 500 to 4500 cm^{-1} at temperatures between 300 and 5K. The measured spectra were fitted and the interband transition energies between the quantized levels in the conduction and valence bands of the PbTe well were determined. A good agreement was obtained when comparing these transition energies with the ones calculated analytically within the envelope function approximation using the Dimmock two-band $k.p$ model. [1] D.L. Partin, Lead Salt Quantum Effect Structures. IEEE J. Quantum Eletronics QE 24, 1716 (1988).

OO5.20

TEMPERATURE DEPENDENT HALL MEASUREMENTS MADE ON $CdGeAs_2$. A.J. Ptak, S. Jain, and T.H. Myers, Department of Physics, West Virginia University, Morgantown, WV; P.G. Schunemann, S.D. Setzler and T.M. Pollak, Sanders, A Lockheed Martin Company, Nashua, NH.

Numerous samples of $CdGeAs_2$ have been extensively characterized by temperature-dependant Hall effect measurements. The samples were grown at Sanders by directional solidification in horizontal transparent furnaces. Due to the anisotropic nature of the electrical properties, carefully matched sample sets with the c-axis both in and out of the plane of the Hall sample were fabricated. The matched samples allowed precise determination of carrier concentration and both in-plane and out-of-plane mobilities as a function of temperature. A distinct correlation between electrical properties and below band gap absorption was observed. The electrical properties of both undoped and lightly doped samples were dominated by either native defects or residual growth impurities, leading to compensated p-type material. N-type material was obtained only with heavier doping. The apparent variation in acceptor activation energy could be best explained in terms of two deep acceptor levels and at least one shallow donor. This work was supported by Air Force Research Labs Materials and Manufacturing Directorate under contract F33615-94C-5415, and by AFOSR under contract F49620-96-1-0452.

OO5.21

CONTROL OF THE INTERMIXING OF InGaAs/InGaAsP QUANTUM WELL IN IMPURITY FREE VACANCY DISORDERING BY CHANGING NH_3 FOLW RATE DURING THE GROWTH OF SiN_x CAPPING LAYER. W.J. Choi, H.T. Yi, D.H. Woo, S. Lee, S.H. Kim, K.N. Kang, Photonics Research Center, Korea Institute of Science and Technology, Cheongryang, Seoul, KOREA; Jaewon Cho, Dept. of Physics, Kwangwoon University, Seoul, KOREA.

We present the result of impurity free vacancy disordering (IFVD) of InGaAs/InGaAsP quantum well (QW) structure grown by chemical

beam epitaxy with SiN_x capping layer. The QW structure consisted of a 7 nm thick lattice matched InGaAs well sandwiched with InGaAsP (lambda$_{PL}$ = 1.3 μm) barrier. Room temperature photoluminescence(PL) measurement of this structure showed an extonic emission peak at 1.54 μm. The characteristics of the SiN_x capping layer over the QW structure was varied by changing the flow rate of NH_3 during film growth by plasma enhanced chemical vapor deposition method. The refractive index of SiN_x capping layers varied from 2.55 to 1.77 as NH_3 flow rate increased from 0 to 40 sccm. IFVD was carried out by semi-open tube type furnace annealing at 750 °C for 8 minutes. The thickness of SiN_x capping layers was set at 100 nm in order to eliminate the effect of thickness on the QW disordering. PL measurement of disordered samples showed blueshifts. Though a 300 nm thick SiO_2 capped sample showed a blueshift of 14.0 meV, the amount of blueshift increased from 12.7 meV to 40.5 meV with increasing NH_3 flow rate from 0 sccm to 40 sccm. More results will be presented in detail.

OO5.22
THEORETICAL AND EXPERIMENTAL INVESTIGATION OF THE DISORDERING EFFECTS ON THE PHOTOLUMINESCENCE SPECTRA OF InGaAs/InGaAsP QUANTUM WELLS. J.C. Yi, School of Electronics and Electrical Engineering, Hong Ik University, Seoul, KOREA. W.J. Choi, S. Lee, D.H. Woo, S.H. Kim Photonics Research Center, Korea Institute of Science and Technology, Seoul, KOREA.

The effect of disordering on the photoluminescence spectra of InGaAs/InGaAsP quantum wells has been investigated theoretically and experimentally. The disordering profile of 1.55Q InGaAs/InGaAsP quantum wells lattice matched to InP has been controlled by the choice of the cap layer materials as well as the diffusion time and diffusion temperatures. The chosen cap layer materials were InP, InGaAs, and InGaAsP under silicon nitride or silicon dioxide, respectively. The diffusion temperature was 750 degree Celsius and the diffusion time was varied up to 16 min. The largest PL peak shift has been 120 meV when the cap layer was InP under silicon nitride. The PL spectrum has also been analyzed theoretically taking into account of the valence band intermixing effects, strain induced energy shift, and excitonic energy shift. In the modeling of the quantum well disordering(QWD), the error function like profile was assumed for the interdiffused In and As atom distribution. The ratio of the diffusion constants between In and As atom also has been varied. By comparing the experimental data and theoretical calculation, the diffusion constant for each atom has been revealed for various experimental samples.

OO5.23
IMPROVED INTERMIXING IN GaAs/AlGaAs QUANTUM WELL STRUCTURES THROUGH REPEATED IMPLANT-ANNEAL SEQUENCE. H.H. Tan, C. Jagadish, Dept. of Electronic Materials Engineering, Research School of Physical Sciences and Engineering, The Australian National University, Canberra, ACT, AUSTRALIA; M.B. Johnston, M. Gal, School of Physics, University of New South Wales, Sydney, NSW, AUSTRALIA.

Post-growth tailoring of electrical and optical properties of semiconductor devices is a very useful concept in the fabrication of integrated optoelectronic devices. For example, in wavelength-division-multiplexing (WDM) applications, there is a need to integrate several lasers of different wavelengths onto a single chip. A simple and effective way of achieving this is via quantum well (QW) intermixing, where the effective band gap of the quantum well is increased due to the interdiffusion between the quantum well and barriers. Ion implantation has been shown to be a very useful and reliable technique for quantum well intermixing. This technique relies on the introduction of controllable amount of defects into the QW heterostructures which enhance the interdiffusion between the various atoms across the interfaces. Thus, to optimise intermixing, the amount and type of defects need to be controlled. It is undesirable to create an amorphous material or even defect clusters as these defects are thermally quite stable and thus do not promote intermixing. In this paper, we will demonstrate how the use of a repeated implant-anneal sequence may suppress the formation of some of these clusters and hence improve the degree of intermixing in GaAs-AlGaAs QW heterostructures. Low temperature photoluminescence is used to monitor the wavelength shift of the QWs. Very large energy shifts (up to 160 meV) were observed after annealing. However, the energy shift was further improved with a repeated implant-anneal sequence by up to about a factor of two. This sequence was used to fine-tune the emission wavelength (up to 40 nm shift in lasing wavelength) of Graded Index Separate Confinement Heterostructure (GRINSCH) QW lasers without severe degradation in the lasing characteristics. This technique is potentially useful for an integrated multi-wavelength laser source.

OO5.24
PHOTOLUMINESCENCE MEASUREMENTS OF INTERBAND TRANSITION IN FAST NEUTRON IRRADIATED $In_{0.07}Ga_{0.93}As/Al_{0.4}Ga_{0.6}As$ MULTIPLE QUANTUM WELLS. M.O. Manasreh[1] and S. Subramanian[2]. [1]Air Force Research Lab (AFRL/VSSS), Kirtland AFB, NM, [2]Department of Electrical and Computer Engineering, Oregon State University, Corvallis, OR.

Interband transitions in n-type InGaAs/AlGaAs multiple quantum wells were studied using a photoluminescence (PL) technique after the samples were irradiated with fast neutrons. It was observed that the PL intensity of the interband transition is reduced as the irradiation dose is increased. In Addition, the peak position energy of the interband transition was increased and then decreased as a function of irradiation dose. The results are explained in terms of electrons trapping, many-body effects, and irradiation-induced damages at the interfaces as well as in the well and barrier regions.

OO5.25
APPLICATION OF ION IMPLANTATION INDUCED INTERMIXING IN TUNING THE DETECTION WAVELENGTH OF QUANTUM-WELL INFRARED PHOTODECTORS. L. Fu, H.H. Tan, C. Jagadish, Australian National Univ, Dept of Electronic Materials Eng, Canberra, AUSTRALIA; Na Li, Ning Li, Xinquan Liu, Wei Lu, S.C. Shen, Shanghai Institute of Technical Physics, National Laboratory for Infrared Physics, Shanghai, P.R. CHINA; M.B. Johnston, M. Gal, Univ of New South Wales, School of Physics, Sydney, AUSTRALIA.

Recently, multi-color quantum-well infrared photodectors (QWIPs) has attracted great interest due to the growing demand for its application in advanced sensing and imaging systems. In many studies, ion implantation induced intermixing has been demonstrated to be able to shift the wavelength of lasers for the integration of multi-wavelength lasers onto a single chip. In this work, two methods of proton implantation, the single energy implantation and the multiple energy implantation were used to investigate the intermixing and hence, tuning the detection wavelength of QWIPs. Up to 0.6 μm and 1.1 μm redshifts of the QWIP's detection wavelength were observed from the single energy implantation and multiple energy implantation, respectively. However, for the case of the former, the linewidth of the photoresponse spectrum from QWIP was broadened due to the narrow displacement profile of single energy implantation, which caused only a small number of quantum wells to be intermixed. By using the multiple energy ion implantation, which was designed to cover all the quantum wells in QWIP sample, not only larger wavelength shift was obtained, but also the spectrum linewidth was effectively maintained. It suggests that multiple energy ion implantation is a promising technique to achieve multi-color QWIP.

OO5.26
REDUCTION OF THE OPTICAL ABSORPTION OF ZINC GERMANIUM PHOSPHIDE VIA POST-GROWTH THERMAL ANNEAL. How-Ghee Ang, Leng-Leng Chng and Yiew-Wang Lee, DSO National Laboratories, SINGAPORE; Colin J. Flynn, Phil C. Smith and Anthony W. Vere, Defence Evaluation and Research Agency, Malvern, UNITED KINGDOM.

We report the progress made in understanding the optical absorption in zinc germanium phosphide (ZGP) as a result of a study of the annealing characteristics of the ZGP crystal. A systematic study of the effect of the various annealing parameters (time, temperature and vapour atmospheres) on the reduction of the optical absorption of ZGP has been performed. The study showed that the optimal annealing temperature of ZGP was 600°C. The optimal annealing time of ZGP was found to be between 200 h - 400 h. Thermal anneal in the absence of additional vapour atmospheres (i.e. vacuum) yielded a larger reduction in the 2 μm optical absorption compared to annealing in the presence of additional zinc and phosphorus vapours. In published work, the origin of the extrinsic optical absorption in the 750 - 3000 nm waveband is usually attributed to native point defects, in particular to the close compensation between singly-ionised zinc vacancy acceptors and neutral phosphorus vacancy donors. The annealing study described above casts serious doubt on the adequacy of this explanation however, particularly since the defect model should show a direct dependence on annealing atmosphere and external vapour pressure, whereas the optical absorption data from our experiments show no dependence on these parameters. We conclude that a more likely explanation is that the close compensation of native defects does indeed occur and would account for the absorption observed in non-stoichiometric material, but that the residual low level absorption (<0.2 cm^{-1}) in stoichiometric material may still be governed by residual impurities. In proposing this model, we draw upon previous observations in other materials systems such as GaAs, CdTe and ZnSe, where early native defect models were also found to be over-simplified.

OO5.27
ELECTRONIC PROPERTIES OF $ZnGeP_2$ AND $CdGeAs_2$ CRYSTALS GROWN ON Ge (100) BY SOLID STATE REACTIONS. Vasilii Yu. Rud', State Technical Univ, Dept of Experimental Physics, St. Petersburg, RUSSIA; Yurii V. Rud', A.F. Ioffe Physico-Technical Inst, Dept of Solid State Physics, St. Petersburg, RUSSIA.

Ternary chalcopyrite compounds $ZnGeP_2$ and $CdGeAs_2$ having a large nonlinear optical coefficient and suitable birefringence for high efficiency phase-matching devices. Up to now the $ZnGeP_2$ and $CdGeAs_2$ single crystals have been grown from near-stoichiometric melts, from solutions in liquid metals, or by chemical vapor transport. In this paper we present the results of the first experimental investigations of the $ZnGeP_2$ and $CdGeAs_2$ crystals with aim to characterize its electronic properties. A new techniques based on solid state interactions between the Ge(100) substrates and controlling vapor phase has been applied in order to grown these ternary compounds. Our method allows us to grown the $ZnGeP_2$ and $CdGeAs_2$ crystals in the forms of thin films and separate single crystals with the preference (112) crystallographic orientation on Ge(111) substrates. The $CdGeAs_2$ as-grown crystals show n-type whereas the $ZnGeP_2$ p-type conductivity. The date of X-ray investigations show that the grown crystals have been the chalcopyrite structure. When the $ZnGeP_2$ crystals were excited at temperatures from 77 to 300 K by He-Cd laser radiation we observed intense orange photoluminescence emissions. The maximum of this broad band photoluminescence lies in the region of pseudodirect interband optical transitions and could be evidence of edge radiative recombination in the $ZnGeP_2$ crystals. The our techniques also allows us to prepare $CdGeAs_2$/Ge and $ZnGeP_2$/Ge photosensitivity structures. These devices had good rectifying properties and exhibited a pronounced photovoltaic effect. The photosensitivity maximum generally occurs deep in fundamental absorption edge of ternary compounds. In summary, our investigations indicate that the use of solid state reactions opens up the new ways for increasing of the radiation converter efficiency.

OO5.28
PROPERTIES OF SILVER THIOGALLATE SINGLE CRYSTALS GROWN BY CZOCHRALSKI TECHNIQUE. Dan Perlov, John Maffetone, Ilya Zwieback and Warren Ruderman, INRAD Inc, Northvale, NJ.

$AgGaS_2$ (AGS) is a unique material for mid-IR nonlinear optical applications. An AGS optical parametric oscillator pumped by a 1.06 μm Nd:YAG laser produces laser radiation continuously tunable from 1.1 to 11 μm . Until recently, AGS single crystals have been grown by the directional crystallization techniques. Practical use of the as-grown material, however, was limited due to growth defects, such as growth inclusions, twin planes and secondary phase precipitates. The stagnant character of the melt and absence of the control on the growth interface shape, which are intrinsic for directional crystallization, contribute to the poor optical quality of AGS. Cumbersome annealing is inevitable to get rid of the secondary phase precipitates. In this work we report on $AgGaS_2$ single crystals grown for the first time by the Czochralski technique from a congruent melt. Original design of the growth station, employing a semi-transparent gold coated two-zone furnace, facilitated fast seeding, reliable crystal diameter control and the growth rate as high as 30 mm/day. The method allows for better quality of as-grown crystals due to melt stirring by crystal rotation and proper choice of the growth direction. No growth inclusions were observed in the as-grown material. The possibility to grow precipitate-free AGS crystals from offstoich-iometric melts in Czochralski geometry is discussed.

OO5.29
DTA STUDIES OF THE PSEUDO-BINARY $ZnGeP_2$-Zn_3P_2 SYSTEM. Jim Harper, John Maffetone and Ilya Zwieback, INRAD Inc., Northvale, NJ.

$ZnGeP_2$ is a material of choice for a variety of nonlinear mid-IR applications, including OPO. Excellent progress in $ZnGeP_2$ crystal growth has been achieved during the last decade. However, a large portion of the Zn-Ge-P ternary phase diagram remains practically unknown. This knowledge is necessary for the further progress in the quality of $ZnGeP_2$ crystals. We report on our work on the pseudo-binary $ZnGeP_2$-Zn_3P_2 section of the ternary diagram using DTA. Zn_3P_2 has the highest melting point among all known compounds in the Zn-Ge-P system, and phase equilibria in the $ZnGeP_2$-Zn_3P_2 system may explain phenomena observed during synthesis and crystal growth of $ZnGeP_2$. Small sample size and high heating/cooling rates of the standard DTA technique are in conflict with the large supercooling effects typical for the chalcopyrite melts. Therefore, we developed a DTA technique, which allowed us to use large (up to 20 g) samples and relatively slow heating/cooling rates, which contributed to the reliability, sensitivity and accuracy of the method. Two major peaks on the heating and cooling curves of the $ZnGeP_2$:Zn_3P_2 mixtures were identified as liquidus and eutectic, which occur at 980°C. Two peaks of smaller amplitude were also observed. One of them near 875°C has been attributed to the solid state transition from α to β phase in Zn_3P_2. The origin of the second peak at 825°Cis discussed.

OO5.30
METAL-ORGANIC CHEMICAL VAPOR DEPOSITION OF Zn-In-Sn-O AND Ga-In-Sn-O TRANSPARENT CONDUCTING OXIDE THIN FILMS. Anchuan Wang, Nikki Edleman, Jason Babcock, Tobin J. Marks, Northwestern Univ, Chemistry Dept, Evanston, IL; Melissa Rocci, Carl R. Kannewurf, Northwestern Univ, Dept of Electrical Engineering and Computer Science, Evanston, IL.

MOCVD (Metal-Organic Chemical Vapor Deposition) techniques have been successfully used for the growth of Sn-doped transparent, conducting Zn-In-O and Ga-In-O films using $Sn(acac)_2$, $In(dpm)_3$, $Ga(dpm)_3$, and Zn_2, as volatile precursors. The 25°C electrical conductivity of the as-grown films is as high as 1000 S/cm (n-type) for Zn-In-O and 700 S/cm (n-type) for Ga-In-O series. After Sn-doping, the Zn-In-O series exhibits 25°C electrical conductivity as high as 2700 S/cm with a higher carrier concentration and mobility, while the Ga-In-O series exhibits higher electrical conductivity (3200 S/cm at 25°C) with much higher carrier concentration but lower carrier mobility. All films have over 85-90% optical transparency in the visible region. Reductive annealing has been carried out in a flowing gas mixture of H_2 (4%) and N_2. Large increases in both carrier concentration and carrier mobility have been measured, and as a result, further enhancement in electrical conductivity has been obtained with little loss in optical transparency. TEM, SEM, XRD, and AFM have been used for surface analysis and microstructural characterization, and property-microstructure relationships will be discussed.

OO5.31
GROWTH AND CHARACTERIZATION OF CdS/CdTe HETERO-JUNCTIONS. Paul Boieriu[1], Robert Sporken[1,2], Yan Xin[1], N.D. Browning[1], S. Sivananthan[1]; [1]Microphysics Laboratory, University of Illinois at Chicago, Physics Department, Chicago, IL, [2]Facultés Universitaires Notre-Dame de la Paix, Laboratoire Interdisciplinaire de Spectroscopie Electronique, Namur, BELGIUM.

Growth of single crystal wurtzite Cadmium Sulphide on CdTe(111)B substrates has been achieved using molecular beam epitaxy. Cadmium sulfide is a wide band gap semiconductor with E_g = 2.42 eV, used mostly as window material for high efficiency solar cells, in tandem with CdTe and CdTe related alloys. Other possible applications include the use of CdS as a window layer for HgCdTe infrared detectors or as an active layer based on the photorefractive effect exhibited in CdSSe alloys, suitable for measuring optical frequency differences. Several attempts of growing CdS using molecular beam epitaxy have had their focus on the zinc-blende structure. However, the wurtzite structure is the thermodynamically stable phase. In this work, we have used MBE to grow wurtzite CdS on CdTe(111)B/Si substrates. Cadmium Sulfide can be doped n-type whereas p-type is very difficult due to strong self-compensation. During the growth In has been used as in-situ dopant. Reflection high-energy electron diffraction (RHEED) patterns show a smooth surface morphology for several hundreds of nanometers since the nucleation. X-ray diffraction confirm the crystalline orientation. The epilayers were further characterized by high-resolution TEM, X-ray photoelectron spectroscopy (XPS) and Auger electron spectroscopy (AES). XPS indicates the existence of a reaction at the interface, the reacted layer being about 10{AA thick. A thin CdTe buffer layer is grown before the growth of CdS. Sulfur incorporation into this CdTe buffer layer has been investigated for various S background pressures. Typicaly, 5 - 10% S is detected in the CdTe buffer layers. Based on Vegards law, the shift in the XRD spectra confirms the value of S concentration of these layers. Finally, ohmic and rectifying contacts have been made on these In-doped CdS layers.

OO5.32
THE DEVELOPMENT OF IR PHOTOSENSITIVE MATERIAL BASED ON POLYCRYSTALLINE PBS FILMS. C. Abarbanel, R. Shneck, Z. Dashevsky, Dept of Materials Engineering, S. Rotman, Dept of Electrical Engineering, Ben-Gurion University of the Negev, Beer Sheva, ISRAEL.

PbS crystals have been widely used as photosensitive material in detectors in the middle IR range. We report the fabrication and characterization of nano-cryslalline PbS thin films and their application in a miniature IR detector, sensitive in the wavelength range up to 3-4 microns at room temperature. PbS was deposited by PVD method, including electron gun evaporator and hot wall for the homogenization of the gas phase. The compound was deposited as polycrystalline thin film with average grain size of 100nm. Photosensitivity was controlled by a subsequent gas phase doping with

indium (from indium telluride source) and/or oxygen. It is believed that segregation of the dopants to grain boundaries induced boundary charge which generated potential barriers for the charge carriers. The barrier height increases by oxygen and decreases by indium. Doping may be controlled to generate barriers larger than the forbidden gap. The barriers separate electron and hole pairs thus give rise to an increase of the carrier life-time (to the order of few microseconds) and to an improved photosensitivity. The technology has been optimized for maximum sensitivity at room temperature. Photosensitive PbS layer was deposited on the tip of a miniature glass tube (few-micron diameter) which was applied as an IR detector at room temperature.

OO5.33
EVIDENCE OF HIGH ELECTRON MOBILITY IN $CdGeAs_2$ SINGLE CRYSTALS. Vasilii Yu. Rud', State Technical Univ, Dept of Experimental Physics, St. Petersburg, RUSSIA; Yurii V. Rud', A.F. Ioffe Physico-Technical Inst, Dept of Solid State Physics, St. Petersburg, RUSSIA; Ravindra Pandey, Michigan Technological Univ, Dept of Physics, Houghton, MI; Mel Ohmer, Wright Lab, Wright Pattersson AFB, OH.

Ternary chalcopyrite semiconductor $CdGeAs_2$ are uniquely suited for applications as nonlinear optical devices, exhibiting the largest of all chalcopyrite materials nonlinear coefficient, wide infrared transparency ranges, and sufficient birefringence for phase-matching. For the improvement of $CdGeAs_2$ quality we propose to prepare this material by low temperature techniques. In this work we present the results of the first study of the electrical properties of n- $CdGeAs_2$ single crystals. The crystals were obtained by crystallization from nonstoichiometric melt at the temperatures below the melting point of this ternary semiconductor. The as-grown $CdGeAs_2$ crystals show n-type conductivity with free electron concentration of $10^{18}cm^{-3}$ and Hall mobility of 10000 $cm^2/(V \times s)$ at room temperature. The electrical properties of their are determined by shallow donor levels. The Hall mobility increases with temperature decrease from 300 to 180 K as $T^{-1.5}$ and reaches 36000 $cm^2/(V \times s)$ at 77 K. The temperature behavior of the electron mobility can be explained assuming the carrier scattering by lattice thermal vibrations. From these data have been estimated that the electron mobility for scattering by lattice vibrations is at least 70000 $cm^2/(V \times s)$ at 77 K. The our results show that the decrease of the crystallization temperature offers new possibilities for the essential improvement of the $CdGeAs_2$ single crystals quality.

OO5.34
PHOTOLUMINESCENCE AND EPR OF PHOSPHORUS VACANCIES IN ZINC GERMANIUM DIPHOSPHIDE. M. Moldovan, K.T. Stevens, L.E. Halliburton, N.C. Giles, Dept. of Physics, West Virginia University, Morgantown, WV; P.G. Schunemann, T.M. Pollak, S.D. Setzler, Sanders-a Lockheed Martin Company, Nashua, NH.

Zinc germanium diphosphide ($ZnGeP_2$) is a nonlinear optical material presently being developed for mid-infrared optical parametric oscillators. Recently, Budni et al. [1] demonstrated greater than 10 watts of average output power in the 3 to 5 μm region from a $ZnGeP_2$ OPO pumped by a Tm,Ho:YLF laser. A feature limiting further improvements in performance is an optical absorption band in $ZnGeP_2$ which extends from the band edge around 0.6 μm to beyond 2 μm, thus covering the pump region. The defects responsible for this absorption are the focus of our study. At liquid-helium temperatures, a broad luminescence band extending from 0.7 μm to beyond 1 μm is typically observed from bulk $ZnGeP_2$. We have analyzed the polarization dependence of this broad emission in a series of bulk crystals and have determined that there are two underlying recombination bands at 1.4 eV and 1.6 eV with different polarization behaviors. The relative intensities of these two bands were found to correlate with the presence of phosphorus vacancies (as determined by electron paramagnetic resonance). The 1.6-eV band was brighter in samples containing larger concentrations of these anion vacancies. Temperature dependence of the two PL bands is used to determine thermal quenching activation energies. Photoluminescence excitation spectra also show that the two bands have different origin. This work is supported by the Air Force Office of Scientific Research under Grants F49620-96-1-0452 and F4962-99-1-0248, and the national Science Foundation under Grant DMR-9807128. [1] P. A. Budni et al., in Advanced Solid State lasers, Technical Digest (Optical Society of America, Washington, DC, 1998) pp. 90-92.

OO5.35
REFRACTIVE INDEX MEASUREMENTS OF ZINC GERMANIUM PHOSPHIDE FROM 2-9 MICRONS AND THEIR IMPACT ON MID INFRARED OPTICAL FREQUENCY CONVERSION. David E. Zelmon, David L. Small, Air Force Research Laboratory, Materials Directorate, Wright-Patterson AFB, OH; Peter G. Schunemann, Sanders, Nashua, NH.

Zinc Germanium Phosphide ($ZnGeP_2$) has been shown to be the material of choice for frequency conversion applications in the 2-9 micron region. Recent advances in growth and post growth processing techniques have resulted in crystals with greater transparency and uniformity, necessitating a re-evaluation of the optical properties of this material. Using the minimum deviation method, we have performed new measurements of the refractive index of $ZnGeP_2$ from 2-9 microns and discuss their implications for frequency conversion processes such as parametric oscillation and frequency doubling of CO_2 lasers.

OO5.36
ZGP CRYSTALS: OPTICAL TRANSPARENCY AND MELT COMPOSITION. G.A. Verozubova, A.I. Gribenuykov, V.V. Korotkova, Inst for Optical Monitoring of SB RAS, Tomsk, RUSSIA.

The optical quality of ZGP, nonlinear optical crystals, transparent in the middle IR depends strongly on composition of melt which can be easily deviated from stoichiometry, as it has two volatile components. In this paper we presents results of investigations of optical properties of the ZGP crystals grown by vertical Bridgman technique from the melts deviated from stoichiometry due to either an addition of own pure components to the melts or by variation of the phosphorus pressure in the growth container. Dependence of the optical absorption from the thermal annealing conditions was also investigated for the grown crystals. It was found that excess of Ge (near 5% at) resulted in a significant increase of the optical losses not only in the impurity region but also in the maximum transparency window (3-8 mkm). The excess of Zn (1-3 % at) produced inclusions of pure Zn and zinc phosphides, what also strongly degraded the optical transparency. On base of the precise measurements of the lattice parameters we concluded that the melt doping by Ge reduced thermomechanical strains in ZGP. With optimal melt compositions close to stoichiometry the as-grown crystals had the absorption coefficient less than 0.01 cm-1 for wavelengths 3-8 mkm, and near 0.3-0.5 cm-1 for ordinary ray at 2 mkm. With use of thermal annealing in phosphorus atmosphere and in presence of zinc diphosphide powder the impurity absorption at 2 mkm can be decreased down to 0.1 cm-1 what related to realignment of native defects. Further reduction of the impurity absorption down to 0.04-0.05 cm-1 could be achieved by point defects introduced by high-energy (4MeV) electrons.

OO5.37
PREPARATION OF NONLINEAR OPTICAL CRYSTALS: ZINC GERMANIUM PHOSPHIDE. A.I. Gribenuykov, G.A. Verozubova, V.V. Korotkova, Inst for Optical Monitoring of SB RAS, Tomsk, RUSSIA.

The paper presents data for synthesis and growth of ZGP, the most interesting IR material for use in non-linear optics. Two-temperature modified technique was used to synthesize 500-600 gms of the material. To determine a possibility to control a composition of ZGP during its synthesis a sequence of physico-chemical transformations taking place in closed two-temperature system Zn-Ge-P with spatially separated the Zn-Ge mixture and the P was studied. X-Ray analysis of the samples obtained by quenching at different stages of heating the Zn-Ge mixture and the P showed that the ZGP ternary compound was formed via zinc and germanium phosphides. ZGP single crystals of big size were grown by vertical Bridgman method. By solving the thermal conductivity equation an influence of various geometric factors on temperature distribution in the growth container was studied. The effect of the seed orientaion on the crystal growth stability was also investigated. Optical absorption data for as-grown, annealed, and irradiated crystals are presented.

OO5.38
ANALYSIS OF Cr-DOPED $CdGeAs_2$ USING THERMAL ADMITTANCE SPECTROSCOPY. S. R. Smith[a], M.C. Ohmer, A.W. Saxler, J.T. Goldstein and J. Solomon[a] and P.G. Schunemann[b] and T.M. Pollak[b], Air Force Research Laboratory, Wright-Patterson Air Force Base, OH. [a]University of Dayton Research Institute, Dayton, OH; [b]Sanders, A. Lockheed Martin Company, Nashua, NH.

The optical and electrical properties of chrome doped $CdGeAs_2$ (CGA), important non-linear optical material, are reported. CGA, a chalcopyrite semiconductor of the pseudo-III-V type, is a close ternary analog to GaAs possessing significant differences. To date, the electrical and optical properties of as-grown undoped CGA have been controlled by a somewhat shallow dominant residual acceptor which it is the source of significant undesirable optical absorption. Highly transparent semi-insulating CGA should be attainable using compensation and counterdoping schemes similar to those used for GaAs. However, identifying suitable deep and shallow n-type and p-type dopants will require extensive empirical studies. As a starting point of survey to find deep levels, the properties of CGA:Cr have been investigated. Cr is a reasonable choice as it has been used extensively to provide a deep level in GaAs. Thermal Admittance

Spectroscopy was used to examine the electrically active levels in this material. These measurements were correlated with temperature dependent Hall effect measurements, and IR absorption measurements. SIMS analysis was utilized to estimate the Cr concentration, as the segregation coefficient for Cr in CGA has not been reported. The results show that there is a p-type level introduced into the band gap at about 0.16 eV above the valence band, a value nominally 50% deeper than that of the native acceptor. That background doping as measured by Capacitance-Voltage measurements was determined to be 8 x 10^{16} cm^{-3} near the surface, and 1.0 x 10^{17} cm^{-3} in the bulk. These results are compared to similar measurements in undoped material.

OO5.39
MODELING OF THE PROPERTIES OF DOPANTS IN THE NLO SEMICONDUCTOR $CdGeAs_2$. Ravi Pandey, Michigan Tech Univ, Houghton, MI; Mel Ohmer, USAF Research Laboratory, WPAFB, OH; J.M. Recio and A. Costales, Universidad de Oviedo, Oviedo, SPAIN.

Cadmium germanium arsenide ($CdGeAs_2$) is a technologically important material due to its suitability for NLO applications in the infrared region since, it has the highest nonlinear optical coefficient, 236 pm V^{-1}, known for a phase matchable compound semiconductor. Additionally, it has a wide transparency region extending across the infrared from 2.4 to 18 μm, though the transparency is limited by the photo-ionization of native acceptors. Attempts are now underway to suppress the concentration of native acceptors in $CdGeAs_2$ by doping the material with both cation and anion dopants. In this paper we will report the results of a theoretical study of various dopants in $CdGeAs_2$ in the framework of an atomistic model where two- and three-body interatomic potentials are used to simulate the perfect lattice. For dopants, we use first principles methods based on the electron-gas approximation to derive the parameters describing their interaction with the host-lattice ions. The calculated results will predict the site preference and the charge compensation mechanism alongwith the solution enthalpies for various dopants including Cu, Ag, B, Al, Ga, S and Se in this material. Binding energy for some of the dopant-complexes will be calculated to predict the ability of these dopants to suppress the native acceptor levels in $CdGeAs_2$.

SESSION OO6: GROWTH, CHARACTERIZATION, AND INNOVATIVE TECHNIQUES
Chair: Robert M. Biefeld
Wednesday Morning, December 1, 1999
Room 206 (H)

8:00 AM *OO6.1
A COMBINED MBE-STM STUDY OF INFRARED MATERIALS. P.M. Thibado, V.P. LaBella, D.W. Bullock, M. Anser, Z. Ding, and C. Emery, Physics Department, University of Arkansas, Fayetteville, AR.

Devices based on III-V compound semiconductors have fueled the growth of the multi-billion dollar telecommunications industry. Unlike silicon based devices, which are produced primarily by ion implantation, III-V device structures must be formed by depositing one plane of atoms after another until the entire structure is grown. Necessarily, III-V device fabrication occurs solely at a surface. The better one can control and manipulate the motion of atoms on surfaces, the more sophisticated the device structures one can make. In order to better understand the surface processes important to device fabrication, we have combined, for the first time, three major advances in semiconductor growth and characterization: (1) state-of-the-art semiconductor growth via molecular beam epitaxy (Riber 32P), (2) fundamental optical substrate temperature determination (0-700°C with ±2°C accuracy, updated at 1 Hz) , and (3) in situ, atomic-resolution surface characterization via scanning tunneling microscopy (Omicron). With these three breakthroughs, we have successfully conducted nanoscale experiments on the technologically important GaAs(001)-(2-4) reconstructed surface. First, we have resolved the correct atomic structural model for the surface. Second, we have determined the activation energy for an individual Ga atom to hop across the surface, the relative probabilities to hop in perpendicular directions, and the relative probabilities to stick to existing islands when approached from perpendicular directions. In addition, we have measured the effect of varying the As4 pressure on the Ga atoms hopping process, and discovered that increasing the As4 pressure forces the Ga atoms to diffuse more isotropically. Finally, we have observed the surface spontaneously forms 2D islands when annealed above a critical temperature (570 C), under a constant As4 flux. This process is reversible and when fit to a free energy model yields information about the surface bonding energies. This work was funded, in part, by the National Science Foundation (DMR-9733994) and the Office of Naval Research (N00014-97-1-1058).

8:30 AM OO6.2
STRUCTURAL CHARACTERIZATION OF ANTIMONIDE-ARSENIDE INTERFACES WITHIN IR DEVICES USING CROSS-SECTIONAL STM. William Barvosa-Carter*, Brett Z. Nosho, Ming-Jey Yang and Lloyd J. Whitman, Naval Research Laboratory, Washington, DC. *Current address: HRL Laboratories, Malibu, CA.

Molecular beam epitaxy using "6.1 Å" materials (GaSb, AlSb, and InAs) has allowed the creation of novel infrared devices in the mid-wavelength (3–5 /mum) range. In order to optimize these devices, precise control over layer thickness must be maintained because even *monolayer-scale* roughness and interdiffusion between layers in the heterostructures can cause significant degradation in performance. Cross-sectional scanning tunneling microscopy (XSTM) is a powerful method for quantifying the structural and interfacial quality of these superlattice structures, but there are a number of aspects related to image interpretation, particularly on the atomic-scale, that are still a matter of discussion. One rarely discussed issue is that on the (110) cleavage face only *every other* III-V growth layer within the superlattice can be directly observed by XSTM. This fact can have important consequences when investigating properties of the superlattice such as the roughness between heteroepitaxial layers, interfacial defects, or variations in chemical bonding at the interface. The impact is especially significant when these effects occur predominantly within a volume only two to three monolayers (ML) wide. We are systematically investigating the appearance of III-As and III-Sb bonds at arsenide-antimonide interfaces as a function of cleavage direction and even-versus-odd layers in specially prepared MBE-grown superlattices. We find it is possible to differentiate between the two bond types, but their appearance depends on cleavage-face and layer order. In addition, a model of the measurement of interfacial roughness reveals errors in the measured power spectrum as the actual interface roughness decreases below a few ML. A simple method for reconstructing the actual power spectrum from the STM data will be described.
Funded by the Office of Naval Research and the Air Force Research Laboratory.

8:45 AM OO6.3
THE GROWTH InAsSb/InPSb MID-INFRARED EMITTERS BY METAL-ORGANIC CHEMICAL VAPOR DEPOSITION. R.M. Biefeld, J.D. Phillips, and S.R. Kurtz, Sandia National Laboratories Albuquerque, NM.

We are exploring the growth of novel mid-infrared emitters (lasers and LED's) by metal-organic chemical vapor deposition (MOCVD) for use in infrared countermeasures and chemical sensor systems. In this presentation we will report on the metal-organic chemical vapor deposition (MOCVD) of mid-infrared InAsSb/InPSb optically pumped lasers grown using a high speed rotating disk reactor. The devices contain AlAsSb cladding layers and strained, type I, InAsSb/InPSb active regions. By changing the layer thickness and composition of InAsSb/InPSb SLSs, we have prepared structures with low temperature (about 20K) photoluminescence wavelengths ranging from 3.4 to 4.8 μm. We find a variation of bandgap from 0.272 to 0.324 eV for layer thicknesses of 9.0 to 18.2 nm. From these data we have estimated a valence band offset for the InAsSb/InPSb interface of about 400 meV. An InAsSb/InPSb SLS, optically pumped laser structure was grown on an InAs substrate with AlAsSb cladding layers. A lasing threshold and spectrally narrowed laser emission were seen from 80 through 240 K, the maximum temperature where lasing occurred. The temperature dependence of the SLS laser threshold is described by a characteristic temperature, To = 72 K, from 80 to 200 K. We are currently exploring new growth techniques to improve these device results. Further results for devices fabricated from these new structures and materials will be presented as they become available.

9:00 AM OO6.4
CORRELATION OF STRUCTURAL AND ELECTRONIC PROPERTIES OF HIGHLY MISMATCHED InSb FILMS. X. Weng, R.S. Goldman, Department of Materials Science and Engineering, the University of Michigan, Ann Arbor, MI; D.L. Partin, J.P. Heremans, Delphi Research and Development Center, Warren, MI.

Due to its low bandgap and high electron mobility, InSb is useful for both long wavelength infrared sources and magnetoresistive sensors. InSb films are generally grown with a 14.6% lattice mismatch on GaAs substrates. Because of the high mismatch, InSb films generally grow in the Volmer-Weber mode, which consists of nucleation and coalescence of three-dimensional islands. The island growth introduces significant surface and interface roughness, which may impact the electron mobility. Furthermore, the large mismatch often results in a high density of strain relaxation-induced defects including misfit and threading dislocations. The electronic properties of such highly mismatched InSb films tend to improve with increasing film thickness. However, the relative effects of dislocations and surface or interface

roughness on the electron mobility of InSb/GaAs heterostructures are not fully understood. Therefore, we have investigated the evolution of the structural and electronic properties of highly mismatched InSb films, with thicknesses ranging from 0.1 to 1.5μm. Cross-sectional transmission electron diffraction, transmission electron microscopy (TEM), triple-axis X-ray measurements, and atomic force microscopy (AFM) indicate that the 0.1μm films are not fully relaxed and consist of colesced islands which appear to contain threading dislcoations at their boundaries. As the film thickness is increased beyond 0.2μm, the surface becomes planar and the strain is fully relaxed. High resolution TEM shows that three types of misfit dislocations contribute to the relaxation of strain. The threading dislocation density decreases as a function of film thickness, dropping from $\sim 10^{11} cm^{-2}$ for 0.1μm films to $\sim 4 \times 10^{8} cm^{-2}$ for 1.5μm films. The reduction in threading dislocation density as a function of film thickness is consistent with a significant increase in electron mobility. These results suggest that carrier scattering from threading dislocations significantly impacts the electron mobility of InSb films.

9:15 AM OO6.5
EMISSIVITY COMPENSATED PYROMETRY OF THE SUBSTRATE SURFACE DURING MOVPE GROWTH OF InGaAsP/InP MATERIALS IN ROTATING DISC REACTORS. J.C. Ramer, V. Boguslavskiy, A. Gurary, B. Patel and R. Stall, EMCORE Corporation, Somerset, NJ.

In order to overcome the inaccuracies usually involved in using conventional pyrometry to determine the temperature of the substrate in a production scale MOCVD reactor, we have applied emissivity compensated pyrometry (ECP). By measuring, in-situ, the emissivity of the substrate, as well as its radiance, the accurate surface temperature of the substrate can be determined in real time, without perturbing the growth process. A novel, real time emissivity sorting algorithm is used to ensure that emissivity and temperature measurements are collected only from the substrate surface. Substrate temperature and emissivity data collected during the growth of common InGaAsP/InP related structures will be presented.

9:30 AM OO6.6
GROWTH OF $InSb_1 - xBi_x$ CRYSTALS BY VERTICAL BRIDGMAN METHOD FOR LWIR APPLICATIONS. Premila Mohan, S. Moorthy Babu, P. Ramasamy, Crystal Growth Centre, Anna University, Chennai, India, N. Senguttuvan, Shonan Institute of Technology, Fujisawa, JAPAN.

Recently there has been considerable interest for detectors operating in the 8 to 25μm long-wave infrared (LWIR) region. HgCdTe (MCT) has been the dominant material system fir such applications, however, because of difficulties in obtaining uniform composition over large areas and processing of Hg-based semiconductors, the more developed III-V materials have been considered as an attractive alternative. InSb is a III-V semiconductor material with a band gap of 0.17eV. It operates in the wavelength range of 3-5μm. $InSb_{1-x}Bi_x$ solid solutions combine narrow bandgap semiconductor with a semimetal allowing the possibility of varying the bandgap from that of InSb to a metallic phase by increasing x. Depending on the value of x it can be used in the midwave and also the LWIR region. $InSb_{1-x}Bi_x$ crystals were grown by vertical Bridgman technique. The crystals were charaterised be X-ray diffraction, differential thermal analysis, chemical etching. The infrared transmission studies were carried out on the cut and polished wafers of the grown crystals.

SESSION OO7: INFRARED PHOTODETECTORS
Chair: Daniel K. Johnstone
Wednesday Morning, December 1, 1999
Room 206 (H)

10:15 AM *OO7.1
TEMPERATURE DEPENDENCE OF PHOTORESPONSE IN p-TYPE GaAs/AlGaAs MULTIPLE QUANTUM WELLS: THEORY AND EXPERIMENT. F. Szmulowicz and G.J. Brown, Air Force Research Laboratory, Wright-Patterson AFB, OH; Aidong Shen, H.C. Liu, Z.R. Wasilewski and M. Buchanan, Institute for Microstructural Sciences, National Research Council, Ottawa, Ontario, CANADA.

Bound-to-continuum absorption and photoresponse of long-wavelength and mid-infrared p-type GaAs/AlGaAs multiple quantum well infrared photodetectors (QWIPs) is investigated theoretically and experimentally as a function of polarization and temperature. Using the 8x8 envelope-function model (EFA), the quantum well electronic structure and wave functions are calculated and then the bound-to-continuum absorption curves are obtained on an absolute scale as a function of photon energy, light polarization, and temperature. Since optimum absorption obtains for structures with the second light-hole (LH2) state at the top of the well, one non-optimized long-wavelength (LWIR) and one optimized mid-infrared (MWIR) structures were grown by MBE and their characteristics measured and compared to theory. Theory indicates that the placement of light-hole-like resonances away from the Brillouin zone-center within the heavy-hole continuum for the non-optimized sample and the placement of these resonances at the center of the Brillouin zone for the optimized designs accounts for their different temperature and polarization dependences. Implications of these resonances for the design of p-type QWIPs are discussed.

10:45 AM OO7.2
TRANSIENT AND STEADY-STATE LOCAL RESPONSIVITY IN QUANTUM WELL INFRARED PHOTODETECTORS. M. Ershov, Department of Physics and Astronomy, Georgia State University, Atlanta, GA.

This work presents the results of the theoretical study of the transient and steady-state local responsivity in quantum well infrared photodetectors (QWIPs). The numerical simulation was based on the self-consistent physical model of QWIP, and its results were confirmed by the analytical models both for the transient and steady-state regimes. The local responsivity, i.e. the photocurrent normalized by incident infrared power under photoexcitation localized in the direction of the current flow, is shown to be strongly coordinate dependent. The responsivity is high near the emitter, an decreases towards the collector. The non-uniformity of the responsivity is more pronounced in QWIPs with smaller number of the QWs. The steady-state responsivity is constant in the bulk of the photodetector; it involves the formation of the dipole layer near the photoexcited QW. The transient photocurrent in QWIP excited locally by a step-like infrared signal, displays a fast and slow components. The fast transient responsivity (corresponding to the primary photocurrent) decreases gradually to zero near the collector, with the characteristic length equal to the drift (capture) length. Its mechanism is related to the sweep-out of the photoexcited carriers. The non-uniformity of the local responsivity can play an important role in QWIPs with non-constant distribution of optical power, especially for devices with small number of QWs and large photocurrent gain, and should be taken into account for optimized QWIP design.

11:00 AM OO7.3
LOW FREQUENCY NOISE AND RANDOM TELEGRAPH SIGNAL IN A MULTIPLE QUANTUM WELL INFRARED PHOTODETECTOR. Lisa Kore, Gijs Bosman, University of Florida, Gainesville, FL.

Current-voltage, voltage-time, and noise measurements were taken on a three well, twenty period, InGaAs/AlGaAs quantum well infrared photodetector (QWIP) at low temperature and low constant current bias. Data from the voltage-time measurements exhibited random telegraph signal (RTS) which is a manifestation of a single electron capture/emission event. It thus contributes to generation-recombination noise of the device. A model is proposed that allows extraction of number of mobile carriers, continuum state electron mobility, electron emission times and trap activation energy from the RTS data. These parameters may then be utilized to predict the excess noise spectrum. Data from the noise spectral density measurements show 1/f like noise at frequencies below 1 kHz. It can be shown to be a sum of Lorenztian curves with various electron emission times. The model proposed predicts that the local number of mobile charge carriers in any barrier section is less than 5 (total in the device around 300), there is nearly ballistic electron transport (mobility values around $3X10^5$ cm^2/Vs), and the traps causing the RTS are in the barriers of the device and there are two of them in the device tested. The model applies to the linear mode of operation and assumes that the well regions are electron reservoirs, i.e. contacts, for the resistive barrier regions. The device is thus divided into a number of resistive portions in series. Each resistive portion is statistically independent from the others at low temperatures since the time the electrons spend in the wells is long compared to intra-well scattering times. This allows the electrons to fully thermalize and lose any statistical information from their previous continuum state trajectory. Assuming that generation-recombination noise is dominant, the noise spectral density is proportional to the variance of the number of mobile carriers and the integral of the probability density function of electron emission times over time. Therefore, extracted numbers of mobile carriers and electron emission times will predict the magnitude of the current noise spectral density.

11:15 AM OO7.4
AUGER SUPPRESSION IN AND NOISE PROPERTIES OF "HOT" HgCdTe IR DETECTORS. Frode Benjaminsen, Arthur D. van Rheenen, X.Y. Chen, University of Tromso, Dept. of Physics, Tromso, NORWAY.

The goal of this effort is to develop a $Hg_xCd_{1-x}Te$-based infrared detector that may be operated at room temperature. At room

temperatures the thermally generated electrons drown out the optically generated ones. By applying techniques of bandgap engineering, sandwiching the optically active narrow-bandgap material (x = 0.188, p = 3x10^{15}cm^{-3}) between layers with a larger bandgap (x = 0.355 on the p-side which is Ag doped & x = 0.304 on the n-side which is In doped), a sort of "p-π-n" structure is created in which the detecting narrow-bandgap layer has few intrinsic carriers under reverse-bias conditions. Both layers grown by MOCVD and by MBE are used to fabricate devices using the same process.
The room temperature current-voltage (I-V) characteristic of such a structure exhibits negative differential resistance regions when reverse biased. These regions are indicative of suppressed Auger recombination. Under forward-bias conditions the I-V relationship is linear. If these types of devices are to compete with cooled infrared detectors their noise performance is very important. Under forward-bias conditions and at room temperature the magnitude of the 1/f noise is proportional with the current squared. This may imply that the noise is limited by the carrier supplying p- and n-regions. Under small reverse-bias conditions the magnitude of the 1/f noise is quadratic but when the bias is increased, approaching the minimum in the I-V curve, the magnitude increases dramatically, deviating strongly from the quadratic behavior. It is proposed that this contribution is associated with the generation processes.

11:30 AM OO7.5
NOVEL DIFFRACTION PATTERN FOR OPTICAL COUPLING IN QUANTUM-WELL INFRARED PHOTODETECTORS. Prafulla Masalkar, Hironori Nishino, Yusuke Matsukura, Hitoshi Tanaka, Kousaku Yamamoto, Yoshihiro Miyamoto and Toshio Fujii, Fujitsu Laboratories Ltd., Atsugi, JAPAN.

Quantum-well infrared photodetector (QWIP) [1] focal plane arrays (FPA) for infrared imaging in 8-12 μm wavelength range detect radiation by inter-subband transitions in AlGaAs / GaAs multi-quantum wells (MQW). The MQW absorb only radiation component that has electric field perpendicular to epitaxial plane. To facilitate absorption, normally incident radiations direction must be changed within detectors pixels. For this optical coupling, a diffraction grating etched on the top of the pixels is commonly used. A pseudo-random grating formed from square unit cells has been shown to produce higher absorption than periodic gratings [2]. We have designed and developed a novel diffraction pattern for optical coupling. It is formed from elliptical grooves in a single etching step. This pattern results in higher absorption efficiency but is significantly easier to fabricate than the pseudo-random grating that requires two etching steps and has finer features. Such a diffraction pattern formed of curved grooves instead of gratings was fabricated and used for QWIP for the first time. It was designed by theoretical simulation of optical coupling based on calculation of diffracted field within the pixel. Design was optimised to minimise radiation escaping out of the pixels while maximising random diffraction and keeping feature size broad. Simulation was also used for estimating effect of fabrication errors. Performance of elliptical groove diffraction pattern was experimentally compared with pseudo-random grating by fabricating photodetector arrays and measuring photocurrent output from individual pixels. It was found that our elliptical groove pattern produced 30% higher photocurrent than pseudo-random grating at a bias voltage of 5V.
[1] Levine B. F., Quantum-well infrared photodetectors, J. Appl. Phys., 74(1993) R1-R80.
[2] Sarusi G. et al, Improved performance quantum well infrared photodetectors using random scattering optical coupling, Appl. Phys. Lett., 64 (1994) 960-962.

11:45 AM OO7.6
THERMAL ANNEALING RECOVERY OF INTERSUBBAND TRANSITION IN PROTON IRRADIATED GaAs/Al$_{0.3}$Ga$_{0.7}$As MULTIPLE QUANTUM WELLS. H.S. Gingrich[1], C. Morath[1], M.O. Manasreh[1], P. Ballet[2], J.B. Smathers[2], G.J. Salamo[2] and C. Jagadish[3]; [1]Air Force Research Lab (AFRL/VSSS), Kirtland AFB, NM, [2]Department of Physics, University of Arkansas, Fayetteville, AR, [3]Department of Electronic Materials Engineering, Research School of Physical Sciences & Engineering, Australian National University, Canberra, AUSTRALIA.

Optical absorption spectra of intersubband transitions in heavily proton irradiated n-type GaAs/AlGaAs multiple quantum wells were studied as a function of isochronal and isothermal annealing. The absorption spectra of intersubband transitions were depleted in samples irradiated with 1 MeV proton doses higher than 1.0x10^{14} cm^{-2}. Thermal annealing of the irradiated samples show that the intersubband transitions are recovered. The relatively lower annealing temperatures at which the recovery is observed, indicate that the irradiation induced defects that trapped the two dimensional electron gas in the quantum wells are vacancy and interstitial related defects. Once these trapped are thermally annealed, the electrons are released back to the quantum wells causing the recovery of the intersubband transitions. The results reported here provide significant information on thermal recycling of irradiated long wavelength infrared detectors.

SESSION OO8: INNOVATIVE MATERIALS AND DEVICES
Chairs: Joseph P. Lorenzo and Bethanie J. H. Stadler
Wednesday Afternoon, December 1, 1999
Room 206 (H)

1:30 PM *OO8.1
STRAINED SiGe MATERIALS FOR HIGH QUANTUM EFFICIENCY PHOTODIODES AT λ=1.3 to 1.55 μm. Laura M. Giovane, Hsin-Chiao Luan, Eugene A. Fitzgerald, Lionel C. Kimerling, Department of Materials Science and Engineering, Massachusetts Insititute of Technology, Cambridge, MA.

Silicon-germanium is a promising materials system for delivering near-IR photodetection on the ubiquitous silicon substrate. The 4%lattice mismatch leads to biaxial strain for SiGe films grown coherently on (100) Si substrates, which both extends the long wavelength detection limit by reducing the band gap and defines the critical thickness for the SiGe film. We have studied the use of strained-layer superlattices grown on high quality relaxed SiGe buffers. Graded buffers are ideal virtual substrates for achieving a complete range of compositions and strains for GeSi alloys. A physical model has been created map out the absorption coefficient as a function of Ge fraction and (100) biaxial strain. Based on calculated absorption spectra as a function of composition and strain, we have designed and grown a Ge/Ge$_{0.5}$Si$_{0.5}$ strained layer superlattice on a high quality Ge$_{0.75}$Si$_{0.25}$ relaxed buffer using UHV-CVD. The relaxed buffer serves as a virtual substrate with relatively low threading dislocation density (10^6 cm^{-2}). The effect of the threading dislocations on the leakage current of PN junctions is also investigated. Electron beam induced current (EBIC)is used to determine the dislocation density of SiGe relaxed buffer junctions grown with different grading rates. Mesa isolated devices are used to determine bulk leakage current densities for the SiGe junctions. The bulk leakage current density scales directly with the dislocation density. Bulk leakage currents density per dislocation length (2 x 10^{-5} A cm^{-1}) agrees with deep level transient spectroscopy (DLTS) determined literature values for SiGe capture cross-section and defect density per dislocation in Si.

2:00 PM OO8.2
PHOTOCONDUCTIVE PROPERTIES OF GaAs/GaAs$_{1-x}$N$_x$ DOUBLE HETEROSTRUCTURES AS A FUNCTION OF EXCITATION WAVELENGTH. R.K. Ahrenkiel, A. Mascarenhas, S.W. Johnston, Y. Zhang, D.J. Friedman, National Renewable Energy Laboratory; S.M. Vernon, Spire Corporation.

The ternary alloy GaAs$_{1-x}$N$_x$ is promising as a 1.0 eV bandgap semiconductor that can be grown epitaxially on GaAs. In this work, we measured the spectral response and recombination lifetime of a number of alloys using the ultra-high frequency photoconductive decay (UHFPCD) method. This is a contactless technique, that measures internal photocurrents in heterostructures and is therefore a measure of the internal spectral response. Our data shows that the spectral or excitation spectra of GaAs0.97N0.03 alloys consists of a rather gradual onset of photoresponse at about 1.0 eV. The recombination lifetime in this region increases with the energy of the exciting photons. For GaAs0.99N0.01 Alloys, the onset of photoresponse is very abrupt, similar to that of a conventional direct bandgap semiconductor. The recombination lifetimes frequently exceeded 5.0 ms in the latter alloy. A number of the experimental features are explained by the spatially inhomogenous band structure produced by the randomness of the nitrogen impurity.

2:15 PM OO8.3
ELECTRONIC STRUCTURE OF SHALLOW ACCEPTORS CONFINED IN Si/SiGe QUANTUM WELL STRUCTURES. Q.X. Zhao and M. Willander, Physical Electronics and Photonics, Department of Physics, Chalmers University of Technology and Göteborg University, Göteborg, SWEDEN.

Energy levels of the shallow acceptor states have been calculated for center-doped Si/SiGe/Si quantum wells (QWs). The impurity states are calculated using an effective-mass theory, in which the valence-band mixing as well as the mismatch of the band parameters and the dielectric constants between well and barrier materials have been taken into account. The energies of the acceptor ground and excited states and the splitting between the acceptor $1S_{3/2}$ (Γ_7) and $1S_{3/2}$ (Γ_6) ground states are studied at different Ge concentrations and different well widths. The results are discussed in comparison with the recent conclusion from the lateral transport measurements in boron doped Si/SiGe quantum wells. The purpose of this theoretical

calculation is to gain a more general understanding of the electronic structures and infrared absorption processes of acceptors confined in Si/SiGe QW structures. Since SiGe alloy is lattice mismatched with Si, we can utilize the built-in strain and QW confinement effects to achieve the acceptor ground splitting-off state to be resonant with the valence band. In this case, the far-infrared stimulated emission may be achieved without an external uniaxial stress in the Si/SiGe QW structures.

2:30 PM OO8.4
Ge PHOTODETECTORS FOR Si MICROPHOTONICS BY DIRECT EPITAXY ON Si. H.-C. Luan[1], D.R. Lim[2], G. Masini[3], L. Colace[3], G. Assanto[3], K. Wada[1], L.C. Kimerling[1], [1]Department of Materials Science & Engineering, [2]Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA, [3]Department of Electronic Engineering, Terza University of Rome, ITALY.

The successful development of integrated Si Microphotonics circuits requires the integration of efficient photodetectors operating at 1.3μm or 1.54μm with Si CMOS devices and polySi waveguides. Ge with its high absorption coefficient at these two wavelengths is a candidate material for this application. In this work we report the development of a process technology for the integration of Ge photodetectors with poly Si waveguide and Si CMOS devices. Our process technology is based on a two-step UHV-CVD epitaxy followed by cyclic thermal annealing. The threading dislocation density in the as-grown Ge was $9.5\pm0.2\text{x}10^{8}\text{cm}^{-2}$. Cyclic thermal annealing reduced the threading dislocation density to $2.2\pm0.3\text{x}10^{7}\text{cm}^{-2}$. When cyclic thermal annealing was combined with selective-area epitaxial growth of Ge on small growth area, threading dislocation free Ge on Si was acheived. We propose that dislocation glide and dislocation reactions due to thermal stress are responsible for the reduction of threading dislocations. We have studied the performance of MSM Ge photodetectors made on Ge film deposited by two-step UHV-CVD process. An improvement of device performance as a result of improved materials quality was observed. We have also studied the effect of leakage current on the GHz operation of Ge photodetectors. Our model shows that bulk leakage current is not a significant source of noise for detectors operating at GHz range. Based on our experiments, we expect that high speed Ge photodetectors can be integrated with polySi waveguides and Si CMOS devices.

2:45 PM OO8.5
PLANAR CONTACT GEOMETRY FOR FAR-INFRARED P-TYPE GERMANIUM LASERS. Danielle R. Chamberlin, Erik Bruendermann and Eugene E. Haller, Lawrence Berkeley National Laboratory and University of California at Berkeley, Berkeley, CA.

We report on increasing the pulse length and repetition rate of p-type germanium lasers through miniaturization and improvement of the electric field uniformity. Currently FIR p-type Ge lasers represent the only powerful, compact source of tunable laser radiation in the wavelength range from 75-300 μm. However, these lasers can only be operated in a pulsed mode because heating during operation destroys the population inversion. We have developed a new, planar contact geometry that increases the electric field uniformity within the laser crystal. Calculations show that the fraction of laser crystal with an electric field within $\pm0.5\%$ of the nominal electric field increases from typical values of $< 10\%$ for a near-cubic cross-section to $> 35\%$ for the planar contact geometry. This geometry also offers improved cooling by increasing the surface-to-volume ratio of the laser crystal. Beryllium-doped germanium lasers fabricated with this geometry exhibit maximum pulse lengths of 22 μs, exceeding values in the literature reported for similarly doped Ge lasers with the traditional contact geometry. Attaching an undoped, high-resistivity, single-crystal Si heat sink to the Ge laser crystal increases the duty cycle of these lasers by an order of magnitude. The physical phenomena underlying these duty cycle improvements will be discussed.

3:30 PM *OO8.6
InAsP/(Ga)InP MULTIPLE QUANTUM WELL STRUCTURES ON InP(001) FOR INFRARED APPLICATIONS: OPTICAL AND STRUCTURAL PROPERTIES, QUANTUM-CONFINED STARK-EFFECT OPTICAL MODULATORS, AND BAND ALIGNMENT ENGINEERING. P. Desjardins, University of Illinois, Urbana, IL; M. Beaudoin, Arizona State University, Tempe, AZ; R.Y.-F. Yip, KLA-Tencor Corp., San Jose, CA; R.A. Masut, Ecole Polytechnique de Montreal, Montreal, CANADA.

A detailed knowledge of the fundamental optical properties of semiconductor alloys, including the band gap energy and the band alignment between heterolayers, is necessary to develop high performance optoelectronic devices. Combined TEM, HR-XRD, and reciprocal lattice mapping analyses are used to determine the exact thickness, composition, and strain in each layer for $\text{InAs}_x\text{P}_{1-x}$/InP ($x<0.39$) and $\text{InAs}_x\text{P}_{1-x}/\text{Ga}_y\text{In}_{1-y}\text{P}$ ($x<0.31$, $0.09<y<0.16$) multiple-quantum-well (MQW) structures on InP(001). The excitonic energies for the major transitions involving light- and heavy-hole observed in the low- and room-temperature optical absorption spectra are predicted accurately for all samples from a solution of the Schrdinger equation in the envelope function formalism using the Bastard-Marzin model. The absolute value of the $\text{InAs}_x\text{P}_{1-x}$/InP and $\text{InAs}_x\text{P}_{1-x}/\text{Ga}_y\text{In}_{1-y}\text{P}$ heterojunction conduction band offsets is found to be linear with the As composition. The bowing parameter of strain-free $\text{InAs}_x\text{P}_{1-x}$ determined by self-consistently fitting a composition series of $\text{InAs}_x\text{P}_{1-x}$/InP MQW structures is 0.10 ± 0.01 eV at 8 K and 0.12 ± 0.01 eV at 300 K. Lower valence band (VB) barrier heights in InAsP/(Ga)InP MQW stacks are found to enhance the quantum confined Stark effect (QCSE) redshift and to reduce the drive field in p-i(MQW)-n optical modulators. This shows that the overall performance of QCSE devices can be improved by using heterostructures with large conduction band (CB) offsets to compensate the effective mass asymmetry in III-V semiconductors. These results are used to develop band alignment engineering device design criteria that account for materials synthesis constraints. We propose to design the MQW band structure based upon two principles: (1) balancing the energy redshift versus the loss of oscillator strength with an appropriate choice of the VB barrier height, and (2) balancing the wave function leakage in the CB to that in the VB with an asymmetric band alignment. The most promising candidates for operation in the 1.3-1.55 μm wavelength range are (1) compressively strained InAsP wells with tensile strained InGaAsP barriers on InP(001), and (2) nearly lattice-matched InAlGaAs wells and InAlGaAs barriers on InP(001).

4:00 PM *OO8.7
INFRARED PHOTOCURRENT AND ENERGY TRANSFER PROCESSES IN ERBIUM-DOPED Si p-n DIODES. P.G. Kik[a], N. Hamelin[a], F.W. Saris[b] and A. Polman; [a]FOM-Institute for Atomic and Molecular Physics, Amsterdam, THE NETHERLANDS, [b]Energy Research Center, Petten, THE NETHERLANDS; S. Coffa, CNR-IMETEM, Catania, ITALY.

Temperature-dependent measurements of the 1.53 μm photocurrent, photoluminescence intensity and lifetime were performed on erbium-implanted silicon p-n junctions in order to study the energy transfer processes between the silicon electronic system and the Er 4f energy levels. Erbium was implanted into a specially prepared p-n junction structure that was optimized for light trapping using a textured surface.
Photoluminescence intensity and lifetime measurements show weak temperature quenching of the erbium intra-4f transition at 1.535 μm for temperatures up to 150 K, attributed to Auger energy transfer to free carriers. For higher temperatures, much stronger quenching is observed, which is attributed to an energy backtransfer process, in which Er de-excites by generation of a bound exciton at an Er-related trap in the Si crystal. Dissociation of this exciton leads to the generation of electron-hole pairs that can be collected as a photocurrent. All temperature-dependent data for intensity, lifetime, and photocurrent can be fitted with a model using one single set of parameters describing the temperature-dependent energy transfer rates in erbium-doped silicon.
While the external quantum efficiency of the 1.53 μm photocurrent generation process is small ($1.8\text{x}10^{-6}$) due to the small erbium absorption cross section and the low erbium concentration, the internal quantum efficiency for current generation is 70 % at room temperature; the internal power conversion efficiency is 95 %. The external power conversion can be greatly enhanced by using an Er-doped channel waveguide geometry, as will be discussed.

4:30 PM OO8.8
ELECTRONIC BANDGAP AND REFRACTIVE INDEX DISPERSION OF SINGLE CRYSTALLINE EXPITAXIAL ZnGeN_2. Long D. Zhu, Peter E. Norris, NZ Applied Tech., Woburn, MA; Lionel O. Bouthillette, Air Force Research Lab, Hanscom AFB, MA.

The electronic bandgap of single crystalline ZnGeN_2 epitaxial layer grown on sapphire substrate by metalorganic chemical vapor deposition was measured by optical transmission and room temperature photoluminescence measurement. The bandgap is 3.0 eV at room temperature, and it is a direct transition type. The oscillation of the transmission spectrum together with rutile prism coupler method was used to determine the dispersion characteristics of the refractive index of ZnGeN_2 single crystal below the bandgap energy. The rutile prism coupler measurement displays the waveguide modes of the film at the wavelength of 6328A, enabling determination of the film thickness and refractive index precisely at the wavelength. The refractive index of ZnGeN_2 crystal is 3.35 at 6328A wavelength. The refraction index dispersion curve can be fitted with the first-order Sellmeier equation $n^2(\lambda)=A+\lambda^2/(\lambda^2-B)$, the fitting parameters determined are A=4.31, B=0.076.

4:45 PM OO8.9
BAND GAP VARIATION, ALLOY MISCIBILITY, AND PARTIAL VAPOR PRESSURES IN TL-BASED III-V INFRARED MATERIALS. A.-B. Chen, Physics Department, Auburn University, AL; J. Piao Epitaxial Laboratory Inc, Stony Brook, NY.

To evaluate the Tl-based alloys for long-wave infrared (LWIR) application, detailed calculations of band gaps versus lattice constants, alloy miscibility gaps, and equilibrium partial vapor pressures in these materials have been carried out. These results are then used to identify promising Tl-based LWIR alloys and other lattice-matched non-Tl bearing alloys for possible substrates, passivation caps, and growth buffer layers. We found that six Tl-bearing pseudo-binary alloys have 0.1 eV band gaps. None of them are lattice matched to a pure III-V compound. However, five of them do have a non-Tl-bearing ternary alloy with the same lattice constant.

SESSION OO9: NONLINEAR OPTICAL MATERIALS
Chairs: Arnold Burger and Melvin C. Ohmer
Thursday Morning, December 2, 1999
Room 206 (H)

8:15 AM *OO9.1
EPITAXIAL GROWTH OF CHALCOPYRITE STRUCTURE SEMICONDUCTORS. Henryk Temkin, Department of Electrical Engineering, Texas Tech University, Lubbock, TX.

We describe growth conditions and properties of epitaxial $ZnSnP_2$, $ZnSnAs_2$, and their quaternary alloys. This class of novel chalcopyrite structure semiconductors, studied in the past primarily in bulk crystals, is known to possess interesting structural, optical, and electrical properties.
We focused on the growth of $ZnSnP_2$, closely lattice matched to GaAs, by gas source molecular beam epitaxy. By carefully adjusting the Sn/Zn flux ratio we were able to obtain either ordered or disordered layers of $ZnSnP_2$. This is a unique transition since it is induced only by the Sn/Zn flux ratio, and not by the growth temperature. We also studied the possibility of preparing heterostructures wells using ordered and disordered modifications of $ZnSnP_2$ and compositionally tuned $ZnSn(P_xAs_{1-x})_2$. High quality interfaces and superlattices could be achieved only with disordered $ZnSnP_2$ and $ZnSn(P_xAs_{1-x})_2$. The difference between epitaxy of ordered and disordered structures is attributed to different growth mechanisms. The disordered (sphalerite) structure can be grown utilizing vapor-solid growth mechanism, but vapor-liquid-solid mechanism must be present to obtain the ordered (chalcopyrite) structure material.
Optimization and control of epitaxial growth, layer characterization, and our present understanding of the order-disorder transition within the metal sublattice of $ZnSnP_2$ will be discussed in some detail.

8:45 AM *OO9.2
DEVELOPMENT OF LARGE HIGH QUALITY CHALCOPYRITE SINGLE CRYSTALS FOR NONLINEAR OPTICAL APPLICATIONS. Warren Ruderman and Ilya Zwieback, INRAD,Inc. Northvale, NJ.

At present, the leading crystal candidates for nonlinear optical applications in the infrared are $ZnGeP_2$, $CdGeAs_2$ and $AgGaS_2$. $ZnGeP_2$ has the highest figure of merit and high thermal conductivity and is a material for OPOs pumped by 2-3 μm lasers. $CdGeAs_2$ has extremely high optical nonlinearity, and is the material of choice for 10.6 μm doublers. $AgGaS_2$ has a lower figure of merit and a low thermal conductivity, but it can be phasematched at 1.06 μm . Over the past ten years we have developed synthesis techniques based on the two-temperature process to produce pure, single-phase and stoichiometric chalcopyrites and developed growth techniques based on Horizontal Gradient Freeze. We studied the causes of the residual optical absorption in $ZnGeP_2$ and $CdGeAs_2$ and developed post-growth treatment procedures that enabled us to improve the optical quality of these materials and make them useful for nonlinear applications. We investigated the mechanisms for the surface laser damage of $AgGaS_2$ and recently built and demonstrated an efficient $AgGaS_2$-based OPO with an extremely broad tuning range from 3.9 to 11.3 μm . As a result of these efforts, large and high quality single crystals of $ZnGeP_2$ have now been made available commercially. These uniform and thermally stable crystals demonstrate an absorption coefficient $\alpha_o$at 2.05 μm of 0.07 cm^{-1} or lower. We are also achieving good results in the development of $CdGeAs_2$. At present, we are able to grow large, crack-free single crystals, up to 400 g in weight. We have shown for the first time that the optical coefficient of $CdGeAs_2$ can be reduced to 0.1 cm^{-1} at wavelengths between 5 and 11 μm . Our efforts are focused now on improving the optical uniformity of $CdGeAs_2$.

9:15 AM OO9.3
NATIVE DEFECT CHARACTERIZATION IN $ZnGeP_2$. A. Hoffmann, H. Born, A. Naeser and W. Gelhoff, Department of Physics, Technical University Berlin, GERMANY; J. Maffetone, D. Perlov, W. Ruderman and I. Zwieback Inrad, Inc., Northvale, NJ; N. Dietz and K.J. Bachmann, Departments of Physics and Materials Science Engineering, North Carolina State University, Raleigh, NC.

The defect characterization on $ZnGeP_2$ crystals grown from the melt by gradient freezing (GF) is reported. Electron paramagnetic resonance (EPR) and time-resolved photoluminescence (PL) has been used to characterize the defect center for various treated $ZnGeP_2$ crystals. Resonance investigations were performed at the X-band and the Q-band frequency range. The different samples, electron-irradiated and annealed under different conditions, reveal a strong signal dependence of the V_Zn-correlated EPR-transitions on optical excitation and cooling conditions. The luminescence spectra reveal a broad infrared emission with peak position at 1.2 eV that exhibits features of classical donor-acceptor recombination. The hyperbolic decay characteristic over an wide energy range, investigated from 1.2 eV up to 1.5eV, suggest that this broad emission band is related to one energetic recombination center. This recombination is interpreted to be between donor-acceptor states related to residual disorder on the cation sublattice that is retained in metastable equilibrium during the formation of the chalcopyrite structure. The emission decay behavior in the energy range from 1.2 eV up to 1.6 eV is characterized by two hyperbolic time constants, viewed as the super-composition of the decay from the broad emission center peaked at 1.2 eV and additional donor-acceptor recombination emissions at 1.4 eV. With increasing temperature, the emission from these high energetic centers are quenched above 100K, while the broad IR emission is observed even at room temperature.

9:30 AM OO9.4
PHOTO-INDUCED CHANGES IN THE CHARGE STATES OF NATIVE DONORS AND ACCEPTORS IN $ZnGeP_2$. Kevin T. Stevens, Nancy C. Giles, Larry E. Halliburton, Physics Dept, West Virginia Univ, Morgantown, WV; Scott D. Setzler, Peter G. Schunemann, Thomas M. Pollak, Sanders-a Lockheed Martin Co., Nashua, NH.

Zinc germanium diphosphide ($ZnGeP_2$ or ZGP) is the nonlinear optical material of choice for tunable mid-infrared optical parametric oscillation (OPO) laser systems. Optical absorption extending from the bandgap region into the near-infrared affects the performance of bulk ZGP in OPOs. The focus of our electron paramagnetic resonance (EPR) studies is identification of the defects responsible for this absorption. As-grown ZGP is known to have a large concentration of an acceptor (identified as a singly ionized zinc vacancy (V_{Zn}^-) by EPR at low temperatures). We have also determined the presence of two donor centers (V_P^0 and Ge_{Zn}^+) using photo-induced EPR. We have now studied the wavelength dependence of the photo-induced changes in all three of these EPR-active native-defect centers. We observe a significant increase in the V_{Zn}^- EPR signal under 633 nm light. This wavelength produces paramagnetic forms of both donor centers, while 1064 nm light only produces the V_P^0 EPR-active center. We have also used the tunable output from a Ti:sapphire laser to monitor photo-induced changes in these three EPR spectra. Our data from photo-induced experiments indicate that $V_{Zn}^=$ is present in high concentrations in some samples. The 633-nm light produces an increase in the 1-micron absorption band, and we have used a spectrophotometer to measure the spectral shape of the photo-induced change in intensity in this near-IR region. By correlating the photo-induced changes in these three EPR spectra with optical absorption data, we are able to show which defects are contributing to absorption near 1 micron in bulk ZGP crystals. This work is supported by the Air Force Office of Scientific Research under Grants F49620-96-1-0452 and F4962-99-1-0248, and the National Science Foundation under Grant DMR-9807128.

10:15 AM *OO9.5
ELECTRONIC STRUCTURE AND DERIVED LINEAR AND NONLINEAR OPTICAL PROPERTIES OF CHALCOPYRITES. Walter R.L. Lambrecht, Sergey N. Rashkeev, Sukit Limpijumnong, and Benjamin Segall, Department of Physics, Case Western Reserve University, Cleveland, OH.

Both II-IV-V_2 (e.g. $ZnGeP_2$, $CdGeAs_2$) and I-III-VI_2 (e.g. $AgGaS_2$, $AgGaSe_2$) chalcopyrites are of interest for nonlinear optical frequency conversion because of their combination of high second order response coefficients, birefringence, and wide ranges of transperancy in the mid-IR. In this work, we undertake a systematic study of the relevant properties in these two families of materials based on first-principles electronic structure calculations. Our study comprises all combinations of II=(Cd,Zn), IV=(Si,Ge), V=(As,P), and of I=(Ag,Cu), III=(Ga,In) and VI=(S,Se,Te). We present calculations for the band structures, the static and frequency dependent SHG coefficients, and the birefringence. The anomalously high value of $\chi^{(2)}$ in $CdGeAs_2$ is discussed in terms of a recently developed

decomposition of $\chi^{(2)}$ into interband and mixed intraband-interband processes. In the case of the I-III-VI_2 family, we find that replacement of Se by Te is far more effective at increasing $\chi^{(2)}$ than replacement of Ga by In even though both decrease the band gap by similar amounts. Surprisingly, the band structures of even the most studied materials in this family are still not well established. In particular, we show that the minimum gap in $ZnGeP_2$ is truly indirect instead of pseudodirect. In fact, we argue that the optical absorption spectra should be reinterpreted taking into account the multiple and energetically closely spaced conduction band minima. Supported by NSF.

10:45 AM OO9.6
HORIZONTAL GRADIENT FREEZE GROWTH OF $AgGaTe_2$.
P.G. Schunemann, S.D. Setzler, and T.M. Pollak, Sanders, A Lockheed Martin Company, Nashua, NH; M.C. Ohmer, J.T. Goldstein and D.E. Zelmon, Air Force Research Laboratory, WPAFB, OH.

$AgGaTe_2$ is a promising nonlinear optical material for infrared laser frequency conversion. The sulfide and selenide isomorphs are well known for their large nonlinear (d_{ij}) coefficients and for their wide transparency and phase-matching ranges. $AgGaTe_2$, by virtue of its smaller band gap, should exhibit a d_{ij}-value more than twice that of $AgGaSe_2$ over a transmission window shifted to slightly longer wavelengths. Single crystals of adequate size and quality for device applications have never been grown, however, and the birefringence of $AgGaTe_2$ has never been measured to determine whether it is sufficient for phase matching. Here we report, for the first time, the growth of large, crack-free single crystals using the horizontal gradient freeze technique. Stoichiometric amounts of Ag, Ga, and Te were pre-reacted at 800°C in an evacuated silica ampoule, and the resulting charge was loaded into a vitreous carbon boat fitted with a single crystal seed, re-encapsulated, and heated in a two-zone, horizontal, transparent furnace. After partial melting of the seed (at a solid-liquid interface temperature of 710°C), directional solidification commenced at 0.5-1mm/hr followed by post-growth cooling at 15-35°C/hr to room temperature. Crack-free single crystals measuring 19mm in diameter and up to 100mm in length were produced in this way. As-grown samples were transparent from 1.2 μm to beyond 16 μm: they exhibited near-theoretical transmission at long wavelengths, but in the near-infrared transmission was limited by scattering from second-phase precipitates (much like $AgGaSe_2$ and $AgGaS_2$). Dilatometer measurements on oriented single crystals revealed severely anisotropic thermal expansion similar to that of the sulfide and selenide analogs. Finally, an oriented prism (28.3° apex angle) was cut and polished for determining the ordinary and extra-ordinary refractive indices as a function of wavelength. These results will be presented, along with their implications for phase-matched infrared laser frequency conversion.

11:00 AM OO9.7
EVIDENCE FOR OPTICAL AND ELECTRON TRANSPORT PROPERTIES OF ATOMIC ORDERING IN $CdGeAs_2$.
B.H. Bairamov, I.K. Polushina, Yu.V. Rud', A.F. Ioffe Physico-Technical Instit, Dept of Solid State Physics, St. Petersburg, RUSSIA; V.Yu. Rud', State Technical Univ, Dept of Physics, St. Petersburg, RUSSIA; G. Irmer, J. Monecke, Bergakademie Freiberg, Inst fur Theoretische Physik, Freiberg, GERMANY; P.G. Schunemann, Lockheed Sanders Inc, Nashua, NH; N. Fernelius, M.C. Ohmer, Air Force Wright Laboratory, WL/MLPO, OH.

A natural extension in the search for new semiconductors is to examine ternary compounds exhibiting diamond-like or tetrahedral coordination. We have recently succeeded in growing high crystallographic quality ordered II-IV-V2 chalcopyrite structure CdGeAs2 by the improved horizontal ultra-low gradient freeze technique from near-stoichiometric melts. The chalcopyrite structure CdGeAs2 (space group I42d) is the simplest noncubic ternary analog of the cubic zinc-blende structure GaAs. The energy band structure of chalcopyrite crystal differs from that of binary analog in several nontrivial ways by virtue of the noncubic structure. The Cd d-levels hybridize with the otherwise s- and p-like orbitals and lead to several anomalous features. The ordered arrangement of Cd and Ge atoms leads to formation of tetragonal superlattice of the zinc-blende structure and CdGeAs2 have larger nonlinearities than binary analogs. This is particularly important in view of the phasematching possibilities in the CdGeAs2. However, extensive realization of their potential is still not achieved. One of the principal difficulties on the way to obtaining high device-quality CdGeAs2 single crystals is undesired optical absorption in the transparency range near fundamental band edge induced by lattice-related defects. The different types of these defects have been found to have a significant effect on both optical and electrical properties of CdGeAs2 single crystals. We will report our results of electron transport measurements, and investigation of optical properties, including absorption in near absorption edge, inelastic light scattering, photoluminescence as well as photoconductivity. The Hall and conductivity measurements of p-CdGeAs2 single crystals revealed an anisotropy of anomalous Hall coefficient, indicating the presence of atomic order.

11:15 AM OO9.8
THERMAL ADMITTANCE STUDIES OF ELECTRON-IRRADIATED $CdGeAs_2$.
S.R. Smith[a], M.C. Ohmer, P.J. Drevensky[b], D.F. Bliss[b], Air Force Resarch Laboratory, Wright-Patterson Air Force Base, OH. [a]University of Dayton Research Institute, Dayton, OH., [b]AFRL/SNHX, Hanscom AFB, MA.

Brudnyi, et al[1], and Zwieback, et al.[2], have shown that introducing damage by irradiation with MeV electrons can alter the electrical and optical properties of undoped p-type as-grown $CdGeAs_2$ (CGA) crystals. Brudnyi's studies of the electrical transport properties of isochronally annealed samples demonstrated type conversion and identified at least two new centers, one a stable donor. Zwieback used multi-MeV electrons to introduce compensating donors, thereby, significantly improving the optical transparency of CGA crystals. However, at the present little is known about these centers. We have studied these centers by observing the properties of electron-irradiated specimens using Thermal Admittance Spectro- scopy (TAS) and correlated the results of these measurements with capacitance-voltage measurements and Hall effect measurements. Measurements before an after irradiation are compared. The as-grown native acceptor concentrations in our samples varied. Significant changes in the electrically active states in the band gap were seen as a result of a single irradiation with 2 MeV electrons to a total dose of 5 x $10^{15}cm^{-2}$. The samples appear to respond more strongly than Brudnyi's samples. The thermal activation energies have been determined using TAS and they will be reported.
1. I. Zwieback, D. Perlov, J.P. Maffetone, and W. Ruderman, Appl. Phys. Lett. 73, 2185 (1998).
2. V.N. Brudnyi, M.A. Kirov, A.I. Potopov, I.K. Polushina, V.D. Prochukhan, and Yu.V. Rud, Phys. Stat. Sol. (a) 49, 761 (1978).

11:30 AM OO9.9
EFFECT OF FAST ELECTRON IRRADIATION ON ELECTRICAL AND OPTICAL PROPERITES OF ZINC GERMANIUM PHOSPHIDE AND CADMIUM GERMANIUM ARSENIDE.
Ilya Zwieback, John Maffetone, Dan Perlov, Jim Harper and Warren Ruderman, INRAD,Inc., Northvale, NJ.

$ZnGeP_2$ and $CdGeAs_2$ have outstanding fundamental properties in the infrared, making them the materials of choice for various nonlinear optical applications. Significant progress has been made lately in the growth of large and high quality $ZnGeP_2$ and $CdGeAs_2$ single crystals. However, in the as-grown state, both materials exhibit optical absorption in their fundamental transparency range. We report on the successful use of fast electron irradiation in order to reduce this absorption. The effects of electron irradiation on the optical absorption (α) and the electrical properties of $ZnGeP_2$ and $CdGeAs_2$ were investigated. Irradiation of $ZnGeP_2$ caused a decrease in α at $\lambda >$ 0.8 μm and increase in $\lambda <$ 0.8 μm. At λ=2.05 μm, α for the o-ray could be reduced to less than 0.07 cm^-1. Further increase in the electron fluence caused saturation in α at 2.05 μm and deterioration in the transmission at λ between 3.5 and 6 μm. In $CdGeAs_2$, irradiation led to a change in the slope of absorption versus wavelength. Irradiation of p-$ZnGeP_2$ and p-$CdGeAs_2$ caused increase in the degree of electrical compensation and amplification of the existing electrical inhomogeneities. In $CdGeAs_2$, conversion from p to n-type was observed at high electron doses. The lowest optical absorption in $CdGeAs_2$ ($\alpha \approx 0.1$ cm^{-1} at λ between 5 and 10 μm) was measured on crystals with the highest degree of electrical compensation. The thermal stability of irradiated $ZnGeP_2$ and $CdGeAs_2$ was studied. Possible mechanisms of optical absorption in $ZnGeP_2$ and $CdGeAs_2$ and those responsible for the changes in their electrical and optical properties upon irradiation are discussed. They include i) absorption in discrete levels and intraband transitions, ii) introduction of shallow and deep levels upon irradiation and iii) quasi-chemical interactions between the point defects pre-existing in the lattice and the radiation damage defects.

11:45 AM OO9.10
GROWTH AND OPTICAL CHARACTERIZATION OF SOME II-VI SEMICONDUTORS FOR OPTICAL LIMITING.
Christian Reyerson, Anteon Corp., Dayton, OH; Shekhar Guha, Tim Pottenger, Air Force Research Labs, Wright-Patterson AFB; S.B. Trivedi, S. Kutcher, R. Chen, R. Rosemeier, Brimrose Corp. of America, Baltimore, MD.

Transition metal doped II-VI materials have been attractive for optical power limiting due to their high electro-optic coefficients, photoconductivities and resisitivities. We are reporting here crystal growth of binary semiconductors CdTe and ZnTe and ternary semiconductors Cd(1-x)Mn(x)Te(x=.15 and .45). Electro-optic coefficients of these materials have been measured and they have been tested for optical limiting. In light of these results suitability of these materials for optical limiting at visible and near infrared wavelengths

is analyzed. Also we discuss materials and device issues for electro-optic power limiting using II-VI semiconductors.

SESSION OO10: INTERDIFFUSION IN QUANTUM WELLS
Chair: Chennupati Jagadish
Thursday Afternoon, December 2, 1999
Room 206 (H)

1:30 PM *OO10.1
QUANTUM WELL INTERMIXING USING SPUTTERED SILICA FOR PHOTONIC INTEGRATED CIRCUITS OPERATING AROUND 1550 NM. John H. Marsh, A. Catrina Bryce, Olek P. Kowalski, Stewart D. McDougall, Maolong Ke, Bocang Qiu, Yahong Qian, University of Glasgow, Department of Electronics and Electrical Engineering, Glasgow, UNITED KINGDOM.

A novel technique for quantum-well intermixing has been developed using sputtered silica. The technique relies on the generation of point defects via plasma induced damage during the deposition of the sputtered silica. The presence of the defects before annealing allows the intermixing to take place at lower annealing temperatures (>200 C) than those needed for conventional impurity free vacancy disordering. The low annealing temperature has allowed the technique to be applied to InP based quantum well systems such as InGaAs/InGaAsP and InGaAs/InGaAlAs, and provides a simple and reliable process for the fabrication of both wavelength tuned lasers and monolithically integrated devices operating around 1550 nm. Wavelength tuned broad area oxide stripe lasers have been demonstrated in InGaAs-InAlGaAs and InGaAs-InGaAsP quantum well. Oxide stripe lasers with integrated intermixed slab waveguides have enabled the production of a narrow (3 degrees), single lobed far field pattern in InGaAs-InAlGaAs devices. Extended cavity ridge waveguide lasers operating around 1550 nm have been demonstrated with low loss (alpha = 4.1 /cm) waveguides, the loss is limited only by free carrier absorption in the waveguide cladding layers. Ridge waveguide, deeply etched surface grating DBR lasers were fabricated both with and without intermixing the grating section. Measurements show that a significant improvement in performance is obtained from the DBR lasers when the grating section is intermixed. The intermixing technique has been further developed in order to realise 3 bandgaps on a chip in a single annealing step for the integration of amplifiers, passive waveguides and bandgap tuned electro-absorption modulators. Modulation depths of 25 dB were measured from the modulators. The results illustrate that the technique can routinely he used to fabricate low-loss optical interconnects and bandgap tuned devices, offering a very promising route toward photonic integration.

2:00 PM *OO10.2
INFLUENCE OF SiO_x CAPPING LAYER QUALITY ON IMPURITY-FREE INTERDIFFUSION IN GaAs/AlGaAs QUANTUM WELLS. P.N.K. Deenapanray, H.H. Tan, C. Jagadish, Department of Electronic Materials Engineering, Research School of Physical Sciences and Engineering, The Australian National University, Canberra, AUSTRALIA.

Recently, quantum well intermixing (QWI) has been used to control the bandgap of quantum confined III-V heterostructures to monolithically integrate optoelectronic devices and circuits. In particular, QWI offers an alternative to regrowth and overgrowth processes, which are currently the main techniques used in realizing optoelectronic and photonic integrated circuits. The main techniques which have been used to initiate interdiffusion in quantum wells (QWs) include impurity-induced disordering, impurity-free vacancy diffusion (IFVD), and ion implantation-induced intermixing. IFVD is, however, the preferred option since it retains a high crystal quality and thus, maintains low optical losses and prevents free-carrier compensation. Plasma enhanced chemical vapor deposition (PECVD) enables low-temperature ($\leq$ 300 °C) deposition of SiO films of varying composition, making it compatible for monolithic integration of optoelectronic circuitry and waveguide fabrication. Although IFVD has been studied since the early 1980's, there is little understanding concerning the effect of dielectric capping layer quality on the overall intermixing process. PECVD SiO layers were deposited using SiH_4/N_2O flow at 1 Torr, 20 W rf power and 710 sccm N_2O. The quality of dielectric cap was changed by varying either the deposition temperature (T), or the SiH_4 flow rate. We demonstrate that the increased porosity of capping layers for $T \leq 200$°C results in a significant increase in QWI. IFVD is shown to follow the deposition rate of capping layers quite intimately when SiH_4 flow rate is varied. The oxygen content, porosity and nitrogen incorporation in dielectric layers can be changed by varying SiH_4 flow rate. The effect of changes in these parameters on IFVD will be discussed. Deep level transient spectroscopy is used as a probe to determine the defects that are introduced during the intermixing process.

2:30 PM OO10.3
DEGRADATION OF INTERSUBBAND TRANSITIONS IN ELECTRON IRRADIATED GaAs/AlGaAs MULTIPLE QUANTUM WELLS WITH SUPERLATTICE BARRIERS. C. Morath[1], M.O. Manasreh[1], and H. J. von Bardeleben[2]; [1]Air Force Research Lab (AFRL/VSSS), Kirtland AFB, NM, [2]Groupe de Physique des Solides, Universites Paris 6 and 7, Paris, FRANCE.

Intersubband transitions in GaAs/AlGaAs multiple quantum wells were studied as a function of 2 MeV electron irradiation doses. The multiple quantum well structure was designed with 5 period AlGaAs/GaAs superlattice barrier, where two transitions are observed in the optical absorption spectra. The two transitions are originated from the ground state to the first excited state and to the miniband formed by the superlattice barrier. The total integrated areas of both transitions were studied as a function of temperature and electron irradiation dose. The total integrated area was decreased as the irradiation dose is increased, which could be explained in terms of the trapping of the two dimensional electron gas in the quantum well by the irradiation induced defects. In heavily irradiated samples, the total integrated area was found to be temperature dependent. Additionally, the intensity of the ground state to miniband transition was found to increase as a function of the irradiation dose. A possible explanation to this effect will be presented. The variation of the integrated areas of both the transitions from the ground state to the first excited state and from the ground state to the miniband was found to be approximately exponential with the irradiation dose.

2:45 PM OO10.4
OPTICAL DIAGNOSTICS OF MICROSTRUCTURES FABRICATED USING QUANTUM WELL INTERMIXING. A. Saher Helmy, A.C. Bryce, C.N. Ironside, J.S. Aitchison and J.H. Marsh, Glasgow University, Electronics Electrical Engr Dept, Glasgow, UNITED KINGDOM.

Various technologies such as quantum well intermixing (QWI), fabrication of low dimensional structures (quantum wires and dots), overgrowth and re-growth, need a non-destructive, swift means by which they can be assessed and hence optimised. These requirements exclude near field optical methods. Micro-PL is one technique that can provide information about the semiconductor microstructures being studied, however it is associated with a number of limitations. Raman spectroscopy is another promising technique for characterising such bandgap variations, with the potential of providing much more information than those obtained through PL. However there are also limitations on the usefulness of Raman spectroscopy in practical structures. In this paper we shall present results from our studies of bandgap gratings fabricated using different QWI techniques, and characterised using PL and Raman spectroscopy. Intermixing was achieved using impurity free vacancy disordering, and intermixing induced by sputtering damage during silica deposition. The gratings have alternating periods of intermixing-promoting and intermixing-inhibiting dielectric caps with various periods, ranging from 2 microns to 12 microns. These measurements lead to interesting findings concerning the technologies' studied. The results show almost complete suppression of intermixing for the IFVD process from bandgap gratings with periods less than 10 microns. We also observed a size dependent intermixing for the IFVD features, highlighting the role of stress as a mechanism in IFVD. The measurements provide insight into the spatial resolution of these processes. Finally, some insight into the limitations and merits of PL and Raman for the precision characterisation of QWI will be presented.

3:00 PM OO10.5
IMPURITY-FREE VACANCY DISORDERING IN AlGaAs/GaAs MULTIPLE QUANTUM WELL. Y.Chan, Michael C.Y.Chan, W.K. Tsui, E.Herbert Li, University of Hong Kong, Department of Electrical and Electronic Engineering, HONG KONG.

Quantum Well (QW) intermixing has attracted considerable interest of many people due to its ability to produce a number of optoelectronic devices such as laser diodes, wave guides and modulators. The integration of all these devices on a single chip in micron scale was the next interest which led to the fabrication of QW optoelectronic integrated circuits (OEICS). Recently, there are immense interests in the Impurity-Free Vacancy Disordering (IFVD) which uses group III vacancies introduced by out-diffusion of Ga into dielectric SiO2 caps at elevated temperature to assist Ga/Al interdiffusion. In this paper, a study of the model of interdiffusion in AlGaAs/GaAs multiple quantum well (MQW) using IFVD is presented. In AlGaAs/GaAs MQW, compositional profiles of Al and Ga are either carried out directly through diffusion of group III vacancy or group III interstitials. The model described here allows an initial, non-equilibrium group III vacancy concentration in AlGaAs/GaAs MQW to be related to the amount of intermixing induced during subsequent annealing and we assume that the

diffusion coefficient for intermixing is the product of the concentration of the point defects and their diffusivity. Our diffusion model will be fitted to the experimental data with different annealing times to determinate the diffusion coefficients, vacancy distribution and the shift of transition energy in MQW.