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E-MRS SPRING MEETING 2003  
June 10 – 13, 2003

## **SYMPOSIUM J**

Rare earth doped materials for photonics

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J.M. Langer, Polish Academy of Sciences, Warsaw, Poland

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# E-MRS 2003 SPRING MEETING

## SYMPOSIUM J

Tuesday, June 10, 2003  
Mardi 10 juin 2003

Morning  
Matin

Session I: Phosphors and related materials  
Session chair: R. Moncorgé

- J-I.1** 9:00 -Invited- RARE-EARTH DOPED PHOSPHORS: OLDIES OR GOLDIES?  
**B. Moine**, LPCML, UCBL, 10 rue Ampère, 69622 Villeurbanne, France  
The scientific research on phosphors has a long history starting more than 100 years ago. But recently the appearance of new kinds of displays and lightning devices (plasma display, fluorescent lamp without mercury...) induced an increase of the research of new phosphors with better luminous efficiency than those available up to now. It has been shown that the behavior of "classical" phosphors in a plasma display panel is quite different than in a cathode ray tube and that the vacuum ultraviolet (VUV) excitation process has to be studied with care in order to improve the phosphors efficiency.  
That is particularly true in PDPs. It is well established now that a good phosphor for electronic or ultraviolet excitation, is not necessarily a good choice for excitation in VUV. This is probably due to the fact that the excitation process is very different in that case and also because the penetration depth of the VUV photons is extremely small inducing a large contribution of the surface of the phosphor. We will illustrate this with some examples. Methods to measure the useful depth of phosphors, to estimate their quantum efficiency and to accelerate its decrease under VUV excitation will be described. Low efficiency, fast aging process are both drawbacks that can be solved only in the framework of fundamental studies. Quantum cutting emission may be a solution for the first one but no satisfactory process was proposed for the moment to solve the second.
- J-I.2** 9:30 BORON AND PHOSPHOROUS GLASS FORMERS INFLUENCE ON THE RADIOLUMINESCENCE PROPERTIES OF Ce<sup>3+</sup>-DOPED SILICATE GLASSES OBTAINED BY SOL-GEL METHOD  
**C. Canevali**, **D. Di Martino**, **M. Fasoli**, **M. Mattoni**, **F. Morazzoni**, **R. Scotti**, **G. Spinolo**, **A. Vedda**, Dept. Scienza dei Materiali, Università Milano-Bicocca, via Cozzi 53, 20125 Milano, Italy and **S. Polizzi**, Dept. Chimica Fisica, Università Ca' Foscari, Calla Larga S. Marta 2137, 30123 Venezia, Italy  
Ce<sup>3+</sup>-doped SiO<sub>2</sub> glasses were recently sol-gel prepared as scintillating materials for x-ray detection, with promising radioluminescence (RL) efficiency and scintillation decay time. RL quenching occurred for Ce:Si molar ratios >0.0005, probably due to rare-earth clustering. In order to have a host glass more suitable to embed rare-earth ions, glass formers (B, P) were included into the SiO<sub>2</sub> network. Phospho-(PSG), boro-(BSG) and borophosphosilicate (BPSG) glasses doped with Ce<sup>3+</sup> were obtained from methoxide of Si, B and P and cerium nitrate. For PSG and BPSG glasses Ce<sup>3+</sup> emission yields were greater than for BSG and SiO<sub>2</sub> glasses. The RL quenching occurred at higher Ce<sup>3+</sup> content for BPSG (>0.005) and PSG (>0.002) than for BSG (0.001) and SiO<sub>2</sub>. In BSG the emission band was observed at ~ 2.90 eV while in PSG and BPSG it peaked at 3.65 eV, a value similar to that of Ce<sup>3+</sup> in melting phosphate glasses. EPR spectra of SiO<sub>2</sub> and BSG glasses, recorded at 4.2 K, showed the resonance lines of isolated Ce<sup>3+</sup> but their amount was not proportional to the rare earth content, suggesting that Ce<sup>3+</sup> resonances could be quenched by clustering and spin coupling effects. BPSG glasses showed two different paramagnetic Ce<sup>3+</sup> centers; one was the same as in SiO<sub>2</sub>, the other was coincident with that of Ce<sup>3+</sup>-doped PSG. It was suggested that the improved RL in Ce<sup>3+</sup>-doped BPSG could be related to dilution of clustered centers, due to Ce<sup>3+</sup> coordination to phosphate.
- J-I.3** 9:45 CHARACTERIZATION OF CRYSTALLINE EUROPIUM DOPED YTTRIA PLD-FILMS GROWN ON CORUNDUM  
**P. Burmester**, **T. Ishii**, **G. Huber**, Institute of Laser-Physics, University of Hamburg, Germany, **M. Kurfiss**, Institute of Applied Physics, University of Hamburg, Germany, **M. Schilling**, Institut für Elektrische Messtechnik und Grundlagen der Elektrotechnik, Technical University Braunschweig, Germany  
Y<sub>2</sub>O<sub>3</sub> is known as an attractive host material for optically active rare earth ions. Eu<sup>3+</sup>:Y<sub>2</sub>O<sub>3</sub> is the unsurpassed red emitting phosphor in fluorescence lamps and efficient laser operation in RE<sup>3+</sup>:Y<sub>2</sub>O<sub>3</sub> bulk crystals has been reported as well. The use of waveguide lasers allows to realize compact and integrated devices with low thresholds. Besides, films of only several monolayers may show modified luminescence properties.  
We demonstrate the epitaxial growth of crystalline Eu:Y<sub>2</sub>O<sub>3</sub> films on Al<sub>2</sub>O<sub>3</sub> substrates using the PLD technique. The spectroscopic characterization shows that the local symmetry of the Eu<sup>3+</sup> centers within the films is not changed in comparison to the bulk crystal as long as the Eu<sup>3+</sup> centers are not located directly at the interface to the substrate. However, at the interface the local symmetry is strongly distorted. Additionally, Eu ions at the interface are responsible for a very strong broad luminescence band centered at E = 3eV which is not observed in bulk Eu<sup>3+</sup>:Y<sub>2</sub>O<sub>3</sub>. We propose that a certain amount of the Eu ions are incorporated as Eu<sup>2+</sup> ions at the interface. The Eu<sup>2+</sup> (4f<sup>5d</sup>) states are supposed to be involved in an energy transfer mechanism which results in the 3eV luminescence. Further, the dopant ions at the distorted interface layer induce traps for excitons which results in a redshift of the exciton excitation peaks. Further, with regard to the application as waveguiding devices the guiding properties of Nd-doped yttria films are investigated.

**J-I.4** 10:00 EMISSION OF Er- and Si-DOPED SILICATE GLASS FILMS OBTAINED BY MAGNETRON CO-SPUTTERING  
F. Gourbilleau, P. Choppinet, C. Dufour, M. Levalois, R. Madelon, R. Rizk, LERMAT, Unité CNRS 2149, ISMRA, 6 Bd Maréchal Juin, 14050 Caen Cedex, France and M. Prassas, Inorganic Materials, Corning S.A., 7 bis av. de Valvins, 77211 Avon cedex, France  
Thin films Er-doped low non-bonding oxygen (LNBO) glasses were fabricated by magnetron co-sputtering of the glass target topped by various number of silicon chips. The silicon excess was monitored through variation of the silicon sputtered Sr area with respect to the glass area. The films were annealed under different atmospheres at temperatures lower than 450 °C, in order to prevent any softening of the glass layers. Microstructural studies reveal the absence of Si nanocrystals for all the samples, regardless of the preparation and treatment conditions. However, the PL measurements performed with resonant (488 nm) and non resonant (476.5 nm) excitations from an Ar laser, revealed an enhancement by more than one order of magnitude of the Er emission when the sample is enriched with Si. This result is the first evidence of the occurrence of energy transfer from Si agglomerates to Er ions. The effects of Si excess, or Sr, as well as those of the annealing treatments on the Er emission were also investigated, discussed and compared to the melted reference glass.

**J-I.5** 10:15 4F ENERGIES IN AN ORGANIC-RARE EARTH GUEST-HOST SYSTEM: THE RARE EARTH TRIS-8-HYDROXYQUINOLINES  
J. Thompson, R.I.R. Blyth, V. Arima, G. Gigli, R. Cingolani, National Nanotechnology Laboratory of INFM, Dipartimento di Ingegneria dell'Innovazione, Università di Lecce, 73100 Lecce, Italy and Y. Zhou, R. Fink, E. Umbach, Experimentelle Physik II, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany  
The systematics of the energy transfer from an organic ligand to a rare earth ion's 4f states, the so-called antenna effect, has been investigated for a series of rare earth tris-8-hydroxyquinolines. The electronic structure of the host organic was studied using photoemission, X-ray absorption, UV-visible absorption and photoluminescence spectroscopies. Resonant photoemission was used to extract the 4f(n-1) excited state energies relative to the host orbitals. Of the potential luminescent 4f-4f transitions in these materials only the infra-red emitting peaks of Nd, Er and Yb are observed. We show that energy transfer from the organic host to the lanthanide ion can proceed either via direct transfer from the triplet excited state, or from the singlet excited state via an internal chemiluminescent redox reaction. Emission from the visible transitions of the rare earth ions is shown to be energetically unfavourable due to the relatively low triplet energy of the organic host.

10:30

**BREAK**

Session II: Devices I

Session chair: F. Priolo

**J-II.1** 11:00 -Invited- CONTROLLED SPONTANEOUS EMISSION IN PHOTONIC MICROSTRUCTURES  
J. Kalkman and **A. Polman**, FOM-Institute AMOLF, Amsterdam, The Netherlands, D. 't Hart and A. van Blaaderen, Debye Institute, Utrecht University, The Netherlands, Y. Jun and D. Norris, University of Minnesota, USA  
We present several novel concepts to control the spontaneous emission rate and spectrum of rare earth doped photonic microstructures.  
Metallo-dielectric gratings were fabricated and doped with erbium. By near-field interaction, the erbium ions cause the excitation of surface plasmon polaritons that propagate along the metal/dielectric interface. Using a properly chosen corrugation in the metal, the surface plasmons re-radiate at well-defined resonance angles and frequencies. In this way the spontaneous emission around 1.5 micron becomes highly directional, and the spectrum highly tunable. Bandwidth enhancements by a factor two are observed, and a novel concept to solve the quenching problem of rare earths in arbitrary materials will be proposed. Next, we present Si photonic crystals with an inverted opal structure, fabricated using silica colloidal self-assembly in combination with Si infiltration and subsequent selective etching. These crystals possess a full photonic bandgap at 1.3 or 1.5 micron, depending on the lattice parameter. Erbium and neodymium ions are incorporated with the aim to probe the photonic bandstructure, and to achieve inhibited spontaneous emission and a modified branching ratio. The data are compared to calculations of the local optical density of states.

- J-II.2** 11:30 CHARGE TRANSPORT, TRAPPING AND ELECTROLUMINES-CENCE IN ERBIUM DOPED a-Si:H/n-Si LIGHT-EMITTING HETERODIODES  
A.N. Nazarov, Ja.N. Vovk, V.S. Lysenko, Institute of Semiconductor Physics, NASU, 03028-Kyiv, Ukraine, O. Kon'kov and E. Terukov, Ioffe Physical and Technical Institute, RAS, 194021-Sankt-Petersburg, Russia  
 This work is devoted to study of the mechanisms of charge transport through the a-Si:H layer doped by Er in the Al/a-Si:H:Er/n-Si structures, connection of these mechanisms with deep levels relating to erbium incorporation into a-Si:H matrix and suggestion of the energy transfer mechanism from charge carriers to excited electrons of Er<sup>3+</sup> ions.  
 The a-Si:H:Er films were deposited on Si by magnetron-assisted silane decomposition technique (MASD). The charge transport mechanisms were studied by current-voltage (I-V) characteristics measured in temperature range from 80 to 400 K; the defects were evaluated by thermally activated current spectroscopy (TACS) and high-frequency capacitance-voltage characteristics. It was shown that tunnel recombination mechanism at voltage from -7 to -30V and tunnel activation mechanism at voltage above -30V are observed in the reverse biased structures. Such mechanisms assume a hole injection from inversion layer of the n-Si substrate. Furthermore, at reverse bias of the structure the net hole trapping in a-Si:H:Er film is observed. Since the TACS demonstrates, that Er incorporation into the a-Si:H matrix results in formation of deep levels with energetic position from EC-0.40 to EC-0.65 eV and from EV+0.44 to EV+0.60 eV, we suggest that for effective EL a trapping of electrons and holes in the defects located near erbium inclusions is needed.
- J-II.3** 11:45 Si NANOCRYSTALS-Er INTERACTION: MODELING AND PERSPECTIVES FOR A Si-BASED OPTOELECTRONICS  
D. Pacifici, F. Priolo, G. Franzò, A. Irrera, M. Miritello, INFN and Dipartimento di Fisica e Astronomia, Via S. Sofia 64, 95123 Catania, Italy, F. Iacona, CNR-IMM, Sezione di Catania, Stradale Primosole 50, 95121 Catania, Italy and Luca Dal Negro, INFN and Dipartimento di Fisica, Via Sommarive 14, 38050 Povo, Trento, Italy  
 In the last decade a strong effort has been devoted towards the achievement of efficient light emission from silicon. Among the different approaches, rare earth doping of Si nanostructures has shown great potentialities. In the present work, a quantitative understanding of the Si nanocrystals-Er interaction is reported. We present a model based on an energy level scheme taking into account the strong coupling between each Si nanocrystal and the neighboring Er ions. By fitting the steady state and time resolved luminescence signals at both the 1.54 and 0.98  $\mu\text{m}$  Er lines and at the Si nanocrystals emission (at 0.8  $\mu\text{m}$ ), we were able to determine a value of  $3 \times 10^{-15} \text{ cm}^3 \text{ s}^{-1}$  for the coupling coefficient. Moreover, an energy transfer time of 1  $\mu\text{s}$  has been estimated, confirming that Si nanocrystals can actually play a crucial role as efficient sensitizers for Er. However, a strong cooperative up-conversion mechanism, active between two excited Er ions and characterized by a coefficient of  $7 \times 10^{-17} \text{ cm}^3 \text{ s}^{-1}$ , is shown to limit the Er excitation rate at high pump powers. The role of Si nanocrystals and of strong gain limiting processes, such as cooperative up-conversion and carriers absorption from an excited nanocrystal, in determining positive gain at 1.54  $\mu\text{m}$  will be investigated in details. The impact of these results on the fabrication of electrically driven optical amplifiers will be finally addressed.
- 12:00 **LUNCH**

Tuesday, June 10, 2003  
Mardi 10 juin 2003

Afternoon  
Après-midi

Session III: Devices II

Session chair: A. Polman

- J-III.1** 14:00 -Invited- RARE-EARTH-DOPED GaN: GROWTH, PROPERTIES AND FABRICATION OF ELECTROLUMINESCENT DEVICES  
**A.J. Steckl**, Nanoelectronics Laboratory, University of Cincinnati, Cincinnati OH 45221-0030, USA  
A review is presented of the fabrication, operation and applications of rare-earth-doped GaN electroluminescent devices (ELDs). GaN:RE ELDs emit light due to impact excitation of the RE ions by hot carriers followed by radiative relaxation. By appropriately choosing the RE dopant, narrow linewidth emission can be obtained at selected wavelengths from the ultraviolet to the infrared. The deposition of GaN:RE layers is carried out by solid-source molecular beam epitaxy, and a plasma N<sub>2</sub> source. Growth mechanisms and optimization of the GaN layers for RE emission are discussed based on RE concentration, growth temperature, and III-V ratio. The fabrication processes and electrical models for both DC- and AC-biased devices are discussed, along with techniques for multi-color integration. Visible emission at red, green and blue wavelengths from GaN doped with Eu, Er, and Tm has led to the development of flat panel display (FPD) devices. The brightness characteristics of thick dielectric EL (TDEL) devices are reviewed as a function of bias, frequency, and time. High contrast TDEL devices using a black dielectric are presented. The fabrication and operation FPD prototypes are described. Infrared emission from GaN:Er ELDs has been applied to optical telecommunications devices. The fabrication of GaN channel waveguides by inductively coupled plasma etching is also reviewed, along with waveguide optical characterization.
- J-III.2** 14:30 THE EFFECT OF BREAKDOWN NATURE TO Er-RELATED ELECTROLUMINESCENCE INTENSITY AND EXCITATION EFFICIENCY IN Si:Er LIGHT EMITTING DIODES GROWN WITH SUBLIMATION MBE TECHNIQUE  
**V. Shmagin**, V. Kuznetsov, D. Remizov, Z. Krasil'nik, L. Krasil'nikova, D. Kryzhkov, Institute for Physics of Microstructures RAS, GSP-105 Nizhny Novgorod, Russia  
Si:Er-based light emitting diodes (LEDs) effectively emitting at 1.54 μm at room temperature under breakdown conditions are grown using the Sublimation Molecular Beam Epitaxy (SMBE). We have investigated in detail the effect of p-n junction breakdown nature on intensity and excitation efficiency of Er-related electroluminescence (EL) in Si at 1.54 μm. Under the gradual evolution of a breakdown nature from tunnel to mixed and further to avalanche the following changes in Er<sup>3+</sup> EL are observed: - at a constant current pumping Er-related EL intensity increases, reaches a maximum in LEDs with a mixed breakdown conditions (U<sub>break</sub>, 77K ≈ U<sub>break</sub>, 300K) and then sharply decreases at a further advance to an avalanche breakdown. Observed in avalanche LEDs the evident decrease of Er-related EL we account for the development of a microplasma breakdown; - the product of an excitation cross-section σ and a life time τ of an Er<sup>3+</sup> excited state 4I<sub>13/2</sub> arises from 1.4x10<sup>-20</sup> cm<sup>2</sup>s at the tunnel breakdown up to 9.4x10<sup>-20</sup> cm<sup>2</sup>s at the mixed character of breakdown. It indicates the increase of EL excitation efficiency and is connected apparently with increase of a high energy carriers number. So we conclude that LEDs operating at mixed breakdown successfully combine high EL intensity and excitation efficiency with homogeneous breakdown conditions and consequently are more promising for reaching strong EL intensity in Si:Er at room temperature. This study was supported by RFBR (01-02-16439, 02-02-16773), INTAS (01-0194) and MWO (047.009.013).
- J-III.3** 14:45 FLUORIDE GLASS PLANAR WAVEGUIDES FOR ACTIVE APPLICATIONS  
**J. Lousteau**, D. Furniss and A.B. Seddon, Novel Glasses for Photonics Research Group, School of M3EM, and P.Sewell and T. Benson, Electromagnetics Research Group, School of E.E.E., University of Nottingham, NG7 2RD, U.K.  
Heavy metal fluoride glass fibers have successfully been doped using rare-earth materials for optical amplification and up-conversion applications. Planar waveguides offer access to these and other integrated photonics applications. As a step towards the fabrication of planar optical rib waveguides in fluoride glasses we have investigated various waveguide geometries focusing on ZBLAN/ZBLANPb materials. We show such waveguides can have large cross-section, to ease fabrication and coupling constraints, whilst providing excellent single mode confinement with well defined optical characteristics. Our results highlight practically important limits to criteria currently applied when designing for single mode operation in large cross-section waveguides. Since absorption in fluoride glasses absorption is very low in the wavelengths range 0.4 μm to 5μm, the main source of loss in the waveguides studied is scattering from rib roughness arising in the fabrication process. We have thus characterized those losses for waveguide structures already identified as single-mode. These results will be crucial for successful development of active planar devices in rare earth doped fluoride glasses.

- J-III.4** 15:00 **LOSS MEASUREMENTS OF Er-DOPED SILICON-ON-INSULATOR WAVEGUIDES**  
M.A. Gad, J.H. Evans-Freeman, Centre for Electronic Materials, Dept. EE&E, UMIST, Sackville St., Manchester M60 1QD, U.K. and N. Cinosi, J. Sarma, Dept. EE&E, Bath University, U.K.  
 Waveguides optimised at 1.5 $\mu$ m have been fabricated from erbium-doped Smart Cut<sup>®</sup> silicon-on-insulator wafers. The wafers were implanted at 1MeV with a low dose of Er, chosen to minimize structural damage to the layers and reduce the need for prolonged thermal treatment. Single mode rib waveguides were designed taking into account the very thin Si top layer (1.5 $\mu$ m) of the wafers and the buried silicon dioxide layer of 3 $\mu$ m. Near field measurements of the horizontal and vertical confinement show a single, symmetric, and well-confined optical mode. As predicted in the literature, when the Er is in the waveguiding region itself, the measured waveguide losses increase. This is attributed to the implant-induced damage, which is observed as a broad defect peak in photoluminescence prior to any annealing. However the silicon remains optically active after the Er-doping by implantation, and the broad peak can be removed by an anneal at 800 $^{\circ}$ C for 20minutes. Loss measurements after annealing reveal different characteristics to those before annealing.
- J-III.5** 15:15 -Invited- **ROOM TEMPERATURE 1.5 mm ELECTROLUMINESCENCE FROM GaInP/Er,O-CODOPED GaAs/GaInP DOUBLE HETEROSTRUCTURE INJECTION-TYPE LIGHT EMITTING DIODES GROWN BY ORGANOMETALLIC VAPOR PHASE EPITAXY**  
**Y. Fujiwara**, A. Koizumi and Y. Takeda, Department of Materials Science and Engineering, Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan  
 We have fabricated GaInP/Er,O-codoped GaAs (GaAs:Er,O)/GaInP double heterostructure (DH) injection-type light emitting diodes (LEDs) by organometallic vapor phase epitaxy (OMVPE) and investigated their electroluminescence (EL) properties under forward bias at room temperature. In this contribution, recent progress in the device performance will be presented.  
 GaInP/GaAs:Er,O/GaInP DH-LEDs have been successfully fabricated with excellent control of the interface between GaAs and GaInP. The EL spectrum from a cleaved edge of the LED under forward bias at room temperature was dominated by the luminescence due to an Er-2O center, e.g., an Er atom located at the Ga sublattice with two adjacent O atoms. It indicates that injected carriers contribute effectively to the excitation of the Er-2O center. The EL intensity increased linearly with the current density. Subsequently, the intensity exhibited a tendency to saturate at higher current densities. Based on the analysis of the behavior, the excitation cross section of Er ions by current injection was determined to be approximately 10-15 cm<sup>2</sup>. It is by five orders of magnitude larger than the optical excitation cross section in Er-doped fiber amplifier (10<sup>-20</sup>-10<sup>-21</sup> cm<sup>2</sup>).
- 15:45 **BREAK**

## Session IV: Rare earth doped GaN I

Session chair: J. Zavada

- J-IV.1** 16:15 -Invited- **RARE-EARTH IMPLANTATION INDUCED DEFECTS IN GaN**  
**A. Vantomme**, B. Pipeleers and V. Matias, Instituut voor Kern- en Stralingsfysica, KULeuven, 3001 Leuven, Belgium, E. Alves and K. Lorenz, Instituto Tecnológico e Nuclear, EN10, 2686-953 Sacavém, Portugal, R.W. Martin, S. Dalmasso and K.P. O'Donnell, Department of Physics, Strathclyde University, Glasgow G4 0NG, U.K., A. Braud and J.L. Doualan, CIRIL-ISMRA, 6 Bd Maréchal Juin, 14000 Caen, France and the RENiBEI Network  
 The incorporation of rare-earth (RE) atoms in wide band gap semiconductors, such as GaN, results in a larger chemical and physical stability compared to e.g. RE(Si), and the luminescence exhibits less thermal quenching. Ion implantation is a suitable technique for introducing these dopants in a well-controlled way. However, the implantation of such heavy elements results in significant lattice damage. It is a challenging task to minimize and recover the implantation-induced damage, which can mask the excitonic luminescence, and generate defect-related emission in the luminescence spectra.  
 The important processes governing the generation and recovery of damage induced by RE implantation in epitaxial GaN/sapphire layers will be overviewed, using energies, fluences and implantation temperatures ranging from 80 to 200 keV, 10E14 to 10E16 at/cm<sup>2</sup>, and room temperature to 450 $^{\circ}$ C respectively. The use of various RE species will be reported, emphasising the case of Er. Information on the dopant distribution and lattice damage is obtained using Rutherford backscattering and channeling spectrometry and X-ray diffraction. The optical response of the doped samples is investigated with cathodo- and/or photoluminescence, including PL excitation. An inverse correlation between implantation-induced damage and the luminescence efficiency is observed. Lowering the defect density can be achieved by optimising the annealing conditions (including high pressure/high temperature annealing and rapid thermal processing), by implanting at elevated temperature, by using a channeling implantation geometry,... Specific examples of these conditions will be shown, and linked to the corresponding optical properties of the RE-doped nitrides.
- J-IV.2** 16:45 **THEORY OF ERBIUM IN GaN**  
J.Sebastien Filhol, Robert Jones, School of Physics, University of Exeter, The Queen's Drive, Exeter EX4 4QJ, U.K.  
 Rare-earth dopants in semiconductors have attracted great attention because of a strong defect related photoluminescence which survives to room temperature. In particular doped materials with Er show luminescence close to the minimum loss wavelength region of silica-based optical fibers that gives them important technological issues. However, there are uncertainties about the defects responsible for the luminescence. We report here density functional calculations of the structure and electrical properties of Er in GaN. We find that Er favours a Ga substitutional site and does not appear to be strongly bound to oxygen. The band structure and energy levels of the impurity are reported.

- J-IV.3** 17:00 **IMPLANTATION AND ANNEALING STUDIES OF TM IMPLANTED GaN**  
K. Lorenz(a), E. Alves(a,b), U. Wahl(a), T. Monteiro(c) 3, S. Dalmaso(d), R.W. Martin(d), K.P. O'Donnell(d), R. Vianden(e), (a)ITN, Estrada Nacional 10, 2686-953 Sacavém, Portugal, (b)CFNUL, Av. Prof. Gama Pinto n° 2, 1649-003 Lisboa, Portugal, (c)Universidade de Aveiro, Dept. Física, 3810-193 Aveiro, Portugal, (d)Department of Physics, University of Strathclyde, Glasgow G4 0NG, U.K., (e)HISKP, Nussallee 14-16, 53115 Bonn, Germany  
 Tm<sup>+</sup> ions were implanted into MOCVD grown GaN films with different fluences and implantation temperatures. Subsequent annealing of the samples was performed in a rapid thermal annealing apparatus or in a conventional furnace. The implantation damage and annealing effects were investigated with the Rutherford backscattering/channeling technique. We observe that implantation at 400°C considerably reduces the induced lattice damage and the amorphisation threshold. The lattice site location of the ions was studied by performing detailed angular scans along the [0001] and [10-11] directions. The results show that Tm ions occupy substitutional Ga sites after implantation and annealing. The optical properties of the ion implanted GaN films have been studied by photoluminescence (PL) and room temperature cathodoluminescence (CL) measurements. With above band gap excitation an unstructured green emission band peaked at 525 nm dominates the PL spectrum of the implanted and annealed samples. Besides this, a well-defined near infrared emission due to intra-4f-shell transitions of the Tm<sup>3+</sup> ions is observed.
- J-IV.4** 17:15 **Er-DEFECT COMPLEXES AND ISOLATED Er SPECTROSCOPY IN Er-IMPLANTED GaN**  
A. Braud, J.-L. Doualan, R. Moncorge, CIRIL-ISMRA, 6 Bd Marechal Juin, 14000 Caen, France, A. Vantomme, Instituut voor Kern-en Stralingsfysica, Departement Natuurkunde, Celestijnenlaan 200 D, 3001 Leuven, Belgium  
 Rare-earth doped GaN is being widely studied for its various applications in optoelectronics. Questions still remain about the fundamental understanding of the mechanisms underlying the excitation of rare-earth ions in this host. In order to deepen our understanding of the incorporation of rare-earth ions in GaN and the excitation processes of the 4f-shell, we investigated the photoluminescence (PL) and photoluminescence excitation (PLE) spectra of the Er<sup>3+</sup> 4I<sub>13/2</sub> → 4I<sub>15/2</sub> transition as a function of temperature in Er-implanted GaN samples. Under below-gap excitation, one type of Er center appears to be predominant while other Er centers are clearly excited via local defects. The PLE spectra show on one hand that the number of these Er-defect complexes is small compared to the Er predominant centers and on the other hand that the absorption cross-section of the defect itself is much bigger than the typical absorption cross-section of Er ions. Therefore, the overall luminescence of these Er-defect complexes is not negligible. Lifetimes measurements show that the 4I<sub>13/2</sub> manifold has a shorter lifetime when Er ions are part of Er-defect complexes than when the Er ions are isolated from any defect. This result indicates the existence of non-radiative energy transfer in Er-defect complexes from the Er ions towards the defect. Evolutions of the PL and PLE spectra as a function of temperature are derived for the different types of Er centers. Combining PL and PLE results we investigated the different processes (homogeneous broadening, Boltzmann distribution..) taking place as the temperature increases from low temperature, typically around 7K, up to room temperature.
- J-IV.5** 17:30 -Invited- **LATTICE LOCATION AND OPTICAL ACTIVATION OF RARE EARTH IMPLANTED GaN**  
U. Wahl, E. Alves, K. Lorenz, Instituto Tecnológico e Nuclear, EN10, 2686-953 Sacavém, Portugal, T. Monteiro, Departamento de Física, Universidade de Aveiro, 3810 Aveiro, Portugal, A. Vantomme, B. De Vries, Instituut voor Kern- en Stralingsfysica, KULeuven, 3001 Leuven, Belgium, R. Vianden, HISKP, 53115 Bonn, Germany  
 GaN epilayers were implanted with rare earth (RE) elements with different energies and fluences to study the RE lattice location and optical activity. The samples were annealed by rapid thermal annealing (RTA) and conventional annealing under nitrogen pressure. Rutherford backscattering/channeling was used to follow the damage behavior of the Ga sublattice and the lattice location of the RE. For all the elements studied (Pr, Dy, Er, Tm and Lu) the results show complete substitutionality on Ga sites following RTA at 1000°C for 2 min. The only exception occurs for Eu, which seems to occupy a site that is displaced up to 0.2 Å from the Ga site. The recrystallization of the amorphous layer is achieved by annealing at 1200°C in nitrogen atmosphere at a pressure of 1 GPa. Additional lattice location studies by means of the emission channeling technique were performed for samples implanted with the radioactive isotopes <sup>143</sup>Pr, <sup>147</sup>Nd/<sup>147</sup>Pm, <sup>149</sup>Gd/<sup>149</sup>Eu and <sup>167</sup>Tm/<sup>167</sup>mEr using fluences below 3E13 ions/cm<sup>2</sup>. In all these cases 70-100% of the RE probe atoms were found on substitutional Ga sites, too, with root mean square displacements in the range 0.1-0.3 Å. After annealing, the photoluminescence of the implanted samples was studied by above and below band gap excitation. For Er implanted samples, besides the 1.54 micrometer emission, green and red luminescence was also observed. Co-doping with O produced a decrease in the Er luminescence after annealing at 1200°C. In the samples implanted with Eu and Pr we observed the red emissions from 5D<sub>0</sub> → 7F<sub>2</sub> and 3P<sub>0</sub> → 3F<sub>2</sub> transitions even at room temperature. For Tm a green emission was found at 525 nm by above band gap excitation, as well as a structured near-infrared emission.

18:15-20:00

POSTER SESSION

## POSTER SESSION

- J/P.01** TERAHERTZ ENHANCEMENT OF ERBIUM LUMINESCENCE IN C-Si  
I.N. Yassievich, A.S. Moskalenko, Ioffe Physico-Technical Institute RAS, Polytechnicheskaya 26, St. Petersburg 194021, Russia  
The processes of enhancement and quenching of erbium luminescence in C-Si under influence of terahertz radiation were intensively experimentally studied by team of T. Gregorkiewicz. In the present work we theoretically investigate a possible mechanism of the enhancement of erbium luminescence by terahertz radiation under conditions of constant band-to-band pumping. The proposed mechanism consist of Auger-excitation of an Er ion by recombination of an electron-hole pair assisted by terahertz radiation. In such a process Er ion is transferred into the second excited state having energy 1.24 eV. After this Er ion relaxes nonradiatively into the first excited state having energy 0.8 eV, from which the radiative transition takes place. The free electron transition takes place through a virtual state in the higher subband in the conduction band. For concentrations of electrons and holes  $10^{18} \text{ cm}^{-3}$ , power of the terahertz laser 10 MW and irradiated area  $1 \text{ cm}^2$  that corresponds to reasonable experimental parameters, we get the value of the excitation probability on the order of  $2 \times 10^6 \text{ s}^{-1}$  for the wavelength of terahertz radiation 15-19  $\mu\text{m}$ . The excitation process has a strong dependence on the frequency of the terahertz radiation and may be observed for wavelengths of the terahertz radiation in the range of 8-20  $\mu\text{m}$ .
- J/P.02** Shifted to oral J-VI.3 on Wednesday 17:00
- J/P.03** RARE EARTH DOPED SESQUIOXIDE THIN FILMS GROWN ON SAPPHIRE BY PLD  
S. Baer, G. Huber, Institute of Laser-Physics, University of Hamburg, Jungiusstr. 9a, 20355 Hamburg, Germany, J. Gonzalo, A. Perea, Instituto de Optica, CSIC, Serrano 121, 28006 Madrid, Spain, A. Climent, F. Paszti, Departamento de Física Aplicada y ICMAM, Universidad Autonoma de Madrid, 28049 Cantoblanco, Madrid, Spain  
The development of integrated optic devices demands the fabrication of optically active thin films. Sesquioxides are very promising materials because they are well known hosts for rare earth doped luminescent materials and solid state lasers. In this work, good quality crystalline thin films of rare earth doped sesquioxides (Y<sub>2</sub>O<sub>3</sub>, Lu<sub>2</sub>O<sub>3</sub> and Sc<sub>2</sub>O<sub>3</sub>) have been grown by pulsed laser deposition on single crystal (0001) sapphire substrates. Sapphire substrates offer a lattice constant that nearly matches that of cubic Y<sub>2</sub>O<sub>3</sub> in the [222] direction. The lattice constants of Lu<sub>2</sub>O<sub>3</sub> and Sc<sub>2</sub>O<sub>3</sub> are 10.39Å and 9.86Å, respectively and thus, these values match better the lattice constant of sapphire leading to the production of films with less dislocation. The crystal structure of the films (thicknesses between 100nm and 500nm) were determined by X-ray diffraction analysis, whereas the film composition was determined by RBS. The X-ray diffraction show that the films were highly textured along the [222] direction. Spectroscopic measurements, including excitation and emission, of the rare earth doped films will be presented. The emission and excitation spectra of the Eu doped films look similar to those of the corresponding crystalline bulk material. A comparison of the thin film optical properties of the three sesquioxides (Y<sub>2</sub>O<sub>3</sub>, Lu<sub>2</sub>O<sub>3</sub> and Sc<sub>2</sub>O<sub>3</sub>) as well as the system LuScO<sub>3</sub> will be presented and the influence of the deposition parameters on the film characteristics will be discussed.
- J/P.04** OPTICAL PROPERTIES OF RARE EARTH COMPLEXES INTERCALATED INTO LAYERED DOUBLE HYDROXIDES MATRIX  
A.A. Eliseev, N.G. Zhuravleva, A.V. Lukashin, Yu.D. Tretyakov, Dept. of Materials Science, Moscow State University, 119899 Moscow, Russia, U. Kynast, Dept. of Chem. Engineering, Muenster University of Applied Science, Stegerwaldstr. 39, 48565 Steinfurt, Germany  
Intercalation of Rare Earths complexes into the interlayer space of layered double hydroxides (LDH) holds the promise of novel hybrid luminophores combining solid state properties with optical features typical for the molecular state. The present research deals with synthesis and the investigation of optical properties of terbium and europium picolinates inside the LDH matrix. The main advantage of LDHs is the possibility to control the loading values of anions by variation Mg to Al ratio in the initial precursor. Thus, compounds with different content of Rare Earth complex can be obtained, allowing the investigation of the concentration dependence of properties of the complex inside the matrix. The absorptive and excitability of rare earth containing LDH is high enough to use as luminescent materials such as phosphors, signaling, sensors and lighting applications in general; their light output is maintained or improved as compared to the molecular complex. Calculated quantum efficiencies range from 30 to 50 % for different Tb-containing samples. Energy transfer studies in corresponding mixed Tb<sup>3+</sup> / Eu<sup>3+</sup> systems also revealed intra- and intermolecular communication channels, among them Ligand→Tb<sup>3+</sup>/Eu<sup>3+</sup> and Tb<sup>3+</sup>→Eu<sup>3+</sup> transfer, geometrical constraints become a governing factor; in the case of Eu<sup>3+</sup>, additionally Lattice→Eu CT states appear to participate.
- J/P.05** CaF<sub>2</sub> CRYSTALS DOPED WITH RARE EARTH IMPURITIES AS A SCINTILLATOR FOR WHITE LED  
Kazutaka Terashima, Satoshi Suzuki, Hiromichi Tanji and Suzuka Nishimura, Shonan Institute of Technology, Materials Science, 1-1-25 Tsujido-nishikaigan, Fujisawa, Kanagawa 251-8511, Japan  
Calcium fluoride (CaF<sub>2</sub>) is a representative alkaline earth fluoride that has been the subject of experimental and theoretical studies for years. It has for many years been one of the important materials used in the design of optical components. Recently, many efforts have been focused on the growth of large-scale crystals for the use in UV lens of IC lithography system. On the other hand, CaF<sub>2</sub> crystals are well known as a fluorescence materials. We have preliminarily studied the growth of CaF<sub>2</sub> by vertical Bridgman technique doped with Rare Earth materials for scintillator for white lamp by using UV LED of GaInN semiconductor devices. This paper describes the growth of doped CaF<sub>2</sub> and the relation as a scintillation crystal. Graphite crucible with 25mm in inner diameter and 400mm in length. The crystal growth was carried out under 10<sup>-6</sup> Torr. It has been found that La and Ce atoms were dissolved into CaF<sub>2</sub> melts. The growth experiments have been carried out without any troubles. There are two regions of emission wavelength in CaF<sub>2</sub> doped into Ce. In the case of La impurity wide range of emission wavelength region. It has been found that the CaF<sub>2</sub> doped with Rare Earth materials is a promising materials for the use in white LED by using GaInN materials.
- J/P.06** THE EFFECT OF IMPLANTATION ANGLE ON DAMAGE PRODUCTION IN RARE-EARTH DOPED GaN  
J. Nord, K. Nordlund, J. Keinonen, Accelerator Laboratory, University of Helsinki, Finland  
Large direct bandgap makes GaN a very attractive candidate for rare-earth doping. However, the damage produced in GaN during implantation is hard to anneal due to the high melting point. Controlling the implantation angle has proved to be a very efficient way of suppressing the damage production and improving the optical properties. The use of molecular dynamics allows us to model the atomic level short timescale processes leading to this reduced damage production. We model the implantation of Er into GaN at different implantation angles and the subsequent annealing process and observe the differences leading to this reduction.

**J/P.07**

**PREPARATION, STRUCTURAL AND OPTICAL STUDIES OF OPAL-ERBIUM COMPOSITES**

V.G. Golubev, A.A. Dukin, D.A. Kurdyukov, A.V. Medvedev, A.B. Pevtsov, L.M. Sorokin, Ioffe Physico-Technical Institute, RAS, 26 Politekhnicheskaya, 194021 St. Petersburg, Russia, J.L. Hutchison, Materials Science Division, Oxford University, Parks Road, Oxford OX1 3PH, U.K.

Erbium has been impregnated in opal pores by using the chemical bath deposition technique. Electron microscope studies revealed that Er is deposited on the pore surface as a thin (3-10 nm) uniform amorphous coating (presumably, Er<sub>2</sub>Si<sub>2</sub>O<sub>7</sub>) in practically all pores. Optical measurements showed that the synthesized opal:Er composites retain the photonic band gap properties of the original opal matrix. When pumped resonantly at a wavelength of 488 nm (4I15/2 - 4F7/2 transition), erbium in the composite efficiently emits light in the visible and near IR regions at several discrete wavelengths corresponding to the radiative transitions 4S3/2 - 4I15/2 (550 nm), 4S3/2 - 4I13/2 (860 nm), 4I11/2 - 4I15/2 (980 nm), 4S3/2 - 4I11/2 (1240 nm), and 4I13/2 - 4I15/2 (1530 nm). Thus, the synthesized opal:Er composites combine the photonic band gap properties of opal (three-dimensional photonic crystal) with the luminescence of Er and can serve as a model object to study the effect of the photonic band gap on the spontaneous emission of the radiating centers.

The work is supported by the RFBR (02-02-16502) and the INTAS (01-0642).

**J/P.08**

**COMPARATIVE STUDY OF Er-IMPLANTED Si, ZnAs<sub>2</sub> AND CuInSe<sub>2</sub>**

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Er-doped semiconductors are considered to be very promising materials for the fabrication of light emitters at 1.54 μm, an important wavelength for optical fiber communication systems. In this paper we describe a study of the optical characteristics of Er ions, incorporated in indirect and direct semiconductors with band gaps in the region of 1 eV. 350 keV Er ions were implanted into the three materials with a dose of 10<sup>16</sup> cm<sup>-2</sup>. The samples were then annealed in vacuum at temperatures from 100 to 6000C for 20 min. The Er-content and composition of the host materials were investigated using wavelength dispersive X-ray analysis. Photoluminescence (PL) measurements revealed an emission line centered at about 1.54 μm in all the materials. This line was associated with the internal 4f - 4f transition (4I13/2 - 4I15/2) of the Er ions. The Er - related emission at 1.54 μm was observed straight after the ion implantation and prior any annealing for the direct-gap semiconductors CuInSe<sub>2</sub> and ZnAs<sub>2</sub>, in contrast to the behavior for Si. The temperature dependence of the Er - related emission in PL spectra was studied in the temperature range from 4.2 to 300K in all the materials. Possible luminescence mechanisms are discussed.

**J/P.09**

**PHOTOLUMINESCENCE OF CaGa<sub>2</sub>S<sub>4</sub>:Eu, Ce COMPOUNDS UNDER HIGH EXCITATION LEVELS**

A.Z. Abasova, L.G. Gasanova, A.G. Kyazym-zade, B.G.Tagiyev, V.M. Salmanov, A.A. Agayeva, Baku State University, Physics Semiconductor, Z. Khalilov Str. 23, 370145 Baku, Azerbaijan

Rare-earth element doped thiogallates are being studied mostly as thin electroluminescent materials. However, here we direct our attention to laser application of these materials, taking the following points into account; high efficiencies, relatively high transition probabilities, broad emission spectra leading to wavelength tunabilities of laser if attained, coverage of whole visible spectrum with suitable selection of host material and rare-earth element combination, high concentration doping capabilities of host materials, etc. With above motivation, photoluminescence characteristics and behavior under high density excitation of single crystals CaGa<sub>2</sub>S<sub>4</sub>: (~1 at %)Eu<sup>2+</sup>, Ce<sup>3+</sup> were investigated. The samples was produced using the iodine transport method from poly crystals which were prepared by heating the evacuated quartz ampoule containing a stoichiometric mixture of binary compounds of CaS, Ga<sub>2</sub>S<sub>3</sub> and EuS, CeS at 1100°C.

Photoluminescence of the samples which were excited by N<sub>2</sub>-laser (337 nm, pulse width 1ns, pulse power 120 kW) and dye laser pumped by the output of a N<sub>2</sub>-laser was dispersed by a diffraction grating monochromator and detected by a photomultiplier tube followed by a gated optical multichannel analyzer system. The spectra absorption and photoluminescence, their temperature dependence, lifetime and quantum efficiency, dependence of the photoluminescence on the excitation power have been investigated. The luminescence spectra contain line emission with maximums 555 nm and 470nm, 517nm for CaGa<sub>2</sub>S<sub>4</sub>: Eu<sup>2+</sup> and CaGa<sub>2</sub>S<sub>4</sub>: Ce<sup>3+</sup>, respectively. At the high excitation levels in CaGa<sub>2</sub>S<sub>4</sub>: Eu<sup>2+</sup> stimulate emission is observed. Lines emission due to electron transition 5D<sub>1</sub> - 7F<sub>2</sub> ionic Eu<sup>2+</sup> and 2D<sub>3/2</sub> - 2F<sub>5/2</sub> ionic Ce<sup>3+</sup>.

**J/P.10**

**LIGHT-INDUCED EFFECTS IN a-Si:H(Er)**

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It was shown that the erbium ions luminescence yield is higher and thermal quenching is smaller in a-Si:H compared to crystalline silicon. While the luminescence of a-Si:H(Er) has been studied quite extensively there is no data on the light-induced effects in this material. The latter, however, are important for electroluminescent devices. We have investigated the light-induced metastable state in a-Si:H(Er) with the measurements of optical absorption in the below-gap region and dark conductivity before and after illumination of the films by band gap light. PECVD a-Si:H(Er) films with different erbium contents have been studied. To elucidate the details concerning the peculiarities of light-induced phenomena in a-Si:H(Er) the obtained results have been compared with the data for a-Si:H(As) films with the same Fermi level position. We have found that after long illumination time the changes of optic and electric properties of a-Si:H(Er) films were determined by dangling bond creation as in a-Si:H(As) film. For short illumination time the persistent photoconductivity was observed in a-Si:H(Er) films. A possible origin of this phenomenon is discussed from the viewpoint of structural disorder induced by erbium-oxygen complexes incorporation. We have shown that light-induced effects in a-Si:H(Er) could be suppressed essentially by co-doping of the films with small amount of boron.

J/P.11

IN-SITU CONTROL OF SIOX STOICHIOMETRY BY SPECTROSCOPIC ELLIPSOMETRY

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SiO<sub>x</sub> thin films are useful materials, for example they are used as antireflective layer in astronomy or as intermediary material to obtain nanocrystalline Si (nc-Si) in a SiO<sub>2</sub> matrix. In the later case, the thin films need to be annealed at around 1000°C to obtain the phase separation. Si nanocrystals embedded in SiO<sub>2</sub> would be appropriated in many opto-electronic components as LED and possibly lasers, amplification medium for the telecoms after Er doping... For all these applications, the size and distribution of nc-Si is a key parameter to tailor the properties of the final component. These parameters could be adjusted via a precise control of the sub-stoichiometry  $x$  of the starting thin film.

SiO<sub>x</sub> thin films, approximately 0.5  $\mu\text{m}$  thick, were deposited by electron-gun evaporation of SiO under O<sub>2</sub> reactive atmosphere on Si and SiO<sub>2</sub> substrates. The complex refractive indices of the layers were extracted from spectroscopic ellipsometry in the [0.25-0.85]  $\mu\text{m}$  range. An appropriate set of dielectric functions was obtained using the Random Bonding Model [1] adapted to our growth conditions and allowed the  $x$  value to be estimated. These values were compared to the values deduced both from in-situ XPS and Rutherford Backscattering Spectroscopy (after venting) and are found in good agreement. The interplay of growth rate and oxygen flux on the final stoichiometry is particularly investigated. It is shown that both oxygen flux and growth rate must be controlled to achieve a constant composition in the films. [1] D.E. Aspnes, J.B. Theeten, J. Appl. Phys. 50, 4928 (1979).

J/P.12

ELECTRICAL AND STRUCTURAL INVESTIGATIONS OF SnO<sub>2</sub>:Sb:Tb<sup>3+</sup>/POROUS SILICON DEVICES

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Luminescent devices, such as solid lasers or light-emitting diodes (LED),...can be further developed through new luminescent materials containing optically active centres of trivalent lanthanide ions. Emission of lanthanide ions presents high efficiency, low temperature quenching, sharp spectral bands and high coherence. Among them, terbium is widely used for the elaboration of green-emitting materials.

In the present work, SnO<sub>2</sub>: Sb sol-gel elaborated thin films doped with terbium (Tb<sup>3+</sup>) were deposited on porous silicon (PS) substrates. Transmission Electron Microscopy (TEM) observations, Electron Diffraction (ED) patterns and Electron Dispersive Xray (EDX) analysis revealed the growth of small crystallites of SnO<sub>2</sub> cassiterite embedded in the porous layer and the presence of rare earth element in the SnO<sub>2</sub> crystallites. Optical and electrical properties of the heterojunctions so formed are investigated. Rapid thermal annealing at T=500°C reveals intense photoluminescence (PL) peaks relative to 5D<sub>4</sub> → 7F<sub>j</sub> (j= 3,4,5,6) transition in Tb<sup>3+</sup> superposed to the PL band of PS. The SnO<sub>2</sub>:Sb:Tb<sup>3+</sup>/PS nanocomposite structure forms a heterojunction which I-V characteristics are presented and analyzed. A large forward current density &#61566; 80 mA.cm<sup>-2</sup> at 10V is obtained. Related results in electroluminescence show that such SnO<sub>2</sub>:Sb/ Tb<sup>3+</sup> on PS heterojunctions will act as very good candidate for highly efficient LED's.

J/P.13

OPTICAL AND STRUCTURAL PROPERTIES OF SnO<sub>2</sub> FILMS DOPED RARE EARTH IONS PREPARED FROM SOL-GEL METHOD

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Recently, a great interest is devoted to metal and rare earth ion – doped nanoparticles because of their practical application. Sol gel glasses reveal interesting fluorescence of highly oxidised transition metal ions and rare earth ions.

We have prepared tin oxide films doped Tb<sup>3+</sup> (SnO<sub>2</sub>: Tb<sup>3+</sup>) and Eu<sup>3+</sup> (SnO<sub>2</sub>:Eu<sup>3+</sup>) by using the sol gel method. The high Resolution Transmission Electron Microscopy (HRTEM) observations and electron diffraction pattern revealed the presence of nanometric crystallites of SnO<sub>2</sub>. The penetration of rare earth ions in the SnO<sub>2</sub> crystallites has been experimentally proved by Energy Dispersive X-ray (EDX). The photoluminescence (PL) and cathodoluminescence (CL) spectra show different peaks corresponding to transitions between the energy levels in rare earth ions. The mechanism of excitation and emission process are discussed. The effect on the PL of co-doping with two different rare earth ions is also investigated.

J/P.14

NANOSTRUCTURED Er AND Yb DOPING FOR IMPROVING THE Er LUMINESCENCE RESPONSE IN THIN FILMS

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The luminescence efficiency of Er ions can be enhanced by the addition of Yb ions to the host, due to its higher absorption cross-section and the resonant energy transfer between both ions. The aim of this work is to show how the Er-Yb transfer can be optimised by nanostructuring both rare earth ion distributions to the nanometric scale besides controlling the Er and Yb relative concentrations. The 300 nm thin films, grown by pulsed laser deposition, consist of amorphous aluminum oxide with the Er and Yb ions distributed in layers. The Er-Er layer separation is 6 nm while the Er-Yb separation is varied from 0 to 3 nm. The Er content is constant and the Er:Yb relative concentration ranges from 1:0 to 1:4.

The Er photoluminescence (PL) at 1530 nm, pumped with a Ti:sapphire laser (910-990 nm) can only be excited in a very narrow band around 975 nm in films with no Yb codoping, while it is observed in the whole 910-990 nm pumping range in the Er-Yb codoped films, thus evidencing the existence of energy transfer from Yb to Er. It is found that, for any Yb concentration, the optimum PL response is obtained for a 1 nm Er-Yb layer separation. The PL intensity increases as the Yb content is increased with no saturation tendency being observed in the studied Yb concentration range. Discussion of these effects on the transfer mechanism will be given.

J/P.15

LUMINESCENCE OF A3B6 TYPE LAYERED CRYSTALS DOPED BY RARE ELEMENTS

À.Sh. Abdinov, N.M. Mehtiev, R.F. Babaeva, R.M. Rzayev, Baku State University, Z. Khalilov str. 23, 370148 Baku, Azerbaijan  
In this report the features of photoluminescence properties of InSe ( $E_g = 1.30$  eV) and GaSe ( $E_g = 1.80$  eV) wide-bandgap monocrystals doped by Ho and Dy rare elements (RE) are investigated at nitrogen temperature ( $T = 77$  K).

Investigated samples by thickness no more than  $d \leq 50$   $\mu\text{m}$  was cut off from brought up by a method of slow cooling at a constant gradient of temperature along ingots of larger monocrystal pieces. The percentage of entered impurities ( $N_i$ ) varied about  $10^{-5}$ - $10^{-1}$  at. %.

Photoluminescence was raised by continuous laser of LGN-208 ( $\lambda = 6328$  Å) and pulse laser of LGI-21 ( $\lambda = 5371$  Å), for InSe and GaSe monocrystals, accordingly. The measurements were made on installation assembled on base of monochromator of MDR-12 with resolution not worse than  $\sim 1$  meV.

In undoped specially monocrystals InSe in the range of  $\lambda = 8750$ - $12400$  Å (near IR spectrum region) is observed photoluminescence with a maximum at  $\lambda = 9380$  Å. With increasing of the  $N_i$  in these crystals, doped by rare elements, the brightness of photoluminescence varies nonmonotone, half wide of the radiation strips is narrowed, and the energetic situation of maximum does not vary almost.

The photoluminescence spectrum of undoped specially GaSe crystals covers a range of  $\lambda = 4000$ - $8000$  Å (almost of all visible spectrum region) and has three maximum (basic at  $\lambda = 5900$  Å and additional at  $6000$  Å and  $6100$  Å).

With increasing of the  $N_i$  in crystals GaSe doped by rare elements, varies both structure of a spectrum, and brightness of photoluminescence radiation.

It is found, that in undoped specially InSe and GaSe crystals photoluminescence is caused by irradiative disintegration direct free and indirect connected excitons depending on various external and intercrystal conditions. In doped crystals the ions of RE, due to the rather small radiuses enter as into natural layers as impurity, and interlayer space. Domination of this or that mechanism first of all depends on meaning of percentage of entered impurity. Owing to what, with increasing of  $N_i$  of a degree spatial and structural inhomogeneity, caused by own defects in investigated crystals varies nonmonotone. This in the turn results in the found out dependences of a spectrum, brightness and half wide of the photoluminescence from the contents of entered impurity of rare elements in investigated crystals.

The received results testify to opportunities of application of the  $\text{A}^3\text{B}^6$  type layered crystals doped by rare elements for manufacturing sources of luminescent radiation in visible and near IR spectrum regions with controlled parameters and characteristics.

J/P.16

SPONTANEOUS AND STIMULATED ELECTROLUMINESCENCE IN LAYERED GASE CRYSTALS

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In the present work the electroluminescence spectra of the "pure" single crystal of GaSe at the 77K have been studied for two polarizations, E<sup>∥</sup>C and E<sup>⊥</sup>C. Samples of GaSe with contact of In and In-Ga were taken for the measurements.

It has been established that while exciting the crystals by electric fields in both crystallographic directions the red emission is observed. The intensity of the threshold electric field for the appearance of the emission changes within the range of 100,200 V/cm depending on the direction of applied voltage, as well as on the current passing through the pattern. Three peculiarities have been observed under I<sub>1</sub>=5950A, I<sub>2</sub>=6240A, I<sub>3</sub>=6530A in both crystallographic directions. On increasing of the applied voltage the emission intensity I<sub>3</sub> corresponding to the impurity emission is decreasing, while for the banding excitons - I<sub>2</sub> increases.

Simultaneously the short-wavelength emission intensity increases linearly depending on value of the applied voltage and shifts to low energies.

There is a certain value of the field intensity under which the short-wavelength emission intensity is sharply increasing and as a result of this, it becomes prevailing over I<sub>2</sub> and I<sub>3</sub>. And it is worth mentioning that energy shifts are absent in this condition. It has also been established that the short-wavelength I<sub>1</sub> corresponds to the recombinative emission of the free excitons. Sharp increase, power dependence of emission intensity on the field intensity under  $E_{cr} > E_1$ , as well as the absence of energy shift and polarization of emission are the evidences of the discovery of stimulated emission in GaSe under 77K. Relative change of intensities of emission lengths I<sub>1</sub>, I<sub>2</sub> and I<sub>3</sub> is connected with redistribution of free and associated excitons and impurities.

J/P.17

Er<sup>3+</sup>-DOPED TELLURITE WAVEGUIDES DEPOSITED BY EXCIMER LASER ABLATION

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Tellurite glasses (TG) combine wide transmission region (0.35-6  $\mu\text{m}$ ), good glass stability and high corrosion resistance. Rare-earth ions in TG show an enhancement of the radiative transition rates due to their high refractive index and a broadening of the emission bands due to the variety of sites available for the optical ions, opening the possibility to use TG for broadband Er<sup>3+</sup>-doped fibre amplifiers. Moreover, the high TG rare earth ion solubility makes them very interesting to develop Er-doped waveguide amplifiers for integrated optics.

In this work, we report on Er<sup>3+</sup>-doped tellurite planar waveguides deposited by pulsed laser ablation (PLD) technique on v-silica (2x2 cm<sup>2</sup>) substrates. 60TeO<sub>2</sub>-20ZnO-20ZnO: 1ErCl<sub>3</sub> mol% target was ablated in dynamical flow oxygen at pressure values of 5 and 10 Pa by ArF(193 nm) excimer laser at the fluence of 2 J/cm<sup>2</sup>. Morphology of thin films was investigated by SEM. From the optical transmission spectra, collected in the 0.2-3.5  $\mu\text{m}$  region, the optical constants (n and k) vs. wavelength and the film thickness were calculated. The waveguiding properties of the deposited films were investigated by the prism coupling technique. Er<sup>3+</sup> 4I<sub>13/2</sub> → 4I<sub>15/2</sub> transition was studied by collecting photoluminescence (PL) spectra in standard lock-in technique, upon CW excitation at 514.5 and 980 nm. The TE<sub>0</sub> mode excitation was used for PL measurements, detecting the scattered light from the front of the waveguide

- J/P.18** LINE STRENGTH OF ELECTRONIC TRANSITIONS BETWEEN STARK SUBLEVELS OF Yb<sup>3+</sup> IMPURITY IONS IN CRYSTALS  
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 In order to explain intensities of spectral lines of rare-earth (RE) impurity ions, Judd and Ofelt developed the theory of indirect electric-dipole transitions between electronic levels with the same parity. According to the theory, line strengths of the transitions one can represent via semi-phenomenological parameters, which are, as rule, obtained from absorption spectra of the material under study. However, for ions with a scanty spectrum of electronic levels (such is indeed the case for both Yb<sup>3+</sup> and Ce<sup>3+</sup> ions) above-mentioned theoretical approach is poorly effective whereas it does not distinguish Stark sublevels and allows to estimate only probabilities of transitions between multiplets.  
 Within frameworks of same theoretical assumptions a method based on a somewhat different parameterization of theory is developed. The technique we tested on NaBi(WO<sub>4</sub>) and KTA crystals doped with Yb<sup>3+</sup> impurity ions. Based on analysis of low-temperature absorption and emission spectra, energy level schemes of the Yb<sup>3+</sup> ions in these matrixes were constructed. The eigenvalue and eigenfunction problem of the impurity ions; Hamiltonian for these crystals was solved, crystal-field parameters and wave functions of the corresponding levels were calculated. Using obtained values, line-strengths of transitions between Stark sublevels, radiative lifetimes of excited states and their branching ratios were determined. Obtained values are in reasonable agreement with experimental ones.
- J/P.19** OPTICAL PROPERTIES OF Er-DOPED SiO<sub>2</sub>-TiO<sub>2</sub> THIN FILMS BY UV-CVD  
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 The ultraviolet photo-induced chemical vapor deposition (UV-CVD) process is a highly flexible and efficient technique for the fabrication of thin oxide films. The Er-doped SiO<sub>2</sub>-TiO<sub>2</sub> system formulated by the sol-gel method has been widely investigated for various optical application, such as waveguide amplifiers. We report in this work the successful growth of Er-doped SiO<sub>2</sub>-TiO<sub>2</sub> thin films on Si substrates using UV-CVD with ultraviolet excimer lamps at temperatures between 350 °C to 500 °C. Erbium isopropoxide, titanium isopropoxide and tetraethoxysilane were used as precursors, which were carried into the photochemical reaction chamber by flowing Ar carrier gas. Films of around 20 - 100 nm in thickness with refractive indices from 1.60 - 1.90 were grown. The chemical, optical, microstructural and spectroscopic properties of the films have been investigated by Fourier transform infrared spectroscopy (FTIR), ellipsometry, photoluminescence (PL) spectra, XRD and x-ray photoelectron spectroscopy. High quality films with various Ti/Si ratios and low carbon content have been achieved, as indicated by x-ray photoelectron spectroscopy measurement. The effects of UV-annealing and thermal-annealing process conditions on the optical property of the films were also investigated, and are reported here.
- J/P.20** GROWTH AND CHARACTERISTICS OF (TbBi)<sub>3</sub>(FeAlGa)<sub>5</sub>O<sub>12</sub> AND (EuBi)<sub>3</sub>(FeAlGa)<sub>5</sub>O<sub>12</sub> GARNET SINGLE CRYSTAL THICK FILMS  
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 Yttrium iron garnet (YIG) has been characterized extensively for its use in magneto-optic devices, such as optical isolators and magnetic field sensors. In optical isolator applications operating at 1.55 μm, where miniaturization, temperature stability, low magnetic field of saturation are important, terbium and europium-containing compositions are considered as alternatives to pure YIG and bismuth substituted YIG.  
 We discuss the single crystalline thick films of (TbBi)<sub>3</sub>(FeAlGa)<sub>5</sub>O<sub>12</sub> and (EuBi)<sub>3</sub>(FeAlGa)<sub>5</sub>O<sub>12</sub> garnet single crystal thick films were grown on (GdCa)<sub>3</sub>(GaMgZr)<sub>5</sub>O<sub>12</sub> (SGGG) substrate by liquid phase epitaxy (LPE). Increasing of the Bi-substitution level in Garnet crystal, the lattice constant of film was increased and the lattice mismatch of substrate and grown (TbBi)<sub>3</sub>(FeAlGa)<sub>5</sub>O<sub>12</sub> film was decreased. (TbBi:YIG=12.50 μm, substrate(SGGG)=12.496 μm). Bi-substitution level and growth rate of Bi:YIG film were increased with the small PbO/Bi<sub>2</sub>O<sub>3</sub> molar ratio melt (rich in Bi<sub>2</sub>O<sub>3</sub>) than the large PbO/Bi<sub>2</sub>O<sub>3</sub> molar ratio melt. Besides magnetic field of saturation get excellent results (150 Oe). The lattice constant of films obtained by a double crystalline diffractometer(DCD). The surface morphology and cross-section were observed by scanning electron microscopy (SEM), and saturation magnetization was measured by vibrating sample magnetometer (VSM). The substitution-level in grown crystal of element was observed by electron probe micro analysis (EPMA).
- J/P.21** OPTICAL PROPERTIES AND DISTRIBUTIONS OF RARE EARTH (Er<sup>3+</sup> OR Nd<sup>3+</sup>) DOPING CONCENTRATION FOR CLAD/CORE FORMING LiNbO<sub>3</sub> FIBERS  
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 The fiber single crystals have already received attention as attractive materials for a variety of electro-optical application because of their extended interaction length and high optical intensity. The oxide single crystal fibers grown by micro-pulling-down method were shown high structural quality and minimal residual stresses. Accordingly, a reasonable way for the further development of highly efficient single crystal fibers is cladding as it is commonly done with optic glass fibers. Rare earth doped LiNbO<sub>3</sub> have received a renewed attention because of the availability of a broad range of laser sources as the pump sources because their emission wavelength 1.34 (Er<sup>3+</sup>) and 1.54 (Nd<sup>3+</sup>) μm are quite useful in the optical communications. In this study, the rare earth (Er<sup>3+</sup> or Nd<sup>3+</sup>) ions doped LiNbO<sub>3</sub> fibers were grown in the form of clad/core by the method of double-die-micro-pulling-down. The homogeneities of distributions of the Er<sup>3+</sup> or Nd<sup>3+</sup> ions concentrations were observed by electron probe micro-analysis and change of optical properties were investigated for addition of Er<sup>3+</sup> or Nd<sup>3+</sup> ions.

- J/P.22** OPTICAL PROPERTIES OF Er<sub>2</sub>O<sub>3</sub> DOPED NEAR STOICHIOMETRIC LiNbO<sub>3</sub> SINGLE CRYSTALS BY USING THE CZOCHRALSKI METHOD  
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 The Erbium-doped LiNbO<sub>3</sub> (Er-doped LiNbO<sub>3</sub>) single crystal is known as the material which can combine the laser characteristics of Er<sup>3+</sup> ion with the electro-optic characteristics of LiNbO<sub>3</sub>. But near stoichiometric LiNbO<sub>3</sub> it grows because the composition change gets, is difficult. The Er-doped near stoichiometric LiNbO<sub>3</sub> single crystal of 15 &#8211; 20mm in diameter and 25 &#8211; 30mm in length were growth by using the Czochralski(CZ). Er-doped LiNbO<sub>3</sub> crystal with a melt concentration ranging from 0.5 to 4.0 mol% have been growth the Er incorporation into the LiNbO<sub>3</sub> lattice. Moreover, it changed a powder quantity to crucible and it made a near decision in near stoichiometric composition. The optical transmittance of Er-doped LiNbO<sub>3</sub> crystal was measured and the energy levels of Er<sup>3+</sup> ion could be calculated. The photoluminescence spectra of Er-doped LiNbO<sub>3</sub> crystals with different doping levels were measurd.
- J/P.23** MAGNETO-OPTIC PROPERTIES OF EuxTbyBi<sub>3-x-y</sub>(FeAlGa)5O12 GARNET SINGLE CRYSTAL THICK FILMS  
G.Y. Kim, S.G. Yoon, Y.T. Kim, and D.H. Yoon, Sungkyunkwan University, Advanced Materials Engineering, ChunChun-dong, JangAn-gu 300, 440-746 Suwon, Korea  
 Using the PbO-Bi<sub>2</sub>O<sub>3</sub> flux system, (EuBi)<sub>3</sub>(FeAlGa)5O12 and (EuTbBi)<sub>3</sub>(FeAlGa)5O12 were grown on SGGG substrates for optical isolator and magnetic bubble memory devices by the liquid phase epitaxial (LPE). This research investigated about magneto-optic properties that appear the substitution amount in films and the change of the lattice constant in difference of doped Eu and Tb. Crystallization that can know difference of lattice constant of substrate and grown films by double crystal diffractometer (DCD). Surface morphology and cross-section were observed by scanning electron microscopy (SEM), and saturation magnetization, coercive force, remanent magnetization value were measured by vibrating sample magnetometer (VSM). The substitution level of Eu and Tb were observed by electron probe micro analysis (EPMA).
- J/P.24** EVALUATION OF THE ENERGY TRANSFER RATE BETWEEN ERBIUM IONS AND SILICON NANOCRYSTALS IN SILICON DIOXIDE  
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 The interaction of excitons in Silicon nanocrystals (nc-Si) and 4f shell electrons in Er ions has intensively been studied. In this work, we estimated the energy transfer rate between Er ions and nc-Si by measuring the time response of the luminescence intensity after pulsed photoexcitation. The samples were Silicon dioxide films containing nc-Si and Er prepared by a cosputtering method followed by thermal annealing. In order to control the average size of nc-Si, the concentration of nc-Si and the annealing temperature were changed in a wide range. We found that the energy transfer rate depended strongly on the annealing condition, while not depended on the nc-Si concentration. The higher the annealing temperature was, the smaller the energy transfer rate was. The energy transfer rate was in the range between 10<sup>4</sup> and 10<sup>6</sup> (1/s). These values were smaller than that estimated so far for similar systems, i.e., > 10<sup>6</sup>(1/s). Since the energy transfer rate of 10<sup>6</sup>(1/s) was several orders of magnitude larger than the excition radiative recombination probability of nc-Si, the energy transfer efficiency from nc-Si to Er ions has been considered to be nearly 100%. However, the present results strongly suggest that in some systems, the exciton radiative recombination process and the energy transfer process are in competition, and the energy transfer efficiency is not always 100%.
- J/P.25** OPTICAL AND MAGNETOOPTICAL STUDY OF CdTe CRYSTALS DOPED WITH RARE EARTH IONS  
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 In this work we report on growth and characterization of cadmium telluride crystals doped with Eu, Gd, Dy ions. The single crystals were grown by the Bridgman technique and the horizontally oriented crystallization method. Concentration of rare earth elements varied between 5 1018 and 1020 cm<sup>-3</sup>. Measurements of optical absorption, reflectance, photoluminescence and Faraday rotation were carried out at temperatures 4.2-300 K in magnetic fields up to 3.5 T. At low temperatures clear exciton structure and its concentration shift can be seen in the reflectance spectra. The observed giant Zeeman spin splitting of the exciton transitions and large Faraday rotation near the absorption edge in CdTe:Dy with NDy= 1020 cm<sup>-3</sup> are interpreted in framework of strong spin exchange interaction between f-electrons of Dy<sup>2+</sup> ions and s,p – band carriers [1]. In contrast, we have no experimental evidence for a such kind of exchange interactions in case of CdTe crystals doped with Eu and Gd.  
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 [1] A.I.Savchuk, V.M.Frasunyak, Ye.O.Kandyba, T.A.Savchuk, P.I.Nikitin, Phys.Stat.Sol. (b), 229. 787 (2002).
- J/P.26** EFFICIENT OPTICAL CONVERTOR OF VISIBLE TO INFRARED LIGHT AT 1.54 μm  
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 Erbium-doped films of a-SiOx:H with a thickness of 1 μm were grown by magnetron assisted silane decomposition deposited (MASD) method. Ob-tained films have efficient room temperature photoluminescence at 1.54 μm. We have found that an increase of oxygen content in the films leads to a significant enhancement of erbium luminescence intensity. We be-lieve that in contrast to Er-doped crystalline silicon in these films a differ-ent mechanism of Er ions excitation operates which determines higher efficiency of emission at 1.54 μm. The studies of this material by TEM have demonstrated that at sufficiently high concentrations of Er (10<sup>20</sup> cm<sup>-3</sup>) and O (10<sup>21</sup> cm<sup>-3</sup>) the system becomes heterogeneous and contains Er<sub>2</sub>O<sub>3</sub> clusters in different structural environment which corresponds either to amorphous silicon or silicon dioxide matrix. The formation of clusters enriched by oxygen is also confirmed by IR absorption spectra. A further support of this idea can be drawn from kinetic measurements of erbium PL. The enhancement of Er PL in oxygen-enriched samples can be ex-plaind by suppression of de-excitation processes, when the processes of excitation and recombination are separated in space. Optimization of ma-terial parameters resulted in an external quantum efficiency amounting up to 0.1% due both to an increase of concentration of optically active Er ions and suppression of temperature quenching of PL.

J/P.27

AUGER QUENCHING INVESTIGATED UNDER EXCITATION WITH SUB-BANDGAP ENERGY PHOTONS

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We have investigated the excitation of Er ions in an Er doped MBE grown Si superlattice by using a pump laser with photons of energy comparable to or lower than the bandgap of Si. Although for band-to-band excitation of these systems the intensity of photoluminescence from Er generally increases with increasing photon flux of the exciting laser, we found it to decrease for very high fluxes. This quenching is related to the (high) free-carrier concentration in the investigated sample. These carriers participate in an Auger process where the energy of the excited Er ion is transferred to the free carrier. This quenching mechanism poses a restriction to the maximum photoluminescence that can be obtained from these systems. Because the number and effective temperature of the carriers will depend on the photon energies used to excite the sample, the magnitude of the Auger quenching process will also depend on these parameters. Indeed, such dependence has been measured in the present study. Highly effective excitation was found for photon energies near the bandgap of the host, where the effects of Auger quenching are severely reduced. Moreover, the use of sub-bandgap excitation reveals new details on the Er excitation mechanism under optical pumping.

J/P.28

EMISSION CHANNELING EXPERIMENTS FROM THE DECAY OF  $^{149}\text{Gd}$  TO  $^{149}\text{Eu}$  IN GaN B. De Vries, A. Vantomme, Instituut voor Kern- en Stralingsfysica, K.U. Leuven, 3001 Leuven, Belgium, U. Wahl, Instituto Tecnológico e Nuclear, EN 10, 2685-953 Sacavém, Portugal, J.G. Correia and the ISOLDE Collaboration, CERN-PPE, 1211 Geneva 23, Switzerland

60 keV implantation of  $^{149}\text{Gd}$  into a GaN thin film was performed at room temperature up to a dose of  $2.0 \times 10^{13} \text{ cm}^{-2}$ . This radioactive isotope decays into short-lived excited states of  $^{149}\text{Eu}$ , accompanied by a nuclear recoil between 0.5 and 5 eV. The conversion electrons emitted in the subsequent decay to the  $^{149}\text{Eu}$  ground state were investigated with the emission channeling technique by means of a position sensitive detector. We measured the angular distributions of electrons around the [0001], [-1102], [-1101] and [-2113] axes in the as-implanted state and after 600°C and 900°C vacuum annealing. Comparing the 2-dimensional channeling patterns with theoretically calculated yields allowed the determination of the lattice location of the excited  $^{149}\text{Eu}$  atoms resulting from the  $^{149}\text{Gd}$  decay.

Already in the as-implanted state around 80% of  $^{149}\text{Eu}$  atoms were found on substitutional Ga sites (S-Ga). The remainder is located at random or low symmetry sites. The root mean square (rms) displacements from the S-Ga sites in the as-implanted state were found to be around 0.13-0.16 Å. Annealing at 600°C increased the substitutional fraction by a few percent and slightly reduced the rms displacements to around 0.10-0.13 Å, most likely due to the removal of crystal defects in the vicinity of the Eu atoms, resulting in a better incorporation into S-Ga sites. After the thermal treatment at 900°C the rms displacements remained around 0.10-0.14 Å and the substitutional fraction decreased only slightly. The lattice location results for  $^{149}\text{Gd} \rightarrow ^{149}\text{Eu}$  will be compared to our previous measurements using the isotopes  $^{143}\text{Pr}$  [1] and  $^{147}\text{Nd} \rightarrow ^{147}\text{Pm}$  [2]. [1] U. Wahl et al. J. Appl. Phys. 88 (2000) 1319.

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J/P.29

VARIOUS ERBIUM DOPED OXIDE MATRIX DEPOSITED BY AEROSOL CVD PROCESS

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The development of the optical telecommunication components requires the realisation of active optical materials especially as thin films. In contrary to the fibers applications, for integrated devices a high efficiency of the optical amplification is required. This is obtained with a high rare earth concentration. But the classical rare earth doped silicate glasses are strongly limited by the clustering effect. In order to avoid this phenomenon, crystalline host materials such as alumina or yttria have been proposed as amplifying media. This kind of material exhibit a low level of phonon losses. As a new deposition approach this paper reports the growth of erbium doped alumina, yttria and mixed thin films by an aerosol atmospheric CVD process. By using aluminium, yttrium and erbium acetylacetonates dissolved in butanol, erbium doped alumina and yttria thin films were deposited between 300°C and 600°C. The deposition rate reached 1  $\mu\text{m/h}$  around 500°C. The refractive index and the density of the films increased with the deposition temperature. At low deposition temperature an organic contamination was revealed by FTIR measurements. This contamination corresponded to the organic ligand of the organometallic precursor. As deposited the films did not exhibit luminescence properties due to the organic contamination. By annealing the films after deposition at 900°C, the luminescence was measured. The spectroscopic and crystallographic properties were discussed according to the deposition condition, the films compositions and the post annealing temperature. For alumina samples even after an annealing at 900°C the films did not exhibit diffraction peaks. Whereas for yttria samples the films were polycrystalline.

J/P.30

OPTICAL INVESTIGATION OF RARE-EARTH EUROPIUM DOPED  $\text{SiO}_2$ -BASED MATERIALS FOR PHOTONIC APPLICATIONS

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The optical properties of rare-earth ions doped amorphous matrix (amorphous  $\text{SiO}_2$ ) have been investigated extensively for application in flat panel display, fluorescent lamp, laser, waveguides and optoelectronic devices. In particular, europium compounds containing  $\text{Eu}^{3+}$  ions are known as intense luminescent materials in the visible region. The emission of europium ions, however, is very sensitive to the surrounding in which the ions are embedded. Co-doping of other impurities such as aluminum, silver, etc., in the host material enhances fluorescence from  $\text{Eu}^{3+}$  by changing environment surrounding the europium ions.

In this paper we report the characteristics of the bulk and thin film  $\text{SiO}_2$  materials, which were doped with  $\text{Al}^{3+}$  and different concentrations of  $\text{Eu}^{3+}$  ions ( $\text{SiO}_2:\text{Eu}^{3+}$  and  $\text{SiO}_2-\text{Al}_2\text{O}_3:\text{Eu}^{3+}$ ). The materials were prepared by a sol-gel method and annealed in the temperature range from 150 to 1100°C. Thin films of these materials were obtained by spin- and dip-coating procedures. Structural analyses, photoluminescence excitation spectra and photoluminescence emission spectra of the materials in the wavelength range of 350-720 nm were recorded and analyzed. Technological conditions such as pH,  $\text{H}_2\text{O}:\text{Si}$  ratio affect optical properties of the films. An enhancement of photoluminescence intensity of  $\text{Eu}^{3+}$  ion was obtained as a result of the presence of aluminum ions and stability of the sample is increased.  $\text{Eu}^{3+}$  ions tend to coordinate with Al-O bonds in the  $\text{SiO}_2-\text{Al}_2\text{O}_3$  material that is deduced from the investigating the ratio of  $^5\text{D}_0 \rightarrow ^7\text{F}_2$  to  $^5\text{D}_0 \rightarrow ^7\text{F}_1$  transition intensities. A reduction of the photoluminescence intensity at high annealing temperature is initially proposed. The results showed that co-doping  $\text{Al}^{3+}$  and  $\text{Eu}^{3+}$  ions in  $\text{SiO}_2$  reduces the concentration quenching of photoluminescence and makes the thin films more stable.

- J/P.31** NEAR INFRA-RED PHOTOLUMINESCENCE OF Nd<sup>3+</sup> IN HYDROGENATED AMORPHOUS SILICON SUB-NITRIDES (a-SiN<sub>x</sub>:H<Nd>)  
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Neodymium-doped hydrogenated amorphous silicon sub-nitrides a-SiN<sub>x</sub>:H<Nd> thin films were deposited by rf-sputtering using a Si target partially covered by metallic Nd chips and Ar + N<sub>2</sub> + H<sub>2</sub> sputtering gas. Characteristic Nd<sup>3+</sup> near infra-red photoluminescence (PL) was detected between 12 and 300K with peaks at ~935, ~1090 and ~1390 nm, corresponding to the transitions 4F<sub>3/2</sub> -> <sup>4</sup>I<sub>9/2</sub>, <sup>4</sup>F<sub>3/2</sub> -> <sup>4</sup>I<sub>11/2</sub> and <sup>4</sup>F<sub>3/2</sub> -> <sup>4</sup>I<sub>13/2</sub>, respectively. Measurements using different excitation wavelengths indicate that the a-SiN<sub>x</sub>:H matrix effectively transfers energy to the Nd<sup>3+</sup> ions. Varying the nitrogen content x from 0 to nearly 1.3 increases the matrix bandgap, enhances the PL intensity and reduces the temperature quenching, yielding samples with a rather low (a factor 5) PL intensity quenching between 12 and 300 K. Thermal annealing in dry N<sub>2</sub> flux at temperatures between (350 and 650 °C, depending the nitrogen concentration) can enhance the PL intensity by up to a factor 10. High concentrations of Nd<sup>3+</sup> (above ~3x10<sup>20</sup> at/cm<sup>3</sup>) reduces the PL intensity probably due to cross relaxation. Along with erbium doped amorphous silicon alloys, a-SiN<sub>x</sub>:H<Nd> can be used in the development of photonic devices in the future.
- J/P.32** A SIMPLE APPROACH FOR UPCONVERSION DETERMINATION USING LOW EXCITATION POWER: THE PHOTOLUMINESCENCE ANALYSIS OF AN ER-DOPED ALUMINOSILICATE GLASS  
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Materials other than silica can offer better performance in terms of Er solubility and band broadness for integrated Er-doped optical amplifiers and a deep knowledge of their optical properties is therefore fundamental. In this work a very simple approach is presented for evaluating the upconversion coefficient even using low pump power excitation, where the standard methods are not so accurate. This is based on the solution of an analytic model which allows the exact calculation of the 1540nm emission intensity (I<sub>13/2</sub> as well as of the 980nm emission intensity (I<sub>11/2</sub>) by considering three energy levels for Erbium.  
The proposed model has been applied to analyze the luminescence properties of an Er-doped aluminosilicate glass. Firstly, in the limit of neglecting the upconversion non linear contributions, some of the system parameters have been evaluated: the lifetime of the 1st excited state, the rate between radiative and non-radiative decay of the 2nd excited state, the absorption cross section at 488nm excitation wavelength. Then, the model has been calibrated by comparing the exact calculated relation between the two emission intensities with the corresponding experimental measurements. This procedure allowed for the determination of the coefficient of cooperative upconversion using pump powers in the range 4mW-32mW. A comparison of the obtained results with previous data reported in literature on similar samples is discussed.
- J/P.33** INFLUENCE OF THE IMPLANTATION ANGLE ON THE DEFECTS AND LUMINESCENCE IN Er IMPLANTED GaN  
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Implantation of different rare earth dopants in GaN has been used for a variety of optoelectronic applications. Ion implantation, however, generates a significant amount of defects in the GaN lattice, which influences the electrical and optical properties. Especially for the heavy rare earth ions, such as Er, this is a major disadvantage. However, performing the implantation along a major axis of the crystal, i.e. channeled implantation, results in a drastic decrease of defects in the substrate and as a consequence also in a significant improvement of the luminescence. Implantations were done at 170 keV and with a dose of 2.5·10<sup>14</sup> at/cm<sup>2</sup> for different implantation angles, ranging from 0° to 10° with respect to the GaN c-axis. Rutherford backscattering and channeling spectrometry (RBS/C) and high resolution X-ray diffraction (HRXRD) are used to investigate the damage accumulation and the lattice deformation after implantation respectively. A gradual increase in damage is observed due to the higher collision rate when tilting the implantation angle towards 10° (i.e. random implantation). The implantation-induced defects generate a lattice expansion along the c-axis and a lattice contraction along the a-axis. For high angles, gradual amorphization masks this effect.  
The samples are annealed at high temperatures under nitrogen atmosphere to reduce the implantation-induced damage in the GaN lattice. Luminescence measurements will be performed.
- J/P.34** LATTICE LOCATION OF 167mEr IN Si CO-IMPLANTED WITH F  
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It is well known that co-doping of Er-doped Si with O or F enhances the Er IR luminescence at 1.54 micrometer. The observation of complexes between Er and F atoms by means of EXAFS has been reported in the literature [1].  
In order to examine the influence of F on the lattice location of Er, four FZ-Si samples were implanted with 15 keV 19F<sup>+</sup> at doses of 1E14, 2.4E14, 6E14 and 1E15 cm<sup>-2</sup>. Subsequently, the radioactive probe atoms 167Tm (t<sub>1/2</sub>=9.25 d) were implanted at an energy of 60 keV and doses of 1.3E13 cm<sup>-2</sup>. Following the decay of 167Tm, the lattice location of 167mEr (2.28 s) was measured by means of conversion electron emission channeling in the as-implanted state and as a function of annealing temperature up to 900°C. We have previously reported that in FZ Si (i.e. Si with low O concentration) the majority of 167mEr (80-100%) is found close to tetrahedral interstitial sites [2]. On the other hand, in CZ Si (i.e. Si with high O concentration) the interaction of Er and O leads to a removal of Er from tetrahedral interstitial sites which is correlated with the O:Er ratio [2]. In the present experiment we observed a strong reduction of the fraction of 167mEr on tetrahedral interstitial sites which was correlated with the implanted dose of F and persisted for annealing temperatures up to 900°C. In direct comparison to the previous results we suggest that F co-doping has a similar effect to O co-doping on the lattice sites of Er in Si, namely removing it from tetrahedral interstitial sites and incorporating it in a variety of sites of low crystal symmetry.  
[1] A. Terrasi, F. Priolo, G. Franzò, S. Coffa, F. D' Acapito and S. Mobilio, J. Lumin. 80 (1999) 363.  
[2] U. Wahl et al, Phys. Rev. Lett. 79 (1997) 2069.

J/P.35

PHOTOLUMINESCENCE STUDY OF SiO<sub>2</sub> THIN FILMS DOPED WITH Si NANO-GRAINS AND ERBIUM

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Erbium doped silica glass is used in telecommunication as an optical amplifier. However, its optical cross sections for intra-4f transitions are quite small restricting its applications. Silicon nano-grains in SiO<sub>2</sub> thin films provide high absorption efficiency at pumping source above the fundamental gap and a strong energy transfer to Er<sup>3+</sup> ions. A fabrication method of this material is annealing of Er doped SiO<sub>x</sub> films. Here we present a photoluminescence study on these films under various growth and annealing conditions. SiO<sub>x</sub>(Er) films were co-evaporated from SiO and metal Er sources by electron beam gun under reactive oxygen atmosphere on Si substrates and then thermal annealed at 1000°C in vacuum or under flowing nitrogen for 1 hour to obtain Si nano-grains and active Er<sup>3+</sup> ions. Two photoluminescence bands with 488nm excitation were observed at around 1530nm and 800nm related to Er<sup>3+</sup> ions and Si nano-grains, respectively. The intensity of the 1530nm band showed a saturation when increasing the pump power. Additionally, this 1530nm band intensity was much more intense with excitation at 488nm than 980nm. The intensity of the 800nm band followed a power law dependence with pump power. The energy transfer between Si nano-grains and Er<sup>3+</sup> ions will be further investigated by photoluminescence excitation experiments and the most efficient excitation wavelength as function of x and annealing conditions will be presented.

J/P.36

THE MICROSTRUCTURE OF Er MBR DOPED GaN

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For a few years now, it has been possible to dope GaN layers using MBE growth. This aims to use the wide band gap semiconductors as hosts to the rare earth and exploit the sharp emission lines from atomic shell transitions. It was shown that the whole visible spectrum can be covered by changing the rare earth or exciting different levels. It is also suspected that like in some systems like Si(nano)/SiO<sub>2</sub>, the energy coupling could involve defects. In this work, we carry out TEM and HREM analysis on GaN layers grown on sapphire and doped in situ. Er concentrations of 1, 6, and 16 atomic % were subsequently measured by wavelength dispersive X-ray (WDX) in an electron probe microanalyser and found to be homogeneous. We discuss the results on the spatial distribution of the rare earth atoms at a nanometer scale and analyse their interaction with structural defects such as threading dislocations whose densities are in the range of 10<sup>10</sup> cm<sup>-2</sup> in these layers.

J/P.37

ELECTRON PROBE-MICRO ANALYSIS AND VISIBLE CATHODOLUMINESCENCE OF ERBIUM-DOPED GALLIUM NITRIDE GROWN BY MBE

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Combining the optical advantages of the wide band gap semiconductors with the sharp emission properties from intra-4f (n) atomic shell transitions, the rare earth (RE) doping of nitrides is promising for numerous technological applications. We describe studies of in situ Er-doped GaN samples grown by Molecular Beam Epitaxy (MBE) using an Electron Probe Micro Analyser (EPMA) modified to allow cathodoluminescence (CL) spectroscopy. Using wavelength dispersive X-ray analysis, mapping of the elemental composition is presented. The results confirm the advantage of the MBE technique in achieving good homogeneity in Er doping. We determine that the Er elements are located on Ga sites. By comparing the Er-concentration measured in a wide range of composition, from 0.5% up to 19%, with the Er/Ga flux ratio used for a given growth run, we determine the Er incorporation efficiency with a very good accuracy. Room temperature CL spectra acquired simultaneously at the same points complement the elemental composition analyses. We report CL spectra acquired using different beam voltages which reveal the presence of several visible sharp lines due to atomic transitions in the RE 4f levels.

J/P.38

Er<sup>3+</sup> EMISSION AND LOCAL STRUCTURE OF Er IN BULK GaN

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During the growth of bulk crystalline GaN doped with Er, pyramidal islands having diameters of several micrometers developed. Micro-Raman spectra taken from these structures show new rather sharp and intense Raman peaks in addition to the phonon dispersion of the GaN host at 172, 200, 321, 474 and 652 cm<sup>-1</sup>. In contrast, the Raman spectrum taken from the smooth region between these islands is dominated with the host phonon mode of GaN (E<sub>2</sub> high) at 567cm<sup>-1</sup>. The new additional Raman lines can be related to scattering from Er complexes. These Er complexes may contain defects or abundantly present impurities like oxygen or carbon and reside in the edges between the side facets of the pyramids. The photoluminescence spectra are dominated by a broad green-yellow emission from the host crystal, centered at 530nm. This emission band exhibits well-pronounced shoulders at 520, 476 and 455nm. All these bands and a rather sharp peak at 665nm we assign to the Er<sup>3+</sup> emission. A further strong and sharp peak is observed at 695 nm. This peak does not follow the behavior of the Er<sup>3+</sup> bands. Cathodoluminescence indicates that this peak stems also from defects built into the pyramids. We discuss, based on photoluminescence, cathodoluminescence, micro-Raman and transmission electron microscopy measurements, the local microstructure of the Er surroundings and mechanisms of their incorporation during crystal growth. In addition, we discuss the microstructure of the centres that cause the emission at 695nm.

J/P.39

PHOTOLUMINESCENCE INVESTIGATION OF EUROPIUM-DOPED XEROGEL FILMS IN POROUS SILICON AND POROUS ANODIC ALUMINA

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Europium is widely used as a dopant for fabrication of phosphors for red light emission. Red photoluminescence (PL) from Eu ions originates from D to F electron transitions resulting in sharp peak at 617 nm. Different methods are used for fabrication of the lanthanide-doped materials such as ion implantation, electrochemical deposition, sputtering in vacuum, sol-gel synthesis, etc. In this work, we investigate europium-doped sol-gel derived films fabricated onto porous silicon and porous anodic alumina (PAA) of pore diameter of 100 nm. Also thin sol-gel films deposited on quartz substrates have been investigated for the comparison. Three different xerogel matrices (Eu<sub>2</sub>O<sub>3</sub>/Al<sub>2</sub>O<sub>3</sub>, Eu<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub>, Eu<sub>2</sub>O<sub>3</sub>/In<sub>2</sub>O<sub>3</sub>) have been fabricated and compared. Strong enhancement of europium luminescence has been observed for all of the sol-gel films fabricated in PAA. The magnitude of europium emission from xerogel/PAA structure is about 100 times greater than for the xerogels fabricated on quartz substrate. Such increase in Eu PL has not been observed for xerogel/porous silicon structure. Influence of the architecture of the pores of porous silicon and PAA on micro-resonator effect and anisotropy of luminescence is discussed.

J/P.40

PECULIARITIES OF ERBIUM EXCITATION IN SUBLIMATION MBE Si:Er STRUCTURES

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Er-doped silicon attracts considerable interest as a promising material for effective light emitting at the wavelength 1.54 μm. Application of the original method of sublimation MBE (SMBE) allows to produce Si:Er and SiGe:Er layers with high crystalline quality and intense PL.

We have analyzed contribution of the different Er centers to the PL in SMBE Si:Er structures. It has been shown that either isolated Er-related centers or Er ions in SiO<sub>2</sub>-like precipitates dominate in PL at low temperatures depending on the growth and annealing conditions. Er centers in precipitates dominate at higher temperatures. Therefore peculiarities of Er excitation in precipitates are of particular interest. Excitation spectra of Er PL for the Si:Er/Si structures with precipitates have been measured. Strong decrease of Er PL intensity at the excitation energies lower than the Si band gap has been observed. No features at the energy of the transition from the ground to the second excited state of Er ion have been revealed. Thus, we have demonstrated for Er ions in SiO<sub>2</sub>-like precipitates low efficiency of direct optical excitation in comparison with excitation through the carriers in Si matrix. Along with explainable decrease of erbium PL intensity at sub-band-gap excitation energies we observed unexpected intensive broad peak in the excitation spectra near the wavelength of the band-to-band transition in silicon. The possible reasons for this peak will be discussed. The work was supported by NWO 047-009-013, INTAS 01-0194 and RFBR 02-02-16773 grants.

J/P.41

INFLUENCE OF POROUS ANODIC ALUMINA MATRIX UPON EUROPIUM LUMINESCENCE FROM SOL-GEL-DERIVED FILMS

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Deposition of lanthanide-doped sol-gel-derived films into periodically arranged pores of anodic alumina gives significant rise in photoluminescence (PL) intensity in comparison to the same films processed onto flat surfaces [1]. PL from such structures is stronger than that of obtained via more costly processes such as ion implantation [2]. There was revealed recently that embedment of Eu or Tb-doped In<sub>2</sub>O<sub>3</sub> and SnO<sub>2</sub> xerogels into porous anodic alumina (PAA) may produce strong emission when electrical current is applied.

In this work, the effect of the annealing and registration temperatures upon PL behavior from Eu-doped In<sub>2</sub>O<sub>3</sub> and SnO<sub>2</sub> xerogels fabricated on PAA has been analyzed. It is revealed that increase of annealing temperature from 200 to 500 °C leads to decrease of intensity of predominant spectral band at 611 nm, whereas further temperature increase up to 900 °C increases the PL intensity over the value obtained at initial annealing temperature. In the case of flat substrates, such dependence is of steadily decreasing character. High temperature processing changes PL behavior with the registration temperatures. Low temperature PL measurements have shown that tin oxide-based xerogels fabricated on PAA and annealed at 900 °C demonstrate stronger PL at room temperature than that of at 10 K.

[1] N.V. Gaponenko, V. M. Parkun, O. S. Katernoga, et al, Thin Solid Films 297 (1997) 202

[2] J. C. Pivin, N. V. Gaponenko, I. S. Molchan, et al, J. Alloys Comp. 341 (2002) 272

J/P.42

LUMINESCENCE OF Er IONS IN Si UNDER ELECTRON BEAM EXCITATION

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Er in Si produces a big variety of different centers that can be distinguished by their characteristic line patterns in photo- and electroluminescence spectra. They can be separated in two categories: i) isolated Er centers with the well-defined geometry of their constituents that exhibit extremely sharp line spectra and high quantum efficiency under both electrical (forward bias regime) and optical excitation at low temperatures, and ii) so-called Er centers in amorphous SiO<sub>x</sub>-like precipitates that are characterized by their inhomogeneously broadened (of about 10..20 nm wide) emission spectra similar to those observed for Er in silica and SiO<sub>2</sub> matrixes. These last centers are of particular interest being held to be responsible for the room temperature electroluminescence achieved in Si:Er light-emitting diodes under reverse bias [1].

In this contribution we present results of cathodoluminescence (CL) studies performed in Si:Er samples prepared on that way to obtain the structures with the distinct type of Er centers - isolated Er or SiO<sub>x</sub>:Er precipitate-type centers. Spatially and spectrally resolved CL analysis in near IR range have been carried out in scanning electron microscope under electron beam excitation with the energies of 0.5÷30 keV. The results obtained are discussed in terms of different excitation efficiencies for impact and electron-hole-mediated processes governing the luminescence for these two types of Er centers in silicon. [1] W. Jantsch, G. Kocher et al., Mat. Science & Engineering B 81, Iss. 1-3, p.86, (2001).

**J/P.43**

**ELABORATION, STRUCTURAL AND SPECTROSCOPIC PROPERTIES OF RARE EARTH DOPED YTTRIUM-HAFNIUM SOL-GEL OXIDE POWDERS FOR SCINTILLATION APPLICATIONS**

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Hafnium dioxide presents a high crystalline density (&#61627;10 in the tetragonal form) which makes it attractive for host lattice activated by rare earths (RE) for applications as scintillating materials. Nevertheless, efficient dopant that makes it work like good scintillator must be determined. The powders are elaborated using sol-gel process because it is an excellent option to prepare high purity materials by drying the solution. The precursor used is hafnium tetra-ethoxide ( $\text{Hf}(\text{OC}_2\text{H}_5)_4$ ) powder dissolved in ethanol and acetylacetonate is added as chelating agent.  $\text{Y}(\text{NO}_3)_3$  is added in various concentrations to stabilize the  $\text{HfO}_2$  tetragonal phase and promote the formation of  $\text{RE}^{3+}$ . The solution is prepared under argon controlled atmosphere and is doped after the hydrolysis with different RE nitrate. Differential thermal analysis (DTA) and Fourier transform infrared (FTIR) spectroscopy are carried out on the sol-gel powders and the structure of the powders is determined using X-ray diffraction and microRaman spectroscopy. First results of scintillation properties of these powders with RE concentration 1% mol are finally presented.

**J/P.44**

**MICROSTRUCTURAL AND ELECTRICAL CHARACTERISATION OF Er IMPLANTED GaN**

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Rare-earth doping of GaN by Er in semiconductors is now receiving much attention due to potential applications for electroluminescence mostly in the telecommunication 1.5  $\mu\text{m}$  range of wavelength. For a few years now, it has been possible to dope GaN layers using MBE growth. This aims to use the wide band gap semiconductors as hosts to the rare earth and exploit the sharp emission lines from atomic shell transitions. It was shown that the whole visible spectrum can be covered by changing the rare earth or exciting different levels. Ion implantation will allow to control the spatial distribution of the Er, and for example give rise to the possibility of having more than one rare earth in a small area and possible white light emission by color mixing. This implantation leads to the formation of damages which need to be annealed. In this work, we use a combination of transmission electron microscopy and deep levels transient spectroscopy along with by high-resolution x-ray diffraction and Rutherford backscattering spectroscopy (RBS) measurements for assessment of the defects which are active in GaN layers subsequent to erbium ion implantation and annealing. Various implantation and annealing conditions are investigated, our aim is to determine the best procedure for optimal devices fabrication.

Wednesday, June 11, 2003  
Mercredi 11 juin 2003

Afternoon  
Après-midi

Session V: Rare earth doped GaN II  
Session chair: Y. Fujiwara

- J-V.1** 14:00 -Invited- PHOTOLUMINESCENCE STUDIES OF RARE-EARTH (Er, Eu, Tm) DOPED GaN  
**U. Hömmerich** and Ei Ei Nyein, Hampton University, Department of Physics, Hampton VA 23668, USA, D.S. Lee, J. Heikenfeld, A.J. Steckl, Nanoelectronics Laboratory, Univ. of Cincinnati, Cincinnati OH 45221, USA, J.M. Zavada, U.S. Army Research Office, Research Triangle Park NC 27709, USA  
The emission properties of rare earth (RE) doped GaN are of current interest for applications in full color displays, white lighting technology, and optical communications. Thin-film electroluminescence (EL) devices operating at the primary colors (red, green, blue) as well as at the optical communication wavelength 1.5 mm have been demonstrated.  
We are currently investigating the photoluminescence (PL) properties of RE (Er, Eu, Tm) doped GaN thin-films prepared by solid-source molecular beam epitaxy. The most intense visible PL under above-gap excitation is observed from GaN: Eu (red: 621 nm) followed by GaN: Er (green: 537 nm, 558 nm), and then GaN: Tm (blue: 447 nm). The blue PL from Tm doped GaN is quite weak at room-temperature and is strongly overlapped by defect related emission from the GaN host. Depending on the excitation wavelength, different emission properties were observed for GaN: RE suggesting the existence of multiple RE sites in GaN with distinct excitation and de-excitation mechanisms. More details of the PL properties of Er, Eu, and Tm doped GaN including temperature and concentration quenching studies, PL decay time studies, as well as high-resolution PL excitation measurements will be presented at the conference.
- J-V.2** 14:30 ELECTRON MICROPROBE ANALYSIS AND VISIBLE LUMINESCENCE OF ERBIUM-IMPLANTED GALLIUM NITRIDE  
**S. Dalmasso**, R.W. Martin and K.P. O'Donnell, Department of Physics, University of Strathclyde, Glasgow G4 0NG, U.K., B. Pipeleers, B. de Vries and A. Vantomme, Katholieke Universiteit Leuven, 3001 Leuven, Belgium and the RENiBEL network  
Rare earth doped GaN structures offer potential for optical devices emitting in the visible region[1,2]. In the frame of the RENiBEL (Rare Earth doped Nitrides for high Brightness Electroluminescent devices) European research training network, we report measurements obtained on Er-implanted GaN. MOVPE-grown samples were implanted under different conditions and annealed for 30 minutes at 950°C under N<sub>2</sub> atmosphere. We describe results obtained by photoluminescence spectroscopy along with cathodoluminescence (CL) experiments and wavelength dispersive X-ray analysis (WDX) measured in an electron probe micro-analyser. WDX, a powerful technique for composition measurement, allows the quantification of the Er-concentrations in GaN down to 0.06 atomic % in layers approximately 60 nm thick; furthermore, by varying the incident electron beam voltage, the Er depth profile was determined. CL measurements performed at room temperature reveal the sharp visible emission properties due to Er<sup>3+</sup> intra-4f(n) atomic shell transitions.  
[1] A.J. Steckl, J. Heikenfeld, D.S. Lee and M.J. Garter, Mater. Sci. Eng., B 81, 97 (2001).  
[2] E. Alves, K. Lorenz, R. Vianden, C. Boemare, M.J. Soares, T. Monteiro, Mod. Phys. Lett. B, 15, 1281 (2001).

J-V.3 14:45

#### SITE-SELECTIVE EXCITATION SPECTROSCOPY OF Er DOPPED GaN

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Wide gap semiconductors (WGS) doped with rare earth (RE) ions are extensively studied since they appear as good candidates for optoelectronic and photonic applications. Among the wider-bandgap semiconductors, III-Nitride alloys are particularly attractive due to their chemical and thermal stability. Full color electroluminescent devices have already been realized with GaN doped with  $\text{Eu}^{3+}$ ,  $\text{Er}^{3+}$  and  $\text{Tm}^{3+}$  ions. Many studies of the spectroscopic properties of different RE ions in GaN thin films are in progress but up to now, a clear correlation between the efficiency of the visible  $\text{RE}^{3+}$  luminescence and the interaction of the RE ion with the semiconductor host has not been established. In particular, to improve the efficiency of the current devices, the RE excitation and de-activation pathways have to be determined. Here we will report the results on the spectroscopic analysis of  $\text{Er}^{3+}$  ions in GaN thin films. Using site-selective excitation spectroscopy, three kinds of sites have been identified for the  $\text{Er}^{3+}$  ions. The main center is assigned to  $\text{Er}^{3+}$  ions substituted on the Ga sub-lattice which, from Rutherford Back Scattering channeling analysis, correspond to the majority of  $\text{Er}^{3+}$  ions introduced in the lattice. The two other sites are ascribed to  $\text{Er}^{3+}$  complexes in interstitial positions and assigned to Er-related defects. The strong quenching of the  $^4\text{S}_{3/2}$  lifetime measured for the main center with increasing Er concentration and its complex decay profile indicate that the optical relaxation involves energy transfer processes between adjacent  $\text{Er}^{3+}$  ions. The fluorescent transients are modeled and interpreted using a diffusion-limited migration of the optical interaction. All the microscopic parameters of the characterizing the interaction were determined and compared to the experimental data. The strong interaction between  $\text{Er}^{3+}$  ions in the main center provides an efficient population pathway for the infrared emitting level. The concentration dependence of the  $^4\text{I}_{13/2}$  multiplet is also explained in a limited-diffusion process, the nature of the quenching centers will be discussed. From the energy of the different multiplets deduced from fluorescence analysis, the crystal field strength of GaN is calculated and compared to that obtained in other inorganic materials. Comparing the  $N_c$  calculated value for GaN with that obtained for other inorganic materials, the crystal field strength was found much weaker in GaN than in oxides. This result should indicate that the rare earth is well embedded in the semiconductor host and not in a parasitic oxide phase. On the other hand, this hypothesis is supported by the covalent character of the bonding of  $\text{Er}^{3+}$  to nitrogen in the main center.

This work has been partially supported by the US Army (Contract number N62558-02-M-5113).

J-V.4 15:00

#### SYNTHESIS AND OPTICAL CHARACTERIZATION OF ERBIUM -DOPED AlGaIn QUANTUM WELLS

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We report on the first successful synthesis and characterization of AlGaIn/GaN:Er/AlGaIn quantum well (QW) structures grown through a combination of metalorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) on c-plane sapphire substrates. The AlGaIn barrier layers, with an Al concentration of ~ 12%, were prepared by MOCVD and the Er-doped GaN layers by MBE. Several different QW structures were synthesized with the well thickness (LW) ranging from 7 nm to 200 nm. The Er concentration was estimated to be ~  $10^{18} \text{ cm}^{-3}$ . The thin films had good morphology, though some cracking was evident in the QW structures having LW ~ 7 nm. The GaN:Er/AlGaIn films and the QW structures were studied using both above-gap excitation (~290, 326 nm) and below-gap excitation (~490, 800 nm) photoluminescence (PL) spectroscopy. Distinct emission lines characteristic of the GaN:Er system (green: 537 nm, 558 nm, infrared: 1530 nm) were observed in all samples, even for those with the narrowest wells. The PL intensity from the thicker GaN:Er films was 2-4 times higher than that from the thinner GaN:Er films. Moreover, with ~336 nm the infrared PL from the QW structures showed a marked improvement compared to the uncapped films. The PL intensity increased and the spectra showed less defect related emission. The enhanced PL properties may be due to more effective confinement of electron-hole pairs in the QW region. These structures exhibited a variety of interesting optical properties that have important implications for optical amplification and light emitting devices.

**J-V.5** 15:15 -Invited- COMPOSITION AND LUMINESCENCE OF EUROPIUM-IMPLANTED GALLIUM NITRIDE LIGHT EMITTERS  
**R.W. Martin**, S. Dalmaso, K.P. O'Donnell, Department of Physics, Strathclyde University, Glasgow G4 0NG, U.K., B. Pipeleers, A. Vantomme, Katholieke Universiteit Leuven, 3001 Leuven, Belgium, Y. Nakanishi, A. Wakahara, A. Yoshida, Toyohashi University of Technology, Tenpaku, Toyohashi 441-8580, Japan & the RENiBEI Network  
We report on the first successful synthesis and characterization of AlGa<sub>0.15</sub>N/GaN:Er/AlGa<sub>0.15</sub>N quantum well (QW) structures grown through a combination of metalorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) on c-plane sapphire substrates. The AlGa<sub>0.15</sub>N barrier layers, with an Al concentration of ~ 12%, were prepared by MOCVD and the Er-doped GaN layers by MBE. Several different QW structures were synthesized with the well thickness (LW) ranging from 7 nm to 200 nm. The Er concentration was estimated to be ~ 10<sup>18</sup> cm<sup>-3</sup>. The thin films had good morphology, though some cracking was evident in the QW structures having LW ~7 nm. The GaN:Er/AlGa<sub>0.15</sub>N films and the QW structures were studied using both above-gap excitation (&#61548;ex~290, 326 nm) and below-gap excitation (&#61548;ex~490, 800 nm) photoluminescence (PL) spectroscopy. Distinct emission lines characteristic of the GaN:Er system (green: 537 nm, 558 nm, infrared: 1530 nm) were observed in all samples, even for those with the narrowest wells. The PL intensity from the thicker GaN:Er films was 2-4 times higher than that from the thinner GaN:Er films. Moreover, with &#61548;ex~ 336 nm the infrared PL from the QW structures showed a marked improvement compared to the uncapped films. The PL intensity increased and the spectra showed less defect related emission. The enhanced PL properties may be due to more effective confinement of electron-hole pairs in the QW region. These structures exhibited a variety of interesting optical properties that have important implications for optical amplification and light emitting devices.

15:45 **BREAK**

## Session VI: Rare earth doping in 'conventional' semiconductors

Session chair: A. Steckl

**J-VI.1** 16:15 -Invited- EXCITATION PATHS IN RE-DOPED III-V SEMICONDUCTORS  
M.A.J. Klik, **T. Gregorkiewicz**, Van der Waals-Zeeman Institute, University of Amsterdam, The Netherlands, J. Phillips, FOM "Rijnhuizen", Nieuwegein, The Netherlands  
Doping with RE ions offers a convenient possibility to tailor optical properties of semiconductors. In that way sharp atomic-like emission bands can be activated by optical or electrical excitation of the host. Such an indirect excitation mechanism implies that an energy transfer takes place between the semiconductor and the 4f-electron core of a RE ion. The energy transfer, whose efficiency determines emission intensity of the optical dopant, is a complex process and usually involves one or more intermediate stages. These increase probability of the energy flow from the host to RE ions, but on the other hand, enable also the reversal of this process, once the core excitation has been accomplished. Specific levels involved in the transfer processes can be induced by the optical dopant itself, but also shallow states generally appearing in semiconductors (excitons, EMT shallow donors and acceptors) play an active role in excitation and de-excitation processes of RE ions.  
Levels in the bandgap of a semiconductor can be addressed optically with photons of the appropriate energy. Therefore two-color spectroscopy in the visible and the mid-infrared (MIR) offers a spectroscopic approach to investigate energy transfers in an optically doped semiconductor. In the contribution, taking InP:Yb as a model system, I will show how this experimental technique (with a free-electron laser as a high-brilliance source of the MIR radiation) can be used track the energy flow paths.

**J-VI.2** 16:45 ELECTRICAL AND STRUCTURAL CHARACTERIZATION OF DEFECTS INTRODUCED IN p-SiGe DURING LOW ENERGY ERBIUM IMPLANTATION  
**M. Mamor**, B. Pipeleers, A. Vantomme, Instituut voor Kern-en Stralingsfysica, KULeuven, 3001 Leuven, Belgium and F.D. Auret, Physics Department, University of Pretoria, Pretoria 0002, South Africa  
Recently rare-earth erbium (Er) in semiconductors has received much attention due to its potential applications in optoelectronic. This combination of erbium as dopant atoms incorporated into semiconductors provides a system, which exhibits a temperature stable luminescence wavelength at about 1.54  $\mu\text{m}$ , which is nearly independent of the specific semiconductor host. This specific wavelength is thus of great interest for optical communication technology. It has been reported that the band gap energy of the host semiconductor is an important parameter to change the energy transfer efficiency. In a SiGe-based host, we can change the band-gap energy with Ge content and thus change the energy transfer. The SiGe materials can also be integrated with the Si technology. We have used electrical measurements (DLTS) complemented by high-resolution x-ray diffraction and Rutherford backscattering spectroscopy (RBS) measurements for assessment of the defects introduced in p-Si<sub>1-x</sub>Ge<sub>x</sub> during 180 keV erbium ion implantation. From Deep-level transient spectroscopy (DLTS) two prominent defects with discrete energy levels above the valence band, were introduced during Er ion implantation. These defects have a concentration, which decreases sharply from the metal-semiconductor surface and their activation energies decreases with increasing Ge content suggesting that these defects are pinned to the conduction band. These defects are also compared to those introduced during alpha particle irradiation.

- J-VI.3** 17:00 STRUCTURAL, ACTIVE AND PASSIVE OPTICAL PROPERTIES OF RE DOPED BaTiO<sub>3</sub> THIN FILMS GROWN BY PULSED LASER DEPOSITION  
O. Pons-Y-Moll, R.M. Defourneau, D. Defourneau, GPS, Univ. Paris VII, Tour 23, 2 pl. Jussieu, 75251 Paris, France, W. Seiler, L3M, ENSAM, 151 bd de l'Hôpital, 75013 Paris, France, B. Vincent, A. Boudrioua, LMOPS, Université de Metz / Supélec, 57078 Metz Cedex 3 France  
Barium titanate exhibits interesting properties for planar optical applications such as a high refractive index (around 2.4), has a wide range of transparency and a crystalline network accepting high RE concentrations (up to 20 % in the case of Erbium). Since pulsed laser deposition (PLD) is an efficient growth method for dense, crystallized films with a complex chemical composition, we chose this path to deposit Er doped and Er-Yb codoped BaTiO<sub>3</sub> waveguides on silica substrates. Dense and smooth films with a high refractive index difference from the substrate are expected, allowing good waveguiding properties and light confinement. Moreover, the Er ions in a crystalline environment emit strongly in the Infra Red range with a large lifetime. Thus, these films could be used in planar optical applications, such as optical amplifiers operating at 1.5 μm. Thin films are deposited under various temperatures and pressures, in order to investigate the influence of these growth parameters on the material properties. The chemical, structural and surface properties of these films are studied by Rutherford Backscattering Spectroscopy, X-Ray Diffraction and Atomic Force Microscopy, respectively. Passive optical properties are evaluated by m-lines spectroscopy and CCD-based losses measurements. The 1.5 μm Er emission spectra and the associated lifetime are recorded by photoluminescence. Optimum conditions for the growth of dense, smooth films with low losses and an intense and broad Er emission are presented. Correlation between the deposition parameters, the structural and optical properties is discussed, as well as the potential use of such films as planar optical amplifiers in the 1.5 μm range.
- J-VI.4** 17:15 -Invited- HIGH RESOLUTION SPECTROSCOPY OF Er<sup>3+</sup> IONS IN 6H SiC  
**A. Kozanecki**, Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warsaw, Poland  
Among large gap semiconductors 6H SiC is among those materials that may offer quite unique opportunities for optoelectronic, especially in multifunctional devices operating at elevated temperatures. It is thus natural to explore optical properties of RE centers introduced to this material. Essential for a possible application is the knowledge of all recombination channels (radiative and nonradiative) involving RE centers. Among them Erbium is a well-known probe of recombination paths and emitter. Quite interesting option arises in SiC because of the optical activation of Er by nitrogen and oxygen that may form optically active centers with Er. Experience from other hosts doped with Er suggests the need of exact identification of the energy structure of all centers involved. Therefore we used the high resolution Fourier-transform luminescence and excitation spectroscopy to determine electronic level structure of optically active Er<sup>3+</sup> centers. Evidence is presented that N-donors act as luminescence sensitizers at low temperatures, however, the Er emission at room temperature does not seem to be affected significantly by the presence of N-donors. The role of oxygen co-doping seems to be a minor one for the PL efficiency.

Thursday, June 12, 2003  
Jeudi 12 juin 2003

Morning  
Matin

Session VII: Rare earth doping in silicon  
Session chair: K.P. O'Donnell

**J-VII.1** 9:00 -Invited-

HIGH EFFICIENCY LIGHT EMISSION DEVICES IN SILICON

**Maria Eloisa Castagna**(a), Salvatore Coffa(a), Liliana Caristia(a), Simona Lorenti(a), Alberto Messina(a) and Corrado Bongiorno(b), (a)STMICROELECTRONICS, CORPORATE TECHNOLOGY R&D, 95121 CATANIA, ITALY, (b)CNR-IMM, CATANIA, ITALY

We report on the fabrication and performances of the most efficient Si-based light sources. The devices consist of MOS structures with erbium (Er) implanted in the thin gate oxide. The devices exhibit strong 1540 nm electroluminescence at 300K with a 10% external quantum efficiency, comparable to that of standard light emitting diodes using III-V semiconductors. Emission at different wavelengths has been achieved incorporating different rare earths (Ce, Tb, Yb, Pr) in the gate dielectric. The external quantum efficiency depends on the rare earth ions incorporated and ranges from 10% (for an Tb doped MOS) to 0.1% (for an Yb doped MOS). Re-excitation is caused by hot electrons impact and oxide wearout limits the reliability of the devices. Much more stable light emitting MOS devices have been fabricated using Er-doped SiO<sub>2</sub> (silicon rich oxide) films as gate dielectric. These devices show a high stability, with an external quantum efficiency reduced to 0.1%. In these devices Er pumping occurs by energy transfer from the Si nanostructures to the rare earth ions. Si/SiO<sub>2</sub> Fabry-Pérot microcavities have been fabricated to enhance the external quantum emission along the cavity axis and the spectral purity of emission from the films that are used as active media to realize a Si-based LED. These structures are realized by chemical vapour deposition on a silicon substrate. The microcavities are tuned at different wavelengths: 540nm, 980nm and 1540nm (characteristic emission wavelength respectively for Tb, Yb and Er). The reflectivity of the microcavities is of 97% and the factor quality ranges from 50 (for the cavity tuned at 540nm) to 95 (for the cavities tuned at 980nm and 1540nm).

**J-VII.2** 9:30

A STUDY ON STIMULATED EMISSION FROM ERBIUM IN SILICON

**M.O. Huda** and S.I. Ali, Dept. of EEE, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh

Stimulated emission from erbium in silicon due to the intra 4f shell transition has been analyzed for its prospective application in laser operation. Shockley-Read-Hall (SRH) recombination kinetics was used to explain the mechanism of erbium excitation. A certain fraction of electron-hole recombination at erbium sites was found to have useful contribution in exciting erbium atoms to the higher energy state. Equating the spontaneous emission rate with the stimulated generation and absorption of photons, an expression for erbium atoms in the excited state has been developed. Our expression shows that, achievement of 100% population inversion of erbium atoms is not possible due to the presence of non-radiative decay processes. Impurity Auger processes involving bound and free carriers were found to have limiting effects in higher doping and stronger excitation levels. For a cavity length of 300 μm with mirror reflectivities of 90%, and an optimistic absorption coefficient of 5/cm, a population inversion of 10<sup>18</sup>/cm<sup>3</sup> was estimated as the laser threshold. Achievement of the laser threshold condition was found to be possible only in cases of low temperature operation with minimized effects from Auger process involving free carriers. For a typical Auger coefficient of the order of 10<sup>-14</sup>cm<sup>3</sup>/s, and erbium concentrations over 10<sup>18</sup>/cm<sup>3</sup>, linear increase of laser output with threshold value of the order of tens of A/cm<sup>2</sup> has been calculated.

**J-VII.3** 9:45

SPECTROSCOPIC CHARACTERIZATION OF Er-1 CENTER IN SELECTIVELY DOPED SILICON

**N.Q. Vinh**, M.A.J. KLIK, T. Gregorkiewicz, Van der Waals-Zeeman Institute, University of Amsterdam, The Netherlands, B.A. Andreev, Institute for Physics of Microstructures, Nizhny Novgorod, Russia

Emission from the Er-1 center dominates photoluminescence (PL) spectrum of selectively Er doped Si/Si:Er multilayer structures grown by the MBE sublimation method. Recently, the symmetry of this optically active Er related center has been investigated in a magneto-optical experiment and established to be orthorhombic I [1]. This first-ever successful observation of the Zeeman effect in Si:Er conclusively proved that preferential formation of a single type of an Er-related optically active center in crystalline Si has been achieved. This represents a major step forward when compared to materials prepared by ion implantation, where multiple Er<sup>3+</sup> centers are simultaneously generated. The possibility of preferential formation makes the Er-1 center a possible candidate for application in future photonic devices based on Si:Er, and provides motivation for further investigation of its properties. In the current study we apply high-resolution time-resolved PL spectroscopy at low temperature. We find that the linewidth of the Er-1 spectrum at LHe temperature is below 10 μeV, i.e., a factor 10<sup>3</sup> smaller than commonly observed in Si:Er. Such an extremely small value has important consequences for theoretical estimates on the possibility of optical amplification in Si:Er. The decay time of PL signal from the Er-1 is measured to be considerably shorter than the ~ 1 ns value usual for Si:Er, and is characterized by two components of ~ 30 and ~ few hundred ps (of comparable amplitudes). In the study we investigate excitation power and temperature dependence of the decay time in order to decide on the origin of its shortening. [1] N.Q. Vinh et al, to appear in Phys. Rev. Lett. (2003).

- J-VII.4** 10:00 PHOTOLUMINESCENCE AND EXCITATION OF ERBIUM INCORPORATED IN OXIDIZED POROUS SILICON  
 V. Bondarenko(a), M. Balucani(b), N. Kazuchits(c) and A. Ferrari(b), (a)Belarussian State University of Informatics & Radioelectronics, 220027 Minsk, Belarus, (b)Unit of Research E6 INFM, Rome University "La Sapienza", 18-00184 Rome, Italy, (c)Belarussian State University, 220050 Minsk, Belarus  
 A significant amount of work has been recently devoted to the study of REE-doped silica glass which may be used as an amplification medium. Oxidized porous silicon (OPS) is a new form of silica-like material capable of being simply doped with REE and different ligands due to the open porosity of initial porous silicon (PS) matrix. Si nanoclusters and clusters of foreign materials may be formed within OPS if regimes of PS oxidation and annealing are carefully developed.  
 In the present work, photoluminescence (PL) and photoluminescence excitation (PLE) spectroscopy was carried out to study Er characteristic emission at 1.53  $\mu\text{m}$  from different OPS samples doped with Er by electrochemical deposition followed by high temperature oxidation. Three types of OPS were investigated: fully oxidized PS with Er incorporated into the silica phase of OPS; partially oxidized PS doped with Er and Si nanoclusters; and partially oxidized PS containing iron oxide nanoclusters with Er incorporated into the clusters. We show that in all these samples Er is incorporated in optically active sites however demonstrates various excitation and luminescence spectra. We identify the Er centers in different OPS and review recent work on the excitation and luminescence mechanisms of Er. Topical problems of application of OPS doped with Er are discussed.
- J-VII.5** 10:15 TEMPERATURE INDEPENDENT  $\text{Er}^{3+}$  PHOTOLUMINESCENCE LIFETIME IN a-Si:H<Er> AND a-SiO<sub>x</sub>:H<Er>  
Leandro R. Tessler and Daniel Biggemann, Instituto de Física "Gleb Wataghin", UNICAMP, C.P. 6165, 13083-970 Campinas, SP, Brazil  
 The photoluminescence (PL) lifetime of  $\text{Er}^{3+}$  in a-Si:H<Er> and a-SiO<sub>x</sub>:H<Er> was measured between 15 and 300K in a set of samples containing ~1 at. % Er and up to ~10 at. % O. The samples were prepared by RF co-sputtering from a Si target partially covered by metallic Er platelets. Photoluminescence spectra were obtained by exciting with the 514nm line of an Ar<sup>+</sup> laser. In general, the room temperature PL intensity increased and the temperature quenching decreased with O content. The maximum PL intensity at 15K, however, is obtained from samples with no intentional oxygen added.  
 The PL lifetimes were obtained using either the Quadrature Frequency Resolved Spectroscopy (QFRS) technique (with a two-channel digital lock-in amplifier) or by directly observing the PL decay in a digital oscilloscope. The excitation beam was modulated by a mechanical chopper (20Hz to 20kHz) and the PL was dispersed by a monochromator and detected by a fast InGaAs receiver. The QFRS signal was well fitted supposing two lifetimes, the fast decay in the 20 – 150 $\mu\text{s}$  range and the slow decay in the 200 – 850 $\mu\text{s}$  range, consistently increasing with the O content of the samples. To our surprise, for all the samples both the fast and the slow lifetimes did not depend on the temperature within experimental incertitude. Very similar results were published for Er implanted in SIPOS [1]. Our results are interpreted supposing two different lattice sites for  $\text{Er}^{3+}$  in the hosts. Moreover, the de-excitation of the  $\text{Er}^{3+}$  ions by multiple phonon emission is negligible in this class of materials. [1] G. N. van den Hoven, J. H. Shin, A. Polman, S. Lombardo, S. U. Campisano, J. Appl. Phys. 78 (1995) 2642.
- 10:30 **BREAK**

## Session VIII: Nanostructures I

Session chair: A. Vantomme

- J-VIII.1** 11:00 -Invited- FABRICATION AND PHOTOLUMINESCENCE PROPERTIES OF ERBIUM DOPED SIZE-CONTROLLED Si NANOCRYSTALS  
Margit Zacharias, Johannes Heitmann, Michael Schmidt, and Lixin Yi, Max-Planck-Institute of Microstructure Physics, Halle, Germany, Victor Yu. Timoshenko, Maksim G. Lisachenko, Pavel K. Kashkarov, Moscow State M.V. Lomonosov University, Physics Department, 119899 Moscow, Russia  
 We present a new approach of ordered Si quantum dots realized by crystallization of by SiO/SiO<sub>2</sub> superlattices. This method allows us to prepare dense arrays of Si nanocrystals clearly separated by SiO<sub>2</sub> in all three dimensions, and realizes an independent control of the nanocrystal size, size distribution, and density. Undoped Si nanocrystals produced by this way are characterized by highly efficient luminescence tunable with nanocrystal size. Er doping of the samples results in a strong Er related luminescence, which efficiency is at least 3 order of magnitude higher than that of Er-doped bulk SiO<sub>2</sub>. Spectra and transients of the photoluminescence of undoped and Er-doped size-controlled nanocrystalline Si/SiO<sub>2</sub> multilayered structures have been comparatively investigated depending on the Si nanocrystal size. It is shown that the energy of optical excitation of Si nanocrystals can be almost completely transferred to the Er<sup>3+</sup> ions resulting in an emission at a wavelength of 1.5 micrometer. The efficiency of the energy transfer increases for higher energy of the exciting photons and for smaller size of the nanocrystals. For the superlattices with nanocrystal sizes of 2 nm under excitation with photons of 3.7 eV a quantum efficiency of the Er<sup>3+</sup> excitation is found to be at least 80% at room temperature. This highly efficient excitation is explained by a strong coupling between excitonic states in Si nanocrystals and excited states of Er<sup>3+</sup> ions embedded in surrounding SiO<sub>2</sub>.

**J-VIII.2** 11:30

**TIME-RESOLVED EXCITATION SPECTROSCOPY OF Er<sup>3+</sup> IONS IN SiO<sub>2</sub> DOPED WITH Si-NANOCRYSTALS: LIMITS OF SENSITIZATION**

**M. Forcales, M. Wojdak, and T. Gregorkiewicz,** Van der Waals-Zeeman Institute, University of Amsterdam, Valckenierstraat 65, 1018 XE Amsterdam, The Netherlands

Doping with silicon nanocrystals (Si-nc) increases effective excitation cross-section of Er<sup>3+</sup> ions in SiO<sub>2</sub> and allows the excitation process to proceed in a non-resonant way, via the nanocrystals. Consequently, intense photo-luminescence (PL) at  $\lambda \approx 1.5 \mu\text{m}$  from SiO<sub>2</sub>:Si-nc,Er can be obtained under optical pumping in a broad wavelength range. Under continuous excitation Er-related PL intensity increases by approximately two orders of magnitude in presence of Si-nc's. This is considerably less than one could expect in view of the much larger excitation cross-section increase, indicating that the role of Si-nc's is not limited to absorption enhancement only. In this contribution, excitation of photoluminescence of Er<sup>3+</sup> ions in SiO<sub>2</sub> matrix doped with Si-nc's has been investigated under resonant and nonresonant, pulsed and continuous pumping. By comparing results obtained for samples with and without Si nanocrystals, their role in the excitation mechanism has been followed. The results show that while Er<sup>3+</sup> effective excitation cross-section is indeed increased by 10<sup>4</sup> upon incorporation of Si-nc's, as commonly reported, only a small number of Er<sup>3+</sup> ions can actually be excited via the nanocrystals. It is found that direct, resonant excitation of erbium occurs also in presence of Si-ncs. The maximum total intensity is lower than that observed for direct excitation of SiO<sub>2</sub>:Er. This indicates that the number of optically active Er<sup>3+</sup> ions is considerably reduced upon introduction of Si-nc's. Based on the experimental findings, role of Si-nc's as sensitizers of Er photoluminescence is discussed.

**J-VIII.3** 11:45 -Invited-

**THE INFRA-RED PHOTO RESPONSE OF ERBIUM-DOPED SILICON NANOCRYSTALS**

**A.J. Kenyon, S.S. Bhambher, and C.W. Pitt,** Department of Electronic & Electrical Engineering, University College London, Torrington Place, London WC1E 7JE, U.K.

We have exploited the interaction between erbium ions and silicon nanoclusters to probe the photoresponse of erbium doped silicon nanocrystals in the spectral region around 1.5  $\mu\text{m}$ . We have produced an MOS device in which the oxide layer has been implanted with both erbium and silicon and annealed to produce silicon nanocrystals. Upon illumination with a 1480 nm laser diode, interaction between the nanocrystals and the rare-earth ions results in a modification of the conductivity of the oxide that enables a current to flow when a voltage is applied across the oxide layer.

12:15

**LUNCH**

Thursday, June 12, 2003  
Jeudi 12 juin 2003

Afternoon  
Après-midi

Session IX: Nanostructures II  
Session Chair: T. Gregorkiewicz

- J-IX.1** 14:00 -Invited- RARE EARTH DOPED Si NANOSTRUCTURES  
**F. Priolo**, D. Pacifici, G. Franzò, A. Irrera, M. Miritello, INFN and Dipartimento di Fisica e Astronomia, Via S. Sofia 64, 95123 Catania, Italy and F. Iacona, CNR-IMM, Sezione di Catania, Stradale Primosole 50, 95121 Catania, Italy  
Silicon is an indirect band gap semiconductor and for a long time it has been considered a quite poor light emitter. In the last decade, a strong effort has been devoted towards the achievement of efficient light emission from silicon. Among the others, quantum confinement effects in low dimensional Si structures and rare earth-doping of Si nanostructures have been recently recognized as the most promising methods. Indeed efficient room temperature light emission can be obtained from both kind of systems. Moreover, this emission can be tuned in both the visible and infrared range by simply changing the mean Si nanocrystals size or by using different rare earths in presence of Si nanocrystals. Indeed, the sensitizing action of Si nanocrystals for the rare earths is shown to produce an emission which is two orders of magnitude more efficient than in pure insulating hosts. The aim of the work is to understand in details the interaction mechanisms occurring between Si nanocrystals and the rare earths ions, with a particular attention for the Er-doped Si nanocrystals system. In view of the realization of an all-Silicon based optoelectronics, high efficiency, tunability, spectral purity and directionality of the light emission are important issues to be first addressed. Indeed, a highly directional and pure light emission from both Si nanocrystals and rare earth-doped Si nanocrystals can be obtained by embedding the emitting centers in an all Si based optical microcavity. Moreover, the feasibility of efficient electrical pumping of both Si nanocrystals and rare earths doped Si nanocrystals embedded in light emitting diodes will be demonstrated. The impact of these findings on the future development of an all Si based microphotonics will be discussed.
- J-IX.2** 14:30 ENERGY TRANSFER FROM SILICON NANOCRYSTALS TO ERBIUM IONS - WHAT IS THE FACTOR DETERMINING THE ENERGY TRANSFER RATE?  
**Minoru Fujii**, Kenji Imakita, Kei Watanabe, Shinji Hayashi, Department of Electrical and Electronics Engineering, Faculty of Engineering, Kobe University, Japan  
Since the discovery that Si nanocrystals (nc-Si) has a function as a photosensitizer to Er ions, many kinds of nc-Si / Er systems have been developed, and based on this finding waveguide type optical amplifiers and electro-luminescence devices have been developed. In these systems, excitation light is absorbed by nc-Si, and Er ions are indirectly excited by the energy transfer from nc-Si. The coupling between nc-Si and Er ions is believed to be very "strong". However, it is not known how the coupling strength is determined or what properties of nc-Si mostly affect the strength. Clarification of these fundamental questions is indispensable to fully understand the energy transfer mechanism, and to further improve device performances. In the present work, in Si dioxide films containing nc-Si and Er, we have succeeded in controlling the coupling strength in a wide range. In weakly coupled systems, the PL intensity of Er ions increased very slowly (~100 microseconds) after the pulsed excitation of nc-Si (5 nanoseconds pulse width), while in strongly coupled systems, it reached maximum immediately. By analyzing the correlation between the PL decaying properties of nc-Si and PL rising properties of Er ions, we will show that imperfection of nc-Si crystallinity plays a crucial role in realizing strong coupling; perfect nc-Si are not an ideal material from the point of view of photosensitizer.
- J-IX.3** 14:45 BLUE, GREEN AND RED EMISSION FROM Ce<sup>3+</sup>, Tb<sup>3+</sup> AND Eu<sup>3+</sup> IONS IN AMORPHOUS GaN AND AlN THIN FILMS  
**S.B. Aldabergenova**, G. Frank, H.P. Strunk, Department of Materials Science and Engineering, Institute of Microcharacterization, Erlangen-Nürnberg University, Cauerstr. 6, 91058 Erlangen, Germany, P.C. Taylor, University of Utah, Salt Lake City UT 84112, USA, A.A. Andreev, A.F. Ioffe Physical-Technical Institute, St. Petersburg 194021, Russia  
We report strong blue, green and red emission from Ce<sup>3+</sup>, Tb<sup>3+</sup> and Eu<sup>3+</sup> ions respectively, at room temperature in amorphous GaN and AlN thin films prepared by DC magnetron co-sputtering. We observe sharp characteristic emission peaks of intra-4f-shell transitions of the Tb<sup>3+</sup> ions (<sup>5</sup>D<sub>4</sub> → <sup>7</sup>F<sub>{3,4,5,6}</sub> transitions) and Eu<sup>3+</sup> ions (<sup>5</sup>D<sub>0</sub> → <sup>7</sup>F<sub>{1,2,3,4}</sub> transitions) and a strong but broad peak of 5d-4f emission from Ce<sup>3+</sup> ions over the temperature range of 2-300K. The photoluminescence decay time from the excited <sup>5</sup>D<sub>4</sub> state of Tb<sup>3+</sup> ions in a-AlN is 1.1ms, which is similar to the radiative lifetime of this state in glasses. The broad photoluminescence peak centered at ~400nm in a-GaN shows a weak temperature dependence and may be attributed to the intrinsic tail-to-tail transitions in the amorphous matrix. The possible origin of the deep states close to midgap in a-AlN is briefly discussed.

- J-IX.4** 15:00 MICROSTRUCTURE AND EMISSION PROPERTIES OF Si NANOCRYSTALS AND Er-DOPED SILICA FILMS OBTAINED BY REACTIVE MAGNETRON CO-SPUTTERING  
P. Singh, F. Gourbilleau, C. Dufour, M. Levalois, J. Vicens, R. Rizk, LERMAT, Unité CNRS 2149, ISMRA, 6 Bd Maréchal Juin, 14050 Caen Cedex, France and C. Garcia, P. Pellegrino, B. Garrido, EME, Departament d'Electronica, Univ. de Barcelona, Martí i Franques 1, 08028 Barcelona, Spain  
 Er-doped-Silicon-rich silicon oxide (RSO) thin films were fabricated by reactive magnetron sputtering of a pure silica target topped by erbium oxide chips. The incorporation of silicon excess in the films was monitored by the hydrogen rate ( $RH = p_{H_2} / (p_{H_2} + p_{Ar})$ ) introduced in the plasma, owing of the ability of hydrogen to reduce the oxygen released from the silica target. Specific annealing conditions have allowed the optimization of the Er emission at 1.54  $\mu\text{m}$ . Microstructural studies revealed the presence of Si nanocrystals for samples fabricated at low RH, whereas for the highest RH values, the films presented a low crystalline fraction, owing probably to the large density of smaller grains appearing amorphous. For this latter case, the IR spectroscopy indicates the best phase separation between Si and SiO<sub>2</sub>, likely due to the large density of Si/SiO<sub>2</sub> interfaces. The PL and PLE measurements performed on these films showed a gradual increase of the 1.54  $\mu\text{m}$  emission with RH, for both resonant and non resonant excitations, hence evidencing a clear energy transfer from Si agglomerates to Er ions, as also supported by the IR. Finally, the emission lifetime was found higher than 5 ns.
- J-IX.5** 15:15 UP-CONVERSION PROPERTIES OF Nd<sup>3+</sup>:LiNbO<sub>3</sub> CO-DOPED WITH ZnO FIBER SINGLE CRYSTALS GROWN BY MICRO-PULLING DOWN METHOD  
I.W. Shur, J.S. Park and D.H. Yoon, Sungkyunkwan University, Advanced Materials Engineering, ChunChun-dong, JangAn-gu 300, 440-746 Suwon, Korea  
 There is increasing interest in the growth of rod or fiber-like micro-single crystals, suitable for application in non-linear optical and electro-optical devices. LiNbO<sub>3</sub> is a material of greatest technological interest for integrated optics. Because of its optical and electro-optical properties, a great number of optical processes can be performed on its basis and optical active impurities like rare earth ions and transition metal ions useful for photonic devices can be incorporated. Another potential application of LiNbO<sub>3</sub> is in Nd<sup>3+</sup> based compact diode-pumped self-frequency-doubled laser which emit green radiation. Also, co-doping with ZnO has been proposed as a way of reducing the photorefractive effect in LiNbO<sub>3</sub>. In this study, Nd<sup>3+</sup>:LiNbO<sub>3</sub> co-doped with ZnO single crystal fibers were grown by micro-pulling down method which is advanced method of fiber crystal growth. The grown crystals were observed homogeneous distributions of the Nd and Zn concentration by electron probe micro-analysis and the changes of transmission spectra and up-conversion properties were investigated.
- J-IX.6** 15:30 -Invited- EXCITATION MECHANISMS OF ERBIUM PHOTOLUMINESCENCE IN SILICON AND SILICON NANOSTRUCTURES  
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 We present a short review of the theoretical and experimental results concerning the problem of excitation mechanism of erbium photoluminescence in silicon and silicon nanostructures. The excitation process consists of two stages, the first being absorption of radiation by bulk silicon matrix or nanocrystals while the second Auger excitation of erbium ions by recombining electron-hole pairs. The large values of Auger excitation cross-section under optical pumping in semiconductor matrices are due to large values of band-to-band absorption coefficient of bulk silicon or silicon nanocrystals exceeding by several orders of magnitude the absorption coefficient of erbium in dielectric SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> matrix. The peculiarities of Auger process in silicon nanocrystals when excitation of erbium ions is produced by quantum-confined electron-hole pairs are discussed. The results of calculations of the probability of excitation of erbium ions which occur outside of nanocrystals via Foster mechanism are presented. The transport of excitation via erbium ions and mechanism of de-excitation are also discussed.