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Luminescence of AlN/GaN Superlattices Implanted with Tb and Tm Ions

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Introduction

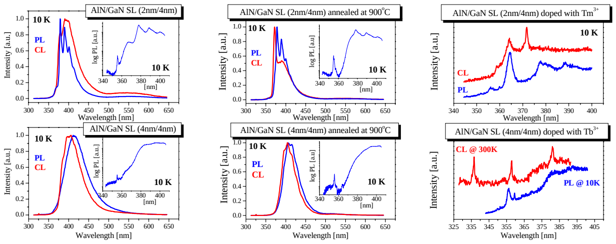
Despite evident progress in research and technological achievements towards the rare earth (RE) doped III-nitrides electroluminescent devices and lasers, one must realize difficulties in making these devices commercially attractive [1-6]. The most challenging obstacle on the path to achieving this goal is the low radiative quantum efficiency of RE ions in these materials. In general, the RE radiative quantum efficiency strongly depends on the carrier mediated energy transfer processes, which have to compete with fast nonradiative recombination channels abundant in III-nitride hosts. It was theoretically shown that the Coulomb excitation of *f* electrons near interface of heterostructures is more effective than a similar excitation in the bulk semiconductors [7-9]. This concept of doping RE ions into quantum wells (QWs) and superlattices (SLs) was recently adopted and explored with Si [10], III-V and II-VI semiconductors [11,12]. The results of these studies show that the photoluminescence intensity of RE ions when incorporated in hetero-quantum-structures increased significantly than that in the bulk semiconductors.

Studies on the optically active RE ions doped III-nitrides QWs and SLs are very scarce, however available data indicates significant improvement in the PL intensities of Eu and Er doped AlGaN/GaN superlattices [13,14]. Despite encouraging initial results, the mechanism for transfer of excitation from electrons and holes produced by electron or photon pumping in such structures is still not entirely clear.

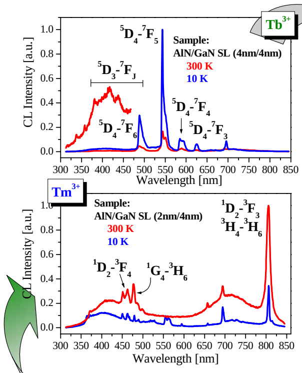
As demonstrated by GaN laser diodes, light emitting diodes (LED), and GaN based electronic devices, all GaN based devices must take advantage of quantum well (QW) structures such as GaN/AlGaN, InGaN/GaN and GaN/AlN [15-21].In order to optimize the device design using RE-doped III-nitrides, it is necessary to study and understand the physical properties of RE doped nitride QWs and SLs as well as the QW structural effects on the device performance.

Experimental Results

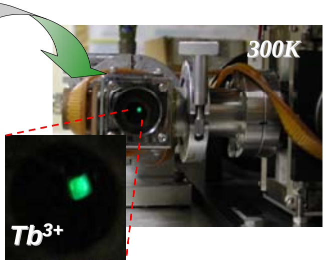
Temperature dependent PL & CL spectra



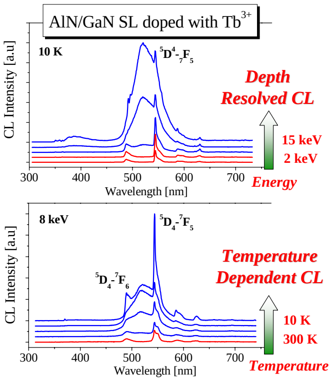
Figures shown above present the low temperature PL and CL spectra of reference AlN/GaN SLs, annealed AlN/GaN SLs and rare earth doped AlN/GaN SLs (UV region only), respectively.



CL spectra of AlN/GaN SLs doped with Tb and Tm ions. Sharp lines due to intra 4*f*-shelf transitions overlap with defect related emission.



Room temperature CL of AlN/GaN SLs doped with Tb. Green emission is strong to the naked eye.



Dept resolved CL spectra and temperature dependent CL spectra of AlN/GaN SLs doped with Tb. It is unclear at this time where the RE Ions predominantly reside in the SLs structure (well or heteroboundry region). The presence of the broad band at 525 nm can be due to: implantation defects related emission, GaN substrate emission due to penetration of an electron beam through the SLs structure.

Samples & Measurements

Samples

The superlattices (SLs) were grown by metal-organic chemical vapor deposition (MOCVD) on a GaN base layer with a thickness of 2 µm underlying the SL on a (0001) sapphire substrate. The samples were grown under identical conditions with wells of 4 nm. The SLs composed of twenty periods of alternating GaN wells and 2 nm (or 4 nm) AlN barriers. All samples were nominally undoped.

Doping

- SLs were doped by implantation with Tb and Tm ions at room temperature
- RE ions were implanted at several energies not exceeding 150 keV
- RE implant doses were chosen to produce maximum of an implant concentration peak in the area of SL structure
- The implanting ion beam was normal to the sample surface
- A computer simulation of the depth profiles was done with SRIM software

Processing

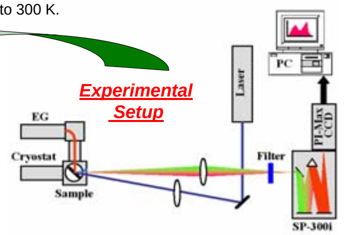
To optically activate incorporated impurities and remove ion implantation-induced damage, the implanted SLs samples were subjected to post-implantation isochronal thermal annealing treatments (duration 20 min) at 900 °C in a tube furnace under a flow of N_2.

Measurements

We have measured photoluminescence (PL) with excitation at 325 nm and cathodoluminescence (CL) in the temperature range between 8 K to 300 K.

1. **Laser** He-Cd, cw 15 mW at 325 nm
2. **SP-300i** spectrograph
3. **PI-Max CCD** 200 nm – 950 nm
4. **Cryostat** 8-320 K
5. **EG electron gun** up to 20 keV
6. **Optics** lenses and long pass filter
7. **PC computer**

Experimental Setup



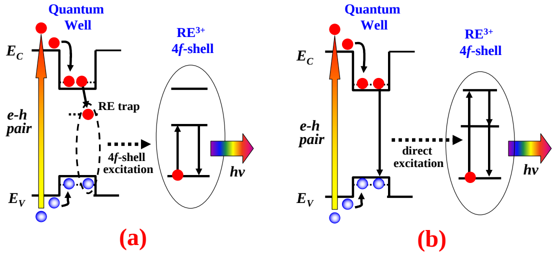
Theory

In QW structures, we expect two kinds of processes for the excitation of RE, i.e., ***(a) trap-mediated excitation process*** and ***(b) direct (resonance) excitation process*** by the photon emitted from QW [11].

✓ **(a)** In the trap mediated process, photo-excited electrons and holes come to QW regions and they are captured by RE traps. The recombination energy is transferred to excite RE ions effectively.

✓ **(b)** In the direct excitation process, the QW photon might excite RE ions resonantly, if the photon energy corresponds to the energy separation between two levels of the 4*f*-shell system. ***In this case the energy of the carriers depends mainly on the parameters of the quantum well (on the width of the well and the heterobarrier). Therefore, by selecting the QW physical properties one can achieve the resonance Auger excitation conditions between RE ion impurity and host [8, 9].***

The mechanism of *f-f* emission excitation in the presence of a heteroboundry (or QW) does not require localization of an electron-hole pair on an impurity center, as in the case of a uniform semiconductor. It is anticipated that the presence of a heteroboundy removes all restrictions imposed on the excitation process by the laws of conservation of energy and momentum [13].



The resonance excitation of an electron in a QW is more efficient than in the case of a bulk semiconductor for three reasons:

(1) by varying the width of the QW it is always possible to obtain an efficient band gap that is equal to the excitation energy of an *f* electron [12]

(2) the overlapping of integrals of an electron and a hole increase significantly because of the electron localization in a direction perpendicular to the QW

(3) the overlap integral for the transition of an electron from the initial to the excited state in an impurity center increases in the presence of a heteroboundry. As a result, states of other impurity are added to *f* states, which in the end allow dipole *f-f* transitions previously forbidden for parity reasons. [7-9].

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