Temperature-Dependent Photoluminescence from Er-implanted undoped and Mg-doped GaN

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Selectively excited photoluminescence (PL) spectroscopy has been carried out on the ~1540 nm $^4I_{13/2}$ to $^4I_{15/2}$ emissions of the multiple Er^{3+} centers observed in Er-implanted *undoped* and *Mg-doped* GaN at temperatures ranging from 6K to 295K. The temperature dependence of the Er^{3+} PL spectra selectively excited by below-gap light demonstrates different quenching rates for the distinct Er^{3+} PL centers, and indicates that the PL spectra with the most rapid thermal quenching rates do not contribute to the room temperature, above-gap-pumped Er^{3+} PL spectrum. In addition, selective PL spectroscopy has been carried out on the Er^{3+} emission in Er-implanted undoped and Mg-doped GaN at temperatures ranging from 6K to 295K. The results indicate that the previously reported enhancement of the violet-pumped centers' contribution to the low temperature above-gap excited Er^{3+} PL in Mg-doped GaN is also evident at room temperature.

Keywords : photoluminescence, Er-implanted, Mg-doped, GaN

1. INTRODUCTION

In recent years, visible and near infrared emission from the intra-4f shell transitions of ion-implanted and in-situ doped rare earth dopants in GaN has been investigated intensively by photoluminescence (PL) and electroluminescence (EL) techniques.[1-10] Our research has focused on PL studies of Er-implanted GaN as a function of excitation wavelength and annealing temperature which was detected nine different Er^{3+} emission centers on the basis of characteristic differences in their sharply structured ~1540 nm $^4I_{13/2}$ to $^4I_{15/2}$ Er^{3+} PL spectra. Selective optical excitation of these centers is accomplished[4,5,8,9] by choosing a pump wavelength within one of the broad, below-gap, defect-related absorption bands observed in the Er^{3+} photoluminescence excitation (PLE) spectra, with subsequent nonradiative energy transfer to the 4f electrons of the neighboring Er^{3+}.

Above-gap excitation at low temperature excites a sub-set of these centers with the relative strengths of their emissions determined by the concentration and capture cross sections of each distinctive center. Only one of these centers can be excited efficiently by direct intra-4f-shell absorption (~809 nm $^4I_{15/2}$ to $^4I_{9/2}$), indicating that it is the highest concentration center, representing over 99% of the optically active Er atoms.[5,8,9] Remarkably, these "4f-pumped" centers are not strongly pumped by above-gap light which implies that less than 1% of the Er atoms is involved in the Er-defect complexes which mediate the excitation of the Er^{3+} emission spectra pumped by above-gap absorption.[8,9] Recently, we demonstrated that the Er^{3+} PL and PLE spectra of Er-implanted Mg-doped GaN exhibit a significant enhancement of the so-called "violet-pumped" Er^{3+} emission spectrum that is selectively excited by a characteristic ~2.8-3.4 eV (violet) below-gap PLE band.[8,9] More importantly, the violet-pumped PL center dominates the above-gap excited Er^{3+} PL spectrum of Er-implanted Mg-doped GaN, whereas it was nearly unobserveable under the above-gap excitation in Er-implanted undoped GaN.[8,9]

In the present work, selective PL spectroscopy has been carried out on ~1540 nm Er^{3+} emission in Er-implanted undoped and Mg-doped GaN at temperatures ranging from 6K to 295K. The results indicate that the previously reported enhancement of the violet-pumped centers' contribution to the low temperature above-gap excited Er^{3+} PL in Mg-doped GaN is also evident at room temperature.

2. EXPERIMENTAL RESULTS AND DISCUSSION

Thin films (~1 μm thick) of undoped n-type and Mg-

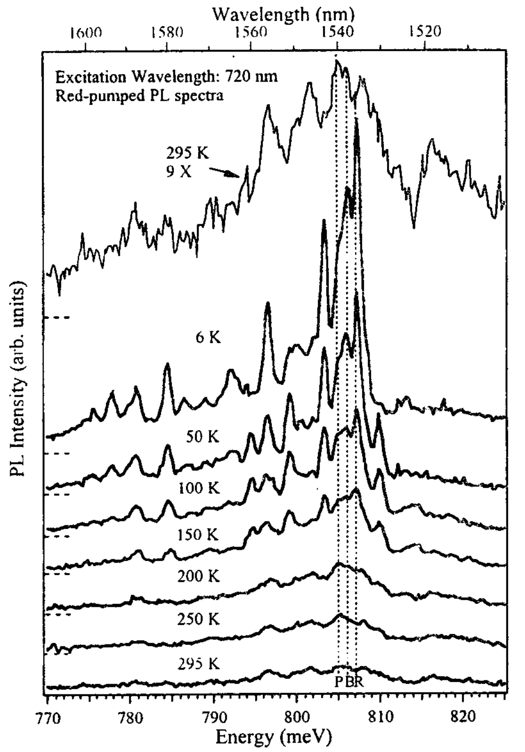

Fig. 1. The red-pumped Er^{3+} PL from undoped Er-implanted GaN at selected temperatures from 6 K to 295 K.

doped p-type GaN were grown on (0001) sapphire substrates by atmospheric pressure metal-organic chemical vapor deposition (MOCVD) techniques that have been described previously[8]. The as-grown Mg-doped GaN samples are highly resistive, with typical hole concentrations of ~ 5 x 10^{17} cm^{-3} after thermal annealing. It was estimated that the concentration of electrically active Mg dopants was ~ 5 x 10^{19} cm^{-3} before the Er implantation. The Mg-doped GaN film was implanted with a dosage of 4 x 10^{13} Er^{3+} ions/cm^2 at 280keV, with the projected range for the 280-keV Er ions estimated to be approximately 0.05 μm. The implanted samples were annealed at 900 °C for 90 minutes under a continuous flow of nitrogen gas. The Er^{3+} PL spectra were excited by a variety of lasers and lamps with wavelengths chosen to match specific below-gap PLE bands, as described in detail elsewhere.[4,5,8,9] The different Er^{3+} PL spectra have been labelled according to the wavelength of the pump light employed, i.e. blue-pumped (458 nm), red-pumped (633 nm), violet-pumped (404 nm), etc.[5,8,9] Luminescence was analyzed by a 1-m single grating monochromator and detected by a cooled Ge PIN detector. The Er-implanted GaN samples were mounted in a Janis Supervaritemp liquid helium cryostat, and the PL spectroscopies were carried out at temperatures in the range from 6 K to 295K.

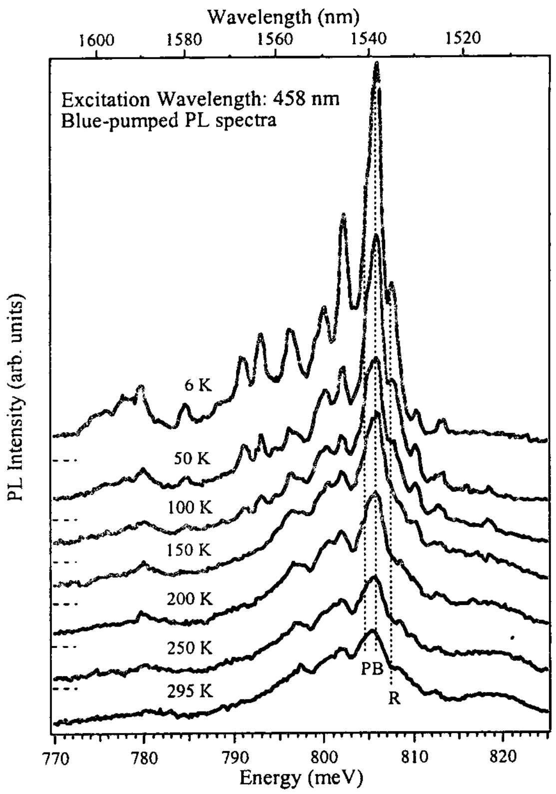

Fig. 2. The blue-pumped Er^{3+} PL from undoped Er-implanted GaN at selected temperatures from 6 K to 295 K.

The temperature dependences of the integrated Er^{3+} PL intensity measured for each of the violet-, blue-, red-, 4f-, and above-gap-pumped PL spectra in the undoped GaN have been reported previously[5]. The violet- and blue-pumped PL spectra exhibit similar temperature dependences, reaching a reduction of a factor of ~2 in integrated intensity as the temperature increases from 6 K to 295 K. The red- and 4f-pumped Er^{3+} PL spectra experience a more rapid thermal quenching, reaching a reduction of a factor of ~ 10 at 295 K, and the dominant peaks of the 6 K red-pumped PL spectrum are unobservable at temperatures above 150 K, as is evident in Fig. 1. In contrast, the blue-, violet-, and 4-f pumped Er^{3+} PL spectra retain the dominant peaks of their 6 K spectra at room temperature, although they are broadened, as shown for the blue-pumped Er^{3+} PL in Fig. 2.

The effects of Mg-doping on the above-gap pumped Er^{3+} PL spectrum at 6 K and room temperaure are compared in Figs. 3 and 4, respectively. The top spectrum of Fig. 3 is the so-called violet-pumped Er^{3+} emission excited from Er-implanted undoped GaN by 404 nm light at the peak of the ~2.8-3.4 eV violet PLE band. The sharp peak at ~798 meV (1554.8 nm) in the violet pumped Er^{3+} PL spectrum is noticebly absent from the above-gap pumped Er^{3+} PL spectrum observed in Er-implanted undoped GaN (bottom of Fig. 3). Careful

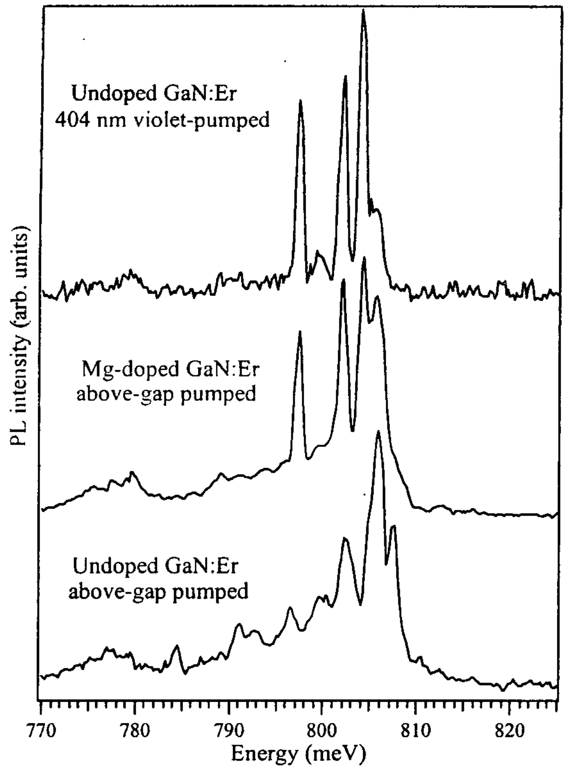

Fig. 3. Violet-pumped Er^{3+} PL spectrum excited from Er-implanted undoped GaN, compared with above-gap-pumped Er^{3+} PL spectra from Mg-doped and undoped Er-implanted GaN. Fig.2(b).

analysis of this spectrum clearly demonstrated that the distinctive violet-pumped Er^{3+} PL spectrum shown in Fig. 3 was not strongly excited by above gap light in the Er-implanted, undoped GaN. In striking contrast, the above-gap pumped Er^{3+} PL spectrum from the Er-implanted, Mg-doped GaN sample shown in Fig. 3 is dominated by the strong, distinctive PL peaks that characterize the violet-pumped Er^{3+} PL spectrum. Thus the Mg-doping has had the effect of making the violet-pumped Er^{3+} emission centers the dominant contributors to the low temperature, above-gap pumped Er^{3+} PL spectrum of Mg-doped GaN, whereas they are virtually undetectable in the 6 K above-gap pumped Er^{3+} PL spectrum of undoped GaN (Fig. 3(c)).[5,8,9]

Spectra (a) and (b) in Fig. 4 are the above gap-pumped Er^{3+} PL spectra obtained at 295 K from the Mg-doped and undoped GaN hosts, respectively. It is evident that the major peak of the Mg-doped spectrum is red shifted by (~3 nm) relative to the 1538 nm peak of the undoped spectrum, which is known to be dominated by contributions from the blue-pumped Er^{3+} PL centers.[5,8,9] Weighted subtraction of the undoped spectrum (b) from the Mg-doped spectrum (a) results in the difference spectrum (d). Comparison of the difference spectrum (d) with the violet-pumped Er^{3+} PL spectrum (c) from the Mg-doped GaN sample reveals that the difference spectrum corresponds to an enhanced contribution of the violet-pumped centers to the room temperature above gap-pumped Er^{3+} PL spectrum (a) of the Mg-doped sample. Thus the Mg-doping has greatly enhanced the contribution of the violet-pumped Er^{3+} emission centers to the room temperature above-gap pumped Er^{3+} PL spectrum of Er-implanted Mg-doped GaN relative to the corresponding spectrum from the undoped GaN. This observation indicates its potential relevance to the performance of room temperature EL devices.

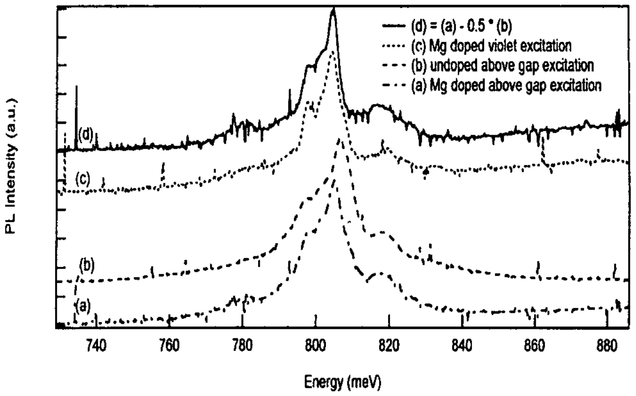

Fig. 4. Spectra (a) and (b) are the above gap-pumped Er^{3+} PL spectra obtained at 295 K from the Mg-doped and undoped GaN hosts, respectively. Spectrum (d) is the subtraction of spectrum (b) from spectrum (a). Spectrum (c) is the 295 K violet-pumped Er^{3+} PL from the Mg-doped GaN.

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