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1 Introduction We have recently reported [1, 2] the first stimulated emission from rare earths in a semiconductor host using Eu-doped GaN. The lasing occurs at 620 nm due to the $^5D_0$ to $^7F_2$ inner shell transition in the Eu ions. In this paper we discuss the effect of several fabrication parameters on the gain and loss in GaN:Eu cavities fabricated on various substrates.

2 Experimental conditions The GaN:Eu cavities were grown by molecular beam epitaxy (MBE) using solid sources for Ga, Al, Eu and a plasma source for nitrogen. The MBE growth was carried out at temperatures between 650 °C and 800 °C depending on substrate choice, with a Ga beam pressure of $\sim 5 \times 10^{-7}$ Torr and a N_2 flow rate of 1.5 sccm to 2 sccm. The GaN growth rate was typically ~0.5 µm/h. Several Eu cell temperatures were selected between 400 °C and 500 °C, in order to obtain different Eu concentrations in the GaN layer. Post growth anneal was performed on some of the samples under the following conditions: 650–675 °C, 100 min, N_2 ambient.

3 Experimental results The effect of Eu concentration on the photoluminescence (PL) intensity is shown in Fig. 1 for GaN:Eu cavities grown on sapphire at 800 °C. The PL emission is obtained under optical pumping with a CW He–Cd laser at a wavelength of 325 nm, corresponding to an energy significantly above the GaN bandgap. A peak in PL intensity is obtained for the Eu cell temperature of 460 °C, which corresponds to a Eu concentration of ~1 at%. A sharp drop in PL intensity is observed for both lower (400 °C, corresponding to <0.5 at%) and higher (500 °C, corresponding to >2 at%) Eu cell temperatures. Stimulated emission in these samples was measured using pulsed (600 ps) N_2 laser pumping at 337 nm, which is also above the GaN bandgap. We have measured the gain in these structures using the variable slit length [3] (VSL) technique. Interestingly, as also shown in Fig. 1, the gain exhibited the same dependence on Eu concentration, as did the PL intensity. This indicates that the maximum concentration of optically activated Eu ions is independent of the pumping power density and pumping mode (CW or pulsed).

The effect of post-growth annealing on Eu stimulated emission gain is shown in Fig. 2 for GaN:Eu samples also grown on sapphire with ~1 at% Eu concentration (Eu cell temperature of 470 °C). A significant increase in gain to 97 cm^{-1} after annealing at 650 °C is obtained compared to the gain of 79 cm^{-1} in the unannealed case. The gain data of Fig. 2 cannot be compared directly to that contained in Fig. 1, since the growth conditions were slightly different.

The optical loss in these structures was obtained using the shifting excitation spot (SES) technique. As can be seen from Fig. 3, the annealing not only increased the gain but also simultaneously reduced the loss. The enhancement in gain and reduction in loss might result from the increase

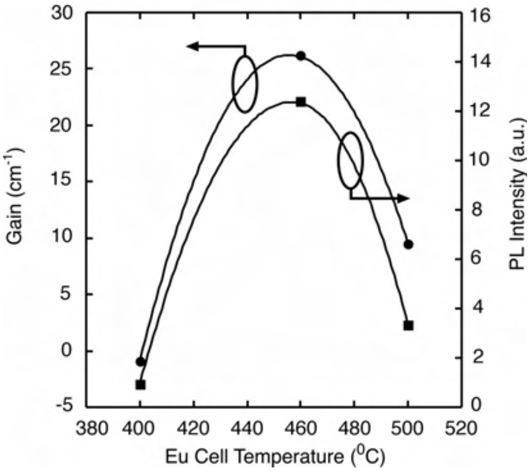

Figure 1 Effect of Eu cell temperature (and consequent concentration in the GaN layers grown on *sapphire*) on photoluminescence (PL) intensity (using CW He–Cd laser at 325 nm) and on gain obtained with the variable stripe length (VSL) technique (using pulsed N_2 laser at 337 nm).

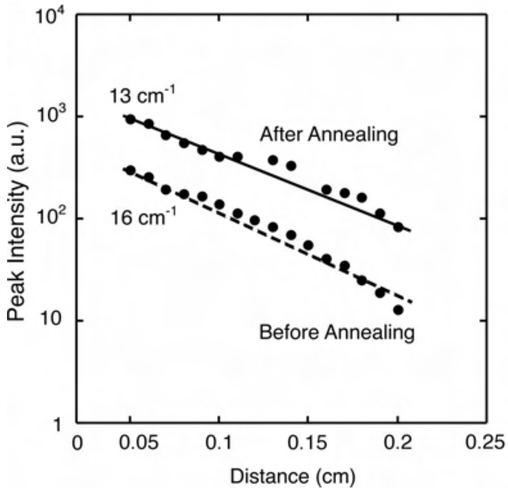

Figure 3 Peak stimulated intensity signal as a function of distance (using the SES technique [4]) for determining the loss in GaN:Eu cavities grown on *sapphire* with and without post-growth anneal. The Eu cell temperature was 470 °C corresponding to Eu concentration of ~1 at%.

in the concentration of optically activated Eu ions and the improvement of the crystal quality of the Eu-doped GaN layers.

The successful integration of light sources with the well-developed Si microelectronics technology is a compelling prospect and hence a very active research field. We report the possibility of integration with rare-earth-doped GaN laser materials on Si substrates. The device structure grown on Si substrates consists of Eu-doped GaN active region sandwiched between AlN cladding layers. An AlN buffer layer was grown on Si for 2 h, which resulted in ~1 µm layer thickness. Next, Eu-doped GaN was grown for 1 h, resulting in a 0.6 µm active layer doped with ~1 at% Eu. To improve light confinement into GaN:Eu layer, an AlN top cladding layer was grown for 1 h. Finally, the sample was furnace annealed at 675 °C for 100 min. The growth temperature was reduced to 650 °C due to the higher thermal conductivity of Si compared to sapphire in order to avoid GaN decomposition during the growth.

Figures 4 and 5 show the Eu emission optical gain and loss for the cavities grown on silicon substrates, also obtained with VSL and SES, respectively. During the measurements, the N_2 pump laser peak power density and repetition rate were kept at 3.73 MW/cm^2 and 10 Hz, respectively. We obtained significantly higher gain (60 cm^{-1}) than the optical loss (10 cm^{-1}) in the cavity. This result in-

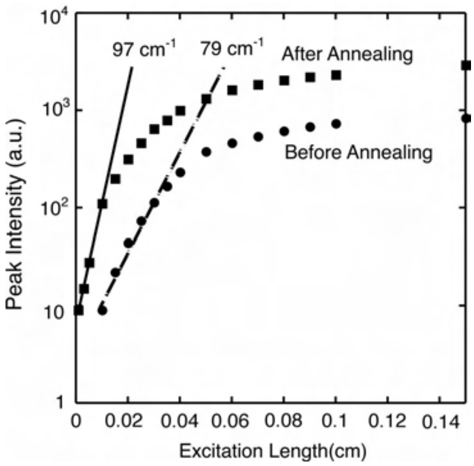

Figure 2 Peak stimulated intensity signal as a function of excitation length (using the VSL technique) for determining the gain in GaN:Eu cavities grown on *sapphire*, with and without post-growth anneal. The Eu cell temperature was 470 °C corresponding to Eu concentration of ~1 at%.

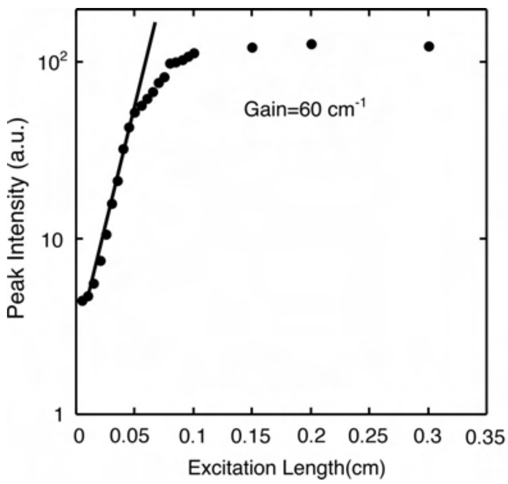

Figure 4 Optical gain obtained from Eu-doped GaN layer with AlN top and bottom cladding layers grown on *silicon* substrate. Peak wavelength of emission is ~620 nm. The sample was pumped by N_2 laser with 3.73 MW/cm^2 at 337 nm.

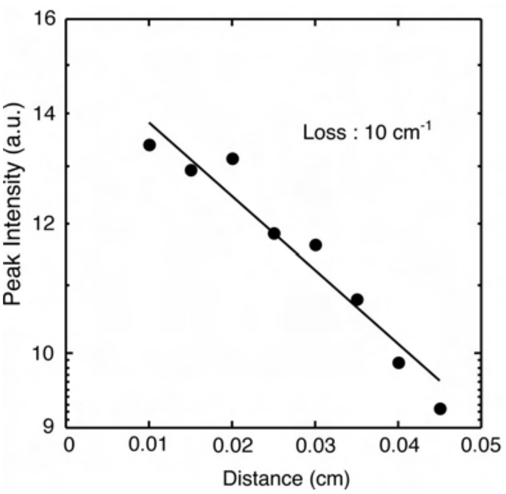

Figure 5 Optical loss obtained from Eu doped GaN layer with AlN top and bottom cladding layers grown on *silicon* substrate. Peak wavelength of emission is ~620 nm. The sample was pumped by N_2 laser with 3.73 MW/cm^2 at 337 nm.

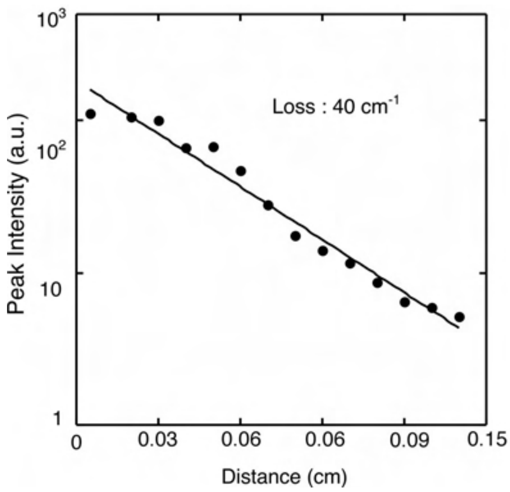

Figure 7 Optical loss obtained from Eu doped GaN layer grown on glass substrate. Peak wavelength of emission is ~620 nm. The sample was pumped by N_2 laser with 3.73 MW/cm^2 at 337 nm.

dicates that the GaN:Eu grown on Si substrate with AlN bottom cladding is a viable option for laser integration on Si substrates.

We previously reported [5] strong photoluminescence and electroluminescence from rare earth GaN grown on glass substrates. To extend the substrate selection options for rare earth doped GaN laser device, we conducted gain and loss measurements from Eu-doped GaN grown on glass substrates. A thin AlN buffer layer was grown for 5 min followed by the growth of GaN:Eu for 45 min with 440 °C Eu cell temperature, resulting in a 0.5 µm active layer. Finally, a thin AlN capping layer was grown for 5 min. The substrate temperature was kept at 600 °C during the buffer and capping layer growth. The Eu-doped GaN layer was grown at 700 °C to prevent the softening of the glass substrate. Finally, the sample was furnace annealed at 675 °C for 1 h.

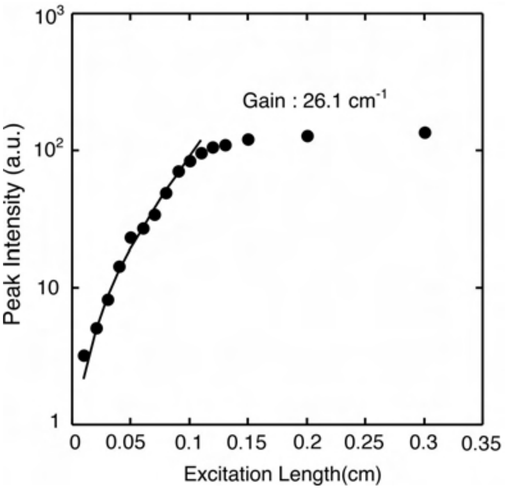

Figure 6 Optical gain obtained from Eu doped GaN layer grown on *glass* substrate. Peak wavelength of emission is ~620 nm. The sample was pumped by N_2 laser with 3.73 MW/cm^2 at 337 nm.

The optical gain and loss results are shown in Figs. 6 and 7. During the measurements, the peak power density and repetition rate of the N_2 laser were maintained at 3.73 MW/cm^2 and 10 Hz, respectively. Optical gain and loss of 26.1 cm^{-1} and 40 cm^{-1} were obtained. The relatively high loss is likely due, among other reasons, to insufficient light confinement into active region due to asymmetric device structure (air/GaN:Eu/glass). Surprisingly, we were able to achieve gain in the structures grown on glass. Not surprisingly, the value of the gain is lower than that achieved on Si or sapphire. However, one must keep in mind the fact that these were preliminary experiments and the gain might be increased with additional investigation of the growth parameters.

4 Summary and conclusions

We have investigated the effect of process conditions on GaN:Eu lasers cavities grown on sapphire, Si and glass substrates. The maximum optical gain was obtained at 460 °C Eu cell temperature, resulting in ~1 at% concentration. A sharp drop in PL intensity and gain was observed from samples with either lower or higher Eu concentration. The post-growth annealing has been shown to significantly improve the optical

Table 1 Representative values of gain and loss from GaN:Eu cavities grown on sapphire, Si and glass. Note that the cavity structures were not the same for each substrate, resulting in different levels of optical confinement.

	sapphire	silicon	glass
gain (cm^{-1})	90–100	50–60	20–30
loss (cm^{-1})	10–20	10–20	30–50

properties of the cavities, resulting in increases in the optical gain concomitant with reductions in the optical loss. This is probably due to a combination of an increased concentration of optically active Eu ions and an improvement in crystal quality.

Representative values of gain and loss obtained on the three substrate types are shown in Table 1. While cavities grown on sapphire substrates exhibit the highest gain and gain-loss difference, the cavities grown on Si are quite promising. Indeed, even cavities grown on glass, which have the lowest gain and a negative gain-loss difference, have the promise of being able to eventually make useful lasers on very low cost substrates.

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