Optical properties of (In,Al)GaN-based structures for near- and deep-ultraviolet emitters

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Successfully realized InGaN-based laser diodes (LDs) reported thus far have emission wavelength lying mostly between 376 nm and 440 nm [1,2]. Further research is needed to achieve emission wavelengths shorter than 370 nm. In the present study, we perform a comparison between AlGaN- and GaN-active medium lasing structures for near- and deep UV LDs through high-density optical pumping experiments combined with picosecond time-resolved and photoluminescence excitation (PLE) experiments. We measured the carrier lifetime and estimated the carrier densities needed to reach the stimulated emission (SE)/lasing threshold in our structures. We believe that optimization of carrier and optical confinement in GaN/AlGaN-based heterostructures is the key to the dramatic lowering of the lasing threshold and substantial improvements of emission intensity.

Figure 1 gives a comparison of emission spectra below and above the SE threshold for the (a) GaN epilayer, (b) GaN/AlGaN separate confinement heterostructure (SCH), and (c) $Al_{0.17}Ga_{0.83}N$ epilayer. The large energy difference between the spontaneous and SE peaks in the GaN and $Al_{0.17}Ga_{0.83}N$ epilayers are due to band-gap renormalization effects associated with electron-hole plasma recombination being the dominant gain mechanism in these structures. On the contrary, by examining the temperature characteristics of spontaneous emission and lasing modes in the GaN/AlGaN SCH [see Figure 1(b)], we concluded that lasing in the SCH is of excitonic origin [3]. Lasing occurs at a much shorter-wavelength (362-364 nm) in comparison to any previously reported results based on the InGaN material system [1,2].

One of the main difficulties hindering the development of GaN-active medium LDs is the high stimulated emission threshold of GaN (~600 kW/cm^2 at RT) in comparison to InGaN structures, as shown in figure 2. We observed that the incorporation of Al into GaN epilayers leads to even higher SE thresholds over the entire temperature range studied. Since most of the carriers recombine non-radiatively, a very high density is required to produce inversion and generate optical gain in GaN and AlGaN epilayers. On the other hand, the lasing threshold of the GaN/AlGaN SCH was observed to be an order of magnitude smaller in comparison to the GaN and AlGaN samples over the entire temperature range from 10 K to 300 K, as shown in figure 2. In fact, the lasing threshold of the SCH is comparable to that observed in high-quality InGaN/GaN multiquantum well samples studied under similar excitation conditions. This indicates that, with adequate progress in the p-doping of AlGaN, the realization of a GaN-active-medium LD is very promising.

We also performed time-resolved photoluminescence and PLE measurements in our samples. The carrier lifetime in AlGaN epilayers (250 ps at 10 K) was measured to be an order of magnitude longer than in GaN epilayers [4]. As opposed to what was commonly reported for InGaN structures, the increase in carrier lifetime does not result in a decrease of the SE threshold for the AlGaN epilayer, as was discussed previously. In

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order to interpret the low lasing threshold in the GaN/AlGaN SCH, we performed a series of PLE experiments, as depicted in figure 3. The PLE signal obtained at the position of the AlGaN waveguide peak shows that carriers generated in the cladding layer efficiently diffuse into the AlGaN waveguide layer. In fact, no substantial increase in the PL intensity of the waveguide region was observed when the carriers were generated in the cladding or directly in the waveguide region. We further note that the carriers in the GaN-active region were found to be generated through both carrier capture and carrier diffusion from the waveguide region. Such efficient carrier generation combined with improvements in optical confinement resulted in the substantially reduced values for the lasing threshold observed in the GaN/AlGaN SCH sample.

Our results indicate that, even though GaN and AlGaN epilayers have relatively high SE thresholds, it is possible to have a dramatically lower lasing threshold in GaN/AlGaN heterostructures. This finding indicates that optimization of these structures is critical for the realization of a UV laser diode.

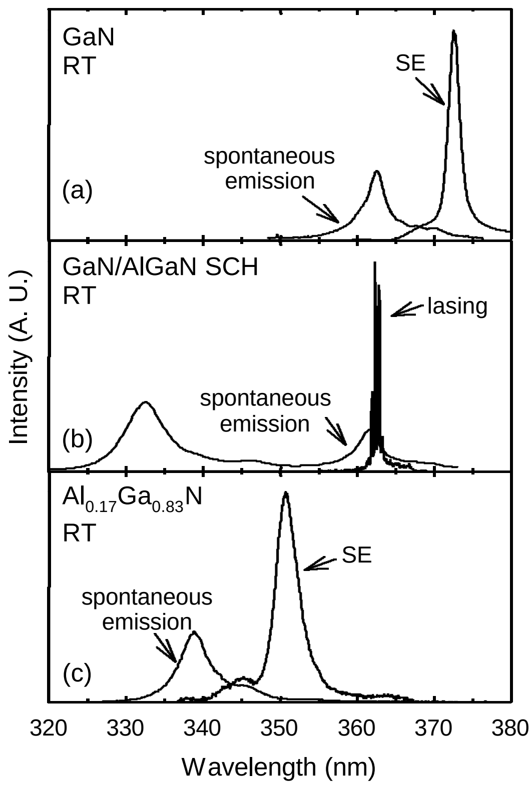

Figure 1. Spontaneous and SE/lasing spectra for the (a) GaN epilayer, (b) GaN/AlGaN SCH, and (c) $Al_{0.17}Ga_{0.83}N$ epilayer at room temperature.

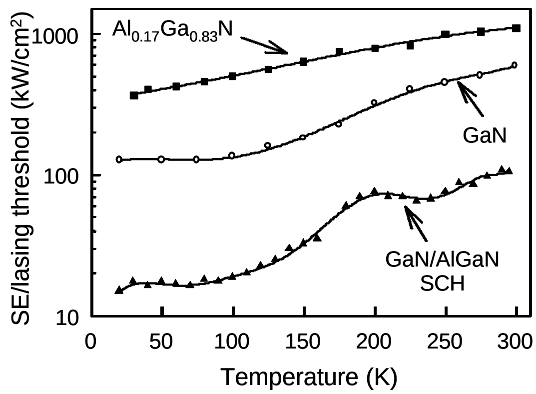

Figure 2. Stimulated emission thresholds for GaN and $Al_{0.17}Ga_{0.83}N$ epilayers and GaN/AlGaN SCH as a function of temperature.

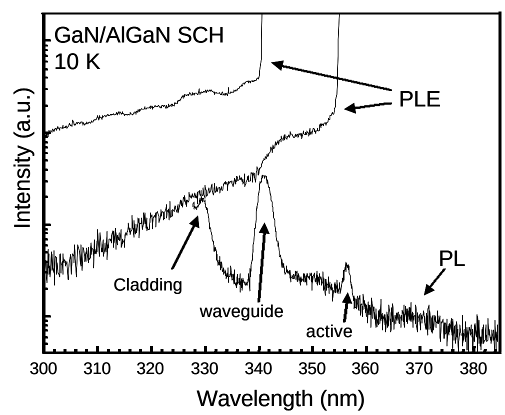

Figure 3. PL and PLE spectra for the SCH taken at 10 K.

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