AlGaInN-based ultraviolet light-emitting diodes grown on Si(111)

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Ultraviolet light-emitting diodes grown on Si(111) by gas-source molecular-beam epitaxy with ammonia are described. The layers are composed of superlattices of AlGaInN/GaN and AlN/AlGaInN. The layers are doped *n* and *p* type with Si and Mg, respectively. Hole concentration of $4 \times 10^{17} \text{ cm}^{-3}$, with a mobility of $8 \text{ cm}^2/\text{Vs}$, is measured in $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}/\text{GaN}$. We demonstrate effective *n*- and *p*-type doping of structures based on AlN/AlGaInN. Light-emitting diodes based on these structures show light emission between 290 and 334 nm. © 2002 American Institute of Physics. [DOI: 10.1063/1.1480886]

Alloys of AlGaInN are the materials of choice for light-emitting diodes (LEDs) operating in the (UV), below 380 nm. UV LEDs are expected to be useful in fluorescence and absorption based detection systems, dye pumping for incandescent light replacement, and applications in which short wavelengths and high brightness are required. There has been remarkable recent progress in the field of multi-quantum well (MQW) based UV LEDs, primarily grown on sapphire and SiC substrates by metalorganic vapor phase epitaxy (MOVPE).¹ Output powers greater than 1 mW at the emission wavelength of 340–350 nm have been achieved^{2,3} and devices with shorter emission wavelengths, 300–330 nm, are the subjects of active research.^{4–7} Higher output powers and shorter wavelengths are limited by the difficulty of preparing high quality Al-rich AlGaInN, limitations on *p*-type doping in large band gap alloys, and questions of designing the active layer structure for optimum emission efficiency. The high deposition temperatures associated with conventional MOVPE make it difficult to control the composition and thickness of AlGaInN quantum wells.⁷

This work describes the growth of AlGaInN-based MQW LEDs by gas-source molecular-beam epitaxy (GSMBE) with ammonia on Si(111) substrates. We describe procedures resulting in the preparation of MQW LEDs with emission wavelengths as short as 290 nm. The *p*-type layers of our LEDs are based on superlattices of AlGaInN/GaN and AlGaInN/AlN doped with Mg.

Schematic cross sections of device structures used in this work are shown in Fig. 1. The MQW LED structure illustrated in Fig. 1(a) consists of a 40-nm-thick AlN buffer layer deposited on Si(111), followed by a 50-nm-thick Si-doped $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ buffer layer and two superlattice structures, *n* and *p* type, with the MQW active region placed between them. Each *n*- and *p*-type superlattice, used to assure high electron and hole concentrations, respectively, consisted of

25 pairs of GaN quantum wells, 1 nm thick, separated by 5-nm-thick barriers of $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$. The *n*-type superlattice, placed above the nucleation layer of AlN and a layer of $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ needed to establish two-dimensional growth, also serves to block threading dislocations⁸ originating at the substrate interface. The active region is based on five quantum wells of GaInN, between 0.6 and 1.5 nm thick, in different device structures, separated by 5-nm-thick barriers of $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$. The detailed structure of this region is discussed next. A 20-nm-thick layer of undoped $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ placed between the active region and the *p*-type superlattice is used to minimize backdiffusion of Mg. We also present preliminary results obtained on homojunctionlike LEDs with *n*- and *p*-type superlattices based on AlGaInN/AlN, shown in Fig. 1(b). The primary goal of this structure is to test carrier injection in high-Al content superlattices. The growth procedure and details of preparation will be published elsewhere.⁹ The growth temperatures of AlN and AlGaInN/Ga(In)N were 830 °C–860 °C and 760 °C–800 °C, respectively. The average growth rates of AlN and AlGaInN, and AlGaInN and Ga(In)N, were 300 nm/h and 350 nm/h, respectively.^{8–12}

Hall measurements of *n*- and *p*-type superlattice structures based on $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}/\text{GaN}$ show average electron and hole concentrations of $2 \times 10^{18} \text{ cm}^{-3}$ and $4 \times 10^{17} \text{ cm}^{-3}$, respectively. These are doped uniformly with Si (derived from silane) and Mg. Room-temperature hole mobility of $8 \text{ cm}^2/\text{Vs}$ was measured in *p*-type superlattices. *n*-type superlattices of AlN/AlGaInN, modulation doped with Si, show carrier concentrations as high as $3 \times 10^{19} \text{ cm}^{-3}$ and mobilities of 15–20 cm^2/Vs . The *p*-type superlattices of AlN/AlGaInN are uniformly doped with Mg. Thermoprobe measurements of the two types of *p*-type superlattices show similar results. The undoped MQW active region has a background electron concentration in the low 10^{17} cm^{-3} range.

Cathodoluminescence (CL) spectra of the active layer MQW, with five GaN wells, are plotted in Fig. 2 for different well thicknesses. In the set of samples shown, the well thickness was changed from 1.5 to 0.6 nm. This has two effects.

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FIG. 1. Schematic cross sections of devices structures: (a) LED operating at 334 nm, and (b) carrier injection test structure based on AlN/AlGaInN superlattices. The buffer layer of this structure consists of an AlGaIn/GaN defect-blocking superlattice, followed by a 1.7- μm -thick layer of GaN.

There is a blueshift with decreasing well thickness, from 350 to 325 nm. The shift, illustrated in detail in the inset of Fig. 2, is linear and controllable. There is also a strong, and very reproducible, dependence of the CL intensity on the well thickness. It has a pronounced maximum at the well width of ~ 0.75 nm (the corresponding spectrum in Fig. 2 is divided by a factor of 5) and decreases for both wider and narrower wells. The optimum CL spectrum is quite narrow, with the full width at half maximum (FWHM) of less than 11 nm. The addition of a small amount of In, less than 0.5%, to the GaN wells increases the overall luminescence intensity by factors of 3–5, without changing the well thickness dependence. The redshift due to the addition of In is less than 2 nm. The double-peak emission often observed in the spectra of these wells is believed to arise from growth procedure artifacts. For instance, the Al and Ga fluxes increase when the shutters are opened and the resulting flux transients change the composition of the well. This may be less important in the growth of narrower wells, which take only 3–5 s

FIG. 2. Room-temperature CL spectra of GaN active layer quantum wells measured as a function of thickness. Inset shows wavelength dependence on the well thickness.

to grow. For the thickest wells, we can not be sure of the well uniformity or continuity. Their spectra show slight broadening, FWHM $\sim (15\text{--}20)$ nm, and weak substructure that is not resolved at room temperature. The possibility of spontaneous formation of one- and two-dimensional structures, analogous to that observed in growth on (311) surfaces of GaAs (Ref. 13) might have to be considered.

A combination of Ga(In)N wells and $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ barriers can not be used for emission wavelengths shorter than ~ 320 nm. In order to obtain shorter wavelengths, Al needs to be added to the well. At the same time, the Al content in the barrier must be increased to provide adequate confinement. Figure 3 shows CL spectra obtained for three AlGaInN quantum well structures with the Al fraction of ~ 0.1 and the In fraction similar to that just described. All of these wells are 0.5 nm thick, a thickness based on the optimization process similar to that shown in Fig. 2. The barriers are all pure AlN. The shortest wavelength of 269 nm was obtained with a barrier width of 5 nm, similar to that used in the active layer of Fig. 2. Reduced barrier thickness results in a redshift to

FIG. 3. Room-temperature CL spectra of 0.5-nm-thick AlGaInN quantum well placed between barriers of AlN, plotted for different barrier thicknesses. Concentrations of Al, Ga, and In are the same in each sample.

FIG. 4. Room-temperature continuous wave electroluminescence obtained from the two structures investigated here. Solid line shows the emission spectrum of a MQW LED with wells based on GaInN. The spectrum was obtained with a current of 10 mA. The dashed line shows the emission spectrum of a carrier injection test structure based on AlN/AlGaInN superlattice. The spectrum was obtained at a current of 100 mA.

273 nm and 280 nm for barriers 2.5 nm and 1.25 nm thick, respectively. This shift is expected from lower confinement of the carrier wave function with thin barriers. However, the barriers of AlN must be thin to allow carrier tunneling in these devices. It should be stressed that the room-temperature CL efficiency of these structures is similar to that of Ga(In)N MQW structures of Fig. 2.

Figure 4 shows room-temperature electroluminescence (EL) spectra from the MQW LED structure illustrated in Fig. 1(a) and from the carrier injection structure of Fig. 1(b). The active region of the LED is based on the MQW design shown in Fig. 2, with wells of GaInN. The EL spectrum is obtained under dc bias, with a forward current of 10 mA and a forward voltage $V_f \sim 15$ V. The diode is processed simply by depositing a *p*-type ohmic contact. This is sufficient to collect spectral information but not to evaluate the power output. The LED emits at 334 nm in a narrow, ~ 12 nm FWHM, and symmetric peak. We do not observe any defect emission at longer wavelengths. The room-temperature EL spectrum of the carrier injection structure, a homojunction-like LED, based on *n*- and *p*-type superlattices of AlN/AlGaInN, is shown as a dashed line in Fig. 4. The EL spectrum is obtained with a dc current of 100 mA and $V_f \sim 25$ V. This structure does not contain an active region, it is used only to evaluate the effectiveness of carrier injection from AlN/AlGaInN superlattices. Since the minority hole diffusion length is considerably shorter than that of electrons, radiative recombination is expected predominantly in *p*-type material. The spectrum shows a well-defined edge at 290 nm, followed by a broader structure at longer wavelength. This demonstrates the effectiveness of AlN-based superlattice in carrier injection. The luminescence efficiency is considerably weaker than that of the GaInN MQW LED operating at 330 nm. This is expected since the recombination region is not well defined and the entire structure is heavily doped.

The use of doped superlattices was proposed in order to bypass the acceptor incorporation limits in AlGaIn. Experimentally, average hole concentrations at least ten times higher than that achieved in a uniform layer appear

possible.^{15,16} The concept was used by Nakamura *et al.*¹⁷ in order to reduce the series resistance of laser structures and was applied recently to UV LEDs.^{1–7} Further refinements through modulation doping appear feasible.¹⁸ Replacement of a difficult to dope uniform layer with a superlattice in which the effective hole density is determined only by its geometry is crucial to the successful preparation of UV LEDs. The work described here shows that the idea can also be applied to superlattices with AlN barriers.

In summary, we describe LEDs based on *n*- and *p*-type superlattices of AlGaIn/GaInN and AlN/AlGaInN with the emission wavelengths between 340 and 290 nm. These devices are grown on Si(111) substrates using GSMBE with ammonia.

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