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**GaN$_{0.011}$P$_{0.989}$–GaP Double-Heterostructure Red Light-Emitting Diodes Directly Grown on GaP Substrates**

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**Abstract**—Novel red light-emitting diodes (LEDs) based on GaN$_{0.011}$P$_{0.989}$–GaP double-heterostructure (DH) directly grown on (100) GaP substrates have been fabricated for the first time. The samples were grown by gas-source molecular beam epitaxy with an RF nitrogen radical beam source to incorporate N in GaP. Compared to conventional GaAs-based AlGaInP red LED’s, this novel LED structure eliminates the complicated steps of etching the light-absorption GaAs substrate and wafer-bonding to a transparent GaP substrate. Based on the uncoated devices made with the heterojunction bipolar transistor masks, the emission efficiency of the DH LEDs is 20 times stronger than that of a GaNP pn homojunction diode.

**Index Terms**—AlGaInP, double heterostructure, GaNP, GaP, GSMBE, LED.

The search for new materials and structures for the fabrication of efficient visible light-emitting diodes (LEDs) are of growing interest due to their wide applications, such as automotive lighting, outdoor variable message signs, and traffic lights, etc. This has stimulated extensive research on the AlGaInP semiconductor alloy system grown on GaAs substrates for high-brightness red LEDs since its band-gap energy can be tuned from green to red with lattice matching to GaAs substrate [1 – 3]. However, there are some drawbacks for AlGaInP LEDs, such as poor current spreading and strong light absorption by the GaAs substrate. Many processes have to be used to solve these problems, including the growth of a thick GaP [2] or AlGaAs “window” layer [1] to improve current spreading, etching the GaAs substrate and wafer-bonding to a transparent GaP substrate to improve light-extraction efficiency [3].

Using 512-atom pseudopotential supercell calculations, Bellaiche et al. predicted a transition from indirect to direct band-gap at an N concentration of 3% for GaNP alloys [4]. Recently, we have shown that incorporation of N in GaN$_x$P$_{1-x}$ alloys ($x \geq 0.43\%$) leads to a direct band-gap behavior of GaNP due to the strong interaction among the N-related bound states which exhibit a quasi-direct nature in the optical transition. Very strong PL emission at room temperature (RT) is produced, making GaNP a promising LED material [5]. A simple red LED based on a GaN$_{0.011}$P$_{0.989}$ pn homojunction directly grown on a GaP substrate was successfully obtained [6]. Compared to conventional AlGaInP LEDs, GaNP–GaP eliminates etching of the GaAs substrate and wafer-bonding of a transparent GaP substrate. It is also easier to grow a thick, high quality homoepitaxial GaP window layer on the GaP substrate. The emission efficiency of the homojunction, however, was low mainly due to the high self-absorption of the generated radiation. The entire structure, including the active region, has the same composition. In this letter, we report for the first time red LEDs with improved efficiency by using a GaN$_{0.011}$P$_{0.989}$–GaP double-heterostructure (DH) directly grown on a (100) GaP substrate.

Fig. 1(a) shows a schematic structure of the GaNP–GaP DH LED. The sample was grown on a (100) GaP substrate by gas-source molecular beam epitaxy (GSMBE) in a modified Varian Gen-II system with a nitrogen RF radical beam source (Oxford Applied Research Model MPD21) to generate active N species. Beryllium and silicon were used as p- and n-type dopants, respectively. The growth details are described elsewhere [5]. Because of the low doping of GaP substrate ($\sim10^{17}$ cm$^{-3}$), the diodes were fabricated by a standard single-mesa wet-etching process. Fig. 1(b) shows a top-view schematic of GaNP LED.
Fig. 2. (400) X-ray rocking curve and the dynamical theoretical simulations of the GaN_{0.011}P_{0.989} DH LED structure.

Fig. 3. Current–voltage (I–V) characteristics of an uncoated GaNP pn homojunction and DH LED. The electrodes were formed by conventional photolithography, metal evaporation, lift-off, and furnace annealing. AuZn was evaporated on the p^-GaP. The n^-GaP was reached by wet chemical etching and subsequently GeAuNiAu was evaporated. The nitrogen composition was determined by high-resolution X-ray rocking curve measurement and theoretical dynamical simulations, as shown in Fig. 2. Due to the thickness much larger than the critical layer thickness calculated from the Matthews and Blakeslee's model (~100 nm) [7], the GaN_{0.011}P_{0.989} layer is partially relaxed and its X-ray peak is broader than the simulation result.

Fig. 3 shows the current–voltage (I–V) characteristics of an uncoated GaNP pn homojunction and DH LED, respectively. The device exhibits normal diode turn-on forward characteristics. The larger turn-on voltage is mainly due to the poor contact of p-type GaP. The ideality factor is 1.8 for the GaNP pn homojunction diode and 1.5 for the DH LED, respectively. The avalanche reverse breakdown of DH LED is larger than 20 V, higher than the 12 V for the GaNP pn homojunction diode.

The nitrogen composition was determined by high-resolution X-ray rocking curve measurement and theoretical dynamical simulations, as shown in Fig. 2. Due to the thickness much larger than the critical layer thickness calculated from the Matthews and Blakeslee’s model (~100 nm) [7], the GaN_{0.011}P_{0.989} layer is partially relaxed and its X-ray peak is broader than the simulation result.

Fig. 4 shows RT electroluminescence (EL) spectra at different forward currents of an uncoated DH LED. The inset is the photoluminescence spectrum of the LED sample. The EL emission peak slightly blue-shifts with an increased current, likely due to band-filling effect. The presence of random composition fluctuations in the GaNP alloy causes a potential fluctuation, which causes a formation of emission tails in Fig. 4. Similar results were also reported in GaNAs alloys [8].

Fig. 5 shows light output power density measured at RT against DC input current of an uncoated GaNP pn homojunction and DH LED with different window size opening. The output power as a function of current was measured for an on-wafer device with a 0.5-in distance between the optical power detector and the device. Therefore, the actual output power was severely underestimated. It is difficult from the measured output power versus current to estimate the external quantum efficiency of the diode because accurate measurements require packaging or an integrating sphere. Compared to GaNP pn homojunction LED, the emission efficiency of the GaNP DH LED is improved by 20 times. Since the fundamental band-gap energy reduction of GaNP due to N incorporation mainly occurs in the conduction band [5], GaNP–GaP DH has the following advantages: enhanced injection efficiency of electrons, strong confinement of injected carriers in the GaNP active layer,
and formation of transparent window and substrate layers for improved light extraction. Therefore, the emission efficiency of a GaNP DH LED is much higher than that of a GaNP pn homojunction LED. Also shown in Fig. 5, the light-output power density is independent of window size, indicating good sample uniformity.

Since standard heterostructure bipolar transistor (HBT) masks were used to fabricate these LEDs, most of the radiation occurred under the metal contact where the current density was highest. The light generated under the contact was either blocked and absorbed by the contact or reflected back into the chip. The reflected light had a high probability of being absorbed within the chip itself. Thus, the emission efficiency of our LEDs was severely reduced. Partially relaxed GaNP active layers could also degrade the emission efficiency. The light extraction efficiency could be improved by growing a thick homoepitaxial GaP current-spreading window layer in a vertical current-flow structure grown on an n+-GaP substrate with contacts on the top and bottom of the device to facilitate adequate current-spreading within the device [9].

In summary, red GaN$_{0.011}$P$_{0.989}$–GaP DH LEDs have been fabricated from a structure directly grown on a GaP substrate by GSMBE, which eliminates two process steps for high-brightness AlGaInP LEDs. It is also easier to grow a thick homoepitaxial GaP window layer. The GaN$_{0.011}$P$_{0.989}$ DH LEDs exhibit an emission around 650 nm, and the emission efficiency is 20 times stronger than that of a GaN$_{0.011}$P$_{0.989}$ pn homojunction LED.

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