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# AlGaN-based 280 nm light-emitting diodes with continuous-wave power exceeding 1 mW at 25 mA

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Optimization of the migration-enhanced metalorganic chemical vapor deposition and further optimization of the contact and active layer design for 280 nm light-emitting diodes resulted in large improvement of cw and pulsed output power and in a superior spectrum purity. The ratio of the main peak to the background luminescence determined by the detection system is higher than 2000:1 at 20 mA dc. The on-wafer cw power was measured to be 255 $\mu$W at 20 mA dc. The power popped up exceeding 1 mW for a packaged device under 25 mA dc and 9 mW under pulse 200 mA. The maximum wall-plug-efficiency of 0.67% was obtained for the packaged device at 25 mA dc. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1831557]

Solid-state deep UV light sources are expected to find numerous applications in detection of biohazardous agents, water, air, and food sterilization, high-density data storage, covert communication, and solid state lighting. Several groups have reported on sub-290 nm UV light-emitting diodes (LEDs).[1–8] High-temperature thick AlN buffers and strain-management-defect-filtering AlN/AlGaN superlattices for thick AlGaN growth were shown to improve device performance.[9–12] Yet the reported deep UV LED powers are still much smaller than those for InGaN-based blue-purple LEDs for several reasons.

Another problem accompanying the deep UV LEDs development is the appearance of long-wavelength emissions in the electroluminescence (EL). The origin of these emissions has been identified as related to conduction-electron-acceptor transitions possibly from electrons entering the $p$-AlGaN/$p$-GaN contact region.[13] Although adding high barrier $p$-AlGaN electron blocking layer greatly suppressed the long-wavelength emissions, the best reported intensity ratio of main-peak/long-wavelength-emission was around 50:1 at 20 mA dc driving current.[2] This is not high enough for many bio-applications like protein/DNA analysis.

This letter reports on our latest progress in developing 280 nm LEDs. We achieved on-wafer cw power at 280 nm of 255 $\mu$W at 20 mA dc. Flip-chip packaged single device on TO39 header gave cw power as high as 1 mW at 25 mA. The spectrum purity was also tremendously improved. The ratio of the main peak to the background luminescence determined by the detection system is higher than 2000:1 at 20 mA dc.

This was achieved by optimizing the migration-enhanced metalorganic chemical vapor deposition (MEMOCVD™) growth of active layers, such as precursor pulse durations and overlaps to improve materials quality, which plays a major role.[11] Indeed, our recent studies show that the diffusion length of light-generated carriers is nearly equal to the average distance between dislocations and that the radiative recombination rate decreases with an increase of the Al molar fraction.[14] Our cross-section transmission electron microscopic study showed that the thick Si-doped $Al_{0.55}Ga_{0.45}N$ layer grown using the above-mentioned defect reduction technology has a threading dislocation density of low $10^9$ cm$^{-2}$, which is comparable to that of regular GaN epilayers. We also used the improved UV design described in Refs. 1 and 15 in more detail.

The UV LED structure was grown in a custom-designed vertical metalorganic chemical vapor deposition system, with trimethyl aluminum (TMA), trimethyl gallium (TMG), silane, Cp2-Mg, and $NH_3$ as precursors and basal plane sapphire as substrates. The AlN buffer and superlattices were grown by the MEMOCVD. The active region consisted of five periods of Si-doped $Al_{0.5}Ga_{0.5}N/Al_{0.4}Ga_{0.6}N$ quantum wells with the barrier and well thickness of 70 and 35 Å, respectively.

LED patterns with various area/perimeter ratios were designed and mesa-type devices were fabricated. The bottom $n$-$Al_{0.55}Ga_{0.45}N$ was accessed by reactive-ion-etching using chlorine plasma. The Ti/Al/Ti/Au $n$-type ohmic contact metallization was performed at 900 °C. Ni/Au metals were used for the $p$-side contact. The representative current–voltage ($I$–$V$) curve for two $100\times100$ $\mu$m$^2$ devices connected in parallel is shown in Fig. 1. The device current was 20 mA at 5.2 V, with a series resistance of 7.2 Ω. The inset

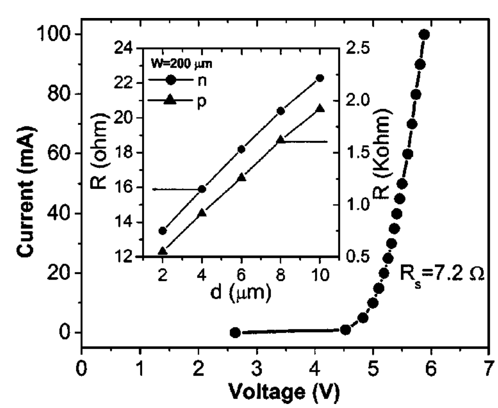


FIG. 1. $I$–$V$ curve for the two 0.0001 cm$^2$ 280 nm parallel packaged UV LEDs. The inset shows the $p$- and $n$-TLM results.

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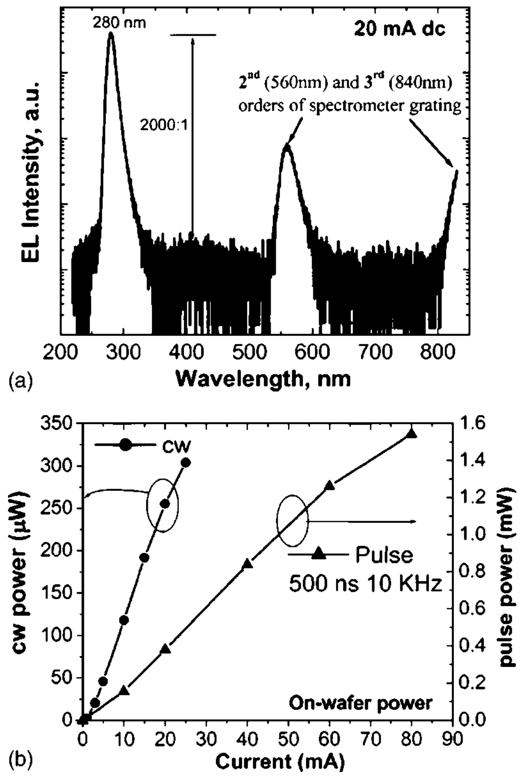


FIG. 2. Room-temperature (a) electroluminescence spectrum of the one 0.0001 $cm^2$ 280 nm UV LED operating at 20 mA dc, (b) on-wafer cw and pulse power measurement for the device.

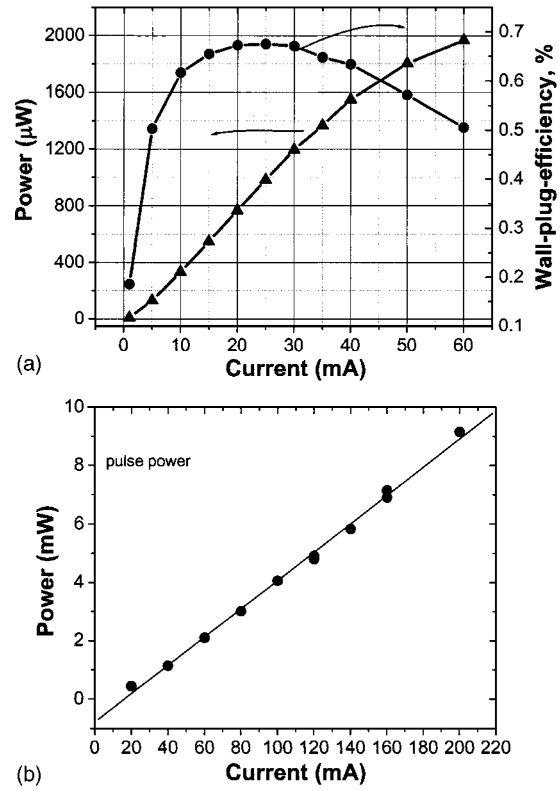


FIG. 3. Room-temperature (a) cw power and wall-plug-efficiency, and (b) pulse power measurement for the flip-chip packaged 280 nm UV LED. (Note: Updated results show cw power in excess of 1 mW at 20 mA with the wall-plug efficiency of 0.85%.)

to Fig. 1 showed the *n*-contact and *p*-contact transfer length measurements (TLM). From TLM measurements we determined the *n*- and *p*-contact specific contact resistances to be $5.91\times10^{-5}$ and $1.42\times10^{-4}\ \Omega\ cm^2$, respectively. The measured sheet resistance of the $n$-$Al_{0.55}Ga_{0.45}N$ was 220 $\Omega/\square$.

We include the EL spectrum of the device in Fig. 2(a). The spectrum was taken on-wafer at room temperature under dc current of 20 mA. To search for any possible long-wavelength emissions, the spectrum was recorded within a broad range, from 200 to 840 nm, and plotted in semi-logarithm. As seen, the spectrum consisted of a strong 280 nm line along with its second and third orders of spectrometer grating lines. There is no long-wavelength emission above the noise level. The intensity ratio of the 280 nm line to the background luminescence is 2000:1 at this current. With this spectrum purity, we were able to measure the on-wafer power by an UV enhanced Si photodetector without bandpass filters. Figure 2(b) presents the on-wafer cw and pulse powers dependencies on the device current. The cw powers linearly increase up to 25 mA, which translates to a current density of 250 $A/cm^2$. At 20 mA an on-wafer cw power of 255 $\mu$W was measured. The on-wafer cw power–current ($L$–$I$) slope as high as 13.7 $\mu$W/mA was obtained, which is about three times higher than our previously reported value for the packaged 280 nm LEDs.[4] The pulse powers were measured using 500 ns pulse duration and 0.5% duty cycle to avoid heating. A $L$–$I$ slope of 22 $\mu$W/mA was measured for the pulse operation, indicating a less serious heating issue. At 80 mA, a pulse power exceeding 1.5 mW was achieved.

Flip-chip packaging with massive contact bumps and optimized package design benefit the LED light extraction and heat removal. Two LED chips of $10^{-4}$ $cm^2$ area were packaged in parallel on commercial TO39 package header with parabolic UV-reflector. Figure 3 presents the results of the cw and pulse power measurements for the packaged device, as were done in an integral sphere. As seen, a total power of 768 $\mu$W was obtained at 20 mA dc, with the $L$–$I$ slope more than 41 $\mu$W/mA. The power went up beyond 1 mW at 25 mA dc. The maximum wall-plug-efficiency of 0.67% was achieved at 25 mA dc, exceeding 0.6% in the currents range of 10–40 mA. In the pulse operation, with pulse duration of 1 $\mu$s and duty cycle 0.5%, the power increased linearly with current up to 200 mA, with the measured pulse power greater than 9 mW. Such a large improvement for the packaged device might be considered as indirect evidence for the device edges as preferred direction for the light extraction.[14,16]

In conclusion, an optimization of the MEMOCVD epitaxial growth combined with defects/strain management and active region design optimization resulted in 280 nm LEDs with a superior spectrum purity. An on-wafer cw power of 255 $\mu$W was measured at 20 mA. The power exceeded 1 mW for packaged devices under 25 mA dc, with the pulsed power above 9 mW at 200 mA. The maximum dc wall-plug-efficiency of 0.67% was measured at 25 mA.

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