Barrier doping increases light from semi-polar nitride quantum wells

UCSB and Mitsubishi create devices with orange-red emissions beyond 600nm.

University of California Santa Barbara (UCSB) and Mitsubishi Chemical Corp researchers have used p-type doping of the middle barrier of semi-polar nitride semiconductor double quantum well (DQW) LEDs to increase light output [Chia-Yen Huang et al, Appl. Phys. Lett., vol99, p141114, 2011]. The emission wavelengths of the devices were longer than 500nm (blue-green), and even — using aluminum gallium nitride barriers — longer than 600nm (orange-red).

The DQW structures were grown using MOCVD on free-standing $(20\bar{2}1)$ semi-polar gallium nitride (GaN) substrates supplied by Mitsubishi Chemical. The thickness of the two wells of indium gallium nitride (InGaN) was estimated to be 3nm. The middle barrier was measured to be 10nm thick. The paper does not give the In fraction of either the wells or barrier.

Doping of the middle barrier was achieved using bis-cyclopentadienyl magnesium (Cp2Mg) source with flow rates of 0 (i.e. undoped), 0.6, 1, 3 and 5 standard cubic centimeters (sccm). With 1sccm flow the Mg concentration was measured using secondary-ion mass spectrometry (SIMS) at $6x10^{18}/cm^3$. It was assumed that the effect of these flow rates on doping concentration was linear.

Some Mg was also present in the wells at about a tenth of the concentration in the barriers, which was attributed either to diffusion or to a 'memory effect' of dopant source in the growth chamber. Ideally, one doesn't want any doping in the wells, since it is known that this increases non-radiative electron–hole recombination, reducing the internal quantum efficiency (i.e. conversion into photons) of the device.

The devices were completed with a 10nm p-type aluminum gallium nitride (AlGaN) electron-blocking layer and 100nm p-GaN cap. The resulting LED chips were 490μm x 292μm with $0.1mm^2$ current injection area.

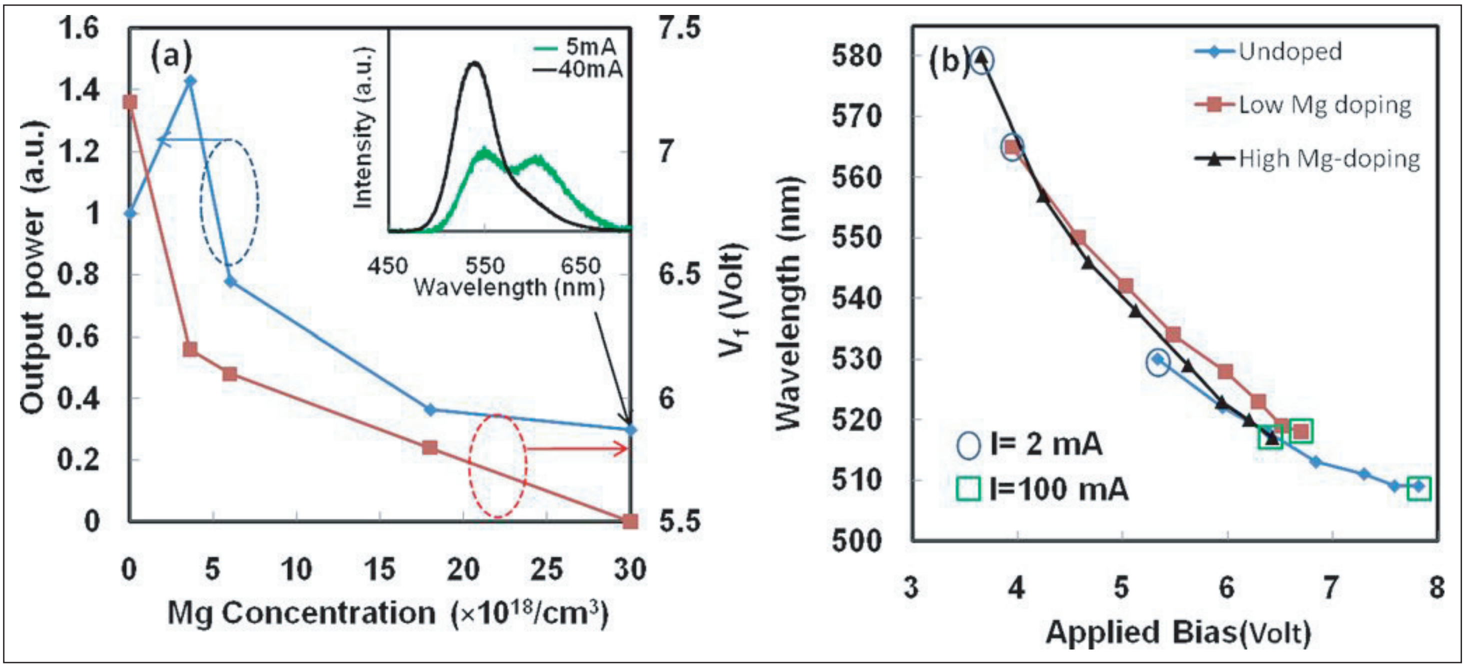

Figure 1. (a) Relative output power and forward voltage (V_f) under 20mA injection for LEDs with different Mg doping levels in barrier. The upper right corner shows the electroluminescence (EL) spectra under 5mA and 40mA injection for LEDs with high Mg doping levels (b) EL peak wavelength versus applied bias for current injection levels ranging from 2mA to 100mA for undoped, low-doped ($3.6x10^{18}/cm^3$), and high-doped ($1.8x10^{19}cm^3$) barriers.

► Forward voltages of the devices at 20mA drop as the doping of the barriers increases (Figure 1a). "This result suggests the existence of carrier transport issues between QWs for long-wavelength $(20\bar{2}1)$ MQW LEDs," the researchers say. At the same current, the light output power peaks and then declines "significantly" with doping level.

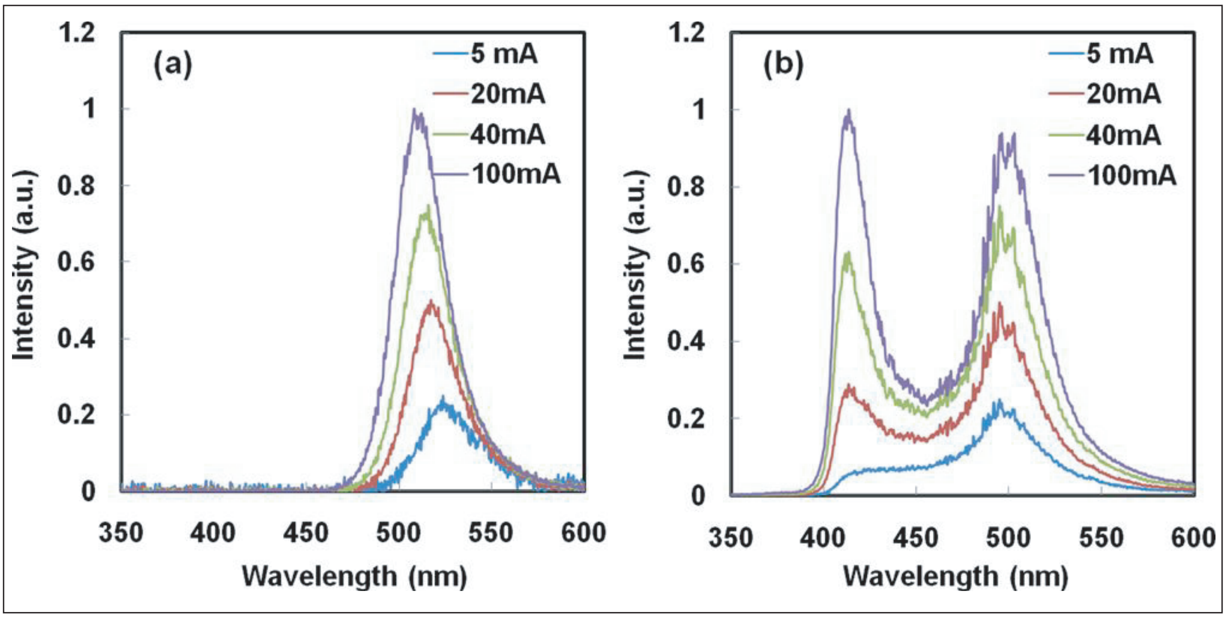

Figure 2. Electroluminescence spectra of dichromatic DQW LEDs with (a) undoped barriers and (b) Mg-doped barriers under various injection levels.

The spectral content of the electroluminescent emission changes according to injection current (Figure 1a inset) and doping (Figure 1b). At low current and high doping, the spectrum has two peaks separated by about 200meV. The researchers suggest that the longer-wavelength peak may be due to transitions between the conduction band and Mg acceptor level or complexes of Mg and hydrogen atoms in the QWs. As the current increases, this route to light output saturates and becomes insignificant in the spectrum.

The reduction in light output with higher doping level is explained as being likely due to inefficiency of the conduction band to acceptor transition or due to the presence of Mg ions in the wells leading to non-radiative recombination such as through the Shockley–Read–Hall mechanism that competes with light emission. "This suggests a trade-off between carrier transport and recombination efficiency in the QWs," the team notes.

Increasing current leads to a blue-shift to shorter wavelengths that could be explained by band filling (increasing the energy separation between electrons and holes), carrier screening or band bending effects. The Mg doping creates a red-shift to longer wavelengths. However, it is to be noticed that, despite these effects, the emission wavelength depends on the applied bias in a similar way between devices (Figure 1b). Thus, the longer emission wavelengths of the more highly doped LEDs are related to their lower forward voltage.

The researchers also studied double quantum wells with different emission wavelengths (Figure 2). This was achieved by growing the n-side well at 865°C and the p-side well at 765°C. With undoped barriers, the emission spectrum appeared to be a single peak in the range 515–520nm (blue-green) with injection currents up to 100mA, suggesting that most of the radiant recombination takes place in the p-side well. With Mg-doped barriers (~$6\times10^{18}/cm^3$), a second peak emerges in the range 410–420nm (violet) as the injection current is increased from 5mA to 100mA. At the upper end of current injection the violet peak becomes comparable in intensity to the longer wavelength.

The tendency for the holes to remain in the well nearest the p-contact in multi-quantum well structures is well known. The UCSB researchers comment: "Considering the trade-off between enhanced carrier transport and radiative efficiency in each QW, the overall radiative efficiency of the active region could be increased with an optimized Mg doping profile in barriers."

Simulations suggest that one effect of doping the middle barrier of the structure is to bend the band profiles so that the barriers to electron and, more importantly, hole injection are reduced.

The Mg-doped barrier technique has also been applied to devices with AlGaN barriers. Such barriers are found to improve crystal quality for green semi-polar green laser diodes and for quantum wells with high indium concentration. The researchers used AlGaN barriers with Mg-doping to create orange-red emission in continuous-wave operation. At 10mA, the emission peak is at more than 650nm, blue-shifting to 590–600nm at 100mA.

The researchers says the long wavelength at low current is due to the low bias allowed by Mg-doping. The large blue-shift at large injection current seems to be due to the strain effects caused by the large difference in lattice constant between InGaN quantum well and AlGaN barrier. Such strain sets up polarization electric fields due to the large piezoelectric effect in nitride semiconductors, leading to strong quantum-confined Stark effects (QCSEs).

http://apl.aip.org/resource/1/applab/v99/i14/p141114_s1

Author: Mike Cooke