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Green electroluminescence from Er-doped GaN Schottky barrier diodes

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Visible light electroluminescence (EL) has been obtained from Er-doped GaN Schottky barrier diodes. The GaN was grown by molecular beam epitaxy on Si substrates using solid sources (for Ga, and Er) and a plasma source for N_2. Al was utilized for both the Schottky (small-area) and ground (large-area) electrodes. Strong green light emission was observed under reverse bias, with weaker emission present under forward bias. The emission spectrum consists of two narrow green lines at 537 and 558 nm and minor peaks at 413 and at 666/672 nm. The green emission lines have been identified as Er transitions from the $^2H_{11/2}$ and $^4S_{3/2}$ levels to the $^4I_{15/2}$ ground state and the blue and red peaks as the $^2H_{9/2}$ and $^4F_{9/2}$ Er transitions to the same ground state. The reverse bias EL intensity was found to increase linearly with bias current. © *1998 American Institute of Physics.* [S0003-6951(98)00343-X]

Starting with the pioneering work[1] of Ennen *et al.* with erbium-doped Si $p-n$ junctions, Er-doped semiconductor light-emitting diodes (LED's) have been shown to emit in the near infrared (IR) at ~ 1.5 μm. The near-IR emission corresponds to transitions between the lowest excited state ($^4I_{13/2}$) and the ground state ($^4I_{15/2}$) of the erbium atoms. Improvements in emission efficiency of Er-doped Si IR LED's obtained by co-doping with oxygen have enabled room-temperature operation.[2,3] Wide-band-gap semiconductors (WBGS) are attractive Er hosts because the emission efficiency appears to increase with the band-gap value,[4] thus allowing room-temperature operation without the need to introduce other impurities. Electroluminescence has been reported from several WBGS hosts, including Er-doped GaAs,[5] GaP,[6] GaN,[7,8] ZnSe,[9,10] and SiC.[11] The properties of Er-doped GaN and other III–V semiconductors has been recently reviewed by Zavada and Zhang.[12] The GaN-based semiconductor structures are of great interest because they appear to be optically very robust, exhibiting high emission levels under conditions of defect density that would normally quench emission in other smaller-gap III–V and wide-gap II–VI compounds.[13] As a consequence, LED's and lasers based on intrinsic emission from GaN (and related alloys) have developed extremely rapidly in the past few years.[14]

We have recently reported visible photoluminescence (PL) from Er-doped GaN films grown on sapphire[15] and Si.[16] In this letter, we report the operation of Er-doped GaN Schottky contact LED's emitting visible light. Er-doped GaN films were grown in a Riber MBE-32 system on 2 in. p-Si (111) substrates. Solid sources were employed to supply the Ga (7N purity) and Er (3N) fluxes, while an SVTA rf-plasma source was used to generate atomic nitrogen. For the work reported here, a GaN buffer layer was first deposited for 10 min at a temperature of 600 °C, followed by GaN growth at a temperature of 750 °C. The growth conditions were as follows: N_2 flow rate of 1.5 sccm at a plasma power of 400 W, Ga cell temperature of 922 °C (corresponding to a beam pressure of 8.2×10^{-7} Torr), and Er cell temperature of 1100 °C. The resulting GaN growth rate was ~ 0.8 μm/h and the Er concentration was $\sim 5\times10^{20}/\mathrm{cm}^3$. GaN films with a thickness of ~ 2.5 μm were utilized.

To fabricate Schottky diodes on the GaN:Er films a semitransparent Al layer was deposited by sputtering. The Al film was patterned into a series of ring structures of varying areas utilizing a lift-off process. The Al rings served as individual Schottky contacts, while the large continuous Al surface was used as the common ground electrode. Electroluminescence (EL) characterization at ultraviolet (UV) and visible wavelengths was performed with a 0.3 m Acton Research spectrometer outfitted with a photomultiplier tube (PMT) detector. All measurements were conducted at room temperature using dc applied bias voltage and current.

Applying reverse bias current of the order of 1 mA to a GaN:Er Schottky LED results in green emission visible with the naked eye under normal ambient lighting conditions. A typical EL spectrum is shown in Fig. 1 for a LED operated at 1.5 mA. The spectrum extends from 350 to 700 nm, covering the UV-to-red wavelength range. The area of the diode is 7.65×10^{-4} cm^2, yielding a current density of ~ 2 A/cm^2. The emission spectrum consists of two strong and narrow

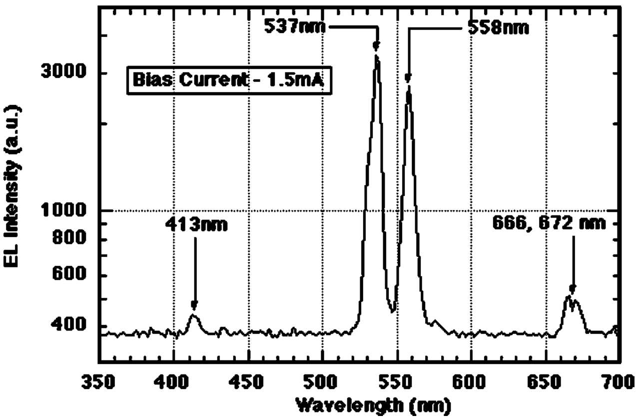

FIG. 1. Room-temperature, visible EL spectrum of GaN:Er Schottky barrier LED (7.65×10^{-4} cm^2 area) operating with 1.5 mA current.

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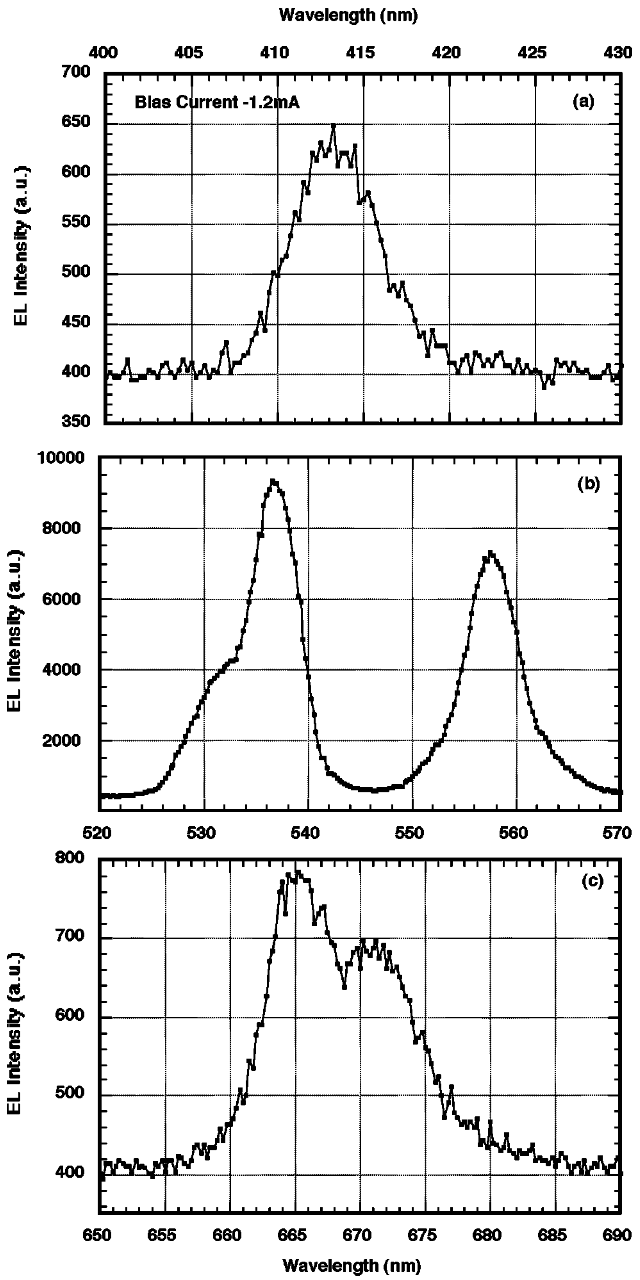

FIG. 2. High-resolution spectra of the EL-active regions from the GaN:Er Schottky barrier diode (7.65×10^{-4} cm^2 area) operating with 1.2 mA current: (a) blue peak; (b) green peaks; and (c) orange-red peaks.

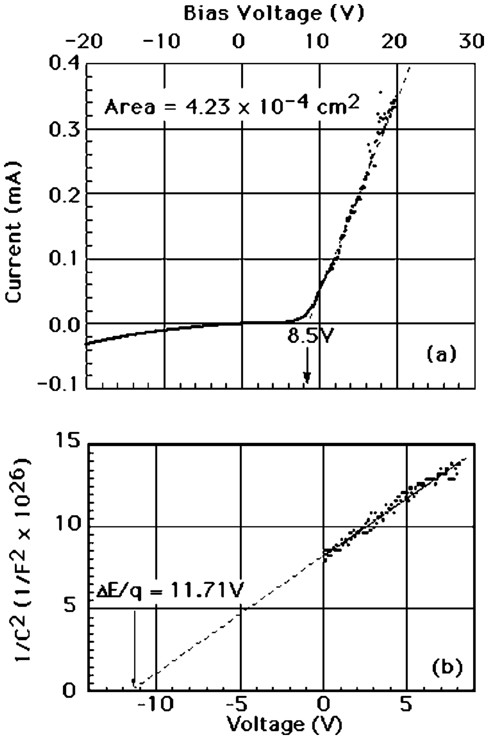

FIG. 3. GaN:Er Schottky diode electrical characteristics: (a) current–voltage; and (b) capacitance–voltage.

lines at 537 and 558 nm, which provide the green emission color. The two green lines have been identified as Er transitions[17] from the $^2H_{11/2}$ and $^4S_{3/2}$ levels to the $^4I_{15/2}$ ground state. Photoluminescence (PL) characterization of the same GaN:Er films grown on Si performed with a He–Cd laser excitation source at a wavelength of 325 nm, corresponding to an energy greater than the GaN band gap, also produced green emission from the same two transitions. Minor EL peaks are observed in Fig. 1 at 413 and at 666/672 nm. They correspond, respectively, to the $^2H_{9/2}$ and $^4F_{9/2}$ Er transitions to the same ground state. No intrinsic band-edge EL emission from the GaN itself was observed.

Expanded sections of the EL emission peaks from the spectrum of Fig. 1 are shown in Fig. 2. The full width at half maximum (FWHM) of these emission lines is around 6 nm. For the largest EL peak at 537 nm, this is equivalent to an energy width of 25.8 meV. The corresponding PL peak has a FWHM of around 3 nm (≈13 meV). It is instructive to compare these emission characteristics to those of conventional GaN-based green LED's. As discussed by Nakamura and Fasol,[14] there are two approaches for obtaining green LED's utilizing III–N alloys: (a) an InGaN/AlGaN double heterojunction (DH) structure; and (b) an InGaN single quantum well (SQW) structure. The DH structure requires heavy codoping ($\sim10^{19}$/cm^3) with Si and Zn to achieve green emission. The InGaN DH LED biased at 0.5 mA emits at a wavelength of 537 nm, with a FWHM of ~90 nm (Ref. 14, see p. 190). The InGaN SQW structure requires the growth of seven layers, including a 2 nm thick quantum well. The composition of the SQW determines the emission wavelength. Green SQW LED's emitting at 525 and 550 nm have linewidths of 45 and 65 nm, respectively (Ref. 14, see p. 204).

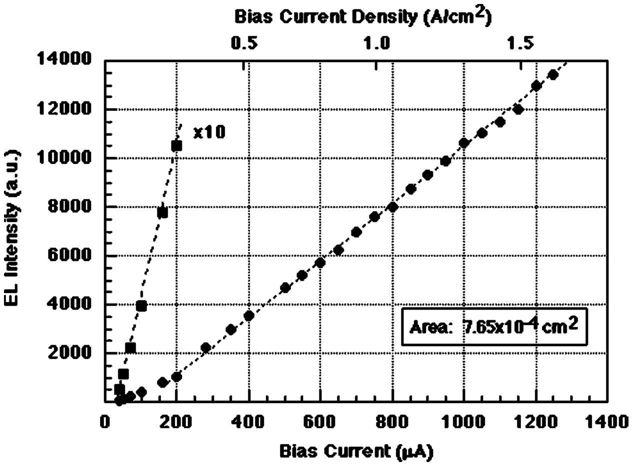

FIG. 4. Total visible EL emission intensity vs bias current at 300 K.

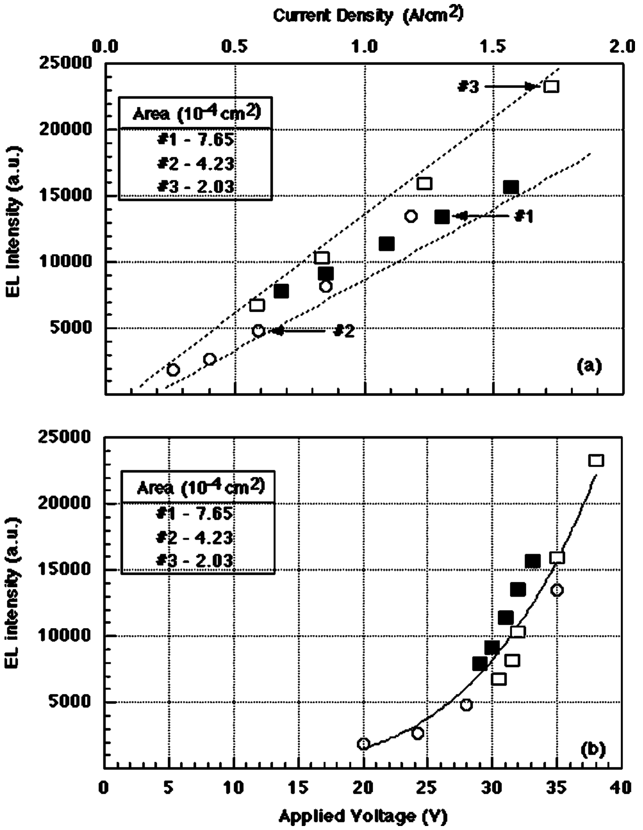

FIG. 5. Electroluminescence intensity as a function of applied bias conditions for three diodes of varying areas: (a) current density; and (b) reverse voltage.

The electrical characteristics of a typical Er-doped GaN Schottky diode with an area of 4.23×10^{-4} cm^2 are shown in Fig. 3. The current–voltage ($I-V$) characteristic contained in Fig. 3(a) shows a threshold voltage for forward conduction of ~8.5 V. At a forward voltage of 20 V, a current flow of 350 μA is obtained. Under a reverse bias of 20 V, a current of ~30 μA is measured. The capacitance–voltage ($C-V$) characteristic of the same diode is plotted in Fig. 3(b) in the form $1/C^2$ vs V. From this plot we obtain an intercept voltage of ~11.5 V and an effective GaN carrier concentration of approximately 10^{12} cm^{-3}. The high diode forward resistance obtained from the $I-V$ characteristics of ~34 kΩ is probably due to the high resistivity of the GaN layer. The Schottky barrier height calculated from the $C-V$ characteristics is approximately 9 V, which is consistent with the threshold voltage obtained from the $I-V$ characteristics. This large voltage probably indicates the presence of an insulating layer at the Al–GaN interface.

The relationship between the reverse bias current and the light output is shown in Fig. 4. The EL intensity plotted in this case is the sum of the two green lines, which represents approximately 95% of the optical emission. As can be seen from Fig. 4, a linear relation is maintained between the optical output and the bias current over a wide range of values. Interestingly, at current values smaller than 200 μA, the relationship is still linear, albeit with a different slope. This fundamental current–light dependence holds for diodes of different areas. As shown in Fig. 5(a), the EL intensity versus current density for three diodes with areas ranging from 2 to 7.65×10^{-4} cm^2 falls within a narrow range. Figure 5(b) indicates the EL intensity levels produced as a function of applied voltage for the same three diodes. Once again, the values for all three diodes fall within a rather narrow range defining a power-law dependence.

In summary, we have reported visible (green) electroluminescence characteristics of Er-doped GaN. The EL of the GaN:Er Schottky LED's as a function of input current indicates a well-behaved device characteristic. The use of Al for both the Schottky and ground electrode provides a simple and rapid process for evaluation of these devices. Significant improvements in diode characteristics will likely come from more sophisticated contact approaches. We conclude that GaN:Er LED's represent a significant addition to the rapidly expanding array of GaN-based light-emitting devices.

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