Green emission from Er-doped GaN grown by molecular beam epitaxy on Si substrates

R. Birkhahn and A. J. Steckl[a)]

Nanoelectronics Laboratory, University of Cincinnati, Cincinnati, Ohio 45221-0030

Visible light emission has been obtained from Er-doped α-GaN thin films grown on Si(111). The GaN was grown by molecular beam epitaxy using solid sources (for Ga and Er) and a plasma gas source for N_2. Photoexcitation with a He–Cd laser resulted in strong green emission from two narrow green lines at 537 and 558 nm identified as Er transitions from the $^2H_{11/2}$ and $^4S_{3/2}$ levels to the $^4I_{15/2}$ ground state. X-ray diffraction shows the GaN:Er to be a wurtzitic single crystal film. The growth temperature is seen to have a strong effect on the GaN:Er surface morphology. © *1998 American Institute of Physics.* [S0003-6951(98)02641-2]

In the development of GaN technology, sapphire is commonly utilized as a substrate due to a lack of homoepitaxial substrates, in spite of its large mismatch to GaN. Silicon, which also has a large lattice mismatch with GaN ($\sim$20%), is a potential alternative to growth on sapphire, due to its high quality and wide availability as a large diameter and low cost substrate. Silicon also benefits from its extensive utilization in the semiconductor industry. Any potential devices that make use of Si can more readily be integrated into industrial processes and exploit current technology. Previous research has reported α-GaN and β-GaN grown by both molecular beam epitaxy (MBE)[1–3] Si(111) and metalorganic chemical vapor deposition[4] on Si(100) substrates.

In situ incorporation[5–8] of Er into AlN and GaN grown by MBE on both sapphire and silicon and its room temperature *infrared* (IR) emission has been reported. We have recently reported[9] the first *visible* (green) emission from Er-doped GaN grown by MBE on sapphire substrates. In this letter, we report on Er-doped GaN growth experiments on Si(111) substrates, which demonstrate the feasibility of Er-induced *visible* light emission and the possibility of integration with Si technology.

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 (7 N purity) and Er (3 N) fluxes, while a SVTA rf plasma source was used to generate atomic nitrogen. The films were grown without initial nitridation. Plasma characteristics were kept constant throughout growth at 400 W rf power with a N_2 flow rate of 1.5 sccm, corresponding to a chamber pressure of mid-10^{-5} Torr. A buffer layer was deposited for 10 min at a temperature 200 °C lower than the growth temperature. Er-doped GaN growth experiments were typically performed for 3 h, with substrate temperatures ranging from 750 to 950 °C and a constant Ga beam pressure during growth of 8.2×10^{-7} Torr (cell temperature of 922 °C). The Er cell temperature was kept constant at 1100 °C producing an approximate Er concentration of $2 \times 10^{20}/cm^3$ as measured by secondary ion mass spectrometry. The resulting GaN film thickness at the lower end

of the temperature range was $\sim$2.4 μm, giving a nominal growth rate of 0.8 μm/h. However, at the higher end of the growth temperature range, the growth rate decreased significantly.

Photoluminescence (PL) characterization was performed with a He–Cd laser excitation source at a wavelength of 325 nm, corresponding to an energy greater than the GaN band gap. The laser beam was focused to a spot size of $\approx$200 μm with incident power on the sample at 4–8 mW. PL excitation resulted in light green emission from the Er-doped GaN films, visible with the naked eye. The room temperature PL at visible wavelengths is shown in Fig. 1 for a GaN film grown on Si at 750 °C substrate temperature. For comparison, a sample previously grown on sapphire at 750 °C under similar conditions (Er cell temperature=1100 °C) is also shown. The PL spectra were not taken with the same excitation power and, therefore, the relative intensities are not directly comparable. However, the same features are observed in both spectra. For growth on both substrates, two major emission multiplets are observed in the green wavelength region with the strongest lines at 537 and 558 nm. These emission lines are produced by the Stark split $^2H_{11/2}$ and
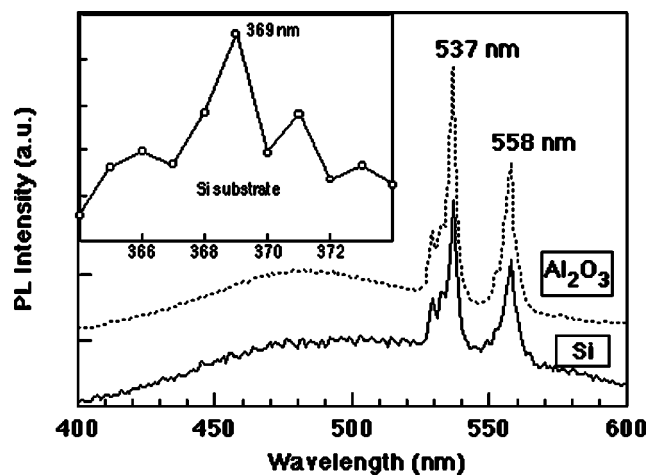

FIG. 1. PL spectra of Er-doped GaN films grown at 750 °C on sapphire and Si(111), with Er cell temperature of 1100 °C. Inset is UV band-edge emission of GaN film grown on Si. The PL is performed at room temperature with the He–Cd laser line at 325 nm.
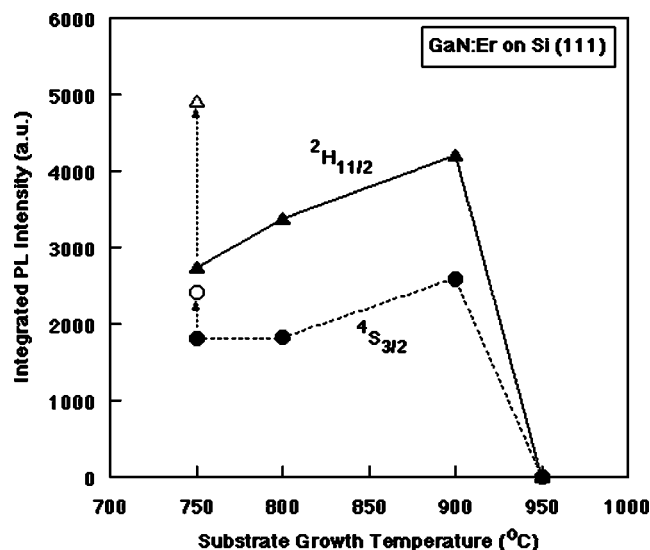
[a)]Electronic mail: a.steckl@uc.edu

FIG. 2. Integrated intensity of the $^2H_{11/2}$ and $^4S_{3/2}$ lines from the GaN:Er film as a function of Si substrate growth temperature. The open symbols are for a GaN film with optimized buffer layer. Lines are drawn to aid the eye.

$^4S_{3/2}$ transitions to the $^4I_{15/2}$ ground state. The full width at half maximum (FWHM) of the main component of these transitions is around 3 nm, which corresponds to an energy width of ~ 13 meV. A broad emission region is also present, peaking in the blue-green around 500 nm. The yellow band PL typically observed at ~ 540–550 nm in conventionally grown GaN is absent. As shown in Fig. 1 (inset) in the ultraviolet (UV) region for the GaN:Er/Si sample band edge (BE) emission is present at 370 nm, although not nearly as intense as the green emission.

Interestingly, Zanatta and Nunes[10] have recently reported green emission at room temperature from Er, in this case utilizing amorphous SiN insulating films as the host material. For a-SiErN, the emission wavelengths were considerably shifted (to values of 520 and 545 nm) from those we observed in GaN:Er and the peaks were much broader (with a FWHM of ~ 0.8 eV). In addition, the intensity of the $^2H_{11/2}$ transition was less than that of the $^4S_{3/2}$ transition in a-SiErN, while in our material it was just the opposite. However, there were many inherent material differences which could explain the differences in the spectra: crystalline versus amorphous structure, wide band-gap semiconductor versus insulator, Er concentration of 10 at. % in a-SiErN versus 0.25 at. % for GaN. Furthermore, the excitation source used for a-SiErN was an Ar laser at 488 nm, while we utilized a He–Cd laser at 325 nm for GaN:Er excitation. We did not observe the Er transitions with excitation at 488 nm.[9]

The integrated intensity of the green emission is shown as a function of growth temperature in Fig. 2. The solid upper line is the integrated signal in the vicinity of the $^2H_{11/2}$ emission, while the lower line contains the values corresponding to the signal in the vicinity of the $^4S_{3/2}$ transition. The general trend of the integrated PL intensity is to increase with increasing growth temperature up to a certain cutoff at 950 °C. It should be noted that, while the height-to-background intensity of the main emission peaks tends to decrease with increasing growth temperature, the overall integrated emission (including the secondary peaks from the
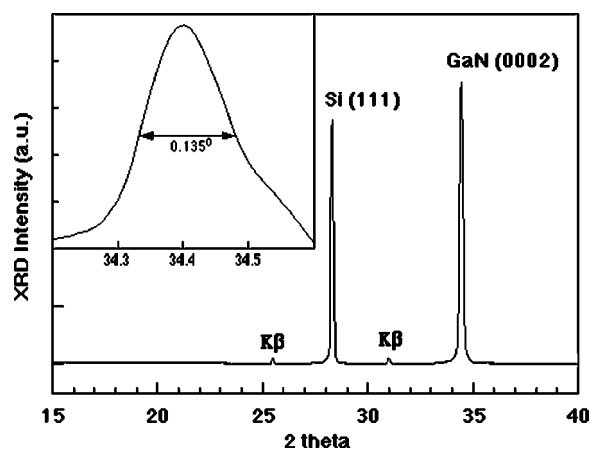

FIG. 3. Representative x-ray diffraction spectrum of Er-GaN film (No. 100R) on Si(111). Inset indicates the FWHM of the GaN(0002) peak. Substrate growth temperature was 800 °C with Er cell temperature of 1100 °C.

Stark-split levels) has increased. A growth temperature of 950 °C greatly reduced the GaN growth rate and no green emission could be detected. On one sample, we attempted to optimize the buffer layer temperature based on the percentage of two-dimensional (2D) structure (or ''streakiness'') on the growth surface as evident from reflection high-energy electron diffraction (RHEED) patterns obtained for previous growths. The result is shown as the open symbols in Fig. 2. This simple preliminary test for optimization demonstrates that the emission intensity can be further increased.

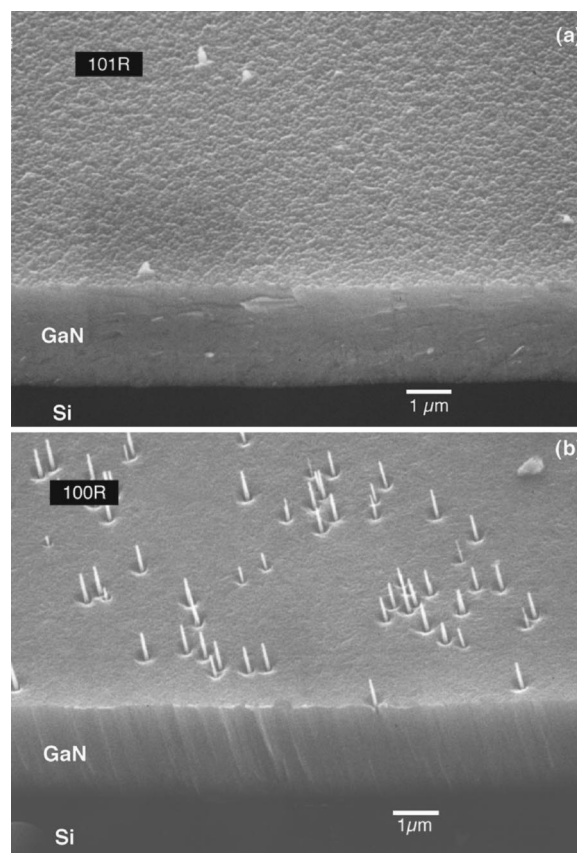The structural properties of the GaN:Er films were inves-

FIG. 4. SEM micrographs of GaN:Er films grown on Si at a growth temperature of: (a) 750 °C; (b) 800 °C. The Er cell temperature was 1100 °C in both cases.

tigated by scanning electron microscopy (SEM) and x-ray diffraction (XRD). Figure 3 shows a representative x-ray spectrum from a thin film (No. 100R) grown at 800 °C. Only the Si(111) and the α-GaN(0002) peaks were present, indicating good crystallinity. The FWHM of the GaN peak was 0.135°, compared to 0.104° for the Si(111) peak. The XRD data were collected up to $2\theta = 120°$, but contained no indication of other α-GaN phases or any β-GaN peaks.

SEM micrographs of GaN:Er samples grown at 750 °C (No. 101R) and 800 °C (No. 100R) are shown in Fig. 4. The Er cell temperature was 1100 °C in both cases. The surface of the GaN film grown at 750 °C is relatively smooth and uniform. The surface of the film grown at 800 °C contains an unusual morphology. Parts of the planar surface contain long spikes protruding ~ 0.5–1 μm with an associated surface depression. It is not clear whether these spikes are nucleation ''rods'' around which the GaN grows or whether they are defects extending from the Si surface. These defects could be a result of a nonoptimized nucleation layer. In cross section, certain sections of the film appear stratified, especially in regions of high spike density. Other regions appear homogeneous and uniform. Interestingly, both films exhibit strong green photoluminescence from the Er atoms incorporated during growth.

In summary, we have reported optical and structural characteristics of Er-doped GaN on Si(111) grown by solid source MBE. We have observed for the first time visible emission from the GaN:Er films grown on Si. These results demonstrate the possibility of future integration with current Si device technology.

[1] A. Barski, U. Rössner, J. L. Rouvière, and M. Arlery, MRS Internet J. Nitride Semicond. Res. **1** (1996).

[2] T. Lei, M. Fanciulli, R. J. Molnar, T. D. Moustakas, R. J. Graham, and J. Scanlon, Appl. Phys. Lett. **59**, 944-6 (1991).

[3] T. D. Moustakas, T. Lei, and R. J. Molnar, Physica B **185**, 36 (1993).

[4] J. W. Yang, C. J. Sun, Q. Chen, M. Z. Anwar, M. A. Khan, S. A. Nikishim, G. A. Seryogin, A. V. Osinsky, L. Chernyak, H. Temkin, C. Hu, and S. Mahajan, Appl. Phys. Lett. **69**, 3566 (1996).

[5] J. D. MacKenzie, C. R. Abernathy, S. J. Pearton, S. M. Donovan, U. Hömmerich, M. Thaik, X. Wu, F. Ren, R. G. Wilson, and J. M. Zavada, Mater. Res. Soc. Symp. Proc. **468**, 123 (1997).

[6] J. D. MacKenzie, C. R. Abernathy, S. J. Pearton, U. Hömmerich, X. Wu, R. N. Schwartz, R. G. Wilson, and J. M. Zavada, J. Cryst. Growth **175/176**, 84 (1997).

[7] D. M. Hansen, R. Zhang, N. R. Perkins, S. Safvi, L. Zhang, K. L. Bray, and T. F. Keuch, Appl. Phys. Lett. **72**, 1244 (1998).

[8] J. D. MacKenzie, C. R. Abernathy, S. J. Pearton, U. Hömmerich, J. T. Seo, R. G. Wilson, and J. M. Zavada, Appl. Phys. Lett. **72**, 2710 (1998).

[9] A. J. Steckl and R. Birkhahn, Appl. Phys. Lett. **73**, 1700 (1998).

[10] A. R. Zanatta and L. A. O. Nunes, Appl. Phys. Lett. **72**, 3127 (1998).