InGaN multiple-quantum-well green light-emitting diodes on Si grown by metalorganic chemical vapor deposition

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We report the characteristics of InGaN multiple-quantum-well (MQW) green light-emitting diodes (LEDs) on Si (111) substrates. The MQW LEDs were grown on Si by metalorganic chemical vapor deposition using $Al_{0.27}Ga_{0.73}N/AlN$ intermediate layers. The LED on Si showed an operating voltage of 7 V, a series resistance of 100 Ω, an optical output power of 20 μW, and a peak emission wavelength of 505 nm with a full width at half maximum of 33 nm at 20 mA drive current. The optical output power was half as compared to that of green LED on sapphire. The LED also exhibited a stable operation over 500 h under automatic current control (20 mA) condition at 27 °C.
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Heteroepitaxial growth of GaAs on Si has been studied for the fabrications of light-emitting diodes (LEDs) and laser diodes due to the low cost and integration potential with electronic devices. However, in spite of significant research efforts, the progress toward fabrication of GaAs-based optical devices on Si has been limited by problems with reliability. In GaAs-based optical devices on Si, a high density of dislocations, which is caused by thermal and lattice mismatch, significantly reduce the device lifetime due to formation and growth of dark-line defects.[1] In contrast, GaN-based LEDs on sapphire have been shown to have high reliability even though the threading dislocation of the system is as high as $10^{10}\ cm^{-2}$, which arises from a 13% lattice mismatch between GaN and sapphire.[2,3] Moreover, growth velocity of dark-line defects in GaN-based LEDs on sapphire is very small compared with that of GaAs-based LEDs on Si.[4,5] It can be expected that the characteristics of GaN-based LEDs on Si may not be significantly affected by the presence of lattice mismatch related defects. Other significant advantages against LEDs grown on sapphire are simplicity of fabrication process, large-scale production, and low cost because Si is conductive and cheap. The ultraviolet, violet, and blue LEDs have been fabricated on Si.[6–9] The previously reported GaN layers on Si suffer from the cloudy morphology and cracks.[6,7,9] Moreover, there is no report on the optical output power measurement of the LED on Si. We reported a high quality GaN layer on Si using $Al_{0.27}Ga_{0.73}N/AlN$ intermediate layers.[10] In this study we report the InGaN multiple-quantum-well (MQW) green LED on Si with the $Al_{0.27}Ga_{0.73}N/AlN$ intermediate layers by metalorganic chemical vapor deposition (MOCVD). In particular, the optical output power of LEDs on Si are compared with that of LEDs on sapphire. The LED aging result is also reported.

Growth of MQW LEDs on *n*-Si (111) substrate was carried out in a Nippon Sanso MOCVD system (SR-2000). Prior to the growth of LED structure, a 120-nm-thick AlN buffer layer and a 380-nm-thick $Al_{0.27}Ga_{0.73}N$ layer were grown at 1130 °C. The MQW LED structure consists of an 800-nm-thick *n*-GaN, an undoped three periods of MQW consisting of 3-nm-thick $In_{0.22}Ga_{0.78}N$ wells and 5-nm-thick $In_{0.01}Ga_{0.99}N$ barrier layers, a 20-nm-thick p-$Al_{0.15}Ga_{0.85}N$ layer and a 200-nm-thick *p*-GaN as a top contact layer. LEDs were fabricated by depositing Ni/Au thin transparent metals and Ni/Au (12/100 nm) *p*-type ohmic metals annealed at 610 °C for 3 min in a N_2 ambient. The *n*-type ohmic contact was made from the backside through Si substrate using AuSb/Au (18/100 nm) annealed at 380 °C for 1 min in a N_2 ambient, unlike the case of LEDs on sapphire where both the ohmic contacts are made on the top of both *p*-GaN and *n*-GaN layers. For comparison, the LED with the same MQW structure was also grown on sapphire. The fabrication process of LED on sapphire has been reported.[11] In order to characterize the MQW structure, photoluminescence (PL) measurement was performed at room temperature using the 325 nm line of a He–Cd laser as an excitation source. Current–voltage ($I-V$) measurements were carried out using

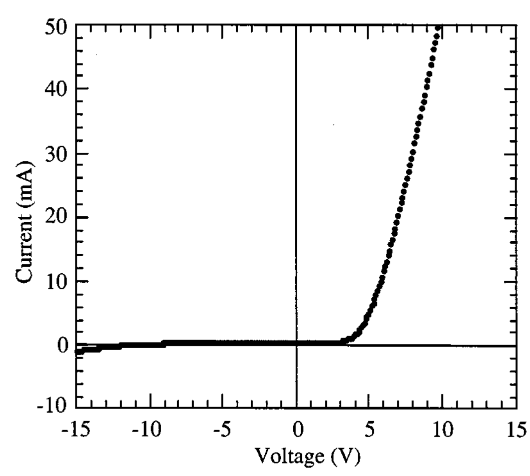

FIG. 1. $I-V$ characteristic of the MQW LED on Si.

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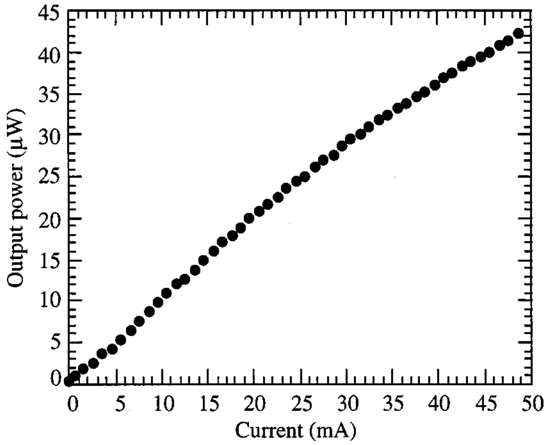

FIG. 2. $L-I$ characteristic of the MQW LED on Si under 20 mA dc current.

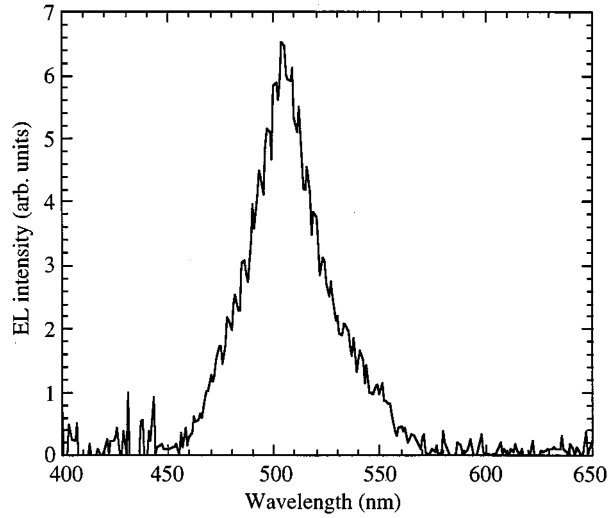

FIG. 3. EL spectra of the MQW LED on Si under 20 mA.

semiconductor parameter analyzer (HP 4145B). Light output power and electroluminescence (EL) spectra were measured at room temperature using optical power meter (Anritsu ML910B) and optical spectrum analyzer (Anritsu MS9702B/MS9030A), respectively. In the case of light output power measurements, the detector was set 1 cm above the surface of LED. The life test was performed under automatic current control (ACC) of 20 mA at 27 °C. The active area of the LEDs was 1.99×10^{-3} cm^2.

Figure 1 shows the $I-V$ characteristic of LED on Si. The forward voltage of 7 V was applied to get 20 mA forward current. The reverse leakage current was 0.17 mA at -10 V. The onset of visible luminescence was observed at the turn-on voltage of 4 V. The forward differential series resistance was measured to be about 100 Ω, which was larger than the value of 40 Ω for the LED on sapphire. The differential resistance of AlN/Si interface may be responsible for high operating voltage and differential series resistance in the LED on Si. The light output power-injected current ($L-I$) characteristic of the LED on Si under 20 mA dc current is shown in Fig. 2. The output power increased with increasing the injected current. The output power of 20 μW was obtained at 20 mA, which was approximately half as compared to that of green LED on sapphire. The green emission from the LED on Si is easily bright enough to be observed under room light. The Si substrate absorbs a part of green emission from the active region. With the same LED structure, one can get more optical output power, if we eliminate the green light absorption by Si. Figure 3 shows the EL spectra of the LED under 20 mA. The intense peak around 505 nm was observed with a full width at half maximum (FWHM) of 33 nm. The peak emission wavelength agrees with the room temperature PL peak. Many fringes were observed probably due to the interference of emitted light reflected between Si and the top GaN layer.[7] The LED grown on sapphire exhibited the operating voltage of 4.5 V, the series resistance of 40 Ω, and the optical output power of 40 μW at 20 mA. Compared with the

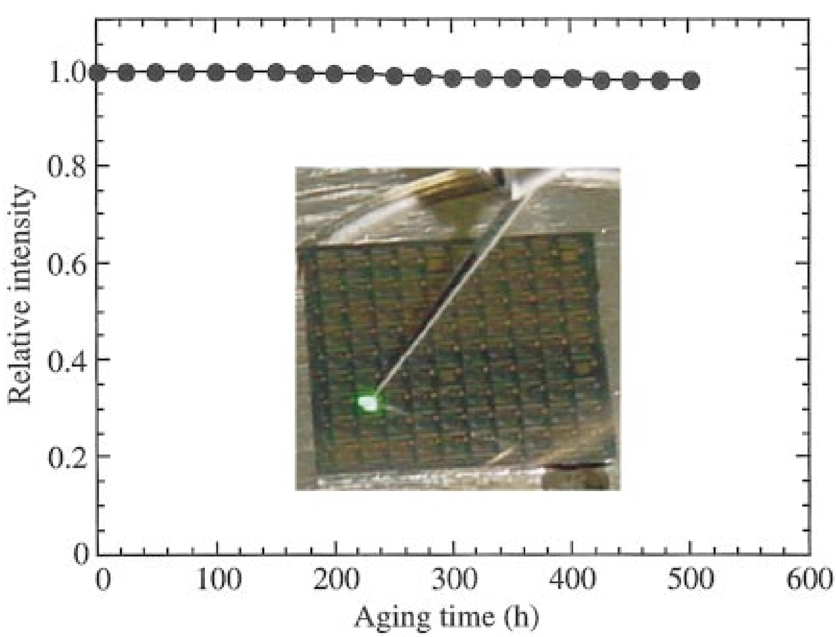

FIG. 4. (Color) Aging result of the MQW LED on Si under ACC condition (20 mA) at 27 °C. Inset shows the green emission from the LED on Si after 500 h aging test.

characteristics of LED on sapphire, the operating voltage and the series resistance in the LED on Si are high. The AlN layer is an insulator with a band gap of $\sim$6.2 eV and a large conduction band offset, which is estimated to be $\sim$2.6 eV.[6] For the study of LED on Si, the electron injection is carried out from Si substrate into the active layer through the AlN layer. Therefore, the electrons experience a large barrier during the injection. A high turn-on voltage comes from the leaky AlN layer due to relatively thick high density threading defect AlN layer on Si.

Figure 4 shows the aging result of the LED on Si at 27 °C under ACC condition. The LED showed stable operation for as long as over 500 h. The reduction in the optical output power is as low as 2% after 500 h aging. The inset shows the image of green emission of the LED after 500 h aging test. The LED continues to emit light maintaining the initial characteristics. Guha *et al.*[6] and Tran *et al.*[7] have reported that the GaN-based LEDs on Si contain a high density of threading dislocations and planar defects. However, it is noticeable that the LED on Si exhibited a visibly good green emission with good reliability in spite of a highly defective structure. Further studies are necessary to understand the mechanisms of LEDs on Si.

In conclusion we have demonstrated the InGaN MQW green LED on Si with the $Al_{0.27}Ga_{0.73}N$/AlN intermediate layers using MOCVD. At a 20 mA drive current, the operating voltage of 7 V, the series resistance of 100 Ω, the optical output power of 20 μW, and the peak emission wavelength of 505 nm with the FWHM of 33 nm have been obtained. The LEDs on Si have also exhibited the reliability of over 500 h at 27 °C.

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