Degradation mechanism of AlGaAs/GaAs laser diodes grown on Si substrates

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We have studied the rapid degradation of the AlGaAs/GaAs single quantum well laser diodes on Si substrates grown by metalorganic chemical vapor deposition. The dislocations propagate at velocities up to $\sim$75 μm/h along ⟨100⟩ and $\sim$20 μm/h along ⟨110⟩, which cause an increase in threshold current and a decrease in differential quantum efficiency. The degraded current–voltage characteristic resulted from the defect-assisted impurity diffusion. The degradation process occurs very rapidly due to the presence of a high density of defects and thermally induced strain.

Heteroepitaxial growth of III–V semiconductors on Si substrates has recently attracted much attention because it allows monolithic integration of Si and III–V devices. In particular, GaAs-based laser diodes on Si substrates play an important role in the field of optoelectronic integrated circuits (OEICs) and optical interconnections between Si very-large-scale integrated circuits.[1,2] Continued improvements in material quality and device structure have made possible room-temperature continuous-wave (cw) operation for AlGaAs/GaAs laser diodes on Si substrates.[3,4] However, the growth of GaAs on Si substrates (GaAs/Si) involves the 4.1% lattice mismatch and the difference in the thermal expansion coefficients between GaAs and Si materials, which result in a calculated $\sim 10^{12}$ cm^{-2} defect density and a large residual tensile stress in the epitaxial layer. Therefore, room-temperature reliable operation of GaAs-based laser diodes on Si is still hindered at the present time by the high dislocation density ($>10^6$ cm^{-2}) and the large tensile stress ($\sim 10^9$ dyn/cm^2) in the active layer.[5]

The degradation process in the AlGaAs/GaAs laser diodes on GaAs substrates is well known.[6,7] It involves the growth of dark-line defects (DLDs) in the [100] directions, which is caused by the presence of nonradiative electron-hole recombination centers. The growth of DLDs, which are enhanced by the strain and the injected current, causes an increase in the threshold current and a decrease in the differential quantum efficiency. It is also well known that GaAs-based laser diodes on Si substrates suffer from rapid degradations due to the high dislocation density and the large tensile stress in the active layers. Previous studies have shown that the rapid degradations result from the growth of DLDs in the ⟨100⟩ direction and the ohmic-like characteristic in the *p-n* junction.[8,9] In this study, we investigate the injected current density dependence of the DLDs growth velocities along the ⟨100⟩ and ⟨110⟩ directions in the AlGaAs/GaAs quantum well heterostructure laser diodes on Si substrates. We also demonstrate the degraded current–voltage (*I–V*) characteristic results from accelerated impurity diffusions.

Details about the epitaxial growth and the device fabrication have been described previously,[3,5] and are summarized as follows. AlGaAs/GaAs single quantum well (SQW) laser diodes were grown on the Si substrates oriented 2° away from the (100) toward [011] in a rf-heated metalorganic chemical vapor deposition (MOCVD) reactor at atmospheric pressure. The laser diode consisted of a 2.0-μm-thick Se-doped (2×10^{18} cm^{-3})n^+-GaAs layer, a 1.0-μm-thick Se-doped (1×10^{18} cm^{-3})n^+-$Al_{0.7}Ga_{0.3}As$ cladding layer, a 70-nm-thick undoped $Al_{0.3}Ga_{0.7}As$ barrier layer, a 9-nm-thick undoped GaAs active layer, a 70-nm-thick undoped $Al_{0.3}Ga_{0.7}As$ barrier layer, a 1.0-μm-thick Zn-doped (1×10^{18} cm^{-3})p^+-$Al_{0.7}Ga_{0.3}As$ layer, and an 80-nm-thick Zn-doped (1×10^{19} cm^{-3})p^+-GaAs layer. Oxide-isolated stripe-geometry laser diodes were fabricated by opening the contact stripes in a 100-nm-thick SiO_2 layer deposited on the epitaxial side. The *p*-side contact metallization consisted of 50 nm of Ti and 150 nm of Au. The *n*-side contact consisted of 50 nm of AuSb and 100 nm of Au. The growth of DLDs was verified using an electroluminescence (EL) observation system. Secondary-ion mass spectroscopy (SIMS) measurement was performed with Cs^+ primary-ion bombardment. Signals determining the depth profiles were taken from 9×9 μm^2 area within the 10×300 μm^2 degraded laser stripe region.

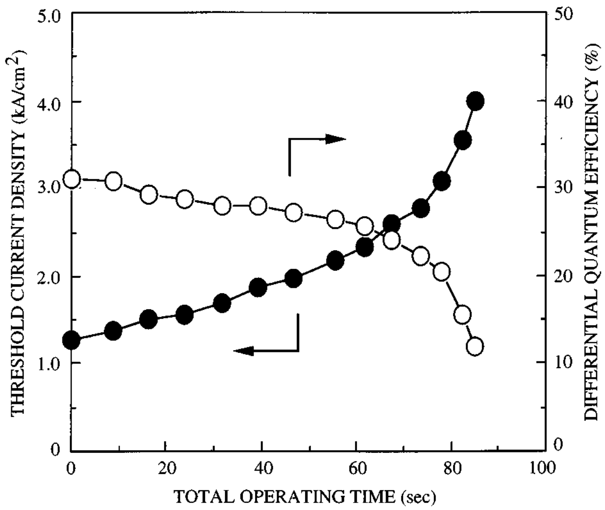

FIG. 1. 300 K pulsed threshold current density and differential quantum efficiency as a function of total operating time for AlGaAs/GaAs laser diode on Si substrate.

Figure 1 shows the 300 K pulsed threshold current density and the differential quantum efficiency as a function of total operating time the current was on. The data were obtained with 0.2-μs-long current pulses at a 5-kHz repetition rate. The threshold current density initially increased slowly, from 1.28 to 2.59 kA/cm^2 in 67.5 s, increased rapidly to 3.98 kA/cm^2 in the next 17.5 s. As a result the threshold increases, the differential quantum efficiency decreases. There is an accompanying increase in lasing threshold current density and a decrease in differential quantum efficiency because the DLDs create the nonradiative recombination centers and form the dark regions of reduced gain. Thus, the AlGaAs/GaAs laser diode on Si rapidly degrades even under the pulsed condition at 300 K. This laser diode has a lifetime as short as 6 min under automatic power control condition at 300 K.

In order to study the degradation process, the DLDs formation was observed for the AlGaAs/GaAs laser diode on Si. Figure 2 shows EL images before and during the aging under 0.5 kA/cm^2 for the AlGaAs/GaAs laser diode grown on Si. With further aging [Figs. 2(b) and 2(c)] the contrast between dark and light becomes more pronounced. Dark regions become broad in the vicinity of its originating defect, and extend preferentially in the ⟨100⟩ directions. Figure 2 shows that there is also the effective growth velocity for the ⟨110⟩ direction.

The ⟨100⟩ and ⟨110⟩ DLDs growth velocities as a function of injected current density are shown in Fig. 3. The DLD growth velocity was estimated by dividing the DLD growth length by the operating time. The growth velocities for the ⟨100⟩ and ⟨110⟩ directions depend on the injected current density. For example, the ⟨100⟩ growth velocities were ~10 and ~75 μm/h at the injected current densities of 0.5 and 2.0 kA/cm^2, respectively. The ⟨110⟩ growth velocities were ~2 and ~20 μm/h at 0.5 and 2.0 kA/cm^2, respectively, which are about 1/4 of those for the ⟨100⟩ DLD. Waters *et al.* reported that the ⟨100⟩ and ⟨110⟩ DLDs growth velocities of the AlGaAs/GaAs laser diode on GaAs were ~2–10 and 0.1 μm/h, respectively.[7] In the AlGaAs/GaAs laser diode on Si, the dislocations propagate at velocities up to ~75 μm/h along the ⟨100⟩ direction and ~20 μm/h along ⟨110⟩ because the cw threshold current density is ~2 kA/cm^2 at 300 K. Thus, the growth velocity of DLD in the laser diode on Si is larger than that on the GaAs substrate. Therefore, the laser diode performance suffers and the current required to main-

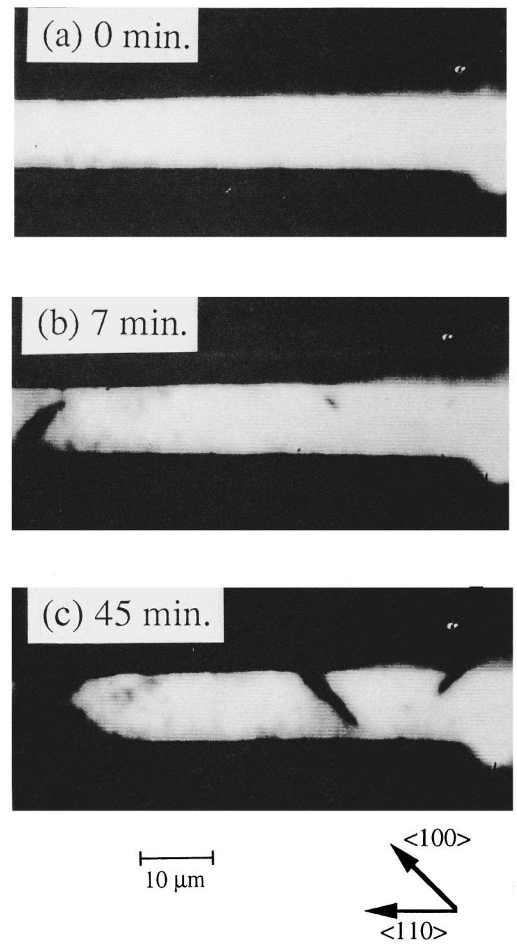

FIG. 2. EL images (a) initially and during (b) and (c) aging of the AlGaAs/GaAs laser diode grown on the Si substrate. (b) and (c) corresponds to aging of 7 and 45 min, respectively. The laser diode has been aged below threshold.

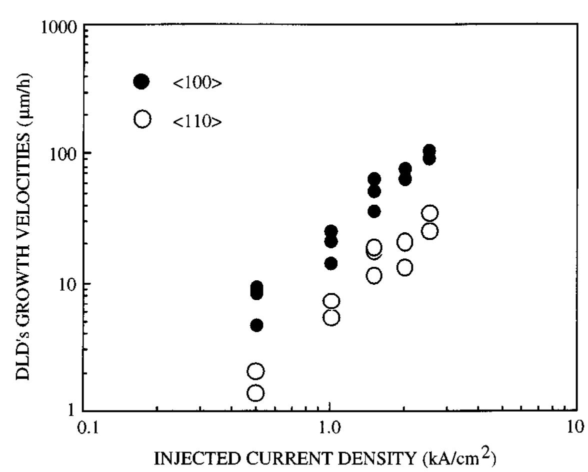

FIG. 3. DLDs growth velocities along ⟨100⟩ and ⟨110⟩ directions as a function of injected current density for AlGaAs/GaAs laser diode on Si substrate.

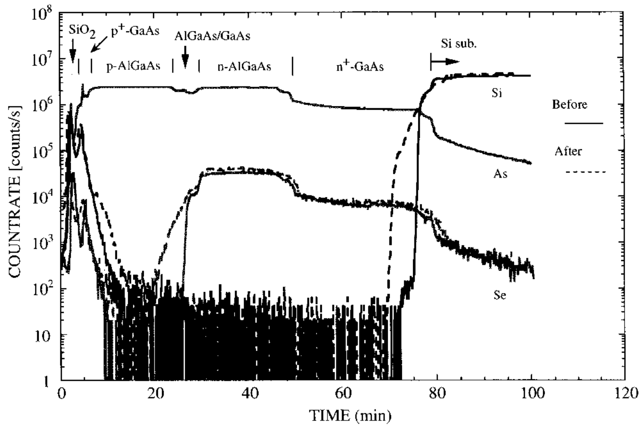

FIG. 4. SIMS profiles of AlGaAs/GaAs laser diode on Si substrate before and after degradations. Signals determining depth profiles were taken from 9×9 μm^2 area within the 10×300 μm^2 degraded laser stripe region.

tain the constant output power increases rapidly because the DLDs grow across the lasing stripe. This higher growth velocity causes the rapid degradation in the laser diode on Si.

We showed that the degraded AlGaAs/GaAs laser diode on Si exhibited the ohmic-like *I–V* characteristic of the *p-n* junction.[9] As shown in Fig. 4, further evidence supporting the degraded *I–V* characteristic comes from comparison of SIMS profiles of the laser diode on Si before and after degradation. Before degradation, much higher concentrations of Si were observed at the GaAs/Si interface and the surface of the p^+-GaAs layer. The increased concentrations of Si near the GaAs/Si interface and the surface have been reported as the typical phenomena in the heteroepitaxial growth of GaAs on Si by MOCVD.[10–12] After degradation, there was significant outdiffusion of Si into the n^+-GaAs layer from the Si substrate and indiffusion of Si into the *p*-AlGaAs layer. Another significant outdiffusion of the intentionally doped Se impurity was observed in the *p*-AlGaAs layer by comparison of Se impurity profiles before and after degradation. No significant diffusion was observed in the Zn impurity profile after degradation. Thus, the indiffusion of Si and the outdiffusion of Se into the *p*-AlGaAs layer would convert the *p*-type upper confining layer to *n*-type. As a result, the *I–V* characteristic of the *p-n* junction leads to the ohmic-like.

Plano *et al.* showed that dislocation-accelerated impurity-induced layer disordering was observed in the annealed AlGaAs/GaAs quantum well heterostructure grown on Si by MOCVD.[11] Martins *et al.* suggested that the degradation in the *p-n* junction on Si is due to the motion and coupling of point defects with doping impurities present in the *n* layers.[13] The dislocations and stress in the GaAs/Si make the impurities such as Si and Se more mobile because the laser diode on Si has a high dislocation density of 2×10^7 cm^{-2} and a large tensile stress of 2.49 kbar.[5] The impurity diffusion is thought to be accelerated by high density dislocations and the large stress in the GaAs/Si. Furthermore, the impurity diffusion process is enhanced by the injected current and the operating temperature during aging test.

In summary, we estimated the DLDs growth velocities of $\sim$75 μm/h along the $\langle 100\rangle$ direction and $\sim$20 μm/h along $\langle 110\rangle$ at the injected current density of 2.0 kA/cm^2 for the AlGaAs/GaAs laser diodes on Si substrates. The ohmic-like characteristic of the *p-n* junction was thought to be caused by the defect-assisted impurity diffusion during the aging process.

[1] H. K. Choi, G. W. Turner, T. H. Windhorn, and B.-Y. Tsaur, IEEE Electron Device Lett. **EDL-7**, 500 (1986).
[2] T. Egawa, T. Jimbo, and M. Umeno, IEEE Photonics Technol. Lett. **4**, 612 (1992).
[3] T. Egawa, T. Soga, T. Jimbo, and M. Umeno, IEEE J. Quantum Electron. **27**, 1798 (1991).
[4] H. K. Choi, C. A. Wang, and N. H. Karam, Appl. Phys. Lett. **59**, 2634 (1991).
[5] T. Egawa, Y. Hasegawa, T. Jimbo, and M. Umeno, Jpn. J. Appl. Phys. **31**, 791 (1992).
[6] P. Petroff and R. L. Hartman, Appl. Phys. Lett. **23**, 469 (1973).
[7] R. G. Waters, D. P. Bour, S. L. Yellen, and N. F. Ruggieri, IEEE Photonics Technol. Lett. **2**, 531 (1990).
[8] J. P. Van der Ziel, R. D. Dupuis, R. A. Logan, and C. J. Pinzone, Appl. Phys. Lett. **51**, 89 (1987).
[9] T. Egawa, T. Jimbo, Y. Hasegawa, and M. Umeno, Appl. Phys. Lett. **64**, 1401 (1994).
[10] A. Freundlich, A. Leycuras, J. C. Grenet, and C. Grattepain, Appl. Phys. Lett. **53**, 2635 (1988).
[11] W. E. Plano, D. W. Nam, K. C. Hsieh, L. J. Guido, F. A. Kish, A. R. Sugg, and N. Holonyak,Jr., R. J. Matyi, and H. Shichijo, Appl. Phys. Lett. **55**, 1993 (1989).
[12] S. Nozaki, A. T. Wu, J. J. Murray, T. George, T. Egawa, and M. Umeno, Appl. Phys. Lett. **57**, 2669 (1990).
[13] R. B. Martins, P. Henoc, B. Akamatsu, G. Bartenlian, and M. N. Charasse, J. Appl. Phys. **68**, 937 (1990).