Extended Abstracts of the 1995 International Conference on Solid State Devices and Materials, Osaka, 1995, pp. 449-451

D-5-4

1100 Hours Stable Operation in 0.87-μm InGaP/GaAs LED's on Si Substrates Grown by MOCVD

Takashi EGAWA[a)], Jie DONG[b)], Kou MATSUMOTO[b)], Takashi JIMBO[a)] and Masayoshi UMENO[a,c)]

[a)]Research Center for Micro-Structure Devices, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466, Japan

[b)]Nippon Sanso Corporation, Tsukuba Laboratories, 10 Ohkubo, Tsukuba, Ibaraki 305, Japan

[c)]Department of Electrical and Computer Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466, Japan

A reliable 877-nm InGaP/GaAs light-emitting diode (LED) has been grown on a Si substrate by metalorganic chemical vapor deposition. A conventional Al-contained AlGaAs/GaAs LED on a Si substrate exhibited a rapid degradation because of formation of dark-line defects (DLD's). On the contrary, an Al-free InGaP/GaAs LED on a Si substrate showed no significant growth of DLD's. As a result, a stable operation for more than 1100 hours has been achieved in an InGaP/GaAs LED on a Si substrate.

I. INTRODUCTION

Reliable light-emitting diodes (LED's) and laser diodes on Si substrates are key devices in high density applications such as optical interconnections in future optoelectronic integrated circuits (OEIC's).[1-3] GaAs on Si substrate (GaAs/Si) involves a high dislocation density ($>10^6$ cm^{-2}) and a large residual thermal stress (10^9 dyn/cm^2), which are introduced by the ~4 % lattice mismatch and the ~250 % difference in the thermal expansion coefficients between GaAs and Si.[4, 5] Therefore, LED's and laser diodes grown on Si substrates suffer from rapid degradations. Previous studies on improvement of reliability have been focussed on reductions of dislocation density and residual stress by uses of post-growth patterning[5], selective-area growth[6] and undercut GaAs on Si (UCGAS) structure.[7] In particular, 1000 hours stable operation has been achieved in the AlGaAs/GaAs UCGAS-LED structure on Si by reduction of the thermal stress.[7] However, the UCGAS-LED structure involves difficulty of fabrication process.

AlGaAs layers are commonly used for cladding and confining layers in conventional structures of LED's and laser diodes on Si as well as GaAs substrates because Al is useful to increase the band-gap energy. Al is well known to cause growth difficulties due to increased incorporation of residual oxygen for metalorganic chemical vapor deposition (MOCVD) growth. We have shown that the rapid degradation in the conventional Al-contained laser diode on the Si substrate is caused by the deteriorations of electrical and optical characteristics, which are related to the defect-accelerated impurity diffusion and the formation of dark-line defects (DLD's).[8, 9] The Al-free materials have the advantages such as less surface oxidation, lower surface recombination velocity, reduction of leakage current and resistance to formation of DLD's. Therefore, the improvement in reliability can be expected for the LED and laser diode on Si substrates using the Al-free structure. In this study, we report the stable operation for more than 1100 hours in Al-free InGaP/GaAs LED's on Si substrates at 300 K.

II. EXPERIMENTAL

In the first growth step, a 1.8-μm-thick n^+-GaAs layer was grown by an rf-heated MOCVD at atmospheric pressure on a (100) n^+-Si substrate tilted 2° toward the [110] direction using the two-step growth technique. During the n^+-GaAs layer growth at 750 °C, the temperature was cycled five times from 350 to 850 °C. Thermal cycle annealing is effective in reducing the density of threading dislocations in the active layer.[10] In the second growth step, this GaAs/Si was transferred to the low pressure (76 Torr) MOCVD growth system and treated as a substrate for the subsequent growth of InGaP/GaAs double-heterostructure. The structure grown at 700 °C consists of a 0.8-μm-thick n-$In_{0.49}Ga_{0.51}P$ lower cladding layer, a 0.1-μm-thick n-GaAs active layer, a 0.8-μm-thick p-$In_{0.49}Ga_{0.51}P$ upper cladding layer, and a 0.1-μm thick p^+-GaAs contact layer. The conventional Al-contained AlGaAs/GaAs double-heterostructure LED was also grown on the Si substrate. In order to confirm the advantages of the Al-free material, the LED's were fabricated using Ti/Au for the p^+-GaAs contact layer and Au-Sb/Au for the Si substrate. The electrode area of Ti/Au was 1.26×10^{-4} cm^2.

The characteristics of LED's on Si substrates were measured under dc bias at 300 K. The lifetime tests for five samples of each LED were also examined under automatic current control (ACC) condition at 300 K. The top $In_{0.49}Ga_{0.51}P$ layers were characterized by a Nomarski microscope, photoluminescence (PL) at 77 K, electron-beam-induced current (EBIC) and 300 K van der Pauw-Hall measurements. 300 K time-resolved PL measurement was carried out using the semiconductor pulsed laser with a wavelength of 655 nm. Growth of DLD's was studied using an electroluminescence (EL) observation system.

III. RESULTS AND DISCUSSION

Figures 1 (a) and (b) show as-grown surface morphology for the conventional Al-contained AlGaAs/GaAs and the Al-free InGaP/GaAs LED's on the Si substrates, respectively. Although the surfaces were mirror-like in the both samples, the AlGaAs/GaAs LED on Si exhibited precipitates, which were probably caused by the excess aluminum. In the growth of the AlGaAs/GaAs laser diode on Si, these precipitates become pronounced as the aluminum composition increases. These precipitates were also observed in the laser diode grown on Si in Fig. 1 of Ref. 11. The dark spot density (DSD) obtained from the EBIC measurement was $9 \times 10^6 \sim 1 \times 10^7$ cm^{-2} in the both samples. The peak wavelength and the full width at half maximum (FWHM) of the PL spectra at 77 K were 642.5 nm and 11.1 nm for the 1.5-μm-thick $In_{0.49}Ga_{0.51}P$ layer on GaAs, and 645.5 nm and 17.2 nm for the $In_{0.49}Ga_{0.51}P$

layer simultaneously grown on GaAs/Si, respectively. This red shift could be due to the biaxial tensile stress caused by the difference in the coefficients of thermal expansion between $In_{0.49}Ga_{0.51}P$ and Si. The electron mobility at 300 K was 989 $cm^2/V\cdot s$ with a carrier concentration of $3.5x10^{17}$ cm^{-3} for the $In_{0.49}Ga_{0.51}P$ layer on the GaAs substrate, and 950 $cm^2/V\cdot s$ with a carrier concentration of $3.8x10^{17}$ cm^{-3} for the $In_{0.49}Ga_{0.51}P$ layer on the GaAs/Si. The PL decay times obtained from the time-resolved 300 K spectra were 0.9 nsec and 2.7 nsec for the AlGaAs/GaAs and InGaP/GaAs LED's on the Si substrates, respectively. Taking account of these results and the previously reported result[12]), the recombination velocity at InGaP/GaAs interface is less than that at AlGaAs/GaAs interface.

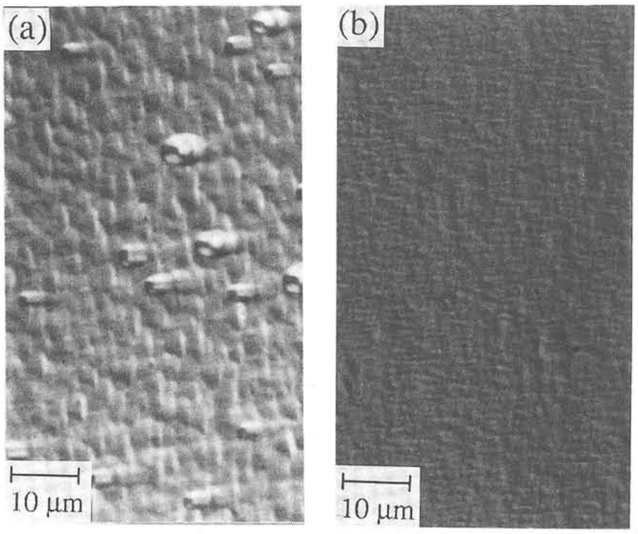

Fig. 1. Nomarski micrographs of (a) Al-contained AlGaAs/GaAs and (b) Al-free InGaP/GaAs LED's grown on Si substrates by MOCVD.

The InGaP/GaAs LED on Si showed the turn-on voltage of 1.5 V and the reverse break down voltage of 9.3 V at 100 µA, which indicate a good characteristic of p-n junction. The ideality factor calculated from the forward I-V characteristic was approximately 2 in the bias region around 0.5 V. The light output power-dc current (L-I) characteristic at 300 K is shown in Fig. 2. For comparison, the previously reported result on the UCGAS-LED[7]) is also shown in this figure. The characteristic of the InGaP/GaAs LED on the Si substrate was almost linear up to an injected current of 40 mA, and the optical output power was 23 µW at 40 mA. The peak in the spectrum of emitted light at 877 nm has the FWHM of about 39 nm. The data from PL and spectrum measurements indicate that the InGaP/GaAs LED on Si is subject to a tensile stress. In comparison with the UCGAS-LED on the Si substrate, this InGaP/GaAs LED exhibits a high power and a linear L-I characteristic. This result indicates that the crystal quality of this LED is better than that of UCGAS-LED. In other words, the InGaP/GaAs LED on Si exhibits a lower density of nonradiative recombination center.

Figure 3 shows the typical result from the lifetime test for the Al-free InGaP/GaAs LED on the Si substrate. The lifetime at 300 K was examined by measuring the output power at a constant current of 10 mA (79 A/cm^2). The conventional AlGaAs/GaAs LED exhibited the rapid degradation (not shown). However, the significant improvement was observed in the reliability of the Al-free InGaP/GaAs LED on the Si substrate. The InGaP/GaAs LED on Si showed the stable operation for more than 1100 hours. Taking account of these results and ease of

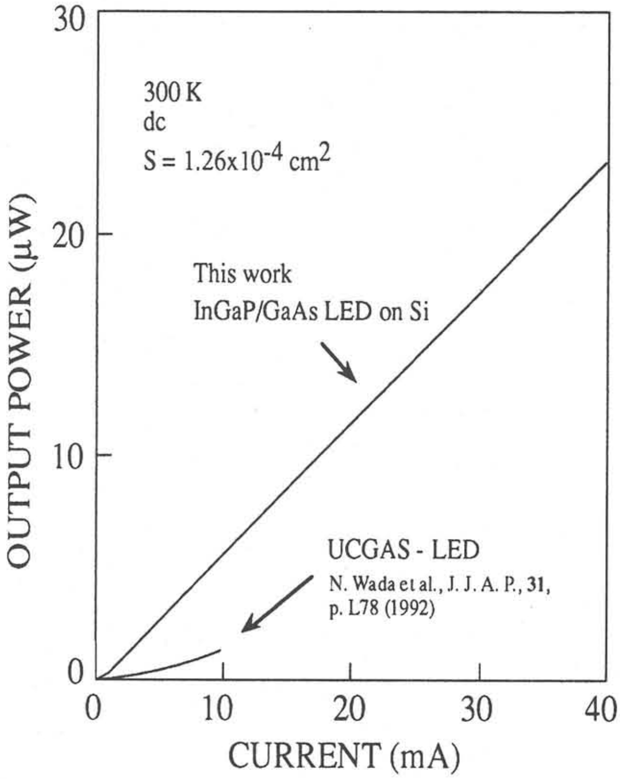

Fig. 2. 300 K L-I characteristics of the InGaP/GaAs LED and UCGAS-LED[7]) grown on Si substrates.

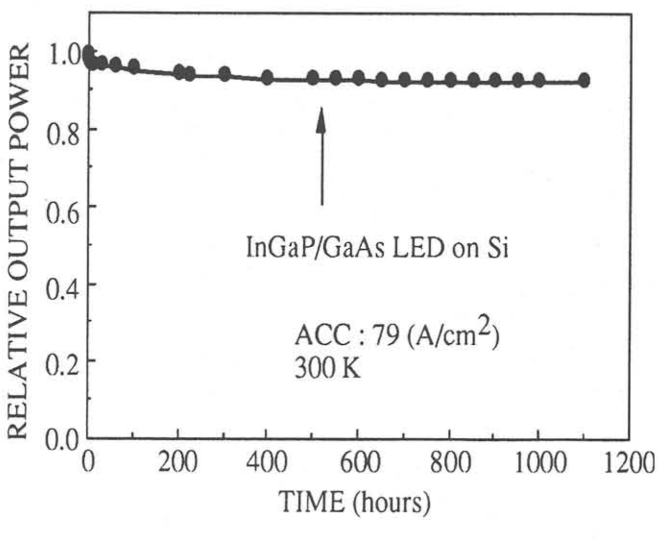

Fig. 3. Result from lifetime test for the InGaP/GaAs LED on Si substrate.

fabrication process, the InGaP/GaAs LED on Si is thought to be superior to UCGAS-LED on Si.

In order to study the optical degradation, the formation of DLD's was observed for the Al-contained AlGaAs/GaAs and Al-free InGaP/GaAs LED's on the Si substrates using the EL observation. Figures 4 (a) and (b) show the EL images of the AlGaAs/GaAs and InGaP/GaAs LED's on the Si substrate after aging process of 50 hours, respectively. As the aging progresses in the AlGaAs/GaAs LED on Si, the growth of DLD's was clearly observed near the electrodes. The DLD's, originating from the threading dislocations, have a high growth velocity along <100> direction. The growth velocities of <100> DLD's were estimated to be 10 and 50 μm/h at the injected current densities of 0.5 and 1.5 kA/cm^2, respectively, which depend on the injected current density.[13] These DLD's are three-dimensional dislocation networks where the nonradiative recombination dominates. On the contrary, the Al-free InGaP/GaAs LED on Si showed no significant growth of DLD's as shown in Fig. 4 (b), which indicates the suppression of the optical degradation in this material. Thus, the Al-free materials are effective in obtaining the stable operation of the LED on the Si substrate. Further study on the reliability under the conditions at higher currents and ambient temperatures is in progress.

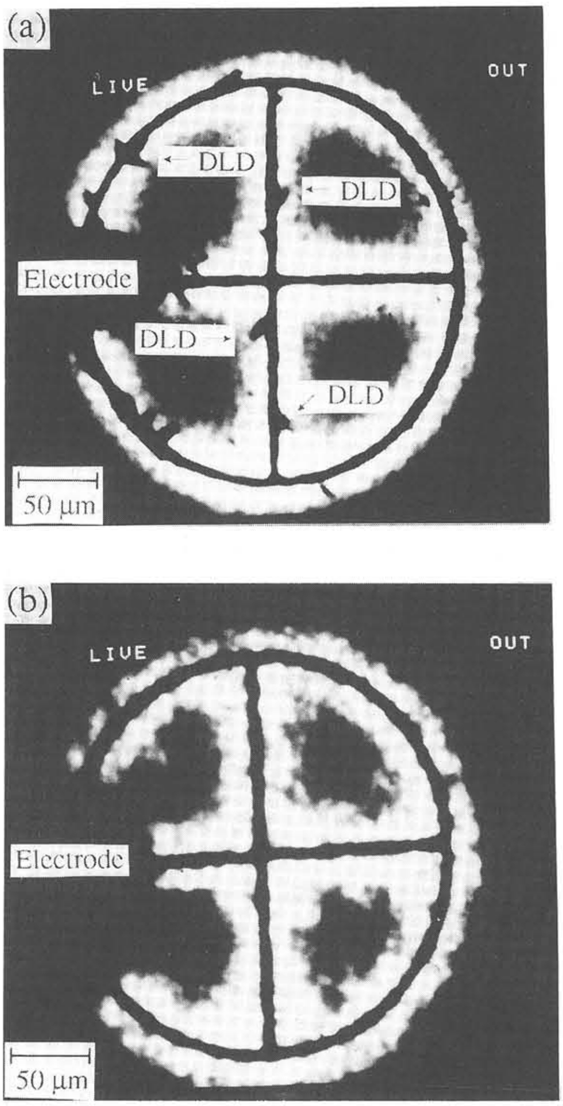

Fig. 4. EL images of (a) AlGaAs/GaAs and (b) InGaP/GaAs LED's on Si substrates after aging process of 50 hours.

IV. CONCLUSION

The high quality $In_{0.49}Ga_{0.51}P$ layer has been grown on the GaAs/Si by MOCVD technique despite the 4 % lattice mismatch. We have also demonstrated the MOCVD-grown reliable InGaP/GaAs LED on the Si substrate using the Al-free materials. The 877-nm emitting InGaP/GaAs LED on Si showed the stable operation for more than 1100 hours, which results from the suppression of the formation of DLD's.

ACKNOWLEDGMENT

The authors are grateful to A. Tanaka and Y. Niwano for their help with sample preparation and device fabrication. This work was partially supported by a Grant-in-Aid for Developmental Scientific Research (No. 06555013) from the Ministry of Education, Science and Culture.

REFERENCES

1) H. K. Choi, G. W. Turner, T. H. Windhorn and B. -Y. Tsaur, IEEE Electron Device Lett. 7 (1986) 500.
2) T. Egawa, T. Jimbo and M. Umeno, IEEE Photonics Tech. Lett. 4 (1992) 612.
3) T. Egawa, T. Jimbo and M. Umeno, IEICE Trans. Electron. E76-C (1993) 106.
4) H. K. Choi, C. A. Wang and N. H. Karam, Appl. Phys. Lett. 59 (1991) 2634.
5) T. Egawa, Y. Hasegawa, T. Jimbo and M. Umeno, Jpn. J. Appl. Phys. 31 (1992) 791.
6) Y. Kobayashi, T. Egawa, T. Jimbo and M. Umeno, Jpn. J. Appl. Phys. 30 (1991) L1781.
7) N. Wada, S. Yoshimi, S. Sakai, C. L. Shao and M. Fukui, Jpn. J. Appl. Phys. 31 (1992) L78.
8) W. E. Plano, D. W. Nam, K. C. Hsieh, L. J. Guido, F. A. Kish, A. R. Sugg and N. Holonyak, Jr., Appl. Phys. Lett. 55 (1989) 1993.
9) T. Egawa, T. Jimbo, Y. Hasegawa and M. Umeno, Appl. Phys. Lett. 64 (1994) 1401.
10) T. Egawa, T. Soga, T. Jimbo and M. Umeno, IEEE J. Quantum Electron. 27 (1991) 1798.
11) D. G. Deppe, D. C. Hall, N. Holonyak, Jr., R. J. Matyi, H. Shichijo and J. E. Epler, Appl. Phys. Lett. 53 (1988) 874.
12) J. M. Olson, R. K. Ahrenkiel, D. J. Dunlavy, B. Keyes and A. E. Kibbler, Appl. Phys. Lett. 55 (1989) 1208.
13) Y. Hasegawa, T. Egawa, T. Jimbo and M. Umeno, Jpn. J. Appl. Phys. 34 (1995) 2994.