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Low-Threshold CW Operation at 300 K of All-MOCVD-Grown MQW Lasers on Si Using Post-Growth Patterning

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Thermal cycle annealing is effective to reduce the threading dislocations in GaAs/Si. The thermally induced biaxial stress in GaAs layer grown on Si is reduced by post-growth patterning of GaAs layer to 10 μm-wide stripe. All-MOCVD-grown MQW laser on Si has the CW threshold current as low as 24 mA at 300 K using the technique of thermal cycle annealing. The rapid degradation can be suppressed by post-growth patterning for the laser with 10 μm-wide stripe, which results from the relief of stress.

1. INTRODUCTION

Room-temperature continuous-wave (CW) operating lasers have been grown on Si substrate by combination of MBE and MOCVD techniques[1)] or MOCVD technique.[2)] However, it is difficult to fabricate reliable lasers on GaAs/Si, because the GaAs/Si has the problems of the high density of threading dislocations and the large biaxial tensile stress (10^9 dyn/cm^2) in GaAs layer. The dark-line defects (DLDs) are caused by the presence of a very high density of threading dislocations, which can act as non-radiative recombination centers.[3)] The large tensile stress can enhance the migration of dislocations and the formation of the DLDs. The DLDs cause the rapid degradation of optoelectronic devices fabricated on GaAs/Si. In order to solve these problems, selective area growth and defect-filtering layers such as thermal cycle anneal and strained-layer superlattice (SLS) have been proposed.[4,5)] In this study, we have demonstrated the low threshold multi-quantum well (MQW) laser grown on Si entirely by MOCVD. We have also studied the effects of dislocations and stress on the laser performance.

2. EXPERIMENTAL PROCEDURE

The samples were grown on Si substrates oriented 2^{o} off (100) towards [011] at 750 ^{o}C in RF-heated MOCVD reactor using the two-step growth technique. A detailed growth procedure for GaAs layer on Si is described elsewhere.[2)] A 2-μm-thick n$^+$-GaAs layer was grown on Si substrate by the two-step growth technique. In order to study the crystallinity of the GaAs/Si and the lasing characteristics, 3-μm-thick GaAs layers and the MQW lasers were grown on Si using three defect-filtering layers. The MQW laser consists of 2-μm-thick n$^+$-GaAs layer, 1-μm n-$Al_{0.7}Ga_{0.3}As$ cladding layer, 63-nm $Al_{0.3}Ga_{0.7}As$ confining layer, 9-nm GaAs active layer, 5.5-nm $Al_{0.3}Ga_{0.7}As$ barrier layer, 9-nm GaAs active layer, 63-nm $Al_{0.3}Ga_{0.7}As$ confining layer, 1-μm p-$Al_{0.7}Ga_{0.3}As$ cladding layer and 80-nm p$^+$-GaAs layer. Three different defect-filtering layers were investigated: (A) without defect-filtering layer, (B) thermal cycle annealing (TCA) during the growth of the n$^+$-GaAs layer, (C) TCA and five pairs of SLS composed of $In_{0.1}Ga_{0.9}As$/GaAs at 750 ^{o}C. TCA was performed five times by varying substrate temperature from 300 to 850 ^{o}C in an AsH_3 ambient.

We also study the relief of the stress in the patterned GaAs layer on Si. After growth, the GaAs layers on Si were chemically etched down to the Si substrate. The width of the GaAs stripe was from 10 to 160 μm. As shown in Fig. 1, mesa and standard oxide stripe lasers were fabricated on Si, and the lasing characteristics were compared.

The GaAs/Si was characterized by the dark spot density (DSD) obtained from cathodoluminescence (CL) at 100 K and the wavelength of band-edge emission from photoluminescence (PL) at 4.2 K. The propagation of the dislocations was observed by cross-sectional transmission electron

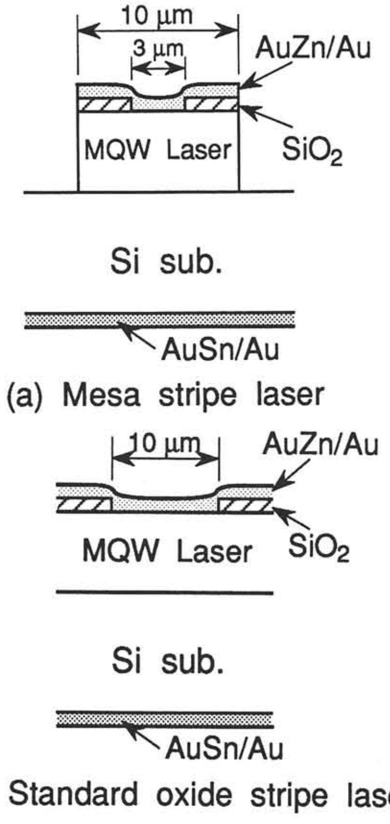

Fig. 1. Geometries of (a) mesa stripe and (b) standard oxide stripe lasers grown on Si.

microscopy (TEM). The lasing characteristics were measured under pulsed and CW conditions at 300 K.

3. RESULTS AND DISCUSSIONS

Table I summarizes the DSD obtained from CL and the wavelength of band-edge emission from PL for the 3-µm-thick GaAs layer on Si. The technique of TCA or SLS is effective in reducing the DSD. The lowest DSD of 3.9×10^{6} cm^{-2} has been obtained using the combination of TCA and SLS. However, the wavelength of the GaAs/Si grown with TCA and SLS is 1 nm longer than that of the sample grown with TCA. This result indicates that the GaAs/Si grown with TCA and SLS is subject to a higher tensile stress than that of the sample grown with TCA.

Table I. DSD and wavelength of band-edge emission for GaAs/Si. The wavelength of the band-edge emission for the GaAs/GaAs is 822.2 nm.

	DSD ($\times10^{6}$ cm^{-2})	wavelength (nm)
without defect-filtering layer	33	837.4
with TCA	5.5	838.9
with TCA + SLS	3.9	839.9

Figure 2 shows the PL peak energy for the patterned GaAs stripes with the width from 10 to 160 µm. The peak energy increases for the patterned GaAs layer with the narrow stripe. In particular, the GaAs layer with 10-µm-wide stripe has the peak emission of 1.494 eV. This results indicates that post-growth patterning of GaAs layer to narrow stripe significantly reduces the thermally induced biaxial tensile stress.

We have studied the effects of defect-filtering layer on the lasing characteristics. The CW operation at 300 K has not been obtained for the lasers without defect-filtering layer (type A) and with TCA and SLS (type C). The pulsed threshold current (I_{th}) and threshold current density (J_{th}) are 210mA and 5.83 kA/cm^2 for the laser without defect-filtering layer (type A), and 141 mA and 5.98 kA/cm^2 for the laser with TCA and SLS (type C), respectively. The reason for not showing the CW operation are the high density of dislocations and the high tensile stress. As shown in Fig. 3, on the other hand, the thermally cycle annealed laser (type B) has exhibited the CW threshold current as low as 24 mA and a differential quantum efficiency of 40 % at 300 K. The reduction of threading dislocations by thermal cycle annealing results in the CW operation at 300 K. The lowest and the averaged threshold current density are 0.99 kA/cm^2 and 1.16 kA/cm^2, respectively. A single-mode operation has been observed with a peak wavelength of 851 nm, which is 12 nm longer than that of the

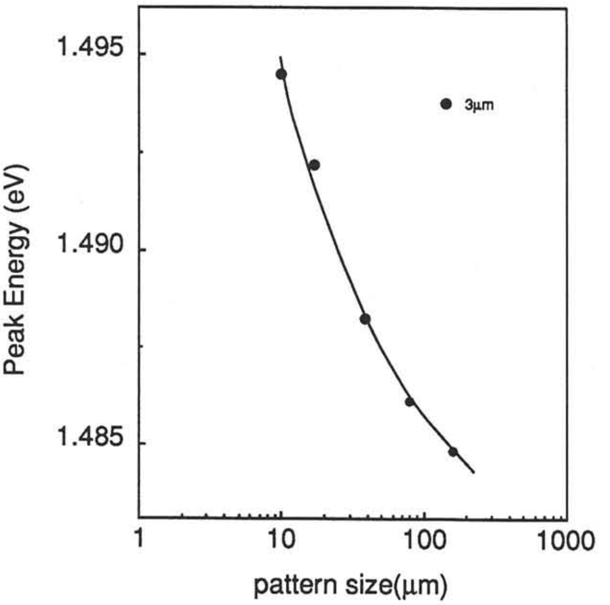

Fig. 2. PL peak energy for GaAs/Si as a function of pattern size. The 3-µm-thick GaAs layer are grown on Si, and then post-growth patterning is performed.

laser grown on a GaAs substrate. This result indicates that the laser grown on Si is still subjected to the residual tensile stress.

Figure 4 shows cross-sectional TEM micrograph of the thermally cycle annealed laser. Many dislocations originate at the GaAs/Si interface, but most of the dislocations are confined into the thermally cycle annealed n^+-GaAs layer and do not intrude the active layer. The reduction of threading dislocations by thermal cycle annealing results in the CW operation at 300 K.

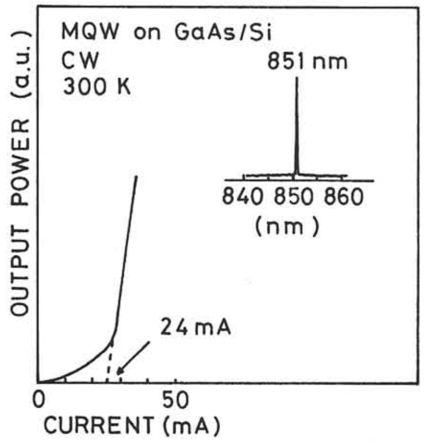

Fig. 3. I-L characteristic under CW condition at 300 K for MQW laser grown on Si (type B).

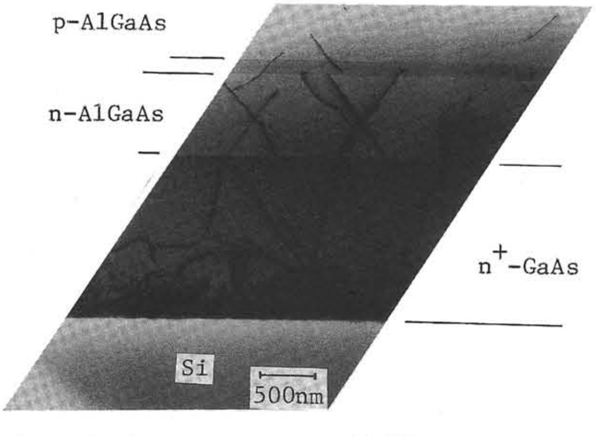

Fig. 4. Cross-sectional TEM micrograph of thermally cycle annealed laser on Si.

In order to study the effect of the stress reduction on the lasing performance, post-growth patterning is applied to the thermally cycle annealed laser (type B). The mesa stripe laser has a 10-μm-wide stripe and a 3-μm-wide oxide window. The laser has exhibited the CW I_{th} of 20.8 mA (J_{th}=3.75 kA/cm^2) at 300 K. A higher J_{th} of this laser is caused by the 3-μm-wide oxide window. A remarkable improvement is observed in the reliability. Figure 5 shows the results from stability tests of two lasers grown on Si operated continuously at 300 K. The oxide stripe laser shows the rapid degradation. However, relatively slow degradation is found for the 10-μm-wide mesa stripe laser. Note that the rapid degradation has been suppressed for the 10-μm-wide mesa stripe laser. By applying post-growth patterning to the laser grown with TCA (type B), the rapid degradation has been suppressed.

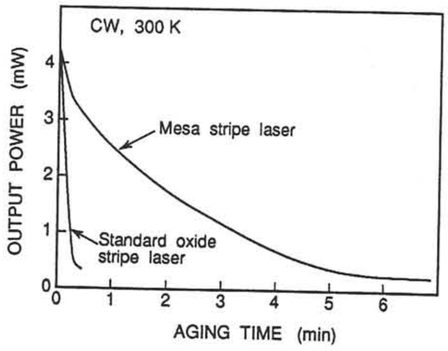

Fig. 5. Stability tests of mesa and standard oxide stripe lasers grown on Si under CW condition at 300 K.

4. CONCLUSIONS

Thermal cycle annealing is effective to reduce the threading dislocations in the GaAs/Si. Post-growth patterning to small size stripe significantly reduces the tensile stress in the GaAs layer grown on Si. We have demonstrated that the all-MOCVD-grown MQW laser on Si has the CW threshold current as low as 24 mA at 300 K using the technique of thermal cycle annealing. By applying post-growth patterning to the thermally cycle annealed laser, the rapid degradation can be suppressed for the 10-μm-wide mesa stripe laser.

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