Extended Abstracts of the 1996 International Conference on Solid State Devices and Materials, Yokohama, 1996, pp. 598-600

The Application of Semiconducting Low-Temperature Grown GaAs to Improve Laser Diodes Grown on Si Substrates

Cheng Chiang PHUA, Tow Chong CHONG, Wai Shing LAU and Leng Seow TAN

Centre for Optoelectronics, Department of Electrical Engineering, National University of Singapore
10 Kent Ridge Crescent, Singapore 119260, Republic of Singapore

The application of semiconducting low-temperature grown GaAs (LT-GaAs) intermediate layer in laser diodes on Si by molecular beam epitaxy (MBE) reduces the threshold currents to half of that obtained in the sample without the semiconducting LT-GaAs intermediate layer. Furthermore, the emission spectra of the sample with semiconducting LT-GaAs intermediate layer were predominantly single mode at and near the threshold currents, as compared to the multimode operations in the sample without the semiconducting LT-GaAs intermediate layer.

1. Introduction

Many approaches have been tried to suppress threading dislocations in GaAs on Si, so as to make this material system a reality in reliable optoelectronic device applications. These include the use of *ex situ* rapid thermal annealing,[1] *in situ* thermal cyclic annealing,[2] selective area growth,[3] undercut GaAs on Si[4] and mesa release and deposit.[5]

Previously, we have reported that the crystalline quality of the GaAs/Si epilayers could be improved significantly by using a low-temperature grown GaAs (LT-GaAs) intermediate layers by photoluminescence (PL), cathodoluminescence (CL) and X-ray diffraction (XRD).[6] This is further confirmed by cross-sectional transmission electron microscope (XTEM) results.[7]

GaAs grown by molecular beam epitaxy (MBE) at low temperatures is usually known to be semi-insulating.[8] However, we found that LT-GaAs grown by MBE on Si is semiconducting and can be heavily doped by Si for higher conductivity.[9] It is generally believed that LT-GaAs is semi-insulating because of the As precipitates in it.[10] Our XTEM results show that LT-GaAs on Si does not have As precipitates whereas LT-GaAs on GaAs does have a lot of As precipitates. Hence, we can claim that semiconducting LT-GaAs on Si is a different class of material. In this paper, the successful implementation of semiconducting LT-GaAs intermediate layer to improve laser diodes grown on Si is presented for the first time.

2. Experiments

In order to demonstrate the benefits of having LT-GaAs intermediate layer in device applications, two graded-index separate-confinement heterostructure (GRIN-SCH) single quantum well (SQW) laser diode structures were grown on Si substrates using similar growth conditions in the same MBE system. The layers for both the samples have the same structure except that one has a 0.5 μm thick LT-GaAs intermediate layer and a 0.5 μm thick GaAs grown at 600°C as buffer layers whereas the other one was grown using only a 1.0 μm thick GaAs grown at 600°C as a buffer layer, as shown in Fig. 1. The layers were grown on n^+Si substrates, with resistivities of less than 0.01 Ω.cm, oriented 4° off (100) towards [011].

The details of substrate treatments before MBE growths had been discussed previously.[6] After 10 cycles of migration-enhanced epitaxy (MEE) of GaAs growth at 280°C, a 500 Å thick Si-doped GaAs nucleation layer was grown at 280°C at a growth rate of 0.2 μm/hr and annealed at 600°C under As_4 overpressure. For sample with LT-GaAs intermediate layer, a 0.5 μm thick LT-GaAs buffer was then grown at 230°C and annealed at 600°C under As_4 overpressure before growing another 0.5 μm thick GaAs buffer layer at 600°C. As for the sample without LT-GaAs intermediate layer, only 1.0 μm thick Si-doped GaAs buffer layer was grown at 600°C. The n^+-type GaAs buffer layers were doped to about 1.5×10^{18} cm^{-3} and grown using a growth rate of 1.0 μm/hr. After growing the GaAs buffer layers, laser structures were grown next at 680°C. A 1.35

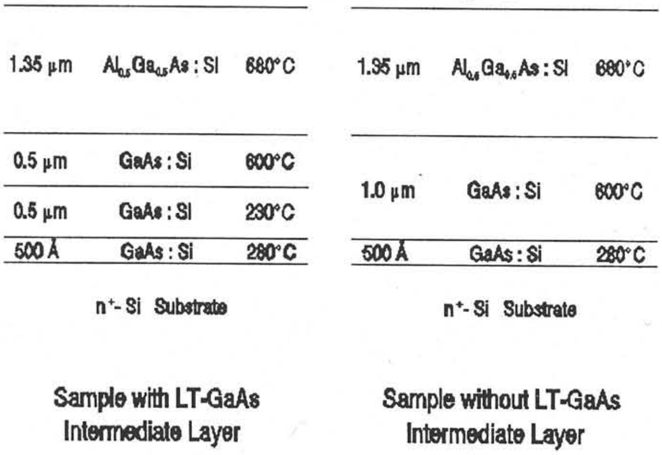

Fig. 1. The GRIN-SCH SQW laser diode structures with and without LT-GaAs intermediate layer.

μm n^+-$Al_{0.5}Ga_{0.5}As$ bottom confinement layer ($\sim 5x10^{17}$ cm^{-3}), a 1905 Å bottom graded n-$Al_xGa_{1-x}As$ layer ($\sim 10^{17}$ cm^{-3}, with x varying from 0.5 to 0.2), a 67 Å undoped GaAs well, a 1905 Å top graded p-$Al_xGa_{1-x}As$ layer ($\sim 10^{17}$ cm^{-3}, with x varying from 0.2 to 0.5), a 1.35 μm p-$Al_{0.5}Ga_{0.5}As$ layer ($\sim 5x10^{17}$ cm^{-3}), and finally a 0.2 μm p^+-GaAs ($\sim 10^{19}$ cm^{-3}) cap layer were grown successively.

A combination of ridge waveguide and Schottky barrier defined stripe geometry[11] was used to fabricate the ridge waveguide stripe geometry laser. The 6 μm stripes p-type ohmic contacts to the p^+-$Al_xGa_{1-x}As$ were Au-Cr/Au, whereas the n-type ohmic contacts to the Si substrates were Au-Ge/Au.

The threshold performance and the spectral characteristics of the laser diodes were evaluated at room temperature under pulse current excitations. The threshold current was determined from the light against current (L-I) characteristic curves by extrapolating the portion of the curve after sharp laser turn-on to zero light intensity. For the spectral characteristic measurements, the light output of the laser diodes were collimated into a monochromator and detected by a photo multiplier-tube (PMT).

3. Results and Discussion

The L-I characteristics of the laser diodes are shown in Fig. 2. The threshold currents indicated are 2.1 A and 4.4 A for samples with and without LT-GaAs intermediate layer, respectively. With the application of LT-GaAs intermediate layer in GRIN-SCH SQW laser structure, the threshold current of the laser was reduced to less than 50% of that obtained in the laser sample without the LT-GaAs intermediate layer. It must be emphasised that the lowest threshold currents obtained from testing various laser diodes from the sample with LT-GaAs intermediate layer was about 1.1 A. However, this value was not very typical for the sample. The threshold current of 4.4 A for the sample without LT-GaAs intermediate layer was the lowest obtainable. The more typical threshold current values were more than 5.0 A. Due to these high threshold currents, the devices failed very rapidly. Also, among the devices tested there were very few that were capable of lasing in the sample without LT-GaAs intermediate layer. As compared to the sample with LT-GaAs intermediate layer, the probability of getting devices that could lase in sample without LT-GaAs intermediate layer was less than 1:5.

The typical room temperature emission spectra of the laser diodes with and without LT-GaAs intermediate layer are shown in Figs. 3 and 4. The emission spectra of the sample with LT-GaAs intermediate layer were predominantly single mode up to about 1.2 times the threshold current injection levels. Typically the emission spectra of the sample without LT-GaAs intermediate layer were multimode in nature. The evolution from single mode to multimode operation upon further increase of current can be attributed to a well known phenomenon of spectral hole burning due to inhomogeneous

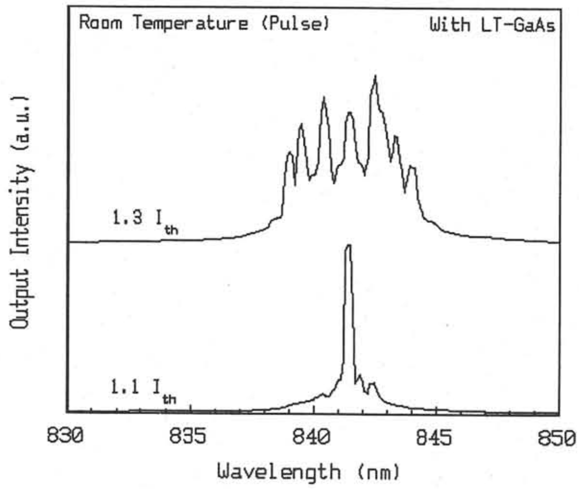

Fig. 3. Room temperature emission spectra of GRIN-SCH SQW laser diode, with LT-GaAs, grown on Si substrate.

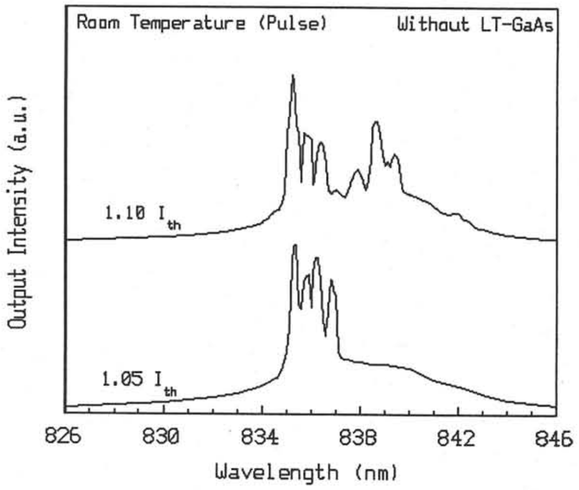

Fig. 4. Room temperature emission spectra of GRIN-SCH SQW laser diode, without LT-GaAs, grown on Si substrate.

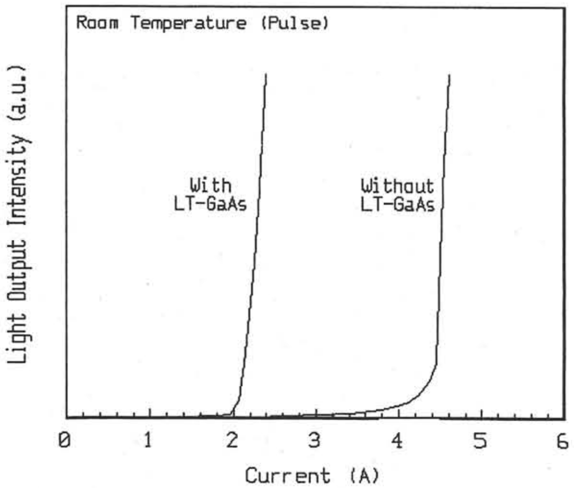

Fig. 2. Light against current chararcteristics of the laser diodes fabricated from GaAs/Si samples.

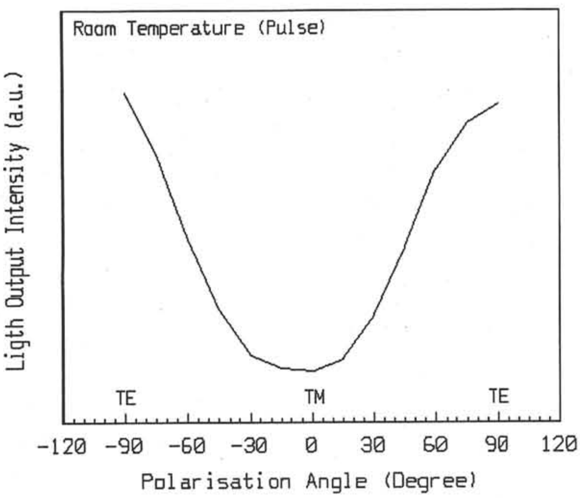

Fig. 5. Typical polarisation characteristics of GRIN-SCH SQW AlGaAs/GaAs laser diodes grown on Si substrates.

gain suppression in semiconductor lasers.[12]

The polarisation characteristics of both the samples were also investigated. Both samples were basically having the same polarisation effects. The typical polarisation characteristic of both samples is shown in Fig. 5. The emission from both the laser diode samples exhibited were predominantly transverse electric (TE) mode at and near the threshold currents, although transverse magnetic (TM) mode also observed. The light output intensity ratios of TE/TM of both the samples were peak at more than 30 at about 1.1 times the threshold currents. The tendency to emit TM emission is a unique property of semiconductor lasers under biaxial tensile strain.[13]

4. Conclusions

With the application of LT-GaAs intermediate layer in the GRIN-SCH SQW AlGaAs/GaAs laser diode structure on Si substrate, the threshold current of the laser diode was reduced significantly. The typical emission spectra of the laser diode structure with the LT-GaAs intermediate layer were predominantly single mode up to about 1.2 times the threshold currents, whereas multimode multimode operations were typically obtained from samples without the LT-GaAs intermediate layer. The emission from both samples exhibited predominantly TE mode at and near the threshold currents, with TE/TM ratios peak at more than 30.

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