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# Monolithic Integration of Strain-Relieved AlGaAs/InGaAs Laser and GaAs MESFET Grown on Si Using Selective Regrowth by MOCVD

Takashi EGAWA, Kei YAMAMOTO, Takashi JIMBO and Masayoshi UMENO

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

We have demonstrated the first successful fabrication of the monolithic integration of an AlGaAs/InGaAs laser, a p-n photodetector and a GaAs MESFET grown on a $SiO_2$ back-coated p-Si substrate using selective regrowth by MOCVD. The reliability of the laser on the Si substrate can be improved by the strain-relieved AlGaAs/InGaAs laser with the InGaAs intermediate layer. During the GaAs layer growth, the p-n photodetector is formed near the surface of the p-Si substrate by diffusing the As atoms. The use of $SiO_2$ back-coated Si substrate is effective in suppressing unintentional Si autodoping and obtaining a good pinch-off GaAs MESFET.

## 1. INTRODUCTION

GaAs-on-Si technology is very promising in the realization of optoelectronic integrated circuits (OEIC's) which will be found in optical interconnection between Si LSI's. Although monolithic integration of LEDs and Si MOSFETs has been fabricated on a Si substrate, the individual devices such as lasers, LEDs, MESFETs and HBTs have been mainly grown on the Si substrates.[1-4] The reliability of the laser is an obstacle to the OEIC's on the Si substrate because the GaAs-based laser on Si has a rapid degradation due to the formation of dark-line defects (DLD's).[5] In this paper we show that a strain-relieved AlGaAs/InGaAs laser with an InGaAs intermediate layer grown on a Si substrate exhibits a increased lifetime. We also demonstrate the first fabrication of a monolithically integrated AlGaAs/InGaAs laser, p-n photodetector and GaAs MESFET grown on a Si substrate using selective regrowth by MOCVD.

## 2. EXPERIMENTAL PROCEDURE

Figure 1 shows the schematic structure of the device grown on the p-Si substrate at 750 °C using the selective regrowth by MOCVD. After the growth of GaAs MESFET on the $SiO_2$ back-coated p-Si substrate using the two-step growth technique, $SiO_2$ film was deposited on the $n^+$-GaAs layer and openings were etched in the $SiO_2$ film to expose the undoped GaAs layer. By using the $SiO_2$ film as a mask, the selective regrowth was performed for the $AlGaAs/In_xGa_{1-x}As$ single quantum well (SQW) laser with the 20-nm-thick $In_{0.08}Ga_{0.92}As$ intermediate layer (InGaAs IL). The SQW laser structure consists of two 60-nm-thick $Al_{0.3}Ga_{0.7}As$ barrier layers and a 9-nm-thick GaAs active layer. The p-n photodetector is formed near the surface of the p-Si substrate during the growth of the undoped GaAs layer. The MESFET with a 2.5x400 $\mu m^2$ gate was fabricated using the conventional recess gate processing technique.[4]

Since the threshold current of the laser increases after the selective regrowth, it is necessary to grow the MESFET before the laser. In order to compare the lasing characteristics, the conventional AlGaAs/GaAs laser and the AlGaAs/InGaAs laser without the InGaAs IL were also grown on the Si substrate. The etch pit density (EPD) was examined using molten KOH etching. The p-n junction in the p-Si substrate was measured by electron beam induced current (EBIC) and secondary ion mass spectroscopy (SIMS).

## 3. RESULTS AND DISCUSSION

The stress in the lasing operation is estimated from the degree of polarization ρ. The degree of ρ is defined by

$$\rho=(L_{TE}-L_{TM})/(L_{TE}+L_{TM})$$

where $L_{TE}$ and $L_{TM}$ are the intensities of the TE and TM polarized light, respectively.[6] Figure 2 shows the ρ as a function of normalized current ($I/I_{th}$). The stress can be estimated by measurements of ρ below threshold. It is noticeable that the stress in the laser on the Si substrate can be changed from tensile to compressive stress with increasing the In composition in the

InGaAs active layer. The data indicate that the strain in the $AlGaAs/In_{0.02}Ga_{0.98}As$ laser with the InGaAs IL on the Si substrate can be relieved, which is equal to that of the laser grown on the GaAs substrate. The $AlGaAs/In_{0.01}Ga_{0.99}As$ laser without the InGaAs IL has the strain-relieved active layer although the data is not shown in Fig. 2.

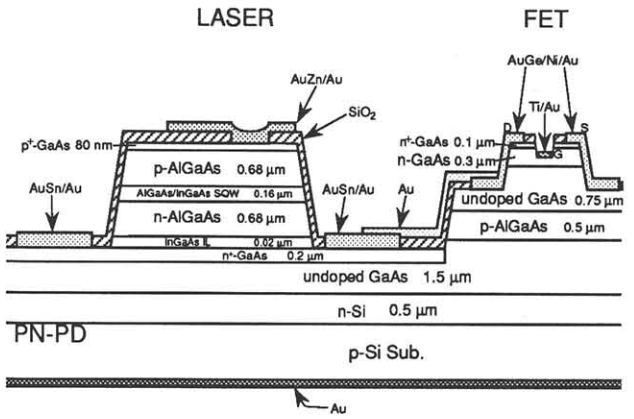


Fig. 1. Schematic cross-sectional structure of the monolithically integrated AlGaAs/InGaAs laser, p-n photodetector and GaAs MESFET grown on the p-Si substrate using the selective regrowth by MOCVD. The p-n photodetector is formed after the epitaxial growth.

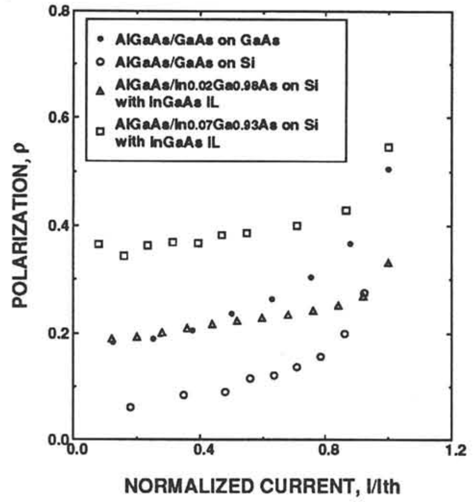


Fig. 2. Degree of polarization ρ as a function of the normalized current ($I/I_{th}$).

Figure 3 shows the results from the aging tests at 300 K for the conventional AlGaAs/GaAs laser and the strain-relieved AlGaAs/InGaAs lasers with and without the InGaAs IL. The AlGaAs/GaAs laser has the threshold current density ($J_{th}$) of 2.4 kA/cm$^2$ and the differential quantum efficiency (η) of 44 %. This laser shows a rapid degradation because the laser has an EPD of $2x10^7$ cm$^{-2}$ and a larger tensile stress in the active layer. Although the $AlGaAs/In_{0.01}Ga_{0.99}As$ laser without the InGaAs IL has the EPD of $2x10^7$ cm$^{-2}$ and the strain-relieved active layer, this laser shows the $J_{th}$ of 1.9 kA/cm$^2$, the η of 50 % and a rapid degradation. In contrast, the $AlGaAs/In_{0.02}Ga_{0.98}As$ laser with the InGaAs IL, which has an EPD of $8x10^6$ cm$^{-2}$ and the strain-relieved active layer, has operated for 100 min with the $J_{th}$ of 1.7 kA/cm$^2$ and the η of 64 %. We have reported that the laser with a lower EPD and a higher stress in the active layer exhibits a rapid degradation.[7] These results indicate that the strain relief by the InGaAs active layer and the reduction of the formation of DLD's by the InGaAs IL are required to fabricate the reliable laser on the Si substrate.

The MESFET with a 2.5 µm gate length exhibits a transconductance of 90 mS/mm, a threshold voltage of -2.2 V and a good pinch-off characteristic, which result from the use of $SiO_2$ back-coated Si substrate.[4]

Figure 4 shows the EBIC profile for the p-Si substrate after the epitaxial growth. The p-n junction is formed near the surface of the p-Si substrate after the epitaxial growth. The build-up of the current is 0.6 V for the p-n junction. SIMS analysis indicates that the As atoms diffuse into the p-Si substrate during the growth of the GaAs layer, which contributes to the fabrication of the p-n photodetector. The carrier concentration and the thickness of the n-type layer can be estimated $1x10^{19}$ cm$^{-3}$ and 0.5 µm, respectively.

Figure 5 shows the modulation characteristic for the light output of the laser in the monolithically integrated device with the gate voltage under the dc condition. The gate voltage corresponding to the lasing threshold is 0.25 V and the abrupt increase of the light output is clearly seen above the threshold gate voltage. The light output can

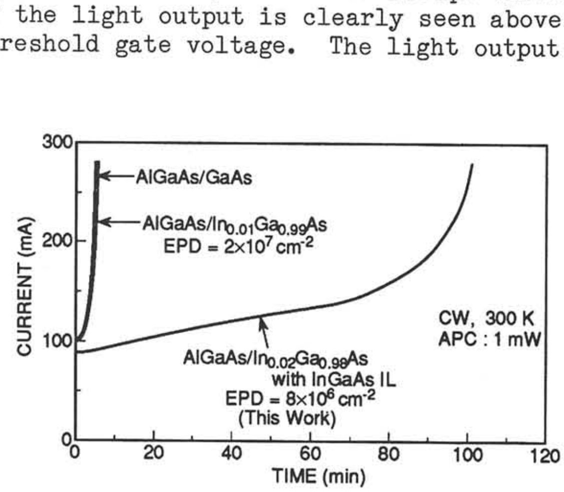


Fig. 3. Results from the aging tests at 300 K for the AlGaAs/GaAs laser and the strain-relieved AlGaAs/InGaAs lasers with and without the InGaAs IL.

be controlled by the gate voltage. The cw light output power-current (L-I) characteristic of the laser using the external detector and the photocurrent monitored by the internal p-n photodetector are shown in Fig. 6. The laser has the cw threshold current of 34 mA, which is small enough to be modulated by the GaAs MESFET. The photocurrent curve slope efficiency is 4 % below the injection current of 34 mA, which corresponds to the threshold current of the laser. Above the injection current of 34 mA, the photocurrent curve slope efficiency is 1.9 % because the lasing emission occurs at 34 mA.

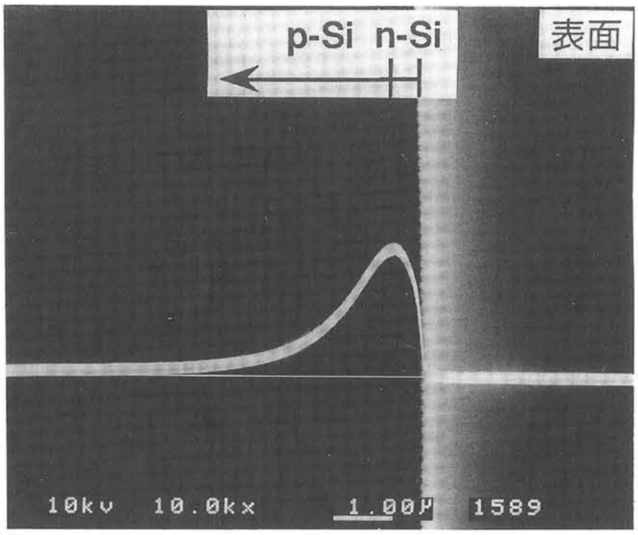


Fig. 4. EBIC profile for the p-Si substrate after the epitaxial growth.

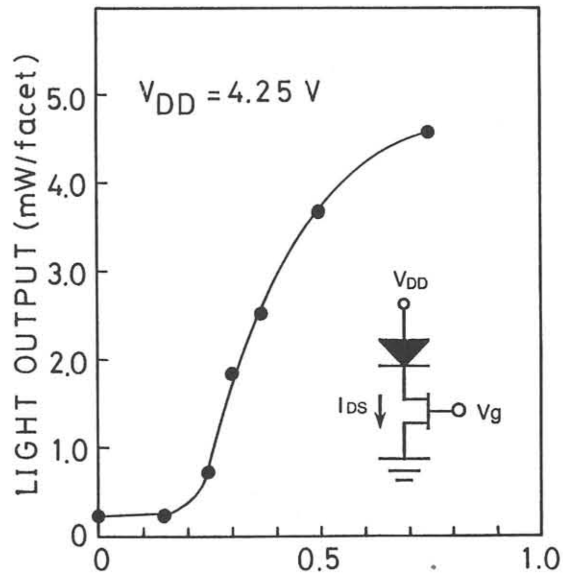


Fig. 5. Gate voltage dependence of the light output in the integrated device under the cw condition. The $V_{DD}$ is set to 4.25 V.

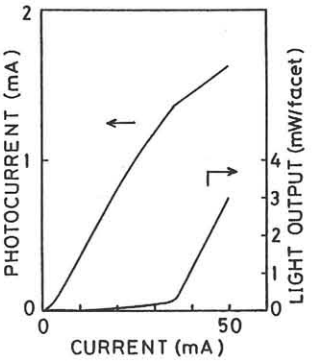


Fig. 6. L-I characteristic of the laser using the external detector and the photocurrent monitored by the internal p-n photodetector.

## 4. CONCLUSION

We have demonstrated the first successful fabrication of the monolithic integration of the AlGaAs/InGaAs laser, the p-n photodetector and the GaAs MESFET grown on the $SiO_2$ back-coated p-Si substrate using the selective regrowth by MOCVD. The use of $SiO_2$ back-coated Si substrate is effective in suppressing unintentional Si autodoping and obtaining the good pinch-off GaAs MESFET. During the growth of the GaAs layer, the p-n photodetector is formed near the surface of the p-Si substrate by diffusing the As atoms. The reliability of the laser on the Si substrate can be improved by the strain-relieved AlGaAs/InGaAs laser with the InGaAs IL. The strain relief by the InGaAs active layer and the reduction of the formation of DLD's by the InGaAs IL are required to fabricate the reliable laser on the Si substrate. This new type of OEIC's is very promising in future applications such as optical interconnection.

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