Stripe-geometry GaAs-InGaAs laser diode with back-side contact on silicon by epitaxial lift-off

J.C. Fan, K.Y. Chen, Gray Lin and C.P. Lee

Indexing terms: Semiconductor junction lasers, Epitaxial lift-off

The transfer of a preprocessed stripe-geometry GaAs-InGaAs laser diode film onto a Pd/Ge/Pd coated n^+-Si substrate is reported with the backside contact on Si using epitaxial lifted-off (ELO) technology. The Pd/Ge/Pd metal layers provide ohmic contacts to both the Si substrate and the GaAs film, making vertical conduction through the Si substrate possible. No device degradation was observed after the ELO process and comparable results were obtained for the ELO laser diodes and the diodes without the ELO process.

The integration of semiconductor lasers with silicon electronic circuits has always been a subject of great interest. This type of III-V/Si integration is important for applications such as optical communications and optical interconnections [1, 2]. Many approaches including heteroepitaxial growth and material bonding techniques have been developed for this purpose [3 – 9]. However, heteroepitaxial growth of GaAs laser diodes on Si suffers from a high dislocation density due to a large lattice mismatch. The poor material quality causes the lasers to degrade [10]. Conversely, wafer bonding techniques such as bonding by atomic rearrangement [6] and epitaxial lifted-off (ELO) [8, 9] have the advantage of combining two different materials with different crystal structures.

Yablonovitch *et al.* [9] and Pollentier *et al.* [8] have demonstrated ELO GaAs-AlGaAs broad-area lasers on a glass and an Si substrate. However, bonding a laser diode film on glass or a bare Si substrate by the Van der Waals force creates an insulating interface, which prohibits vertical conduction between the laser and the Si substrate. Hence, both the n- and p-type contacts must be fabricated on the front side of the grafted film. In this Letter, we describe an ELO technique for the fabrication of stripe-geometry lasers on an Si substrate with the backside contact on Si. Vertical conduction through the Si substrate was obtained and no device degradation was observed after the ELO process.

We have recently found that very good ohmic behaviour can be obtained between a GaAs thin film and an Si substrate if the ELO-GaAs film is grafted onto a Pd/Ge/Pd coated Si [11]. This technique is applied here to fabricate an ELO laser diode on Si. The strong metallurgical bonding between the GaAs thin film and the Si substrate also makes the facet cleavage possible without any danger of breaking the grafted film and the substrate.

The lasers used in this study were 980nm InGaAs/GaAs strained single quantum well lasers grown by MBE. The whole structure is the same as a conventional GRINSCH laser, except an n-AlAs sacrificial layer (100Å thick, Si = 5×10^{18}cm^{-3}) was grown between the laser structure and the substrate. Conventional ridge waveguide lasers with a 5µm width were fabricated. The preprocessed laser diodes on the GaAs substrate were covered with black wax on top and soaked in 10% HF solution to selectively remove the AlAs layer. The ELO film, after separation from the GaAs substrate, was dipped in HCl and HF before the bonding process.

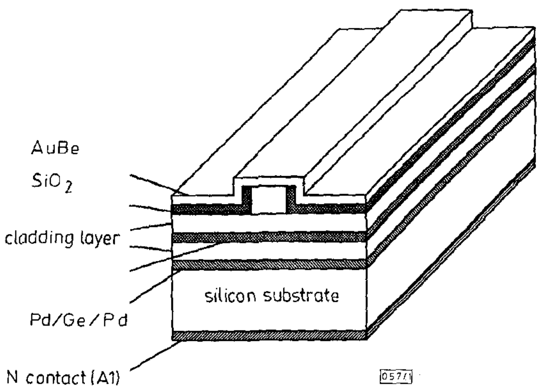

Fig. 1 *Structure of oxide-defined ELO stripe-geometry InGaAs/GaAs/AlGaAs GRIN-SCH lasers diode on n^+-Si substrate with backside contact on Si*

The n^+-(100) Si substrate (R = 0.01–1Ωcm) was used as the host substrate in the ELO process. A 1000Å Pd/1300Å Ge/2500Å Pd metallic multilayer was deposited on the Si substrate by an electron-gun deposition system under a base pressure of $< 8 \times 10^{-7}$ torr. After deposition, the Si substrate was lapped down to 100µm thick, and a 5000Å thick Al film was evaporated onto the backside as the back side ohmic contact. The prepared 100µm thick n^+-Si substrate with Pd/Ge/Pd metallic overlayer was then dipped in an HF solution. Finally, the ELO laser film and the n^+-Si substrate were bonded together by Van der Waals bonding. The bonded sample was heated in a furnace at 400°C for 30min under a forming gas ambient. No external pressure was needed during the heat treatment. Ohmic contacts were formed at this stage both at the interface between the grafted film and the Si substrate and the backside of the substrate. As described in our previous work, the ohmic contact formed by Pd/Ge/Pd provides a low resistance conduction path between the film and the substrate [11]. The bonded sample was then cleaved into bars along the [110] direction. This metallurgical bonding at the interface provides enough strength for the facet cleavage process. A schematic diagram of the finished device is shown in Fig. 1.

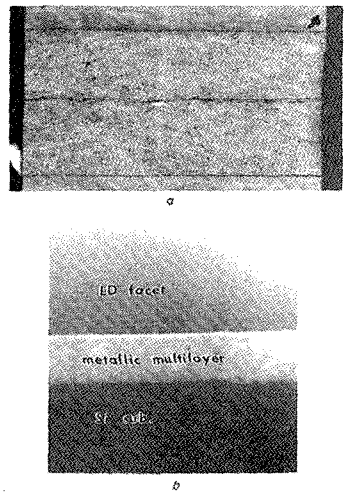

Fig.2 *Photographs of laser diode*

a Top view photograph of ELO stripe-geometry InGaAs/GaAs/AlGaAs GRIN-SCH laser diode on n^+-Si substrate after cleaved into bars
b SEM photograph of cleaved facet of ELO laser diode

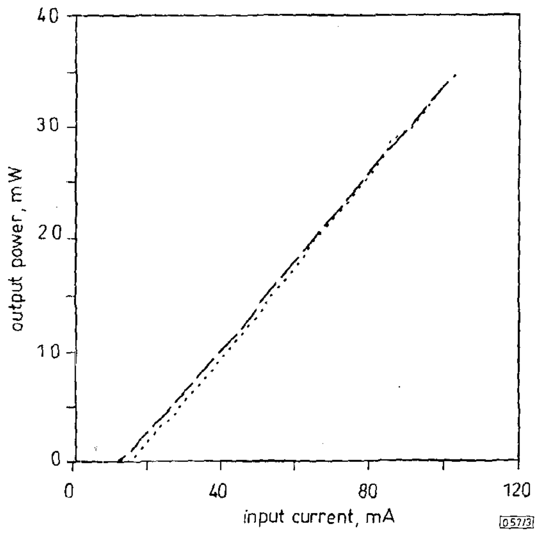

Fig.3 *Measured light-current characteristics of ELO laser on Si and laser on GaAs without ELO process*

Stripe width: 5µm
Cavity length: 800µm
– – – – as grown LDs
·········· ELO LDs

Fig. 2*a* shows the top view of a laser diode on Si after being cleaved into bars. Fig. 2*b* shows the SEM photograph of the cleaved facet of a laser diode. From the photograph, we can clearly see the uniform and smooth bonding interface between the laser diode and the Si substrate. Fig. 3 shows the light-current characteristic of a bonded laser/silicon diode with a 800μm long cavity. The threshold current was 16.3mA and the slope efficiency was 0.4W/A per facet without facet coating. For comparison, we also include a light-current curve for a laser diode on GaAs substrate without the ELO process. The results are very similar between the two. To our knowledge, this is the first successful fabrication of an ELO stripe-geometry laser diode on Si without performance degradation.

In summary, we have demonstrated an ELO stripe-geometry laser diode on an Si substrate with the backside contact on Si. The performance is similar to that of a conventional laser diode on a GaAs substrate.

Acknowledgments: This work was supported by the National Science Council of the Republic of China under Contract No. NSC85-2215-E009-043.

22 April 1997

Electronics Letters Online No: 19970717

J.C. Fan, K.Y. Chen, Gray Lin and C.P. Lee (*Department of Electronic Engineering and Institute of Electronics, National Chiao Tung University, Hsin-Chu, Taiwan, Republic of China*)

References

1 KOYANAG, M., TAKATA, H., MORI, H., and IBA, J.: 'Design of 4-bit × 4 layer optically coupled three-dimensional common memory for parallel processor system', *IEEE Solid-State Circuits*, 1990, **25**, pp. 109–116

2 HAYASHI, I.: 'Optoelectronic devices and material technologies for photoelectronic integrated systems', *Jpn. J. Appl. Phys.*, 1993, **32**, pp. 266–271

3 RAZEGHI, M., DEFOUR, M., OMNES, F., MAUREL, PH., CHAZELAS, J., and BRILLOUET, F.: 'First GaInAsP-InP double-heterostructure laser emitting at 1.27μm on a silicon substrate', *Appl. Phys. Lett.*, 1988, **53**, pp. 725–727

4 RAZEGHI, M., DEFOUR, M., BLONDEAU, R., OMNES, F., MAUREL, PH., ACHER, O., and BRILLOUET, F.: 'First cw operation of a $Ga_{0.25}In_{0.75}As_{0.5}P_{0.5}$-InP laser on a silicon substrate', *Appl. Phys. Lett.*, 1988, **53**, pp. 2389–2390

5 SUGO, M., MORI, H., TACHIKAWA, M., and ITOH, Y.: 'Room-temperature operation of an InGaAsP double-heterostructure laser emitting at 1.55μm on a Si substrate', *Appl. Phys. Lett.*, 1990, **57**, pp. 593–595

6 LO, H.Y., BHAT, R., HWANG, M.D., CHUA, C., and LIN, H.C.: 'Semiconductor lasers on Si substrates using the technology of bonding by atomic rearrangement', *Appl. Phys. Lett.*, 1993, **62**, pp. 1038–1040

7 WADA, H., and KAMIJOH, T.: 'Room-temperature cw operation of an InGaAsP lasers on a Si fabricated by wafer bonding', *IEEE Photonics. Technol. Lett.*, 1996, **8**, pp. 173–175

8 POLLENTIER, I., BUYDENS, L., VAN DAELE, P., and DEMEESTER, P.: 'Fabrication of a GaAs-AlGaAs GRIN-SCH SQW laser diode on silicon by epitaxial lift-off', *IEEE Photonics. Technol. Lett.*, 1991, **3**, pp. 115–117

9 YABLANOVITCH, E., KAPON, E., GMITTER, T.J., YUN, C.P., and RHAT, R.: 'Double heterostructure GaAs/AlGaAs thin film diode lasers on glass substrates', *IEEE Photonics. Technol. Lett.*, 1989, **1**, pp. 41–42

10 VAN DER ZIEL, J.P., DUPUIS, R.D., LOGAN, R.A., and PINZONE, C.J.: 'Degradation of GaAs lasers grown by metalorganic chemical vapor deposition on Si substrates', *Appl. Phys. Lett.*, 1987, **51**, pp. 89–91

11 FAN, J.C., LEE, C.P., CHEN, K.Y., and LIN, : 'Epitaxially lifted-off n-GaAs film onto Pd/Ge/Pd coated Si substrate leading to vertical conduction across ELO film and Si substrate', submitted to *J. Appl. Phys.*, 1997

Threshold reduction of *p*-type δ-doped InGaAs/GaAs quantum well lasers by using auto-doping of carbon

N. Hatori, A. Mizutani, N. Nishiyama, F. Koyama and K. Iga

Indexing terms: Semiconductor junction lasers, Semiconductor quantum wells

An InGaAs/GaAs quantum well laser using *p*-type δ-doping selectively in the barriers has been demonstrated to reduce the threshold current and carrier lifetime. A δ-doping technique is proposed, based on the experimental evidence of high density carbon inclusion during AlAs growth by metal organic chemical vapour deposition (MOCVD). A threshold current density as low as 160A/cm² (54A/cm²/well), has been obtained for three quantum well stripe lasers grown at $1.7 \times 10^{18} cm^{-3}$ carbon doping.

InGaAs/GaAs quantum well (QW) surface-emitting lasers have been studied for optical interconnection due to their low threshold operation and low power consumption. In future parallel optical transmission systems under zero-bias modulation, it is important to reduce turn-on delay time [1, 2]. For this purpose, it is desirable that the threshold current be < 100μA for 1Gbit/s. The carrier lifetime should also be reduced further to obtain a decrease in turn-on delay time. There are already several reports on low threshold InGaAs/AlGaAs or Al-free InGaAs edge emitting lasers [3 – 5]. To achieve its further reduction, modulation doped QWs [6, 7] are attractive, because the absorption determined by $f_v(1 - f_c)$, where f_c and f_v are the Fermi-Dirac distribution functions for the conduction and valence bands, respectively, decreases whenboth f_v approaches 0 by *p*-type doping and f_c approaches 1 by *n*-type doping. In particular, *p*-type modulation doped QW lasers have both larger gain and larger differential gain than conventional undoped QW lasers, resulting in a lower threshold operation and higher modulation bandwidth. Furthermore, it has been seen that the carrier lifetime is also reduced.

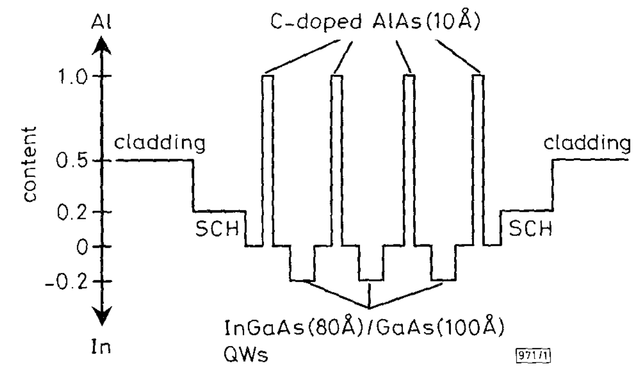

Fig. 1 *Schematic band structure of active region using p-type δ-doped AlAs layers*

Not to scale

In this work, we propose a novel *p*-type δ-doping technique on InGaAs/GaAs QWs for low threshold operation, and have demonstrated threshold reduction in edge emitting lasers using the *p*-type δ-doped InGaAs/GaAs QWs. We obtained a threshold current density of 160A/cm² (< 54A/cm²/well) for three $1.7 \times 10^{18}cm^{-3}$ δ-doped QWs edge-emitting lasers. Fig. 1 shows a schematic diagram of the proposed structure. The active region consists of three $In_{0.2}Ga_{0.8}As$ QWs of 80Å thickness, separated by GaAs barriers of 100Å thickness. The carbon-doped *p*-type AlAs (10Å) layers are located only around the centre of the barriers. We call the layers 'δ-doped layers'. In each of the 10Å thick AlAs layers, the carrier would be expected to flow by tunnelling. In this structure, we realised heavy carbon doping of the AlAs layers by only controlling the [As]/[Al] ratio in the growth. We call this technique, without additional dopant sources, 'auto-doping'. We use AlAs layers as δ-doped layers in this work since it is easy to dope carbon in AlAs layers by the auto-doping technique.

To realise this structure, the heavy doping of a less diffusing dopant is crucial. To achieve this, we grew an AlAs layer by