1.54 µm GaSb/AlGaSb multi-quantum-well monolithic laser at 77 K grown on miscut Si substrate using interfacial misfit arrays

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A GaSb quantum-well (QW) laser diode grown monolithically on a 5° miscut Si (001) substrate is presented. The III-Sb epi-structure is grown monolithically on the miscut Si substrate via a thin (50 nm) AlSb nucleation layer. The 13% lattice mismatch between AlSb and Si is accommodated by a self-assembled, 2D array of interfacial misfit dislocations (IMF). The 5° miscut geometry enables simultaneous IMF formation and anti-phase domain suppression. The 1 mm × 100 µm GaSb QW laser diode operates under pulsed conditions at 77 K with a threshold current density of 2 kA/cm^2 and a maximum peak power of ~20 mW. Furthermore, the device is characterised by a 9.1 Ω forward resistance and a leakage current density of 0.7 A/cm^2 at −5 V.

Introduction: Recent developments in CMOS integrated optoelectronics make a III-V laser on Si a highly desirable and researched device [1–4]. The monolithic growth of III-V materials on Si offers sought-after features such as efficient use of the integrating platform and low processing complexity. However, material incompatibilities, such as mismatch in lattice constant, thermal expansion coefficient and process temperature, hinder a stable and repeatable production process based on monolithic integration [5]. Recently, our group has demonstrated a novel growth technique involving 90° interfacial misfit (IMF) dislocation arrays formed during the growth of AlSb on Si (001). The IMF growth mode on Si (001) results in low defect density bulk epitaxy (~10^6/cm^2) that has enabled optically pumped VCSELs along with super-luminescent light emitting diodes [6, 7]. However, anti-phase domains (APDs) have deterred the demonstration of laser diodes on Si (001) substrates.

The APD formation in the growth of AlSb on Si (001) is an inherent issue with the growth of polar III-Vs on non-polar Si [8, 9]. In the absence of step-free Si (001) substrates, the established method to achieve single domain III-Vs uses miscut Si (001) substrates [10–12]. Miscut Si (2.5° to 5°) substrates, typically characterised by a double atomic step height [13], facilitate registration of the III and V sub-lattices on the 001 plane, thus suppressing APD formation. In the past, high quality III-V material on Si has been produced using the APD annihilation or suppression combined with a strain-relief and defect filtering mechanism, usually a thick buffer layer [14]. These previously reported methods require a two-step growth process initiated at a rather low temperature to enable 60° and 90° dislocation formation followed by normal growth temperatures for metamorphic and bulk layer growth. Lattice-matched bulk GaAs epitaxy on miscut Ge has also been demonstrated to produce very low defect and low APD density [15].

Growth and fabrication: In this Letter, we present a GaSb quantum-well (QW) laser diode monolithically grown on a 5° miscut Si (100) substrate. The device operates at a wavelength of 1.54 µm under pulsed conditions at 77 K. The 13% lattice mismatch at AlSb/Si interface is spontaneously relieved by an interfacial misfit array (IMF), resulting in low-defect density, single-domain III-Sb bulk material, on which the laser is grown. The schematic of the device is shown in Fig. 1. The entire epi-structure is grown using molecular beam epitaxy (MBE) at 400°C. The epitaxy is initiated with a 50 nm AlSb nucleation layer that is optimised for simultaneous IMF formation and APD suppression on Si. The AlSb layer is followed by a 2 µm n-GaSb contact layer, a 2.3 µm $Al_{0.55}Ga_{0.45}Sb$ lower n-type clad, a 0.3 µm undoped $Al_{0.3}Ga_{0.7}Sb$ waveguide layer surrounding the QW active region, a 1.5 µm $Al_{0.55}Ga_{0.45}Sb$ upper p-type clad and a highly doped 50 nm GaSb p-type contact layer. The active region comprises six GaSb (10 nm) QWs separated by $Al_{0.3}Ga_{0.7}Sb$ (10 nm) barrier layers. The samples are processed such that they form gain-guided stripe lasers with widths ranging from 25 to 100 µm. The process involves an inductively coupled plasma reactive ion etch (ICP-RIE) into the n-GaSb contact layer using boron trichloride (BCl_3) chemistry, Ti/Pt/Au metal evaporations to both the n-GaSb and p-GaSb contact layers. The Si substrate is thinned to 70 µm and cleaved to bar lengths of 1 mm. Poor facet quality along with the low gain of the active region hinders room-temperature operation of the GaSb QW lasers on Si substrate. In future structures, we shall make use of high gain InGaSb QWs.

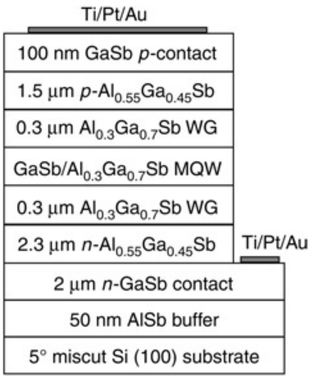

Fig. 1 *Device structure for GaSb/$Al_{0.3}Ga_{0.7}Sb$ MQW laser on 5° miscut Si substrate*

Characterisation: The *L-I* curve and lasing spectra are shown in Fig. 2. Lasing occurs at 77 K under pulsed conditions with 2 µs pulse width and a 0.1% duty cycle. The lasing is observed at a wavelength of 1.54 µm with a threshold current density of 2 kA/cm^2 for a 1 mm × 100 µm device. The high threshold current density of the laser can be attributed to the poor quality of the cleaved facets similar to observations made by other groups [16]. The maximum peak power from the device is ~20 mW. The current-voltage (*I-V*) characteristics indicate a diode turn-on of 0.7 V, which meets the theoretical built-in potential of the laser diode. A very low forward resistance of 9.1 Ω and reverse bias leakage current density of 0.7 A/cm^2 at −5 V and 46.9 A/cm^2 at −15 V has been observed.

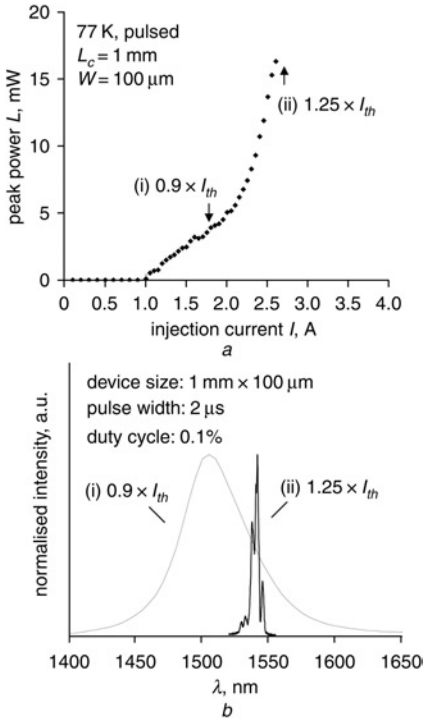

Fig. 2 *Peak power against injection current (L-I) characteristics of 100 µm × 1 mm laser diode and lasing spectra measured below and above-threshold at 77 K under pulsed conditions*

a Peak power against injection current characteristic
b Lasing spectra

Conclusions: We have demonstrated a monolithically grown III-Sb laser on 5° miscut Si (001), operating at a commercially favourable wavelength of 1.54 µm. The device operates under pulsed conditions at a temperature of 77 K. With improvements to the facets and incorporation of indium into the QWs, we believe a room-temperature laser can be achieved in future.

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References

1 Linder, K.K., Phillips, J., Qasaimeh, O., Liu, X.F., Krishna, S., Bhattacharya, P., and Jiang, J.C.: 'Self-organized $In_{0.4}Ga_{0.6}As$ quantum-dot lasers grown on Si substrates', *Appl. Phys. Lett.*, 1999, **74**, (10), p. 1355

2 Kwon, O., Boeckl, J.J., Lee, M.L., Pitera, A.J., Fitzgerald, E.A., and Ringel, S.A.: 'Monolithic integration of AlGaInP laser diodes on SiGe/Si substrates by molecular beam epitaxy', *J. Appl. Phys.*, 2006, **100**, p. 013103

3 Rong, H., Jones, R., Liu, A., Cohen, O., Hak, D., Fang, A., and Paniccia, M.: 'A continuous wave Si Raman laser', *Nature*, 2005, **433**, p. 725

4 Fang, A.W., Park, H., Cohen, O., Jones, R., Paniccia, M.J., and Bowers, J.E.: 'Electrically pumped hybrid AlGaInAs-silicon evanescent laser', *Opt. Express*, 2006, **14**, (20), p. 9203

5 Hwang, I., Lee, C., Kim, J.-E., and Park, H.Y.: 'Clustering effect and residual stress in $In_xGa_{1-x}As/GaAs$ strained layer grown by metal-organic chemical-vapor deposition', *Phys. Rev. B*, 1995, **51**, (12), p. 7894

6 Balakrishnan, G., Jallipalli, A., Rotella, P., Huang, S.H., Khoshakhlagh, A., Amtout, A., Krishna, S., Dawson, L.R., and Huffaker, D.L.: 'Room-temperature optically pumped (Al)GaSb vertical-cavity surface-emitting laser monolithically grown on an Si(1 0 0) substrate', *IEEE J. Sel. Top. Quantum Electron*, 2006, **12**, (6), p. 1636

7 Balakrishnan, G., Metha, M., Kutty, M.N., Patel, P., Albrecht, A.R., Rotella, P., Krishna, S., Dawson, L.R., and Huffaker, D.L.: 'Monolithically integrated III-Sb CW super-luminal light emitting diodes on non-miscut Si (100) substrates', *Electron. Lett.*, 2006, **43**, (4), p. 244

8 Fan, J.C.C., and Poate, J.M.: 'Heteroepitaxy on silicon', *Mat. Res. Soc.*, 1986, **67**, Pittsburgh, PA

9 Choi, H.K., Hull, R., Ishiwara, H., and Nemanich, R.J.: 'Heteroepitaxy on silicon: fundamentals, structure and devices', *Mat. Res. Soc.*, 1988, **116**, Pittsburgh, PA

10 Adomi, K., Strite, S., Morkoc, H., Nakamura, Y., and Otsuka, N.: 'Characterization of GaAs grown on Si epitaxial layers on GaAs substrates', *J. Appl. Phys.*, 1991, **69**, (1), p. 220

11 Andre, C.L., Carlin, J.A., Boeckl, J.J., Wilt, D.M., Smith, M.A., Pitera, M.L., Lee, M.L., Fitzgerald, E.A., and Ringel, S.A.: 'Investigations of high performance GaAs solar cells grown on Ge-SiGe-Si substrates', *IEEE Trans. Electron Devices*, 2005, **52**, (6), p. 1055

12 Sieg, R.M., Ringel, S.A., Ting, S.M., Samavedam, S.B., Currie, M., Langdo, T., and Fitzgerald, E.A.: 'Toward device-quality GaAs growth by molecular beam epitaxy on offcut $Ge/Si_{1-x}Ge_x/Si$ substrates', *J. Vac. Sci. Technol. B*, 1998, **16**, (3), p. 1471

13 Barbier, L., Khater, A., Salanon, B., and Lapujoulade, J.: 'Observation of the double-step–single-step transition on a vicinal surface of Si(100)', *Phys. Rev. B*, 1991, **43**, (18), p. 14730

14 Mi, Z., Yang, J., Bhattacharya, P., and Huffaker, D.L.: 'Self-organised quantum dots as dislocation filters: the case of GaAs-based lasers on silicon', *Electron. Lett.*, 2006, **42**, (2), p. 121

15 Tanoto, H., Yoon, S.F., Loke, W.K., Fitzgerald, E.A., Dohrman, C., Narayanan, B., and Tung, C.H.: 'Growth of GaAs on (100) Ge and vicinal Ge surface by migration enhanced epitaxy', *Mater. Res. Soc. Symp. Proc.*, 2005, **891**, p. 0891-EE03-17

16 Roelkens, G., Van Thourhout, D., Baets, R., Nötzel, R., and Smit, M.: 'Laser emission and photodetection in an InP/InGaAsP layer integrated on and coupled to a silicon-on-insulator waveguide circuit', *Opt. Express*, 2006, **14**, (18), p. 8154