Monolithically integrated III-Sb CW super-luminal light emitting diodes on non-miscut Si (100) substrates

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Reported is super-luminescent emission under room-temperature, continuous-wave conditions from GaSb quantum-well-based light emitting diodes (LED), monolithically integrated on Si (100) substrates. The LEDs are realised with substrate growth temperature under 500°C for the entire process and the Si (001) substrate is non-miscut. The lattice mismatch at the AlSb/Si interface is accommodated by interfacial misfit dislocation arrays (IMF) resulting in low defect-density III-Sb material without thick metamorphic buffers. The devices are grown in etched trenches on the Si substrate to reduce anti-phase domains in the III-Sb. The n-Si substrate is contacted directly and thus current flows through the III-Sb/Si IMF interface. The diodes have extremely low leakage current density ($J_{leakage} < 0.2$ A/cm^2) in the reverse bias (-10 V) and show very good diode characteristics but exhibit a slightly elevated forward resistance ($R \sim 27\ \Omega$), likely to be because of the IMF. The super-luminal spectra peaks at 2.14 μm with maximum output power ~0.125 mW.

Introduction: The integration of III–V materials with Si substrates has been a heavily researched topic in semiconductor sciences owing to the extensive technological benefits that would result from the merger of the two material systems [1–4]. Two decades of research have resulted in numerous devices such as lasers, detectors and transistors grown on Si substrates [5–8]. At present, however, the goal of III–V/Si integration is to achieve optoelectronic and electronic devices on CMOS platforms, with considerable effort placed towards obtaining reliable light sources on CMOS circuits [9]. Recent publications by several research groups have been focused on this very goal. While some researchers have demonstrated monolithic integration [10–12], Bowers and co-workers have achieved evanescent mode coupling using a wafer bonded integration approach that may be attractive for back-end processing since the necessary temperatures are very low (< 400°C) [13]. A monolithic approach, however, may be more attractive for achieving more dense and more cost-effective integration solutions compared to wafer bonding if it circumvents thick metamorphic buffers and can be conducted on non-miscut (100) Si substrates.

In this Letter, we demonstrate monolithic III-Sb based super-luminal light-emitting diodes (LEDs) on Si(100) substrates using material that has extremely low domain density and threading dislocation density. The III–Sb material is nucleated on the Si substrate through an interfacial array of misfit (IMF) dislocations resulting in low threading dislocation densities without a thick buffer. We have already demonstrated optically pumped devices using such interfaces [14, 15]. However, the presence of anti-phase domains (APDs) and the resulting anti-phase boundaries (APBs) have prevented electrically injected devices. A well-demonstrated recipe to overcome these domains involves the growth of diodes on miscut (100) substrates, with the magnitude of the miscut ranging from 2 to 4° [2]. This approach is impractical, at least for short-term integration, since the miscut wafers render the process incompatible with CMOS. Blakely *et al.* have demonstrated that the steps in etch-confined non-miscut Si(100), when annealed under high temperatures, tend to migrate to the perimeter of the confinement resulting in step-free regions in the centre [16, 17]. In fact, complete step-removal on Si(100) can be achieved at temperatures > 1200°C, which would then result in regions on the Si(100) surface where domain-free growth can be achieved. We have observed, however, that the growth of III–Vs in etch-confined Si regions alone, without any annealing, results in significant APD density reduction. The devices demonstrated in this Letter have been grown in trenches on Si(100) without the use of any pre-growth annealing procedures and with a trench width of 40 μm and a trench depth of 0.5 μm.

Fabrication and results: Fig. 1 shows the structure of the device. The devices are grown on the stripe-etched Si(100) substrate that is n-doped at 1×10^{18}/cm^3. The device growth is preceded by an HF oxide removal etch to passivate the surface with H-atoms. The growth of the device is initiated with the 100 Å thick AlSb nucleation layer consisting of the interfacial misfit dislocations, grown at 500°C and doped at 5×10^{17}/cm^3. An n-doped (5×10^{17}/cm^3) Al$_{0.45}$Ga$_{0.55}$Sb cladding layer (2.3 μm), followed by an Al$_{0.35}$Ga$_{0.65}$Sb waveguide layer (0.3 μm) completes the lower half of the device. The active region consists of six GaSb QWs (120 Å) separated by 45 Å wide Al$_{0.35}$Ga$_{0.65}$Sb barriers. The active region is followed by an upper Al$_{0.35}$Ga$_{0.65}$Sb waveguide (0.3 μm and a p-doped Al$_{0.45}$Ga$_{0.55}$Sb cladding layer (1.5 μm), doped 5×10^{17}/cm^3, followed by a highly p-doped GaSb contact layer (1×10^{19}/cm^3). Deposited Ti/Au and Al/In metal forms the top p-contact and the bottom n-contact, respectively. The sample is then cleaved into bars with a 2 mm cavity length.

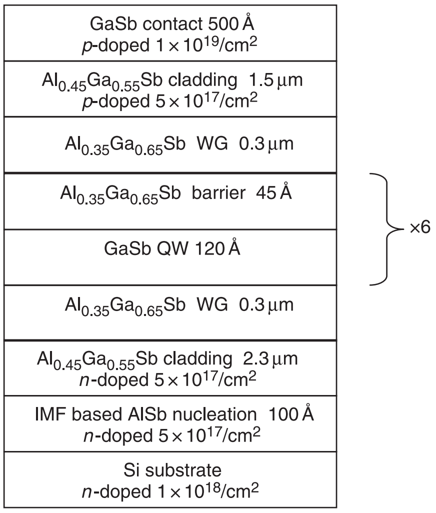

Fig. 1 *Device structure of monolitically grown III-Sb edge emitter on Si(100)*

The diodes are pumped using a CW current source. The LED emission is collected using a multimode fibre and coupled to a monochromator/InSb detector. The fibre has a uniform spectral response at the wavelengths of interest. Fig. 2 shows the emission from the device at various injection currents, including 350, 450 and 500 mA. At ~350 mA, the emission is primarily spontaneous. The FWHM of the emission envelope is 352 nm. At higher injection currents, both narrowing of the spectral envelope to ~30 nm and nonlinear emission intensity suggest stimulated emission. The peak emission wavelength is at 2.14 μm and the maximum spectrally integrated output power from the device at $I = 500$ mA is 0.125 mW. Poor facet quality along with near-threshold operation contributes to the highly multimode characteristic of this device. Facet polishing is expected to improve the device performance. We note that the emission wavelength is considerably longer than expected for GaSb QWs. This is attributed to the mismatch in thermal expansion coefficient between GaSb and Si leading to a slight tensile strain (< 0.7%) in the QWs along with possible heating effects from the electrical injection process.

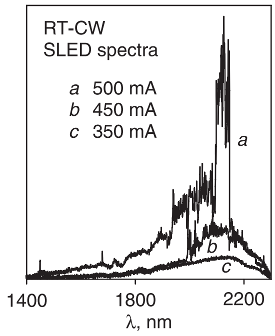

Fig. 2 *Spectra from 50 μm × 4 mm device at injection currents of 350, 450 and 500 mA CW*

Conclusions: We have demonstrated room temperature CW super-luminal LEDs monolithically grown on Si(100) substrates. The single domain III-Sb growth is achieved through growth of the devices in etch-confined regions and low defect density is achieved through an IMF array-based growth mode. The reduced domain and defect density results in excellent diode characteristics. Electroluminsecence spectrum at 2.14 μm is shown with maximum output power of 0.125 mW from the device.

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References

1 Fan, J.C.C., and Poate, J.M., (Eds.): 'Heteroepitaxy on silicon'. Proc. MRS Symp., Vol. 67, 1986

2 Fan, J.C.C., Phillips, J.M., Tasur, B.Y., (Eds.): 'Heteroepitaxy on silicon II'. Proc MRS Symp., Vol. 91, 1987

3 Choi, H.K., Hull, R., Ishiwara, H., Nemanich, R.J., (Eds.): 'Heteroepitaxy on silicon: fundamentals, structure and devices', Proc. MRS Symp., Vol. 116, 1988

4 Georgakilas, A., Panayotatos, P., Stoemenos, J., Mourrain, J.-L., and Christou, A.: 'Achievements and limitations in optimized GaAs films grown on Si by molecular-beam epitaxy', *J. Appl. Phys.*, 1992, **71**, p. 2679

5 Windhorn, T.H., Metze, G.M., Tsaur, B.Y., and Fan, J.C.: 'AlGaAs double-heterostructure diode lasers fabricated on a monolithic GaAs/Si substrate', *Appl. Phys. Lett.*, 1984, **45**, p. 309

6 Deppe, D.G., Holonyak, N. Jr., Nam, D.W., Hsieh, K.C., Jackson, G.S., Matyi, R.J., Shichiujo, H., Epler, J.E., and Chung, H.F.: 'Room-temperature continuous operation of p-n $Al_xGa_{1-x}As$-GaAs quantum well heterostructure lasers grown on Si', *Appl. Phys. Lett.*, 1987, **51**, p. 637

7 Deppe, D.G., Chand, N., Van der Ziel, J.P., and Zydzik, G.J.: '$Al_xGa_{1-x}As$-GaAs vertical-cavity surface-emitting laser grown on Si substrate', *Appl. Phys. Lett.*, 1990, **56**, p. 740

8 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**, p. 1355

9 Jalali, B., Raghunathan, V., Dimitropoulos, D., and Boyraz, O.: 'Raman-based silicon photonics', *IEEE J. Sel. Top. Quantum Electron*, 2006, **12**, p. 412

10 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

11 Groenert, M.E., Leitz, C.W., Pitera, A.J., Yang, V., Lee, H., Ram, R.J., and Fitzgerald, E.A.: 'Monolithic integration of room-temperature cw GaAs/AlGaAs lasers on Si substrates via relaxed graded GeSi buffer layers', *J. Appl. Phys.*, 2003, **93**, p. 362

12 Mi, Z., Bhattacharya, P., Yang, J., and Pipe, K.P.: 'Room-temperature self-organised $In_{0.5}Ga_{0.5}As$ quantum dot laser on silicon', *Electron. Lett.*, 2005, **41**, pp. 742–744

13 Fang, A.W., Park, H., Jones, R., Cohen, O., Paniccia, M.J., and Bowers, J.E.: 'A continuous-wave hybrid AlGaInAs-silicon evanescent laser', *IEEE Photonics Technol. Lett.*, 2006, **18**, p. 1143

14 Balakrishnan, G., Huang, S.H., Khoshakhlagh, A., Hill, P., Amtout, A., Krishna, S., Donati, G.P., Dawson, L.R., and Huffaker, D.L.: 'Room-temperature optically-pumped InGaSb quantum well lasers monolithically grown on a Si(100) substrate', *Electron. Lett.*, 2005, **41**, p. 531

15 Balakrishnan, G., Huang, S.H., Khoshakhlagh, A., Jallipalli, A., Rotella, P., Amtout, A., Krishna, S., Haines, C.P., Dawson, L.R., and Huffaker, D.L.: 'Room-temperature optically-pumped GaSb quantum well based VCSEL monolithically grown on a Si(100) substrate', *Electron. Lett.*, 2006, **42**, p. 350

16 Tanaka, S., Umbach, C.C., Blakely, J.M., Tromp, R.M., and Mankos, M.: 'Fabrication of arrays of large step-free regions on Si(001)', *Appl. Phys. Lett.*, 1996, **69**, p. 1235

17 Lee, D., Blakely, J.M., Schroeder, T.W., and Engstrom, J.R.: 'A growth method for creating arrays of atomically flat mesas on silicon', *Appl. Phys. Lett.*, 2001, **78**, p. 1349