Room-temperature optically-pumped GaSb quantum well based VCSEL monolithically grown on Si (100) substrate

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Monolithic vertical cavity surface emitting lasers (VCSELs) on Si are demonstrated. The GaSb multi-quantum well active region embedded in an Al(Ga)Sb half-wave cavity spacer layer enables lasing under room-temperature optically-pumped conditions. The 13% lattice mismatch is accommodated by a spontaneously formed 2-D array of 90° misfit dislocations at the AlSb/Si interface. This growth mode produces very low defect density ($\sim 8 \times 10^5/cm^2$) and relaxed materials growth (98%) without the use of a buffer layer. Presented are VCSEL lasing spectra, light-in against light-out curves along with defect density measurements performed by microscopy and etch-pit density. A threshold excitation density of $I_{th} = 0.1$ mJ/cm^2 and a multimode lasing spectrum peaked at 1.62 µm, results from a 3 mm pump-spot size.

Introduction: Monolithic integration of III-V photonics with Si circuitry offers several desirable features including efficient use of the integrating platform, reduced processing complexity and better heat dissipation. For over two decades, significant research and development efforts have focused on the monolithic approach utilising several distinct technologies [1–8]. The monolithic approach utilising GaAs/AlGaAs has resulted in room-temperature (RT) edge emitting lasers [2] and even vertical cavity lasers (VCSELs) [3] on Si (100). However, very large mismatch in lattice constant, thermal expansion coefficient and process temperature pre-empted a stable and manufacturable process. Thus, monolithic device characteristics have been marginal due to micro-cracks (due to thermal mismatch) and high dislocation density in the GaAs buffer [4]. Use of III-Sb circumvents all three mismatch issues since thermal expansion coefficients are well matched ($\alpha_{Si} = 2.05 \times 10^6/cm^2$, $\alpha_{AlSb} = 2.55 \times 10^6/cm^2$), the III-Sb growth temperature is < 450°C and the material system produces spontaneous 90° misfits for strain relief as described below.

Our approach to monolithic III-V growth on Si is fundamentally different from the previously reported work owing to the unique growth mode of AlSb on Si compared to GaAs on Si. We utilise a very thin AlSb layer (50 Å) nucleated on Si, which relieves almost the entire strain caused by the 13% lattice mismatch via 90° misfit dislocations that propagate within the epi-substrate interfacial plane and do not thread into the material. This growth mode is very different from that of GaAs on Si, which predominantly forms 60° misfits and results in extensive threading dislocations [9, 10]. While previous studies of AlSb on Si have been reported by other groups, they have been limited to X-ray diffraction studies and basic photoluminescence (PL) characterisation without analysis of the nucleation layer or growth mode [11, 12]. Our research has extended this body of knowledge to define, analyse and model the mismatched growth mode and strain relief mechanism [10]. Further, we have previously demonstrated room-temperature (RT), photopumped (PP) operation of a monolithically grown edge-emitting laser on Si [13]. In this Letter, we demonstrate RT, PP lasing of a GaSb quantum well (QW)-based VCSEL monolithically grown on a Si (100) substrate.

Experiment and results: The VCSEL epitaxial structure is grown in a V80H molecular beam epitaxy reactor. Prior to growth, the Si substrate surface is hydrogen-passivated by immersing the wafer in a HF bath. The loosely bonded hydrogen is removed by heating the substrate to 500°C in vacuum. A thermal cycle at 800°C ensures removal of oxide remnants. This is verified by reflection high-energy electron diffraction.

The VCSEL structure, shown in Fig. 1, is designed for PP operation at 1650 nm. The lower distributed Bragg reflector (DBR) includes 30 pairs of AlSb/$Al_{0.15}Ga_{0.85}Sb$ quarter-wave layers (1197 and 1013 Å thick, respectively). The half-wave AlSb cavity spacer includes the 6×100 Å GaSb QWs separated by 100 Å AlSb barriers. The upper DBR is the output coupler and includes 25 pairs AlSb/$Al_{0.15}Ga_{0.85}Sb$ quarter-wave layers, capped with a quarter-wave layer of GaSb (d = 975 Å) to prevent native oxidation of the Al-bearing layer. The VCSEL growth is initiated at 420°C with a 50 Å AlSb nucleation layer, then the temperature is ramped from 420 to 500°C for the device growth. We note that excellent material quality is achieved at growth temperature ranging from 420 to 500°C.

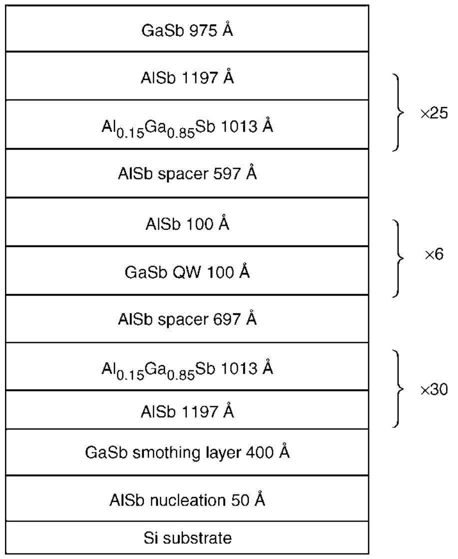

Fig. 1 *Monolithic VCSEL structure schematic shows GaSb/AlSb QWs in half-wave cavity spacer surrounded by AlGaSb/AlSb DBRs*

Table 1: Etch-pit density for different sections of VCSEL

Etchant	1000 nm (lower DBR)	7000 nm (active region)	14 000 nm (top DBR)
20% KOH solution	$9 \times 10^5/cm^2$	$8.5 \times 10^5/cm^2$	$8.5 \times 10^5/cm^2$
H_2O_2:H_2SO_4 (2 : 1)	$1.4 \times 10^6/cm^2$	$9 \times 10^5/cm^2$	$9 \times 10^5/cm^2$

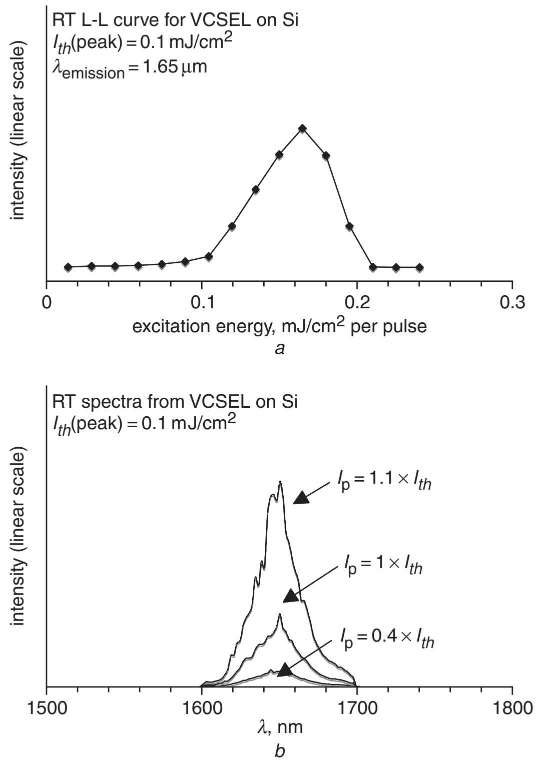

Fig. 2 *RT-PP lasing results at 1.65 µm from VCSEL grown on Si*

a L-L curve showing threshold intensity (I_{th}) at pump power of 0.1 mJ/cm^2 per pulse

b Spectra at pump intensities $0.4 \times I_{th}$, $1.0 \times I_{th}$ and $1.1 \times I_{th}$

The quality of the epi-material is indicated by defect density estimated by etch-pit density tests. The etch-pit density decoration count offers a ceiling for the defect-density count and indicates the presence of threading dislocations. Two kinds of etches were used for this test, a 20% solution of KOH and a mixture of H_2O_2 and H_2SO_4 (in a 2:1 ratio). The two density tests produced almost identical results (tabulated in Table 1). The Table shows the etch pit density at three etch depths of 1000, 7000 and 14 000 nm within the VCSEL structure corresponding to regions very close to the nucleation layer, within the QWs and in the upper DBR, respectively. The defect density is fairly constant throughout the structure with a maximum value of $2 \times 10^6/\text{cm}^2$ and an average value of $8 \times 10^5/\text{cm}^2$.

The VCSEL structure is analysed under RT, PP conditions. The pump source is a TOPAS optical parametric amplifier ($\lambda_p = 1.475$ µm) pumped by a modelocked Ti-sapphire laser. The 200 fs pulse width at a 1 kHz repetition rate produces a maximum energy per pulse of 20 µJ or 0.28 mJ/cm^2 within the 3 mm circular pump spot obtained on the sample. The light-in against light-out (LL) curve and spectral data are shown in Figs. 2*a* and *b*. The LL curve shows threshold for the device is $I_{th} = 0.1$ mJ/cm^2. With increasing pump intensity, the output continues to increase from threshold to $1.6 \times I_{th}$ above threshold. At this point, the output intensity rolls over very rapidly owing to the red-shift in the gain caused by heating. Fig. 2*b* spectral changes in intensity and shape from subthreshold to lasing at $0.4 \times I_{th}$, $1.0 \times I_{th}$ and $1.1 \times I_{th}$. The lasing spectrum is highly multimode (FWHM = 20 nm) owing to the very large pump spot size.

Conclusion: We have demonstrated an RT-PP III-Sb VCSEL monolithically-grown on Si (001). Very high quality material with defect density $<8 \times 10^5/\text{cm}^2$ is indicated by etch-pit density studies. Both spectra and LL curves indicate a threshold excitation density of $I_{th} = 0.24$ mJ/cm^2. The lasing spectra, peaked at 1.65 µm, is highly multimode just above threshold owing to the large pump-spot diameter. This collection of data indicates a promising technology for monolithic integration of III-V emitter on Si.

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