Long Wavelength Lasers on Silicon

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Abstract. *We demonstrate lasing at 77K of GaSb/AlGaSb quantum wells monolithically grown on a 5° miscut Si (001) substrate via a thin (50nm) AlSb layer. A 13% lattice mismatch between AlSb and Si is accommodated by using an interfacial misfit (IMF) array. The 5° miscut geometry enables both IMF formation and suppression of an anti phase domain.*

Introduction

Recent developments in CMOS-integrated optoelectronics make III-V lasers on Si a highly desirable and researched device. A monolithic growth of III-V materials on Si offers intriguing features such as an efficient use of the integrating platform and reduced processing complexity compared to growth on GaAs, GaSb substrates [1-4]. However, material incompatibilities such as mismatch in lattice constant, thermal expansion coefficient and process temperature hinder stable and repeatable production processes based on monolithic integration [5]. Recently, our group has demonstrated a novel growth technique involving 90° interfacial misfit (IMF) arrays formed during the growth of AlSb on Si (001) [6]. The IMF growth mode on Si (001) results in low defect density bulk epitaxy (~ 10^6/cm^2) that has enabled optically pumped vertical cavity surface emitting lasers (VCSELs) and super-luminescent diodes [7,8]. 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. In the absence of step-free Si(001) substrates, the established method to achieve single domain III-Vs uses miscut Si(001) substrates [9-11]. Miscut Si (2.5° to 5°) substrates, typically characterized by a double atomic-step height [12], facilitate registration of the III and V sub-lattices on the (001) plane, resulting in the suppression of APD formation. So far, 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 [13]. These 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 [14].

Growth and Fabrication:

We demonstrate GaSb quantum well (QW) laser diodes monolithically grown on a 5° miscut Si (100) substrate by using the IMF growth mode. A 13% lattice mismatch at AlSb/Si interface is accommodated by an IMF array, resulting in low-defect density, single-domain III-Sb bulk material, on which the laser is grown. A schematic

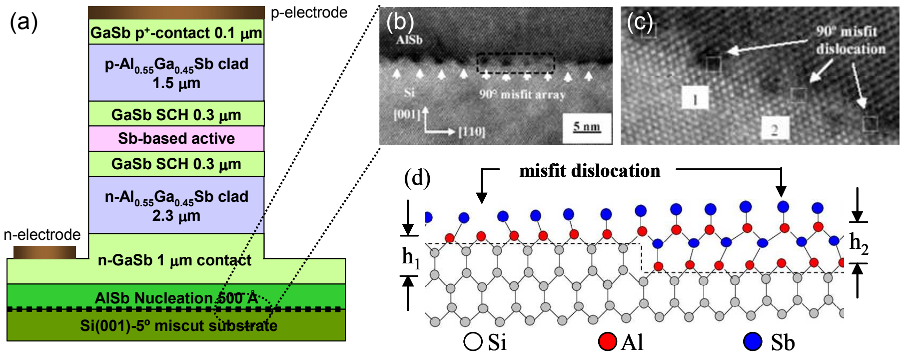

Fig. 1 (a) Schematic illustration of fabricated III-Sb based laser structures monolithically grown on 5° miscut Si (001) substrates. (b) and (c) cross-sectional transmission electron microscope images of the interface between AlSb and Si. (d) Schematic illustration of the IMF interface between AlSb and Si.

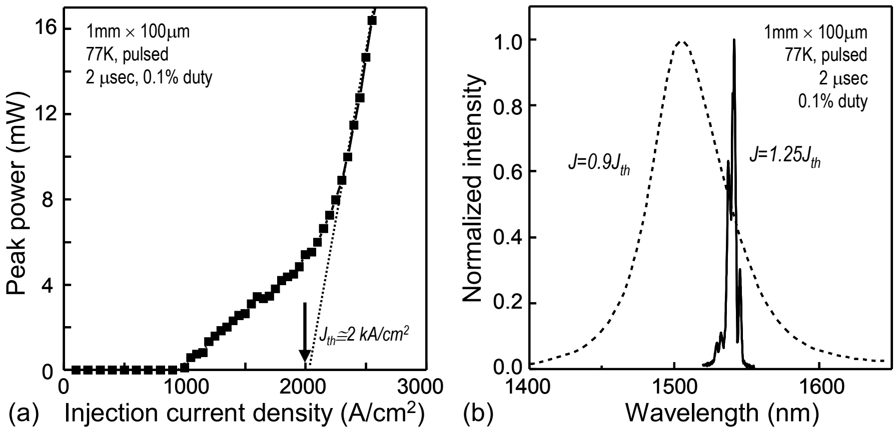

Fig. 2 (a) L-I curve of the fabricated laser devices at 77K under pulsed operation. (b) EL spectra above and below the threshold current density, Jth≅2 kA/cm^2.

illustration of the fabricated device is shown in Fig. 1(a). All the structures are grown by solid-state molecular beam epitaxy at 400°C. The growth is initiated with a 50 nm AlSb nucleation layer that is optimized for IMF formation and APD suppression on Si as shown in Figs. 1(b) and (c). It is noted that the misfit separation is ≅ 3.46 nm and corresponds to exactly 8 AlSb lattice sites grown on 9 Si lattice sites (Fig. 1(d)). The AlSb layer is followed by a 2 μm n-GaSb contact, a 2.3 μm $Al_{0.55}Ga_{0.45}Sb$ n-type clad, an active region, a 1.5 μm $Al_{0.55}Ga_{0.45}Sb$ p-type clad and a highly doped 50 nm GaSb p-type contact layer. The active region is comprised of six GaSb (10 nm) QWs separated by $Al_{0.3}Ga_{0.7}Sb$ (10 nm) barrier cladded by $Al_{0.3}Ga_{0.7}Sb$ waveguide layers. Samples are processed such that they form broad-area lasers with a stripe width of 100 μm. The process involves an inductively coupled plasma reactive ion etch into the n-GaSb contact layer, Ti/Pt/Au metal evaporations for contact to both n- and p-GaSb. The wafer is thinned to 70 μm and cleaved to bar lengths of 1 mm. It is noted that poor facet quality along with the low gain of the active region hinders the continuous wave room temperature operation of the GaSb QW lasers on Si substrate.

Device Characterization

The current-output power (L-I) curve and electroluminescence (EL) spectra are shown in Fig. 2. Lasing operation is observed at 77K is observed at a wavelength of 1.54 µm with a threshold current density (J_{th}) of 2 kA/cm^2 for a 1 mm-long device under pulsed conditions with 2 µsec pulse width and a 0.1% duty cycle. A higher J_{th} compared with the same active grown on GaAs substrates [15] is attributed to the poor quality of the cleaved facets, like observed by other groups [16]. The maximum peak output power from the device is ~ 20 mW. The current-voltage (I-V) characteristics indicate a diode turn-on of 0.7 V, which is consistent with a theoretical built-in potential of the laser diode. A very low 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 is obtained.

Conclusions

We demonstrate III-Sb based lasers monolithically grown on 5° miscut Si (100), at a emission wavelength of 1.54 µm suitable for the fiber-optic communication systems. The device operates under pulsed conditions at a temperature of 77K. We believe room-temperature lasing can be achieved by improving the facets and incorporation of indium into the active region. This IMF technique will enable the demonstration of III-Sb based VCSELs emitting at the fiber-optic communication wavelength grown on a Si platform.

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