Novel monolithic integration of III-Sb materials on Si substrates

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Ga-Sb based quantum well lasers emitting at 1.54 µm can be grown on a 5° miscut Si (001) substrate and operate at 77K with a threshold current density of 2 kA/cm².

The monolithic growth of III-V materials on silicon substrates offers highly desirable features for the fabrication of complementary metal-oxide semiconductor (CMOS)-integrated optoelectronic devices. Compared to hybrid growth methods, including conventional wafer bonding, monolithic integration reduces processing complexity and improves heat dissipation characteristics. However, the approach has been hindered by process temperature and III-V material incompatibilities such as mismatch in lattice constants (e.g. 4% for GaAs/Si vs 8% for InP/Si) and thermal expansion coefficient differences, all of which have prevented the emergence of stable and repeatable production processes based on monolithic integration. Another issue is the formation of anti-phase domains (APDs) in the growth of polar III-V materials on non-polar Si, which prevents the realization of electrically-injected lasers monolithically grown on Si (001) substrates.

Our group has demonstrated a novel growth technique involving 90° interfacial misfit (IMF) arrays formed during the growth of AlSb on Si (001) which enables a bulk AlSb epitaxy with a low defect density (∼ 10⁶/cm²). To accommodate the 13% lattice mismatch at the AlSb/Si interface, we use the IMF array without a thick metamorphic buffer. In addition, miscut Si (2.5° to 5°) substrates, typically characterized by a double atomic-step height, facilitate registration of the III and V sub-lattices on the (001) plane, and effectively suppress APD formation.

Our recent work has demonstrated GaSb quantum well (QW) lasers monolithically grown on a 5° miscut Si (001) substrate using the IMF growth method. The device schematics are shown in Figure 1(a). All the structures are grown by solid-state molecular beam epitaxy at 400°C, initiated with a 50nm AlSb nucleation layer optimized for IMF formation and APD suppression on miscut Si as shown in Figures 1(b) and (c). The misfit separation of ∼ 3.46nm exactly corresponds to eight AlSb lattice sites on nine Si lattice sites, as schematically illustrated in Figure 1(d)). The AlSb layer is followed by a 2µm n-GaSb contact, a 2.3µm Al₀.₅₅Ga₀.₄₅Sb negative (n)-type clad, an active region, a 1.5µm Al₀.₅₅Ga₀.₄₅Sb positive (p)-type clad, and a highly-doped 50nm GaSb p-type contact layer. The active region consists of six-layer GaSb (10nm) QWs separated by an Al₀.₅₃Ga₀.₄₇Sb (10nm) barrier cladded by 300nm Al₀.₅₃Ga₀.₄₇Sb waveguide layers. For broad-area edge-emitting lasers, conventional top-top contact processing is performed with a stripe width of 100µm. The resulting wafer is then thinned to 70µm and cleaved to bar lengths of 1mm.

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Device properties including current-voltage (I-V), output power-current (L-I), and electroluminescence (EL) spectra are characterized at liquid-nitrogen temperature (77K). I-V characteristics are indicative of a diode turn-on of 0.7 V, consistent with the theoretical built-in potential of the laser diode. A very low resistance of 9.1Ω and leakage current density of 0.7A/cm² under a reverse bias of -5V is obtained. Figure 2 shows the L-I curve and EL spectra acquired under pulsed conditions with a 2µsec pulse width and a 0.1% duty cycle. Lasing operation at 77K is observed at 1.54µm with a threshold current density ($J_{th}$) of 2kA/cm² and a maximum peak output power of $\approx 20$mW. A comparatively high $J_{th}$ is attributed to the poor facet quality and lower modal gain of the active region. We believe that room-temperature lasing can be realized by improving facet quality as well as the active region. This could be achieved by incorporation of indium or aluminum into the active region for higher modal gain. By allowing III-Sb growth on a Si platform, our IMF technique should also enable the demonstration of electrically-injected vertical-cavity surface-emitting lasers at the fiber-optic communication wavelength.

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References