High-Speed Modulation of InGaAs : Sb–GaAs–GaAsP Quantum-Well Vertical-Cavity Surface-Emitting Lasers With 1.27-μm Emission Wavelength

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***Abstract*—1.27-μm InGaAs : Sb–GaAs–GaAsP vertical-cavity surface-emitting lasers (VCSELs) were grown by metal–organic chemical vapor deposition and exhibited excellent performance and temperature stability. The threshold current changes from 1.8 to 1.1 mA and the slope efficiency falls less than $\sim$35% as the temperature raised from room temperature to 70 °C. With a bias current of only 5 mA, the 3-dB modulation frequency response was measured to be 8.36 GHz, which is appropriate for 10-Gb/s operation. The maximal bandwidth is measured to be 10.7 GHz with modulation current efficiency factor (MCEF) of $\sim$5.25 GHz/(mA)$^{1/2}$. These VCSELs also demonstrate high-speed modulation up to 10 Gb/s from 25 °C to 70 °C.**

***Index Terms*—Characterization, InGaAsSb, laser diodes, metal–organic chemical vapor deposition (MOCVD), optical fiber devices, semiconducting.**

I. Introduction

LONG-WAVELENGTH vertical-cavity surface-emitting lasers (VCSELs) are key devices in optical fiber metropolitan-area networks. Recently, Koyama *et al.* [1] and Tansu *et al.* [2] employed of highly strained InGaAs QW active lasers to extend the emission wavelength to 1.2 μm. Highly strained InGaAs VCSELs with a photoluminescence (PL) peak at 1.205 μm and a laser emission wavelength of $\sim$1.26–1.27 μm have demonstrated very promising performance and continuous-wave operation at up to 120 °C as well as 10-Gb/s operation [3]. However, the emission wavelength of 1.26 μm barely meets optical communication standards, such as IEEE 820.3ae 10-Gb/s Ethernet. Furthermore, this laser performs relatively poorly at room temperature due to the large negative gain-cavity offset. Antimony (Sb) present during GaInAsN growth has been believed to act as a surfactant and improve PL [4]. The authors have observed that adding Sb into samples with high In content sharply increases the PL intensity, and have found that the alloy thus formed not only behaves as a surfactant but contributes significantly to red-shift of the optical emission [4]. Additionally, adding a surfactant such as Sb [5] and Te [6] significantly increases the critical layer thickness of InGaAs on GaAs. This work presents high-performance InGaAs : Sb–GaAs–GaAsP QWs VCSELs grown by metal–organic chemical vapor deposition (MOCVD). The light output and voltage versus current (L–I–V) performance and high-speed performance proved these VCSELs a good candidate of long wavelength VCSEL.

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II. Experiment

All structures were grown on semi-insulating GaAs (100) substrates by low-pressure MOCVD. The group-V precursors were the hydride sources AsH_3 and PH_3. The trimethyl alkyls of gallium (Ga), aluminum (Al), indium (In), and antimony (Sb) were the group-III precursors. The epitaxial structure was as follows (from bottom to top)—n^+-GaAs buffer, 40.5-pair n^+-$Al_{0.9}Ga_{0.1}As$/n^+-GaAs (Si-doped) DBR, undoped active region, p-$Al_{0.98}Ga_{0.02}As$ oxidation layer, 25-pair p^+-$Al_{0.9}Ga_{0.1}As$/p^+-GaAs DBR (carbon-doped) and p^+-GaAs (carbon-doped) contact layer. The graded-index separate confinement heterostructure active region consisted mainly of a double QW's active region $In_{0.41}Ga_{0.59}As$: Sb–GaAs–$GaAs_{0.85}P_{0.15}$ (60/100/100 Å), with PL emission at 1.214 μm, embedded between two linear-graded $Al_xGa_{1-x}As$ ($x = 0$ to 0.6 and $x = 0.6$ to 0) confinement layers (growth temperature = 550 °C with AsH_3–TMSb flow ratio $\sim$50). The thickness of the cavity active region was 1λ. Carbon was used as the p-type dopant in the DBR to increase the carrier concentration ($2-3\times10^{18}$ cm^{-3}). The interfaces of both the p-type and n-type $Al_{0.9}Ga_{0.1}As$–GaAs DBR layers are linearly graded to reduce the series resistance. The optical characteristics of QWs were optimized through PL measurement and structural analysis. The details of growth optimization will be published elsewhere [7].

Fig. 1 compares the PL spectra of $In_xGa_{1-x}As$ QW with various In contents ($x = 0.41$ and 0.42), and that of $In_{0.41}Ga_{0.59}As$ QW with incorporated Sb. All samples have a well thickness of 60 Å with a GaAs spacer and a $GaAs_{0.85}P_{0.15}$ strain-compensating layer. The PL peak emission wavelengths (λ_p) of the grown $In_{0.41}Ga_{0.59}As$–GaAs–GaAsP and $In_{0.41}Ga_{0.59}As$: Sb–GaAs–GaAsP QWs are 1.194 and 1.214 μm, respectively. A red-shift of 20 nm is observed. The full-width at half-maximum (FWHM) of the PL emission peak from $In_{0.41}Ga_{0.59}As$: Sb is larger and the PL intensity slightly

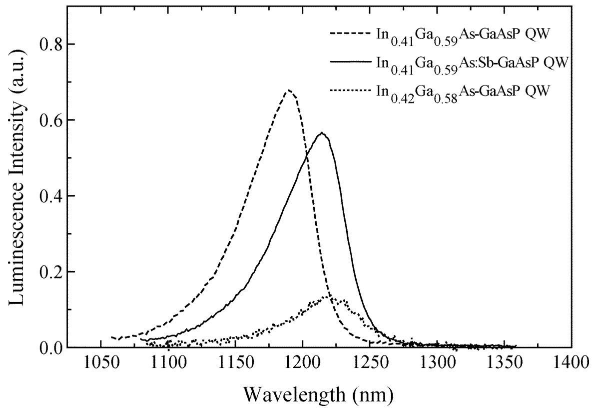

Fig. 1. Comparison of the PL spectra of InGaAs with different In composition and $In_{0.41}Ga_{0.59}As$ with Sb incorporation.

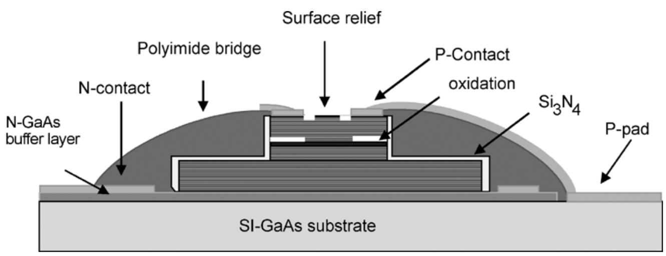

Fig. 2. Schematic cross section of high-speed VCSEL structure. The oxide-confined aperture is 5 μm and the surface relief size is 3.5 μm.

lower. The red-shift of InGaAs : Sb can be attributed to the Sb in the alloy constituent and red-shifts the optical emission. As the Indium composition increases to 0.42, the FWHM of the PL emission increases significantly and the PL intensity drops dramatically.

Fig. 2 schematically depicts the VCSEL structure. A processing sequence involved six photomasks to fabricate oxide-confined polyimide-bridged VCSELs with coplanar waveguide probe pads. This process was designed to minimize capacitance while keeping a reasonably low resistance [8]. Device fabrication began with the formation of cylindrical mesas with a diameter of 30 μm by etching the surrounding semiconductor into the bottom n-type mirror to a depth of 5 μm, using an inductively coupled plasma reactive ion etching system. The sample was wet-oxidized in a 420 °C steam environment for 20 min to form the current aperture and provide lateral index guiding to the lasing mode. The oxidation rate was 0.6 μm/min for the $Al_{0.98}Ga_{0.02}As$ layer, so the oxide extended 12.5 μm from the mesa sidewall. Ti–Au was evaporated to form the p-type contact ring, and AuGeNiAu was evaporated onto the etched n-buffer layer to form the n-type contact, which is connected to the semi-insulating substrate. Contacts were alloyed for 30 s at 420 °C using rapid thermal annealing. After the contact formation, the photosensitive polyimide was spun on the sample to form insulation. Ti–Au was deposited to a thickness of from 200 to 3000 Å to form the metal interconnects and coplanar waveguide probe pads. Heat treatment following metal deposition was applied to strengthen the metal-to-polyimide adhesion. Finally, surface relief etching with a diameter of 3.5 μm was performed to a depth of $\sim \lambda/2$ for single-mode operation [9].

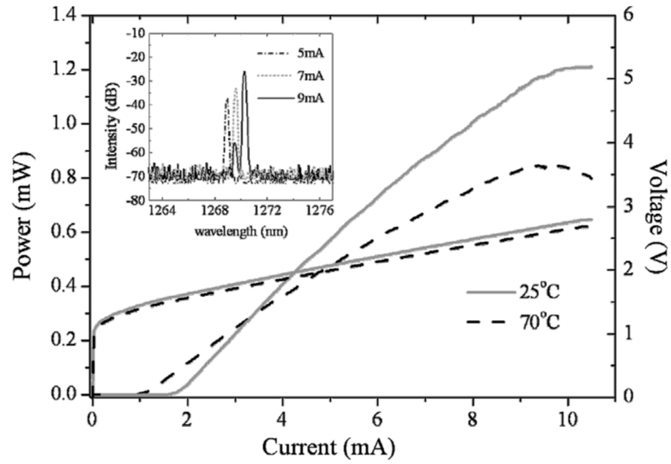

Fig. 3. Temperature-dependent L–I–V curves. Inset is the emission spectra of InGaAs : Sb–GaAs–GaAsP VCSELs at different driving currents.

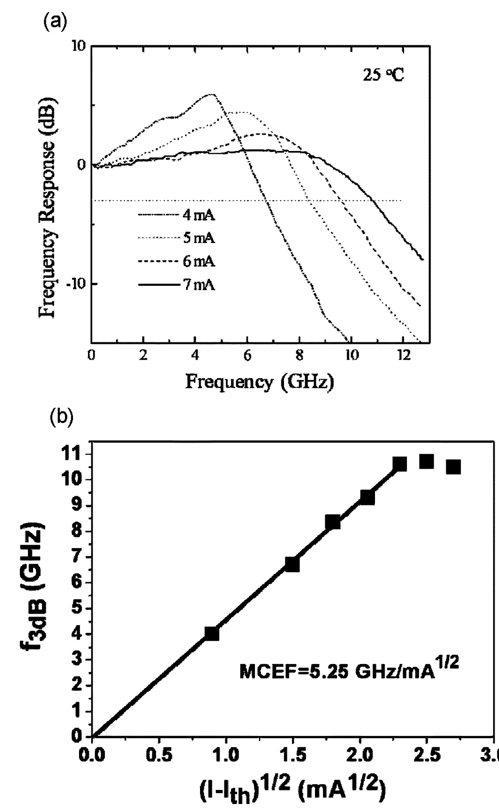

Fig. 4. (a) Small signal modulation measurement on VCSELs; the maximal bandwidth measured to be 10.7 GHz with MCEF is $\sim$5.25 GHz/(mA)$^{1/2}$. (b) 3-dB bandwidth ($f_{3\text{ dB}}$) is plotted as a function of the bias current above threshold.

Fig. 3 plots curves of temperature-dependent L–I–V. The devices exhibit single transverse mode characteristics at a lasing wavelength of $\sim$1.27 μm, with a sidemode suppression ratio of >30 dB, as in the inset in Fig. 3, over the whole operating range. Notably, the maximal single-mode output power exceeds 1.2 mW at room temperature (0.8 mW at 70 °C). Output power rollover occurs as the current increases above 10 mA at 25 °C (9.5 mA at 70 °C). The threshold current changes between 1.8 and 1.1 mA with temperatures from 25 °C to 70 °C and the slope efficiency drops less than $\sim$35% from 0.17 to 0.11 mW/mA

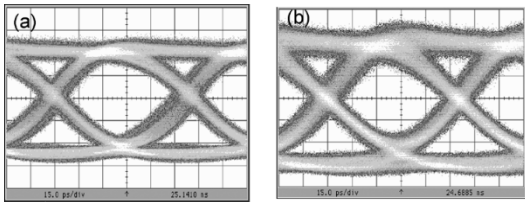

Fig. 5. (a) Room temperature (b) 70 °C eye diagram of our VCSEL data up to 10-Gb/s and 6-dB extinction ratio. The time scale is 15 ps/div and the vertical scale is 90 mV/div for (a) and 60 mV/div for (b).

due to the large gain-cavity offset. The resistance of the VCSEL is $\sim 120\ \Omega$ and the capacitance is ~ 0.1 pF. Accordingly, parasitic effects limit the devices to a frequency response of around 13 GHz.

Fig. 4(a) indicates the modulation frequency increases with the bias current, until it flattens at a bias of about 7 mA. At a bias current of only 5 mA, the maximum 3-dB modulation frequency response is measured as 8.36 GHz, which is suitable for 10-Gb/s operation. In Fig. 4(b), the 3-dB bandwidth $(f_{3\ \mathrm{dB}})$ is plotted as a function of the bias current. The maximal bandwidth is measured to be 10.7 GHz with a modulation current efficiency factor (MCEF) of $\sim 5.25\ \mathrm{GHz}/(\mathrm{mA})^{1/2}$ and the differential gain at room temperature was estimated to $\sim 2 \times 10^{-16}\ \mathrm{cm}^2$.

To measure the high-speed VCSEL under large signal modulation, microwave and light wave probes were used in conjunction with a 10-Gb/s pattern generator (MP1763 Anritsu) with a pseudorandom bit sequence of $2^{23} - 1$ and a 12.5-GHz photoreceiver. Eye diagrams were obtained for back-to-back (BTB) transmission on VCSEL. Fig. 5(a) demonstrates that the room temperature eye diagram of the presented VCSEL biased at 6 mA, with data up to 10 Gb/s and an extinction ratio of 6 dB. The clear open eye pattern indicates good performance of these InGaAs : Sb VCSELs with the rise time T_r of 30 ps, the fall time T_f of 41 ps, and jitter (p-p) <20 ps. The VCSELs also exhibit superior performance at high temperature. The reasonably open eye diagram in Fig. 5(b) demonstrates the high-speed performance of the VCSEL (biased at 7 mA) at 10 Gb/s with an extinction ratio of 6 dB at 70 °C. Fig. 6 shows average received power dependence of the BER at 10-Gb/s modulation under BTB transmission and temperature of 25 °C and 70 °C. In this experiment, multimode fiber was aligned to realize the highest coupling efficiency. An error rate of 10^{-12} was achieved without any indication of a BER floor. This result further verifies the superior performance of the presented VCSELs.

III. Conclusion

High-performance InGaAs : Sb–GaAs–GaAsP QWs VCSELs with an emission wavelength of 1.27 μm were successfully demonstrated. The VCSELs exhibit a very low threshold current, good temperature performance, and a high modulation bandwidth of $\sim$10.7 GHz with MCEF of $\sim 5.25\ \mathrm{GHz}/(\mathrm{mA})^{1/2}$. The VCSELs also demonstrate high-speed modulation up to 10 Gb/s from 25 °C to 70 °C. The results reveal the performance of the InGaAs : Sb VCSELs comparable to that of GaInAsN

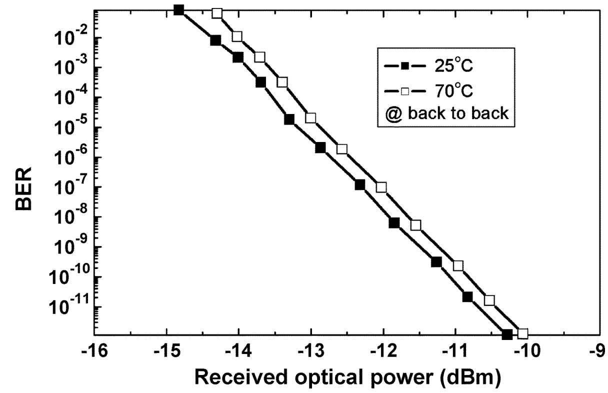

Fig. 6. (a) 25 °C and (b) 70 °C average received power dependence of the BER at 10-Gb/s modulation under BTB transmission.

VCSELs, but with better thermal stability. Longer wavelength is possible with incorporating more Sb or In content into the QW by reducing of growth temperature. Thus, the InGaAs : Sb VCSEL should be viable low-cost light source of optical fiber data link systems.

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