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MOCVD growth of high-performance InGaAsP/InGaP strain-compensated VCSELs with 850 nm emission wavelength

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Abstract

We present in this paper the metalorganic chemical vapor deposition growth and characterization of high-performance 850 nm InGaAsP/InGaP strain-compensated MQWs vertical-cavity surface-emitting lasers (VCSELs). The InGaAsP/InGaP MQWs growth condition was optimized using photoluminescence. These VCSELs exhibit superior characteristics, with threshold currents ~0.4 mA, and slope efficiencies ~0.6 mW/mA. The threshold current change is less than 0.2 mA and the slope efficiency drops by less than ~30% when the substrate temperature is raised from room temperature to 85°C. These VCSELs also demonstrate high-speed modulation bandwidth up to 12.5 Gbit/s from 25°C to 85°C.

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1. Introduction

The 850 nm vertical-cavity surface-emitting lasers (VCSEL) have become a standard technology for application in local area networks from 1.25 to 10 Gb/s [1–4]. The main advantages of VCSELs are the low threshold current, low divergent angle, and circular beam, which lead to simpler packaging and low electrical power consumption. The surface emission from the VCSELs also makes easy the two-dimensional array integration and allows wafer level testing, in turn leading to low fabrication cost. The use of an Al-free InGaAsP-based active region is an attractive alternative to the conventional (Al)GaAs active region for IR VCSELs. Edge emitting diode lasers with Al-free active regions have demonstrated performance and reliability surpassing those of AlGaAs active devices [5]. In addition, theoretical calculations have predicted a lower-transparency current density, high differential gain and better temperature performance in VCSELs with strained InGaAsP active region as compared to devices with lattice-matched GaAs quantum-well active region [6]. These parameters are all very important in high-speed and high-temperature VCSEL design because the relaxation resonance frequency of the laser depends on the square root of the differential gain as well as on the difference between operation current and threshold current

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[4]. The use of tensile-strained barriers (InGaP) can provide strain compensation and reduce active region carrier leakage. Al-free materials are significantly less reactive to oxygen than AlGaAs, which makes them ideal for reliable manufacturing [5]. Proton implanted VCSELs using an $In_{0.18}Ga_{0.82}As_{0.8}P_{0.2}$ strained active region have demonstrated good performance [7]. In this paper, we demonstrate for the first time the high-speed and high-temperature operation of 850 nm oxide-confined VCSEL utilizing $In_{0.18}Ga_{0.82}As_{0.8}P_{0.2}/In_{0.4}Ga_{0.6}P$ strain-compensated MQWs (SC-MQWs).

2. Experimental procedure

All structures were grown on semi-insulating GaAs (1 0 0) substrates by low-pressure metalorganic chemical vapor deposition (MOCVD). The group-V precursors are the hydride sources AsH_3 and PH_3. The trimethyl alkyls of gallium (Ga), aluminum (Al) and indium (In) are the group-III precursors. The VCSEL structure as shown in Fig. 1 consists of an n-type 35-period $Al_{0.15}Ga_{0.85}As/Al_{0.9}Ga_{0.1}As$ distributed Bragg reflector which was grown at 750°C. Then, a three-quantum-well active region $In_{0.18}Ga_{0.82}As_{0.8}P_{0.2}/In_{0.4}Ga_{0.6}P$ (80A/100A) and cladding layer (total 1λ thickness) were grown, followed by the growth of a 22-period $Al_{0.15}Ga_{0.85}As/Al_{0.9}Ga_{0.1}As$ p-type mirror and a 1λ thickness of current spreading layer and thin GaAs contacting layer. The quantum-well region growth temperature was set to 650°C. Growth interruptions of 5, 10, or 15 s were introduced before and after $In_{0.18}Ga_{0.82}As_{0.8}P_{0.2}$ QW growth. Fig. 2 shows the comparison of the photoluminescence spectra of $In_{0.18}Ga_{0.82}As_{0.8}P_{0.2}/In_{0.4}Ga_{0.6}P$ with different growth interruption times. The 5 s growth interruption is not enough to evacuate residual As in the growth reactor, resulting in the carry-over of As into the $In_{0.4}Ga_{0.6}P$ barrier. The 15 s growth interruption is so long that some impurities can be gettered at the interface or indium segregation can take place after strained layer growth, resulting in the degradation of luminescence. The 10 s growth interruption seems to give the best luminescence quality. For the VCSEL structure, the gain peak position = 835 nm was determined by photoluminescence of an angle-etched sample while the FP-dip wavelength = 842 nm was determined by reflection measurement. The VCSELs were fabricated utilizing the high-speed VCSEL processing to minimize capacitance while keeping reasonably low resistance [3]. The VCSEL has a 5 μm diameter emitting aperture defined by lateral oxidation and Ti/Pt/Au, AuGe/Ni/Au for p contact and n-metal, respectively.

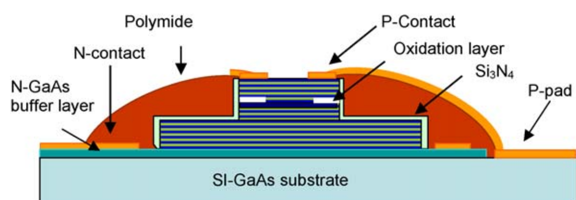

Fig. 1. Schematic cross section of high-speed VCSEL structure.

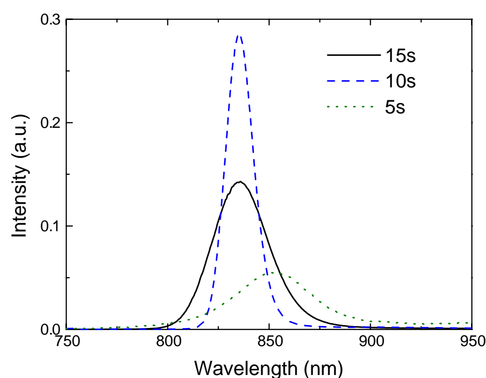

Fig. 2. Photoluminescence spectra of InGaAsP/InGaP MQWs with 5, 10, 15 s growth interruption time.

3. Results and discussion

Fig. 3 shows the typical SC-MQWs InGaAsP/InGaP VCSEL light output and voltage versus current (LIV) curves at room temperature and 85°C. These VCSELs exhibit kink-free current–light output performance with threshold currents ~0.4 mA, and slope efficiencies ~0.6 mW/mA. The threshold current change with temperature is less than 0.2 mA and the slope efficiency drops by less than ~30% when the substrate temperature is

raised from room temperature to 85°C. This is superior to the properties of AlGaAs/GaAs VCSELs with similar size [4]. The resistance of our VCSELs is ~95 Ω and capacitance is ~0.1 pF. As a result, the devices are limited by the parasitics to a frequency response of approximately 15 GHz.

The small signal response of VCSELs as a function of bias current was measured using a calibrated vector network analyzer (Agilent 8720) with on-wafer probing and 50 μm multimode optical fiber connected to a New Focus 25 GHz photodetector. Fig. 4 shows the smoothed small-signal modulation responses of a 5 μm VCSEL at different bias current levels. The modulation frequency is increased with increasing bias current until flattening at a bias of approximately 5 mA. With only 3 mA (5 mA) of bias current, the maximum 3 dB modulation frequency response is measured to be ~13 (14.5) GHz. About 14.5 GHz at 25°C is suitable for 12.5 Gb/s operation.

To measure the high-speed VCSEL under large signal modulation, microwave and light wave probes were used in conjunction with a 12.5-Gb/s pattern generator and a 12-GHz photoreceiver. The eye diagrams were taken for back-to-back transmission on SC-MQWs InGaAsP/InGaP VCSEL. As shown in Fig. 5(a), the room temperature eye diagram of our VCSEL biased at 4 mA with data up to 12.5 Gb/s and 6 dB extinction ratio has a clear open eye pattern indicating good performance of the VCSELs. The rise time T_r is 28 ps and fall time T_f is 41 ps with jitter (p–p) = 20 ps. The VCSELs also show superior performance at high temperature. Fig. 5(b) demonstrated the high-speed performance of our VCSEL (biased at 5 mA) with reasonably open eye diagrams at 12.5 Gb/s and

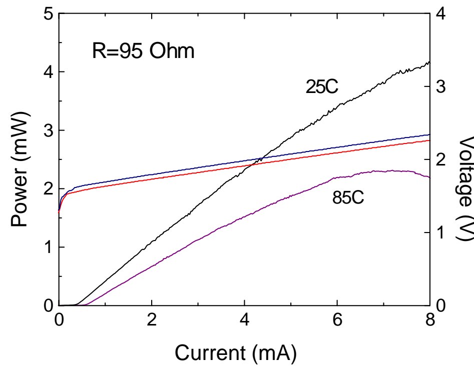

Fig. 3. SC-MQWs InGaAsP/InGaP VCSEL light output and voltage versus current (LIV) curves at room temperature and 85°C.

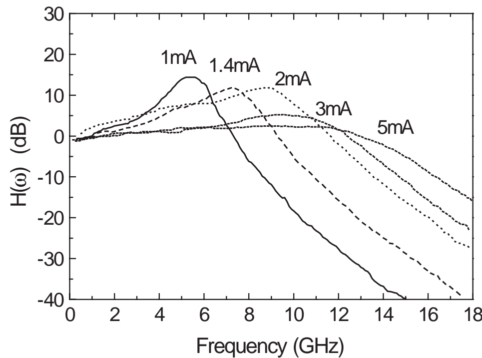

Fig. 4. Small-signal modulation responses of a 5 μm diameter VCSEL at different bias current levels.

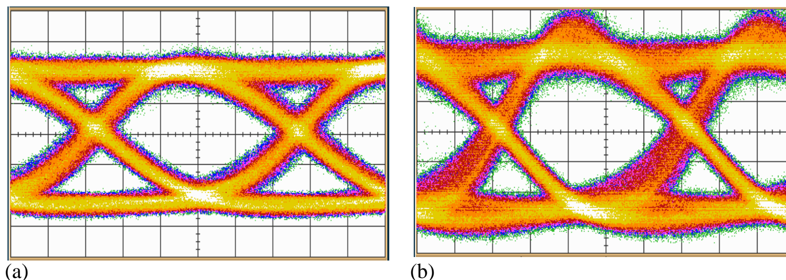

Fig. 5. (a) The room temperature (b) 85°C eye diagram of our VCSEL data up to 12.5 Gb/s and 6 dB extinction ratio. The scale in the figure is 15 ps/div.

6 dB extinction ratio at 85°C. This further confirms the superior performance of our VCSEL.

4. Conclusion

High-performance SC-InGaAsP/InGaP MQW VCSELs were successfully grown by MOCVD. These VCSELs show very low threshold current, good temperature performance, and high modulation response of up to 12.5 Gb/s from 25°C to 85°C. All of these advantages—kink-free L-I, good temperature properties, high-speed performance—make the novel VCSEL promising for optoelectronic and other commercial applications.

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