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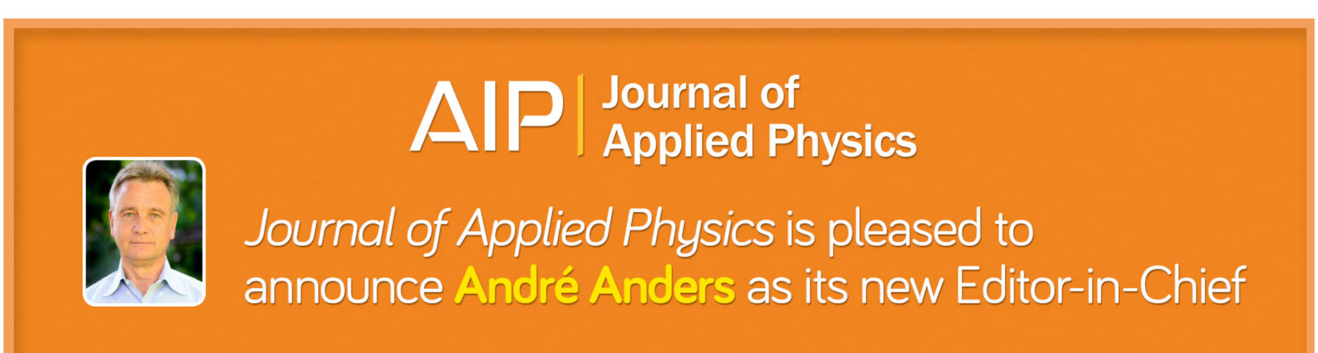

InGaAsP(1.3 μm)/InP vertical-cavity surface-emitting laser grown by metalorganic vapor phase epitaxy

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We report InGaAsP/InP vertical-cavity surface-emitting lasers (VCSELs) with an emission wavelength near 1.3 μm grown by metalorganic vapor phase epitaxy. The VCSEL structure contains a double-heterostructure cavity, a metal mirror, and a SiO_2/Si dielectric stack (three pairs) mirror with a measured reflectivity of 98%. A threshold current as low as 5 mA for 15-μm-diam devices with a 1-μm-thick active layer at 77 K was achieved, which is close to the best reported value (6 mA) within the accuracy of the pulse measurement. The highest operating temperature was 220 K.

Vertical-cavity surface-emitting lasers (VCSELs) are of interest as components of a two-dimensional laser array with a narrow-divergent beam output. In addition, surface-emitting lasers offer the advantage of wafer scale testing and the possibility of monolithic integration with other electronic devices. Recently, room-temperature cw operations of GaAs/AlGaAs VCSELs at 0.88 μm wavelength was reported.[1-4] Fiber butt coupling and random data modulation with open eyes up to 500 Mbits/s were also demonstrated[3] in these lasers. However, for VCSEL lasing at 1.3 and 1.55 μm wavelengths of interest to optical communications, a threshold current of 6 mA at 77 K was reported by Iga and Uchiyama[5] and Oshikiri *et al.*[6] In this letter we report the fabrication and performance of the InGaAsP (1.3 μm)/InP VCSE laser which employs a double-heterostructure cavity, a metal back mirror, and a SiO_2/Si dielectric stack mirror. The threshold current as low as 5 mA achieved from 15-μm-diam devices at 77 K is comparable to the best reported value (6 mA) for the VCSE laser in this material system within the accuracy (0.5 mA) of the pulse measurement.

The VCSEL structure is shown in Fig. 1. Using atmosphere pressure metalorganic vapor phase epitaxy (MOVPE), a 0.4 μm S-doped[7] InP buffer layer was grown on an n-type (100)InP substrate, followed by a 6-nm-thick InGaAs etch stop layer. The laser cavity consists of a 1-μm-thick S-doped (2×10^{18} cm^{-3}) InP n-cladding layer, a 1-μm-thick S-doped (1×10^{17} cm^{-3}), $In_{0.72}Ga_{0.28}As_{0.61}P_{39}$ active layer, a 0.5-μm-thick Zn-doped (5×10^{17} cm^{-3}) InP p-cladding layer, a 0.5-μm-thick Zn-doped (1×10^{18} cm^{-3}) InP p-cladding layer, and a 0.12-μm-thick Zn-doped (2×10^{19} cm^{-3}) $In_{0.88}Ga_{0.12}As_{0.28}P_{72}$ contact layer. The heavily doped contact layer facilitates the top nonalloyed contact. A threshold current density of 6 kA/cm^2 μm at room temperature was obtained from the fabricated wide stripe edge-emitting lasers, indicating a high material quality of the grown sample.

The sample was first thinned down to about 100 μm thick. Ni/Ge/Au/Ag/Au N-type metal contact was electron beam evaporated on the back side of the sample and lifted off to form 100-μm-diam windows. Contact annealing was carried out at 400 °C for 15 s. Then, a chemical vapor deposited (CVD) SiO_2 etching mask with 15 μm diameter was patterned by standard photolithography. 0.6-μm-high mesas were etched by Br: methanol. After removing the SiO_2 etching mask, another 300-nm-thick SiO_2 was deposited. Contact windows were opened using a photoresist mask. Then, 150 nm Ag/50 nm Au were evaporated to form the P-type metal contact and the back mirror of the laser. In order to fabricate the front mirror on the other side of the cavity, the InP substrate under the mesa area has to be removed. The substrate etch was done by 3HCl:1H_2O solution at room temperature. Due to the excellent etching selectivity, the etch stopped on the etch stop layer and left a mirror-like surface. Then, the etch stop layer was removed by $4H_2SO_4$:$1H_2O_2$:$10H_2O$ solution at 4 °C. Finally, a three-pair SiO_2/Si dielectric stack mirror was electron beam evaporated to form the front mirror of the laser. From a test InP substrate, the deposited dielectric mirror on a test InP substrate was tested and a reflectivity of 98% $\pm$ 1%, to our experimental accuracy, was obtained for the wavelength near 1.3 μm. The VCSEL devices were cleaved from the wafer and mounted to a Au-plated Si substrate for testing.

Figure 2 shows the light-current (L-I) characteristics of the laser operating under the pulsed condition (60 ns, 100 kHz) at 77 and 210 K. At 77 K, a sharp lasing threshold was seen. The threshold current is about 5 mA, which is very close to the best reported value (6 mA) for InGaAsP/InP

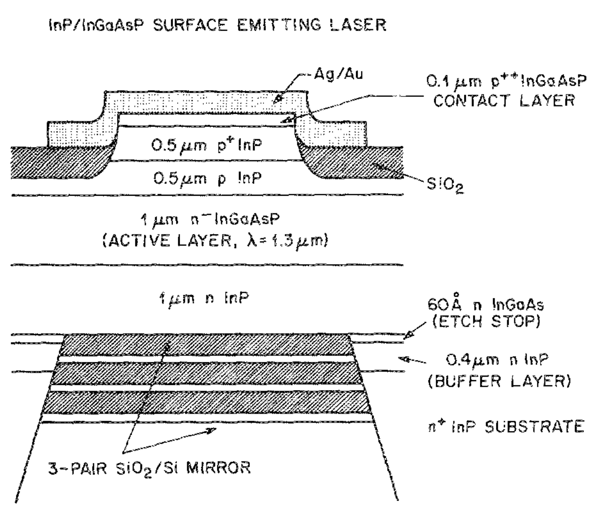

FIG. 1. Device structure of the InGaAsP/InP vertical-cavity surface-emitting laser.

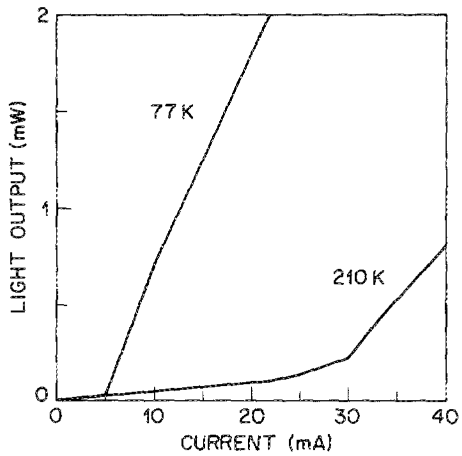

FIG. 2. Light output vs the current characteristics of the VCSE laser at 77 and 210 K. The pulse width and the repetition rate were 60 ns and 100 kHz, respectively.

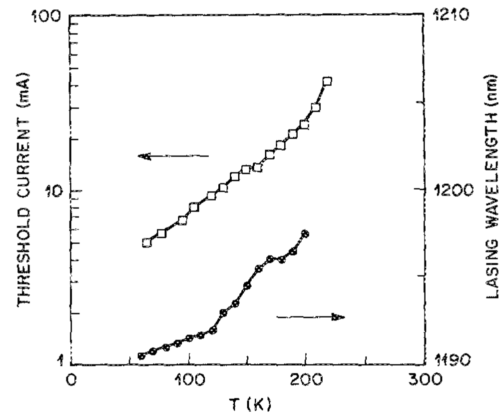

FIG. 4. Threshold current and the lasing wavelength as functions of temperature. The characteristic temperature T_0 is found to be 87 K between 77 and 200 K.

VCSE lasers within the accuracy ($\sim$0.5 mA) of the pulse measurement at this temperature. The threshold current density is calculated to be 2.8 kA/cm^2. The output power is in the mW range which leads to an external quantum efficiency of 12%, considering the front mirror only. The lasing spectrum at 77 K is shown in Fig. 3 when the laser was pumped at $1.6I_{th}$ pulses with 50% duty cycle. Single-mode operation was observed with a linewidth of 0.6 nm limited by the experimental setup. A far-field beam divergence angle of 5° was measured. The light output threshold was found to be linearly polarized. The threshold current and the lasing wavelength as functions of temperature are plotted in Fig. 4. The highest operating temperature was 220 K, limited presumably by a poor heat sink. The external quantum efficiency decreases gradually with increasing temperatures as shown in Fig. 2. The characteristic temperature T_0 for the temperature ranging from 77 to 200 K is 87 K, which is close to those of edge-emitting lasers fabricated from the material provided by our MOVPE system.

Shown in Fig. 5 is a typical room-temperature electroluminescence of the devices observed. We can see three sharp peaks superimposed on a broad spectrum. The broad spectrum represents the gain spectrum of the active material. Three sharp peaks are the Fabry–Perot modes. The linewidth of the central peak is 2.5 nm. The mode separations ($\sim$97 nm) are in agreement with the calculated values using the layer thicknesses in Fig. 1 and considering the effect of the dielectric mirror. A finesse of 40 is obtained, indicating that a mirror reflectivity product close to 0.94 was achieved. In order to operate the devices at room temperature, in addition to improving the heat sink of the device, we have to prevent the current spreading in the active layer. This can be achieved, for example, by the buried-heterostructure scheme with regrown Fe:InP as a current blocking layer. With the combination of the regrowth approach and reducing the device area, room-temperature operations should be possible.

We have fabricated InGaAsP/InP vertical-cavity surface-emitting lasers with the threshold current (5 mA) at 77 K close to the best reported value (6 mA) within measurement accuracy. A reflectivity of 98% was obtained from the electron beam evaporated SiO_2/Si dielectric stack mirror. Room-temperature operation of InGaAsP/InP VCSE laser should be possible by reducing the area of the laser and regrowing a Fe:InP current blocking layer.

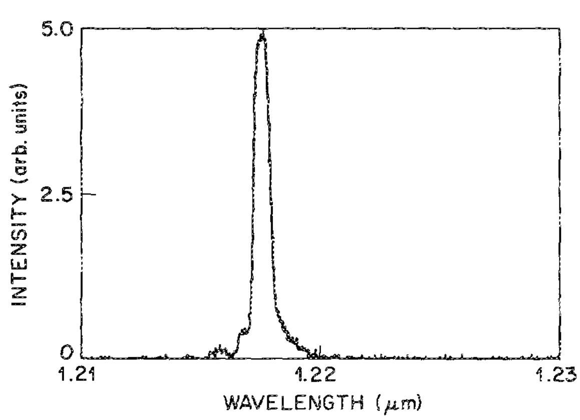

FIG. 3. Lasing spectrum of the VCSE laser pumped at $I = 1.6I_{th}$ with 50% duty cycle at 77 K. The linewidth is 0.6 nm.

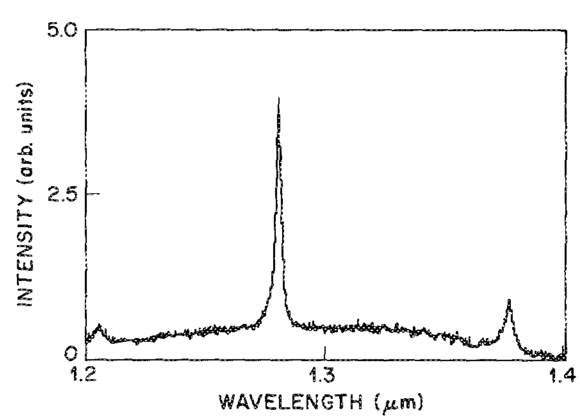

FIG. 5. Electroluminescence at room temperature measured from the VCSE laser. Three Fabry–Perot modes can be clearly seen.

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