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First Lasing Operation of Aluminum-Free 0.98-μm-Range InGaAs/InGaP/GaAs Vertical-Cavity Surface-Emitting Lasers

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Lasing operation has been demonstrated for an aluminum-free InGaAs/InGaP/GaAs vertical-cavity surface-emitting laser (VCSEL) with a strain-compensated triple-quantum-well active region. The 11-μm diameter VCSEL exhibited a threshold current of 1.7 mA and a low threshold voltage of 1.6 V under pulsed operation at room-temperature. Continuous-wave operation was also attained with a threshold current of 2.8 mA at 953 nm.

1. INTRODUCTION

Vertical-cavity surface-emitting lasers (VCSELs) provide a number of advantages over edge-emitting lasers, such as high two-dimensional packing density for arrays, a low-divergence circular beam, and wafer-scale testing ability. They are thus attractive as light sources for low-cost, short-distance optical interconnections. An important issue for these lasers is to decrease the threshold current in order to reduce the power dissipation.

Up to now, extremely low threshold operation below 100 μA were demonstrated in the 0.98-μm-range VCSELs with InGaAs strained-quantum-well active region[1), 2), 3)]. This is attained because they have the advantages of a high-gain strained-quantum-well active region and high-reflectivity cavity mirrors, which are transparent at the lasing wavelength. In these devices, a conventional structure, i. e., AlAs/GaAs distributed Bragg reflectors (DBR) and AlGaAs cladding layers, was used. However, aluminum easily oxidizes, which might deteriorate the reliability of the devices. Therefore, we expect advantages to result from using aluminum-free materials for highly reliable operation. A promising alternative to AlGaAs as a wide-band-gap material is InGaAsP lattice matched to GaAs.

The 0.98-μm edge-emitting laser fabricated by using the InGaAsP system has been studied intensively[4), 5)]. Degradation due to oxidation during fabrication and laser operation was not found when using an InGaAsP system instead of an AlGaAs system[6)]. The use of an InGaAsP system has another advantage. By introducing tensilely strained InGaAsP barrier layers instead of conventional GaAs barrier layers, a strain-compensated active region can be obtained, improving the crystal quality in the active region[7)]. This structure thus allows more strained wells than in conventional devices, offering advantages for low-threshold, high-power devices. Recently, an InGaP/GaAs DBR with reflectivity of over 99% was reported that can replace the AlAs/GaAs DBR[8), 9)]. In this letter, we report, for the first time, pulsed and CW lasing operation of aluminum-free 0.98-μm-range InGaAs/InGaP/GaAs VCSELs with a strain-compensated triple-quantum-well active region.

2. EXPERIMENT

Figure 1 shows a schematic cross-section of the VCSEL structure studied here. It was grown by metal-organic vapor phase epitaxy on an n-type GaAs substrate. The structure consists of a 45.5-pair n-type InGaP/GaAs DBR with a 5-nm-thick InGaAsP intermediate step layer at each hetero-interface, a strain-compensated triple-quantum-well active region with three 7-nm-thick compressively strained ($\Delta a/a$: +1.4%) InGaAs quantum wells separated by 8-nm-thick tensilely strained ($\Delta a/a$: -0.3%) InGaAsP barriers, a 0.2-μm-thick p-type InGaP cladding layer, and a 0.5-μm-thick p^+-type GaAs contact layer.

The active region was placed at the optical field maximum in the 3.5-λ cavity to maximize the longitudinal confinement factor from the view point of matched gain effect[10)]. The number of quantum wells was optimized as follows. Figure 2 shows the calculated mean reflectivity dependence of the threshold current density Jth in 0.98-μm InGaAs VCSELs with a strain-compensated multi-quantum-well active region at various number of quantum wells. It is found that Jth decreases with the increase of the number of quantum wells in the range below 99.5%, which is easily obtained in our VCSEL structure. A large number of quantum wells is thus desirable to achieve low threshold operation. However, cross-hatch patterns appeared on the wafer when the well number exceeded three. This was caused by the lattice distortion in the strained-quantum-well active region. Therefore, low threshold current could be expected by employing the triple-quantum-well structure. More strained quantum wells with reduced lattice distortion can be obtained by optimization of the structure of the strain-compensated active region.

In previous publication[9)], we showed the measured reflectivity spectra of InGaP/GaAs DBR. In the 45 pair DBR wafer, the reflectivity was over 99.5%, and good agreement was obtained with a numerical simulation. In

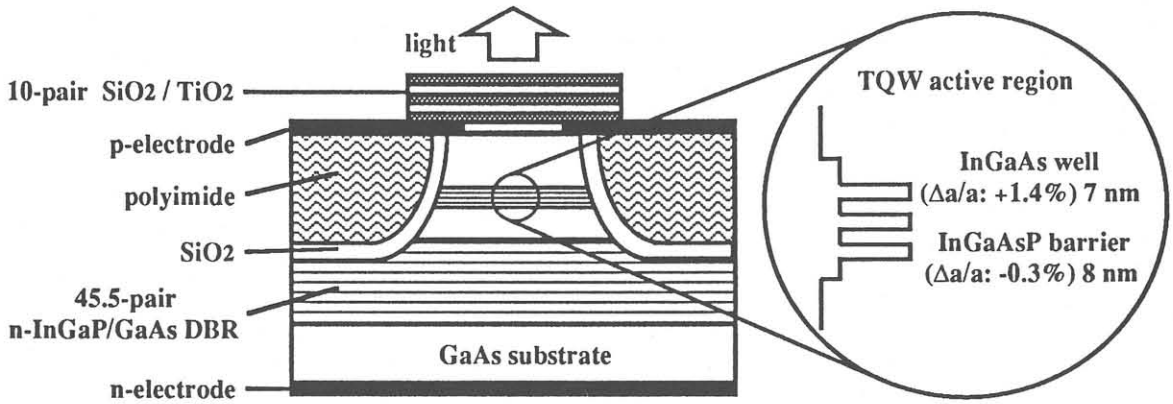

Fig. 1 Schematic cross-section of aluminum-free InGaAs/InGaP/GaAs VCSEL.

the VCSEL structure here, modification to improve the quality of the InGaP/GaAs hetero-interfaces in the DBR was made by inserting a 5-nm InGaAsP intermediate step layer at each hetero-interface. This modification did not affect the optical reflectivity and reflectivity of about 99.5% was obtained. This is because the optical reflectivity in the DBR structure is determined by the power spectrum of the Fourier transform of the position dependent refractive index. The two DBR structures have nearly identical first-order Fourier components and consequently nearly identical optical reflection spectra. The calculated reflectivity drop due to the intermediate step layer was only about 0.01%.

Ten pairs of alternating SiO_2/TiO_2 layers, instead of a p-doped semiconductor DBR, were used to form a p-side mirror. This eliminated the need for high-voltage operation, which would be necessary if a p-doped semiconductor DBR was used. This dielectric p-side mirror has reflectivity of about 99.5% and a stopband of 300 nm. The mean reflectivity of the mirrors was thus estimated to be about 99.5%. Individual laser elements were formed by wet-chemical etching, followed by coating with polyimide. Since these lasers are etched deeper than the active region, current flow is automatically confined within the mesas. The p-electrode has a circular laser output window so the laser beam can be obtained from the top surface.

3. RESULTS AND DISCUSSION

Figure 3 shows the measured reflectivity spectrum of the wafer with a 3.5λ–thick cavity sandwiched between the InGaP/GaAs DBR and the GaAs/air interface. The dip, caused by the 3.5λ–thick cavity, at the center of the high reflection region, indicates that the thickness of the cavity and the InGaP/GaAs DBR were obtained as designed. This dip at around 950 nm defines the wavelength of the lasing mode.

Figure 4 shows the light output and voltage against the current characteristics for an 11-μm-diameter

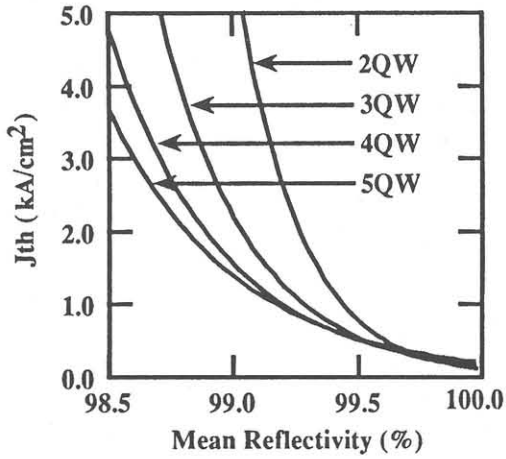

Fig. 2 Calculated mean reflectivity dependence of threhold current density Jth at various number of quantum wells.

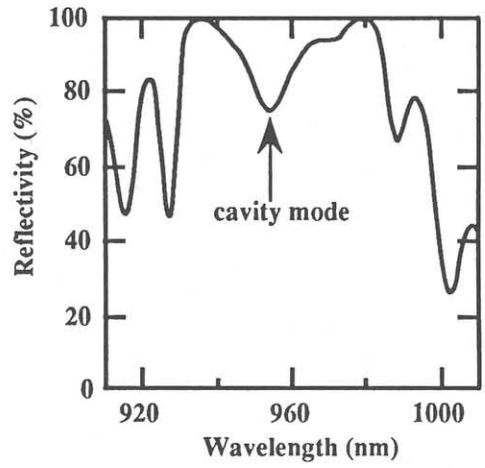

Fig. 3 Measured reflectivity spectrum from top of the wafer after epitaxial growth.

VCSEL under pulsed operation (500 ns, 100 kHz) at room temperature. The threshold current is 1.7 mA, and the corresponding threshold current density is about 1.8 kA/cm². The threshold current density Jth for the mean reflectivity of

99.5% should be 0.55 kA/cm^2, which means that the measured Jth is three times higher than the theoretical one. This high Jth may be due to the lower actual reflectivity of dielectric p-side mirror inside the ring contact or the nonuniform current injection into the active region. The threshold voltage is 1.6 V. This value is comparable to the lowest threshold voltage of 1.33 V for AlGaAs-based InGaAs VCSELs[11]. The relatively low threshold voltage of our VCSEL is due to the absence of the p-doped semiconductor DBR.

Figure 5 shows the light output against current characteristic of the same VCSEL as in Fig. 4 under CW operation at room temperature. The threshold current was 2.8 mA. This value is higher than the pulsed value, which is due to the excessive device heating. A maximum output power of 90 μW, limited by thermal saturation, was obtained. These results indicate that the improvement of the thermal conductivity and the threshold current density is important issue that should be overcome by optimizing the laser structure. Single longitudinal operation was obtained at 953 nm, as shown in the inset of Fig. 5. Sub-milliampere operation can be achieved by reducing the active diameter.

4. CONCLUSION

We have demonstrated the first lasing operation of an aluminum-free, 0.98-μm-range InGaAs/InGaP/GaAs VCSEL with a strain-compensated triple-quantum-well active region. The threshold current for the 11-μm active diameter VCSEL was 1.7 and 2.8 mA under pulsed and CW operation at room temperature. The threshold current is expected to be reduced by further optimization. Since this VCSEL consists of aluminum-free materials, highly reliable operation is expected.

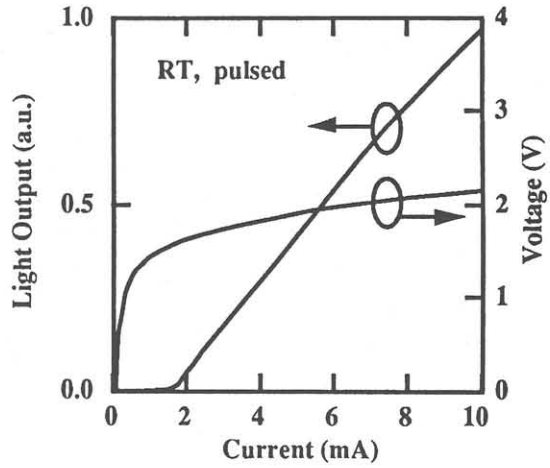

Fig. 4 Light output and voltage vs. current characteristics under pulsed operation at room temperature for an 11-μm-diameter VCSEL.

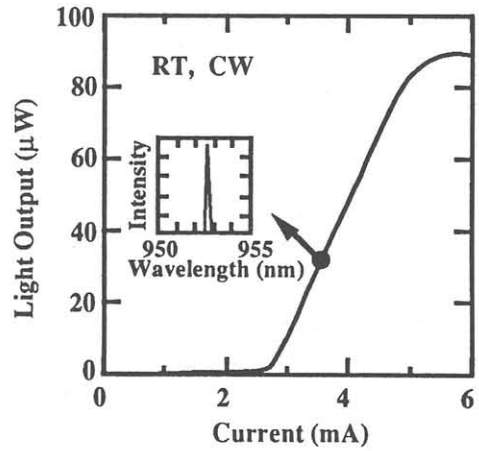

Fig. 5 Light output vs. current characteristics under CW operation at room temperature for an 11-μm-diameter VCSEL. The lasing spectrum is shown in the inset.

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