Long-wavelength GaInNAs VCSEL With Buried Tunnel Junction Current Confinement Structure

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We proposed for the first time the introduction of a buried tunnel junction structure to a GaInNAs vertical-cavity surface-emitting laser (VCSEL) and demonstrated high power and low resistive operations. By introducing a buried tunnel junction as a current confinement structure, the differential resistance was reduced to 65 Ω, which is 40% lower than that of a conventional long-wavelength oxide VCSEL. The maximum output power was 4.2 mW at 25˚C and 2.2 mW at 85˚C. A 3-dB modulation bandwidth over 9 GHz was obtained even at 85˚C. Also, clear eye openings were confirmed at 10 Gb/s over the temperature range of 25˚C to 85˚C. This new VCSEL is promising as a light source that achieves high speed operation with low power consumption.

1. Introduction

Long-wavelength vertical-cavity surface-emitting lasers (LW-VCSELs) are attractive light sources because of their unique features such as low power consumption, narrow beam divergence, and ease of fabricating two-dimensional array. Although power consumption of optical transceivers in long-wavelength fiber-optic communication systems has been reduced, that of semiconductor lasers used as light sources for optical transceivers still remains high. It is expected that further power consumption reduction for optical transceivers can be achieved by using LW-VCSELs.

LW-VCSELs are categorized into two types according to their substrates: One is GaAs-based VCSELs with GaInNAs active layers and the other is InP-based VCSELs with AlGaInAs or GaInAsP active layers. InP-based LW-VCSELs use buried tunnel junction (BTJ) for current confinement, thereby greatly improving performance.[(1)-(3)] However, their high-temperature dynamics have not yet met the requirement for 10 Gb/s applications. In GaAs-based LW-VCSELs, AlGaAs oxide current confinement structure is widely used. GaAs-based LW-VCSELs up to 4 Gb/s are already available in the market,[(4)] but those for 10 Gb/s applications are more sensitive to current aperture size and not yet commercialized. Repro-ducible fabrication of current apertures by AlGaAs oxidation had been difficult because it is necessary to control Ga composition, layer thickness, oxidation temperature, humidity, and other parameters that strongly affect the rate of oxidation. Therefore, a new approach has been awaited for fabrication of current confinement structure that is highly reproducible.

The authors report on this paper the development of a GaInNAs BTJ-VCSEL that overcomes the problems with LW-VCSELs.

2. Features of GaInNAs BTJ-VCSEL

GaAs-based LW-VCSELs have three major advantages over InP-based LW-VCSELs. The first is that they use GaInNAs quantum wells (QWs) grown on a GaAs substrate as an active region. These GaInNAs QWs have a large bandgap discontinuity of over 350 meV in the conduction band, showing excellent temperature characteristics in terms of threshold current.[(5)] The second is that AlGaAs/GaAs DBR structures can be easily grown epitaxially because AlGaAs is lattice matched to GaAs substrates, and that high-reflectivity, wide-bandwidth mirrors can be obtained with fewer DBR pairs compared to InP-based DBRs. The third is that AlGaAs/GaAs DBR structures are binary and the ternary semiconductors thereby having high thermal conductivity.

A current confinement structure with BTJ allows the shape and the size of current aperture to be control using the well-established processes of photolithography and etching. Electron-hole conversion occurs in the tunnel junction and P-type layers can be replaced by n-type layers, leading to a large reduction of optical absorption loss. In addition, because electrons in n-type layers have high mobility, the electrical resistance in the spacer is reduced. The low-resistance n-type current spreading layer allows a lossless dielectric DBR or an undoped semiconductor DBR to be used as a top mirror, without increasing the device resistance.

The authors have proposed and demonstrated the world's first GaInNAs BTJ-VCSEL.[(6), (7)] Its bottom DBR consists of an AlGaAs/GaAs DBR having good broadband reflectance and high thermal conductivity. The active layer consists of GaInNAs QWs that exhibit excellent temperature characteristics. A tunnel junction is incorporated as the current confinement structure. The top mirror is a dielectric DBR that is suited for high-speed operation. Because refractive index contrast is larger in a dielectric DBR than in a semiconductor DBR, the penetration depth of light into a dielectric DBR is smaller than that into a semiconductor DBR. The smaller penetration depth leads to the shorter effective cavity length, resulting into higher modulation efficiency. The drawback of a dielectric DBR is that its thermal conductivity is lower than that of a semiconductor DBR. This drawback can be minimized by using a semiconductor DBR bottom mirror and efficiently transferring heat generated in the active region through the bottom mirror. Therefore, the combination of a dielectric DBR top mirror and a semiconductor DBR bottom mirror is suitable for achieving high-speed operation at high temperatures.

3. GaAs-based Tunnel Junction

A low-resistance tunnel junction needs to be fabricated in order to develop a low-resistance BTJ-VCSEL. A BTJ test structure was fabricated and its resistance was evaluated. A tunnel junction was grown on a p-type substrate. After forming a 5-µm diameter circular mesa, an n-type current spreading layer was grown to cover the tunnel junction. The top and bottom electrodes were deposited on both sides of the wafer, with the top electrode having an inner diameter of 15 µm. **Figure 2** shows the voltage-current (V-I) curve and the current-differential resistance (I-Rd) curve of the tunnel junction. The figure indicates that a reverse bias is applied to the tunnel junction. The differential resistance of the test structure is 35 Ω at 10 mA, which corresponds to the specific resistance of 6.9×10^{-6} Ω/cm^2. It should be noted that the resistance of the tunnel junction alone is assumed as less than 35 Ω since this value also includes the resistances of the n-type contact, the current spreading layer, and the p-type contact.

4. Device Performances

4-1 Static Characteristics

Figure 3 shows the temperature dependence of the light-current (L-I) characteristics of the test structure's 6-µm diameter tunnel junction aperture. The threshold current and the maximum output power at 25°C are 2.3 mA and 4.2 mW, respectively. Even at 85°C, the threshold current is 2.2 mA and the maximum output power is as high as 2.2 mW. The oscillation wavelength is 1274 nm at 25°C. **Figure 4** shows the temperature dependence

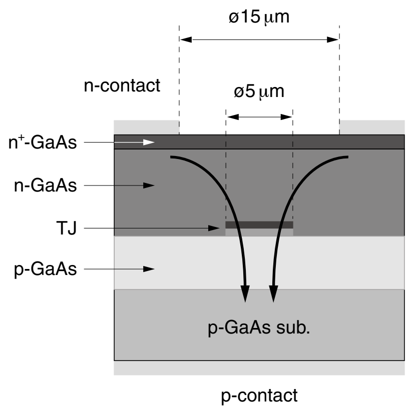


Fig. 1. Schematic diagram of BTJ test structure

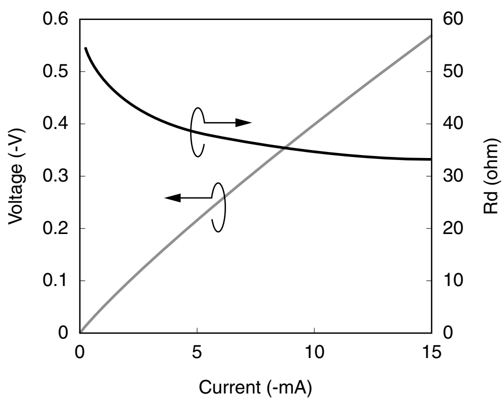


Fig. 2. Voltage-current (V-I) and current-differential resistance (I-Rd) characteristics of test structure

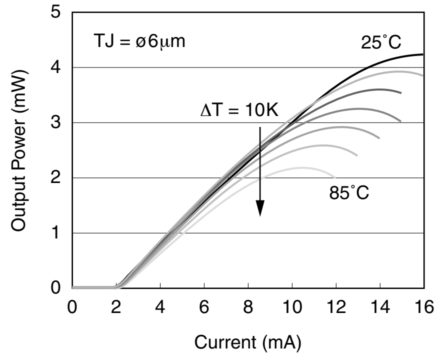


Fig. 3. Temperature dependence of light-current (L-I) characteristics of GaInNAs BTJ-VCSEL with 6-µm diameter tunnel junction aperture

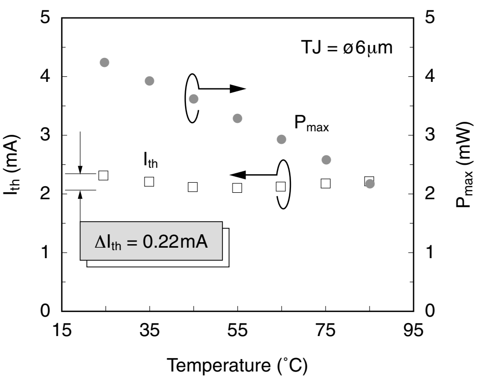


Fig. 4. Temperature dependence of threshold current and maximum output power of GaInNAs BTJ-VCSEL with 6-µm diameter tunnel junction aperture

of the threshold current and the maximum output power. The variation of the threshold current over a temperature range of 25°C to 85°C is as low as 0.22 mA. This indicates that the wavelength detuning between cavity resonance and gain peak has been optimized. **Figure 5** shows the V-I and I-Rd characteristics at 25°C. The differential resistance at 7 mA is 65 Ω, which is 40% lower than that of a conventional long-wavelength VCSEL with an oxide aperture. It is confirmed that the tunnel junction and the other parts of the device are well designed in terms of the doping profile.

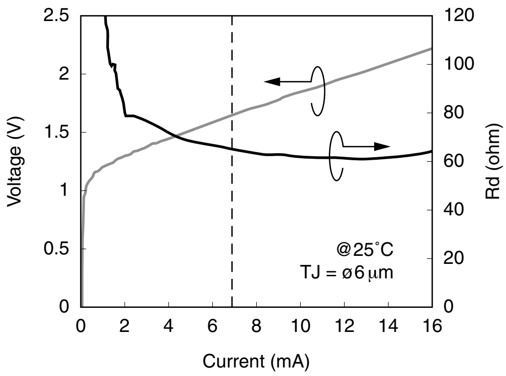
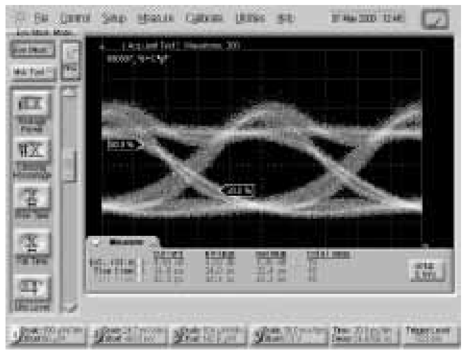


Fig. 5. Voltage-current (V-I) and current-differential resistance (Rd-I) characteristics of GaInNAs BTJ-VCSEL with 6-µm diameter tunnel junction at 25°C

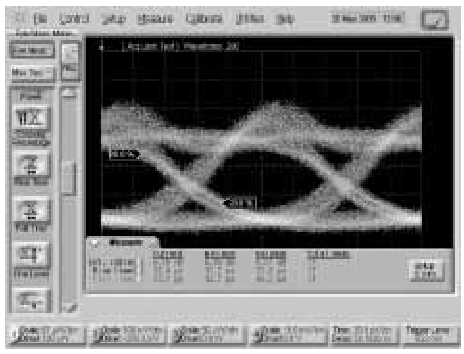
4-2 Dynamic Behavior

The dynamic responses of the VCSEL chip were measured. Before measurement, the chip was mounted onto a carrier and bonded by wires. The output signal from the chip was butt coupled to a tapered fiber. **Figure 6** shows the small signal responses measured at 85°C. The diameter of the tunnel junction aperture is 6 µm. The resonance frequency is larger than 6 GHz, and the 3-dB modulation bandwidth is 9.3 GHz at 8 mA. The D-factor is 3.47 GHz/mA$^{1/2}$, which is 1.5 times higher than that of edge emitting lasers used in 10 Gbps applications. **Figures 7(a) and 7(b)** show the 10.3125 Gb/s eye diagrams at 25°C and 85°C. The extinction ratio is kept to 5.0 dB. The bias currents at 25°C and 85°C are 5.8 mA and 6.9 mA, respectively. Clear eye openings are obtained over a temperature range of 25°C to 85°C.

These results indicate that the GaInNAs BTJ-VCSEL the authors have developed provides excellent temperature characteristics and is promising for high-speed operation.



(a) 25˚C



(b) 85˚C

Fig. 7. 10.3125 Gb/s eye diagrams of GaInNAs BTJ-VCSEL with 6-µm diameter tunnel junction aperture at (a) 25°C and (b) 85°C

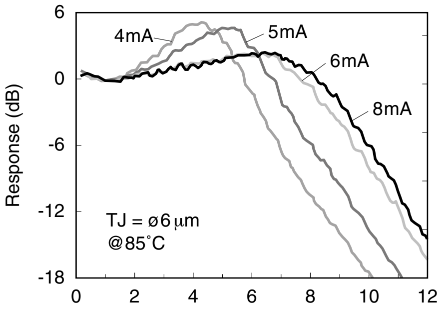


Fig. 6. Small signal responsiveness of GaInNAs BTJ-VCSEL with 6-µm tunnel junction aperture at 85°C

5. Conclusion

The authors have fabricated and demonstrated a long-wavelength GaInNAs VCSEL that uses a buried tunnel junction. The maximum output power of 4.2 mW with a low resistance of 65 Ω has been obtained at 25°C with a tunnel junction aperture diameter of 6 µm. 10 Gb/s operations have been achieved over a temperature range of 25°C to 85°C, with an operation current below 7 mA and an extinction ratio of 5.0 dB. These results clearly indicate that the GaInNAs BTJ-VCSEL the authors have developed provides excellent temperature characteristics and is promising for high-speed operation.

References

(1) W. Hofmann et al., "1.3 μm InGaAlAs/InP VCSEL for 10G ethernet," Proc. International Semiconductor Laser Conference 2008, Sorrento, Italy, MB3.
(2) N. Nishiyama et al., "Long-wavelength vertical-cavity surface-emitting lasers on InP with lattice matched AlGaInAs-InP DBR grown by MOCVD," IEEE J. Sel. Topics in Quantum Electron., 11, p.990 (2005).
(3) A. Caliman et al., "Wafer-fused 1550-nm band VCSELs with fundamental mode output exceeding 6 mW," Proc. European Conference on Optical Communications 2008, Brussels, Belgium, We.3.C.5.
(4) J. Jewell, "Vcsels - billions and billions," Proc. International Symposium on VCSELs and Integrated Photonics, A-1, pp. 8-10, 2007.
(5) M. Kondow et al., "GaInNAs: A Novel Material for Long-Wavelength-Range Laser Diodes with Excellent High-Temperature Performance," Jpn. J. Appl. Phys., 35, p.1273 (1996).
(6) Y. Onishi et al., "High power and low resistive GaInNAs-VCSELs with buried tunnel junctions," Proc. International Semiconductor Laser Conference 2008, Sorrento, Italy, TuB2.
(7) Y. Onishi et al., "100°C, 10 Gbps operation of buried tunnel junction GaInNAs VCSELs," Proc. European Conference on Optical Communications 2008, Brussels, Belgium, We.3.C.6.

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