High-Speed Vertical-Cavity Laser Diodes at 1.55 µm

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Abstract: Buried tunnel junction vertical-cavity surface-emitting lasers (BTJ-VCSELs) for 1.55 µm wavelength, 3dB-cut-off-frequencies around 8 GHz, modulation bandwidths up to 10 Gbit/s and excellent stationary characteristics are demonstrated. Technological challenges have recently been mastered, so that even higher modulation bandwidths are expected.

Introduction

Vertical-cavity surface-emitting lasers (VCSELs) feature numerous advantages compared with classical edge-emitters such as low threshold currents, single longitudinal mode operation, low beam divergence and on-wafer testability. Nowadays, 850 nm VCSELs have achieved significant performance and are the preferred light sources in high-bit-rate data communications [1]. The development of VCSELs in the wavelength ranges around 1.31 and 1.55 µm, however, encountered several technological challenges that have been solved only quite recently. GaAs-based approaches using InGaAsN [2] or strained GaAsSb have shown promising results covering the 1.3 µm wavelength range. For 1.55 µm, tunnel-junction VCSELs based on InP show optimal performance [3].

In particular, the buried-tunnel-junction (BTJ) VCSEL, which has been developed at our institute, shows excellent stationary and dynamic behaviour. Sub-mA cw threshold currents, cw operating temperatures beyond 100 °C, side-mode-suppression of at least 30 dB, and a small-signal modulation frequency around 7 GHz enabling error-free data transmission at modulation bandwidth up to 10 Gbit/s.

In this paper we present the dynamic characteristics of long-wavelength BTJ-VCSELs and technological improvements, which imply further progress.

Design and Fabrication

Figure 1 shows a schematic cross-sectional view of the BTJ-VCSEL. The appliance of the BTJ with its self-adjusted current and optical confinement yields several benefits for high-speed applications. Firstly, the major part of the p-side

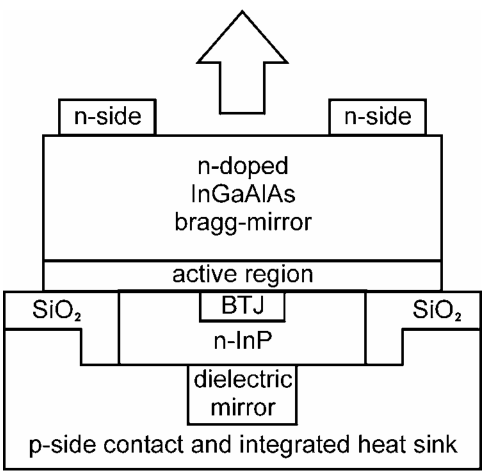

Fig.1 *Schematic cross-section of a 1.55 µm BTJ VCSEL*

confinement layers are converted from high-resistive p- to n-conducting materials, which leads to a low electrical series resistance of about 35 Ω and low threshold currents. On the one hand the small-signal 3dB-cut-off frequency is proportional to

$$\sqrt{\frac{I}{I_{th}} - 1}$$

with I and I_{th} as bias and threshold current, respectively. On the other hand, the RC-product of the differential laser resistance and the parasitic capacitance must be sufficiently small, too.

Secondly, the upside-down mounted structure (the InP substrate on top is completely removed) with its electroplated Au pseudo-substrate that serves as an excellent heat sink yields low threshold and high operation temperature.

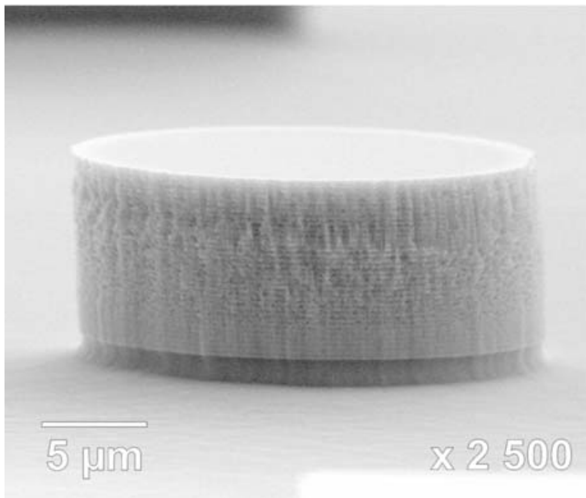

Fig.2 *InGaAlAs Bragg-mirror etched by electron cyclotron resonance reactive ion etching (ECR-RIE) with Cl_2*

As mentioned above, the parasitic capacitance plays an important role with respect to modulation bandwidth. However, there are large capacitances of the n-side contact pads, and space-charge capacitances at the blocking diode around the tunnel-junction.

In order to reduce these parasitics, smaller contact pads and thicker insulation layers were realized. Moreover, to remove the space-charge capacities a dry etching technique was needed that allows the structuring of Indium- and Aluminium-containing semiconductors. Therefore an ECR-process with chlorine was developed, which allows separating the whole VCSEL-structure with vertical sidewalls. Figure 2 shows an SEM-image of an etched sample.

Since single-mode emission is essential for fibre-optic communication, the thickness of the burying n-InP layer is increased in order to reduce index-guiding and to improve thermal conductivity.

Results and Discussion

Figure 3 shows typical output characteristics (a) and spectrum (b) of a single-mode BTJ-VCSEL at 1.55 µm. The maximum output power is 0.72 mW at 6.6 mA at single-mode operation and an initial slope efficiency of 0.2 W/A. The threshold voltage is 0.9 V, the threshold current 0.5 mA and the differential series resistance 57 Ω due to the small BTJ diameter of 3.7 µm that is needed for single-mode operation. The emission spectrum is measured under constant current. The side mode suppression ratio (SMSR) is at least 35 dB over the whole current and temperature range.

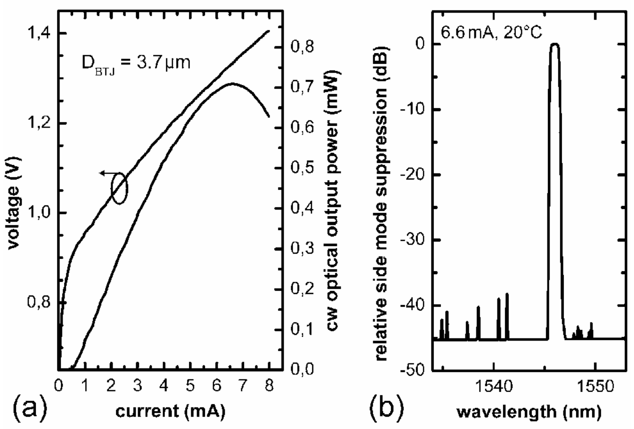

Fig.3 *Output characteristics (a) and spectrum (b) of a single-mode BTJ-VCSEL at 1.55 µm*

Figure 4 shows the small signal modulation of a BTJ-VCSEL. The 3dB-cut-off-frequency is around 8 GHz, which was achieved by using small area contact pads with lower parasitic capacitance. Further reduction of parasitic capacitances should enable even higher modulation bandwidths.

Data-transmission experiments of SMA-mounted VCSELs [4] allowed error-free back-to-back (BTB) transmission up to 10 Gbit/s. As can be seen in figure 5 (a) error-free data transmission with bit error rates (BER) better than 10^{-12} can be maintained up to 10 Gbit/s. For BTB transmission at 8 Gbit/s the minimum received optical power is -15.5 dB and the measured attenuation over 10.5 km standard single-mode fibre (SSMF) is only 0.5 dB. The eye-diagram (b) is wide open for BTB transmission of PNG-patterns at 10 Gbit/s. Due to very low electrical resistances combined with small capacities, the bonding scheme plays an important role and an optimization has to be found, which may be dependent on the respective laser mounting.

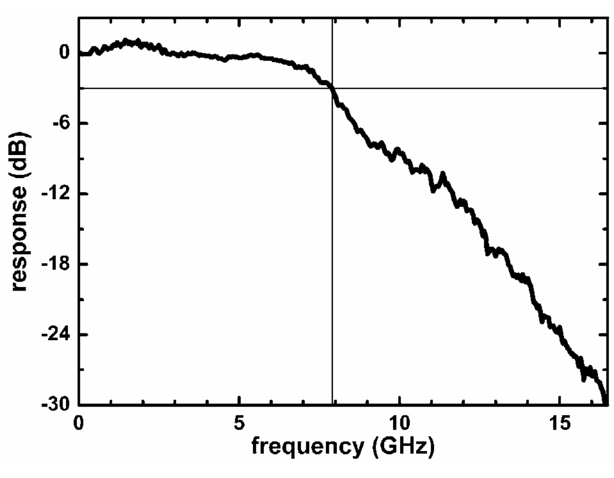

Fig.4 *Small signal modulation of a BTJ-VCSEL at 1.55 µm*

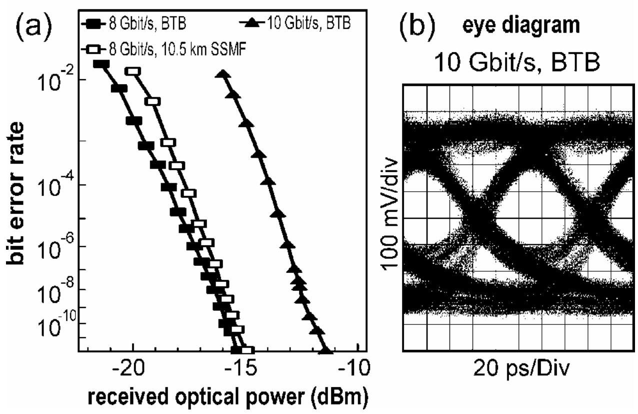

Fig.5 *Bit error rates (BER) (a) and eye-diagram (b) of a SMA-mounted VCSEL*

Conclusion

To sum up, BTJ-VCSELs with modulation bandwidths up to 10 Gbit/s and superior stationary laser characteristics are shown. We expect even higher modulation bandwidths to be achieved by reduction of space-charge capacitances with new etching technology and optimized design. Together with single-mode operation at further increased output power, the BTJ-VCSEL may become the ideal light source in high-speed data transmission.

Acknowledgement

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References

[1] K. J. Ebeling, U. Fiedler, R. Michalzik, G. Reiner and B. Weigl, AEU-Int. J. Electron. Commun., **50**, 316 (1996)

[2] A. Ramakrishnan, G. Steinle, D. Dupper, C. Degen, G. Ebbinghaus, Electron. Lett. **38**, 325 (2002)

[3] M-C. Amann, M. Ortsiefer, R. Shau, J. Rosskopf, F. Köhler and G. Böhm, Adv. Solid State Phys., **41**, 75 (2001)

[4] M. Ortsiefer, R. Shau, F. Mederer, R. Michalzik, J. Rosskopf, G. Böhm, F. Köhler, C. Lauer, M. Maute, and M.-C. Amann, 28th European Conference on Optical Communication (ECOC), 2002, Post-Deadline Papers, PD4.9