Parallel-Driven VCSELs With Optically Controlled Current Confinement

Sven Bader

We present vertical-cavity surface-emitting lasers (VCSELs) with integrated phototransistor (PT) layers, arranged as four parallel-driven mesas in one row connected by thin ridges. Detailed studies about the turn-on process of the device are shown, as well as a direct visualization of the optically controlled current confinement. Light–current–voltage (LIV) operation curves with hysteresis loops were measured and simultaneous camera images were taken from the back side of the structure to record the turn-on/-off order of this device.

1. Introduction

VCSELs are widely known for their low threshold current [1] which requires a high current density in the active layers. Therefore, current spreading in the semiconductor material must be prevented by either mesa etching [2] or current-blocking layers, e.g., by proton implantation [3]. Epitaxial solutions with regrowth steps are also applicable [4]. Nowadays in most commercially available VCSELs, buried Al_xO_y oxide apertures funnel the pump current into the middle of the mesa [5]. The wet-thermal processing of these insulating layers depends on parameters like temperature and pressure which must be strictly controlled to obtain reproducible devices. Moreover, the volume of the aperture layers shrinks during oxidation. This results in a potentially problematic built-in strain near the light-emitting quantum wells (QWs) of the active zone of the VCSEL [6]. A novel oxide-free and regrowth-free approach uses the generated spontaneous light in the laser resonator in association with an epitaxially integrated PT for an optical definition of the current path through the device [7]. Initially, the PT, which is configured as an optical switch, acts as an insulating barrier layer. Only leakage current generates some spontaneous emission in the active zone, which is partly absorbed in a thin InGaAs quantum well (α-QW) embedded between the base and the collector layers. The resulting photocurrent takes the role of a base current and turns the most illuminated part of the PT layers conductive after exceeding a certain threshold base current, depending on the PT's current gain and the layer structure of the VCSEL. Hence, the current–voltage operation curve shows a negative differential resistance (NDR) region when the PT opens and the resistance decreases. Once opened, the current aperture remains stable in diameter, thus lasing starts after reaching the threshold current density. The advantages of this method are a less complex and accelerated manufacturing process and in addition, due to the lack of the oxide aperture, a reduced strain near the active zone. Ultimately, the PT-VCSEL is intended to exhibit improved reliability and efficiency compared to present oxidized VCSELs.

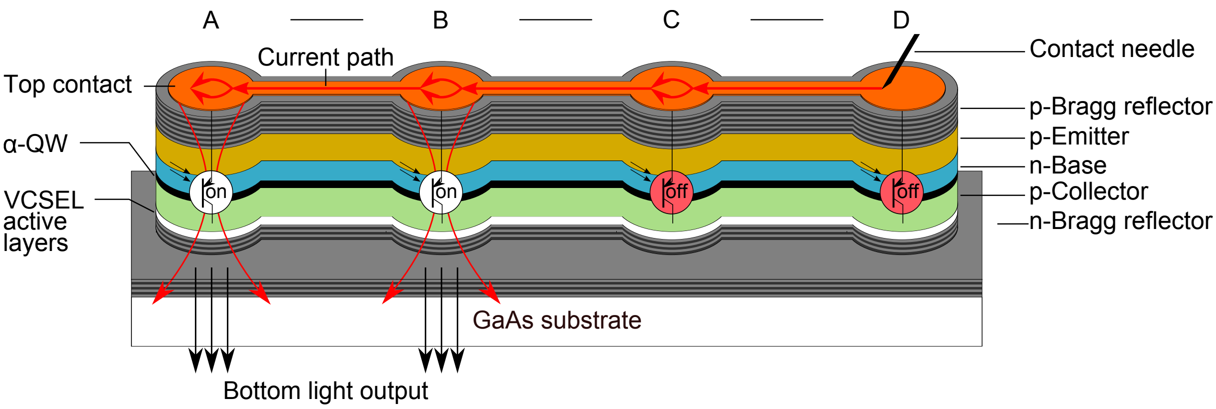

Fig. 1: Layout and operation principle of the four parallel-driven bottom-emitting VCSELs with integrated phototransistor layers for optically controlled current confinement. Initially, the phototransistor with the lowest voltage drop during dark-current operation begins to open and becomes conductive. The resulting spontaneous photons reach the neighboring mesas through the thin ridges and switch them on successively.

2. Device Structure

Bottom-emitting PT-VCSELs were grown on a n-type GaAs substrate by molecular beam epitaxy (MBE). The resonator is formed by p- and n-doped AlGaAs/GaAs Bragg mirrors consisting of 29 and 26.5 layer pairs, respectively. The simulated lossless reflectivities are $R_{\mathrm{top}} = 99.91\,\%$ (including the top metal) and $R_{\mathrm{bottom}} = 99.87\,\%$, while the estimated threshold gain is $1520\,\mathrm{cm}^{-1}$. The active zone with three InGaAs QWs for lasing and the pnp-structure of the PT with a calculated current gain of only ≈ 2 are placed inside the cavity. The 6 nm thin α-QW, embedded between base and collector, has an absorption coefficient of $\approx 3500\,\mathrm{cm}^{-1}$. Owing to its small thickness and the low current gain, the PT requires high photon densities to switch its layers conductive. We have arranged four InGaAs/AlGaAs-based PT-VCSELs in one row which were reactive ion etched to the bottom reflector (see Fig. 1). Each mesa with a diameter of 45 µm is connected with a 60 µm long and 20 µm wide ridge. The Ti/Pt/Au metal contact is placed on the top reflector and extends over the whole structure. The back side of the substrate was kept free from metal to guarantee an unobstructed view at the light output pattern of the PT-VCSEL. Instead, a large-area n-contact is established between the sample and a Au-coated vacuum holder.

3. Experimental

The sample holder has a center opening for transmission of the bottom-emitted light. In addition to optical power measurements, the setup allows to take CCD camera images from the bottom side of the wafer and obtain new insights about the turn-on/-off process of the laser structure. The current source is connected to the sample holder and to a tungsten needle which contacts the metalization of the PT-VCSEL. After a measurement, the needle is moved to a different mesa to judge the influence of the contact position. The measured

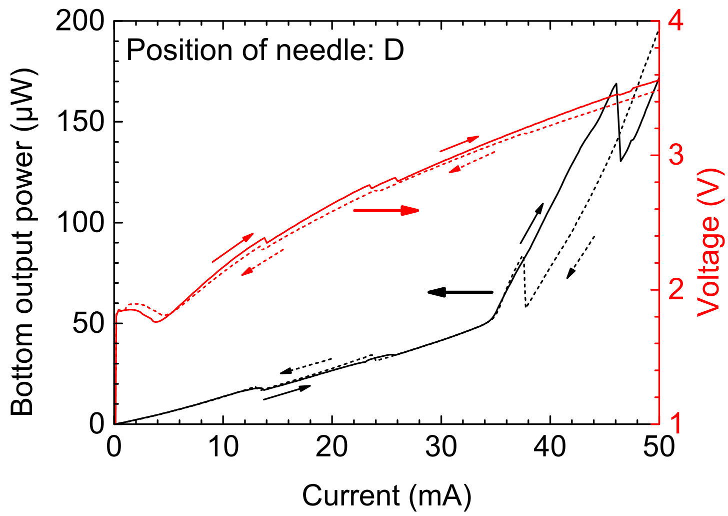

Fig. 2: Measured continuous-wave operation curves of the four parallel-driven PT-VCSELs. Each kink indicates a turn-on/-off point of a PT. The turn-off order of the PTs is different from that during turn-on, hence hysteresis loops exist.

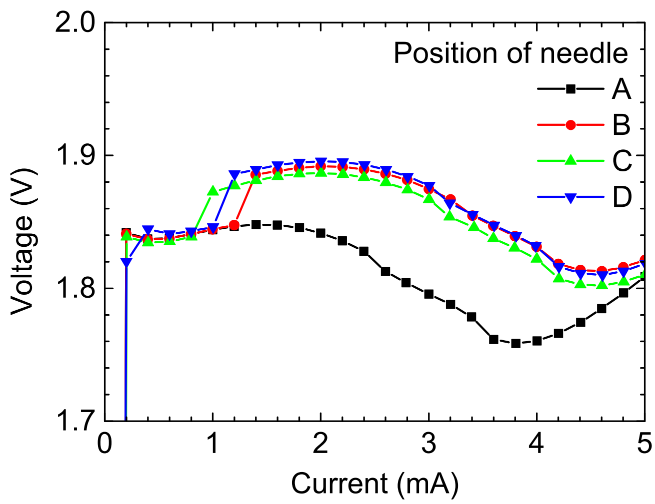

Fig. 3: Current–voltage measurements of the leakage current in the dark-current region for all contact positions of Fig. 1. For each trace, the pump current is reduced from 50 mA to zero to ensure the needle-contacted PT turns off last. Only the range from 0 to 5 mA is shown here. The voltage drop of the left mesa (position A) is less than of the others. Hence, due to the highest initial photon density, this PT always begins to turn on first.

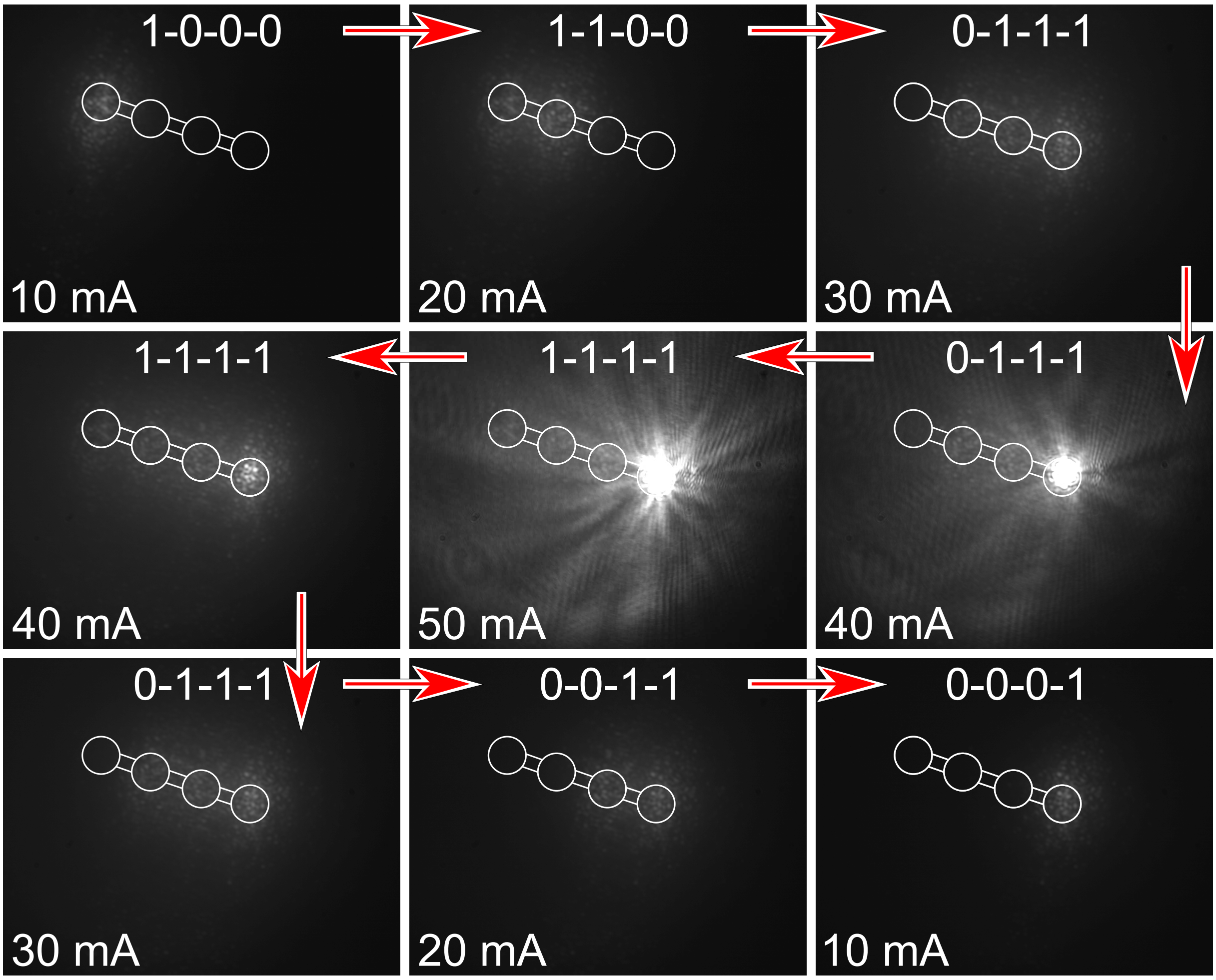

Fig. 4: Camera images of the bottom side of the PT-VCSEL arrangement at different currents during turn-on and -off. The four parallel-driven mesas are highlighted in white. "0" and "1" represent the off-/on-state of the PT in each mesa. The needle contacts the right mesa (position D in Fig. 1).

LIV curves when contacting the right mesa (see Fig. 1) are shown in Fig. 2. Ramping up the current from zero to 50 mA, each NDR region indicates the turn-on of a PT in one mesa. Owing to reflections of spontaneous photons at the etched walls, the whole mesa area becomes conductive. Initially, the PT with the lowest voltage drop during dark-current operation (see Fig. 3) begins to open, independent of the position of the needle. In the investigated structure it is the left mesa (see Fig. 4 (top left)) where the highest leakage current, respectively spontaneous emission, of the base–collector junction is to be expected. Subsequently, while further increasing the current, spontaneous emission reaches through the ridges to the neighboring mesas and successively turns these PTs on. The output power drops due to the decreased current density in the mesas. Lasing always starts at the needle-contacted mesa where the highest current density is expected owing to lateral ohmic losses. This leads to confinement effects where distant PTs can even switch off again, namely here while increasing the current from 20 to 30 mA (from switching state 1-1-0-0 to 0-1-1-1). In the NDR region around $I = 23$ mA, the light output as an exception raises slightly due to the turn-off of the left PT, whereas the PT at position C opens. The NDR region at 26 mA originates from the turn-on of the right mesa. Only while further increasing the current, the left PT is able to open again because of the increasing current density, respectively the spontaneous emission, which reaches again the left mesa. While decreasing the pump current, the distant PTs switch off first, thus the turn-off order of the PTs is different from that during turn-on, as long as the needle does not contact the mesa which opens first. Therefore, hysteresis loops occur while the output power and voltage rise at each turn-off of a PT. The needle-contacted PT always turns off last, hence it is possible to characterize the leakage current (see Fig. 3) of each mesa separately.

4. Conclusion

In summary, we have presented a PT-VCSEL arrangement with four parallel-driven mesas connected with thin ridges, which experimentally demonstrates the process of optically controlled current confinement. Measured operation curves could be identified with camera images which illustrate the turn-on/-off behavior of the mesas. It is thus understood that each NDR region represents a new opening of a PT area owing to spontaneous photons traveling through the ridges. The leakage current has a major influence during the initial turn-on. The different sequence of the PT's switching points also represents the impact of non-negligible lateral ohmic losses in the layer structure. Lessons learned will be transferred to future generations of solitary device which will be optimized with respect to the degree of confinement (depending on the parameters of the PT, in particular the current gain), threshold current, and electro-optic efficiency.

Acknowledgment

The author thanks Philips Technologie GmbH, U-L-M Photonics for the project support and the MBE growth of the PT-VCSEL wafer. Furthermore the author is grateful to Dr.-Ing. Philipp Gerlach for many great discussions and the fruitful cooperation. The technical assistance of Susanne Menzel and Rudolf Rösch is highly appreciated.

References

[1] R. Michalzik (Ed.), *VCSELs — Fundamentals, Technology and Applications of Vertical-Cavity Surface-Emitting Lasers*, Springer Series in Optical Sciences, vol. 166, Berlin: Springer-Verlag, 2013.

[2] J.L. Jewell, A. Scherer, S.L. McCall, Y.H. Lee, S. Walker, J.P. Harbison, and L.T. Florez, "Low-threshold electrically pumped vertical-cavity surface-emitting microlasers", *Electron. Lett.*, vol. 25, pp. 1123–1129, 1989.

[3] M. Orenstein, A.C. Von Lehmen, C. Chang-Hasnain, N.G. Stoffel, J.P. Harbison, L.T. Florez, E. Clausen, and J.E. Jewell, "Vertical-cavity surface-emitting InGaAs/GaAs lasers with planar lateral definition", *Appl. Phys. Lett*, vol. 56, pp. 2384–2386, 1990.

[4] M. Ortsiefer, W. Hofmann, J. Rosskopf, and M.C. Amann, “Long-Wavelength VCSELs with Buried Tunnel Junction”, Chap. 10 in *VCSELs*, R. Michalzik (Ed.), pp. 321–351, Berlin: Springer-Verlag, 2013.

[5] D.L. Huffaker, D.G. Deppe, K. Kumar, and T.J. Rogers, “Native-oxide defined ring contact for low threshold vertical-cavity lasers”, *Appl. Phys. Lett.*, vol. 65, pp. 97–99, 1994.

[6] B.M. Hawkins, R.A. Hawthorne III, J.K. Guenter, J.A. Tatum, and J.R. Biard, “Reliability of various size oxide aperture VCSELs”, in Proc. *52nd Electron. Comp. and Technol. Conf., ECTC 2002*, pp. 540–550. San Diego, CA, USA, May 2002.

[7] S. Bader, P. Gerlach, and R. Michalzik, “Optically controlled current confinement in vertical-cavity surface-emitting lasers”, *IEEE Photon. Technol. Lett.*, vol. 28, pp. 1309–1312, 2016