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# First vertical-cavity surface-emitting laser made entirely in Poland

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**Abstract.** The paper presents the first vertical-cavity surface-emitting lasers (VCSELs) designed, grown, processed and evaluated entirely in Poland. The lasers emit at ∼850 nm, which is the most commonly used wavelength for short-reach ($<2$ km) optical data communication across multiple-mode optical fiber. Our devices present state-of-the-art electrical and optical parameters, e.g. high room-temperature maximum optical powers of over 5 mW, laser emission at heat-sink temperatures up to at least 95°C, low threshold current densities ($<10$ kA/cm$^2$) and wall-plug efficiencies exceeding 30% VCSELs can also be easily adjusted to reach emission wavelengths of around 780 to 1090 nm.

**Key words:** semiconductor laser; GaAs; optical communication; VCSEL.

## 1. Introduction

Semiconductor lasers are one of the numerous sources of coherent radiation currently available. First semiconductor lasers were presented in 1962 by several research laboratories [1–4]. However, these early prototypes had unsatisfactory operating parameters. In the early seventies, first room-temperature (RT), continuous-wave (CW) semiconductor lasers were produced, employing a heterostructure design. These edge-emitting structures were relatively easy to manufacture, and have found a very wide variety of applications in science and technology [5]. Nonetheless, in some respects their properties remain limited, as they emit highly divergent output beams and produce many longitudinal modes. External conditions can also have a considerable impact on their operation.

## 2. Vertical-cavity surface-emitting lasers

The disadvantages of edge-emitting semiconductor lasers (EELs) have encouraged researchers to consider surface-emitting semiconductor lasing devices known as vertical-cavity surface-emitting lasers (VCSELs). Numerous research groups contributed to the development of what is known as a VCSEL today [6]. In 1965, Melngailis reported on a p-n junction laser diode emitting radiation from the surface [7]. In 1974, Dingle et al. demonstrated emission from GaAs quantum wells (QWs) [8]. In 1975, van der Ziel et al. demonstrated lasing from multiple optically pumped GaAs/AlGaAs QWs [9]. In the same year, van der Ziel and Ilegems put forward the idea of using distributed Bragg reflectors (DBRs) as mirrors [10]. In 1975, Scifres et al. presented a surface-emitting distributed feedback laser [11], and in 1976, Scifres and Burnham presented an electrically pumped diode laser with alternating AlGaAs/GaAs DBRs [12]. In 1979, Soda et al. demonstrated a device working at 77 K, which is seen by many the first electrically driven pulse-emitting VCSEL [13]. The works of Ogura et al. in 1983–1985 contributed to further significant development of VCSELs [14–16]. The first RT CW VCSEL (threshold current of 32 mA) fabricated using a GaAlAs/GaAs heterostructure grown on a GaAs substrate, was demonstrated in 1988 by Koyama et al. [17]. Following these achievements, VCSELs have been continuously developed by many research groups and today they constitute very efficient and affordable devices.

A schematic image of a VCSEL made within GaAs-based technology is presented in Fig. 1. The optical length of the VC-

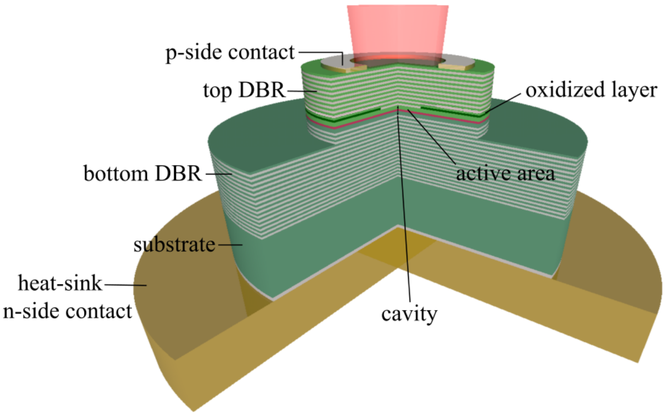

Fig. 1. Scheme of a typical structure for a modern cylindrically symmetric VCSEL

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SEL cavity containing the active area is extremely short, on the order of the lasing wavelength. Typically, a VCSEL is terminated on each side by DBR mirrors, with reflection coefficients close to 1. The driving current is injected through the electrical p-side and n-side metal contacts. The path of the current is directed by one or more electrical apertures, which are usually created using partly oxidized AlGaAs high-resistivity layers containing about 98% AlAs. The whole laser structure is grown on a GaAs substrate and is soldered to a heat-sink.

The main challenge when designing and producing any semiconductor laser is to tune in together three wavelength-dependent laser characteristics: active-layer gain, reflectivity of the DBRs and longitudinal resonance inside the laser cavity. These three spectral characteristics combine to produce the desired emission wavelength.

**2.1. VCSEL applications.** For many years, VCSELs remained overshadowed by the more common edge-emitting semiconductor lasers. An EEL can emit multiple times more output power than a typical VCSEL, which is important for many applications. More recently, however, new uses for lasers have emerged for which the relatively low output power of VCSELs is not a disadvantage. Indeed, in many such applications the advantages of VCSELs have become more crucial. The advantages of VCSELs include their small size, minimum power consumption (from a few to several dozen milliwatts), and distinctly less divergent output beam, as well as the fact that they are easily coupled with a fiber and can be used to create two-dimensional laser arrays. By 2017, the value of the VCSEL market had increased to over USD 700 million, and according to predictions made in 2019, it may reach over USD 3.5 billion by 2024 [18].

The first widespread application of VCSELs was in laser computer mice. VCSELs are now used as emitters in optical systems [19] for short-range data transfer between computers in data centers and between supercomputer nodes. Another developing market is in automotive lighting systems. Such lighting systems employ two-dimensional VCSEL arrays, since they are able to emit very high output powers despite the relatively low emission power of each individual VCSEL [20]. The most important current application of VCSELs, however, is in smartphones, where they are used in face-recognition systems [21] and as proximity sensors. In the future, VCSELs could also be used in LIDAR systems [22] for autonomous vehicles and in gesture-recognition systems, as well as in other applications, some as yet unimagined. The vast majority of current applications use VCSELs emitting infrared radiation. This is because there are well-developed and relatively straightforward methods for the fabrication of VCSELs based on AIIIAs compounds. Anticipated improvements in the fabrication of VCSELs based on other materials, however, could result in VCSELs emitting in the ultraviolet (UV), visible or deeper IR regions. This would further expand the range of potential applications. Nonetheless, it should be remembered that VCSELs have a much more complicated structure than edge-emitters, as they consist of several different materials. Thus, the production of commercially viable VCSELs presents a serious challenge.

## 3. Electrically-driven semiconductor lasers in Poland

In Poland, the development of electrically-driven semiconductor lasers has been limited almost exclusively to edge-emitting lasers. The first Polish semiconductor laser was produced in 1966 by Professor Bohdan Mroziewicz at the Institute of Fundamental Technological Research, Polish Academy of Sciences (IPPT PAN) [23]. This was only four years after first such devices had been presented to the world. Research on semiconductor lasers based on GaAs was continued at the Institute of Electron Technology (ITE) by the group under Professor Mroziewicz, followed by Professor Bugajski, as well as by a team led by Professor Maląg at the Institute of Electronic Materials Technology. On 12 December 2001, only five years after the first demonstration to the world by Shuji Nakamura from Nichia Chemicals and very shortly after the first European demonstration by Osram Opto Semiconductors GmbH (Regensburg, Germany), a blue-emitting EEL, based on gallium nitride, was produced in Poland at the Institute of High Pressure Physics, by a group of researchers led by Professor Sylwester Porowski [24]. In 2004, at ITE, M. Bugajski and his coworkers began research on another very advanced type of an edge-emitting laser, namely quantum-cascade lasers. In 2009, the first Polish quantum cascade laser was presented [25].

Despite these achievements, only very recently did researchers in Poland attempt to fabricate VCSELs. The most similar devices that had been fabricated up to that point in Poland were resonant-cavity light-emitting diodes, by Muszalski at ITE in 2000 [26]. This paper presents the first Polish VCSEL, which was built in 2020. The laser emits radiation from the first telecommunication window (around 850 nm).

## 4. Technical details

The VCSEL design and the processing steps presented here were developed by the Photonics Group at the Institute of Physics, Lodz University of Technology, in collaboration with Vigo System S.A. The VCSEL structure was grown on an $n^+$-GaAs substrate doped with silicon, on which the first 1500 nm buffer GaAs layer was deposited, also doped with silicon. Next, 35.5 alternating pairs of $\mathrm{Al_{0.9}Ga_{0.1}As}$ and $\mathrm{Al_{0.2}Ga_{0.8}As}$ layers (each doped with silicon up to $2 \cdot 10^{18}\ \mathrm{cm}^{-3}$) were grown with thicknesses of 48.6 nm and 43.1 nm, separated by gradient layers, creating the bottom DBR mirror. In the gradient layers, the Al composition changes linearly, making a continuous transition between the adjacent layers. The 20 nm-thick graded layers were linearly graded from $\mathrm{Al_{0.9}Ga_{0.1}As}$ to $\mathrm{Al_{0.2}Ga_{0.8}As}$ or vice versa with n-doping concentrations of $2 \cdot 10^{18}\ \mathrm{cm}^{-3}$ or $4 \cdot 10^{18}\ \mathrm{cm}^{-3}$, respectively. Carrier concentrations were measured using the Hall method, as well as both the ECV and SIMS methods. The last $\mathrm{Al_{0.9}Ga_{0.1}As}$ layer of the bottom DBR was covered with a 119 nm-thick gradient $\mathrm{Al_{0.9}Ga_{0.1}As/Al_{0.4}Ga_{0.6}As}$ layer of linearly changing composition. Its lower 71.4 nm part was doped with silicon up to the $2 \cdot 10^{18}\ \mathrm{cm}^{-3}$ level, but the remaining 47.6 nm part is undoped. The 1-$\lambda$ (optically thick) laser active cavity is composed of five 3.4 nm $\mathrm{In_{0.11}Ga_{0.89}As}$ quantum wells separated by four 6.8 nm $\mathrm{Al_{0.4}Ga_{0.6}As}$ barriers. It is covered with a 119 nm $\mathrm{Al_{0.4}Ga_{0.6}As/Al_{0.8}Ga_{0.2}As}$ layer of linearly changing composition. The 59.5 nm part closer to the active area is undoped, but its remaining 59.5 nm part is doped with carbon (p-type doping) up to the $2 \cdot 10^{18}$ cm$^{-3}$ level.

The p-doped gradient layer is terminated with a 50 nm $\mathrm{Al_{0.8}Ga_{0.2}As}$ layer doped with carbon up to the $2 \cdot 10^{18}$ cm$^{-3}$ level, over which a 15 nm $\mathrm{Al_{0.98}Ga_{0.02}As}$ layer doped with carbon up to the $2 \cdot 10^{18}$ cm$^{-3}$ level was deposited. This layer was selectively oxidized to create an electrical aperture. Subsequently, a 10 nm $\mathrm{Al_{0.8}Ga_{0.2}As}$ layer, a 20 nm linearly grading $\mathrm{Al_{0.8}Ga_{0.2}As/Al_{0.2}Ga_{0.8}As}$ layer, a 15.6 nm $\mathrm{Al_{0.2}Ga_{0.8}As}$ layer, a 20 nm linearly grading $\mathrm{Al_{0.2}Ga_{0.8}As/Al_{0.9}Ga_{0.1}As}$ layer, and a 48.6 nm $\mathrm{Al_{0.9}Ga_{0.1}As}$ layer were deposited sequentially, all doped with carbon up to the $2 \cdot 10^{18}$ cm$^{-3}$ level. Next, 17 alternating pairs of 43.1 nm $\mathrm{Al_{0.2}Ga_{0.8}As}$ layers and 48.6 nm $\mathrm{Al_{0.9}Ga_{0.1}As}$ layers (each doped with carbon up to the $2 \cdot 10^{18}$ cm$^{-3}$ level) were deposited, creating the upper DBR mirror. These were separated by $\mathrm{Al_{0.2}Ga_{0.8}As/Al_{0.9}Ga_{0.1}As}$ and $\mathrm{Al_{0.9}Ga_{0.1}As/Al_{0.2}Ga_{0.8}As}$ layers of linearly changing composition, doped with carbon at levels from $2 \cdot 10^{18}$ cm$^{-3}$ to $4 \cdot 10^{18}$ cm$^{-3}$. The upper DBR mirror is terminated with a 60 nm $\mathrm{Al_{0.9}Ga_{0.1}As/GaAs}$ layer of linearly changing composition, doped with carbon up to the level of $4 \cdot 10^{18}$ cm$^{-3}$, and with an 50 nm cap GaAs layer doped with zinc up to the ~$1 \cdot 10^{20}$ cm$^{-3}$ level.

The epitaxial VCSEL structures were manufactured by Vigo S.A. using the metal-organic chemical-vapor deposition (MOCVD) method, with an AIX 2800 G4 Aixtron reactor enabling growth in $12 \times 2'', 3'', 4''$ or $8 \times 6''$ configurations. Oriented $3''$ (100) GaAs substrates were applied. Growth was controlled in-situ using LayTec GmbH (Berlin, Germany) equipment. Use of double gas lines for the metal-organic precursor gases, trimethylaluminum (TMAl) and trimethylgallium (TMGa), enabled precise control of chemical composition of the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ layers, with spatial resolution on the order of nanometers. A mixture of 200 ppm of $\mathrm{SiH_4}$ in $\mathrm{H_2}$ was used for n doping and $\mathrm{CBr_4}$ and DEZn were used for p doping. Growth took place at constant 700°C inside the reactor with an inductive heating system using hydrogen as the carrier gas. Parameters of the epi-structures were characterized using the Hall method, X-ray diffraction (XRD), photoluminescence (PL), scanning electron microscopy (SEM), transmission electron microscopy (TEM), secondary ion mass spectrometry (SIMS), optical power reflection, electrochemical capacitance-voltage (ECV), and an optical microscope with Nomarski contrast. Under optimized growth conditions, it was possible to control the thicknesses of the layers with an accuracy on the order of 1 nm, with very good homogeneity and repeatability.

Subsequent wafer processing to produce VCSELs was carried out by both Vigo System S.A. and the Photonics Group at the Lodz University of Technology. The upper p-side annular Ti/Pt/Au contact was sputtered onto the upper surface of the wafer. Next, the mesa structures of 45 to 55 nm in diameter were etched in $\mathrm{Cl_2/BCl_3}$ plasma by means of inductively-coupled-plasma reactive-ion etching (ICP-RIE). The etching was stopped below the active layer. The outside part of the $\mathrm{Al_{0.98}Ga_{0.02}As}$ layer uncovered by the etching was oxidized at 420°C at 50 mbar using a mixture of water vapor and nitrogen, transforming it into highly resistive material commonly denoted as $\mathrm{Al}_x\mathrm{O}_y$ [27]. The oxidation time was selected in such a manner that an adequate part of the non-oxidized $\mathrm{Al_{0.98}Ga_{0.02}As}$ layer remained in the central part of the mesa. A uniform n-type $\mathrm{Ni/Au_{0.88}Ge_{0.12}/Au}$ contact was deposited on the bottom surface of the substrate and then annealed for one minute at 420°C in a nitrogen atmosphere. The sample top surface was then covered with a light-sensitive benzocyclobutene polymer (BCB) to create an even surface, enabling deposition of the top contact pad. In the final step, the 100 µm × 100 µm contact pads were deposited together with paths joining them with the upper laser contact. Figure 2 shows a photograph of the surface of one of the VCSELs.

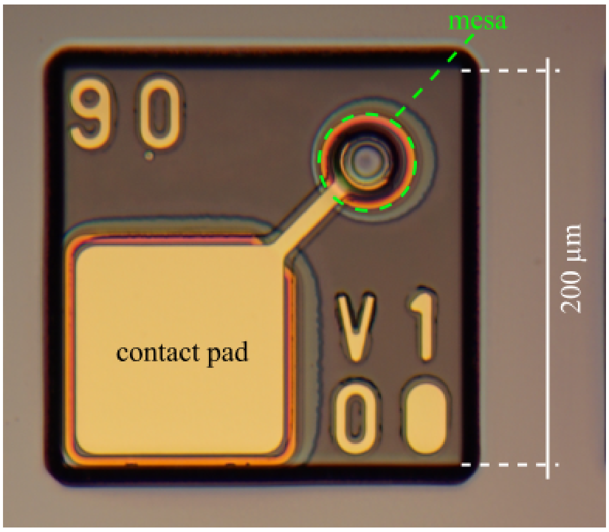

Fig. 2. Upper surface of one of the VCSELs fabricated, with dimensions and descriptive labels

## 5. Laser characterization

Characterization of the laser structures was carried out at the laboratory of the Photonics Group at the Lodz University of Technology. Measurements were performed on the wafer, i.e. before the wafer was thinned and diced into individual lasers. The possibility of characterizing individual lasers at this stage is a considerable advantage of VCSELs. An example emission spectrum for a VCSEL with an oxide aperture diameter of around 3.5 µm, at 25°C and for a current of 2 mA is shown in Fig. 3. The side-mode suppression ratio (SMSR) is 25 dB.

Example experimental optical-power $P$ versus operation current $I$ curves are shown in Fig. 4a, for a VCSEL with an electrical aperture diameter of around 4 µm and for laser heat-sink at temperatures of between 15°C and 95°C. It is important to note that the measured laser operated stably at an ambient temperature of up to 95°C, whereas in most commercial applications 85°C is considered the highest operating temperature. The VC-

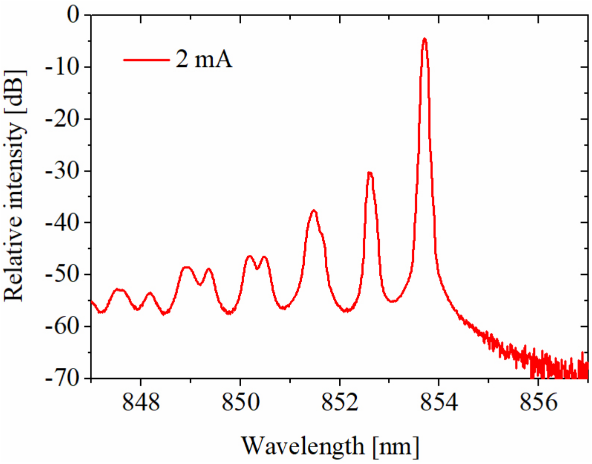

Fig. 3. Measured emission spectrum at 25°C for a VCSEL with an electrical aperture diameter of around 3.5 μm

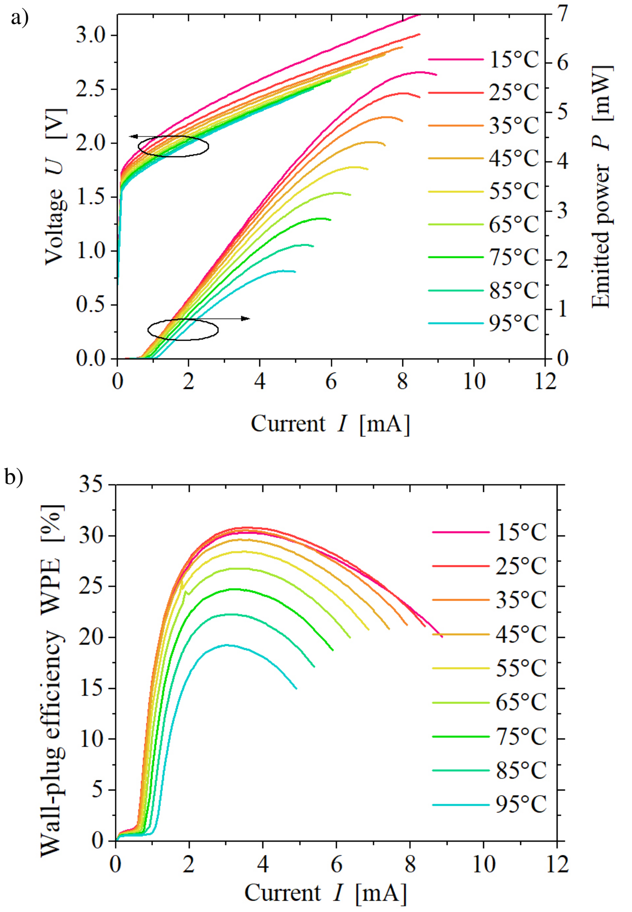

Fig. 4. Measured dependencies on the operating current $I$ of: a) optical power $P$ and voltage $V$; b) wall-plug efficiency WPE, for a VCSEL with an electrical aperture diameter of about 4 μm and laser heat-sink temperatures rising from 15°C to 95°C

SEL wall-plug efficiency was the highest, at slightly over 30%, for operating currents of between 2 mA and 4 mA and at operating temperatures of between 15°C and 25°C. It then decreased with temperature to around 18% at 95°C.

Figure 5 presents two curves versus temperature: (a) threshold current; and (b) maximum optical output power. The first curve can be used to estimate the alignment between the peak of the optical gain spectrum and the cavity resonance wavelength. Because of the temperature dependencies of the refractive indices of the cavity materials, as the heat-sink temperature increases, the resonance wavelength is shifted towards higher wavelengths at a rate of 0.04–0.06 nm/K. The maximum optical gain is also shifted in the same direction, but at a much higher rate. As a result, if the VCSEL resonator is detuned at room temperature towards longer wavelengths relative to the gain peak, the gap between the two values is steadily reduced at higher temperatures (followed by a decrease in the threshold current), until both values overlap at a certain temperature. At higher temperatures, threshold current increases again, because of the gradual detuning of the VCSEL optical gain and the cavity resonance peak. This behavior can be observed in Fig. 5a. The lowest threshold current was measured for heat-sink temperature of 35–45°C. The decrease in maximum output power with temperature shown in Fig. 5b is almost linear.

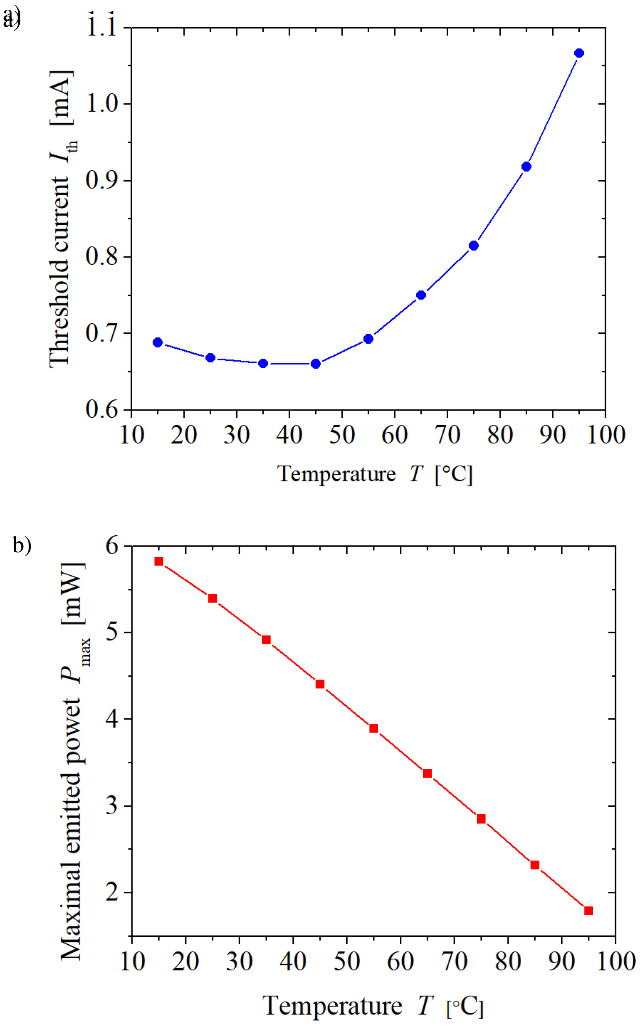

Fig. 5. Dependencies Maximum emitted power on the heat-sink temperature $T$ of the threshold current $I_{th}$ (a) and the maximum output power $P_{max}$ (b) of a VCSEL with a 4 μm electrical aperture diameter

Because of their relatively short one-wavelength optical cavities, our VCSELs emit single-longitudinal-mode radiation. However, with larger device apertures, higher-order lateral modes, beside the fundamental Gaussian modes, may be excited. Figure 6 shows one such higher-order $LP_{21}$ lateral mode, in a VCSEL with an ~7 µm aperture supplied with a current of 8 mA at heat-sink temperature of 25°C. With oxide aperture diameters not larger than ~3 µm, the radiation of a typical VCSEL emitting at ~850 nm comprises a single lateral Gaussian mode for all supplied currents. With larger apertures, the laser can emit single-lateral-mode radiation only for low operation currents (just over the lasing threshold), and it emits many lateral modes for higher currents. With very large apertures, the VCSEL emits radiation containing many lateral modes, even just over the lasing threshold.

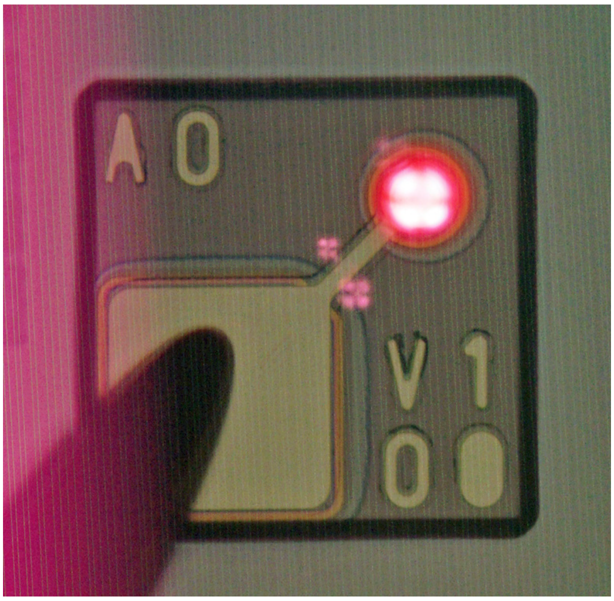

Fig. 6. Picture of a higher-order laser mode excited in a VCSEL with a ~7 µm electrical aperture diameter at an operating current of 8 mA and with heat-sink temperature of 25°C. The tip of a needle is visible, connecting the contact pad with a positive supply potential

## 6. Conclusions

This paper has presented 850-nm VCSELs designed, manufactured and evaluated entirely in Poland. The threshold current densities of the devices are low (below 10 kA/cm$^2$). They emit high power radiation even at temperatures above 85°C and reach over 30% efficiency. These parameters exceed the typical requirements for commercial VCSELs [28]. VCSELs emitting IR radiation of wavelengths of up to around 1 µm, manufactured using the same arsenide technology have been demonstrated by many groups [29–31]. We believe that our technology and experience enable us to create world-standard VCSELs of various types, emitting in the near-infrared region. Work is ongoing to further develop this technology to meet the challenges of the future.

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