Bottom-Emitting VCSEL Arrays for Integrated Optical Particle Manipulation

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The purely optical manipulation of particles has gained increasing interest in recent years. Especially the combination of optical manipulation with microfluidics offers new possibilities, such as the contamination-free handling of micrometer-sized particles in biology and medicine without any mechanical contact. VCSELs (vertical-cavity surface-emitting lasers) are an excellent choice for optical trapping laser sources, offering the formation of two-dimensional arrays for parallel particle manipulation. Furthermore, they enable miniaturization by means of integration. In this report, we present a new concept for the realization of a so-called integrated optical trap. For this purpose, bottom-emitting AlGaAs–GaAs-based VCSEL arrays with a very small device pitch were fabricated and densely integrated with microfluidic channels.

1. Introduction

In 1970, Arthur Ashkin [1] reported the acceleration of particles by the radiation pressure of a laser beam, commonly called scattering force. Furthermore, he discovered an additional force which pulled the particles towards the laser beam center. Assuming a laser beam with a transverse (ideally Gaussian) intensity gradient, this effect can conveniently be explained by means of ray optics. All rays incident on a spherical particle are refracted and cause forces because of their change in momentum. The resulting net force points towards the maximum of intensity and is commonly called gradient force [2]. It increases with a stronger intensity gradient and is exploited in so-called optical traps which are useful tools for the manipulation of micrometer-sized particles. Optical manipulation offers the possibility of handling biological material without mechanical damage or contamination [3].

Microfluidic channels with widths and heights of typically several tens of micrometers enable the examination of biological samples with strongly reduced sample volumes, parallel cycling and exact timing [4, 5]. The combination of microfluidics and purely optical manipulation enables the non-mechanical handling of particles inside the channels [6, 7]. VCSELs are highly suitable for this field and have been investigated as trapping lasers in microfluidic channels [7–12]. One advantage of very common 850 nm VCSELs is their emission in the near-infrared range, where biological material has only little absorption. The vertical emission of VCSELs allows the fabrication of two-dimensional laser arrangements (arrays). Thus, patterns of multiple optical traps (or optical lattices) can be generated without the need for extensive beam splitting or steering setups. Besides the use of

VCSELs in a classical tweezers setup with objective lenses for beam collimation and focusing, even a strongly miniaturized setup can be realized by directly integrating VCSEL arrays and microfluidic channels. Thus, a portable, low-cost particle manipulation device is feasible, whereas one can hardly imagine the realization of similar integrated modules with other laser sources.

2. Bottom-Emitting VCSEL Arrays as Laser Sources for Optical Manipulation

VCSELs can be realized as top or bottom emitters. The schematic structure of a bottom-emitting VCSEL is depicted in Fig. 1. It is grown in the AlGaAs material system using molecular beam epitaxy, with a composition designed for an emission wavelength of around 850 nm. The laser resonator is built by distributed Bragg reflectors (DBRs). Top and bottom DBR are p- and n-doped, respectively, to achieve a p–i–n-like structure with an intrinsic active region. The bottom DBR has a reduced number of mirror pairs compared to the p-type DBR as this is the light outcoupling side of the VCSEL. The p-contacts are structured as full metal circles, in contrast to top-emitting VCSELs, where ring contacts are required. Such a full contact allows to reduce the mesa diameter and the device pitch in an array. The active region in the inner cavity consists of three 8 nm thick GaAs quantum wells, separated by 10 nm thick barriers. An AlGaAs layer with about 98 % aluminum content located above the active region is selectively oxidized after mesa etching, thus providing current confinement.

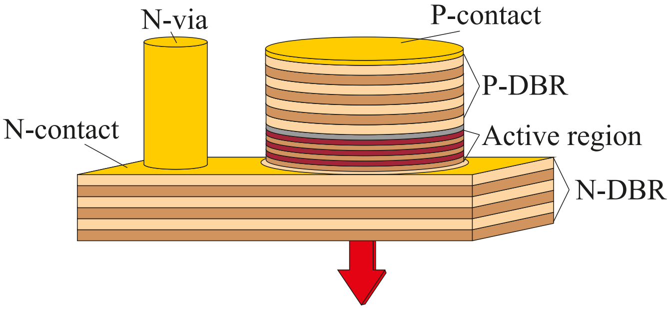

Fig. 1: Schematic of a bottom-emitting VCSEL structure with removed substrate and an n-via for flip-chip soldering.

Because VCSELs offer the advantageous possibility of creating various two-dimensional arrays, it is very obvious to realize patterns of optical traps, so-called optical lattices. They are based on the following principle [13, 14]: particles in liquid solution pass the optical trap array or optical lattice and are attracted to the beam centers of the individual lasers. If trapping force and fluidic drag force are in the same range, the particle can follow the lattice and is thus continuously deflected from its initial flow direction. By using two optical lattices and a microfluidic Y-junction, as indicated in Fig. 2, particles can be separated without mechanical or electrical intervention.

An ultra-dense spacing of the VCSELs is highly desirable for such optical lattices and a challenging requirement. The typical device pitch of commercial VCSELs for data

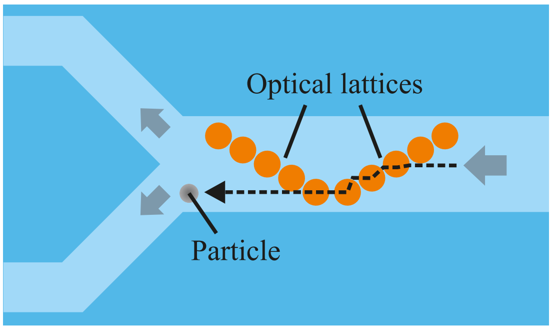

Fig. 2: Schematic particle separation by means of two optical lattices and a fluidic Y-junction.

communication applications is 250 µm [15]. For interruption-free optical manipulation this value needs to be reduced at least by an order of magnitude. Such a drastic reduction requires not only a minimized distance of about 2 µm between adjacent mesas but also reduced mesa diameters. As mentioned above, the full circle p-contact of bottom-emitting VCSELs helps to shrink the laser cross-section. The mesa diameters of the fabricated devices range from 16 to 20 µm, leading to device pitches from 18 to 22 µm.

3. Miniaturized Particle Deflection by an Integrated Optical Trap Concept

By means of tilted linear VCSEL arrays in a classical tweezers setup with objective lenses for beam forming, the continuous deflection of particles in aqueous solution was already demonstrated [16]. However, this setup is bulky and requires extensive alignment.

The so-called integrated optical trap represents a strongly miniaturized version of the classical tweezers setup where objective lenses are avoided. The trapping laser module with VCSEL arrays is directly integrated with the microfluidic chip. For an efficient particle deflection with the integrated optical lattice, the distance between microfluidic channel and trapping laser arrays must be minimized to reduce the beam expansion.

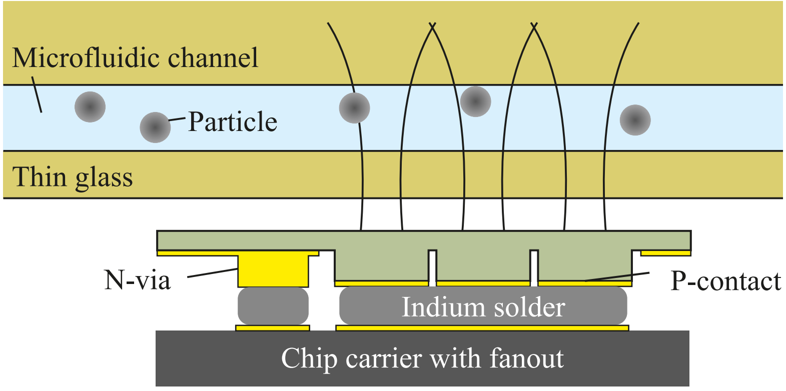

Fig. 3: Schematic of the novel integrated optical trap module. The bottom-emitting VCSEL chip is flip-chip soldered to a chip carrier and integrated with the microfluidic chip with a few micrometers distance.

Our integration approach for such an optical trap module is shown in Fig. 3. The flip-chip soldered laser chip with bottom-emitting VCSEL arrays is integrated with the microfluidic chip with a distance of only a few micrometers. Thus, the use of external optics can be avoided. By indium solder bumps, the laser chip is electrically connected to the chip carrier, where fanout tracks enable easy access to the electrical contacts after integration.

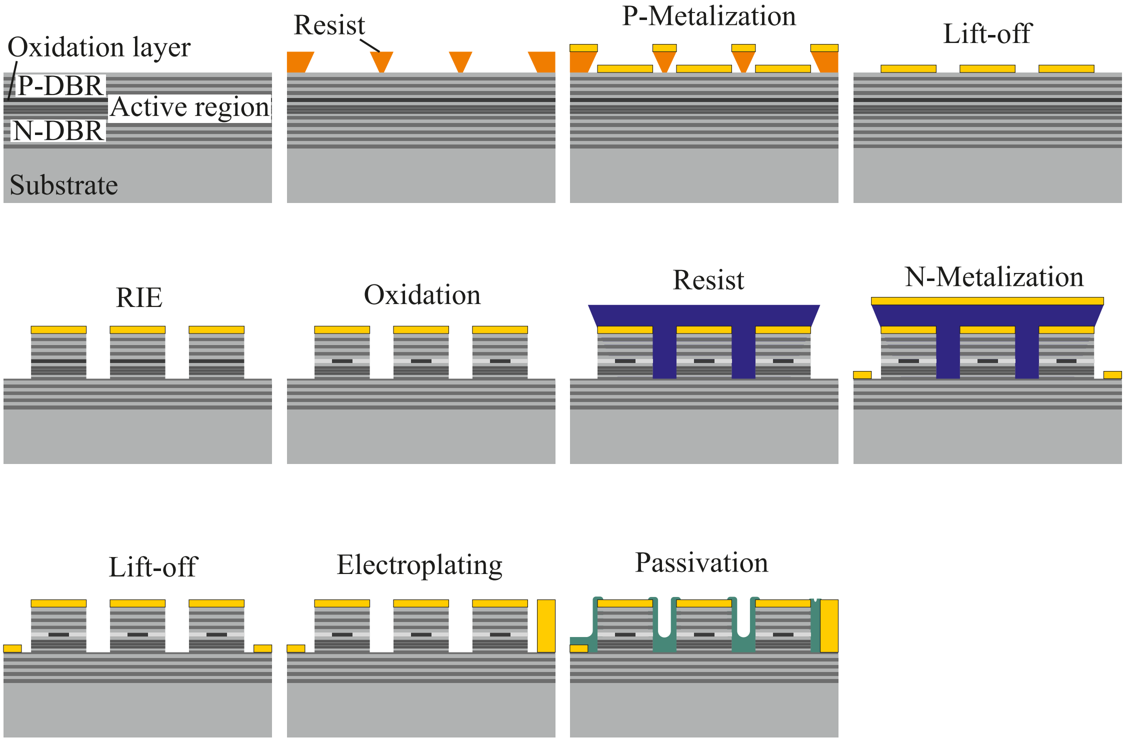

Fig. 4: Processing steps for the fabrication of densely packed bottom-emitting VCSEL arrays. Reactive-ion etching provides for vertical side walls needed for close spacing.

The processing steps for densely packed bottom-emitting VCSEL arrays are shown in Fig. 4. In the first step, the p-contacts are defined by photolithography, metal evaporation and lift-off. After that, the VCSEL mesas are defined by reactive-ion etching (RIE), where the metal of the p-contact serves as a stable etch mask. After etching, the oxidation layer is selectively oxidized by water vapor, with nitrogen as carrier gas. In the next step, the lasers are covered completely with photoresist and the etched region around the lasers is metalized. Close to the laser arrays, n-vias with the same height as the laser mesas are generated by electroplating. Thus, it is possible to solder the laser chips stably to the chip carriers. The fabrication of these carriers is shown in Fig. 5. Silicon with a high resistivity ($\rho > 15\,\mathrm{k\Omega cm}$) and 380 µm thickness is covered with a 100 nm thick layer of Al_2O_3 to improve the electrical isolation. After that, fanout tracks are defined by lithography, metal evaporation and lift-off. The fanout metal is then electroplated to a thickness of approximately 2 µm. In the last step, indium bumps are structured to build the solder connection to the laser arrays and the n-vias on the laser chip.

Laser chip and carrier are combined by flip-chip soldering (Fig. 5), where the two components can be carefully aligned to each other. The melting indium creates both the electri-

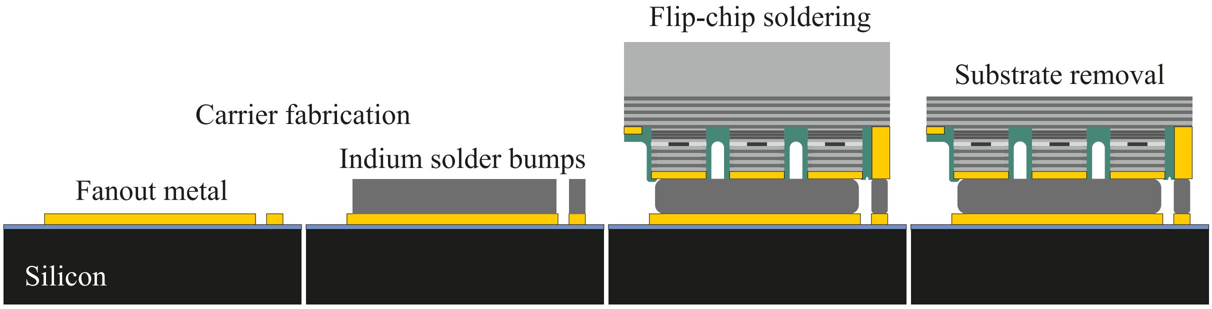

Fig. 5: Fabrication of silicon laser chip carriers with fanout tracks and indium solder bumps. By flip-chip soldering, laser chip and chip carrier are combined. Finally, the substrate on the back side of the laser chip is removed.

cal and mechanical connection. For a minimized distance between lasers and microfluidic channel, the substrate is wet-chemically removed. Thus, absorption of the 850 nm laser emission in the substrate is avoided as well. After substrate removal, the remaining structure is only a few micrometers thin. Figure 6 shows a microscope picture of an etched laser chip. The VCSEL arrays shine through the thin semiconductor material. At the corners of the laser chip, the n-vias are also visible.

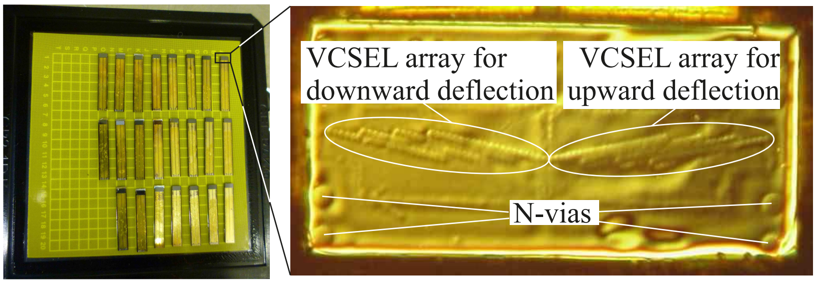

Fig. 6: Laser arrays at the tip of chip carriers in a sample box (left) and micrograph of a soldered laser chip with removed substrate (right). Both laser arrays and n-vias shine through the thin remaining semiconductor material.

The microfluidic channels are fabricated in polydimethylsiloxane (PDMS), a transparent and biocompatible polymer widely used for the manufacture of microfluidic chips [17]. In the first step, master wafers are fabricated which contain the inverse channel structures. A PDMS base (liquid) is mixed with a cross-linking agent and poured over the master wafer. The PDMS is then cured at 65°C and can be peeled off the reusable master wafer. Inlets from the top of the chip are created. By short exposure to an oxygen plasma, the channel can be sealed irreversibly with 30 µm thin glass.

For integration, laser arrays on the carrier and microfluidic channel are carefully aligned to each other. Observation during alignment is possible through the transparent microfluidic chip. For good adjustment, the laser chip can be moved in x-,y-, and z-directions, whereas the microfluidic chip can be rotated to adjust the tilt of the samples. After alignment, the components are fixed by an adhesive which is cured by ultraviolet light. A printed circuit board serves as the device platform and facilitates the handling.

4. Particle Experiments

The integrated VCSEL-based module described above was used for particle deflection. For this purpose, the microfluidic channel was filled with 15 µm polystyrene particles solved in water. Figure 7 shows snapshots of the experiment. The very left picture depicts the position of the lasers relative to the channel. Here, they were operated below threshold to make them visible. During the experiment, the laser power inside the channel was about 2.5 mW per laser with 25 lasers in total. Flow direction was from right to left. As the particle approached the lasers, it was attracted by the laser beams and at the same time pulled forward by the fluidic drag force. Thus, it was stepwise redirected from the channel center to the side wall of the 60 µm wide channel. Such deflection experiments have also been performed with other particle diameters to prove the flexible use of the device.

Fig. 7: Deflection experiment with a 15 µm polystyrene particle inside a microfluidic channel. The particle is stepwise redirected by the VCSELs in the array.

5. Conclusion

In this report we introduced bottom-emitting VCSEL arrays as excellent laser sources for combination with microfluidic channels. Owing to circular beam profiles, low power consumption, and arrangement in two-dimensional arrays, VCSELs are highly suitable for this purpose. By using VCSEL arrays as sources for optical trap patterns, continuous particle deflection becomes possible. We have shown our new approach for the integration of bottom-emitting VCSEL arrays with microfluidic channels, thus enabling miniaturized particle manipulation in compact, portable devices. We presented the fabrication of all necessary components as well as their integration. Finally, a particle manipulation experiment with an integrated particle deflection device was presented using 15 µm diameter polystyrene particles.

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