

Optical Particle Manipulation by Application-Specific Densely Packed VCSEL Arrays

Andrea Kroner

Densely packed arrays of vertical-cavity surface-emitting lasers (VCSELs) are presented, serving as low-cost and small-sized laser sources in optical particle manipulation systems. A novel, self-aligned fabrication process enables both a pitch in the 20 μm range and a selective surface etch for enhanced transverse single-mode emission. Homogeneous array performance and single-mode output powers of up to 3.8 mW are observed. By inserting the arrays into an optical tweezers setup with external optics, multiple optical traps are easily created. Non-mechanical particle translation by switching between individually addressable devices as well as continuous particle deflection in a one-dimensional optical lattice are demonstrated.

1. Introduction

Optical particle manipulation by focused laser beams has become a key technology in biophotonics due to the possibility of damage- and contamination-free handling of microscopic biological material, such as living cells [1]. Here, the use of VCSELs as light sources has gained increasing interest owing to their high beam quality, low cost and small device dimensions [2–4]. Furthermore, VCSELs offer the unique possibility of a straightforward creation of multiple optical traps by using two-dimensional, monolithic laser arrays. Other methods, like holographic optical tweezers, are based on interference or splitting of a single laser beam and require expensive optics and critical adjustment [5]. With VCSEL-based multiple optical tweezers, simultaneous trapping of several cells was demonstrated [2], as well as stacking and non-mechanical translation of DNA bound to microbeads [3]. However, mainly standard VCSEL arrays designed for data communication have been applied so far, which have a large pitch of typically 250 μm and necessitate the use of additional microlens arrays. A different approach targets the drastic miniaturisation of the trapping setup by integrating a microlens directly on the VCSEL output facet, abandoning any external optics [4]. However, for this so-called integrated optical trap, the typical multimode output beam profile of VCSELs is inappropriate. The layout of densely packed VCSEL arrays for optical manipulation should therefore enhance transverse single-mode emission. This is efficiently achieved with the inverted surface relief technique, which uses a shallow, selective surface etch [4].

2. Fabrication

We have fabricated different two-dimensional arrangements of GaAs/AlGaAs-based top-emitting VCSELs with emission wavelengths in the 850 nm range. The inverted surface relief technique requires the upper p-doped mirror of the VCSEL structure to be terminated with an additional $\lambda/4$ -antiphase layer. By removing the layer selectively only in the centre of the output facet, the threshold gain of the transverse fundamental mode can be preferentially reduced, leading to enhanced single-mode emission. However, an exact overlap of the shallow relief and the active laser aperture is mandatory. Furthermore, aspired array pitches of about 20 μm and gaps of only 2 μm between the devices require steep, dry etched mesa sidewalls. Therefore, a novel fabrication process has been developed, based on multiple resist layers (Fig. 1). To achieve self-alignment, relief and p-contact ring are both structured within the first exposure step and are contained as openings in an otherwise closed layer of PMGI (polymethylglutarimide) resist (Fig. 1a). During wet etching of the surface relief, the p-contact area is protected by a novolak-based resist, requiring only low alignment accuracy (Fig. 1b). Afterwards, this layer can be selectively removed by acetone, thus restoring the initial resist structure (Fig. 1c). For p-contact metallisation, the relief is protected likewise and the subsequent lift-off step removes all resist layers (Fig. 1d-f). Finally, the VCSEL output facet is protected by resist and the p-contact metal serves as stable hard mask for reactive ion etching of the mesa (Fig. 1g-h), such that the following oxidation step leads to a self-aligned oxide aperture. On the left side of Fig. 2, a scanning electron microscope (SEM) image of an array with 24 μm pitch and 3.4 μm surface relief diameter is presented, showing almost vertical mesa edges and exact alignment of mesa, p-contact ring and surface relief. The process is completed by surface passivation and bondpad metallisation. The right side of Fig. 2 shows an optical microscope image of a finished array of standard top-emitting devices. Here, no relief is etched but the antiphase-layer is completely removed.

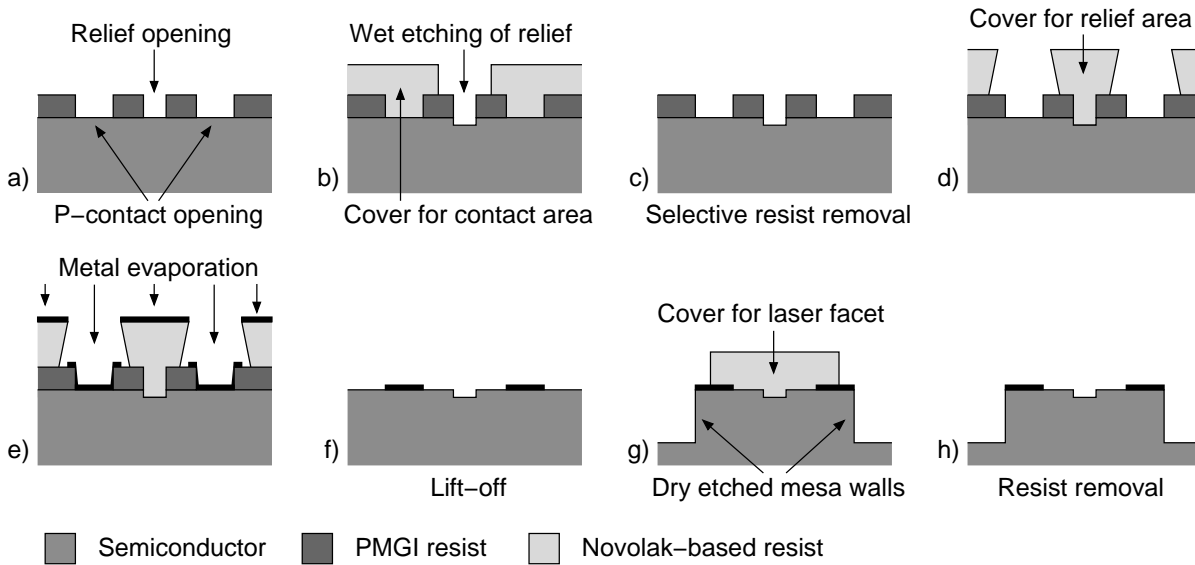


Fig. 1: Novel fabrication process to achieve self-alignment of relief, p-contact ring and mesa.

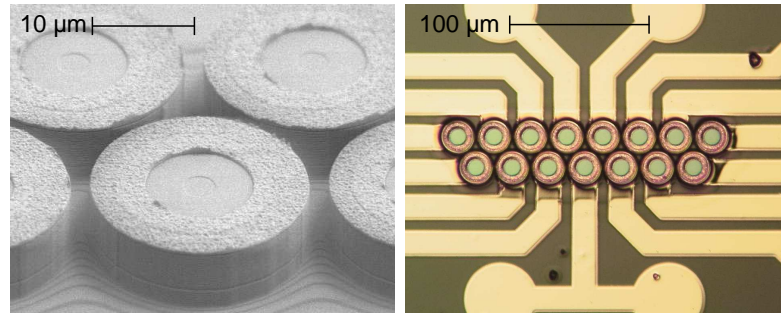


Fig. 2: SEM image (left) and optical microscope image (right) of densely packed VCSEL arrays with $2\ \mu\text{m}$ mesa gap.

3. Experimental Results

Figure 3 presents the operation characteristics of 15 individually addressable devices from a VCSEL array with $8\ \mu\text{m}$ diameter oxide apertures according to Fig. 2 (right). Threshold currents of around $1.6\ \text{mA}$ and maximum multimode output powers of about $8\ \text{mW}$ with only minor variations are observed. In the optical tweezers setup [4], the output beams of the lasers are tightly focused by an immersion objective with a high numerical aperture of 1.25, creating an individually addressable tweezers array in the sample stage with a pitch of about $5.5\ \mu\text{m}$. Figure 4 shows sequences of the experiment as top views on the sample stage, which contains polystyrene particles with a diameter of $10\ \mu\text{m}$ solved in water. A partial image of the VCSEL array can be seen, indicating the position of the optical tweezers. In Fig. 3a, the VCSEL in the lower left corner is emitting, trapping a particle in its beam with an optical power of about $2.1\ \text{mW}$ at the sample stage. When switching to an adjacent device, the sphere follows the maximum of light intensity (Figs. 4a–d). After $1.5\ \text{s}$, the particle is moved non-mechanically by about $16\ \mu\text{m}$ to the upper right trap of the array (Fig. 4d). Obviously, this scheme can be extended to laser arrays with a much higher number of elements.

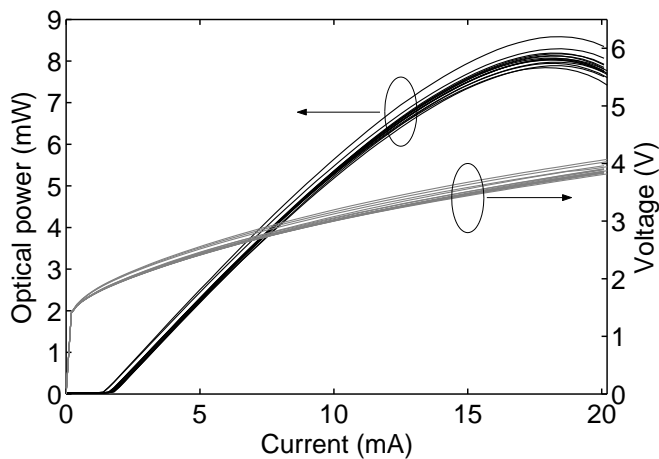


Fig. 3: Operation characteristics of an array containing 15 individual VCSELs without relief and an active diameter of $8\ \mu\text{m}$ (according to Fig. 2 (right)).

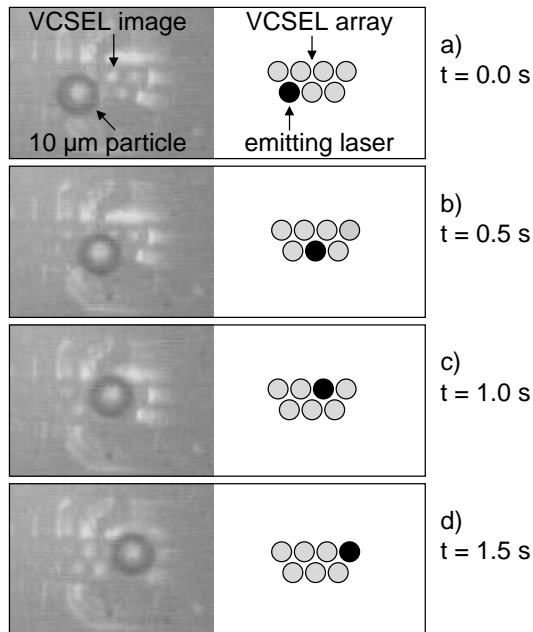


Fig. 4: Non-mechanical translation of a $10\ \mu\text{m}$ particle by switching between adjacent lasers. Sequences of the experiment are shown as top views on the sample stage (left) and schematically to highlight the emitting laser in the array (right).

Furthermore, the high-density arrays are employed for continuous optical particle deflection, which is of particular interest for particle handling and sorting in microfluidics. Here, a linear tweezers array is used to create a one-dimensional optical lattice. A particle passing the tilted lattice will not be stopped by a single trap, but piecewise deflected [6, 7]. Since an individual addressing of lasers is not required in this operation scheme, also arrays with devices connected in parallel were fabricated in order to decrease the number of contacts significantly. Figure 5 shows the light versus current curve of three jointly lasing devices, which have a $6\ \mu\text{m}$ wide oxide aperture and $3.4\ \mu\text{m}$ relief diameter. A mean threshold current of $1.7\ \text{mA}$ and a high maximum output power of $3.8\ \text{mW}$ per device can be deduced. Figure 6 presents the three optical spectra at thermal rollover, revealing single-mode emission with a side-mode suppression ratio above $30\ \text{dB}$ owing to the mode-selective effect of the surface relief. In Fig. 7, optical particle deflection using a similar array with six simultaneously emitting devices and an optical power of $6.4\ \text{mW}$ in the sample plane is demonstrated. For this purpose, the laser chip is again inserted as laser source into the optical tweezers setup and by tightly focusing the output beams with external optics, an optical lattice is created in the sample plane. A $10\ \mu\text{m}$ polystyrene microsphere is moved from left to right with a velocity of $25\ \mu\text{m}/\text{s}$ by a computer-controlled positioning system connected to the sample stage (Figs. 7a–b). While passing the optical lattice, the particle follows the 21° tilt of the array (Figs. 7b–e) and is eventually deflected by a total distance of about $18\ \mu\text{m}$ orthogonal to its initial flow direction (Fig. 7f). Beyond a certain maximum tilt of about 30° , which also depends on the particle velocity, deflection was no longer possible.

4. Conclusion

By using densely packed VCSEL arrangements, multiple optical tweezers are easily created in a straightforward manner. A novel fabrication process does overcome the limitations

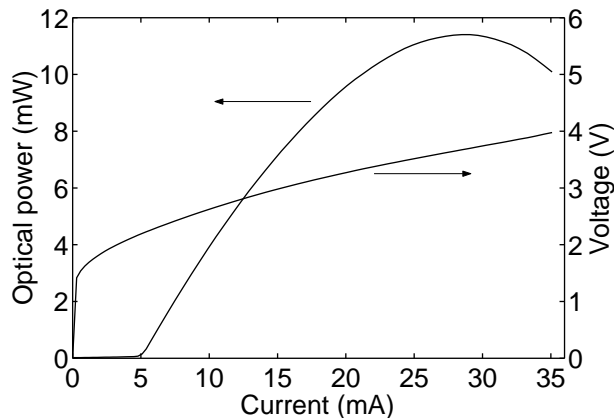


Fig. 5: Operation characteristics of three relief VCSELs driven in parallel with a $6\ \mu\text{m}$ wide oxide aperture and $3.4\ \mu\text{m}$ relief diameter.

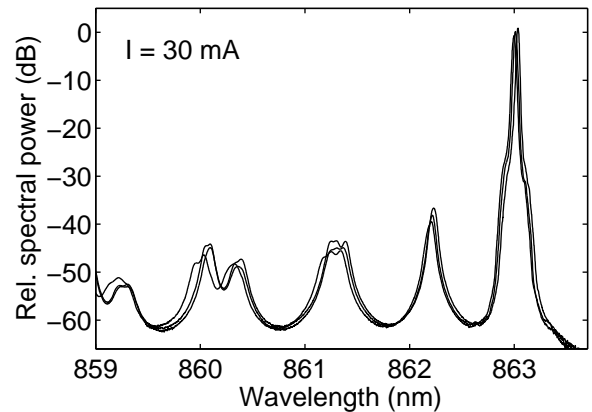


Fig. 6: Optical spectra of the three relief VCSELs presented in Fig. 5 at 30 mA driving current.

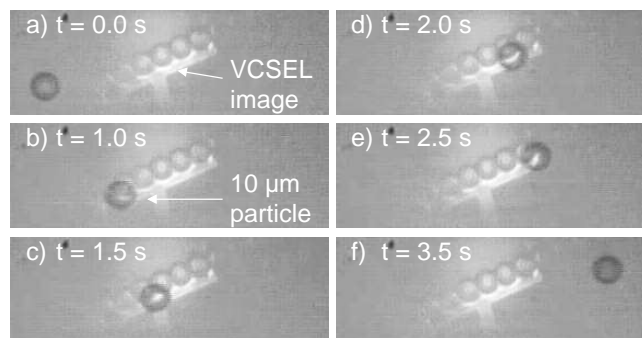


Fig. 7: Continuous deflection of a passing particle by a tilted VCSEL array. The $10\ \mu\text{m}$ polystyrene microsphere is moved from left to right with a velocity of $25\ \mu\text{m}/\text{s}$ and is eventually deflected by a total distance of about $18\ \mu\text{m}$ orthogonal to its initial flow direction.

of standard VCSEL arrays and seamlessly integrates the surface relief technique for enhancement of single-mode emission. Non-mechanical translation as well as continuous particle deflection are demonstrated, where for the latter, a dependence on the geometric and material properties of the particle is to be expected [6, 7]. Therefore, applications in microfluidic particle sorting are intended as well as a further miniaturisation towards the integrated optical trap, where the laser array will be in direct contact to the sample plane [4].

5. Acknowledgement

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