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Review Article

Collective Micro-Optics Technologies for VCSEL Photonic Integration

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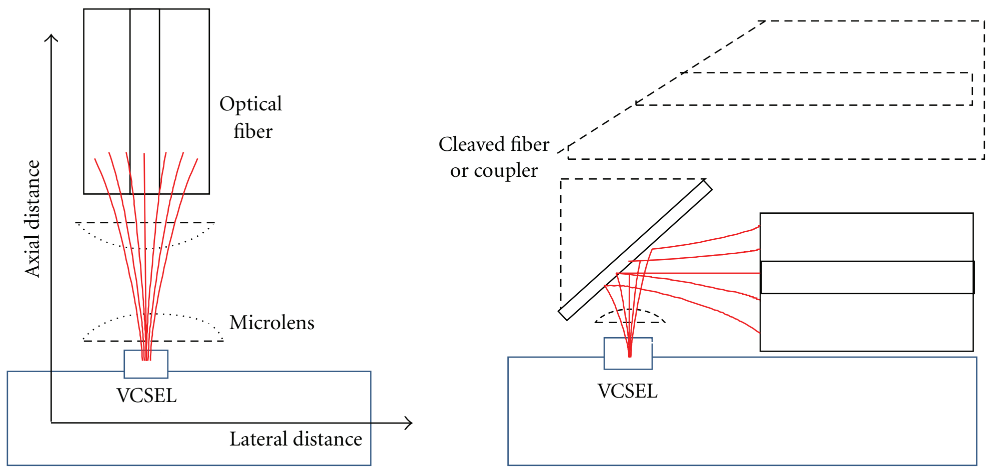
We describe the main recent technological approaches that associate micro-optical elements to VCSELs in order to control their output beam and to improve their photonic integration. These approaches imply either a hybrid assembly or a direct integration technique. They are compared with regards to their tolerance to alignment errors and to their ease of implementation onto arrays of devices at a wafer level. In particular, we detail the integration techniques we have developed for self-aligned polymer microlens fabrication for beam collimation and short distance beam focusing. Finally, designs to achieve active micro-optics or to exploit novel nanophotonic effects are discussed.

1. Introduction

Due to their unique advantages such as low threshold, parallel operation, symmetrical and circular beam, on-wafer test capability, and high bandwidth modulation, VCSELs now constitute strategic light sources for photonic applications, ranging from optical communications to instrumentation as well as optical storage or printing [1]. Current research on these devices concerns enhancement of emission performances by means of novel confinement designs, spectral extension to UV-visible and mid-infrared ranges, but also improvement of their photonic integration. For this latter issue, precise beam control is strongly in demand. Despite a limited far-field beam divergence, typically in the range from 10° to 20°, (half angle at $1/e^2$), these laser diodes have indeed to be more and more associated with microoptical elements to improve the performance of the system in which they are inserted and to develop their use in novel application fields. In this paper, we review the main approaches recently proposed in the literature to combine free-space micro-optics with VCSEL arrays. In the first part, we sum up the main requirements for VCSEL beam shaping in function of the aimed application. In Sections 2 and 3, we review different fabrication methods for passive micro-optics integration on VCSELs, from hybrid report to direct fabrication on device surface. In Section 4, we describe recent advances in the field of active micro-optics for VCSEL beam adaptation to a dynamic environment. Finally, we discuss on emerging approaches based on nanostructured integrated lenses.

2. Micro-Optics for VCSELs: Main Requirements

Up to now, the major market for VCSEL devices remains short-distance high-speed optical interconnects. In this area, key considerations concern coupling efficiency of VCSEL arrays to optical fibers. This efficiency depends strongly on the laser natural beam divergence and on two correlated parameters: VCSEL to fiber lateral alignment and VCSEL to fiber distance (Figure 1(a)). For instance, to keep a coupling efficiency as high as 85% in a silica multimode fiber, tolerances on lateral positioning do not exceed $\pm 5\,\mu$m [2–4]. The efficiency also decreases with the VCSEL-fiber distance, with typical optical losses of ~ 3 dB at 500 μm. These last years, a strong effort has been put towards enhancing tolerances to vertical and lateral misalignments through passive alignment designs based on etched silicon V-grooves or indium flip-chip bonding. Nevertheless, insertion of a focusing microlens in the optical path between the VCSEL and the fiber could greatly



(a) (b)

FIGURE 1: (a) Critical parameters for VCSEL-to-fiber coupling efficiency and possible configuration for lens insertion. (b) Schematic view of an horizontal VCSEL-to-fiber association through the use of a 45° tilted mirror or a TIR microprism for light deflection in the horizontal plane. Direct coupling with a 45°-ended fiber or coupler is also possible.

improve coupling tolerances. However, the technique to be used for lens fabrication should allow a simple alignment procedure and be of low cost for mass production.

Additionally, VCSEL beams emitting in the horizontal plane are strongly in demand to reduce packaging volume and costs, as well as to make easier intrachip and interchip communications with photodetectors. Therefore, out-of-plane coupling by means of a deflection of light at 90° is often preferred. This can be done using specific element such as 45° tilted micromirrors or TIR (total internal reflection) microprisms (Figure 1(b)). These elements can be also combined with a focusing microlens to improve light collection.

As for emerging applications such as sensing, VCSEL beam generally propagates in free space and its beam waist has to be precisely controlled to fit the detection area, at distances from few hundred of μms [5, 6] to several centimeters [7]. Consequently, major requirements concern beam collimation with divergences of $\sim 1°$. Beam focusing and beam steering at precise working distances are also necessary. For example, in reflection-based sensing microsystems, the laser light must be focused towards photodiodes located on the same chip. Besides, in VCSEL-based optical tweezers, focused beams from single-mode or multimodes devices are required [8]. More specific requirements concern the development of optical microprobes arrays for near-field scanning optical microscopy (NSOM) [9, 10] or high-density data storage and optical reading [11]. In these cases, a strong beam focusing is desired at short distances (micrometric range) thanks to high throughput microtips. Finally, active micro-optics instead of passive is more and more in demand to allow dynamic lateral beam steering as well as vertical beam scanning [12].

As indicated in Figure 2, collimation and focusing of the Gaussian beam emitted by a VCSEL are usually achieved using a refractive microlens (a), a Fresnel-like microlens, or a diffractive lens (b). Microtips are more suited for strong focusing at short distances (c). Diffractive optical elements (DOEs), fabricated with continuous relief, binary or multi-level structures, present specific advantages for size and volume reduction as well as for achieving beam steering [13], but they are more complex to fabricate and wavelength dependent. Note that diffractive and refractive lenses can also be combined to minimize optical aberrations [14].

Whatever the aimed optical function, lens dimensions have to match with VCSEL arrays topology and to fit with the initial Gaussian beam properties of individual devices. To avoid cross-talk from adjacent beams, maximal diameters are limited by the VCSEL channel spacing (or pitch), which is generally equal to 250 μm. For top-emitting devices, the maximum propagation distance of the beam in free space is thus more limited, for instance, it should not exceed 350 μm for an initial beam divergence of 20° FWHM.

The vertical positioning of microoptical elements relatively to the laser is highly critical since it influences the whole system performance. Lenses can be positioned directly on the VCSEL output facet in both top- and bottom-emitting configurations. However, large numerical apertures (NA = f/D, f being the focal length and D the lens diameter) are typically desired to achieve an optimal light coupling in the lens as well as low aberrations. Most used refractive lenses are plano-convex rather than ball lenses. Consequently, for top-emitting VCSELs, a thick transparent pedestal (dotted lines in Figure 2) has to be inserted to place the back focal plane of the lens in VCSEL plane. Depending on the used fabrication technique, pedestal and microoptical elements can be realized with the same or a different material. A trade-off has often to be found on the pedestal thickness in function of the pitch and of the initial and the aimed optical properties of the VCSEL beam.

The choice of the most suitable shape and dimension is not only a function of optical performance but also of fabrication considerations. Hence, tolerances to fabrication fluctuations or to alignment errors decrease when the lens is close to the surface. Moreover, microlens geometry can be easily optimized if the chosen fabrication technique is able

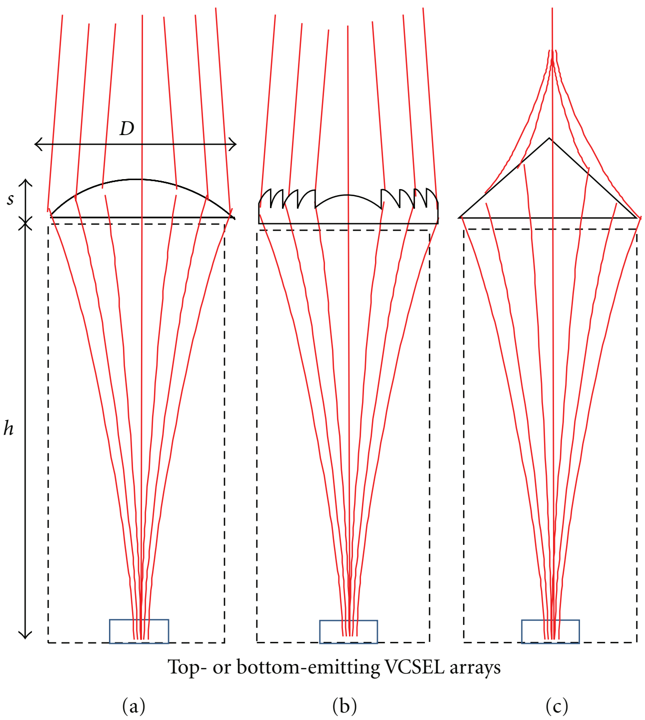


Figure 2: Main microoptical elements developed for VCSEL beam shaping: refractive lens (a), Fresnel-like or diffractive microlens (b), microtip (c). These objects can be fabricated either directly on the emitting surface (top or bottom) or above an intermediate transparent pedestal layer (dot line).

to control and to adjust separately pedestal height h, lens thickness (or sag) s, diameter D, and focal length. For refractive lenses, this optimization can be achieved using a simple Gaussian beam propagation tool. However, more sophisticated methods taking into account diffraction effects are often necessary for a precise optical design. Taking into account the optical feedback in the semiconductor microcavity laser due to the lens presence can be useful to control VCSEL modal properties and/or to render lasing operation robust to lens lateral misalignments [13, 15]. In the following sections, we review main techniques proposed for integration of such microoptical elements on VCSEL devices. First, a short description of hybrid assembly solutions is presented. Secondly, direct integration methods are detailed, ranging from modifications of the internal semiconductor laser structure to surface engineering techniques implying polymer-based technologies.

3. Passive Micro-Optics for VCSEL: Hybrid Assembly

To achieve VCSEL beam collimation, hybrid assembly of commercial glass or plastic lenslet is the most usual way (Figure 3). By assembling silica-based microlenses on 2D broad-area bottom-emitting devices, H. Chen et al. first reported beam divergences of 1.6° ($1/e^2$) over 1 cm^2 [16]. Similar results were also demonstrated on top-emitting

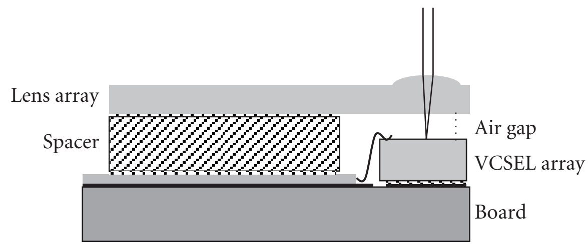


Figure 3: Basic principle of hybrid assembly of a lenslet array on a VCSEL array for beam collimation (reprint from [17], SPIE 2005).

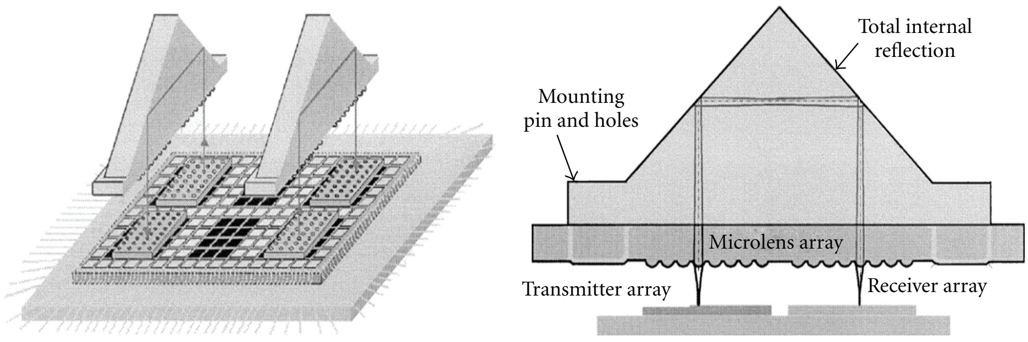
VCSELs by mounting lens arrays with the convex side directed towards [2] or backwards [17] the laser. This method enables the use of "on the shelf" microlenses but implies tricky alignment steps to meet the requirements on vertical and lateral positioning relatively to the VCSEL sources. Usually, lateral alignment is controlled by the precision of the chip report equipment used (typically 2-3 μm for a Karl Suss FC-150 flip-chip bonder), whereas vertical positioning is highly sensitive to uncertainties on spacer and adhesive thicknesses. To improve alignment accuracy, S. Eitel et al. inserted additional Fresnel plates to use focusing alignment spots during the assembly step and reduced the beam divergence to 5° FWHM with a lateral alignment better than 2 μm [18].

For optical links applications, more sophisticated configurations were developed to combine beam shaping with a coupling in the horizontal plane (Figure 2(b)). One can cite, for example, passive alignment of micro-Fresnel lens arrays with side-mounted VCSELs [19]. A low-cost plastic multichannel interconnection module including a lenslet and a high-quality microprism was also successfully developed for increasing misalignments tolerances to $\pm 40\,\mu$m (Figure 4) [20].

More recently, fabrication by inkjet printing of an elliptical mirror on a planar waveguide was reported for lateral coupling with a lensed VCSEL [21]. The use of polymer-lensed fibers instead of standard ones was also proposed to improve tolerances [22] as well as the polymer bonding of 90° connectors [23]. In the past several years, diverse assembly designs including a 45° end facet optical guide equipped with an integrated mirror close to the VCSEL surface were reported to achieve coupling and deflection with no need for a lens [24]. A fully flexible optoelectronic foil based on such direct coupling configuration was also recently demonstrated [25]. Despite significant advances on alignments tolerances, hybrid assembly remains sensitive to positioning errors and is not totally collective. Therefore, direct integration of microoptical elements on VCSEL surface can constitute a better solution for packaging cost reduction.

4. Direct Integration Techniques for Passive Micro-Optics on VCSEL

Direct integration methods can be classified in two types: the firsts imply a modification of the III-V semiconductor



(a) (b)

Figure 4: (a) Optical interconnection module (OIM) for intrachip interconnections. (b) Side view with a beam trace of the optical link (reprinted from [20], SPIE 2003).

structure; the seconds can be applied on the device surface using polymeric materials.

4.1. Monolithic Integration with III-V Technology. Monolithic lenses can be realized by modifying the semiconductor structure on both faces of the VCSEL wafer. A first way consists in etching the back side of the device. This was first reported in 1991 by K. Rastani et al. using selective ion milling of binary-phase diffractive lenses for focusing the emitted beam of bottom-emitting InGaAs-based VCSELs [26]. Reactive ion etching was also developed to fabricate refractive microlenses on bottom-emitting devices (Figure 5(a)). These studies enabled an efficient board-to-board interconnection with no need for any other external optics [27]. More recently, Wang et al. implemented refractive lenses fabrication on a densely packed 2D-VCSEL array using a one-step diffusion limited wet etching method. An emitted power of 1 W and a reduced divergence of 6.6° for each individual pixel were demonstrated with this technique [28]. Design and fabrication of hybrid microlens—both refractive and diffractive—to compensate aberrations and achieve athermalization was also proven, with the achievement of a very low beam divergence (0.3° half-angle) (Figure 5(b)) [14]. Finally, GaAs-integrated microtips were also etched on the back surface of VCSELs for light-emitting cantilever microprobes realization (Figure 5(c)) [9]. The main drawback of these solutions is the restriction to bottom-emitting devices, due to optical absorption of GaAs substrate below 870 nm. Moreover, they are difficult to apply to devices that need a substrate thinning for thermal management purposes.

Application of similar etching techniques to top-emitting devices requires the insertion of an additional thick transparent material on the top surface. Epitaxial growth of a transparent semiconductor layer such as InGaP over the top mirror was investigated by S. Park et al. [29]. These authors reported a significant beam divergence reduction of oxide-confined VCSELs as well as a modal selection. Hybrid assembly of stacked GaN was also suggested for this goal [30]. An alternative solution was recently proposed by K.S. Chang et al.: it is based on an internal oxide lens fabrication by selective oxidation of a composition-graded AlGaAs layer above the top-Bragg mirror (Figure 6) [31]. This approach is very attractive as it allows for a self-alignment of the oxide lens with the emission zone, although it requires high control of the epitaxial step. With this method, VCSEL beam focusing was demonstrated at distances of ∼30 μm, limited by lens location close to the active zone. To conclude on this part, monolithic integration methods present the advantages of being powerful and collective. However, most of them are not applicable to top-emitting devices or are still technically challenging for mass production.

4.2. Surface Engineering Using Polymer Materials. Microlens fabrication using polymer materials has been a key topic in micro-optics for more than 15 years because of their low cost and their ease of use [13, 32, 33]. Research is currently very active in this field, and many fabrication techniques are possible: thermal resist reflow, deep lithography by protons, LIGA process, photopolymerization, inkjet printing, UV imprint, laser ablation, direct writing by electronic beam or laser beam. Among all possible methods, those compatible with a postprocess treatment are the most attractive for VCSEL devices as they allow for a direct integration at a wafer scale.

4.2.1. Self-Assembly by Thermal Reflow. A simple way to fabricate refractive microlens arrays is to use resist thermal reflow. This self-assembly technique is based on the patterning of cylindrical resist posts by photolithography, followed by a controlled melting. This leads to the formation of hemispherical lenses owing to surface tension effects. The final lens dimensions depend on diameter and height of the initial posts and on the wettability properties of the substrate. Fabrication of sags of up to ∼20 μm is possible, as well as achievement of high optical quality lens due to low surface roughness. Application to VCSELs was thus successfully performed using different types of resists, such as polyimide, on the back surface for beam collimation [34] or on top-emitting devices surfaces for beam focusing [35]. This method was also applied to the fabrication of μ-lensed optically pumped fiber VECSELs using a UV-curable epoxy resist [36]. It is noteworthy that it can be also combined to a dry etching technique

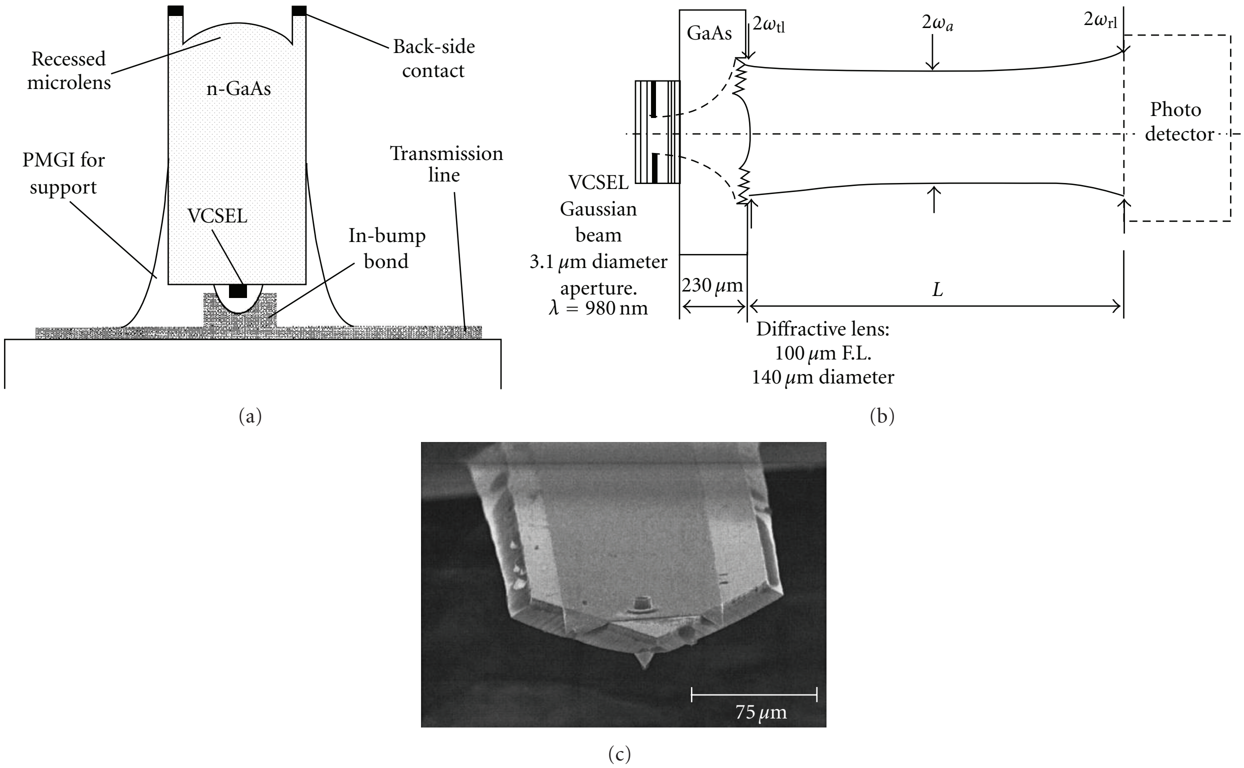


Figure 5: Lens fabrication by etching the back surface of a bottom-emitting VCSEL (a) refractive lens [27], (b) hybrid (refractive + diffractive) lens [14], (c) VCSEL with an integrated GaAs microtip (bottom) for light emitting cantilever microprobe [9] (reprinted, resp., from [27] OSA 2004, [14] IEEE 2001, [9] American Institute of Physics 2000).

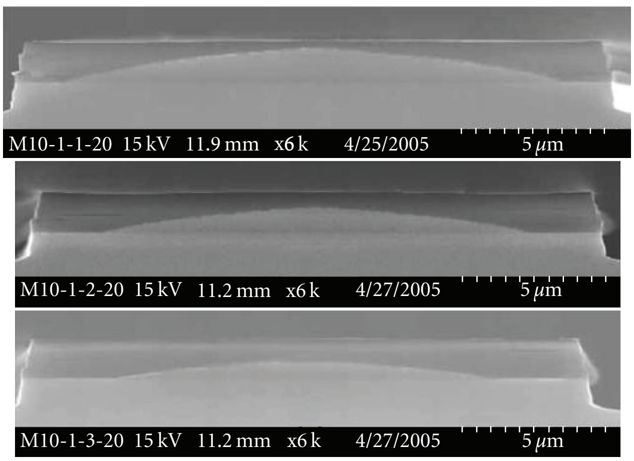


Figure 6: Cross-sectional SEM (scanning electron microscopy) images of 20-μm-wide stripe mesa after oxidation of composition-graded digital alloy Al Ga As. Oxidation time: (a) 20, (b) 30, and (c) 45 min for a self-aligned oxide integrated lens (reprinted from [31], IEEE 2006).

in order to transfer lens patterns in inorganic materials [18]. This simple technology is convenient for collective integration at a postprocessing stage but requires a thermal treatment which can be conflicting with prior fabrication of a polymer pedestal. Consequently, development of alternative self-assembly methods that would not require any thermal step, such as localized hydrophilic/hydrophobic treatments, could give more degrees of freedom in lens geometry [37].

4.2.2. Replication Methods. Replication methods are of major interest for the direct integration of micro-optics on VCSELs at a wafer scale. Several techniques are possible either for original mould fabrication (dry etching, e-beam, or laser writing) than for replication process: injection molding, hot embossing, or UV casting with transparent moulds. It can be applied to liquid polymers or to more robust materials such as organically modified sol-gel. Moreover, this technique enables thick pedestal fabrication for accurate lens vertical positioning. Collective replication of refractive as well as diffractive elements was successfully demonstrated on multimode VCSEL wafers using sol-gel materials (Figure 7) [38]. Note that this technique is better suited for mass production than for custom-made prototyping, since the lens mould has to be modified in case the real numerical aperture of the devices does not match exactly with the aimed value.

4.2.3. SU-8 Technology. Microoptical fabrication involving epoxy-based negative-tone SU-8 photoresist is currently in strong development, as it leads to the definition of high-aspect-ratio patterns with vertical sidewalls using a single photolithography step. For instance, SU-8 was used to fabricate integrated guiding holes for coupling plastic optical fibers to VCSELs [39]. Three-dimensional SU-8 microprisms

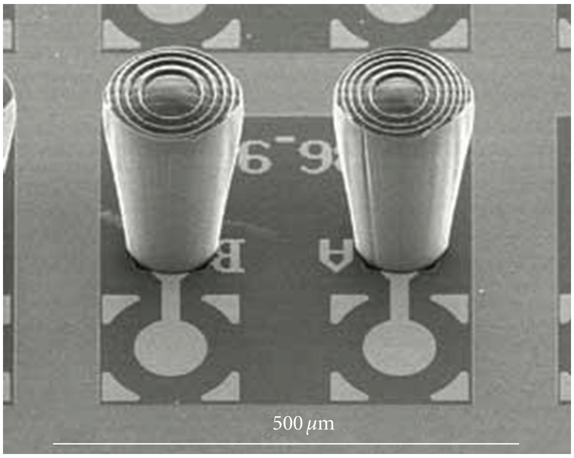


Figure 7: SEM image of a sol-gel diffractive lens replicated on VCSEL arrays (reprinted from [38], SPIE 2004).

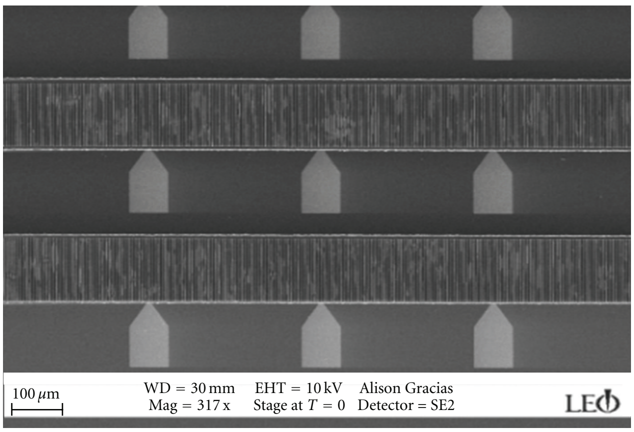


Figure 8: SEM images of a DOE (diffractive optical element) replicated on SU-8 pedestals on VCSEL arrays for beam steering (reprinted from [42], SPIE 2008)

were also directly integrated on VCSEL surface by inclined exposure photolithography for in-plane optical coupling [40]. Moreover, SU-8 microprisms were fabricated by electron beam grey-scale lithography for static VCSEL beam steering [41]. Additionally, wafer-scale replication of DOEs phase-shift gratings on SU-8 rectangular pedestals was reported for the same application [42] (Figure 8). Foremost, as reported hereafter, SU-8 properties were successfully combined to local polymer dispending methods for accurate VCSEL beam shaping.

4.2.4. Local Dispending Methods. Liquid polymer drop-on-demand techniques are highly competitive for micro-optics fabrication. They indeed offer numerous advantages such as high flexibility, wafer-level and maskless technology, high surface quality, and compatibility with nonplanar process. In particular, inkjet printing ensures a wide range of lens shapes and numerical apertures by simply modifying the number of printed polymer droplets [3, 43]. An additional advantage for VCSELs is to enable lens fabrication on thick polymer pedestals for vertical positioning. For instance, by inkjet printing a UV-curable polymer on the top of a thick "bank," previously fabricated with a higher-volume dispending method, Y. Ishii et al. succeeded to improve VCSEL-to-fiber coupling tolerances up to ± 2 mm for axial misalignments and $\pm 10\,\mu$m for lateral ones [4]. As for lens lateral positioning issue, it was solved by A. Nallani et al. [44] by associating inkjet printing with SU-8 cylindrical pedestals (Figure 9(a)). These authors demonstrated a precise control of lens dimensions owing to a liquid self-positioning on the SU-8 pillar (Figure 9(b)). They successfully applied this method for VCSEL beam collimation and for VCSEL beam focusing in optical fibers. More recently, we have exploited the same self-centering properties using an alternative low-volume deposition technique based on a robotized silicon-cantilever spotter (Figure 9(c)) [45]. With this low-cost contact method, fabrication of small f-number lenses is also possible. Moreover, in our case, deposition conditions are only ruled by surface tension effects, leading to a constant dispended volume on the SU-8 pedestal surface, that is to say, to a stable lens contact angle. Thanks to these properties, we have demonstrated that VCSEL beam divergence can be tailored by adjusting only pedestal diameter during the SU-8 photolithography step. The efficiency of our approach has been demonstrated with divergence reduction of 850 nm single-mode devices to values as low as 1.2° (half-angle at $1/e^2$) [46].

4.2.5. Self-Writing by NIR Photopolymerization. To go further and achieve a perfect alignment with the emitted beam, the integrated microlens should be ideally created by the laser source itself. With this aim, we have exploited novel near infra-red (NIR) photopolymers [47] to fabricate collectively microoptical elements by self-guided photopolymerization (Figure 10) [48]. The main advantages of this promising method are to require a single fabrication step and to be compatible with postprocess at a wafer-scale and with post-packaging stages. We have applied it to 760 nm emitting single-mode VCSELs to fabricate self-aligned microtips for strong laser beam focusing at short distances ($\sim 1\,\mu$m). These devices could be used in novel miniaturized near-field optical probes or for compact optical storage heads. Current work on this method now concerns the increase of focal length and the optimization of lens geometry for beam collimation. Extension to longer wavelengths is also under study.

A comparison of the main approaches reported in the literature or explored by the authors for integrating microoptical elements on VCSEL arrays by means of collective and self-aligned techniques can be found in Table 1.

5. Towards Active Micro-Optics on VCSELs

The possibility to dynamically control VCSEL beam shape or VCSEL beam axis during laser operation constitutes a significant advantage for increasing device functionalities and systems performances. This could for instance give birth to novel types of reconfigurable optical routers or to miniaturized vertical scanners. To fulfill this goal, several silicon-based

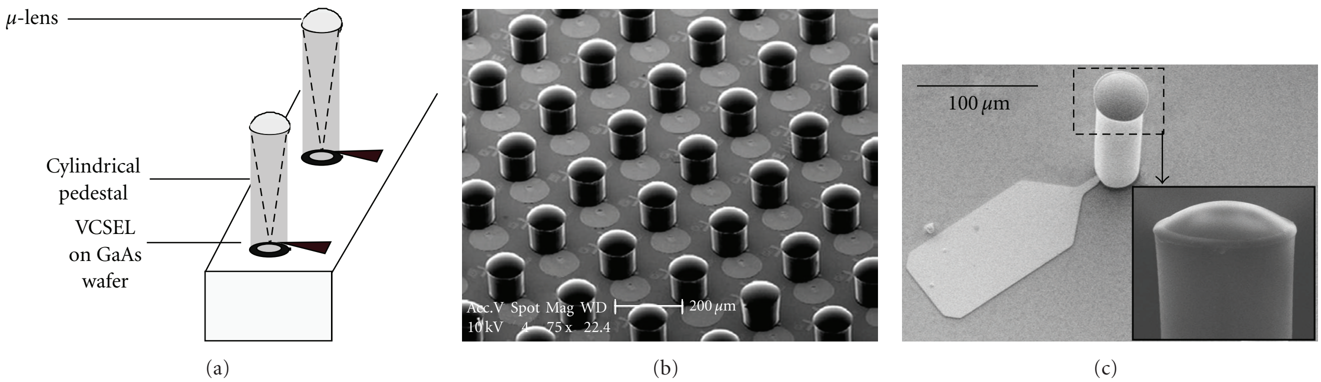


FIGURE 9: (a) Principle of lens integration on VCSEL wafer using a local dispending method coupled to high aspect ratio cylindrical SU-8 pedestals: the low-viscosity polymer is self-centered on the top of the pedestal owing to surface tension properties. (b) SEM images of inkjet-printed lenses (reprinted from [44], SPIE 2005). (c) SEM image of a spotted lens. Inset: SEM image of a microlens self-centered on SU-8 cylindrical pedestal (reprinted from [46], IEEE 2010).

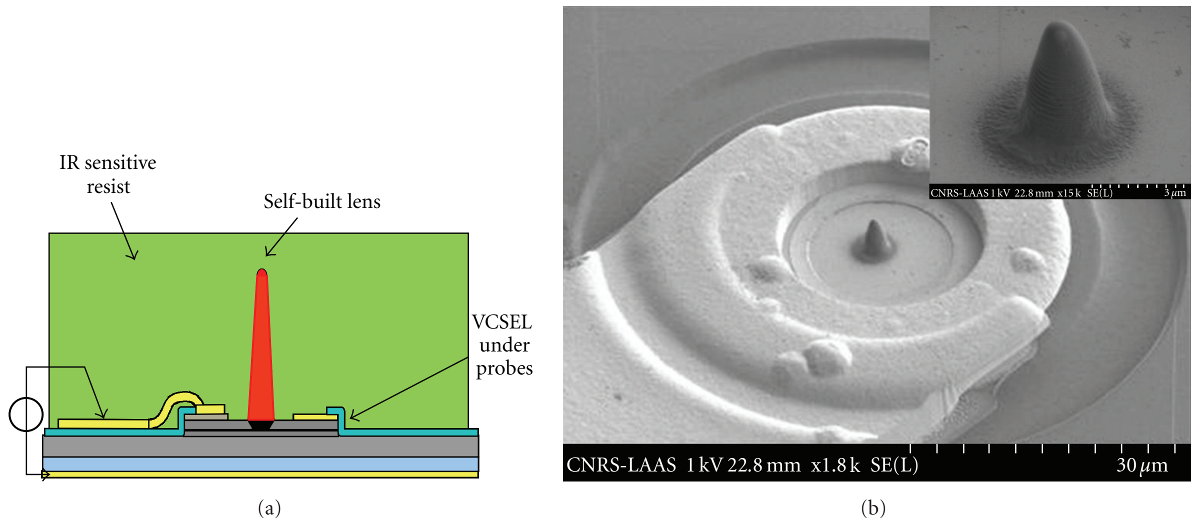


FIGURE 10: (a) Principle of lens self-writing using NIR photoresists. (b) SEM image of a microtip self-written at 760 nm for beam focusing at short distances (reprinted from [48], American Institute of Physics 2010).

TABLE 1: Summary of main approaches proposed in the literature for integrating microlens on VCSEL devices. The three last columns concern polymer-based technologies.

Integration method	Hybrid assembly	Monolithic integration	UV photolithography	Replication	NIR self-writing
Lateral alignment precision	~2-3 μm (flip-chip~1 μm)	~1-2 μm (Top-oxidation = self-aligned)	~1 μm	~1 μm	Self-aligned
Vertical positioning	Controlled by spacer and adhesive thicknesses	Controlled by semiconductor process fabrication	Controlled by spin coating conditions	Controlled by molding conditions	Controlled by exposure conditions
Wafer-scale process	No	Yes	Yes	Yes	Yes
Applicable after packaging	Yes	No	No	No	Yes
References	[2, 16–21]	[14, 26–31]	[3, 4, 34–36, 44, 46]	[38, 42]	[48]

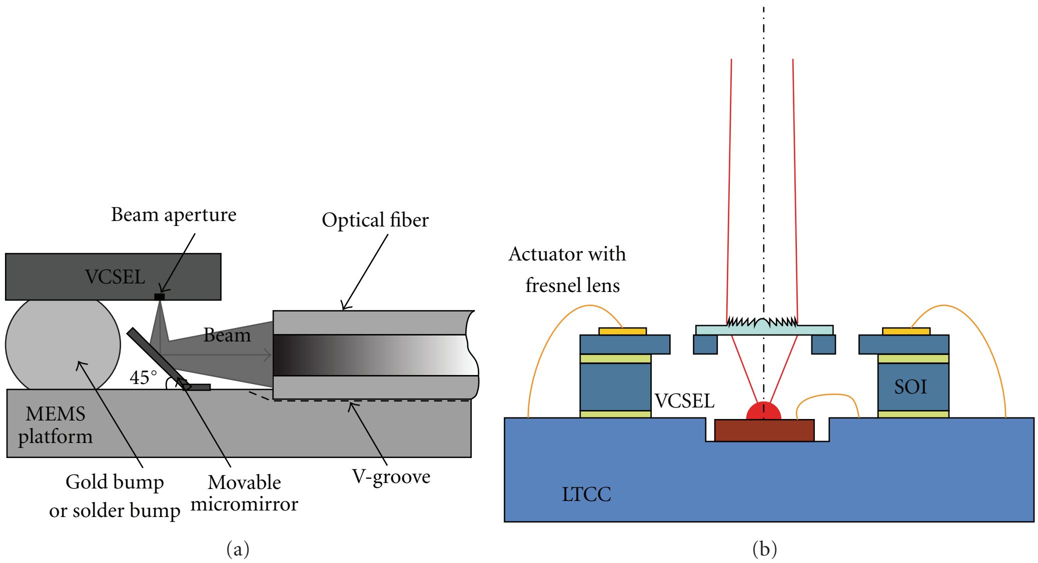


Figure 11: (a) Hybrid assembly of a movable silicon 45°-micromirror for VCSEL-fiber active alignment (reprinted from [52] Elsevier 2003). (b) MEMS-based VCSEL including a diffractive lens on a reported silicon MEMS for optical beam steering (reprinted from [53] Elsevier 2008).

MEMSs (micro-electrical mechanical systems) have been associated to VCSEL devices by means of hybrid assembly techniques [49, 50]. Up to now, most attempts have concerned top-emitting devices and beam steering applications. For instance, flip-chip bonding of a silicon XY translatable plate integrating a polymer refractive lens controlled by electrothermal actuators was assembled on a 4 × 4 VCSEL array for lens off-axis dynamic displacement [51]. Using the same actuation principle, a movable silicon 45°-micromirror was also reported for VCSEL-to-fiber active alignment with alignment tolerances up to 25 μm (Figure 11(a)) [52]. More recently, K. Hedsten et al. reported lateral deflections up to ~10 μm with applied voltages of ~70 V by assembly of an electrostatic silicon MEMS including a Fresnel lens fabricated by a hot embossing collective method (Figure 11(b)) [53].

Design of such MEMS with dimensions compatible with VCSEL pitch remains quite challenging. Moreover, as mentioned before, direct integration fabrication methods are often preferred to avoid tricky assembly steps. Recent progress on tunable lasers technology could be inspiring to solve these issues. In such devices, a vertical shift in the optical path is achieved thanks to a micromachined sacrificial layer in the semiconductor microcavity [54–56] or owing to an intracavity liquid crystal layer [57]. These geometries are not directly usable for active beam shaping but derivate designs could be conceived. For instance, integrated SU-8-based optical MEMS could meet active beam shaping requirements [58].

6. Conclusions and Future Prospects

The main needs for VCSEL beam shaping have been presented, along with collective methods for passive and active micro-optics integration on VCSEL arrays. Among possible solutions, the self-aligned and postprocessing ones, and the ones applicable to all types of VCSELs and suitable with mass production have been highlighted. In particular, direct fabrication of polymer microlens on VCSELs surface was found of major interest. Several demonstrations based either on thermal reflow, molding methods or dispending techniques were reported. To our knowledge, most advanced results were obtained using localized dispensing methods such as microjet printing or microspotting. These methods open indeed the possibility to adjust lens dimensions during the fabrication process. Moreover, they lead to a good surface morphology and to high optical quality, since lens formation originates from surface tension of liquid polymer droplets. Furthermore, combination of such methods with cylindrical SU-8 transparent pedestals allows for lens self-centering with an alignment accuracy provided by photolithography precision (~1 μm). To achieve a perfect alignment, we have demonstrated that the use of NIR photopolymers, sensitive at the laser wavelength, could be a very promising tool. Main issues for this approach now concern lens shape control for beam collimation as well as spectral range extension. Finally, VCSEL association with optical MEMS in view of active beam shaping has been discussed, as well as wafer-scale integration abilities of such microsystems.

Prospectively, several designs involving e-beam lithography have been recently proposed for VCSEL output beam profiling. In particular, introduction of a photonic crystal (PC) in the top mirror of a VCSEL not only achieves a reproducible singlemode operation but also enables a beam divergence reduction to 5.5°, owing to the weakly guiding waveguide characteristic of the PC [59]. Interest of photonic crystals was also proven for 2D electronically driven beam steering of in-phase coupled VCSELs arrays [60]. A narrow beam divergence of 3.2° was also demonstrated in a two-dimensional petal-shaped holey VCSEL thanks to a suited refractive index profile in the holey region and near the optical aperture [61]. In addition, the use of nonperiodic high-contrast subwavelength mirrors (SWG) proposed recently to replace thick Bragg mirrors in tunable MEMS-VCSEL [62] is considered as a future solution for active phase front correction and dynamic focusing [63, 64]. Nonetheless, precise fabrication of these nanostructures using low-cost and collective techniques, such as nanoimprint UV lithography, is still challenging, as well as their association to integrated MEMS.

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