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ABSTRACT

We report on the design and fabrication of polymer microlenses fabricated on patterned SU-8 layers in view of integrating microlenses on VCSEL arrays for laser beam shaping. For a standard top-emitting VCSEL, the lens has to be fabricated on a thick intermediate layer (pedestal) whose optimal thickness can be modelled as a function of the initial and of the aimed optical properties of the VCSEL beam. In this work, pedestals are fabricated with SU-8, which is a negative-tone photoresist transparent at the lasing wavelength. Lens deposition is realized using a robotized silicon microcantilever spotter technique after a simple SU-8 photolithography step in order to define high aspect ratio cylindrical pedestals with wide range diameters [30-140µm]. The effect of pedestal diameter on the final contact angle and curvature radius has been investigated using non contact optical profilometry and scanning electron microscopy. We show that this technique leads to a complete delimitation of the polymer droplets and to a better control of the final lens size. Moreover, lens positioning is fully ensured by the self-alignment of the droplet with the pillar center and consequently with the VCSEL source, and allows for meeting the stringent requirements on alignments.

Keywords: VCSEL, micro-optics, polymer, microcantilevers, SU-8.

1. INTRODUCTION

Thanks to their low power consumption and their highly parallel operation, VCSEL (Vertical Cavity Surface-Emitting Lasers) have become extremely attractive light sources for many applications, ranging from optical communications, instrumentation and sensing. However, despite a limited far-field beam divergence, these sources have often to be associated with micro-optical components to enhance their performances or to improve their integration in photonic systems. Most of the requirements concern beam collimation (beam divergence~1°) or beam focusing with fixed values of waist around few tens of microns and working distances comprised between 10µm to 1mm.

The hybrid assembly of a microlens array above a VCSEL array[1] is the most common way to solve this problem. However this approach implies a tricky hybridation step on active devices to meet the requirements on the vertical and lateral positionings of the microlenses relatively to the source placed above. Moreover this assembly can not be achieved collectively onto a whole wafer. Consequently, microlenses monolithically integrated on the VCSEL surface are often preferable. Such an integrated optical system allows for reduction in packaging costs and makes VCSEL integration in microsystems easier. Moreover it allows to precisely optimize the lens geometrical parameters taking into account the real numerical aperture of the source - VCSELs being testable under probes before dicing and assembly steps - and according to the aimed application: collimation or focusing… leading to a kind of "custom-made" microlens.

Integrated lenses can be defined on either of the two faces of the VCSEL wafer. However, lenses defined by etching the back surface of the wafer are only usable for long-wavelength bottom-emitting VCSELs because of GaAs substrate optical absorption[2,3] For a more general approach, microlenses have to be defined on the emitting surface of the device

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and a thick intermediate transparent layer, named pedestal in the following, has first to be deposited[4,5]. We report here on the collective fabrication of self-aligned polymer microlenses arrays deposited on SU-8 pedestals using a polymer robotized silicon-cantilever-based microsystem. As presented in the next section, microlenses have been first modelled to optimize their geometrical parameters. Results of lens design as well as the influence of the fabrication parameters fluctuations on the divergence will be detailed. Technological steps to achieve high optical quality polymer lenses will be described in Section 3. Finally, results on droplets deposition on SU-8 cylindrical pedestals leading to a self-alignment of the lenses relatively to VCSEL sources will be presented.

2. DESIGN OF INTEGRATED MICROLENSES FOR VCSEL COLLIMATION

The deposited microlenses are assumed to modify the divergent Gaussian beam emitted by the VCSEL into a well controlled laser beam, whose divergence is as low as possible. To optimize this divergence, we used the optical simulation tool Zemax. The simulation implements two layers between the VCSEL laser source and the free air propagation space, as showed in the Fig.1: a thick pedestal and the polymer-made lens meniscus. The VCSEL source has a 1.3µm waist size, corresponding to a 14° FWHM divergence, which is a typical value measured on our single-mode oxide-confined devices. It emits light at 850nm and the VCSEL array presents a source pitch equal to 250µm. The pedestal material is composed of SU-8 photoresist. The simulation and optimization focused on the lens geometry as far as the pedestal height, the association both of theses parameters leading to the required divergence.

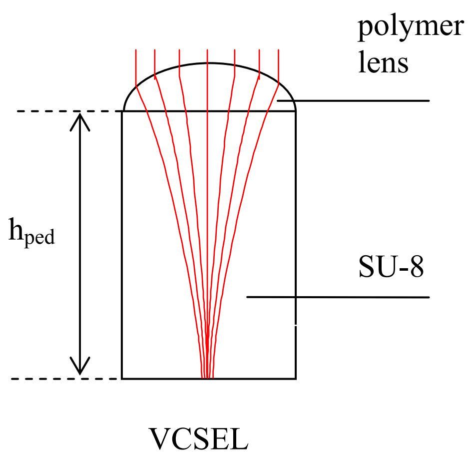

Fig.1: Description and notation of the system pedestal + lens

The notations used for dimensioning the lens are given in Fig.2.

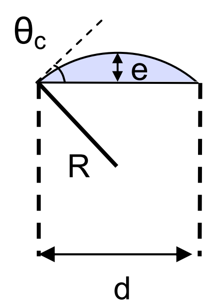

Fig. 2: Scheme and notation of the simulated lens

R is the radius of curvature of the lens, e its thickness and d its diameter. θ_c is the contact angle of the lens. We have the following relations between these different parameters:

$$R = \frac{1}{2e}\left(\frac{d^2}{4} + e^2\right) ; \ \theta_c = \arcsin\left(\frac{d}{2R}\right) \text{ and } e = R\left(1 - \cos\theta_c\right) \qquad \text{(1), (2) and (3)}$$

The study of the source divergence has been carried out as a function of the lens diameter and of the pedestal height, for different lens diameters.
The results are shown in Fig.1 and Fig.2 and point out that a minimum divergence of 1° (corresponding to a reduction of can be reached over a wide range of the structural parameters combination. It has to be noted that the system is more tolerant when the lens diameter increases, as it implies an increase of the pedestal height too.

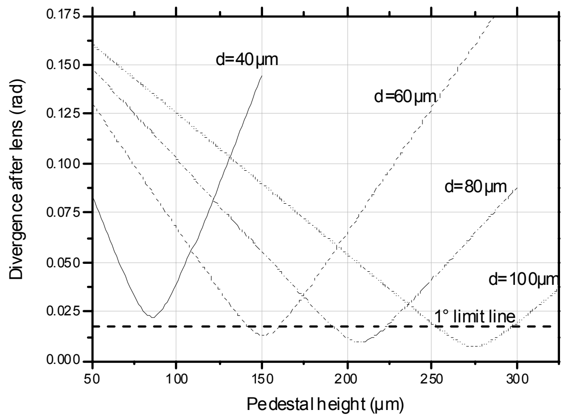

Fig.1. Divergence as a function of pedestal height – Contact angle = 40°

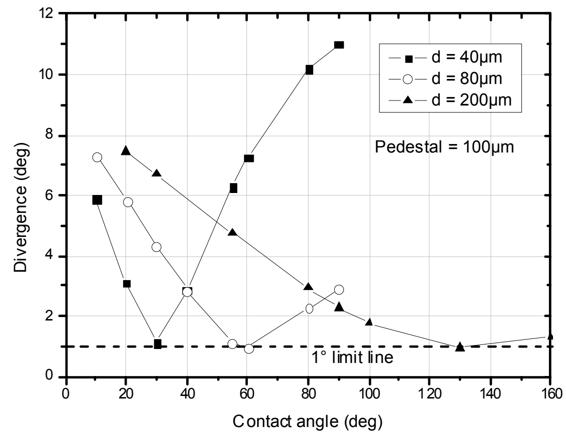

Fig. 2. Divergence as a function of drop contact angle Pedestal height = 100µm

Nevertheless, these results have to be related to the technological facilities and the realization parameters. Corresponding polymer volumes to drop have been also calculated[16] and are comprised in a range from few picoliters to few hundred picoliters. This implies the use of a deposition technique suitable to this volume range.

3. MICROLENS FABRICATION TECHNOLOGY

The fabrication of microlens arrays has been a key subject in micro-optics for more than 15 years[7,8]. Nowadays, most of the studies concern polymer microlenses because of their low cost and their convenience. Many fabrication techniques are possible: thermal photoresist reflow[9], laser ablation[10], direct writing by electronic beam or laser beam[11], deep lithography by protons[11], LIGA process[12], photo-polymerization[13], ink-jet printing[5],UV-imprint[6],... However, many of these techniques are not consistent with a device post-processing. Consequently, only few demonstrations of monolithic integration of microlenses on VCSELs arrays have been done up to now using ink-jet, dispensing methods and UV-molding techniques. To our knowledge, the most advanced results have been obtained with dispensing methods allowing a localized polymer deposition such as micro-jet printing[15] as they open the possibility to adjust the size and the shape of the lenses during the deposition process. Because the lens formation originates from surface tension of the liquid polymer droplet, these methods lead to good surface morphology and thus to high optical quality.
We have recently proposed an original approach that can lead to similar results and which is based on the deposition of low viscosity polymer droplets using an automatized array of silicon microcantilevers. This microsystem-based spotting tool, consisting of a cantilever array fixed on a three-stage automated spotter, was initially developed for picoliter biological sample deposition[16]. The microcantilever array is spatially moved owing to a computer-controlled three-axis translation stage (Fig.5). Liquid droplet deposition is achieved by putting the cantilevers in contact with the substrate surface. The polymer used in this study is a home-made thermocurable polymer with a very low viscosity [15]. After deposition, droplets are *in situ* polymerised at 120°C owing to the use of a heating plate.

The ability of this technique to deposit hemispherical lenses in the size range required for integration on VCSEL has been recently experimentally demonstrated[17]. As seen in Fig.6 and Fig.7, the droplet diameter can be tuned by increasing the contact time. For contact times higher than 30s, lens diameter does not increase anymore and the maximum value achievable depends of the size of the fluidic channel of the microcantilever, of the surface tension of the liquid polymer and of the wettability of the surface. In our conditions (channel size: 5µm, epoxy-siloxane polymer and SU-8 surface), this value is equal to 130µm. Corresponding focal lengths evolve linearly with the diameter and are in the range [60-180µm] (Fig.8). A detailed study of the properties of such microlenses can be found in a previous published work[18].

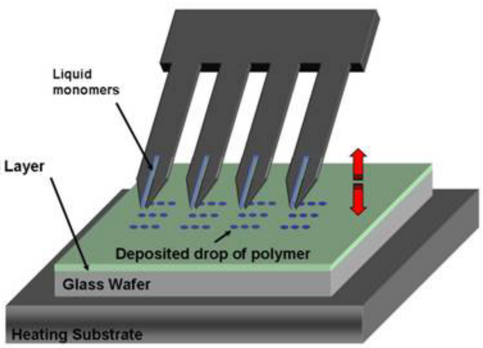

Fig.5. Principle of polymer lens deposition using a robotized silicon-cantilever microspotter

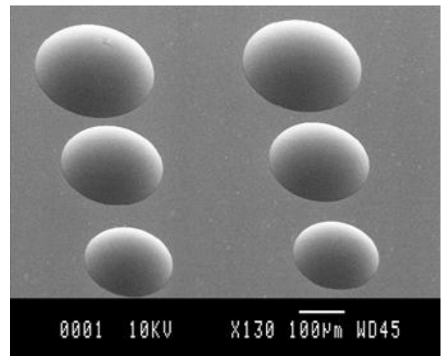

Fig.6. SEM (Scanning Electron Microscopy) image of microlenses obtained for three different contact times using the microspotter system

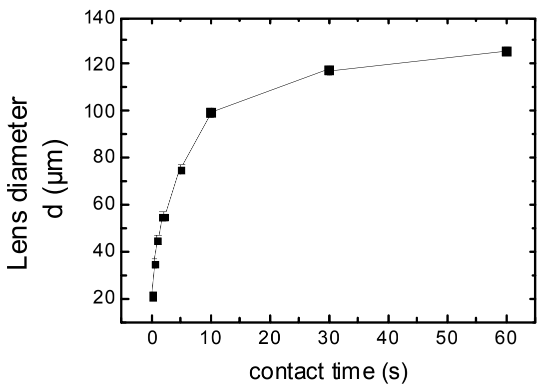

Fig.7. Evolution of lens diameter as a function of contact time

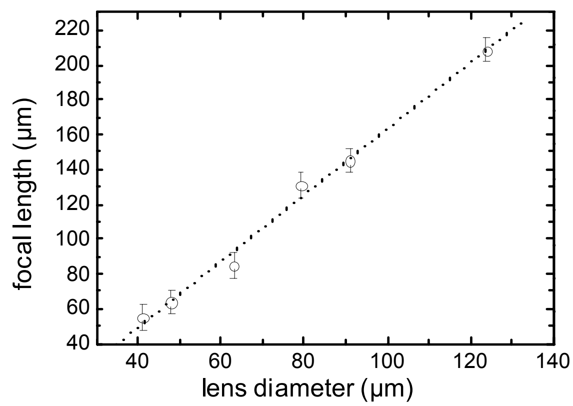

Fig.8. Evolution of focal length as a function of lens diameter

4. SU-8 PATTERN FABRICATION AND SELF-CENTERING PROPERTIES

As mentionned previously, the realization of a thick intermediate layer is necessary to integrate microlenses on VCSEL for beam collimation. Localized pedestals have to be defined on the VCSEL wafer following the laser device fabrication, to allow microlenses deposition on devices and to keep a free electrical access for each device.

These pedestals are composed of SU-8, a negative-tone photoresist often used for MEMS or microfluidic applications (SU-8 3050 – MicroChem Corporation). The SU-8 photoresist is spin-coated, and a simple photolithography step is then realized to define pedestals. SU-8 has been first deposited on silicon and glass wafers in order to check our ability to deposit microlenses on patterned layers whose thickness is close to 100µm. Such a thickness is a trade-off between an efficient reduction of the initial beam divergence and facilities to obtain uniform SU-8 layers.

Polymer microlens deposition has been first tested on band-shaped pedestals arrray comprising large strips. Microlenses deposited on such strips are illustrated in Fig. 9. The polymer behaviour is found to be similar to the one encountered in the case of flat SU-8 layers: droplets dimensions are controlled by the contact time of the cantilevers on the surface. For these kind of patterned surfaces, the droplets dimensions are indeed much lower than the strips dimensions (300 µm x 1000 µm). Consequently, the droplets are not affected during the deposition by the strips boundaries.

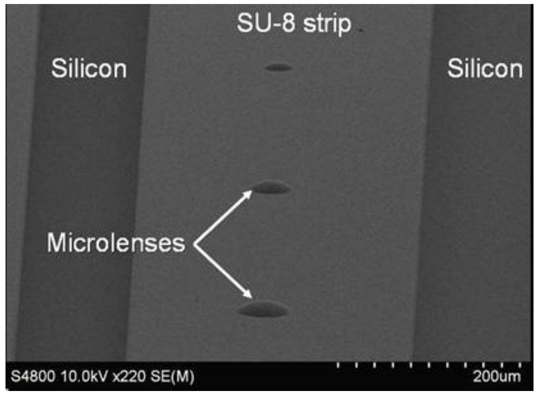

Fig. 9. SEM image of microlenses deposited on a strip-shaped SU-8 pedestal

As it can be seen in Fig.9, the microlenses are aligned with to the strip center. However, although cantilevers can be moved with a micrometric relative resolution, the positioning accuracy of the microlenses with the VCSEL source located 100µm below is found to be not better than 5µm due to the limitations of the optical visualisation system used. Moroever, whatever the highest accuracy of the positioning achievable using a localized dispending technique, it is better to set the lens position with a photolithographic step to meet the stringent requirements on lens/VCSEL alignment (accuracy±1µm). This can be done by defining high aspect ratio cylindrical patterns (Fig.10) to localize polymer droplets[18]. As illustrated in Fig.11, above a minimum value of deposited volume, lens positioning is fully ensured by the self-alignment of the droplet with the pillar center and consequently with the VCSEL source.

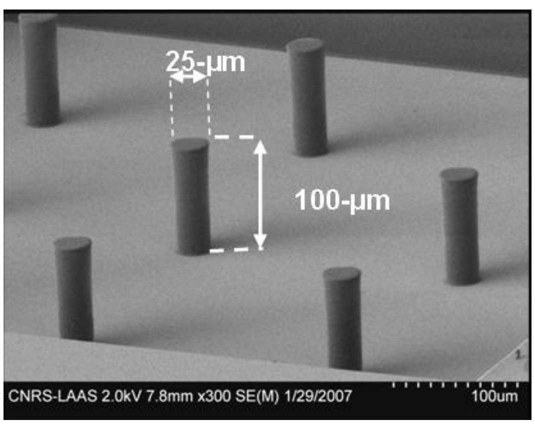

Fig. 10. SEM image of high aspect-ratio cylindrical SU-8 pedestals arrays.

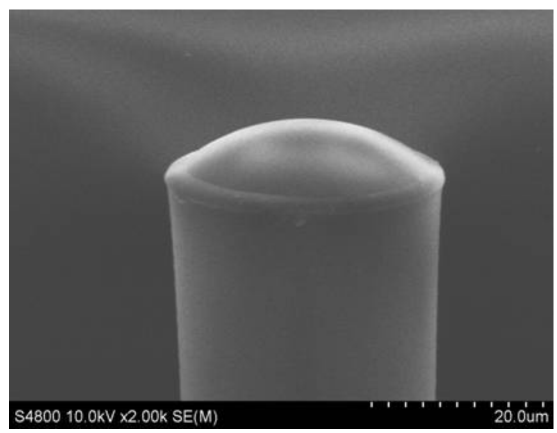

Fig. 11. SEM image of a microlens with a diameter of 30-µm deposited on a cylindrical pedestal.

Non-contact optical profilometry characterizations have been carried out on microlenses deposited on cylindrical pedestals of various sizes (Fig. 12). For this study, high aspect ratio cylindrical pedestals have been fabricated in a wide range of diameters [30-140µm]. These characterizations showed that in each case, the microlenses diameters are well fixed by the pedestals perimeter. As a consequence, a better control is also obtained on the radius of curvature, and on the SAG of microlenses. These parameters are reported for different pedestals diameters in Fig. 13, for which all the deposited microlenses are found to be delimited by pedestal boundaries. For each size, the deposition of 12 successive identical droplets on 12 identical pedestals have been realized and characterized. Circular fits have been performed on the measured profiles. After a geometrical analysis, we can conclude that all microlenses have a spherical shape similar to the ones observed in the case of deposition on a plane surface. Moreover, as illustrated in Fig. 13, the curvature radii is totally set by the pedestal dimension and is comprised between 38-µm for the smallest pedestal to 110-µm for the largest.

A similar behaviour is observed for the SAG of the lens. Moreover, we have measured a standard deviation of 5% on these two parameters. These results show that the combination of our deposition technique with a single micro-patterning photolithography step of SU-8 leads to a complete delimitation of the microlens size as well as of its positionning.

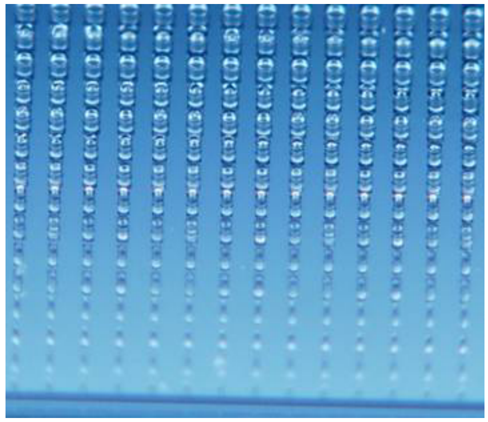

Fig. 12. Microscope image of an array of cylindrical pedestals of various diameters [30-140µm] with microlenses deposited on their surfaces.

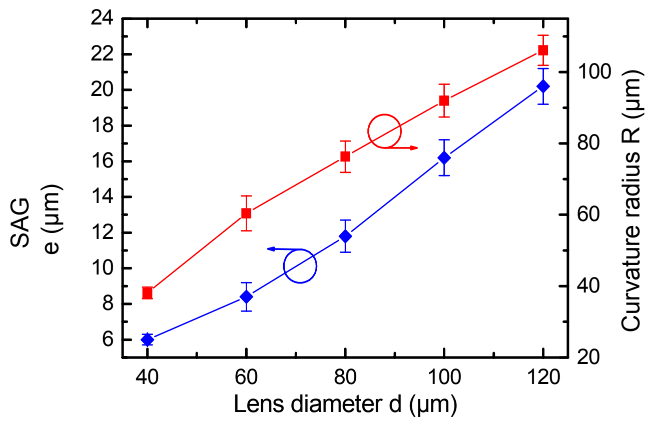

Fig. 13: Image of an array of cylindrical pedestals with microlenses deposited on their surfaces.

Fig.14 represents a schematic view of the fabricated laser devices including integrated lenses. The semiconductor laser diodes are standard top-emitting VCSEL designed for emission at 850 nm.

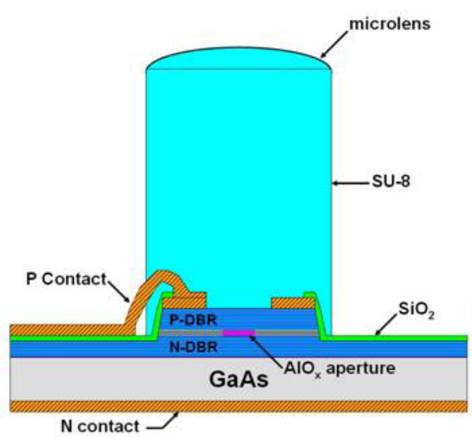

Fig. 14: Schematic view of the fabricated VCSEL with an integrated microlens

An AuGe/Ni/Au electrode is evaporated on the backside of the GaAs substrate to realize the p-type bottom contact. The p-type contact consists in a Ti/Au annular ring. These metallic layers are deposited before the mesa etching by ICP. Lateral electrical and optical confinements are provided by oxidizing an AlGaAs layer to form an oxide aperture with a diameter close to 4µm. The surface is passivated with a SiO_2 layer before the realization of a 1µm-thickness air-bridge final metallization to ensure a good metal continuity on the side of the mesa. Final steps consist in pedestal fabrication and lens deposition. First far-fields measurements on such devices demonstrate that laser beam divergence is divided by a factor 5 without significant modification of laser performances.

5. CONCLUSIONS

In conclusion, a low-cost deposition technique based on a microcantilever-based spotter has been used to deposit microlenses on SU-8 patterned surfaces. Simulations have been performed demonstrating that the microlenses sizes achievable with this method are well suited for VCSEL beam application. In order to integrate such microlenses onto VCSEL devices, uniform thick SU-8 pedestals implementing different geometries and sizes have been fabricated and their influence on the deposited microlenses has been studied. We have shown that a cylindrical shape is the best suited to ensure a self-alignment of the polymer droplets on the top of the pedestal. It allows for an accurate positioning of the lens with the VCSEL sources by means of a single photolithography step, reducing thus strongly the requirements on the accuracy on the dispended volume. Finally, the application of this method to the monolithic integration of self-aligned polymer refractive microlenses on VCSEL has been realized and has led to a reduction by a factor 5 of the initial beam divergence.

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