Direct laser writing for active and passive high-Q polymer microdisks on silicon

Tobias Grossmann,[1,2,4,*] Simone Schleede,[1,4] Mario Hauser,[1] Torsten Beck,[1]
Michael Thiel,[1] Georg von Freymann,[3,1] Timo Mappes,[2] and Heinz Kalt[1]

[1]Institute of Applied Physics and DFG Center for Functional Nanostructures CFN,
Karlsruhe Institute of Technology KIT, 76128 Karlsruhe, Germany
[2]Institute of Microstructure Technology, Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany
[3]Institute of Nanotechnology, Karlsruhe Institute of Technology, 76021 Karlsruhe, Germany
[4]Both authors contributed equally to this work.
**tobias.grossmann@kit.edu*

Abstract: We report the fabrication of high-Q polymeric microdisks on silicon via direct laser writing utilizing two-photon absorption induced polymerization. The quality factors of the passive cavities are above 10^6 in the 1300 nm wavelength region. The flexible three-dimensional (3D) lithography method allows for the fabrication of different cavity thicknesses on the same substrate, useful for rapid prototyping of active and passive optical microcavities. Microdisk lasers are realized by doping the resist with dye, resulting in laser emission at visible wavelengths.

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1. Introduction

Active and passive polymeric microcavities with high quality factors (Q factors) are promising photonic components for a wide variety of applications, such as lasers [1,2], sensors [3,4] and filters [5,6]. Over the last years, improved lithographic and soft lithographic fabrication techniques have enabled the development of high-Q polymeric microcavities based on whispering gallery modes (WGMs). The combination of long photon lifetime with the advantages of polymers, such as low material cost and easy doping, make them potentially attractive for a wide range of applications. In order to achieve high-Q polymeric microcavities via lithographic structuring, techniques like replica molding [7,8] and thermal-reflow methods with surface-tension induced cavity geometries [9,10] have been investigated. These methods allow for smooth cavity surfaces with reduced lithographic blemishes, which typically limit the Q factors of the WGMs due to surface scattering loss. Besides these planar lithography methods, commercially available three-dimensional (3D) structuring methods, such as direct laser writing (DLW) by two-photon absorption of a photoresist have emerged. This flexible method to fabricate 3D photonic micro/nanostructures [11] offers an additional degree of freedom compared to conventional planar lithography. Recently, this serial technique was proven to be suitable in the fabrication of WGM-microcavities with Q factor values in the order of 10^5, where the whole cavity structure including suspending pedestal was written by two-photon polymerization (TPP) on a glass substrate [12].

In this work, we show that the DLW-technique can be applied on non-transparent substrates, by directly structuring Ormocomp microdisks with Q factors above 10^6 on a silicon substrate. We demonstrate that by varying the offset between the focal area where TPP occurs and the polymer-silicon-interface, different microdisk thicknesses can be fabricated on the same substrate. This cannot be achieved with planar lithographic methods and constitutes a useful tool for rapid prototyping of optical microcavities. Furthermore, by doping the resist with laser dye and subsequent structuring of doped microdisks, we fabricate WGM-lasers via direct laser writing on silicon.

2. Fabrication

Fabrication of polymeric microdisks was performed with the negative-tone photoresist Ormocomp (Micro Resist Technology), an inorganic-organic hybrid material with high optical transparency in the visible and infra-red spectral region [13]. A commercial DLW system (Photonic Professional, Nanoscribe), equipped with a frequency-doubled fiber laser (below 150 fs pulse duration with a repetition rate of 100 MHz at 780 nm wavelength) as a laser source was used for the exposure of the photoresist. The laser beam was focused into the resist by an immersion oil objective (numerical aperture NA = 1.4, 100x).

Samples were prepared by drop casting the resist onto a glass cover slip, which was then placed on top of a silicon substrate with the resist side facing the silicon. A schematic of the resulting layer system is depicted in Fig. 1(a). After exposure, cover slip and silicon are separated and the sample is developed for 5 min in methyl isobutyl ketone (MIBK). Development is stopped by rinsing the sample with isopropanol. Then the silicon substrate is isotropically etched using XeF_2 in order to fabricate free-standing microdisks on silicon pedestals. Figure 1(b) shows a microscope image with a top view of an Ormocomp microdisk on a silicon pedestal fabricated by DLW. A side view of such a resonator is shown in the scanning electron micrograph in Fig. 1(c). The depicted microdisk has a diameter of 47 µm and a thickness of 4 µm.

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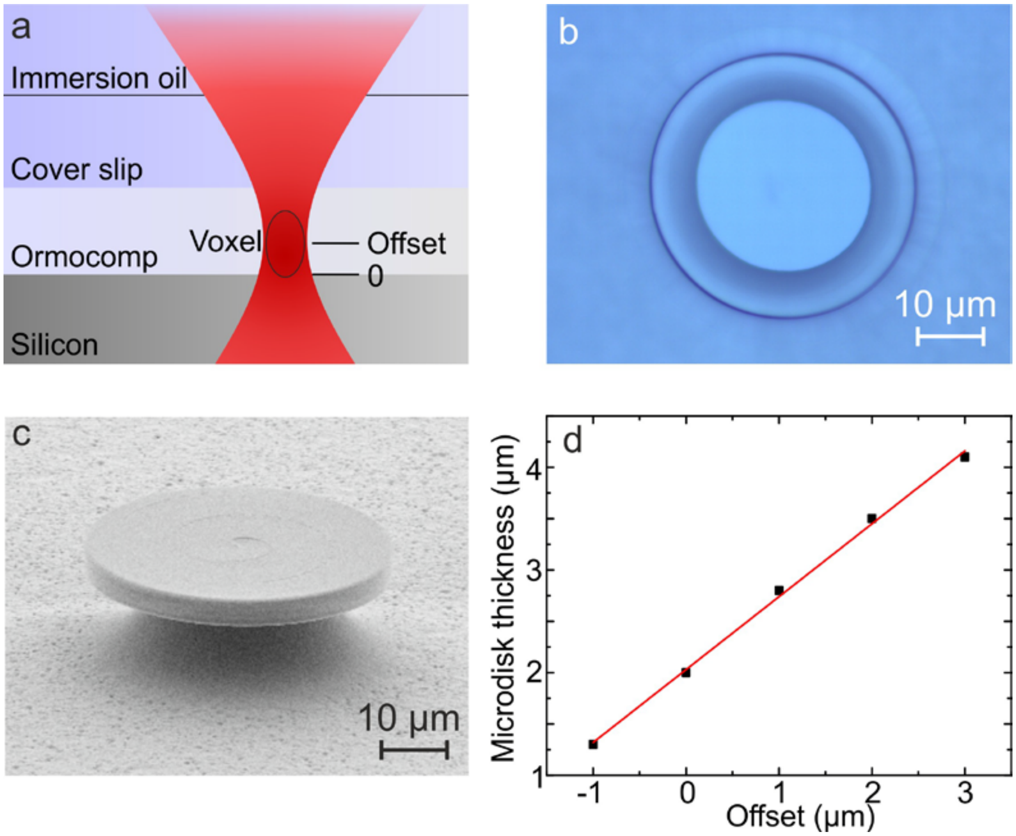

Fig. 1. (a) Schematic of the layer system used to fabricate Ormocomp microdisks on silicon via DLW. (b) Microscope image of a fabricated microdisk with a diameter of 47 µm standing on a silicon pedestal. (c) Scanning electron micrograph showing a 4 µm thick polymeric microdisk. (d) Microdisk thickness can be controlled by varying the offset between voxel position and Ormocomp-silicon interface.

In order to demonstrate the advantages of an additional degree of freedom for device fabrication compared to planar lithographic methods, like UV or electron beam lithography, we fabricated different microdisk thicknesses on the same substrate. This was achieved by benefiting from the geometrical sharply defined region where TTP occurs in the resist. Thus the different microdisk thicknesses were created by varying the offset between Ormocomp-silicon interface and center of the ellipsoidal volume pixel (voxel) in which the TPP occurs, indicated in Fig. 1(a). Resulting microdisk thicknesses (measured in scanning electron micrographs) as a function of different offset values fabricated on the same substrate are shown in Fig. 1(d). A positive (negative) offset value means that the voxel center was located in the Ormocomp (silicon) layer. Laser power and exposure mask were identical for all offset values. The linear behavior between offset value and microdisk thickness depicted in Fig. 1(d) demonstrates the possibility of fabricating microdisks with varying thicknesses (here between 1.3 and 4.1 µm) by controlling the position of the voxel with respect to the polymer-silicon interface. Larger cavity thicknesses could be fabricated by either adding further exposure layers (shown results were accomplished using a single writing layer in beam direction) and/or by increasing the laser power, resulting in increased voxel size [14].

3. Optical characterization of passive microcavities

Modal structure and Q factors of the fabricated WGM-microcavities were measured using tapered optical fiber coupling and a single-mode, tunable, external-cavity laser (linewidth 200 kHz) with a wavelength around 1300 nm. Tapered optical fibers (SMF-28) with minimum

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waist diameters of approximately 1 µm are utilized to evanescently excite WGMs of the cavity. For resonator-waveguide positioning, the tapered fiber is mounted on a five axis positioning stage with a resolution of 20 nm. The intensity transmitted through the tapered fiber is detected by a photodiode. The laser wavelength is swept from 1300 to 1340 nm. The Q factors are determined by measuring the linewidth (full width at half maximum) of the Lorentzian-shaped dips in the transmission spectrum in the undercoupled regime [15].

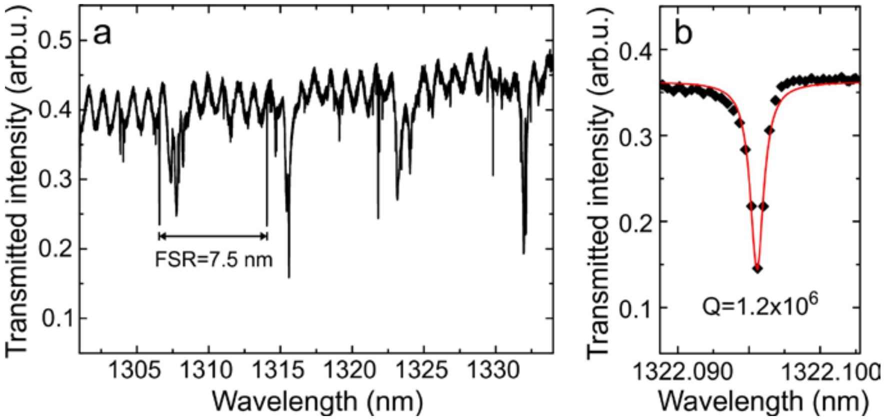

Fig. 2. (a) Transmission spectrum showing WGM-resonances of an Ormocomp microdisk with a diameter of 47 µm and a thickness of 3 µm standing on a silicon pedestal. The free spectral range is 7.5 nm. (b) WGM-resonance with a loaded Q factor of $1.2x10^6$, determined from the Lorentzian fit (red curve).

A resonance spectrum of an Ormocomp microcavity with a diameter of 47 µm and a thickness of 3 µm with various excited WGMs in the 1300 nm wavelength region is depicted in Fig. 2(a). The free spectral range between adjacent longitudinal modes is 7.5 nm. The Q factors take on values as high as $1.2x10^6$, inferred from the Lorentzian fit shown in Fig. 2(b). This indicates that DLW on silicon enables fabrication of smooth cavity surfaces with low surface-scattering loss of the WGMs. For decreasing microdisk thickness (below 2 µm) the measured Q factors are limited to values around 10^5, as the surface-scattering loss at the top and bottom microdisk surface increases. This could be improved by further optimizing the exposure pattern, which defines the position of the exposed voxels. For microdisks with thicknesses above 3 µm the surface-scattering loss of the WGMs at the top and bottom microdisk surface becomes negligible. Q factors above 10^6 are comparable to values achieved in polymeric microcavities fabricated by replica molding [7,8] and by thermal reflow techniques [9,10], making DLW a competitive fabrication technique with the additional advantage of a high degree of design freedom.

4. Dye-doped microdisk lasers

Besides the fabrication of passive optical microcavities, 3D-structuring methods are also promising for development of active photonic components. We utilized the above introduced DLW-technique in order to fabricate polymer microdisk lasers on silicon. As active material, we used the laser dye Pyrromethene 597, which was directly dissolved in the photoresist, resulting in typical dye concentrations of several micromoles per gram solid content. The subsequent structuring of doped Ormocomp on a silicon substrate was performed analog to the passive resonators as described in Section 2.

In order to characterize the lasing properties, doped microcavities were optically pumped with 5 ns pulses of a frequency doubled Nd:YAG laser at a pump wavelength of 532 nm and a repetition rate of 10 Hz. Pump pulses were focused onto the microcavity under an angle of 45° with respect to the substrate normal using a lens. Output emission is collected perpendicularly to the microdisk with a microscope objective (NA = 0.4, 20x) and analyzed in a spectrometer (grating with 1200 lines/mm) connected to a CCD-camera with an overall spectral resolution

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of 62pm. Output intensity as a function of increasing excitation pump energy of a microdisk with a dye concentration of 18.7 µmol/g solid Ormocomp is shown in Fig. 3(a). Excitation power was regulated with a Pockels cell in combination with a linear polarizer. The input-output curve has a kink at a threshold pump energy of 24 nJ per pulse, determining the onset of lasing (see Fig. 3(a)).

In comparison, lasing thresholds achieved in other dye-doped microcavity lasers with similar Q factors are even lower [16]. This is mainly contributed to the effect of photobleaching and aggregation of dye molecules due to high incident power during the two-photon absorption [17] in the DLW process, which lowers the lasing efficiency. In future, this effect could be decreased using lower laser powers for exposure or by integrating gain media, e.g., inorganic quantum dots, which are stable under the strong optical excitation needed for TPP.

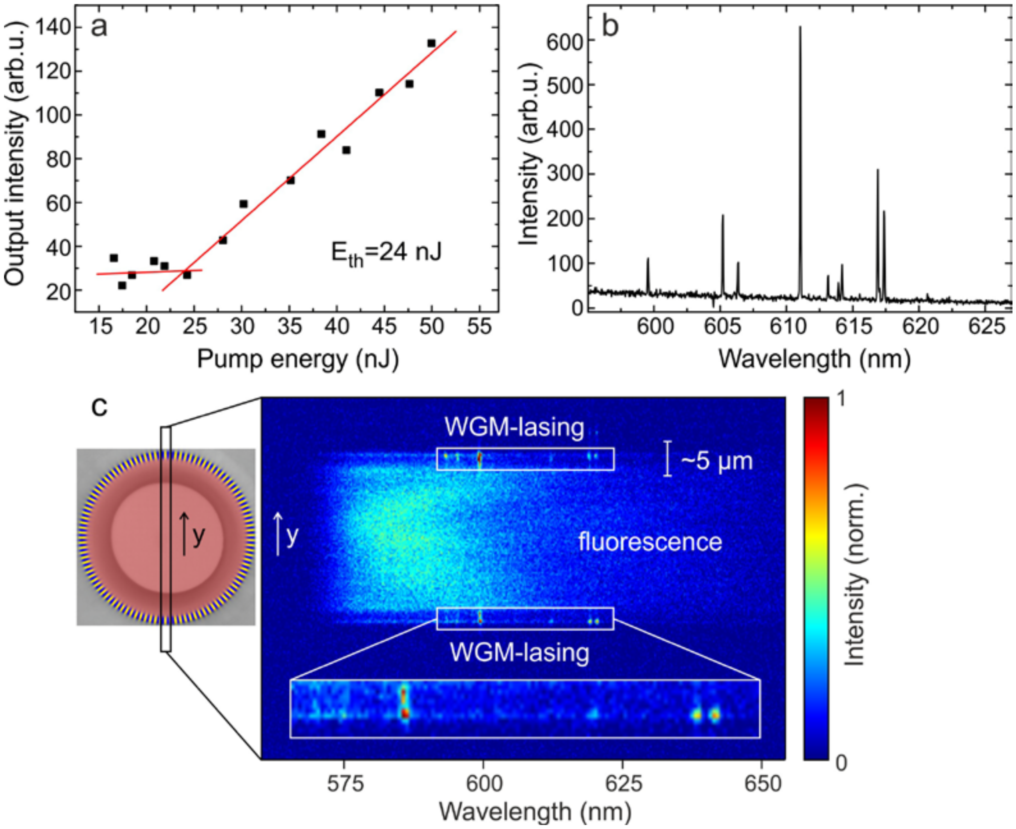

Fig. 3. (a) Input-output curve of an optically pumped dye-doped microdisk laser with a threshold energy of 24 nJ. (b) High-resolution spectrum above lasing threshold, showing multiple laser modes around 610 nm with linewidths of 62 pm. (c) CCD image with color-coded photoluminescence intensity, with a spatial resolution in the vertical dimension (y-axis) and spectral information along the x-axis. The imaged region from the center of the microdisk shows spectrally and spatially narrow WGM-lasing at the border of the disk.

Above threshold, several sharp lasing modes appear in the spectrum due to the amplification of WGMs by the dye. A high resolution spectrum above threshold is depicted in Fig. 3(b) with laser linewidths limited by the resolution of the spectrometer. We proved that lasing occurs in WGMs by spatially resolving the emission from the sample, imaged on the CCD coupled to the spectrometer. A typical CCD image recorded in the imaging mode is depicted in Fig. 3(c). The horizontal axis shows the spectrally resolved photoluminescence. The vertical axis (y-axis) in Fig. 3(c) gives spatial information of the emission from a several micrometer wide stripe of the central region of the microdisk, which is imaged on the CCD.

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From the central region of the disk only spectrally broad fluorescence is measured due to spontaneous emission of dye molecules in this region. However, at the border of the disk spectrally and spatially narrow lasing modes are observed due to stimulated emission in WGMs propagating along the disk circumference. The spatial extent of the lasing modes extracted from Fig. 3(c) is in the order of 1 µm, as expected for WGMs at wavelengths around 600 nm.

5. Conclusions

In summary, we have applied a commercially available direct laser writing system to fabricate active and passive high-Q polymeric microcavities on silicon. The Q factors of the WGMs are above 10^6, showing that smooth cavity surfaces with low surface-scattering loss can be achieved via two-photon polymerization on an opaque substrate. We showed that microdisk thicknesses can be controlled by relative positioning of the TPP voxel with respect to the polymer-silicon interface. Furthermore, by doping the photoresist with laser dye we realize optically pumped microdisks supporting WGM-lasing at visible wavelengths, confirmed by spatially and spectrally resolved emission.

The demonstrated application of DLW on non-transparent substrates opens up the possibility of combining TPP with CMOS-compatible parallel fabrication techniques, making it promising for rapid and low-cost prototyping and small-volume fabrication of high-Q optical microcavities. The prospect of integrating optical waveguides on the same chip combined with the demonstrated high surface qualities make DLW a versatile and promising technique to realize 3D integrated photonic circuits or polymeric WGM-sensing systems.

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