Transfer of Electron Beam-Patterned Photonic Nanobeam Cavities to Flexible Substrates

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Abstract:

The recent demonstrations of high-Q/V photonic-crystal nanobeam cavities in low-index materials allows for their application in a broad array of material systems (polymers, glasses, etc.). An elastomeric platform for high Q/V cavities has a wide range of potential applications in biosensing and microfluidics. We studied the transfer of an e-beam resist, ZEP 520, as well as cavities fabricated in it, onto the silicon elastomer PDMS (Sylgard 184). Films were deposited on various sacrificial substrates. PDMS bonding was facilitated through deposition of a thin silicon dioxide (SiO_2) layer on the ZEP520 film and plasma oxidation of the PDMS surface. Oxide adhesion to the ZEP520 layer was found to be poor, limiting the effectiveness of the transfer process.

Introduction:

The past few years have seen a significant advancement in the field of nanoscale optics. Nanophotonics is now at the forefront of research agendas for applications in communication and information processing systems [1]. This progress was driven by innovations in microfabrication techniques, due to continuous demands for faster, smaller, and cost-efficient computation systems, as well as new insight into fundamental physical laws that govern the behavior of photons on a nanoscale level [1].

Nanobeam cavities are photonic resonators that confine light in one dimension with the use of Bragg mirrors, and in the other two directions by total internal reflection [2]. Wavelength-scale nanobeam cavities can have ultra-high quality (Q) factors, even in materials with a low refractive index (n ~ 1.5) [3]. Fabricating nanobeam cavities in low-index materials has many promising applications in photonic devices at visible frequencies, as many materials that are sufficiently lossless in this range have a low refractive index. The incorporation of soft materials (polymers, glasses etc.) into high-Q photonic-crystal cavities also allows the exploitation of the diverse properties of this class of materials into future photonic devices. One such material property is the ability to stretch. Recent advances in mechanics and materials research are leading to means for integrated circuits to be stretched, compressed, and deformed, while still maintaining their electrical properties and functionality. Nanostructured electronic materials integrated with elastomeric substrates offer mechanical properties and other attractive characteristics, such as bendability, light-weight, and rugged construction. This technology has promising applications in many sub-categories, such as robotics and *in vivo* imaging [4].

The broad goal of this research project was to fabricate high-quality, soft material nanophotonic devices on a flexible platform. This study focused on PDMS as a substrate. The nanobeam cavities could either be fabricated directly on a PDMS substrate, or fabricated on a sacrificial substrate and subsequently transferred onto the flexible platform. We chose to focus on the latter option for the following reasons: High-Q nanobeam cavities in low-index materials require, for sufficient index-contrast, an immediate substrate of either air (suspended geometry [2]) or an artificial material with a refractive index close to that of air (e.g. mesoporous silica [5]). We hypothesized that both options would be more compatible with a transfer-based fabrication protocol. Successful transfer would instigate the development of flexible photonic technology, making possible, for example, bio-conformable and stretch-tunable photonic devices.

Experimental Procedure:

Thin-films of e-beam resist, as well as devices fabricated in e-beam resist, were fabricated on sacrificial substrates. After bonding the resist to the PDMS substrate, the original substrate was wet-etched in a carefully chosen solvent. Cavities were made from the high-resolution electron-beam resist ZEP520 (Zeon Corporation). We explored the following sacrificial substrates: PVA, spin-coated on top of a Si wafer, dissolved in water; NaCl rock salt cubes, also dissolved in water as the solvent; and bare Si wafers, with a 30% w/v aqueous potassium hydroxide solution as the etching solution. A thin layer of gold (~ 30 nm) was sputtered onto the NaCl substrates to allow sufficient adhesion of the ZEP520 film. In order to promote adhesion of the ZEP520 layer to an oxidized PDMS surface, we deposited a thin

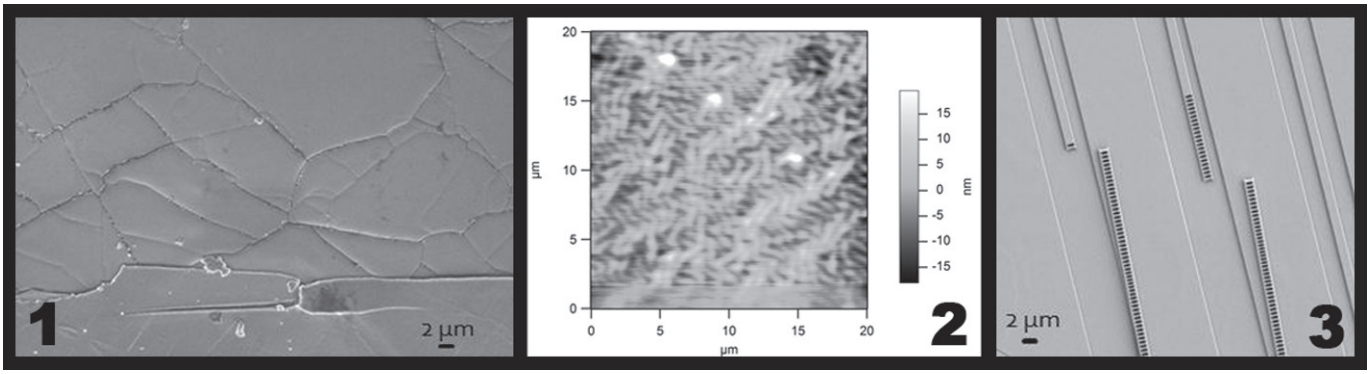

Figure 1: Thin film of ZEP 520 transferred onto PDMS from an NaCl sacrificial substrate.

Figure 2: AFM image of a PDMS slab that was cured from liquid on top of a ZEP layer and manually separated, demonstrating the potential transfer of the ~ 10 nm SiO_2 layer deposited to enhance adhesion.

Figure 3: ZEP520 nanobeams remained on the original Si substrate after the dry-transfer procedure.

(~ 10 nm) layer of SiO_2 on the ZEP520 layer before bonding using a room temp. process developed by Hatton, et al. [6].

In addition, a dry transfer process was also attempted, whereby the removal of the sacrificial substrate took place before the bonding of the devices. For these experiments, a sacrificial layer of sol-gel silica, prepared from a weakly acidic aqueous solution of TMOS, was spin-coated on top of a clean Si wafer. 300 μm long beams containing cavities were fabricated in ZEP520 on top of the sacrificial layer. The sacrificial silica layer was then etched in a buffered oxide etching solution ($HF:NH_4F:H_2O$), releasing the beams, which remained attached to the substrate only at the endpoints. The beams were then bonded to the PDMS substrate as described above, followed by manual separation of the two substrates. Transferred films and devices were characterized by optical microscopy, scanning electron microscopy (SEM) and atomic force microscopy (AFM).

Results and Conclusions:

Figure 1 shows the PDMS substrate after a typical transfer of a bulk thin film of ZEP520 from a NaCl substrate. Cracking and delamination of the film were observed with thin films transferred from all sacrificial substrates listed above, indicative of poor adhesion between the resist and the PDMS. To examine the properties of this adhesion, we cured liquid PDMS on top of a ZEP520 film (on a Si substrate) that had been coated with 10 nm of SiO_2 (as described above). Having found that the two substrates easily separated before etching of the underlying Si, we observed that while the ZEP520 film remained on the Si substrate, there was some faint iridescence on the surface of the PDMS slab. Examining the PDMS surface with AFM, we observed a periodic ridge pattern (see Figure 2), with a vertical amplitude of ~ 30 nm and a period of ~ 1 μm, suggesting that the ~ 10 nm SiO_2 layer had been transferred, detaching from the underlying ZEP substrate. This, combined with the ease at which the PDMS and ZEP520 layers separated implies poor adhesion between ZEP520 and the deposited SiO_2.

Figure 3 shows a typical result of the dry-transfer process: while cracking of the beams indicates that some force has been applied to the beams during the transfer process, the beams consistently remained on the original substrate, and none were found to have sufficiently bonded to the PDMS substrate.

Based on our results, we believe that our procedure of room temperature deposition of SiO_2 onto the ZEP520 does not sufficiently enhance bonding between ZEP520 and PDMS to allow for successful transfer of devices fabricated in ZEP520 to PDMS substrates.

Future Work:

In the future, we hope to transfer devices fabricated in the silica-based negative electron beam resist HSQ/FOx, as a substitute for ZEP520. While high resolution control of the three-dimensional shape and refractive index of nanobeams is more compatible with ZEP520 structures, we expect HSQ to have an improved adhesion compatibility with PDMS in comparison to ZEP520. As all of the sacrificial layers used here would be incompatible with the HSQ-patterning process, substitutes for the sacrificial layer and various etching techniques are also being explored.

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