Development of Three Dimensional Photonic Integrated Circuits Through a Bottom-Up Approach

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METHODS

❑ The PIC substrates were silicon wafers about 2cm x 2cm. The wafers were washed with acetone, methanol, and isopropyl alcohol and dehydration baked on a hotplate at 100° C for 1.5 minutes to remove any organic residue.

LATERALLY INTEGRATED PIC

❑ The originally designed PIC comprised of laterally integrated microdisk resonators and waveguides was fabricated by soft lithography (Fig 2 left side).

- ❑ PDMS was poured over a master template to create a stamp that was a negative image of the desired circuit.
- ❑ The replicas of the master PICs were realized by soft embossing, a technique of soft lithography.

❑ MicroChem's negative photoresist, SU-8 2002, (n=1.565) was placed onto a silicon substrate. The master stamp was placed on top of the substrate, and through capillary action, the SU-8 2002 filled the grooves, imprints from the template, of the stamp.

❑ The PIC was exposed to UV light under an ABM contact mask aligner to crosslink the photoresist and to pattern the structures onto the substrate (Fig 2 right side).

❑ After the PIC was post exposure baked to solidify the SU-8 2002, the master stamp was then removed and cleansed with acetone, methanol, and isopropyl alcohol .

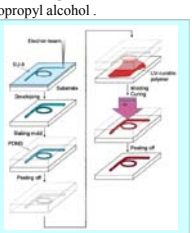

Figure 2: Schematic drawing of soft lithography process used to realize laterally integrated PIC. (Adapted from Huang, et al. 2004)

PDMS Cure Times

Temperature	Time
70° C (Room Temperature)	24 hours
140° C	15 minutes

Soft Lithography Replication Process (SU-8 2002)

Step	Temperature	Time
Dehydration Baky	100° C	1.5 minutes
UV Exposure	------	12 seconds
Post Exposure Bake	95° C	1.5 minutes
Developing	------	40 seconds
Hard Bake	160° C	30 minutes

Figure 3: Specifications for PDMS cure and SU-8 2002 bake times. (Cheng & Kumar)

SURFACE PROFILE MEASUREMENT AND CHARACTERIZATION

❑A Nanonics atomic force microscope and surface profiler was used to obtain images and measurements of the surface topography of the films and multilayered PICs.

PHOTOLUMINESCENCE OF QD EMBEDDED PICs

❑A custom setup was used to observe the photoluminescence of the QDs in a colloidal QD based SU-8 3D PIC lacking an intermediate planarizing layer.

- ❑An Argon-Ion laser was used as a radiation source to excite the QDs. The reflected light was filtered and collected through the AFM's charge-coupled device (CCD) camera. The collected data was transferred and observed on etACMAP on a computer.

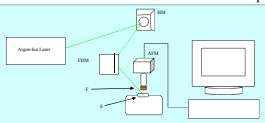

Figure 8: Schematic drawing for the setup of the photoluminescence analysis of the QD embedded SU-8 3D PIC. S is the 3D PIC sample. Here, AFM is the Nanonics atomic force microscope, which is used for high resolution imaging to observe the QD emission. HM is the height mirror, which is used to raise the laser beam, the FHM is the focusing height mirror, used to focus the beam onto the PIC sample, and F is the laser filter. The green line represents the laser beam path. (Cheng & Kumar)

VERTICALLY INTEGRATED PIC

A 3D PIC was fabricated completely by photolithography:

❑ The first layer of the PIC consisting of SU-8 2002 spun and spread onto the surface of the substrate with a Laurell Technologies spin coater. The solvent of the SU-8 2002 was evaporated by soft baking the PIC on a hotplate.

❑ The bus waveguides were patterned onto the SU-8 by placing the substrate under a chromium mask with a contact mask aligner and exposing the device to UV light. It was then post exposure baked and developed.

❑ A fluoropolymer, Teflon (n=1.33) was used as an intermediary layer to planarize the bottom layer. Teflon AF2400 was dissolved in 3M FC-40 at 50°C in a Branson sonicator. Solutions of different concentrations were prepared to find the correct viscosity to yield the desired thickness of the planarizing layer. Teflon layers were spun onto substrates using the spin coater and baked.

❑ As the planarizing layer was being developed, prototypes of the top layer were tested and realized. The development of the top layer was the same as the first layer, except that the top layer consisted of active microdisks made of Evident Technologies Cadmium Selenide (CdSe) QDs (620 nm λ) embedded SU-8 2002. The 1:20 ratio by volume colloidal QD based SU-8 solution was prepared following the process proposed by Pang and his colleagues in their research (Pang et al., 2005).

❑ Prototypes of the top layer were placed in front of an Argon-Ion laser and hit with a beam perpendicular to its surface to ensure the QDs were only in the patterned areas.

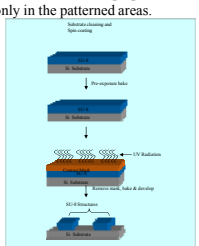

Figure 4: Schematic drawing for the fabrication process of the bottom layer of the PIC using photolithography. (Cheg & Kumar)

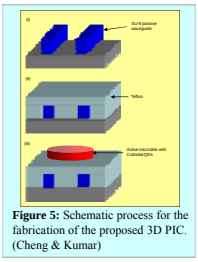

Figure 5: Schematic process for the fabrication of the proposed 3D PIC. (Cheng & Kumar)

Photolithography Process Bottom Layer (SU-8 2002)

Step	Temperature	Time
Dehydration Bake	100° C	1.5 minutes
Spin Coating	------	(2500 RPM) 40 seconds
Soft Bake	95° C	1.5 minutes
UV Exposure	------	9.7 seconds
Post Exposure Bake	95° C	1.5 minutes
Hard Bake	160° C	30 minutes

Figure 6: Specifications for fabrication of bottom layer of PIC. (Cheng & Kumar)

Photolithography Process Top Layer (Teflon)

Step	Temperature	Time
Sonicator Bath	50° C	1.5 minutes
Spin Coating	------	(1000 RPM) 40 seconds
Hard Bake	100° C	6 minutes

Photolithography Process Intermediary Layer (QD embedded SU-8 2002)

Step	Temperature	Time
Dehydration Bake	100° C	1.5 minutes
Spin Coating	------	(2000 RPM) 40 seconds
Soft Bake	65° C	1.0 minutes
	95° C	2.5 minutes
UV Exposure	------	19.5 seconds
Post Exposure Bake	95° C	1.5 minutes
Hard Bake	160° C	30 minutes

Figure 7: Specifications for fabrication of top and intermediary layer of PIC. (Cheng & Kumar)

ANALYSIS OF RESOLUTION OF PIC STRUCTURES

❑An optical microscope was used to take images of the development of the PICs and assess the quality of the waveguides and microdisks.

❑A scanning electron microscope (SEM) was used to acquire high resolution three dimensional images of the sidewalls of the structures, the definitive gap between the microdisk resonators and waveguides, and to examine overall structure design.

RESULTS

LATERALLY INTEGRATED PIC

❑ The stamps to replicate vertically integrated PICs were found to be inaccurate when the replicated devices were observed under a scanning electron microscope.

- ❑ The PICs had extremely smooth sidewalls, but the 200 nm gap between the waveguides and microdisk resonators for efficient coupling were not present. The waveguides were often damaged and touched the microdisks.

Figure 9: PDMS stamp with microdisk and waveguide negatives. (Cheng & Kumar)

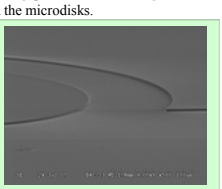

Figure 10: SEM image of PIC with smooth sidewalls. (Cheng & Kumar)

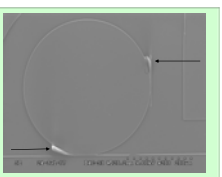

Figure 11: SEM image of a PIC with damaged waveguides touching a microdisk. (Cheng & Kumar)

VERTICALLY INTEGRATED PIC

❑ The first vertical PIC had only two layers to test whether SU-8 could be directly spun on top of itself.

- ❑ The PIC was observed under the SEM. The structures of the upper layer were found to have curled around the structures of the bottom layer (Fig 9, 10, 11).

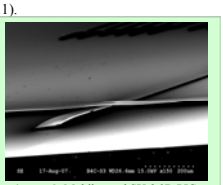

Figure 12: Multilayered SU-8 3D PIC without intermediate planarizing layer. (Cheng & Kumar)

Figure 13: SU-8 structures overlapping each other. (Cheng and Kumar)

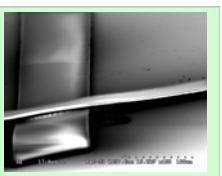

Figure 14: Multilayered SU-8 3D PIC without intermediate planarizing layer. (Cheng & Kumar)