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

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Introduction:

Microscale photonic integrated circuits (PICs) have been essential to the development of telecommunication systems and optical data transmission. In the past few years, PICs have also gained significance in the biomedical field. Electronic integrated circuits (ICs), which rely on the transfer of electrons, have been utilized for more than half a century. These ICs have the advantage over PICs in that they require only the presence of a single active device - the transistor - which is responsible for the computing and processing functions of the circuit. Processing speeds are limited, however, since data transmission is dependent on the flow of subatomic particles. In contrast, PICs rely on the movement of photons, which, if harnessed, could enable the creation of ultrafast (terabit/s) and high capacity telecommunication devices and networks (Kaiser et al., 2002).

PICs are structurally complex circuits that require multiple devices to perform three fundamental photonic functions: (i) the generation and enhancement of light; (ii) the guiding and coupling of light; and (iii) the detection of light (Xia et al., 2005). These optical processes are accomplished by means of multiple structures in the circuit, such as low loss waveguides, optical amplifiers, and detectors. Lateral integration of these photonic devices on a single chip requires larger footprints. The vertical integration scheme would facilitate the development of more compact PICs.

Polymeric materials are an ideal material system for these complex function PICs because the monomers, functional groups or other structural elements of a polymer can be altered, making the modification of the chemical properties of polymers possible. In addition, polymers possess an inherently flexible structure, which makes them remarkably versatile in fabrication processes. For the above stated reasons, polymeric materials, in lieu of traditional semiconductors, have become favorable in creating inexpensive and dependable optical structures (Huang et al., 2004).

Semiconductors are materials which possess neither the electrical conductivity of conductors nor the electrical resistance of insulators, falling somewhere between the two classes of materials. Two types of semiconductors exist - direct and indirect bandgap semiconductors, which differ in their spontaneous emission properties. If an electron of a semiconductor is excited by a stimulus, such as photons, the electrons in the valence band cross the bandgap or forbidden energy barrier into the conduction band and leave behind a hole. When the electron reunites with its hole in a direct bandgap semiconductor, energy is emitted in the form of photons. Indirect bandgap semiconductors, however, do not exhibit this spontaneous emission when the electron reunites with its hole. Quantum dots (QDs) (2-10 nm), also known as semiconductor nanocrystals, are direct bandgap semiconductors whose intrinsic and discrete luminescent properties result from quantum-size confinement. This confinement occurs when the size of the semiconductor approaches the exciton Bohr radius, the physical distance between an electron and its

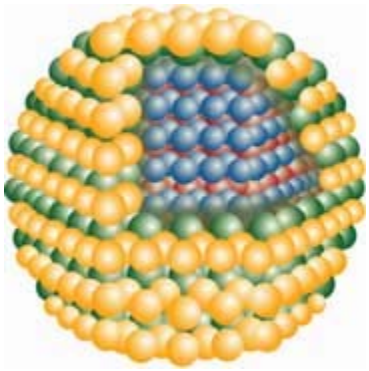

Figure 1: Structure of Evident Technologies Core-Shell Quantum Dot. The nanoparticles are coated with organic molecules known as surfactants in order to provide a stable packing. (http://www.evidenttech.com/)

hole. Therefore, the continuous energy levels that exist in bulk semiconductors (>10nm) do not exist in QDs, instead discrete energy levels are present. When the excited electron reunites with its hole in QDs, it emits a discrete wavelength of light, not a broad emission spectrum as is the case for bulk semiconductors. QDs also present unparalleled tunability since the size of the QD determines the bandgap of the semiconductor, thus the wavelength and intensity of the light emitted, along with certain electrical and magnetic properties, can be regulated (Parker, 2000). Colloidal QDs usually comprise two elements from the periodic table groups 2 and 6, 3 and 5, or 4 and 6, coated with organic molecules that act as surfactants (Fig 1). These surfactants prevent the QDs from clustering and control their growth rate during the production process by creating a stable packing that sets an optimal size (Whitesides et al., 2007). QDs exhibit rapid recovery times, do not lose their emission properties when embedded in a polymer, and are not easily degraded, which makes them highly valuable in science and technology. QDs are expected to play a significant role in the development of light emitting diodes (LEDs), biological sensors, and active and passive layered PICs, which perform ultrafast complex optical processing (Chan et al., 1998).

Electron beam lithography (E-beam lithography) is the most accurate technique used to fabricate PICs. E-beam lithography uses a beam of electrons, which does not diffract on the atomic level, to expose and chemically alter a thin layer of photoresist, a radiation sensitive polymer used to pattern structures onto a substrate. E-beam lithography directly patterns high quality nanometer scale structures on photoresists which no other nanofabrication technique is capable of producing (Huang et al., 2004). The million dollars plus price tag of electron beam writers makes this technique

expensive. Also, the time required to produce PICs one at a time limits the throughput of this technique. Consequently, this fabrication process prevents commercialization of PICs.

One current alternative microfabrication technique to e-beam lithography is photolithography. This process uses a beam of radiation such as UV, ions or X-rays to etch patterns for a circuit on a structure known as mask. This mask is made of UV transparent material, typically glass with chromium patterns (non-transparent to UV). The mask is analogous to a photographic negative and can be used to pattern the features of the circuit onto substrates. In this process, PICs are realized by aligning the photoresist-coated substrate under the mask using a contact mask aligner. UV radiation is used to pattern the structures from the mask onto the exposed photoresist. Photolithography successfully mass produces many devices; this technique produced nearly 3 billion transistors per second in the US in the year 2007 (Whitesides et al. 2007). However, the major drawback of photolithography is its dependence on an expensive and difficult to modify mask that takes nearly a month to create. The protocol for photolithography is complex and requires equipment that is costly, which has motivated engineers to search for an alternative fabrication technique to meet escalating consumer demands for low-cost PICs.

A novel fabrication technique - soft lithography - has been highly praised for the minimal equipment and time it requires to fabricate PICs. Several techniques for soft lithography have arisen in since its development in the early 1990s, such as microcontact printing and micromolding. The general soft lithography protocol calls for the fabrication of a master, or template, which is used to create a polydimethylsiloxane (PDMS) stamp.

PDMS is a viscous and elastomeric polymer characterized by its high molecular weight and inert chemical properties. When it is cast and cured on the bas-relief template, it produces a negative image. The PDMS stamp can be utilized as an inexpensive mask to create exact replicas at a high throughput. However, this technique has several shortcomings: (i) the initial fabrication of a mask is still dependent on e-beam lithography and photolithography; (ii) its inability to fabricate three dimensional, vertically integrated PICs; (iii) despite its low adhesive force of 23 dyn/cm, PDMS still tends to adhere to the substrate; and (iv) the PDMS stamp can deform easily during the stamping process (Whitesides et al., 2007). The limiting feature size of soft lithography is a controversial issue drawing the attention of many research groups. Yanyi Huang and his research group fabricated PICs with a 250 nm separation gap between the waveguide and microring, claiming that the theoretical limiting feature size of 1 nm is achievable (Huang, et al 2004). Se-Jin Choi and his research group claim that sub-micrometer structures realized with soft lithography are of low quality since the PDMS loses its mechanical properties (Choi et al., 2004). In spite of the multitude of fabrication techniques available for PICs, the development of micro and nanotechnology requires innovation and research to overcome their fabrication limitations.

Most PICs are currently realized using the top-down approach, regardless of the fabrication technique used. The top-down methodology starts with the fabrication of a large scaled device onto which individual nanostructures are carved. The significance of these nanostructures lies in their patterning and function rather than their size. Examples of PICs fabricated using this top-down approach include microchips, the PICs on the complementary metal–oxide–semiconductor (CMOS) platform, and Asymmetric Twin

Guide (ATG) based PICs, all of which are expensive to produce and possess large footprints. The top-down approach is limited by its high cost and the time consumed to fabricate PICs (Whitesides et al., 2007). In contrast, the approach employed in the current research relies on building devices from the bottom up, enabling the creation of smaller sized and low cost PICs with smaller footprints (Fig 2). Although the bottom-up approach has been studied before, no one has attempted to create PICs using this approach to produce multilayered structures with interlayer communication.

The choice material system for creating monolithic 3D PICs would be MicroChem's negative photoresist, SU-8 2002, (n=1.565) due to its high aspect ratio imaging, relatively high optical absorption of conventional UV (350-400 nm λ), and its durability after exposure. The favorable QDs for creating active structures would be Evident Technologies Cadmium Selenide (CdSe) QDs suspended in hexane with an emission wavelength of 620 nm. Creation of efficient coupling between the passive layer of plain SU-8 and an active layer of colloidal QD based SU-8 in the 3D PICs requires an intermediate layer of low refractive index. This intermediary layer serves the purpose of planarizing or leveling the bottom passive layer of SU-8 since spin coating does not deposit precisely flat layers. Due to its high density and low refractive index

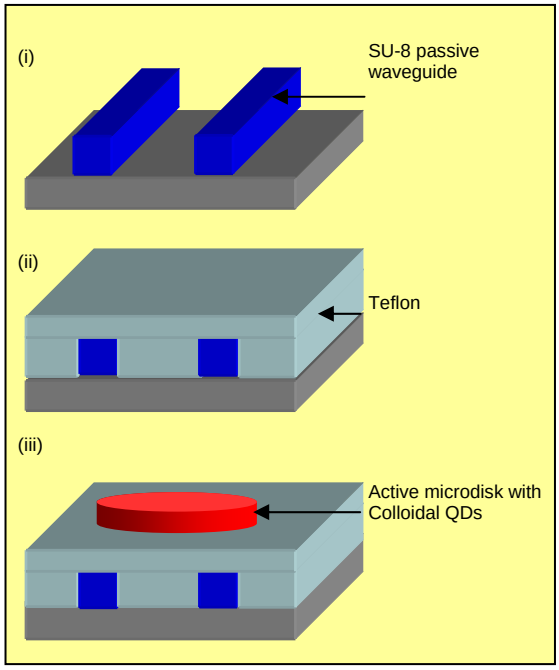

Figure 2: Schematic process for the fabrication of the proposed 3D PIC.

(n=1.33), Teflon is a possible planarizer that could create the efficient coupling necessary for interlayer communication. These versatile and low cost materials would make the creation of multifaceted, smaller sized, and economical 3D PICs viable.

The objective of this research is to create economically and functionally efficient 3D PICs with the expectation of making commercialization feasible. It was hypothesized that if the bottom-up technique was adopted along with innovative material systems and monolithic integration of fundamental photonic functions, the realization of commercially accessible 3D PICs could be possible. These innovative and multifaceted devices would have a breadth of applications as ultrafast and high performance PICs in telecommunications and as bio-sensors in biomedical research. The approach presented in this project could pave the way for creation of PICs in which the device designer could adapt the PICs to his personal requirements, instead of being constrained by the limitations of the device.

Materials and Methods:

Laterally Integrated PIC:

The originally intended PIC comprising of laterally integrated microdisk resonators and waveguides was fabricated using soft lithography. Here, a stamp that was a negative image of the desired circuit was made. The stamp was made by pouring PDMS, also known as Dow Corning's Sylgard 184, over a master template. This master template, consisting of photonic circuits etched out on glass, was obtained from collaborators at Brooklyn Polytechnic University. The PDMS mixture was created by combining a 10:1 ratio by mass of PDMS base and PDMS curing agent, which was then degassed in an in-house built degassing chamber. The mixture was poured over the

template and cured on a hot plate. The curing time was dependent on the curing temperature. The cured PDMS mixture, now known as a stamp since it is the exact negative image of the template, was gradually and cautiously peeled from the template.

The replicas of the master PICs were realized by soft lithography, specifically soft embossing. The schematic drawing in Figure 3 shows this process.

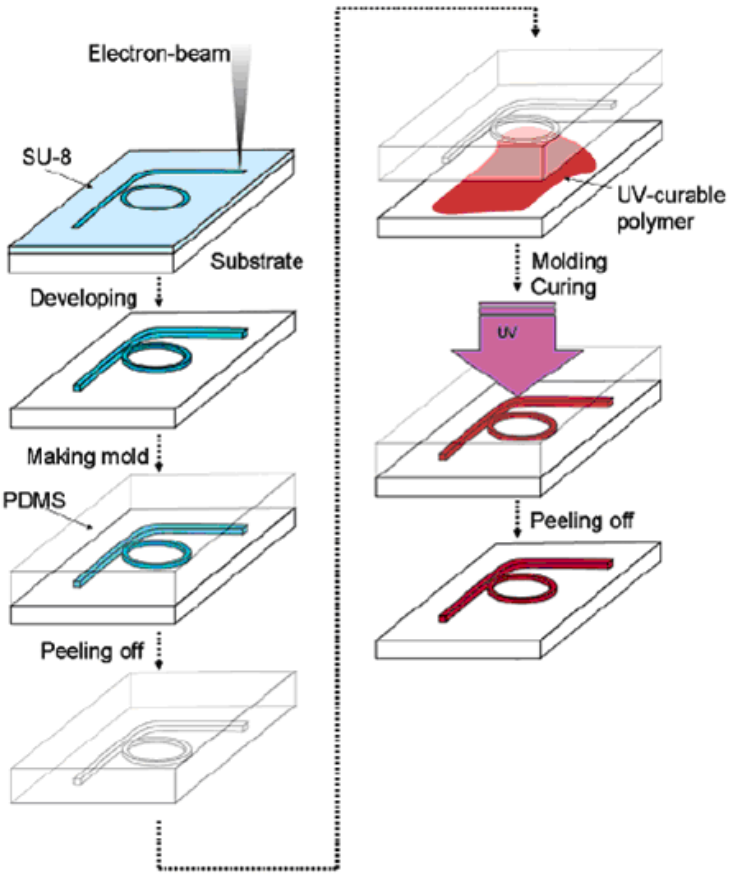

Figure 3: Schematic drawing of soft lithography process used to realize laterally integrated PIC. (Adapted from Huang, et al. 2004)

A small piece of silicon wafer, which would act as the substrate for the PIC, was cleaned using acetone, methanol and isopropyl alcohol and dehydrated on a hotplate at 100° C for 1.5 minutes. This pre-fabrication process removes any organic residue that would otherwise result in adhesion issues and uneven thicknesses of the photoresist. A few drops of the negative photoresist SU-8 2002 were deposited at the center of the substrate, covering a region approximately 2 mm in diameter. SU-8 2005, a higher viscosity form of SU-8 2002, was also utilized as a material system to create PICs, but due to adhesion issues between the polymer and photoresist, experimentation was

limited. The master stamp was placed on top of the substrate, and through capillary action, the SU-8 filled the grooves, imprints from the template, of the stamp. The sample was then placed under an ABM contact mask aligner and exposed to UV light for 12.0 seconds at an energy level of approximately 90 mJ/cm^2 to crosslink the photoresist and to pattern the structures onto the substrate. The sample was then placed on a hotplate at 95° C for 1.5 minutes to help solidify the SU-8. The master stamp was then carefully lifted off the sample and cleansed with acetone, methanol, and isopropyl alcohol. Due to resolution issues to be discussed later in the discussion section, we had to abandon this approach and proceed using conventional photolithography.

Vertically Integrated PIC:

After the research objective was altered to a multilayer vertically integrated photonic circuit, the PIC was fabricated completely by photolithography (Fig 4). Once again a small piece of silicon wafer, which would act as the substrate for the PIC, was cleansed using the same substrate cleaning process from soft lithography. The first layer of the PIC, consisting of bus waveguides, consisted of SU-8 2005 spun and spread at 2500 RPM for 40 seconds in total onto the surface of the silicon substrate using a Laurell Technologies Model WS-400-B-6NPP/LITE/10K spinner. The solvent of the SU-8 polymer was

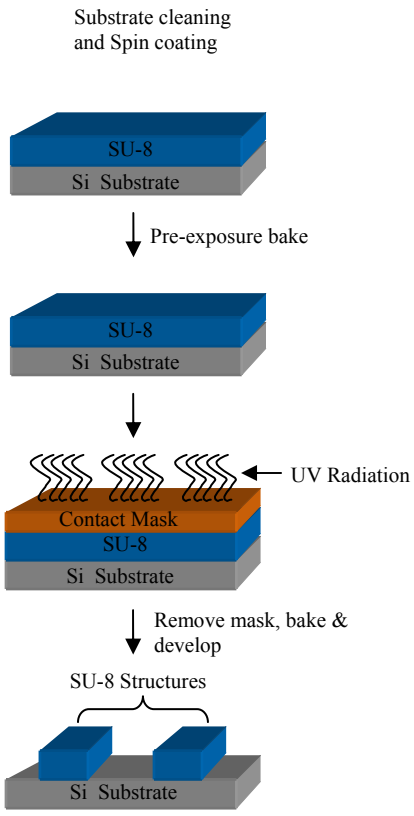

Figure 4: Schematic drawing for the fabrication process of the bottom layer of the PIC using photolithography

evaporated by heating the devices on the hotplate during a pre-exposure bake at 95° C for 1.5 minutes. After the sample was allowed to cool for five minutes, it was placed under a contact mask aligner. A chromium mask, patterned with the structures of the PIC and alignment marks, was aligned and put in place. The sample was exposed to UV light for a period of 9.7 seconds to pattern the SU-8. After the exposure, the sample was baked at 95° C for 1.5 minutes to dry out any remaining solvent and to bind the photoresist to the substrate. After the sample was allowed to cool, it was developed in a beaker of SU-8 developer (propylene glycol monomethyl ether acetate), which washed off any SU-8 that was not exposed to UV light, leaving only the patterned structures.

SU-8 layers created through spin coating are not precisely smooth and a well defined gap must be present between multilayered vertically integrated photonic structures requiring vertical coupling. Therefore, a middle layer would have to be added in between two SU-8 layers in order to planarize the bottom layer. A middle layer posed a problem, as it would have to be a solution that would spin evenly and be level on the surface. Thickness measurements of possible planarizers were taken before actually being spun onto SU-8 structures. Different photoresists were tested first as possible planarizers. The tested photoresists, OG-125 and an experimental solution of Opti-Clad, were spun at experimental speeds for 40 seconds onto a cleaned silicon substrate. The samples were then flood exposed, or exposed without a contact mask placed over the substrate, under UV light. The flood exposure crosslinks the photoresist, but does not pattern structures on it. Then, the samples were baked on the hotplate. Thickness measurements of the films were taken using a Dektak IIA surface profiler.

An alternate planarizing agent that was found to be used in a similar application was a fluoropolymer, Teflon (Rabiei et al., 2002). Various Teflon AF2400 solutions of different concentrations were prepared to find the correct viscosity to yield the desired thickness of the planarizing layer. Since Teflon is a fluoropolymer, a fluorinated solvent was needed to dissolve the Teflon. The Teflon solutions were prepared by initially measuring out a desired amount of 3M's Fluorinert Electronic Liquid FC-40, a fluorinated solvent. After calculating the target Teflon percentage by weight of the solution, the desired amount of Teflon was measured and added to the FC-40, and sonicated in Branson's 1510 sonicator for three days with heat, 50° C, added. When the solution was prepared, it was spun onto a cleaned silicon substrate at 1000 RPM for 40 seconds and baked at 100° C for six minutes. The thickness of the Teflon was measured using Nanonics atomic force microscope and surface profiler.

As the planarizing layer was being developed, the top layer was being tested and realized. The development of the top layer was the same as the first layer, with the exception that the top layer consisted of active microdisks realized with QD embedded SU-8 2002. The colloidal QD based SU-8 solution was prepared following the process proposed by Pang and his colleagues in their research on quantum dot composites (Pang et al., 2005). 0.1 mL CdSe QDs suspended in solvent were slowly stirred into a vial containing 2.0 mL of SU-8. This created a 1:20 ratio by volume of QDs to SU-8, a relatively low ratio because QDs aggregate easily in SU-8. The slow stirring process recommended by them to add the QDs to the SU-8 was used, but the results were no different. A silicon substrate was cleansed using the same substrate cleaning process from soft lithography. A solution of SU-8 and QDs was spun onto the surface at 2000 RPM for

40 seconds, and baked for 1 minute at 65° C and then 2.5 minutes at 95° C. The prototype top layer was then exposed to UV light for 19.5 seconds in the contact mask aligner with the specialized photomask over it. The prototype was then baked at 95° C for 1.5 minutes and then developed in SU-8 developer. Then, the prototype was placed directly in front of the Argon-Ion laser and hit with a beam perpendicular to its surface. This was done to ensure the QDs were only present in the patterned areas.

Surface Profile Measurement and Characterization:

The established protocol for operating the Nanonics atomic force microscope and surface profiler was followed to obtain images and measurements of the surface topography of the films and multilayered PICs.

Analysis of Resolution of PIC Structures:

An optical microscope was used to take images of the development of the PICs with the addition of each layer and assess the quality of the waveguides and microdisks. A Hitachi S-2600N scanning electron microscope 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 the overall structure design.

Photoluminescence of QD Embedded PICs:

A custom setup was used to observe the photoluminescence of the

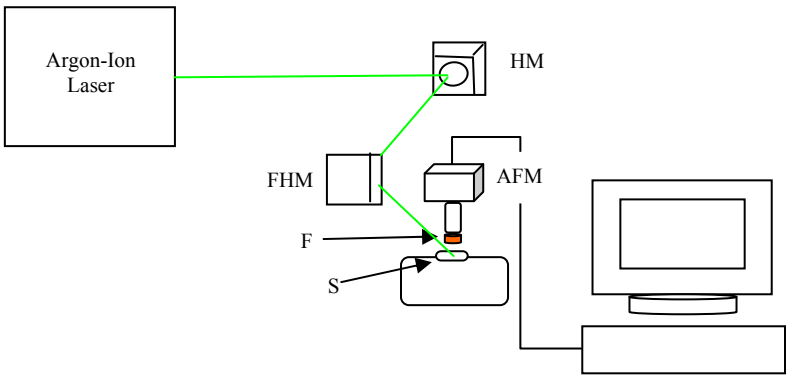

Figure 5: Schematic drawing for the setup of the photoluminescence analysis of the QD embedded SU-8 3D PIC. S is the 3D PIC sample. Here, AFM is the Nanonics atomic force microscope, which is used for high resolution imaging to observe the QD emission. HM is the height mirror, which is used to raise 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. The images collected from the AFM's camera were viewed on an etAMCAP program.

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 laser beam was directed through a series of mirrors and focused, at a grazing angle, onto the bottom waveguides of the 3D PIC. The reflected light was filtered and collected through the AFM's charge-coupled device (CCD) camera. The collected data was transferred and observed on an etACMAP program on a computer.

Results:

The stamps to replicate the original intended laterally integrated microdisk resonators and waveguides were created (Fig 6), but were found to be inaccurate when used to replicate PICs. It is not possible to evaluate the resolution of the stamp; the PICs had to be created and observed under a Hitachi S-2600N scanning electron microscope (SEM). While the PICs had extremely smooth sidewalls (Fig 7), the 200 nm gap between the waveguides and microdisk resonators needed for efficient coupling was not present. As indicated by the arrow in Figure 8, the waveguides were often damaged and touched the microdisks.

Figure 6: PDMS stamp with microdisk and waveguide negatives.

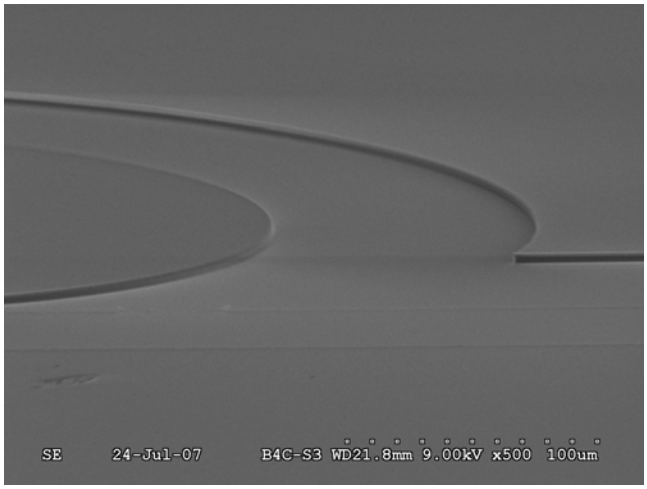

Figure 7: SEM image of PIC with smooth sidewalls.

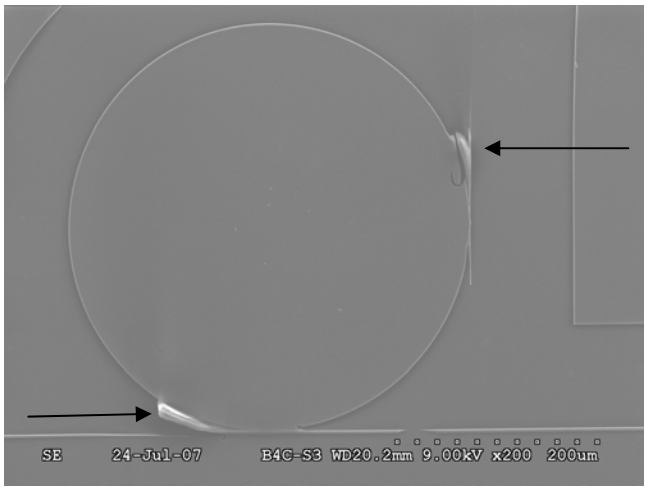

Figure 8: SEM image of a PIC with damaged waveguides touching a microdisk.

The first vertical PIC only had two layers to test whether SU-8 could be directly spun on top of itself. The PIC was observed under the SEM and, as pointed out by the arrow in Figure 9, the structures of the upper layer were found to have curled around the structures of the bottom layer.

Various Teflon solutions were prepared and tested. The first solution - 11% Teflon AF2400 by weight - appeared to be solid when completely sonicated. The second solution was diluted to 1% Teflon by weight, which yielded a homogenous solution that could be deposited on the bottom layer of the PIC using the spin coater. Observed under a Nanonics atomic force microscope and surface profiler, the Teflon layer was found to be too thin. The Teflon had sloped, slowly decreasing in thickness as it approached the waveguides. Additional Teflon solutions are still being prepared and tested.

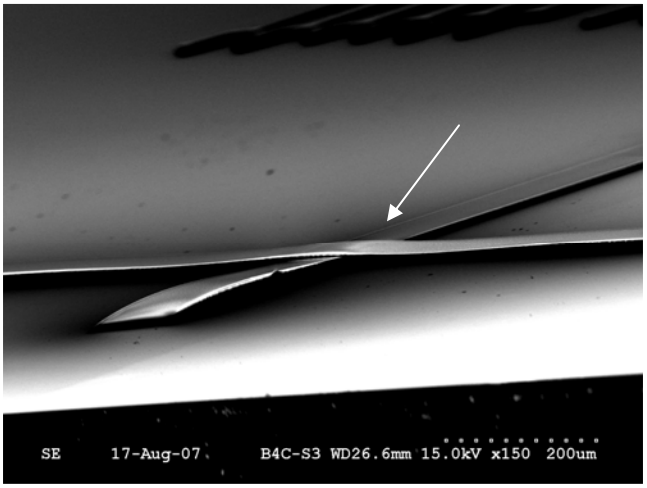

Figure 9: Multilayered SU-8 3D PIC without intermediate planarizing layer.

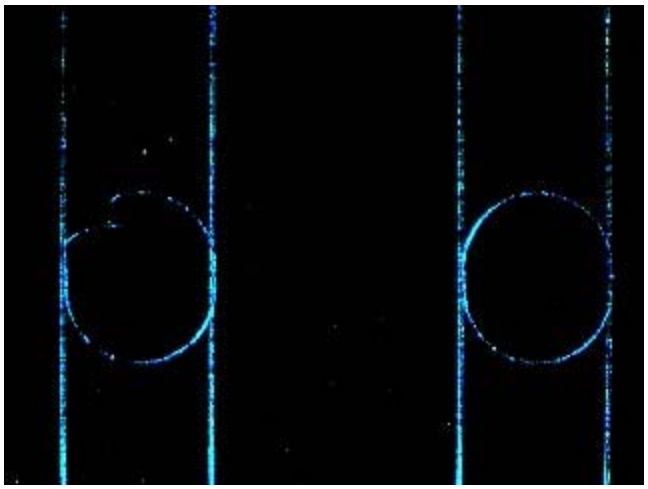

Figure 10: High resolution image of a photoluminescence analysis of QD embedded 3D PIC taken with AFM's CCD camera.

Hitting the prototype top layer directly with the Argon-Ion laser revealed that the CdSe QDs had not washed off since spontaneous emission was exhibited on the entire top layer. After switching to CdSe QDs dissolved in hexane, a prototype PIC with passive bottom layer and an active upper layer and no intermediary planarizing layer was successfully fabricated. During the photoluminescence of this PIC, enhanced emission from the CdSe QDs, which is reddish-orange light (620 nm λ), was not exhibited (Fig 10). The blue light seen in the image is scattered light from Argon-Ion laser beam. Nearly identical images were obtained when a multilayered completely passive PIC was tested.

Discussion:

In future years, engineers and researchers will rely heavily on PICs to provide a platform for the development of micro and nanotechnology. Thus, the growth in performance and reliability in technology requires an essential improvement in the fabrication and functionalities of PICs. Our research objective was to create innovative monolithic PICs that integrate fundamental photonic functions on a single substrate in a cost and time effective scheme.

Our first approach was to create PICs consisting of microdisks and waveguides with lateral separation by utilizing soft lithography. In theory, soft lithography would have provided a low-cost and time efficient process to replicate PICs, which is crucial for

the commercialization of PICs. However, in practice, we encountered resolution issues with the replica PICs. The 200 nm gap between the disks and bus waveguides was not well defined. Consequently, efficient coupling between the two structures was not possible; the PICs were unable to perform the fundamental photonic functions (Fig 8). The dispute on the limiting feature size of soft lithography definitely played a significant role in our research. Our results support Choi and his research group's claims that sub-micron structures replicated with PDMS stamps are of low quality because the stamp loses its integrity and deforms at that scale (Choi et al,. 2004) The PDMS lost its resolution capability at 200 nm since the gap between our structures was not well-defined. Huang's group may have realized a 250 nm gap in their structures, but according to our results anything less than 250 nm is extremely difficult to realize. The primitiveness and lack of technicality of soft lithography made it a difficult technique to use. The resolution and material system issues of soft lithography must be resolved before smaller scale PICs can be commercially fabricated with precision and accuracy using this approach.

After attempting soft lithography, we determined that the bottom-up approach employing photolithography would be used to realize three dimensional PICs. Aligned, multilayered circuits with active and passive devices have been successfully fabricated (Fig 9). However, these PICs lacked the intermediate planarizing layer required for efficient coupling. Upon observation under the Hitachi scanning electron microscope, the OG-125 and Opti-Clad solutions prepared to level the SU-8 layers were found to be poor planarizers. The solutions did not level the bottom layer, which led to the use of the alternative planarizing agent Teflon. The viscosity of the Teflon solution has not yet been

optimized for the thickness the PICs require, but it is the focus of current experimentation and will soon be resolved. In addition, the QDs embedded in the SU-8 matrix do not wash off in the unexposed areas when stripped in SU-8 developer. Preliminary results indicated that this may be a result of the phenomenon of self-organization of QDs due to solvent separation. Researchers at Evident Technologies discovered that SU-8 was chemically incompatible with toluene, the liquid in which the CdSe dots were dispersed, and recommended using hexane instead (personal communication, mid-November 2007). Pang and his research group encountered aggregation issues with QDs embedded in SU-8 and also recommended using QDs suspended in hexane (Pang et al., 2005). Therefore, CdSe dots dissolved in hexane were used. The slow stirring process recommended by Pang and his colleagues to add the QDs to the SU-8 was used, and the same aggregation issues were encountered. An active and passive layered PIC analyzed under the AFM's CCD camera did not exhibit any enhanced emission because no amount of light from the waveguides in the bottom layer coupled into the microdisks in the top layer. Since there was no coupling, the QDs in the microdisk could not be excited. However, when the Argon-Ion laser beam was used to hit the sample's top layer, spontaneous emission was exhibited on the entire layer since no coupling was required. Therefore, the CdSe QDs are still aggregating in the SU-8 matrix. The issue of QD aggregation, although an obstruction to the development of PICs in this project, is an interesting discovery that will be investigated. As for the PICs, a three dimensional monolithic PIC with efficient coupling will soon be fabricated, facilitating the realization of multifaceted, compact, and commercially available optical devices.

These PICs would have applications as bio-sensors in biomedical research and as ultrafast and high performance PICs in telecommunications. The surface plasmon resonance sensor, replacing the fluorescent labeled bio-sensor, has led the way for unlabelled, real-time detection of biological molecular interaction. Surface plasmon resonances are electromagnetic waves that oscillate parallel to gold or silver coated prism surface and are sensitive to surface changes, such as bio-molecular interaction. However, single molecular detection could not be realized with these sensors. The recent addition of the microsphere bio-photonic resonator based on the phenomenon of whispering gallery modes (WGMs) could facilitate single molecule recognition (Vollmer et al., 2003). These WGMs occur when the resonant wavelength couples into and oscillates in the microsphere. If two bio-molecules were to interact at the surface of the microsphere, the refractive index of the microsphere's surface would change. This would create a precise shift in the resonant wavelength, enabling the detection of ultrasensitive bio-molecular interaction. Due to production, packaging, and cost constraints, the microsphere resonators will be difficult to commercialize. As exhibited in Figure 11, the PIC presented in this project can be used in bio-sensing research as a chip-scale vertically integrated biosensor using a waveguide

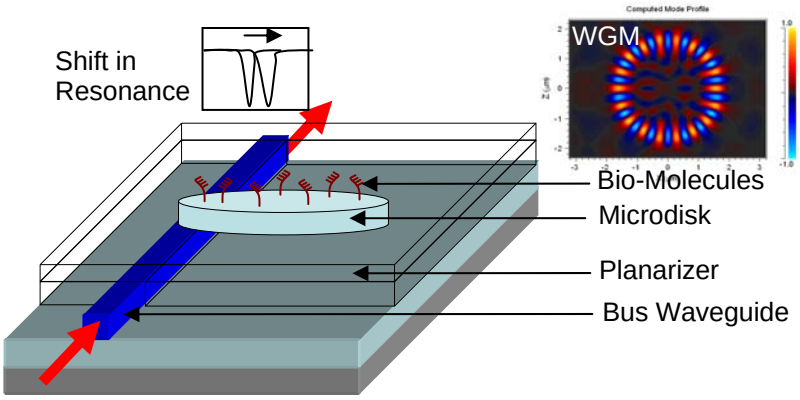

Figure 11: Schematic drawing of the 3D PIC for bio-sensing application. Also shown is the resonant wavelength shift and simulation displaying the WGM of the microdisk.

coupled to a microdisk resonator. Like the microsphere resonator, this novel bio-photonic sensor would detect molecular interaction based on WGMs. However, unlike the microsphere, the smaller footprints of this vertically integrated PIC would allow numerous resonators to exist on one chip, enabling the detection of multi-molecular interaction in real-time. This ultrasensitive bio-photonic circuit would follow the cost and time effective scheme proposed in this paper, making commercialization of these devices feasible.

Development of the PICs using the bottom-up approach pioneered in this project will also enable the creation of more efficient, faster performing, and more cost-effective circuits for telecommunications networks. Novel approaches must be employed to sustain extensive growth in the technology sector. When realized, these PICs will perform the essential photonic processes on a single chip. These devices are predicted to become the platform for flexible all-optical telecommunications systems for mobile communication systems, satellite networks, and other technologies requiring ultrafast (terabit/sec) processing devices that current systems have not realized yet (Kaiser et al., 2002). Moore's Law, which provides the foundation for the development of electronics technology, states that the number of transistors on an IC must double every 18 months. The integration of PICs and ICs will preserve Moore's Law and facilitate the creation of transistors and other circuits with smaller footprints and higher functionalities. The mergence of the photonics and electronics fields will enable the creation of devices which process at terahertz speed instead of the conventional gigahertz speed of ICs. Science and technology have a bright future with the development of three dimensional monolithic PICs.

Works Cited

Chan, W. C., & Nie. S.(1998). Quantum Dot Bioconjugates for Ultrasensitive Nonisotopic Detection [Electronic version]. *Science (*281), 5385, 2016-2018.

Choi, S., Yoo, P., Baek, S., Kim, T., & Lee, H. (2004). An Ultraviolet-Curable Mold for Sub-100-nm Lithography [Electronic version]. *Journal of American Chemical Society* (126), 25, 7744-7745.

Huang, Y., Paloczi, G.T., Yariv, A., Zheng C., & Dalton, L.R. (2004). Fabrication and Replication of Polymer Integrated Optical Devices Using Electron-Beam Lithography and Soft Lithography [Electronic version]. *Journal of Physics Chemistry B.*, 108, 8606-8613.

Kaiser, R.,& Helmut H (2002). Optoelectronic/Photonic Integrated Circuits on InP between Technological Feasibility and Commercial Success [Electronic version]. *IEICE Transactions on Electronics* (E85-C), 4, 970-981.

Pang, L., Tetz, K., Yaoming, S., Chen, C., & Fainman, Y. (2005). Photosensitive quantum dot composites and their application in optical structures [Electronic version]. *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures* (23), 6, 2413-2418.

Parker, A. (2000 August). Mighty Small Dots. *Science and Technology Review*, 20-21.

Rabiei, P., Steier, W.H., Cheng, Z., & Dalton, L.R (2002). Polymer micro-ring modulator with 1 THz FSR [Electronic version]. *Journal of Lightwave Technology* (20), 11, 1968-1975.

Vollmer, F., Arnold, S., Dieter, B., Iwao, T., & Libchaber, A. (2003). Multiplexed DNA Quantification by Spectroscopic Shift of Two Microsphere Cavities [Electronic version]. *Biophysical Journal* (85), 3, 1974-1979.

Whitesides, G. M., & Love, J. C. (2007, September). The Art of Building Small. *Scientific American Reports*, 13-21.

Xia, F., et al (2005). Photonic Integration Using Asymmetric Twin-Waveguide (ATG) Technology: Part 1- Concepts and Theory. *IEEE Journal of Selected Topics in Quantum Electronics* (11), 1077-260X, 17-29.