INTRODUCTION

ELECTRONIC INTEGRATED CIRCUITS (ICs) versus PHOTONIC INTEGRATED CIRCUITS (PICs)

- ICs require the presence of a single active device - the transistor - for the computing and processing functions of the circuit.
- IC's processing speeds are limited since data transmission is dependent on the flow of subatomic particles.
- PICs are structurally complex circuits that require multiple photonic 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).
- Traditional 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 for commercialization.
- PICs rely on the movement of photons, which, if harnessed, could enable the creation of ultrafast (terabit/s), high capacity telecom. devices and networks (Kaiser et al., 2002).

MATERIAL SYSTEMS

- Polymeric materials have replaced traditional semiconductors as material systems for creating PICs because
  - i. the monomers, functional groups, and other structural elements can be altered and
  - ii. they possess an inherently flexible structure (Huang et al., 2004).
- Continuous energy levels exist in bulk semiconductors (>10nm). Quantum dots (QDs) (2-10 nm) or semiconductor nanocrystals, are direct bandgap semiconductors whose intrinsic and discrete luminescent properties result from quantum-size confinement. QDs have discrete energy levels leading to discrete emission wavelengths.
- QDs are highly tunable since the size of the QD determines the bandgap. The wavelength and intensity of the light emitted, along with certain electrical and magnetic properties, can thus be regulated (Parker, 2000).
- QDs exhibit rapid recovery times, retain their emission properties when embedded in polymers, and are not easily degraded. These properties make them highly valuable 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).

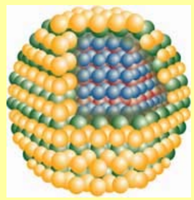

Figure 1: Structure of Evident Technologies Core-Shell Quantum Dot. The nanoparticles are coated with organic molecules known as surfactants in order to provide a stable packing. (http://www.evidenttech.com/)

MICROFABRICATION TECHNIQUES

ELECTRON BEAM LITHOGRAPHY

- Electron beam (E-beam) lithography is the most accurate technique for fabricating PICs. In this process, a photoresist (radiation sensitive polymer) is chemically altered and patterned with structures using a beam of electrons.
- The E-beam fabrication of PICs has limited commercial value due to its limited throughput (PICs can only be produced one at a time) and the price tag of electron beam writers.

PHOTOLITHOGRAPHY

- Photolithography requires the fabrication of a mask (UV transparent material, such as glass) onto which chromium is patterned. The chromium portions of the mask are analogous to a photographic negative that can be used to pattern circuit features onto devices. PICs are realized by:
  - (i) aligning the photoresist-coated substrate under the chromium mask using a contact mask aligner and
  - (ii)UV radiation patterns the structures from the mask onto the exposed photoresist.
- Photolithography successfully mass produced nearly 3 billion transistors per second in the US in the year 2007 (Whitesides et al. 2007). However, the technique depends on an expensive and difficult to modify mask that takes nearly a month to create.

SOFT LITHOGRAPHY

- Soft lithography requires minimal equipment and time to fabricate PICs. Since its development in the early 1990s, several techniques, such as microcontact printing and micromolding, have arisen.
- A master is fabricated, which is used to create a polydimethylsiloxane (PDMS) stamp. PDMS is a viscous and elastomeric polymer with a high molecular weight. When it is cast and cured on the bas-relief template, it produces a negative stamp that can be used to create exact replicas at a high throughput.
- This technique has several shortcomings:
  - (i) fabrication of a mask is 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 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; some research groups claim that a resolution of 1nm is achievable while others claim the structures would be of too low quality to be effective (Huang, et al 2004).

TOP-DOWN versus BOTTOM-UP APPROACH

- Most PICs are currently realized using the top-down approach, which starts with the fabrication of a large scaled device from which individual nanostructures are carved. PICs fabricated using this approach include microchips, PICs on the complementary metal–oxide–semiconductor (CMOS) platform, and Asymmetric Twin Guide (ATG) based PICs.
- The top-down approach is limited by its high cost and the time consumed to fabricate PICs (Whitesides et al., 2007). The PICs created also have large footprints, which prevents commercialization.
- The approach employed in this research builds devices from the bottom up, creating smaller sized and low cost PICs with smaller footprints. 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.

HYPOTHESIS:

Adoption of the bottom-up technique along with innovative material systems and monolithic integration of fundamental photonic functions, will make the realization of commercially accessible 3D PICs possible.

RESULTS (cont.)

VERTICALLY INTEGRATED PIC (cont.)

- The prototype top layer had CdSe QDs that did not wash off since spontaneous emission was exhibited on the entire top layer.
- After switching to CdSe QDs dissolved in hexane, a prototype PIC with a passive bottom layer, an active upper layer, and no intermediary planarizing layer was successfully fabricated.
- During a photoluminescence test, enhanced emission from the CdSe QDs was not exhibited.

Figure 15: High resolution image of a photoluminescence analysis of QD embedded SU-8 3D PIC taken with AFM's CCD camera. (Cheng & Kumar)

TEFLON

- Various Teflon AF2400 solutions were tested. Each solution had Teflon dissolved in 3M FC-40
  - An 11% Teflon AF2400 by weight solution appeared to be solid when completely sonicated.
  - A 1% Teflon by weight solution yielded a homogenous solution that could be spun evenly. Observed under an atomic force microscope and surface profiler, the Teflon layer was found to be too thin (Figure 13).
  - Teflon solutions of higher concentration are being prepared and tested to obtain the desired thickness.

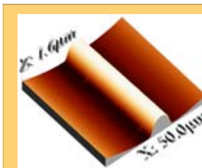

Figure 17: Teflon layer slowly decreasing in thickness towards waveguide. (Cheng & Kumar)

DISCUSSION

- Our first approach to was to create laterally integrated PICs consisting of microdisks and waveguides with lateral separation by utilizing soft lithography. We encountered resolution issues with the replica PICs: the 200 nm gap between the disks and bus waveguides was not well defined (Fig 7, 8).
  - The resolution and material system issues of soft lithography must be resolved to commercially fabricate smaller scale PICs with precision and accuracy before the technique can be effectively used.
- 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, 10, 11). However, these PICs lacked an intermediate planarizing layer, which is the current focus of our experimentation.
  - The viscosity of the Teflon solution has not yet been optimized for the thickness our PICs require; this issue is currently being resolved.
  - Also, 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 self-organization of QDs due to solvent separation. CdSe dots dissolved in hexane were used as an alternative, but the same aggregation issues occurred. The slow stirring process recommended by researchers at the University of California to add the QDs to the SU-8 was also used, but the results did not differ (Pang et al., 2005).
- An active and passive layered PIC analyzed under the AFM's CCD camera did not exhibit any enhanced emission, which is abnormal since QDs retain their luminescent properties after being conjugated (Chan W., et al. 1998).
- 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 a breadth of applications as bio-sensors in biomedical research and as ultrafast and high performance PICs in telecommunications.
  - Surface plasmon microsphere resonators and microsphere bio-photonic resonators based on the phenomenon of whispering gallery modes (WGMs) have led the way for unlabelled, highly sensitive, real-time detection of biological molecular interaction (Vollmer, F. 2005). However, due to production, packaging, and cost constraints, they have limited commercial value.
  - The PIC presented in this project can be used in bio-sensing research as a chip-scale biosensor. This ultrasensitive bio-photonic circuit would follow a cost and time effective scheme, making commercialization of biosensors feasible. Also, this bio-sensor would allow numerous resonators to exist on one chip, allowing detection of multi-molecular interaction in real-time.
- Development of the PICs using the bottom-up approach in this project will also create more efficient, faster performing, and more cost-effective circuits for telecommunications networks.
  - These PICs will perform the essential photonic processes on a single chip and will become the platform for flexible all-optical telecommunications systems for mobile communication systems, satellite networks, and other technologies requiring ultrafast (terabit/sec) processing devices (Kaiser R. 2002).
- Moore's Law states that the number of transistors on an IC must double every 18 months. The integration of PICs and ICs will bolster the opto-electronics field and facilitate the creation of transistors and other devices capable of processing at terahertz speed instead of the conventional gigahertz speed of ICs.

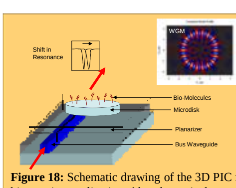

Figure 18: Schematic drawing of the 3D PIC for bio-sensing application. Also shown is the resonant wavelength shift and simulation displaying the WGM of the microdisk. (Menon)

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