3D nano-manufacturing processes for nanophotonic devices and systems

NSF NIRT Grant 0304650
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Nanophotonics is an emerging field at the intersection of photonics and nanotechnology. The University of Colorado Nanoscale Interdisciplinary Research Team (CU-NIRT) is advancing this new discipline by bringing together a team of investigators coming from different backgrounds and disciplines with a new generation of graduate students and postdoctoral researchers.

The primary objective of this project is to establish an interdisciplinary research and education program in a new area of nanomanufacturing involving *scalable* processes for the fabrication of wide-bandgap three-dimensional (3D) photonic crystals (PC) possessing engineered defects and their integration into photonic devices and systems.

It has become clear that new approaches are needed for the miniaturization and integration of optical components into compact functional systems capable of generating, processing, and detecting light signals. Photonic crystals have been recognized as one of the most promising technologies. PCs are structured materials that can exhibit bandgaps for which certain photon modes are not allowed to propagate, providing novel means to control the emission and propagation of light. A key aspect of a PC is the possibility of introducing defects that can control the propagation of light within very small volumes, which is a critical need for large-scale photonic integration.

However, there are strict requirements on spatial resolution and index contrast for the fabrication of PCs. Therefore, the fabrication of 3D PC structures for the visible and IR spectrum remains a considerable challenge. This project addresses three principles that any fabrication technique needs to meet in order to fully realize the potential of the PC paradigm for industrial application and commercialization: *performance, flexibility, and scalability*.

The need to address the fundamental issues of nanophotonic manufacturing requires an interdisciplinary approach. Accordingly, this project builds on the strength of the investigators and combines traditionally unrelated techniques: *atomic layer deposition (ALD), self-assembly of colloidal nanospheres*, *3D femtosecond nanomachining*, and *lithographic processing*. The possibility of integrating dielectrics, metals, and semiconductors opens up additional flexibility for applications such as photonic integrated systems for communications and sensing or selective emitters for thermophotovoltaic systems.

Bottom up and Top down assembly

The possibility of combining bottom-up and top-down approaches opens up new nanomanufacture capabilities. In particular, a technique known as nanoparticle self-assembly is capable of assembling highly mono-dispersed nanoparticles in a close-packing structure and provides an excellent means to create 3D PCs. Recent advances enabled large-scale production of high quality artificial opals and controlled infiltration of optically active materials.

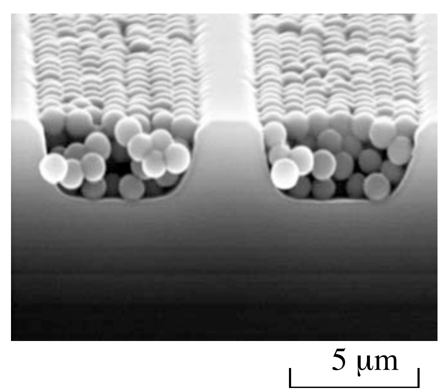

Figure 1. Silica spheres self-assembled in silicon trenches

Self-assembly of nanospheres is a powerful scalable technique that results in periodic structures with a lattice spacing that is accurately determined by the nanosphere size. However, to take full advantage of this technique one must create periodic structures made with the right materials, locate them in well-defined areas and integrate them with other optoelectronic devices. The CU-NIRT group is investigating the monolithic integration of photonic crystals with silicon optoelectronic elements including waveguides, detectors, modulators, and electronics.

The group has fabricated opal structures, selectively grown in dry-etched micro-scale trenches on silicon wafers. The artificial opals are then used as a template for metal electroplating. This process creates metal inverse opal structures confined to specific locations on the wafer. All the processes are compatible with standard silicon microfabrication techniques and provide an attractive method to integrate photonic crystals with CMOS integrated circuits.

The monolithic integration with silicon electronics could result in compact, low-cost building blocks for optical communication systems, optical interconnects, and optoelectronic metrology with improved performance and enhanced functionality.

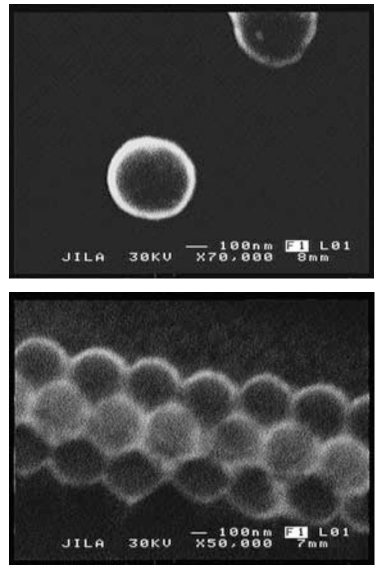

Figure 2: (a) SEM micrograph of silica-gold core-shell particles (Core diameter: 365 nm, estimated shell thickness: 20 nm), and (b) The self-assembled structure of core-shell

Conformal nanolayer deposition

Theoretical studies predict that opal structures made of metal-coated dielectric spheres should exhibit wide photonic bandgaps without the need for inversion. The CU-NIRT has developed a new process for metal shell growth. In this method, gold nanoparticles are first embedded in silica particles to form silica cores with some degree of affinity to gold nanoparticles. The subsequent gold shell growth process has been carefully studied and optimized to produce continuous and uniform gold shells with controlled thickness. Both scanning electron micrographs (SEMs) and optical spectra confirmed the formation of uniform and continuous gold shells. These shells were further coated with silica for the subsequent self-assembly process. The formation of metal-dielectric opals was verified by SEM micrographs (Fig. 2). These metal-dielectric opals are expected to exhibit wide and robust 3D photonic bandgaps and will therefore serve as an excellent platform for 3D nanophotonic devices and systems.

Another promising technique for the creation of nanolayers is atomic layer deposition (ALD). ALD grows conformal films of a wide variety of materials. ALD is a subset of chemical vapor deposition (CVD). Unlike conventional CVD, the substrate is only exposed to one reactant at a time. This temporal separation eliminates gas phase reactions and allows every available surface site to react under an excess of the precursor. After every available site has reacted with the first precursor, the reaction stops in a self-limiting fashion. The precursor can then be purged

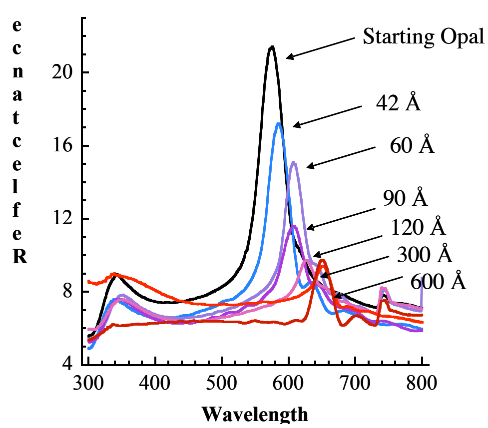

Figure 3: Tuning of the optical response of synthetic opals using conformal atomic layer deposition.

from the reactor and the next precursor can be exposed to the new surface sites on the substrate.

Aluminum oxide was used to investigate how an ALD film fills the voids of synthetic opals. Figure 3 shows optical results for synthetic opals infiltrated with Al_2O_3 ALD. The plot displays a shift in optical properties as the Al_2O_3 ALD film becomes thicker. This system will allow us to predict how other ALD systems will fill the colloidal crystal.

Ultrafast nanomachining of dielectrics and composites

Ultrashort light pulses are used to concentrate energy in a time interval of a few optical cycles and produce extremely high peak powers with moderate pulse energies. In this project we use tightly focused femtosecond pulses to modify the physical properties of dielectric materials on a sub-micron scale. We are taking advantage of such pulses for nanofabrication in three dimensions.

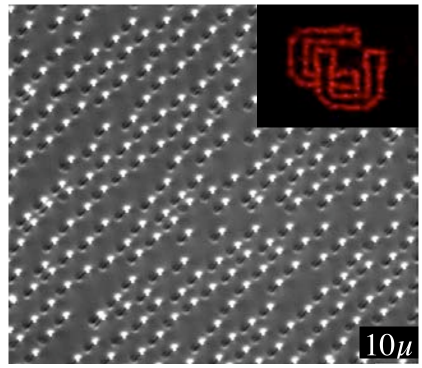

Figure 4: Detail of a 3D aperiodic modulated grating for the generation of prescribed diffraction patterns (DIC microscope). The insert shows the far-field diffraction pattern of the structure.

A proper system design for the delivery of ultrafast high-repetition rate pulses has led the CU-NIRT to demonstrate the lowest pulse-energy modifications using unamplified pulses. The group has also created high-quality 3D waveguides and demonstrated their use in high speed optical interconnects, as required for future chip-to-chip and on-chip communication.

Another fascinating area of application is the creation of three-dimensional diffractive structures such as high efficiency gratings. The group has demonstrated for the first time 3D computer-generated aperiodic modulated gratings for the generation of diffraction patterns (see Fig. 4).

Education and Outreach

In order to create a successful program, well-defined partnerships have been established with the National Institute of Standards and Technologies, Agilent technologies laboratories, and the NAVAIR Navy Research laboratories.

The CU- NIRT program is designed to provide students with a very solid scientific and technical training in the basic areas of nanophotonics so they will be well qualified for employment in a wide variety of disciplines. Towards this goal CU - NIRT and the Research Labs at NAVAIR in China Lake have established a new partnership for graduate training and professional development in nanophotonics. The program is based on an interdisciplinary approach to graduate education and research that will create a diverse and well trained workforce with ties to the Navy and capable of generating an accelerated transition of the latest university research into applications in the Navy.

Several other educational and outreach activities are underway: (1) Various presentations to the local industry have been given, including the organization of meetings and poster presentations with the Colorado Photonics Industry Association. (2) Undergraduate students have participated of the research. (3) New courses are being developed or modified to incorporate the outcome of the research. (4) A series of seminars and meetings on nanotechnologies is underway. (5) A new website is under development.

* For further information about this project link to http://ece.colorado.edu/~piestun/CU-NIRT.htm or email piestun@colorado.edu