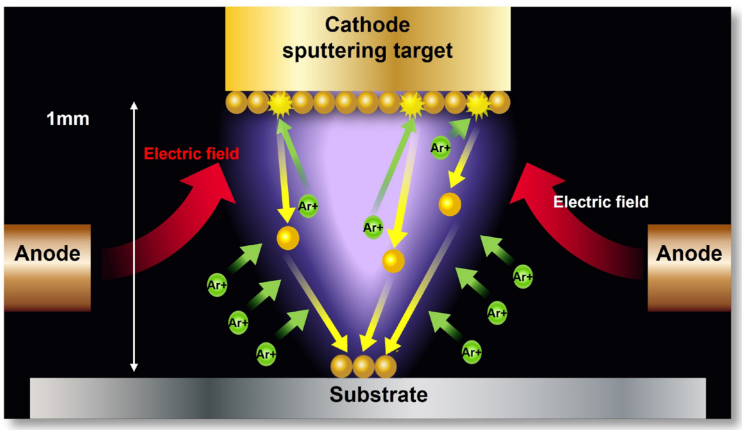
Semiconductor Manufacturing and Supply Chain

Plasma Microsputtered Materials for Agile Manufacturing of Electronics and Microsystems

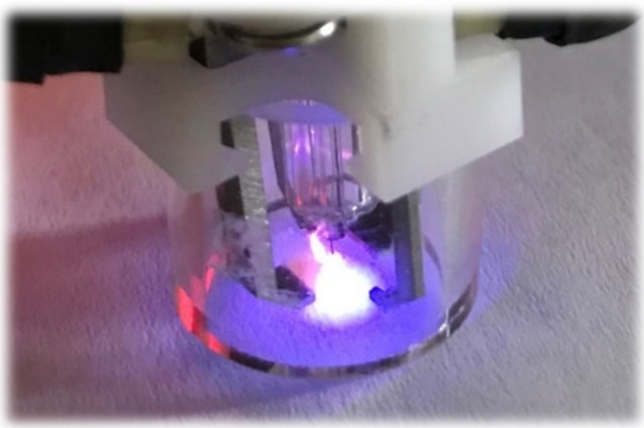
N. Lubinsky, L. Parameswaran, R. Mathews, L. M. Racz, L. F. Velásquez-García
Sponsorship: Kansas City National Security Campus

Agile manufacturing of electronics and microsystems could benefit from and be enabled by additive manufacturing technology capable of depositing high-quality thin films in non-planar, temperature-sensitive surfaces. Our approach utilizes a direct current (DC) microplasma generated at ambient temperature and pressure, obviating the need of a vacuum. Using a three-dimensional stage that rasters the microsputterer head across space, freeform planar structures made of high-quality materials can be deposited on non-planar surfaces. Moreover, using a multi-material sputtering head can monolithically fabricate objects that attain complex functionalities.

The basic functionality of the DC microsputterer is shown in Figure 1, where 4 electrodes help guide ions to a narrowly defined region while argon gas flow sustains the plasma. Additionally, the laminar gas flow works to further constrain the sputtered material into thin trace films, as ions collide and interact with the fluidic forces at work, collectively driving "ionic drag" that acts as a net focusing effect. This can be seen in the synthesized, additively manufactured sputter head in action shown in Figure 2. Current efforts focus on synthesizing the next generation of microsputtering write heads and conducting simulations to improve deposition yield and explore new modes of operation.



◀ Figure 1: Conceptual schematic of microsputtering head using gold wire as feedstock. The combination of electric fields and laminar gas flow helps project and focus the sputtered material onto printing surface. Adapted from Kansas City National Security Printed Electronics Consortium Proceedings.



◀ Figure 2: Picture of microplasma printer head generating gold trace on paper substrate. Adapted from Kansas City National Security Printed Electronics Consortium Proceedings.

FURTHER READING:

- Y. Kornbluth, R. H. Mathews, L. Parameswaran, L. Racz, and L. F. Velásquez-García, "Fully 3D-printed, Ultrathin Capacitors via Multi-material Microsputtering," *Advanced Materials Technologies*, vol. 7, no. 8, p. 2200097, 2022, doi: 10.1002/admt.202200097.
- Y. Kornbluth, R. H. Mathews, L. Parameswaran, L. Racz, and L. F. Velásquez-García, "Nano-additively Manufactured Gold Thin Films with High Adhesion and Near-bulk Electrical Resistivity via Jet-assisted, Nanoparticle-dominated, Room-temperature Microsputtering," *Additive Manufacturing*, vol. 36, p. 101679, 2020, doi: 10.1016/j.addma.2020.101679.
- Y. Kornbluth, R. H. Mathews, L. Parameswaran, L. Racz, and L. F. Velásquez-García, "Room-temperature, Atmospheric-pressure Deposition of Dense, Nanostructured Metal Films via Microsputtering," *Nanotechnology*, vol. 30, no. 28, p. 285602, 2019, doi: 10.1088/1361-6528/ab1281.

One-class Anomaly Detection Using Kernel Density Estimation Methods for Semiconductor Fabrication Processes

R. Owens, F.-K. Sun, C. Lang, B. Lawler, D. S. Boning
Sponsorship: Analog Devices, Inc.

In semiconductor fabrication processes, undetected faults can be extremely costly. Machine learning has allowed for advances in fault detection and classification, but there are still difficulties in applying these techniques to the monitoring of fabrication processes. Concept drift, infrequency of faults, and differences between processes, tools, and recipes all present challenges distinct to the semiconductor industry.

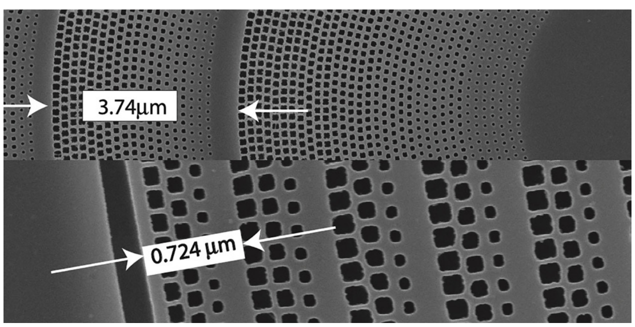
In this work, we present a one-class time series anomaly detection method that uses univariate sensor data to detect faults in semiconductor fabrication processes. The proposed method uses kernel density estimation (KDE) to create probability distributions for nominal process runs. Incoming sensor data can then be compared to these trained distributions to determine the likelihood that the new signal is nominal or anomalous. Critically, the use of a first-in, first-out queue for creating the probability distributions allows for the model to adapt to new conditions, thus overcoming the challenge of concept drift. The KDE method can be combined with techniques for transfer learning, which enables startup of the anomaly detector with as little as 25 previous process runs. This allows for model information to be transferred between similar tools or recipes, even ones that are used infrequently. We also consider the use of dynamic time warping to improve the accuracy of the sensor probability distributions. The proposed KDE methods are tested on historical data from plasma etch and ion implantation processes, outperforming benchmark methods including traditional statistical process control (SPC), one-class support vector machine (OC-SVM), and variational auto-encoder (VAE) based detectors.

Diffractive-optical Microlenses for Maskless Photolithography

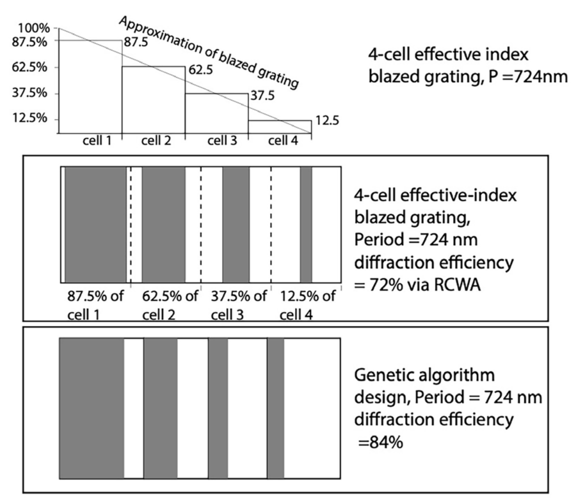
H. I. Smith, M. Mondol, F. Zhang, T. Savas, M. Walsh
Sponsorship: LumArray, Inc.

Maskless lithography plays an important role in nanostructures research by avoiding the delay and cost of mask manufacture. Maskless photolithography, using an array of diffractive-optical microlenses, offers the additional advantages of full-wafer areas and long-range spatial-phase coherence, a feature that is essential in photonic and other advanced applications. To improve the focal efficiency and resolution beyond that of the binary pi-phase zone plates currently employed and to exceed the depth-of-focus characteristic of classical lenses, diffractive-optical microlenses (also called metalenses) each 135 microns in diameter and operating at 405 nm wavelength are investigated theoretically and experimentally. A microlens is first divided into Fresnel zones, across which the effective index-of-refraction is modulated by forming appropriate pillars or holes such that beams diffracted from the zones interfere constructively at the focal spot, located 100 microns in front of the microlens plane.

The diffraction efficiency of each zone is evaluated using rigorous coupled-wave analysis (RCWA). A genetic algorithm is then used to determine if higher efficiency can be achieved by repositioning of the pillars or their widths. MEEP software is used to predict focal efficiency of the complete microlens. Scanning-electron-beam lithography was used to fabricate effective-index-modulated metalenses in CSAR-62 e-beam resist. Focal efficiencies up to 54% were achieved, a significant increase over zone plates. However, problems with stability and dimensional control favor reactive-ion etching over direct exposure. In a dielectric of 1.9 index, the maximum height-to-width ratio is about 10-to-1. Theoretical models and experimental results indicate that extreme precision in fabrication, on the order of 10 nm, well below the 213 nm wavelength within the dielectric, is needed to achieve theoretical expectations.



◀ Figure 1: Scanning-electron micrograph of hole-based effective-index modulation: (upper) central zone (9 micron radius) and next zone (3.74 micron width). (lower) outer 5 zones. Dielectric was electron beam resist (CSAR-62) with refractive index of 1.59. Maximum focal efficiency of 54% was measured.



▶ Figure 2: (upper and middle) Schematics of linearly varying refractive index by effective-index modulation across 4 sub-wavelength cells. (lower) Genetic algorithm maximizes diffraction efficiency by adjusting widths and locations of pillars specified by effective-index model, illustrating necessity of precision control of dimensions and lateral position to achieve maximum efficiency and lowest background.

FURTHER READING

- H. I. Smith, R. Menon, A. Patel, D. Chao, M. Walsh, and G. Barbastathis, "Zone-plate-array Lithography: A Low-cost Complement or Competitor to Scanning-electron-beam Lithography," *Microelectronic Engineering*, vol. 83, pp. 956-961, 2006.

Sub-micron Defect-free and Freestanding Microporous Poly(Arylene Ether) Thin Films for Membrane-based Gas Separations

J. Y. Yeo, G. Sheng, F. M. Benedetti, D. Syar, T. M. Swager, Z. P. Smith
Sponsorship: ENI, Office of Naval Research – Young Investigator Program (ONR-YIP)

Membrane-based gas separations are viewed as a critical component to accessing low-energy feedstocks and decarbonizinge the chemical industry. However, it is exceedingly challenging to synthesize membrane materials that are high performing, scalable, and processable especially at the nanometer scale. It requires the polymer to have a high molecular weight while still being soluble in organic solvents. As a class of materials, microporous organic polymers (MOPs) have been attracting significant attention for membrane-based gas separations due to their high gas permeability as compared to current commercial polymers. For this project, we present the rational design and synthesis of a new class of linear microporous poly(arylene ether)s (PAEs) via Pd-catalyzed C-O polymerization reactions. The scaffold of these new microporous polymers consists of rigid three-dimensional triptycene and highly stereocontorted spirobifluorene, which endow these polymers with large internal free volume as well as high porosity with angstrom-sized pores. Unlike classic polymers of intrinsic microporosity (PIMs), this robust methodology for the synthesis of poly(arylene ether)s allows for the facile incorporation of functionalities and branched linkers for control of permeation and mechanical properties. This allowed for the fabrication of a submicron defect-free film with permeance-selectivity property sets that are comparable to high-performance ultrathin polymer membranes reported in the literature. The structural tunability, high physical stability, and ease-of-processing suggest that this new platform of microporous polymers provide generalizable design strategies to address outstanding separation challenges for gas separation membranes.