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Fundamentals of Embossing Nanoimprint Lithography in Polymer Substrates

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Fundamentals of Embossing Nanoimprint Lithography in Polymer Substrates

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Abstract

The convergence of micro-/nano-electromechanical systems (MEMS/NEMS) and biomedical industries is creating a need for innovation and discovery around materials, particularly in miniaturized systems that use polymers as the primary substrate. Polymers are ubiquitous in the microelectronics industry and are used as sensing materials, lithography tools, replication molds, microfluidics, nanofluidics, and biomedical devices. This diverse set of operational requirements dictates that the materials employed must possess different properties in order to reduce the cost of production, decrease the scale of devices to the appropriate degree, and generate engineered devices with new functional properties at cost-competitive levels of production. Nanoscale control of polymer deformation at a massive scale would enable breakthroughs in all of the aforementioned applications, but is currently beyond the current capabilities of mass manufacturing. This project was focused on developing a fundamental understanding of how polymers behave under different loads and environments at the nanoscale in terms of performance and fidelity in order to fill the most critical gaps in our current knowledgebase on this topic.

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1. SUMMARY OF PROJECT

The mechanical forming of polymers is ubiquitous in the manufacture of consumer products, electronics, and materials for biotechnology. Technologies that enable the mechanical formation of polymer microstructures or nanostructures were invented in the mid-1990's, with the related research and development focusing on applications in nano-electronics.

This PECASE LDRD focused on providing answers to three main questions:

1. Can we develop a fundamental understanding of polymer flow at micrometer and nanometer length scales and thereby enable design tools for the mechanical formation of polymer microstructures and nanostructures?
2. Can we use our knowledge of manufacturing polymer microstructures and nanostructures be scaled up to large sizes and shapes relevant to the engineering of real components and systems?
3. Understanding that molded polymers are used in nearly every application in all of biotechnology - can we use polymer microstructures and nanostructures for novel biotechnological applications?

These questions were addressed in research supported by a DOE-NNSA PECASE LDRD awarded to Prof. William P. King of UIUC over the period 2005-2010. There were numerous papers on the outcome of this research. Here we summarize the main findings, leaving the deep technical details to be found in these articles (a list of the references are included in this document).

The following paragraphs detail the major findings of this project:

Fundamentals of Nanometer-Scale Polymer Mechanical Behavior

Miniature probe tips with integrated heaters allow for precise mechanical measurements at the nanometer-scale. Such probe tips can measure sub-nm displacements and sub-nN forces while the probe temperature is monitored and controlled. In the attached papers, we show how such probes can measure the elastic, plastic, and viscoelastic properties of polymer films. The main idea of the early papers is that one can use a heated probe to make quantitative mechanical response measurements of polymers at the nanometer scale, and include the effects of temperature. As the research matured, we began to look at how the properties of polymers at the nanometer scale can be different than polymers at macroscopic scales. On our Science paper from 2008, we show that plastic yield, elastic modulus, and viscosity are all different for polymer films of nanometer-scale thickness and high molecular weight rather compared to thick films of low molecular weight.

Manufacturing Polymer Microstructures and Nanostructures

The above studies of polymer flow at micrometer and nanometer scales provided the basis for work on manufacturing polymer microstructures and nanostructures using mechanical forming and embossing. We usually begin with microstructures or nanostructures fabricated onto a silicon wafer using standard processes, and then replicate those structures into a polymer sheet.

One advantage of using polymers in manufacturing is their mechanical flexibility. This flexibility – the ability to bend or distort polymer sheets – allows us to transform microstructures or nanostructures formed on flat, rigid silicon wafers onto polymer sheets that can be bent and formed into three-dimensional shapes. The curved, microstructured polymer can then be used in that form or can serve as a mandrel for further manufacturing steps, such as for the casting of another polymer, a ceramic, or a metal. The resulting part can then have the size and shape of a real engineering material while preserving the microstructures from the original silicon template.

Polymer Microstructures and Nanostructures for Cell Culture Substrates

Microstructures and nanostructures fabricated onto polymer surfaces present outstanding opportunities for biomedical devices. Such microstructures or nanostructures can direct the growth or differentiation of cells, can affect the surface wetting characteristics, or can increase the surface area for biomaterial adhesion. Molded polymers are ubiquitous in the biotechnology laboratory. They are used in cell culture dishes, test tubes, and as hardware in many assays. This project focused on developing microstructured and nanostructured polymer substrates for cell cultures. We additionally developed ways to combine microstructures and nanostructures with microscale chemical patterns.

List of Papers Supported by this PECASE Award

E. Wornyo et al., **Nanoindentation of shape memory polymer networks**, *Polymer*, 2007, 48, 3213-3225

F Yang et al., **Nanoscale indent formation in shape memory polymers using a heated probe tip**, *Nanotechnology*, 2007, 18, 285302 (8pp)

H.D. Rowland and W.P. King, **Predicting Polymer Flow during High-Temperature Atomic Force Microscope Nanoindentation**, *Macromolecules*, 2007, 40, 8096-8103

H.D. Rowland et al., **Measuring Glassy and Viscoelastic Polymer Flow in Molecular-Scale Gaps Using a Flat Punch Mechanical Probe**, *ACS Nano*, 2008, 2(3), 419-428.

H.D. Rowland et al., **Molecular Confinement Accelerates Deformation of Entangled Polymers During Squeeze Flow**, *Science*, 2008, 322, 720-724.

A.H. Cannon and W.P. King, **Casting metal microstructures from a flexible and reusable mold**, *J. Micromech. Microeng.*, 2009, 19, 095016 (6pp)

A.H. Cannon and W.P. King, **Microstructured metal molds fabricated via investment casting**, *J. Micromech. Microeng.*, 2010, 20, 025025 (7pp)

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