Hydrogels have been an active area of research for a variety of applications due to their ability to retain large volumes of water within their polymer gel networks. Stimuli-responsive hydrogels provide the added advantage of the ability to control the water retention by means of external stimuli. For example, N-isopropylacrylamide (NIPAAm) is a thermosensitive hydrogel that exhibits a Lower Critical Saturation Temperature (LCST) around 32°C, above which the gel becomes hydrophobic and expels the water molecules, resulting in a drastic swelling/shrinking ratio. The goal of this project is to utilize this pseudo-binary transition in the fields of microfluidics and drug delivery.

By imbedding magnetic nanoparticles into the gel networks, the Hamad-Schifferli group [1] could control the temperature of the gels by inducing eddy currents by means of an oscillating magnetic field. We are developing the concept further into micro-scale devices that can be monolithically integrated into many microfluidic systems. We have demonstrated the ability to photopattern the hydrogels and have shown control of the swelling behavior by controlling the amount of cross-linking in the network. This allowed for the creation of hydrogel valves for microfluidic devices. Unlike pressure controlled valves, these valves do not require any physical interconnects to macro-scale devices. This advantage could prove extremely useful in the commercialization of microfluidic analysis systems where users might not have equipment such as syringe pumps or air compressors available. In addition to valves, applications of the swelling behavior to micropumps are also being examined.

Figure 1: (a) Controlable microfluidic valve activated by means of external magnetic field. (b) NIPAAm MIT logo with top of “T” removed from substrate.

REFERENCES
Thermal Ink Jet Printing of Lead Zirconate Titanate Thin Films
S. Bathurst, H.W. Lee, S.G. Kim
Sponsorship: DARPA, Hewlett-Packard

The ferromagnetic and piezoelectric properties of ceramic lead zirconate titanate (PZT) thin films have made PZT an appealing choice for micro-sensors and actuators. Significant work has been done integrating PZT with standard MEMS processes, including the development of PZT sol-gels for spin coating [1-2]. Cracking is often a problem with PZT spin coating due to the brittle nature of the films coupled with the thermal strain experienced during annealing. This propensity for cracking limits the overall thickness deposited and the size out of plane features over which PZT can be reliably coated. Furthermore, spin coating requires a large volume of the expensive PZT precursor solution. We propose thermal ink-jet printing of a modified PZT sol-gel as a new method of depositing PZT films for MEMS applications. Preliminary work has shown ink jetting to be a reliable method for depositing PZT films of the correct thickness for MEMS applications and that annealed films can crystallize into the piezoelectric perovskite phase using the same thermal process developed for spin-coated PZT (see Figure 1) [3]. The goal of this research is to develop a deposition process that will enable reliable manufacturing of high-quality PZT films with greater deposition flexibility and lower material costs than spin coating.

Thermal ink jetting technology supports a wide range of ink viscosities and solid particle contents. The ink composition can therefore be adjusted to control both the contact angle of solution with the substrate (1000Å Pt/ 200Å Ti) and the as-deposited film thickness. This flexibility allows for the deposition of films with thickness and uniformity that are acceptable for the fabrication of piezoelectric devices (see Figure 2). Multiple layers can be deposited to attain the thickness as needed. Currently, annealed films have been prepared as thick as 0.5 µm, corresponding to an as deposited thickness of approximately 1 µm. This is comparable to the current limit of standard spin-coated PZT sol-gel processed; printing of thicker films is under investigation.

We acknowledge Hewlet Packard for providing the POEMS thermal ink-jet printer.

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**Figure 1:** Comparison of X-ray diffraction of spin-coated PZT film with thermal ink-jetted film.

**Figure 2:** Optical microscope image and profilometry of as deposited thermal ink-jetted lead zirconate titanate thin film.

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**References**


MIT-OSU-HP Focus Center on Non-lithographic Technologies for MEMS and NEMS

Sponsorship: AFOSR

This newly formed center is part of an overall set of centers on MEMS/NEMS fundamentals supported by DARPA. The MIT-OSU-HP Focus Center aims to develop new methods for fabrication of MEMS and NEMS that do not use conventional lithographic methods. The Center leverages the leading expertise of MIT and OSU in MEMS and printed devices, with the printing expertise of HP. The focus center is organized into four primary areas: tools, materials and devices, circuits, and demonstration systems.

In the area of tools, we are leveraging the existing thermal inkjet (TIJ) technology of HP and augmenting it with specific additional features, which expand the palette of available materials for printing. We are developing materials and devices over a broad spectrum from active materials, photonic and electronic materials, to mechanical materials. In the circuits area, we are studying the behavior of the devices that can be realized in this technology with the goal of developing novel circuit architectures. Lastly, we intend to build several “demonstration” systems that effectively communicate the power of the new technologies that will emerge from this center.

Figure 1: An HP TIPS system for direct printing of a wide range of MEMS and electronic/photonic materials.

Figure 2: Examples of printed optical and electronic devices.
Transplanting Assembly of Single-strand Carbon Nanotubes

S. Kim, H.W. Lee, S.G. Kim
Sponsorship: Intelligent Microsystems Center

Most of the potential applications of carbon nanotubes (CNTs) such as field emitters, scanning probe microscopy (SPM) tips, and nanowire interconnection require deterministic assembly techniques with control of shape (diameter and length), orientation, location, and range. We are developing a new deterministic assembly method for single strand CNTs such that the individual CNTs can be integrated into micro-scale devices. For this purpose, we propose and demonstrate a concept of transplanting assembly of individual CNTs. An array of nickel catalytic dots is seeded at the predefined locations on a titanium deposited silicon wafer using electron beam lithography followed by a metal liftoff process. An array of vertically aligned CNTs is grown from the Ni catalysts (Figure 1) using plasma enhanced chemical vapor deposition (PECVD) machine developed by Micro & Nano Systems Laboratory of MIT [1-2]. Each single strand CNT is embedded into polymer blocks, which work as CNT carriers. A 1.5-μm-thick positive photoresist is coated on the silicon wafer before 20-μm-thick negative photoresist (SU8 of MicroChem Corp.) is coated on top of it. The SU8 layer is patterned into cylindrical blocks. Finally, each SU8 block encapsulating one single-strand CNT is released by removing the positive photoresist layer (Figure 2). Each released SU-8 block can be transplanted to the location of interest using the assembly methods readily available at the micro scales.

Figure 1: An array of vertically aligned single strand CNTs. CNTs were grown straight on the seeded area, and the enlarged view shows that each CNT has a uniform diameter from the top to the bottom.

Figure 2: An SU8 block with a single CNT on one side. The length of the extruded CNT is 1.5μm, and this is the same as the thickness of the positive photoresist layer.

REFERENCES


A Large-strain, Arrayable Piezoelectric Microcellular Actuator by Folding Assembly

Z.J. Traina, S.G. Kim
Sponsorship: Korean Institute of Machinery and Materials

A low-power, piezoelectric, contracting cellular MEMS actuator has been developed that demonstrates a peak strain of 3% under a 10 V stimulus. Since the motion of the end effector is linear and in-plane, the actuator can be arrayed in series to amplify the total stroke or in parallel to amplify the total force, as needed. Location of the piezoelectric member through the structural center of stiffness reduces the potential for parasitic out of plane bending present in previous designs [1].

Cellular actuators arrays can be assembled into a larger array of actuators. We demonstrated that sets of cellular microactuators can be assembled out of plane by folding them over thin gold hinges. To our knowledge, this study is the first effort in this field. The gold hinges serve dually as mechanical assembly guides and electrical interconnects. Long chains of devices may be assembled by rolling out of plane. Figure 2 shows a smaller collection, assembled by folding three actuator triplets onto one another. Actuation of the collection is contingent on the manufacturing of functional thin-film PZT.

Figure 1: An array of three cellular actuators fabricated in series, which demonstrates a total static displacement of more than 15 µm under 10V stimulus. The strain of the assembly exceeds that of unmodified PZT by a factor of more than 29:1.

Figure 2: A total of 9 actuators (three actuator triplets) assembled into one collection by folding out of plane over gold hinges. Actuation of a folded device collection is contingent on the manufacturing of functional thin film PZT.

REFERENCES

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Sponsorship: NSF, Korean Institute of Machinery and Material

A novel thin-film, lead zirconate titanate Pb(Zr,Ti)O$_3$ (PZT), energy-harvesting MEMS device is being developed for autonomous wireless monitoring systems. It is designed to harvest energy from parasitic vibrational energy sources and convert it to electrical energy via the piezoelectric effect. We envision that harvesting parasitic energy from the vortex-induced vibration of the oil pipelines will deploy a massive number of microsensors along the hundreds of miles of pipeline in very cold and remote areas. The proposed system consists of a corrosion sensor, a radio transceiver, a microcontroller, a power management module, and a piezoelectric micro power generator (PMPG) to supply the needed power of the system without replacing batteries.

The new pie-shaped design for the harvester (about a size of a nickel) has a radical departure from previous design concepts. This energy harvester design can be regarded as revolutionary as the first self-rectifying piezoelectric power generator. The new design avoids the high Q resonance, which is also a big change from previous designs. This will enable more robust power generation even if the frequency spectrum of the source vibration varies unexpectedly. Furthermore, the beam shape is optimized to achieve uniform allowable strain throughout the PZT layer. Currently, the first prototype, which is shown schematically, is being fabricated at MTL.

Figure 1: Wireless sensor system schematics. The self-powered sensor node transmits data to a receiver at the base station.

Figure 2: The structure of a pie-shaped PMPG.

REFERENCES

MEMS Vibration Harvesting for Wireless Sensors
W.S. Kim, A. Mracek, Y. Manioloux, B.L. Wardle (in coll. with S.G. Kim)
Sponsorship: AFOSR, NSF Fellowship

The recent development of “low power” (10’s-100’s of μW) sensing and data transmission devices, as well as protocols with which to connect them efficiently into large, dispersed networks of individual wireless nodes, has created a need for a new kind of power source. Embeddable, non-life-limiting power sources are being developed to harvest ambient environmental energy available as mechanical vibrations, fluid motion, radiation, or temperature gradients [1]. While potential applications range from building climate control to homeland security, the application pursued most recently has been that of structural health monitoring, particularly for aircraft.

This SHM application and the power levels required favor the piezoelectric harvesting of ambient vibration energy. Current work focuses on harvesting this energy with MEMS resonant structures of various geometries. Coupled electromechanical models for uniform beam structures have been developed to predict the electrical and mechanical performance obtainable from ambient vibration sources. The optimized models have been validated by comparison to prior published results [2] and verified by comparison to tests on a macro-scale device [3]. A non-optimized, uni-morph beam prototype (Figure 1) has been designed and modeled [4-5]. Dual optimal frequencies with equal peak powers and unequal voltages and currents are characteristic of the response of such coupled devices when operated at optimal load resistances (Figure 2). Design tools to allow device optimization for a given vibration environment have been developed for both geometries. Future work will focus on fabrication and testing of optimized uni-morph and proof-of-concept bi-morph prototype beams. System integration and development, including modeling the power electronics, will be included.

REFERENCES

\[\text{Figure 1: Illustration of MPVEH uni-morph configuration (left) and SEM of a prototype device.}\]

\[\text{Figure 2: Power vs. normalized frequency with varying electrical load resistance [4].}\]