SINGLE MATERIAL MEMS/NEMS

What is Single Material MEMS (SMM)?

Basic Concept:
- Undoped Poly-C (10^{12} \ \Omega \cdot cm) ➤ Mechanical Material
- Lightly-doped Poly-C (p, 1-10 \ \Omega \cdot cm) ➤ Sensor
- Highly-doped Poly-C (p', 10^{-3} \ \Omega \cdot cm) ➤ Interconnect

Why Diamond SMM?
- Electrochemical Potential Window = ± 3 V (± 6 to ± 2 V)
- Dielectric Constant = 5.7
- Saturation Velocity = 27 x 10^{6} \ \text{cm/s}
- Chemical inertness & Stability
- Young's Modulus = 10^{12} \ \text{Pa}
- Background Current = 1 nA
- Breakdown Field = 10 MV/cm
- K = 20 W/K °C
- Resistant to Fouling
- \mu_s = 1.600 \ \text{cm}^2/V \cdot \text{s}
Stress Sensors were fabricated to inspect the residual stress of the poly-C film grown under the optimized growth condition. The invisible displacement of indicators shows very small residual stress in the poly-C thin film.
Poly-C SMM technology includes the deposition of high quality poly-C thin films and the challenge to achieve insulating and semiconducting poly-C thin films. Arguably, the most important technology is poly-C patterning. Finally, the technical issues of building multilayer structures made of poly-C will be addressed.
One problem with undoped poly-C is that it is not highly insulating. The resistivity is on the order of $10^3 \ \Omega \cdot \text{cm}$. Introducing O2 during poly-C growth can increase the bulk resistivity to $10^8-10^9 \ \Omega \cdot \text{cm}$. Typically a four-point probe method, with a probe tip contact area in the range of 400 $\mu$m², is used for resistivity measurements. However, it is very difficult to measure the high resistivity. In the present study, an undoped poly-C resistor was first patterned on top of thermal SiO2, followed by the patterning of metal interconnects with a four-point probe measurement setup. Using this approach, the contact area was increased by five orders of magnitude, making it possible to measure the high resistivity of undoped poly-C.
Lightly Boron-doped poly-C has piezoresistive effect, which makes poly-C a good candidate for a sensor material. A novel all-diamond structure is built to characterize the piezoresistive effect to derive the gauge factor. In this structure, the undoped poly-C is used as a structural material and insulator. The highly-doped poly-C is used as interconnect for electrical conduction. This structure was built based on Single-Material MEMS concept. The resistivity of piezoresistor is selected to be 22 $\Omega \cdot \text{cm}$ in consideration of the signal to noise ratio. The released structure is shown in this figure. The piezoresistor is shown in this close-up view. The beam bending method is used to derive the gauge factor. The relative change of the resistance as a function of the microstrain can be plotted as shown. The gauge factor of 20-28 can be estimated from the slope.
Poly-C patterning is performed as follows. Al is used as a hard mask during the dry etching of poly-C. Since diamond is inert to all wet chemical etching solutions, a sacrificial SiO2 layer or Si substrate can be removed by wet etching, leaving a free-standing poly-C film.
Surface roughness can affect high resolution patterning. By using an optimized photolithography recipe and lift-off process, a narrow Al layer can be patterned on a rough poly-C surface successfully.
Regarding the minimum size of diamond MEMS features, we have produced beams of 400 nm wide. This shows that the device width can be even smaller than the grain size. Therefore it is possible to build a single crystal sensor within one grain of poly-C.
Etching recipes have been developed for different thicknesses of poly-C to achieve smooth surfaces on the underlying layer (Si, SiO₂ or Si₃N₄) after the removal of poly-C.

- To dry etch thin poly-C layers, only O₂ plasma is needed.
- To dry etch thick poly-C layers, a 3-step etching recipe is developed.

**Step 3 Poly-C Etching in H₂ Plasma**

First, poly-C is grown on Substrate. Then CF₄ plasma is used to etch the poly-C layer until only a thin poly-C layer remains. Next, O₂ plasma is used to remove the rest of poly-C without damaging the underlying substrate. Diamond needles are always created in O₂ plasma. The removal of diamond needles through O₂ etching can take an extremely long time. So H₂ etching is used as the last step to remove the diamond needles. Patterned diamond films with preserved SiO₂ and Si can be seen.
The Etch rate, selectivity and aspect ratio of poly-C dry etching were studied to optimize the process.
By patterning poly-C with Inductively Coupled oxygen Plasma, both the aspect ratio and the etch rate can be improved as shown in the figure.
Since low seeding densities can lead to discontinuities of diamond thin films, seeding density has been optimized to ensure continuous surface conformity over large step heights (> 6μm) with insignificant powder aggregation.
A typical fabrication process of SMM structures is as following using SiO2 as sacrificial layers.
Many structures based on the SMM fabrication technology were built to inspect the fabrication process. Here shows the structures used to inspect the vertical gap. The top poly-C layers in the figures are 2-um above the bottom layer. Here is another similar structure. Ideally, a small gap of several hundreds of nm is possible when a high quality and low stress SiO2 layer is used.
The minimum lateral gap using RIE was also investigated. A small gap not only requires high resolution of photolithography but also a dry etching process with excellent aspect ratio. Unfortunately, due to the high roughness of poly-C surface, the minimum lateral gap for a 2 µm thick poly-C layer is ~3 µm using RIE. Using ICP, sub-micron lateral gaps have been realized. After an initial study of lateral gap, we fabricated a combdrive as shown in the picture on the right.
RFMEMS is an application of interest for SMM. This slide shows a capacitive MEMS structure where both the detection and excitation are capacitive. The bottom poly-C layer consists of undoped poly-C and doped poly-C which were patterned together. The bottom poly-C layer is used for the I/O pads and interconnects. The top doped poly-C layer is used for resonators. Close-up views are shown here. The main focus has been developing technology of different RFMEMS structures.
The fabricated integrated field emission device is shown. The fabrication is a 4-mask process which uses SiO2 as a sacrificial layer. The SEM on the top left shows the micro-tip array made of diamond pillars. The SEM on the bottom left shows the gap between poly-C anode and cathode. One of the challenges in this process is to create separate diamond pillars on a continuous poly-C cathode. This needs precise control of the etching time.
RFMEMS needs high-vacuum packaging to improve its performance. While the measurement of the resonant frequency and quality factor of RFMEMS is still in progress, the Single material thin film packaging is being investigated. Diamond is an excellent material for the packaging due to its unique properties. Here shows the schematic of thin film packaging. It includes poly-C pads, poly-C feedthroughs, poly-C device and poly-C package on an insulating undoped poly-C layer. Here is the SEM picture of an all-diamond package with poly-C Pirani gauges encapsulated. The pirani gauge is shown here before the package is patterned. Here is the SEM taken from an angle of 45 degrees. Here shows the poly-C feedthroughs. The fluid access port is also inspected by SEM, as shown here. The package was sealed by additional poly-C growth in MPCVD again.

A preliminary test regarding the package’s fluidic hermeticity was performed. The result shows that poly-C thin film package has good fluidic hermeticity in an acidic environment. This was reported elsewhere.
EARLY VERSIONS OF DIAMOND NEURAL PROBES
ELECTRICAL AND CHEMICAL DETECTION

Chemical

I = V_out/R

Electrical

In-vivo Recording (Guinea Pig)

Electrochemical potential window

F-Terminated poly-C, 4.4 V
O-Terminated poly-C, 2.3 V

FBE

In-vitro Chemical Detection

Norepinephrine (NE) Detection

Current Density (mA/m²)

Voltage (V)
Another example based on SMM concept and technology is SMM probe in BioMEMS. The single material MEMS probe is a four mask process. The probes are fabricated on a silicon substrate coated in sacrificial silicon dioxide. The first step is to grow diamond. An undoped layer and highly doped layer are deposited. Next, reactive ion etching is used to pattern the doped-diamond electrodes, interconnects and bonding pads. Another layer of undoped diamond is grown for the top insulating layer. Both undoped layers are etched to define the shape of the probe. Next the top layer of undoped diamond is patterned using RIE to expose the electrode and the bonding pads. Chromium and gold are deposited on the backend bonding pads for packaging purposes. In this optional step, the diamond electrodes can be selectively modified for other applications, such as electrochemistry. Finally, the probes are released by etching the sacrificial silicon dioxide layer in hydrofluoric acid.
Figure on the left shows the experimental setup of using probe for in vivo electrical recording. A speaker was placed in the guinea pig’s ear for audio stimulus. The signals from each of the recording sites were amplified and filtered, then saved on a computer. The recorded neural signals were shown on the right. A histogram is made from the frequency distribution of the action potentials. Normally, we would expect to see the most neural activity near the onset of stimulus, as shown in this histogram.
Zero-Energy SMM Systems

Static Charge Energy Scavenging

How Much Energy is Available?
ZERO-ENERGY MEMS/NEMS

Energy Scavenging From Human Body

Energy Available

Energy Scavenged

Each data point taken after 5 steps.

Polyurethane-coated cement floor in 18% humidity

1 μF

2.5 μC,

3.13 μC

10 μF

100 μF

Electrode Touches
Next Gen SMM: Chemical Sensing and Pathogen Detection

RESEARCH GOALS:
- MIGRAINE
- HEADACHES
- CANCER
- EPILEPSI
- DEPRESSION,
  ANGER

(a) Integrated SMM Microprobe:
Optical Integration Using SMM (Front-end) and Si-based (backend) Technologies
Unique Aspects:
- Multi-Function SMM Probe
- Single Material Multilayer Interconnects
- Integrated RFID for Networked Data Sharing

(b) Integrated SMM Microprobe
with Ribbon Cable

Signal Processing Chip
10u Chip with
built-in Energy
Scavenger
Very Low Power
Microprocessor

Interface
Chip

Backend
Ribbon Cable
Interconnects

SMM Probe