ABSTRACT
An atmospheric pressure low-power, capacitively coupled RF plasma probe was designed and fabricated for selective-area chemical vapor deposition of materials at room temperature. The probe consisted of a gas channel with two electrodes forming a capacitor through the gas and channel wall. An inductor was used to match the capacitive electrodes to 50 Ω RF source at 600 MHz. The resulting LC circuit along with the plasma formed a second order system with a stable resonance near 600 MHz. Ge, Si, Si_{1-x}Ge_{x} and Ni were respectively deposited using SiH_{4}, GeH_{4}, and nickelocene on various substrates including microscope glass slide, gold, p- and n-type Si, SiO_{2} and Si_{3}N_{4}. SEM, AFM and EDX studies were used to study the deposited materials. Similar approach was then adopted to generate plasma between conducting AFM tip and a substrate to deposit and pattern materials at 10-500 nm scale.

KEYWORD
RF Plasma, AFM-CVD, plasma CVD, tip-based nanofabrication, atmospheric plasma

INTRODUCTION
Local probes have been used in the past to perform lithography and anodic oxidation of materials to build single electron transistors, quantum dots, and other devices. Figure 1 shows oxidation pattern on silicon that was written using Cypher (Asylum, Inc.) in our laboratory. Our main objective during the past 3 years has been to extend the local probe’s applications to deposition and etching of various electronic materials on arbitrary (conducting and non-conducting) substrates in atmospheric pressures and low (room) temperatures. We have selected to deposit and etch materials using appropriate gases as opposed to liquids with the provision that the reaction by-products also to be in the gas phase. Figure 2 shows the schematic of the AFM probe currently under development in our laboratory. It consists of a gas channel with an opening near the AFM apex. The gases that are brought near the AFM apex can be then ionized using different techniques including, low voltage ac or dc signal (1-100 V), high-voltage ac or dc signal (dc-100 kHz, 100-3,000 V), rf signal (0.1-10 GHz), laser and optical signals (IR to UV) and thermal energy. We have primarily investigated the low and high voltage dc, ac, and rf signals for ionization of gases near the AFM apex. Combination of different forms of energy, such as dc + laser, or dc + thermal, or dc + RF, can also be used with better outcome than a single signal.
molecules should be adsorbed at the surface such that AFM-substrate distance is small enough to generate ionizing electric fields that are typically around $10^6$ V/cm. Scanning tunneling microscope is used with 1-2 volt dc bias to desorb hydrogen at silicon surface for epitaxial growth of silicon on silicon. Hi-voltage dc signals work well with AFM but result in a large electrostatic clamping force between the AFM and the conducting substrate and deteriorate the tip. High-voltage ac signals are less corrosive and can be used to deposit and etch materials on insulating substrates but for impedance matching, they require large inductances for tip capacitances of around $10^{-15}$ F. RF signals are ideal since one can use microwave techniques for impedance matching. One can also extend the frequency range to coincide with some of the vibrational modes of the gas molecules to achieve resonance ionization.

The result of finite element simulation gas flow through AFM channel is shown in Figure 3. The cross-section of the tip apex clearly shows the electrodes, deposited material under the tip apex, the strength of electric field needed to ionize the gas molecules, and dynamic focusing where the gas flow carries the ionized species and deposits them on an insulating substrate.

Figure 3: Simulation results showing different parts of the AFM tip, ionization electric field and deposition of materials under apex.

Figure 4 shows an actual AFM image under the schematic AFM probe with a deposited silicon spot and etched region. For deposition SiCl$_4$ was used while for etching SF$_6$ was used.

RF signals are used in generating plasma for deposition, etching and processing of electronics materials. Three different methods can be used to generate plasmas using RF signals that include inductive coupling, capacitive coupling and direct coupling. Direct coupling requires conductive substrates and results in tip deterioration. Inductive coupling is less sensitive to variations in plasma properties but it is slightly more challenging than capacitive coupling discussed here. Generating plasma at atmosphere pressure has attracted interest due to its applications in the fabrication of self-organized nanostructures [1], portable liquid analysis [2], small-scale materials processing, etc. Localized plasma probe provides an approach to selective-area CVD. The study of the probe-based plasma CVD will also pave the way to the plasma-assisted AFM CVD, which can deposit materials in the scale of nanometers [3]. RF plasmas are more stable than dc plasmas [4] and, hence, more suitable for AFM.

PLASMA PROBE

Figure 5 shows the image of our plasma probe. A pipette was used as the gas channel. A wire inside the glass tube along with a copper foil around the outside of the tube formed the capacitive electrodes. The inner electrode was offset with respect to the outside foil to reduce capacitance [1, 5,6]. The capacitive electrodes were impedance matched to 50 Ω source using an inductor (Figure 5). The RF power was produced by an HP 8656B Signal Generator and an RF power amplifier (model TIA-1000-4, 12.5 W).
The plasma probe was connected to an atomic layer deposition control system and different chemical gases were passed through the probe for the plasma assisted chemical vapor deposition. The gas flow rates were typically between 20-50 sccm.

Figure 6 shows $S_{11}$ spectrum of the above probe obtained using a network analyzer after impedance matching using the inductor. The excitation frequency for this probe was around 600 MHz.

At resonance, the voltage across the capacitive probe can be much larger than the voltage supplied by the microwave source as shown by a simple calculation results shown in Figure 7 assuming a capacitance of 3 pF and an inductance of 40 nH. The voltage across the electrode was 23X that of the source signal. After formation of the plasma in the tube, the voltage across the gas drops, increasing the capacitance between the electrodes. Thus, the resonant frequency of the probe decreases by a small amount. The shift in the resonant frequency can be used to control the plasma.

Using the above probe we deposited Ge, Si, Si$_{1-x}$Ge$_x$, and graphene respectively using germane, silane, and acetylene. Figure 8 shows SEM of graphene regions deposited on a glass slide along with the EDX of the deposited region showing the carbon peak.

To perform patterning, we used a conducting AFM probe over a silicon substrate and impedance matched the probe-sample capacitive electrodes to 50 $\Omega$ at 575 MHz as shown in Figure 9.
Large silicon dots were deposited to enable EDX measurement of their material as shown in Figure 10. The EDX clearly shows a prominent silicon peak clearly verifying the ability of the AFM probe in depositing silicon from SiCl₄.

Figure 9: $S_{11}$ spectrum of conducting AFM sample matched to 50 Ω at 575 MHz.

Figure 10: SEM of large silicon dots deposited using conducting AFM from SiCl₄ and their EDX showing the Si peak.

Figure 11 shows a 125 nm silicon dot that was deposited using the conducting AFM plasma probe. The dot is very uniform as shown by the linescan. A reference shallow dot was formed at the center of the image.

Figure 11: A 125 nm Silicon dot deposited using AFM plasma probe.

CONCLUSION

We fabricated an RF plasma probe for the chemical vapor deposition at room temperature. The plasma was generated in a capacitively coupled probe at 600 MHz and was sustained and stable at low power. Utilizing the plasma probe we deposited different materials. Then we used a conducting AFM to form plasma over a sample to deposit and pattern materials on glass, silicon and gold on silicon.

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REFERENCES:


