Design and Development of an Integrated MEMS Sensor for Real Time Control of Plasma Etching

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ABSTRACT

This paper explores a novel technique for monitoring film thickness in reactive ion etching that incorporates a micromachined sensor. The prototype sensor correlates film thickness with the change in resonant frequency that occurs in the micromachined platform during etching. The prototype sensor consists of a platform that is suspended over a drive electrode on the surface of the substrate and electrically excited into resonance. As material is etched from the platform, its resonant vibrational frequency shifts by an amount proportional to the amount of material etched, allowing etch rate to be inferred. The micromachined sensor is simulated using ANSYS 7.0. Simulation shows a direct correlation between platform film thickness and resonant frequency, as well as between the platform thickness and its capacitance. Modeling the sensor as a variable capacitor in an auto-zeroing floating gate amplifier (AFGA) circuit using HSPICE reveals that the deflections of the platform are amplified as expected.

Keywords: ANSYS, micromachined sensor, reactive ion etching, real-time control, resonant frequency

I. INTRODUCTION

State-of-the-art integrated circuits currently employ upwards of 60 million transistors, six layers of metal, and operate at clock frequencies over 1 GHz. As device dimensions continue to shrink and the speed of computing and communications systems increases, the effect of fluctuations in the manufacturing process becomes critical. Achieving tight specifications, given the continuing trend toward even further miniaturization, represents a major challenge in process control, an issue of critical importance to the semiconductor industry.

Reactive ion etching (RIE) has emerged as a crucial process in IC manufacturing because of the need to process devices with extremely small geometries and its ability to provide etches necessary to define submicron features. Ideally one would like to monitor the RIE process in-situ and control practical manufacturing parameters such as etch rate, film thickness, uniformity and anisotropy in real time. However, the current lack of robust on-line RIE monitoring and control methodologies can lead to unacceptable large volumes of defective material to be processed, resulting in significant wasted material and lower yield.

In this paper, a MEMS device for real-time RIE monitoring is evaluated using ANSYS and HSPICE simulation software. Ultimately, this device is expected to facilitate closed-loop feedback control using hardware and algorithms designed to integrate the sensor output signals with a neural network based control scheme. As an application vehicle, process control will be demonstrated in the Plasma Therm SLR series RIE system located in the Georgia Tech Microelectronics Research Center.

II. DESIGN CONSIDERATIONS

There are several key elements to consider in the design of a resonant sensor. The sensor typically has an element vibrating at resonance, which changes its output frequency as a function of a physical or chemical parameter. The vibrating element must be sensitive enough to adequately respond to the impact of what is being measured. The conversion from the measured quantity to the resonant frequency is based on the changes in internal forces and stresses in the resonator, which will change the resonant frequency. Another method of conversion is by mass loading on the vibrating element, where changes in the equivalent mass of the resonator change the resonant frequency. It is also possible to let the quantity to be measured change the shape of the resonator and thereby the stiffness of the vibrating structure, where an increased stiffness structure causes the resonant frequency to increase [1].

The mechanical Q-factor is an important parameter in the design and operation of resonators. The Q-factor depends on different damping mechanisms such as imbalances, viscous and acoustic radiation losses. The sensor should be designed with a very high Q, since the sensor stability and performance is then almost entirely dependent on the mechanical properties of the resonator elements [2].

III. PRINCIPLE OF OPERATION

The RIE sensor relies on a principle of electrostatic excitation and capacitive detection. This technique requires two electrodes that are in close proximity to a vibrating structure. A voltage applied across the electrodes creates an electrostatic pulling effect on the vibrating element and a displacement current result from the air gap capacitance between the electrodes and the vibrating structure.

Figure 1 shows the prototype micromachined sensor designed to assess RIE etch rate. The sensor is composed of a micro-machined platform 700um long, 140 um wide and extends 4 um above drive and sense electrodes [3]. During operation, the MEMS platform is coated with the same material to be etched from the substrate and positioned above drive and sense electrodes. As etching takes place, the sensor is excited into resonance by the drive electrodes

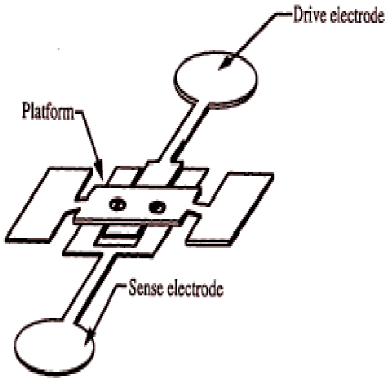

Figure 1: Prototype micromachined sensor showing the platform suspended over drive and sense electrodes [3].

As the mass loading of the platform decreases, its resonant vibration frequency shifts by an amount proportional to the amount of material etched, allowing etch rate to be inferred. The sensor provides direct real-time feedback on the wafer state during the etching by correlating film thickness with resonant frequency. The RIE sensor operability has been previously evaluated and the resonant frequency was determined experimentally to be approximately 33 kHz [3].

IV. MODELING

The design of the RIE sensor was analyzed and optimized by finite element analysis (FEA). This computer-based numerical technique for calculating the strength and behavior of engineering structures was conducted using ANSYS 7.0. With the ANSYS model, we were able to simulate deflection, stress, vibration and other phenomena. The MEMS structure was deformed and examined to establish the relationship between applied loads and deflections. A static ANSYS simulation of the RIE sensor yielded a fundamental frequency of 50.4 kHz, which is within the desired range. We were also able to verify the expected correlation between the platform height and its resonant frequency.

Steady state, transient and random vibration behavior was also analyzed to study the effects caused by the applied load to the sensor. Boundary conditions were employed to indicate where the structure was constrained and restricted against movement or in the case of our symmetric RIE structure when only a portion of the sensor needed to be modeled.

The RIE sensor in [3] was composed of a polyimide platform 700 µm long and 140 µm wide that extends 4 µm above drive and sense electrodes. The platform was modeled as a uniform beam with both ends clamped and suspended above a ground plane. The ANSYS parameters are given in Table 1 below.

Parameter	µMKSV units
Platform Length	700 µm
Platform Width	140 µm
Platform Height	9 µm
Young’s Modulus	8.3e3 GPa
Poisson Ratio	0.34
Density	1400e-18 kg/µm

Table 1: ANSYS parameters for RIE sensor model

The sensor was first modeled and meshed using a 2-D element type, and then extruded into the 3-D model shown in Figure 2.

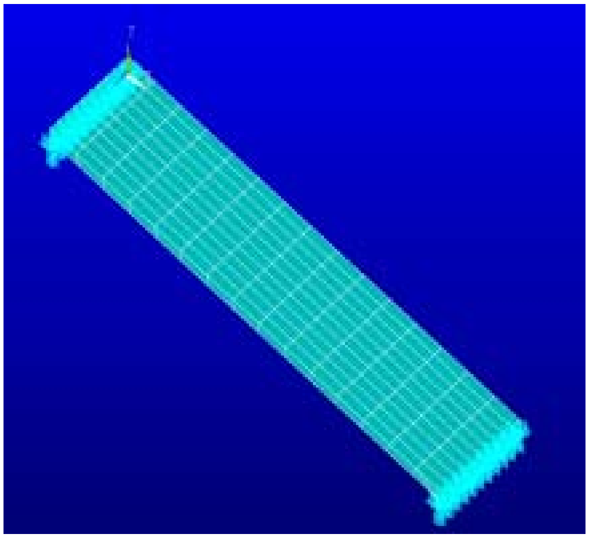

Figure 2: 3-D meshed model of RIE sensor

We obtained the profile of the first three mode shapes and resonant frequencies and found that the fundament and harmonics were within the expected range. Simulations compare closely with the expected value of 33.3 kHz. The results are summarized in Table II.

Harmonics	Frequency
f1	50.4 kHz
f2	137.3 kHz
f3	137.3 kHz

Table 2: RIE sensor resonant frequencies

To confirm the expected response of the sensor, an electrostatic force was applied. The application of a range of voltages between 10-100 volts caused the platform to deflect. The resonant frequency and displacements varied with the application of the load. Figure 3 show that the platform had its maximum deflection at the center, as expected, with a maximum displacement of 0.03216 µm.

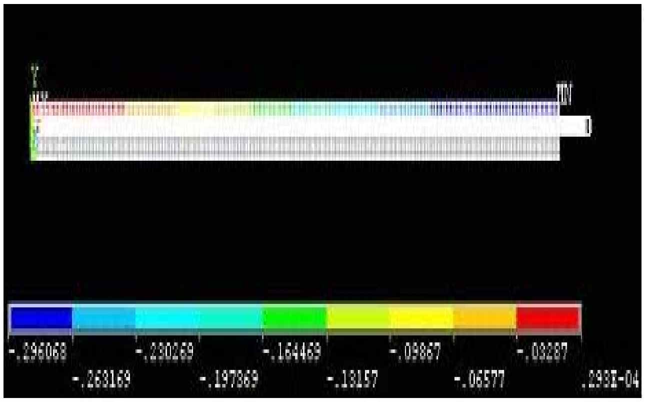

Figure 3: RIE sensor displacement contour plot showing maximum displacement of 0.03216 µm

Changes in the mass loading of the platform are simulated by varying the height of the platform which produces a change in the capacitance between the platform and electrodes, resulting in the change in the resonant frequency of the structure. The platform height was varied from 4µm to 16µm to simulate the changes in film thickness that occurs during etching. The height increases as material is etched since there is reduced bending in the middle of the beam due to its own weight. When the height of the platform increased, the resonant frequency shifts to the right on the frequency spectrum and vice versa.

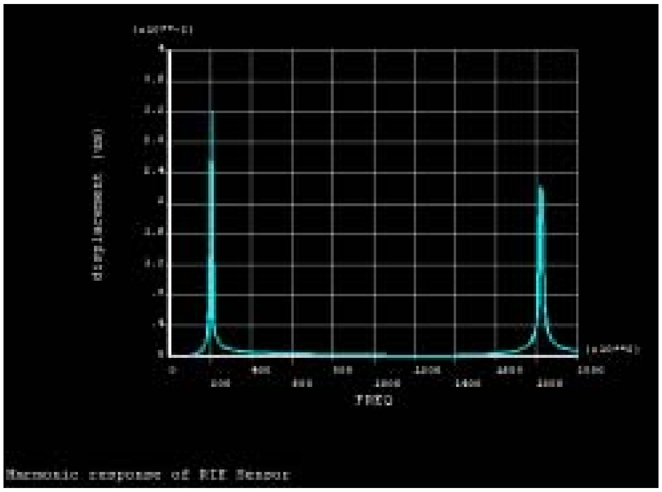

Figure 4: First harmonics f_1 = 20.45 kHz. Beam height is 9 µm. Maximum displacement at platform center is 0.032166 µm.

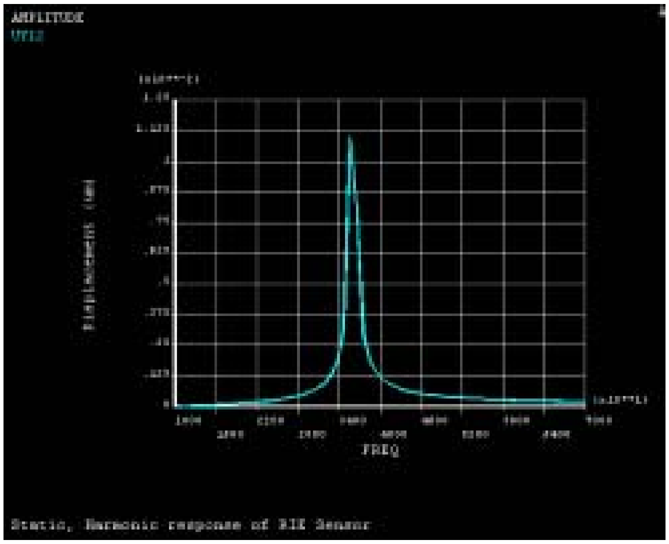

Figure 5: First harmonics f_1 = 35.65 kHz. Beam height is 16 µm. Maximum displacement at platform center is 0.011 µm.

The frequency spectra in Figures 4 and 5 illustrate how changing the height of the platform from 9µm to 16µm affects resonant frequency. The 9 µm platform has a resonant frequency of 20.45 kHz and a maximum displacement at the center of 0.03216 µm. The resonant frequency occurred at 35.65 kHz for a platform of height of 16µm. This value is closer to the expected resonance frequency of 33.1 kHz. The maximum displacement at the platform center was reduced to 0.011 µm. The direct correlation of platform thickness and resonant frequency is evident, potentially providing the desired mechanism for real-time feedback on the wafer state during etching.

The platform is modeled as a 3-D beam that is positioned above the drive and sense electrodes, represented by the ground plane. An applied voltage coupled to the beam causes the beam to deflect and change the air gap between the beam and the ground plane.

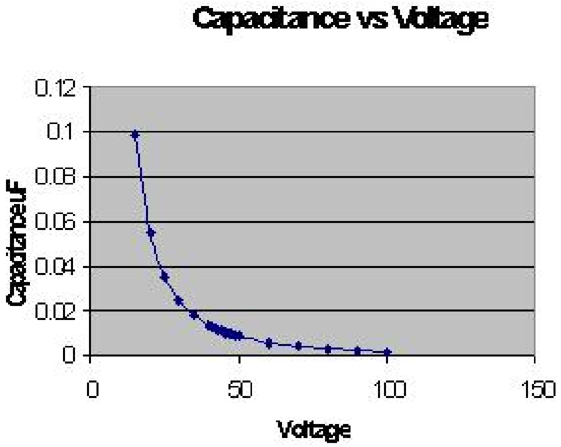

Figure 6: RIE sensor voltage vs. air gap capacitance

A plot of the air gap capacitance versus applied voltage provides insight into the stability of the sensor. Figure 6 shows that the device appears to be well behaved, since it exhibits a nearly linear dependence on the applied voltage for voltages below approximately 40 V.

V. AFGA IMPLEMENTATION

Figure 7 shows the proposed implementation of the sensor in an auto-zeroing floating gate amplifier (AFGA) circuit [4]. The variable capacitor represents the micromachined RIE structure. The change in capacitance of the sensor is directly related to the output voltage of the amplifier. The capacitance values were obtained from the ANSYS simulation and represent the effects of the mass loading of the top plate of the capacitive structure that occurs during etching.

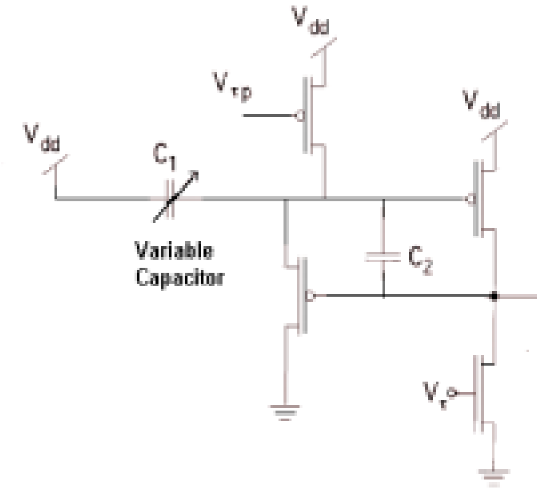

Figure 7: RIE sensor as variable capacitor in the AFGA circuit

This modified AFGA circuit with the RIE sensor as the variable capacitor is modeled using HSPICE to determine whether the small scale deflections of the platform and the small current signals that are used to locate the resonant condition will be properly sensed and amplified. From the voltage waveform shown in Figure 8, it appears that the unique sensor implementation results are consistent with what is expected from this amplifier circuit, since the small scale deflections of the platform are indeed amplified.

VI. DISCUSSION

Preliminary design of a MEMS sensor for RIE monitoring has been conducted and verified using ANSYS. ANSYS simulation is an effective tool for verification of the RIE sensor design and for illustrating potential areas for improvement. Ansys Parametric Design Language (APDL) input files were useful for building and solving the RIE sensor models. APDL is an extension of the ANSYS command mode which allows the user to create an input text file and execute the commands in batch mode rather than line by line. The model is created in terms of parameters (variables), which makes it easy to change the design later.

Overall, the sensor design appears to be feasible. The relationship between the height of the platform and resonant frequency has been established. There may also be potential advantages in minimizing the platform width or varying the platform height. Optimization of the design will result in the best properties for the minimum cost and impact future fabrication processes. The successful development of this sensor could lead to significant productivity enhancements in RIE.

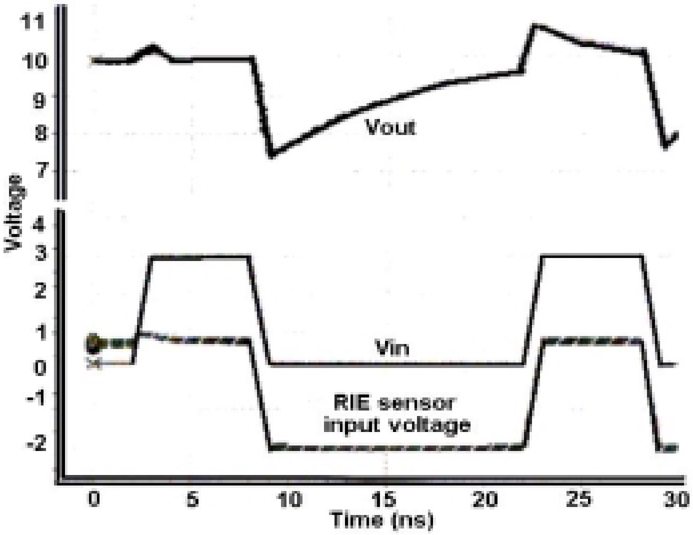

Figure 8: Voltage waveforms from RIE sensor as variable capacitor in the AFGA circuit

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