Fabrication of a Real Time Reactive Ion Etching Resonant Sensor Using a Low Temperature Sacrificial Polymer

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ABSTRACT

This paper presents a sacrificial layer process using a low temperature polymer as the sacrificial material in fabricating a surface micromachined reactive ion etching (RIE) resonant sensor. The sensor monitors film thickness and etch rate in the RIE process and will ultimately facilitate closed-loop control using hardware and algorithms designed to integrate the sensor output signals with a neural network based control scheme.

This RIE monitoring methodology exploits the accuracy of resonant micromechanical structures, whereby shifts in the fundamental resonant frequency measure a physical parameter. A majority of these systems require free-standing mechanical movement and utilize a sacrificial layer process as the key technique to develop and release the structure on a substrate. The low temperature sacrificial layer process released the suspended sensor with excellent performance and is capable of fabricating other low cost, high performance and reliable suspended MEMS devices.

Keywords: resonant sensor, sacrificial layer process, reactive ion etching (RIE), in-situ monitoring, endpoint detection

1 INTRODUCTION

Reactive ion etching (RIE) has emerged as a critical step in IC fabrication as it offers high etch directionality, enabling accurate pattern transfer not obtainable with wet etching. Despite its widespread use in the semiconductor manufacturing industry, process control techniques for plasma etching are inhibited by the inadequacy of existing process sensor technology. Although real-time monitoring techniques exist for the regulation of process conditions such as gas flow, RF power, and chamber pressure, extant process monitoring methods are unable to provide direct, real-time measurements of the actual wafer state during the etch [1].

As a step toward addressing this issue, a prototype sensor has been developed to monitor etch rate in situ by using a micromachined sensor. Figure 1 shows the prototype RIE sensor designed to assess etch rate [2]. The sensor consists a micromachined platform that is suspended over the drive and sense electrodes on the surface of the substrate.

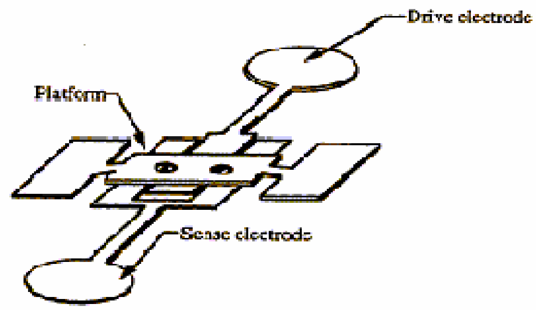
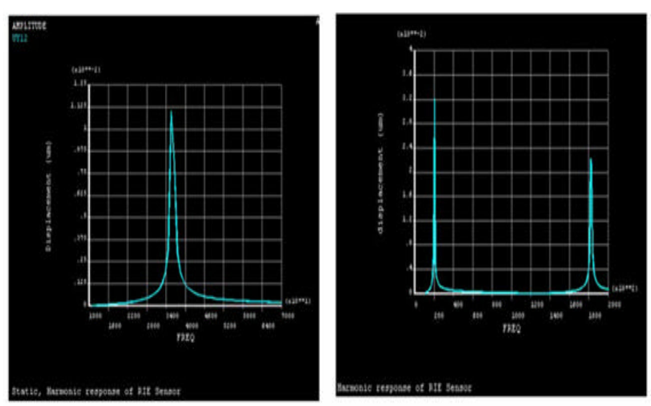


Figure 1: Prototype RIE MEMS sensor measures 700x140 um and is suspended 16 um over the drive and sense electrodes.

The sensor is driven into resonance electro-statically as material is etched from the platform. As the mass loading of the platform decreases, its resonant vibrational frequency shifts by an amount proportional to the amount of material remaining. The shift in resonance is detected by monitoring the change in impedance between the drive electrodes and the platform. Finite element analysis simulation results shown in Figures 2 and 3 illustrate the correlation between film thickness and change in resonant frequency that occurs in the micromachined platform during etching which allows etch rate to be inferred [3].

This sensor can therefore provide direct real-time feedback on the wafer state during the etching process by correlating film thickness with resonant frequency.



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

First harmonics f_1 = 20.45 kHz. Beam height is 9 μm. Maximum displacement at platform center is 0.0322 μm.

Figure 2: Simulated resonant frequency for varying film thickness.

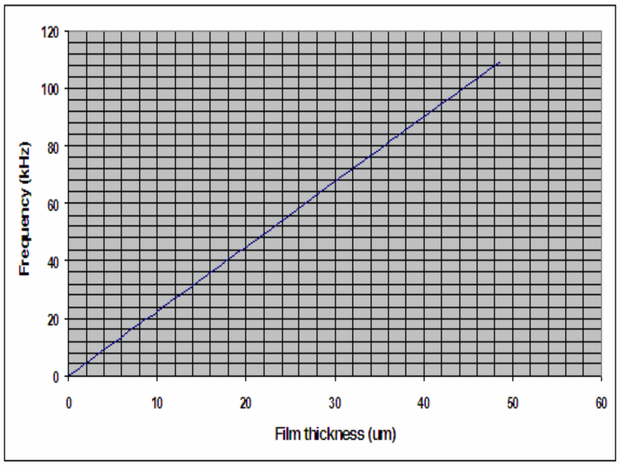


Figure 3: Correlation between film thickness and changes in resonant frequency allows endpoint detection.

2 EXISTING SACRIFICIAL LAYER METHODS

Metals have traditionally been used as sacrificial materials. In recent years, the trend has been towards photoresists and polyimide-based sacrificial materials. The difficulties inherent in achieving free-standing micro-structures with the existing sacrificial materials are well documented and include lengthy deposition cycles, slow and expensive release process using hazardous materials, sacrificial thicknesses limits, and the occurrence of stiction [4,5,6]. The latter is a well-known problem, (shown in Figure 4) that occurs when the device is removed from the aqueous solution after wet etching of the underlying sacrificial layer.

Figure 4: SEM images showing RIE sensor damage observed after wet etching of the underlying copper sacrificial layer.

In view of the importance of sacrificial layers in MEMS devices, we demonstrated a sacrificial layer processes that possess the following attributes: (1) the process is simple and reproducible; (2) the coating process is compatible with dry or aqueous etching processes; (3) the release-stiction problem is alleviated by thermal cure and decomposition of the sacrificial material.

3 RIE SENSOR FABRICATION

3.1 Design Considerations

The prototype sensor described in this paper consists of three major parts: the drive electrode, the sense electrode, and the platform itself. The sensor was designed such that the end of the electrode was precisely centered beneath the platform. This is very important because the location of the drive electrode will impact the mode being excited. The sense electrode is placed in close proximity of the drive electrode, yet not in contact with it.

The platform has maximum displacement at its center and the capacitance change there is greatest. This implies that not only should the sense electrode be placed near the center of the platform, but the platform should be long compared to the width of the sense electrode. Centering the drive electrode relative to the platform is optimal.

Electrical isolation between the electrodes and the platform is critical. The isolation barrier and resulting air gap is created by utilizing a sacrificial layer material and process to develop and subsequently release the free standing sensor structure.

3.2 Fabrication Process

Figure 5 is an overview of the fabrication process. The RIE sensor measures (700 um x 140 um) and the sacrificial layer is 16 um. The electrodes are etched from the first metallization layer. The sacrificial layer material is the low temperature polymer Unity 2000P, which is spun on the substrate to the desired thickness. The spin curve in Figure 6 is utilized to attain sacrificial layer thicknesses between 2-80 microns.

A dehydrate bake at 100 ^{o}C on the hotplate is followed by 1000 mJ dose exposure with a quartz mask. The post exposure bake on the hotplate develops the sacrificial polymer and an IPA rinse removes the unexposed sacrificial material. Metallization and a dielectric coat is patterned and etched to create the RIE sensor platform. Thermal curing in a 200 ^{o}C oven decomposes the sacrificial material and also releases the suspended micromachined resonant sensor.

4 BENEFITS OF THE NEW SACRIFICIAL LAYER PROCESS

The advantage of using this low temperature sacrificial material and process is dependent on the application. The low temperature sacrificial material is easily coated to the wafer using standard process in a variety of different thicknesses. Thermal curing to convert the sacrificial material and decompose the material releasing the suspended structure is well suited for applications where critical dimension is not easily achieved using the other methods.

The sacrificial material is thermally stable, making the cured properties well suited for most semiconductor fabrication applications. The cured film is also highly resistant in most wet and dry processing chemical used in production, and the cured film's properties can be further optimized for a given application by varying the thickness of the sacrificial material coating.

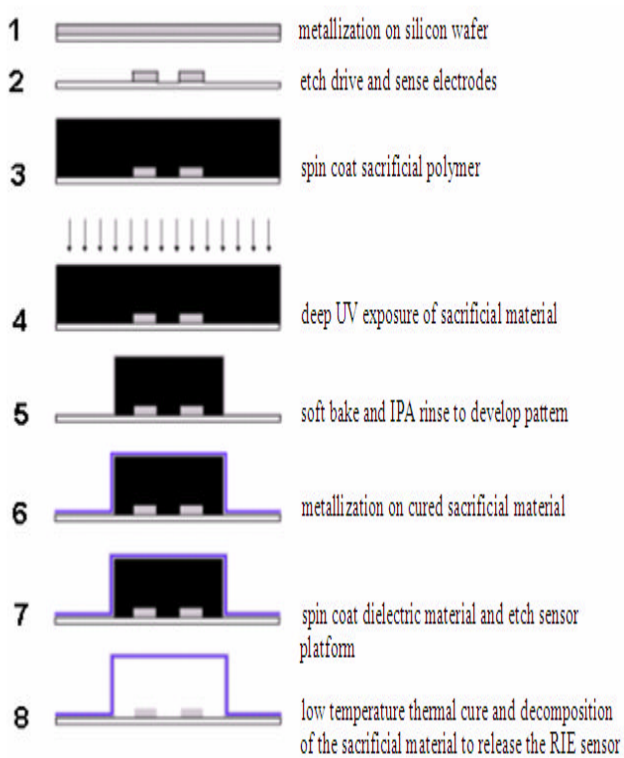


Figure 5: Prototype RIE sensor fabrication process

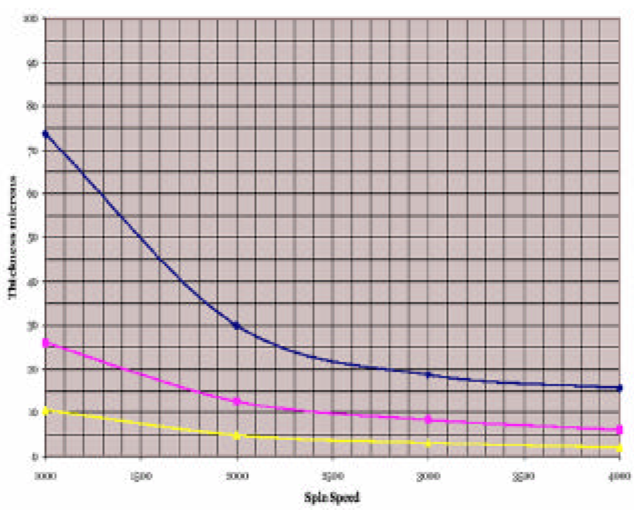


Figure 6: Sacrificial polymer material spin curve

4.1 Improvements in Process

The sacrificial layer material is self-priming, photosensitive and photodefinable, which permits the overcoat material to function without an additional resist masking step. The sacrificial layer material is patterned like photoresist on I or g-line semiconductor exposure tools. There are also improvements in the resolution associated with utilizing this semitransparent sacrificial layer polymer material, in contrast with using other sacrificial materials.

Metal sacrificial layers require lengthy deposition cycles to achieve comparable thicknesses. An additional photoresist process is necessary to pattern the metal prior to the slow and expensive etch and release process using hazardous materials. Metal sacrificial layer materials significantly increase the number of fabrication steps and lengthen the process cycle time.

4.2 Reduction in Complexity

In recent years, the trend has been toward photoresists and polyimide-based sacrificial materials. Polyimides are not inherently photosensitive, but can be made photodefinable with the addition of a methacrylate-based photo-polymerizable additive using an ester. Non-photodefinable self-priming polyimides, such as PI-2556 can be patterned in conjunction with a positive resist to achieve a 2 um polyimide overcoat layer which serves as a sacrificial layer.

Due to the precise pattern definition requirements of single mask processing, the wet etch polyimide process had a narrower process window and needs to be tightly controlled. As a result, critical dimension control is difficult. Cured film thicknesses were limited by resolution requirements to < 3 um [7].

The new sacrificial layer polymer offers improved resolution and adhesion compared with the wet etch polyimide process. A photoresist process is unnecessary as the exposed material is developed by heating the substrate in an oven at 110 ^{o}C to dry develop the photo defined features. The sacrificial polymer film is then rinsed with isopropyl alcohol (IPA) to remove any remaining residue.

4.3 Reduction in Cost

Photodefinable polyimide sacrificial materials also eliminate the need for a photoresist coat and strip process. The total number of processing steps is reduced when compared with previous sacrificial layer processes. The improved resolution and adhesion characteristics of photodefinable polyimide material permit the application of a thicker sacrificial layer. This increased film thickness, combined with improved adhesion is expected to have good device reliability. The drawback of the photodefinable polymer sacrificial material process is an increase in material costs compared with the other existing sacrificial layer process [8].

5 PROCESS INTEGRATION

Integration of the new sacrificial material process is relatively straightforward. Some key variables that were adjusted are the soft bake time and temperature, exposure energy, post exposure bake, and develop time and technique. The sacrificial material is exposed through a quartz mask.

The desired sacrificial layer thickness was achieved without the long deposition times of the metals. The new overcoat process repeatedly patterned 16 um sacrificial layer coatings. The underlying layer electrodes are clearly visible in the semitransparent sacrificial material film, which facilitates easier alignment and exposure between the 1st and 2nd mask steps. The resolution was improved and patterning was insensitive to the underlying wafer topology.

There is improvement in process latitude and room temperature stability as no discernable degradation of pattern quality was noticed between coat exposure and development. The sacrificial material offered excellent resistance to the etch process gases during the processing and development of the platform metallization and dielectric layers.

Overall process complexity is reduced as the release process is improved. There is no need for the wet etch process to dissolve the sacrificial layer. The release-stiction problem is alleviated by thermal cure and decomposition of the sacrificial material which results in better sensor performance and reliability.

Scanning electron micrograph images in Figure 7 show the sacrificial material during the fabrication process. The new sacrificial layer process can be readily integrated into the desired mask process scheme. There are potential improvements in process complexity, steps and cost using this low temperature sacrificial layer process.

6 SUMMARY

Sacrificial layers are a proven technology for creating suspended micromachined structures. In view of the importance of sacrificial layers in MEMS devices, we demonstrated a sacrificial layer processes that possess the following attributes: (1) the process is simple and reproducible; (2) the coating process is compatible with dry or aqueous etching processes; (3) the release-stiction problem is alleviated by thermal cure and decomposition of the sacrificial material.

The low temperature sacrificial polymer presents a straightforward alternative to existing sacrificial layer methods. There are improvement in process complexity, adhesion and resolution. The sacrificial layer technique is compatible with other surface micromachining processes and can be applied in fabricating low cost, high performance and reliable MEMS devices.

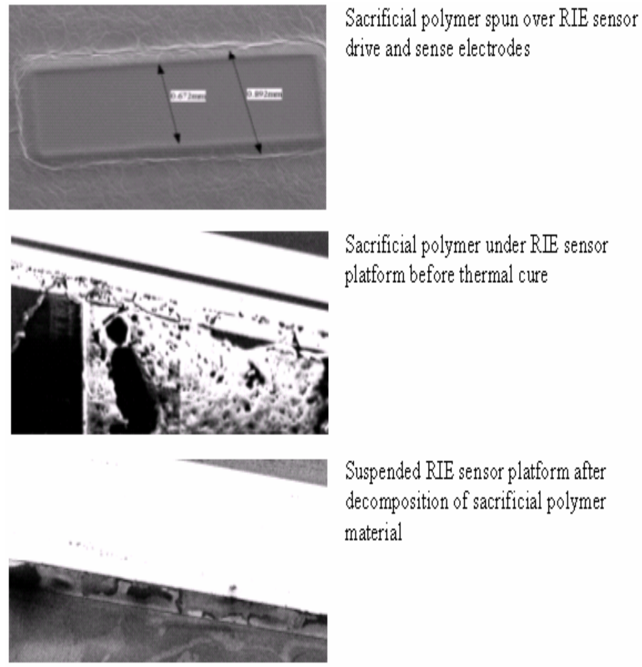


Figure 7: SEM images showing underlying sacrificial polymer material during the spin coat, thermal cure and decomposition to release the suspended micromachined resonant sensor

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