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Short Communication

Plasma etching processes for the realization of micromechanical structures for MEMS†

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Abstract

Plasma-assisted etching technology has been used for the development and fabrication of silicon-based micromechanical structures for the realization of microelectro mechanical systems (MEMS). This paper reports on the reactive ion etching in fluorocarbon gases such as SF_6, CHF_3 and their mixtures with O_2, Ar for high fidelity pattern transfer from patterns delineated in positive photo-resist into underlying substrates (i.e. Si, SiO_2). SiO_2 layer has been etched in CHF_3/Ar gas plasma and the effect of rf power and CHF_3 gas flow in Ar (5 sccm) on the etch rates has been studied. SiO_2 etch rates in the range 50–300 Å/min have been obtained at different process parameters. Nearly vertical side walls in SiO_2 have been achieved at 100 watts of RF power (DC bias = –210 volts) and 30 scccm CHF_3+5 sccm Ar gas flow rate at 6 mtorr having SiO_2 etching rate of 150 Å/min. Microgears of diameter 50 μm and linear grating type pattern with 1.8 μm periodicity having etching depths of 2.6 μm have been realized in SiO_2. Patterns have also been etched in silicon using $SF_6/O_2/CHF_3$ with nearly vertical walls.

Keywords: Plasma etching, micromechanical structures, reactive ion etching.

1. Introduction

Plasma etching is important for the fabrication of micromechanical structures in silicon, silicon dioxide, etc. with fine feature size. The ability to manufacture micromechanical components is essential for the realization of micromechanical systems. Micromachining technology is being widely employed for the fabrication of various micromechanical structures needed for many types of sensors and actuators.[1–3] Wet etching is widely used for micromachining since the etching rate and the selectivity of a wet process are higher than those of dry process.[1] Many three-dimensional miniature structures such as thin membranes, cantilevers and bridges used in sensors and actuators have been realized using several alkaline etchants such as KOH or EDP.[4] However, wet etching has some disadvantages as it involves a pure chemical reaction which results in an isotropic etching profile unless a crystal orientation-dependent etching is used. On the other hand, directional etching perpendicular to the surface can be carried out by reactive ion etching (RIE) independent of the crystallographic orientation.

Reactive ion etching is one of the most promising techniques available for the fabrication of silicon-based micromechanical structures owing to its ability to pattern fine line structures and high fidelity of pattern transfer.[5–7] In fact, plasma etching has become a key technology in micromachining where fine line micromechanical structures are required. In the development of plasma etching process, it is important to optimize the process parameters so that the above-mentioned etching requirements can be met.[7,8]

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RIE is a chemical-physical etching process capable of providing highly anisotropic etch profiles with good selectivity.[9–12] Anisotropy is attributed to ionic bombardment which is basically a physical phenomenon. On the other hand, selectivity is a chemical phenomenon that occurs on the surface to be etched due to the chemical reaction of the active radicals and the neutral species present in the plasma thereby producing loosely bound compound. This compound is then pumped away from the etched surface due to physical bombardment of energetic ions present in the plasma. The degree of anisotropy and selectivity depends on a larger number of parameters such as etch, pressure, radio frequency (RF) power, gas flow rate and the type of reactant gas or their combinations used.

In this paper, we describe the fabrication of some micromechanical components such as gears, grooves, etc. in SiO_2 layer and silicon using a combination of reactant gases. Plasma etching process was optimized for photo-resist removal using oxygen plasma and the etching end point was determined by *in-situ* monitoring of the emission spectral lines of different species present in the plasma.

2. Experimental

A parallel plate RIE system[5] developed in our laboratory was employed to carry out all the experiments. The process chamber having a diameter of 304 mm and 108 mm height and water-cooled substrate electrode (cathode) of diameter 225 mm were made of stainless steel. The gas distribution in the process chamber is provided by feeding the gas through equispaced holes along the top inner edges of the electrode through an annular ring built along the water-cooled jacket. The RF power limit (13.56 MHz) is capable of supplying 600 watts through an automatic impedance matching network system. The DC-bias voltage is measured which is indicated on the built-in digital display. Gas flow rates are monitored through mass flow controllers being used, mixed and fed to the reactor chamber. Pressures are measured with a capacitance manometer which works in a closed feedback loop with the throttle valve controller to maintain the reactor pressure at a preset value. The gases and the etch products are pumped off the reactor by a Fomblin-adapted 350 m^3/h root pumping system. A cleaning process of the system by O_2 plasma was employed to maintain the reproducibility of the method after each etching step.

All experiments employed silicon wafers (*n*-type) with <100> orientation. SiO_2 layer of 2.6 μm thickness was grown on silicon wafers by wet oxidation and then coated with photo-resist. Photo-resist was patterned through a mask by photolithography step. The pattern in the photo-resist was delineated onto the SiO_2 layer by using the CHF_3/Ar plasma. Process parameters such as RF power, CHF_3 gas flow in argon were optimized to achieve good anisotropy and etch rates. The etching process in silicon was carried out by using the gas mixtures of SF_6, CHF_3, O_2 and Ar, etc. and the process parameters were optimized at different substrate temperatures. The etch rates were measured by surface profilometer (DEKTAK-3030ST) and the etched patterns were evaluated by scanning electron microscope.

3. Results and discussion

The results described here are limited to the etching of SiO_2 in CHF_3 + Ar gas plasma and the effect of RF power and gas flow rate on the etch rates. The etch rates of SiO_2 at different applied RF power

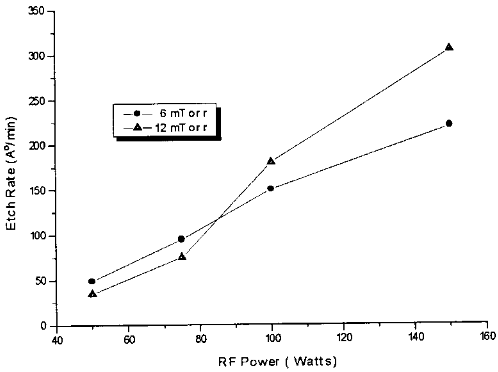


FIG. 1. Variation of SiO_2 etch rate (Å%min) w.r.t. RF power (watts) at two different process pressures at 30 sccm CHF_3 + 5 sccm Ar gas flow rate.

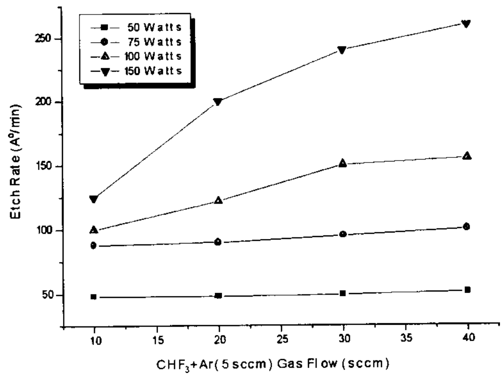


FIG. 2. Variation of SiO_2 etch rate (Å/min) w.r.t. CHF_3 gas flow rate in 5 sccm Ar at different RF power (watts) levels at 6 mtorr process pressure.

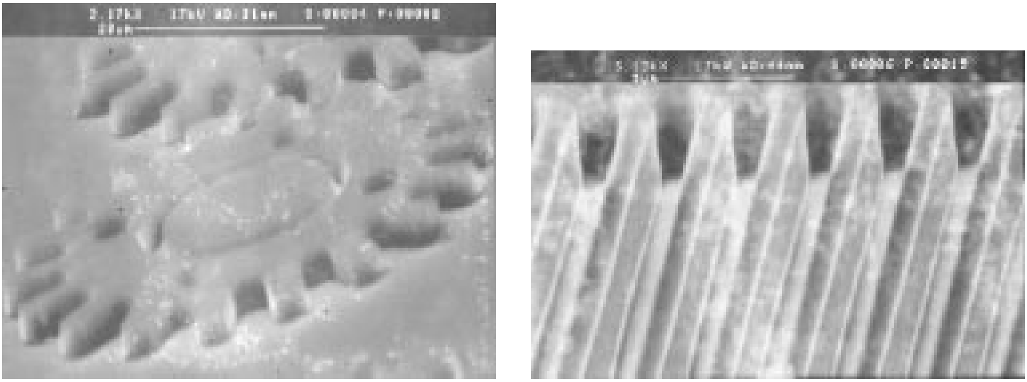
levels were evaluated at a constant gas flow of 30 sccm CHF_3 + 5 sccm Ar and at constant pressures of 6 and 12 mtorr (Fig. 1).

The analysis reveals that the SiO_2 etch rate increases when the applied RF power is increased. It is observed that the etch rates increase even at higher pressure at high RF power. The etching mechanism in SiO_2 is ion-enhanced where the energetic ions play an important role apart from the chemically reacting species. The addition of argon to CHF_3 gas also gives rise to the physical component of the etching with the contribution of argon ions in the plasma. Thus, ion energies and ion densities are important determining parameters of the etch rates.[13] Figure 1 also suggests that at a given pressure and gas flow, higher RF power levels lead to higher ion density and to higher etch rates. The results also show that with increase in pressure there is an increase in the etch rate. This is possibly due to the contribution of chemical etching mechanism, as a consequence of enhanced plasma density.

There is variation in SiO_2 etch rates with increase in CHF_3 gas flow in 5 sccm argon at constant RF power levels (Fig. 2). The results reveal that the etch rates are almost constant at 50 and 75 watts of RF power level despite increase in the flow rate. For RF power levels of 100 and 150 watts, the SiO_2 etch rate was found to increase with increase in CHF_3 gas flow rate. It could be due to decrease in reactant concentration at lower gas flow rates and higher RF power. The higher etch rates at high gas flow rates at higher RF power are due to significant increase in the chemical reacting species.

The etched patterns in SiO_2 were evaluated using scanning electron microscope. Micrographs of the microgears and the grating pattern are shown in Fig. 3.

These patterns have been delineated in SiO_2 using patterned positive photo-resist as the mask by using the following process parameters: RF power=100 watts, process pressur=6 mtorr, 30 sccm CHF_3 + 5 sccm argon gas flow rate having a self DC-bias of –210 volts. The SiO_2 etch rate measured at these parameters was 150 Å/min.



(a) (b)

FIG. 3 Microstructures etched in SiO_2 by RIE: (a) microgears and (b) grating pattern.

The microgears in Fig. 3(a) have a diameter of 50 μm and depth of 2.6 μm with nearly vertical walls. Figure 3(b) shows etched pattern of a grating of periodicity of 1.8 μm and depth of 2.6 μm. These micrographs reveal that the bottom surface of the etched patterns is extremely smooth after etching in CHF_3 + Ar and the side walls are nearly perpendicular.

Silicon-etched profiles (5 μm deep) using $SF_6/O_2/CHF_3$ gas mixtures at low temperature (–25°C) are shown in Fig. 4. The process parameters are pressure = 10 mtorr, $SF_6/O_2/CHF_3$ gas flow rate of 10/2/2.5 sccm, self DC-bias = –175 volts.

We believe that the passivating layer SiO_xF_y[14] and free atomic fluorine freezes on the silicon side walls. At room temperature, free atomic fluorine is released from the silicon side walls which reacts with the silicon surface giving rise to a parallel movement of the vertical walls inside the mask. This undercutting may also be due to the off-axis energetic ions which strike the side walls.

4. Mechanism of SiO_2 etching

In a CHF_3-based plasma, ionisation processes, due to energetic electron collisions, produce reactive species such as F atoms, CF_2 radicals and CHF_2^+ ions. The polymer-forming radicals such as CF_2[10,14,15] can deposit and form a polymer layer on the substrate thus inhibiting the chemical reaction of the reactive species such as F atoms with the substrate atoms. Therefore, the rate-limiting steps in such a chemistry are adsorption of the reactive species to the substrate surface and chemical reaction of the species with the substrate. The energetic ions present in the plasma contribute to the physical etching process in controlling polymer formation for chemical reaction to proceed further.

The etching of SiO_2 in CHF_3 results mainly in products like SiF_4, CO_2, COF_2 and water. The etching process is primarily of chemical nature and the reactive species are produced directly at the substrate surface by the ion–molecule reactions involving primary CHF_2^+ ions and neutral gas molecules.

Noble gases such as argon and helium are added to stabilize the plasma or cooling purposes. Argon addition causes inert ion bombardment of the surface which results in enhanced anisotro-

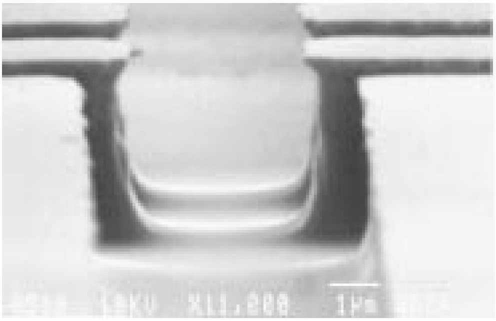


FIG. 4. Etched profile in silicon using $SF_6/O_2/CHF_3$ gas mixtures.

pic etching. The addition of argon to CHF_3 significantly changes the electron energy distribution in plasma and alters the reactive species population in the discharge causing the etching process dominated by the energetic ions to give rise to anisotropic etched profiles.

5. Conclusions

In this work, the usefulness of the CHF_3/Ar plasma chemistry has been demonstrated for the etching of SiO_2 by using photo-resist as the etching mask. The etching is due to a chemical reaction between highly reactive species produced directly on the substrate surface by an ion–molecule reaction. The addition of argon to CHF_3 has resulted in enhanced anisotropic-etched profiles with clean and smoother bottom surfaces of the profiles. This is due to inert ion bombardment on the surface to be etched.

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