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Plasma-Induced Etching of Silicon Surfaces

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Abstract. In this work, p-type silicon surface was etched to (100) crystalline direction using plasma-induced etching technique. The structural characteristics of the etched surface were presented and studied. The optimum conditions to achieve etching process on p-type silicon surface are determined by 750 W processing power and 15mtorr gas pressure required for generation of plasma. According to the reasonable quality of the obtained samples and comparing to other techniques, the plasma-induced etching is simple and low cost technique as well as large dimensions of etched substrates can be produced.

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1 Introduction

The fact is that a gas discharge containing charged (ion) and neutral (radical) species can be used to initiate chemical processes required for etching of a substrate placed inside [1]. All etching techniques include the removal of a layer from the sample surface in a specified crystalline direction (orientation) and due to the chemical reaction between sample surface and the particles performing etching process. The nature of chemical reaction determines the crystalline orientation in which the particles are removed. Hence, the major parameters affecting this reaction, such as temperature and pressure, can be considered as controllers to the characteristics of the etched surfaces.

High charge density plasmas are being used increasingly in etching silicon and other semiconductors. Such etching reactors use one of several types of high-charge density sources, such as helical resonators (HR), electron cyclotron resonance (ECR) plasmas and inductively coupled plasmas (ICP). These sources share well defined characteristics and an independent control of the ion strikes onto the wafer. Consequently, in some ways, thin film processes induced by these different sources are thought to be interchangeable. However, the details of the mechanism of plasma-induced etching maybe different for these sources [2].

Plasma-induced etching (PIE) processes have found an increasingly important role as the interest in micro-fabrication continues to grow. Plasma-induced etching processes utilize the thermal action to locally accelerated chemical etching reaction on the surface of a solid, which is preferred sometimes situated in a suitable liquid or gas etchant [3]. In reactive gaseous or liquid environments, the material removal can be affected by localized activation of chemical reactions at much lower surface temperatures than ablation techniques. The plasma-induced etching technique is one of the non-contact, flexible and accurate processes applicable to a wide range of materials. The technique can offer advantages over conventional techniques in terms of process simplicity, flexibility and cost efficiency [4].

Plasma-induced etching processes have been investigated for a wide variety of applications in the field of micro-fabrication by many works [1, 5-9]. Their achievements include a wide variety of driven processes that can be used to directly and controllably etch fine features in solid materials. A number of studies have shown that plasma-induced or plasma-assisted chemical etching can be applied to numerous materials such as metals, ceramics, semiconductors, and some polymers [10-11].

2 Experimental Work

The samples used in this work were p-type silicon substrates of (SQ.cm) resistivity. These samples were washed with distilled water then rinsed in ethanol and subjected to the ultrasonic waves for 10 minutes, then dried by hot air. The samples were ground and polished until a mirror-like surface was resulted. They were then cleaned with CP-4 solution for 5 minutes to remove any residual oxides that might be induced on the surface due to friction. After that these samples were rinsed in ethanol to remove acids then dried to be ready for processing.

The plasma-induced etching system was operated at 10^{-5} torr vacuum pressure but it was operated at 10^{-8} torr to remove any residuals inside the chamber. The anode of electric discharge system is made of stainless steel and the silicon substrate to be etched is mounted on the cathode at a specified opposite distance from the anode. The maximum discharge voltage is 15 kV_{DC} and the discharge current reaches to 3 A. Argon gas at a pressure of (1 mbar) was employed to generate the discharge plasma. The sample was maintained inside the operated system for 10 minutes before being removed and tested. The phases of the processed surfaces were introduced by X-ray diffraction patterns and the topography of the processed surfaces was carried out using an optical microscope.

3 Results and Discussion

Figure 1 explains the topography of the silicon substrate processed at 150W (IkV, 150mA) and lOmtorr gas pressure inside the chamber. As shown, the surface has been subjected to heat treatment without any melting or vaporization. Hence, the conditions required for etching were not satisfied. Such process is needed for re-alloying, coating and hardening applications. However such treatment may cause rearranging of the atoms on the surface in a certain direction. In some cases, it causes disfiguring of the surface. No crystalline orientation was distinguished on the surface.

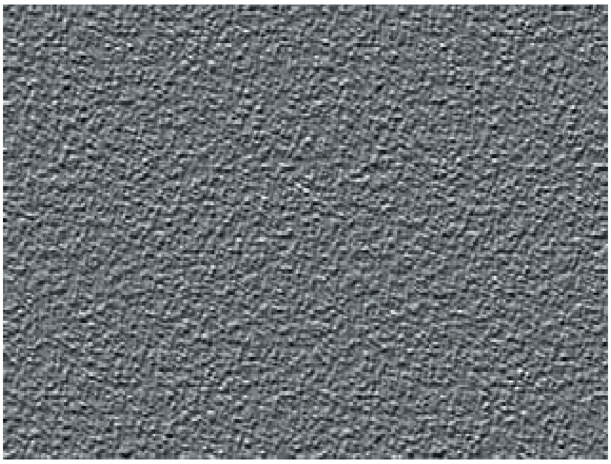

Figure 1. Topography of the silicon substrate processed at 150 W and 10 mtorr ($5O\times$).

The processing power was increased to 2 kW (4 kV, 500 mA) in order to stimulate the processing effect. The surface of silicon substrate was melted completely and when the sample was removed from the plasma system, it was left to resolidify but the phases of surface might differ from the initial case. As shown in Figure 2, some regions on the surface appeared different (dark areas) from the rest of the surface and these areas should be supposed to be locally oxidized regions, as confirmed by the X-ray diffraction in Figure 3. Such process is technically important when it is required to induce the diffusion of impurities into the substrate (silicon) and this is similar to the principle of solid-phase doping. In melting processing of semiconductors, some orientation can be obtained if the heating source is removed and the surface has enough time to resolidify. Otherwise, the surface cannot be oriented due to the thermodynamic and thermal conductivity principles [10].

Figure 4 shows the topography of silicon substrate as the processing power was reduced to 1.2 kW (3 kV, 400 mA) and the gas pressure inside the chamber is

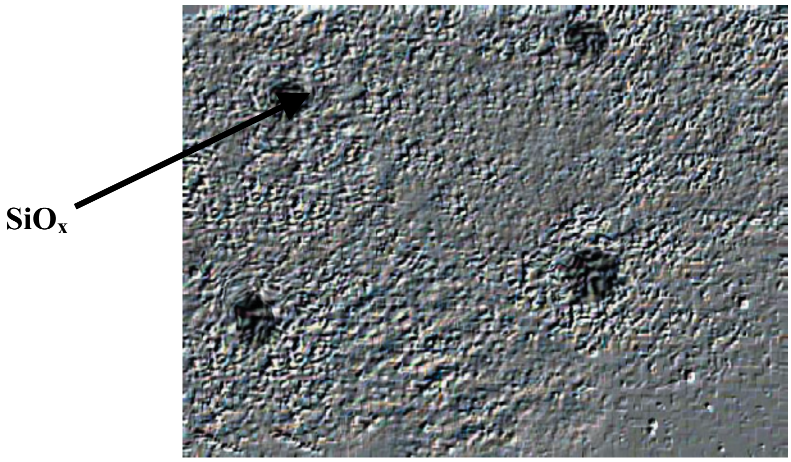

Figure 2. Topography of the silicon substrate etched at 2 kW and 10 mtorr ($5O\times$).

10 mtorr. The obtained orientation is distinct along the surface but some craters appear through. The formation of these craters might be attributed to the impurities or contaminants available in the vacuum chamber. The most important impurities and contaminants are oxygen and nitrogen molecules. The increasing of discharge power may prepare the conditions for the oxygen and nitrogen molecules to react with silicon atoms on the surface to form SiO_x and SiN_x.

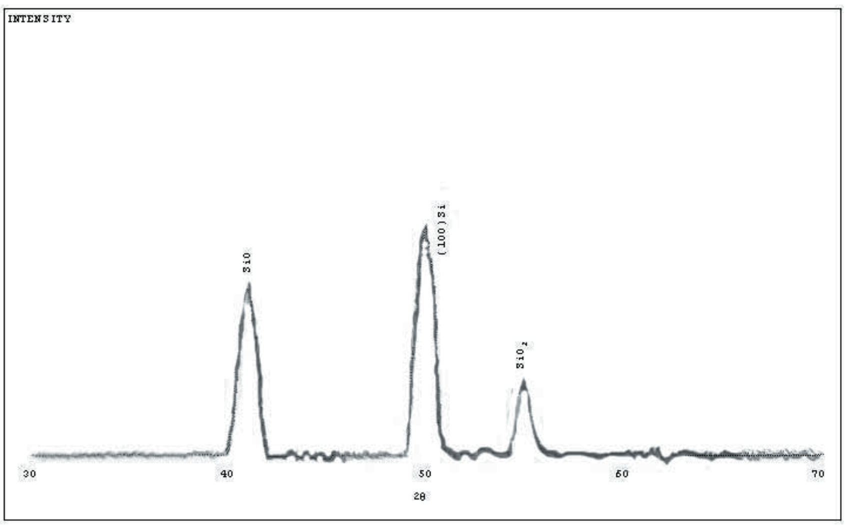

Figure 3. X-ray diffraction pattern for the sample processed at 2 kW and 10 mtorr.

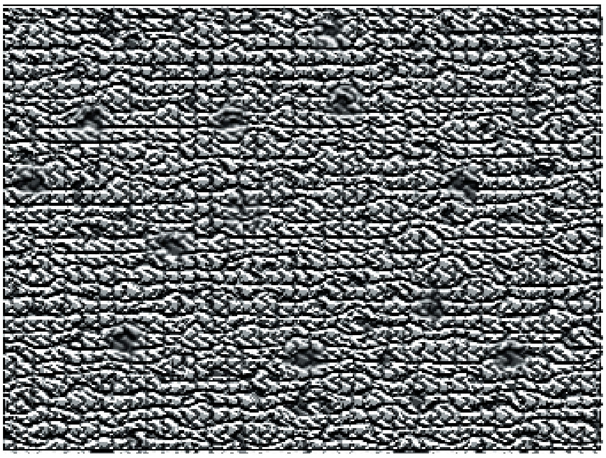

Figure 4. Topography of the silicon substrate etched at 1.2 kW and 15 mtorr ($5O\times$).

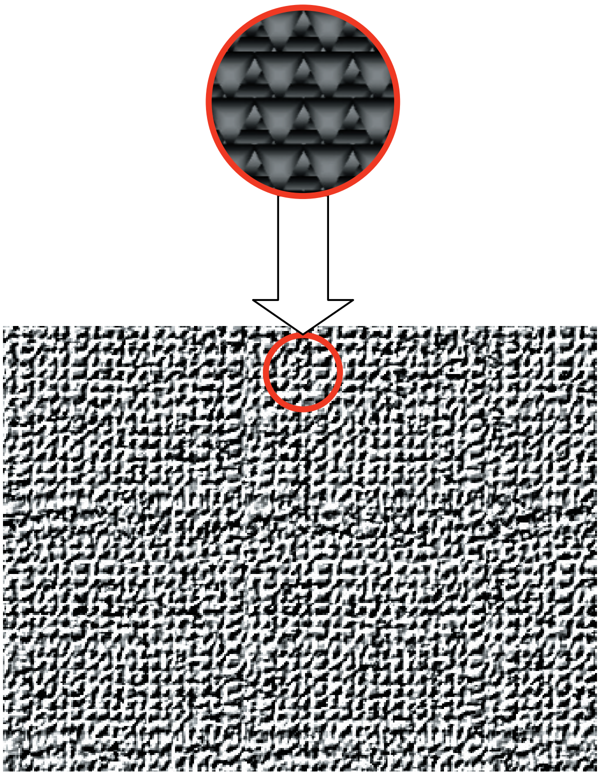

Figure 5. Topography of the silicon substrate etched at 750 W and 15 mtorr ($5O\times$).

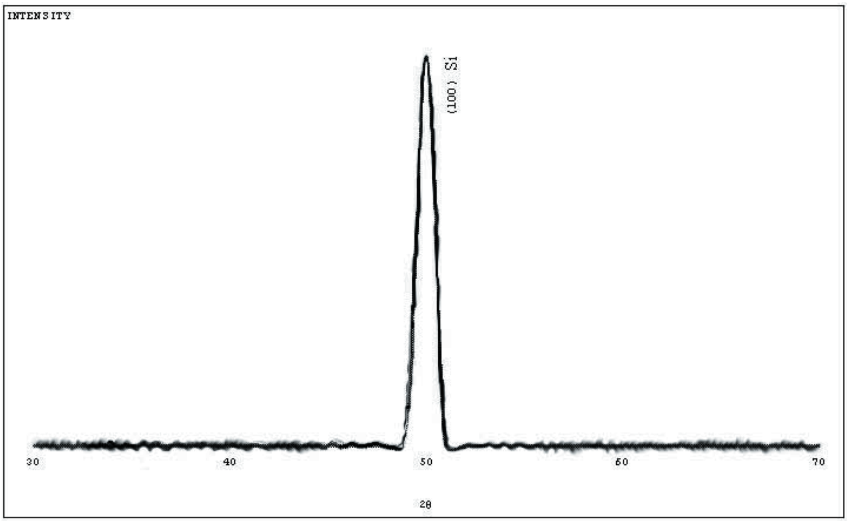

Figure 6. X-ray diffraction pattern for the sample processed at 750 W and 15 mtorr.

These oxides and nitrides cannot remain through the structure of silicon substrate because they are larger in size and higher electro-negativity [9-10]. So, they are often extracted from the surface leaving the sites of atoms as craters.

The former attempts were carried out and presented to reach the optimum conditions of etching and we have realized that the 10^{-5} torr vacuum is not sufficient to remove all residuals from the vacuum chamber. So the plasma system is operated at 10^{-8} torr vacuum pressure and Figure 5 shows the obtained sample at 750 W (3 kV, 250 mA) processing power and 15 mtorr gas pressure. The crystalline orientation is distinguished by several layers of (100) pyramids of about 1 μm in height. There are no craters on the surface that means the processing conditions (power and pressure) are optimal to perform etching process. The dominance of (100) crystalline orientation was confirmed by the X-ray diffraction pattern shown in Figure 6.

4 Conclusion

According to the obtained results in this work, plasma-induced etching process of silicon substrate was performed. Orientation of (100) was achieved at the optimum conditions of 750 W processing power and 15mtorr gas pressure. Plasma-induced etching technique is too sensitive to the contaminants and residuals inside the processing chamber and they may cause some imperfections in the resulted surface. Plasma-induced etching is simple, relatively low cost and efficient technique as well as large-dimensioned samples can be produced. We realize that this work needs to be improved and extended to introduce the definite values of threshold conditions at which etching is supposed to stimulate.

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