Excimer-Laser Etching on Silicon

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Abstract. Studies have been made of poly- and single Si etching induced by excimer-laser irradiation of the silicon surfaces in halogenated gases. Etching was investigated for different conduction types, impurity concentrations and crystallographic planes. Chlorine atoms accept electrons generated in photoexcited, undoped p-type Si, thus becoming negative ions which are pulled into the Si. However, the n- type Si is etched spontaneously by Cl− as a result of the availability of conduction electrons. Fluorine atoms, with the highest electronegativity, take in electrons independent of whether the material is n- or p-type. And thus, the easy F− ion penetration into Si causes spontaneous etching in both types. New anisotropic etching for n+ poly-Si is investigated because of its importance to microfabrication technology. Methyl methacrylate (MMA) gas, which reacts with Cl atoms, produces a deposition film on the n+ poly-Si surface. The surface, from which the film is removed by KrF (5 eV) laser irradiation, is etched by Cl atoms, while the film remains on the side wall to protect undercutting. However, with the higher photon energy for the ArF (6.4 eV) laser, the Si–OH bonds are broken and electron traps are formed. These electron-trapping centers are easily annealed out in comparison to the plasma-induced centers. Pattern transfer etching for n+ poly-Si has been realized using reflective optics. The problems involved in obtaining finer resolution etching are discussed.

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Low-temperature plasma processes, such as insulator deposition and Reactive Ion Etching (RIE), have played important roles in the major recent advances in VLSI devices. In particular, energetic ion bombardment, applied to Si, SiO2, and Al, provides a highly directional etched feature, which has led to higher density circuits. However, charged particles impinging onto solid surfaces cause radiation damage, such as surface contamination by the reactants, crystal defects [1], and oxide breakdown by the charged-up insulator surface [2]. As the minimum feature size is reduced for submicrometer devices, the damage problems have become more serious. Because of this ion effects, an useful, damage-free process requires not only the minimum energy for the chemical/physical reaction but also a totally neutral reaction system. Accordingly, the application of a photochemical reaction to semiconductor processing is now being studied intensively [3].

A photoexcited process offers the following advantages: (i) A specific reaction is controlled by particular wavelength of the photoirradiation source. (ii) A reaction in a desirable special direction (anisotropy) can be accomplished using a collimated laser beam. (iii) Direct writing or single-step pattern transfer is achievable using appropriate optics. At present, the promise of these techniques has generated a growing number of studies. However, outstanding or practically useful performances have not yet been attained. More intensive work should be carried out for further development.

In this paper, Si photoetching, employing an excimer laser, is reported, including the subject of the etching mechanism, n+ poly-Si anisotropic etching, radiation damage, pattern transfer and the resolution limit.

1. Experimental

Figure 1 shows a schematic illustration of the experimental system. A high-pressure Hg–Xe lamp was used as the light source at the initial stage of this study [4].
Fig. 1. Schematic illustration of the etching apparatus

This source was subsequently replaced by the present excimer laser [5]. The laser wavelengths and powers used were 350 nm (XeF) at 1 W/cm², 308 nm (XeCl) at 3 W/cm², 249 nm (KrF) at 10 W/cm², and 193 nm (ArF) at 1 W/cm², respectively. The repetition-rate and pulse length were 100 pps and 10 ns, respectively. The 10 x 20 mm² rectangular laser beam was irradiated through a quartz window onto the silicon (Si) wafer in a reactor filled with 10 to 100 Torr of reactive gases, such as C₂Cl₂, XeF₂, and methyl methacrylate (MMA).

Each samples of polycrystalline (poly-) Si or single Si was mounted on the sample holder after it was dipped in a buffered-HF solution to remove its native oxide layer. Etching experiments were carried out with a gas system using a mechanical pump; the chamber was initially evacuated to a pressure below 10⁻⁶ Torr.

2. Etching Mechanism

2.1. Poly-Si Etching

Poly-Si etching using Cl₂ gas, was investigated for different doping types and sheet resistivities, as shown in Fig. 2 [6]. Phosphorous (n-type) and boron (p-type) ions were implanted at 150 and 50 keV accelerating voltages for the same 1 x 10¹⁶ cm⁻² dosages. The sheet resistance was changed using two different heat treatment by 40 min at 550°C and 10 min at 1000°C, respectively, after which the dopant concentrations were assumed to be uniformly distributed within the films. The abscissa for n- and p-types was scaled inversely, as will be discussed later. In this experiment, a Hg–Xe lamp was focused to a 2 mm diameter (275 mW/cm²) on the surface, using a quartz lens. Both the Hg–Xe lamp and XeCl laser dissociated Cl₂ gas directly showing a 300 to 400 nm absorption peak corresponding to chlorine (Cl) atoms. At present, both of these sources provide the same order poly-Si etch rates. An Al film was used for the etching mask.

The etch rates decreased in the order of n⁺ (heavily doped), n (lightly doped), undoped, p and p⁻ types. The profile of the etched feature were an isotropic in the n⁺ type; anisotropic features appeared only with increasing resistivities. In the undoped and p types, only anisotropic etching was observed. Samples of n⁺ poly-Si also etched isotropically with parallel phototrradiation. This fact suggests that the Cl atoms, produced in the gas phase, contribute to the spontaneous etching of the n⁺ poly-Si. In contrast, the undoped and p-type poly-Si samples did not etch when the surfaces were not phototirradiated; in other words, etching did not occur until the hole-electron pairs were generated. Considering that electrons are minority carriers in p-type Si, the variation in etch rate corresponds quite closely to the electron concentration in the conduction band, as indicated in the abscissa of Fig. 2.

The photoexcited etching reaction can be explained as follows [7]. Model which is based on a field-assisted mechanism in a metal oxidation process first is proposed by Cabrera and Mott [8]. Photodissociated Cl atoms first adsorb on the Si surface. Simultaneously, the separation of photoelectrons and hole pairs which have different carrier mobilities produce a high, surface, electric field of 0.1 to 1 eV nm⁻¹ [9]. This effect can cause band bending [10] and facilitate charge transfer from Si to the adsorbate Cl species. The negatively charged species, Cl⁻, can penetrate into the Si lattices. The volatile reaction products of this penetrations, SiClₓ (x = 1 to 4), are finally desorbed to the gas phase.

2.2. Field-Assisted Etching

The experiment, inset in Fig. 3, was tried out to verify the field-assisted reaction [11]. A platinum (Pt) tip electrode was contacted onto the oxide grown thermally on a p-type Si samples. The XeF laser used effectively dissociated the Cl₂ gas. Subsequently, posi-