Reactive Ion Etching of Microphotonic Structures

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Abstract: Fabrication of microphotonic structures such as planar waveguides and periodic structures or photonic crystals based on silicon technology has become increasingly important due to the potential for integration of planar optical devices. We show that by varying the main RIE parameters such as gas pressure, rf power and $CF_4/Ar/O_2$ gas composition it is possible to produce microstructures with near-vertical sidewalls and smooth surfaces. To achieve high etch selectivity we employed Ni-Cr metal masks and used Ar^+ ion milling instead of wet chemical etching to open the mask. This improves the edge quality of the mask and ultimately results in smooth sidewalls.

1. Introduction

Fabrication of micro-photonic structures such as waveguides and photonic crystals is important for integration of planar optical devices. Plasma etching is a key step in the fabrication process. Features such as surface roughness and the sidewall angle or steepness of photonic microstructures are critical factors as they account for most of the propagation loss. They depend on the variables that control the etching process, and on the quality of the etching mask. Here, we report on the fabrication of various periodic microstructures on Si and silicon-on-insulator (SOI) wafers using standard optical lithography and reactive ion etching (RIE) in fluorinated plasmas. The quality of the mask, gas pressure, gas mixture (CF_4 /Ar/O_2) and rf power (13.56 MHz) are shown to have a significant influence on the quality of the etched microstructures.

2. Importance of masks

For our RIE system, the selectivity of photoresist against Si for CF_4 etching is very low (≤1:2). This makes deep etching of Si difficult. If a thick layer of photoresist is used as the etching mask, the low-angle slope and poor edge profile of the resist are transferred to the etching layer resulting in low angle and rough sidewalls as shown in Figure 1(a).

Poor quality of the edge of an etching mask is often the primary cause of sidewall roughness [1]. We found that in CF_4 plasmas a Ni-Cr film etches at a very low rate compared with Si and thus is ideal for use as an etching metal mask. Also, we employed Ar^+ ion milling (Kaufman ion source) rather than wet chemical etching to open the Ni-Cr metal mask. This improved the edge quality of the Ni-Cr mask, and combined with optimized etch parameters, smoother sidewalls were obtained as shown in Figures 1(b, c).

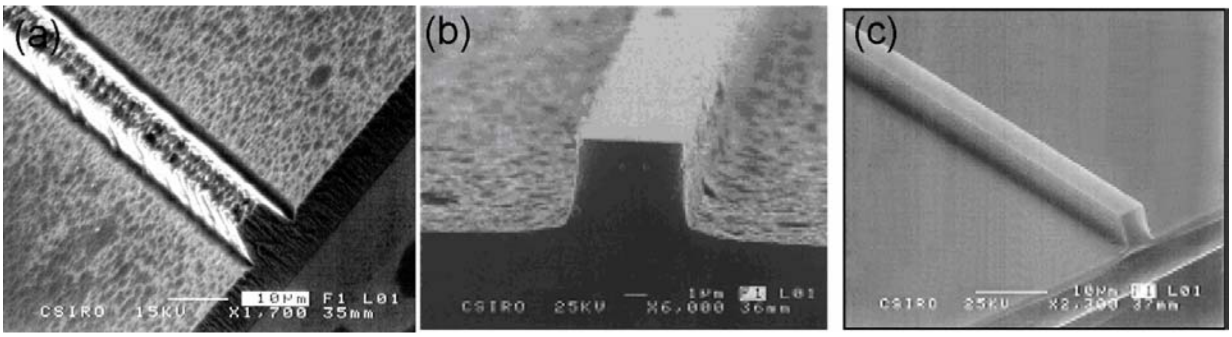

Figure 1. Silicon rib waveguides etched using (a) resist mask, and (b, c) Ni-Cr masks.

3. Influence of etching parameters on Si etch profile

When Si is etched with fluorinated plasma, the etching process is a combination of contributions from the chemical reaction between F and Si, the ion-bombardment-induced component, and some physical sputtering. Figure 2(a, b) shows etch profiles of 10×10 μm^2 features, obtained at 50 W rf power and 10 and 3 Pa CF_4 gas pressure, respectively. The small degree of undercut seen in image (a) is almost absent in image (b). At high CF_4 gas pressure chemical effects are dominant and the etching process tends to be isotropic causing some lateral undercut. As the pressure is lowered the ion-assisted etching becomes more important. Since the ions are directed normal to the substrate surface, near-vertical sidewalls are obtained at some optimal combination of chemical and ion-assisted etching.

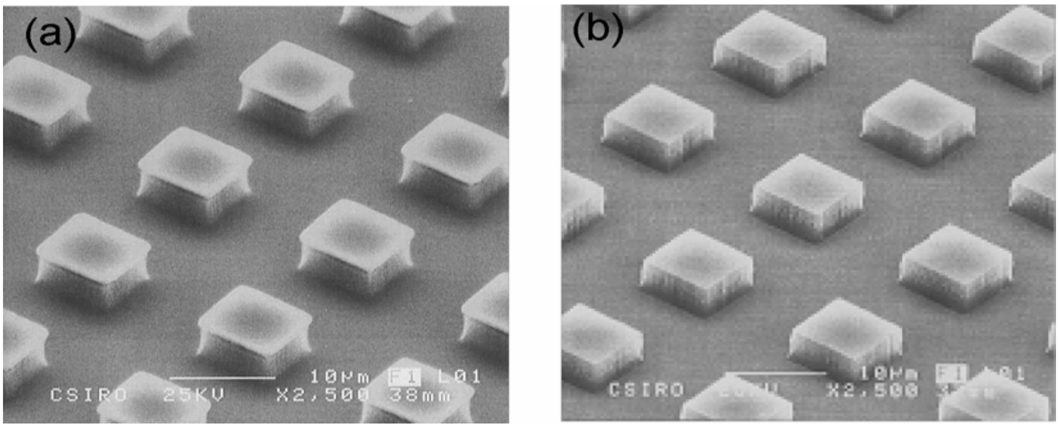

Figure 2. Array of 10×10×4 μm^3 pillars on Si etched at CF_4 pressure (a) 10 Pa and (b) 3 Pa.

4. Effect of Ar addition on etch characteristics

The profiles in Figure 3 (10×10 μm^2 and 4 μm high) were obtained using a mixture of ~20% Ar in CF_4, 6 Pa total pressure, and 50 W rf power. Near-vertical sidewalls and smooth surfaces were obtained. A small degree of rounding of walls is visible but can be reduced by operating at lower gas pressures. Rib waveguides in SOI with desirable profiles [2, 3], as shown in Figure 1(c), were fabricated using the above conditions. The addition of a small amount of Ar drives the process toward anisotropic etching so that vertical sidewalls result. In addition, the bombardment of lateral surfaces by energetic Ar^+ ions prevents the formation of polymeric films and results in clean and smooth surfaces.

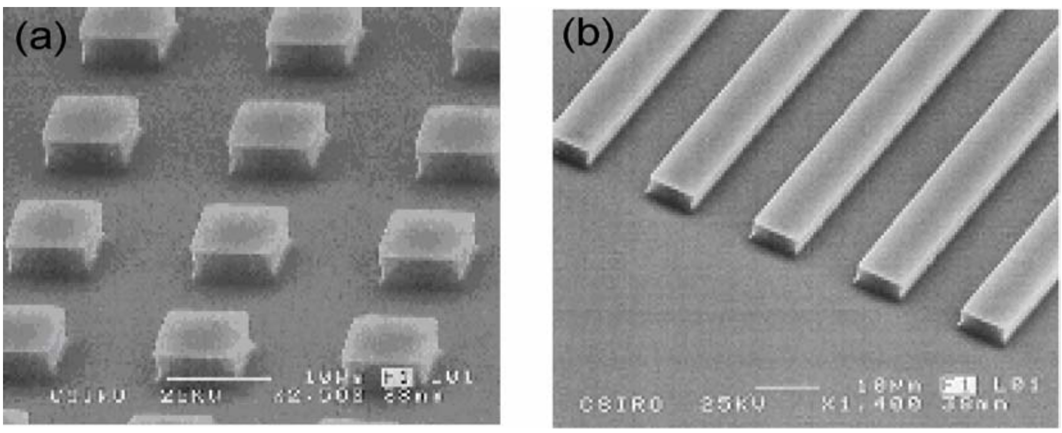

Figure 3. Smooth surfaces and near-vertical sidewalls observed on SOI arrays of 10×10 μm^2 pillars and 6 μm waveguides etched using CF_4/Ar mixture.

5. Effect of O_2 addition on etch rate and profile

A preliminary study was carried out on the effect of the addition of ~20% O_2 to CF_4. The presence of O_2 increases the chemical etching rate significantly. Figure 4(a) shows microstructures etched by CF_4/O_2 plasma using the same conditions as in Figure 3 but with O_2 replacing Ar. These conditions led to a doubling of the etch rate but the degree of undercut also increased due to the aggressiveness of the chemical etching. However, the addition of O_2 was found to be useful for the etching of holes in Si as shown in Figure 4(b). RIE-lag effects and fluorocarbon-polymer building-up on the floor of holes are often observed [4, 5] and lead to reduced rates and rough floors. The addition of O_2 to the fluorinated plasma decreased the roughness and improved the etch rate.

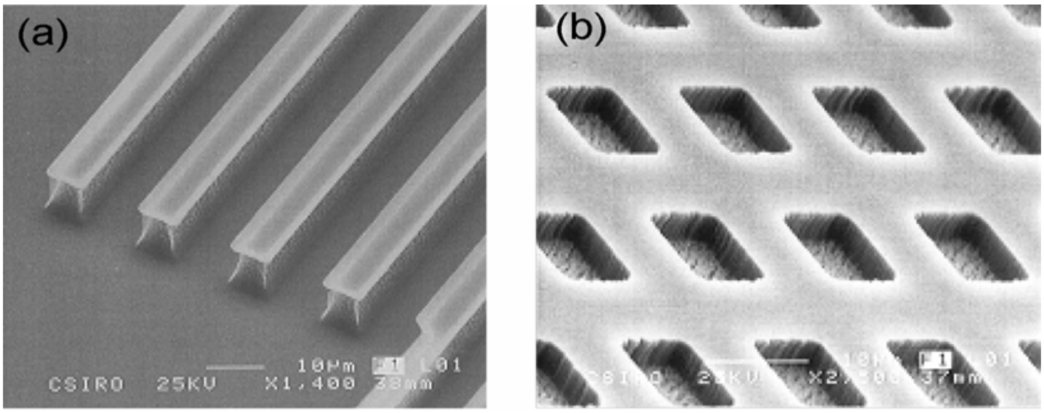

Figure 4. Microstructures etched using CF_4/O_2.

6. Summary

Optical waveguides and periodic microstructures were fabricated in Si and SOI wafers by reactive ion etching (RIE) in fluorinated plasmas using CF_4 with small additions of Ar and O_2. The fluorinated plasma is an isotropic etchant and under certain conditions it can lead to severe undercutting. However, the etching characteristics of the plasma can be changed by varying the etch parameters (gas pressure, rf power) and adding Ar and/or O_2 to CF_4.

The presence of Ar^+ ions in the plasma enhanced the ion-assisted and sputtering processes thereby driving the process towards anisotropic etching. Consequently surfaces that lie normal to the ion direction, i.e. in the substrate plane, etch much faster than vertical surfaces. This directional anisotropy is further enhanced at the lower pressures. Oxygen prevented polymeric formation resulting in increased etch rates, and was particularly useful for etching holes and grooves.

Our results show that under optimum conditions reactive ion etching using a gas mixture of CF_4 and Ar allows to fabricate microstructures that have desirable near-vertical sidewalls and smooth surfaces.

References

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