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RIE of sub-50 nm high aspect-ratio pillars, ridges, and trenches in silicon and silicon-germanium

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Abstract

Sub-50 nm high aspect-ratio pillars, ridges, and trenches have been patterned in Si and SiGe using reactive ion etching (RIE) with Cr masks defined by ultra-high resolution electron beam lithography and a lift-off process. Using an optimized mixture of Cl_2 and $SiCl_4$ gases, sub-50 nm features with aspect ratios greater than 10 were readily and consistently achieved. For achieving similar nanostructures in SiGe, an identical gas mixture at lower pressures is required.

1. INTRODUCTION

The ability to etch nanoscale features in Si is of great interest to many areas: trench isolation [1], trench capacitors [2], and high capacitance stacked capacitors [3] in very large scale integrated circuits; novel quantum effect Si devices; and high resolution, high aspect-ratio atomic force microscope tips. Recently, silicon-germanium alloys grown on Si substrates have become very attractive to future VLSI circuits due to material properties and the ability to tailor the bandgap. Therefore, etching nanostructures in SiGe has become important, yet is not well studied.

Chlorine based RIE is well suited for etching nanoscale Si features with good control of undercutting and etch profiles [4]. Profile analysis of $Si_{1-x}Ge_x$, $x \leq 0.2$, trenches etched in Cl-based gases indicate that, like Si, etching requires ion bombardment [5], and suggests that nanoscale, anisotropic features can also be achieved in SiGe.

Here we present the fabrication of sub-50 nm high aspect-ratio pillars, ridges, and trenches in both Si and SiGe alloys using ultra-high resolution electron beam lithography and Cl-based reactive ion etching. The aspect ratios for these etched structures are greater than 10.

2. EXPERIMENTAL TECHNIQUES

The Si wafers are *p*-type with a 10 $\Omega \cdot$cm resistivity and a (100) orientation. The SiGe samples were grown by atmospheric pressure

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chemical vapor deposition and consist of a Si buffer grown at 900 °C, 1000 Å of $Si_{0.75}Ge_{0.25}$, and finally a 70 Å thick Si cap grown at 625 °C. The Si wafers were first cleaned using H_2SO_4:H_2O_2:H_2O (1:1:5) for 10 min at 120 °C, DI rinse for 5 min, and buffered HF for 30 sec. The SiGe samples were cleaned with a buffered HF dip to remove the native oxide, and a DI H_2O rinse. After cleaning, a 70 nm thick layer of 950 K polymethyl methacrylate (PMMA) was spun and baked at 165 °C for 12 hours. Arrays of dots and lines were exposed in the PMMA using a modified JEOL-840A SEM described elsewhere [6], and developed in a mixture of 2-ethoxyethanol and methanol. 50 nm of Cr was then deposited via electron beam evaporation. A lift-off process left arrays of Cr dots and lines on the Si wafer, which were used as the mask for RIE.

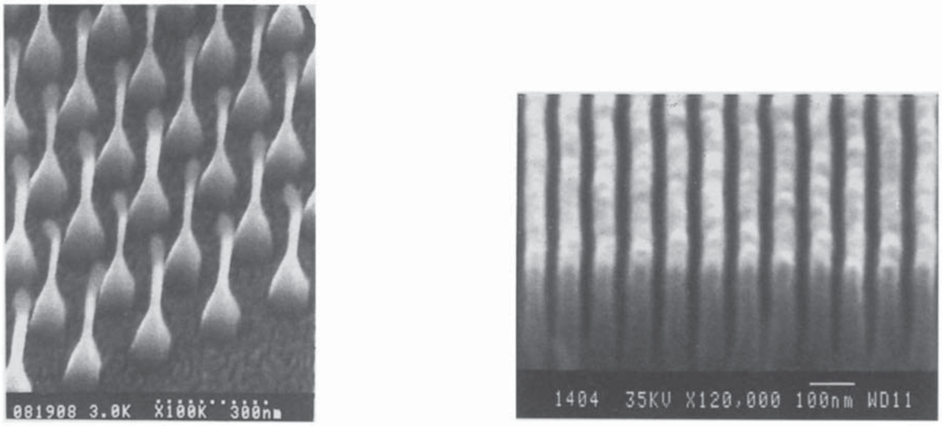
RIE was performed using a Plasma-Therm parallel plate RIE system operated at 13.56 MHz. A variety of recipes based on Cl_2 and $SiCl_4$ gases were tested. Chlorine was used because it has been shown to produce vertical sidewalls [4] due to the ion assisted etching mechanism [7], but has the drawback of producing trenches in the bottom corners. $SiCl_4$ was added to control trench formation by simultaneous re-deposition [8]. Prior to etching the chamber was always cleaned for 10 min with an Ar plasma, and then pre-conditioned for 10 min using the same etching recipe that was to be used. After inserting the sample, the chamber was pumped below 2×10^{-5} torr.

Optimum sidewall profiles were obtained using Cl_2 and $SiCl_4$ with a flow rate of 76.6 and 13.3 sccm, respectively, a power density of 0.32 W/cm^2, and a pressure of 40 mtorr. These parameters were found to produce the sidewall profiles necessary for nanoscale, high aspect ratio features without trenching at the bottom corners and were used for all of the etching reported here. Lower pressures, however, were necessary for etching densely spaced SiGe nanostructures. The substrate temperature during etching was maintained at 32 - 40 °C. After etching, the samples were analyzed using high resolution scanning electron microscopy.

3. RESULTS

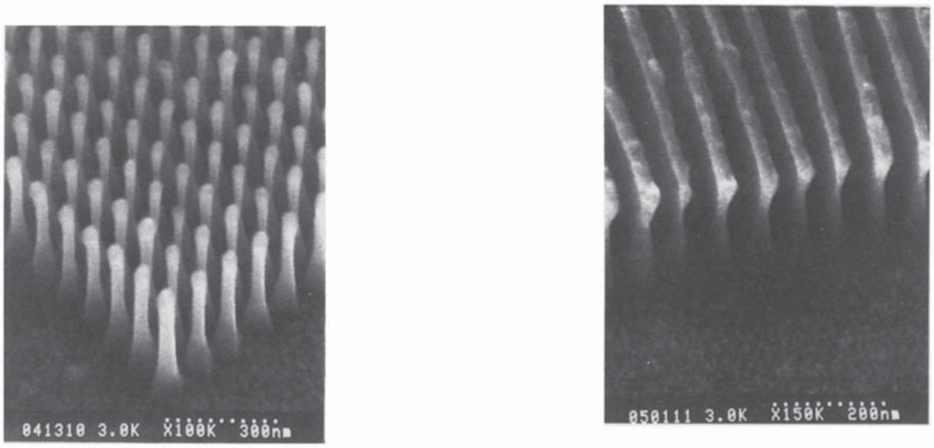
Sub-50 nm Si pillars, trenches and ridges have been achieved using the above process. Figure 1 (a) shows an array of etched Si pillars having diameters of approximately 40 nm, a period of 100 nm, and a height of 520 nm. Since the hemispherical Cr dots were not removed, this picture shows that no undercutting of the mask has occurred. It also shows no trenching at the bottom corners has occurred. Figure 1 (b) shows 50 nm wide Si ridges spaced by 30 nm which are also 520 nm high. The Cr mask was left in place to again verify that no undercutting of the mask occurred during etching. In both cases the aspect ratio is greater than 10. Using a pressure of 40 mtorr, the etch rate is 250 nm/min for Si, and is 615 nm/min for SiGe. The disparity in etch rates was found to decrease with decreasing pressure.

These results suggest that the size of these etched features is not limited by the etching itself, but by the masks and the mechanical



(a) (b)

Figure 1. Scanning electron micrographs of: (a) Si pillars having sub-40 nm diameters, 100 nm pitch, and a height over 0.5 μm (tilt = 40°), and (b) 30 nm wide Si trenches with 50 nm spacing (tilt = 70°).



(a) (b)

Figure 2. Scanning electron micrographs of: (a) SiGe pillars of sub-40 nm diameter, 200 nm pitch, and over 0.5 μm high (tilt = 40°), and (b) 30 nm wide SiGe/Si ridges spaced by about 40 nm, and 500 nm deep (tilt = 70°).

stability of Si. Pillars, like those shown in figure 1 (a), can be further modified by overetching, or by removing the Cr mask and performing a subsequent wet etch in HF to achieve extremely sharp, high aspect ratio spikes that would be useful as field emitters or as atomic force microscope tips.

Sub-50 nm SiGe pillars, trenches and ridges have also been achieved using this Cl_2:$SiCl_4$ RIE process. Figure 2 (a) shows an array of etched SiGe pillars having sub-35 nm diameters, a period of 200 nm, and a height of about 600 nm. Here again, the hemispherical Cr dots were not removed for this picture; slight undercutting of the mask has occurred, but there is no trenching at the bottom corners. Figure 2 (b) shows 30 nm wide SiGe ridges spaced by about 40 nm; the total etch depth is 500 nm. Some lateral etching of the SiGe alloy layer has occurred. The grating was etched using a pressure of 8.5 mtorr, which is significantly lower than the pressures required for etching identical grating structures in Si. At higher pressures it was found that the lateral etching of the SiGe had a higher rate, causing undercutting which can cause densely spaced nanostructures to collapse in the middle. At a pressure of 8.5 mtorr the etch rate is 230 nm/min for SiGe and 280 nm/min for Si.

4. CONCLUSIONS

Sub-50 nm high aspect-ratio pillars, ridges, and trenches have been patterned in both Si and SiGe using RIE with Cl_2 and $SiCl_4$ gases with Cr masks. Aspect ratios greater than 10 were readily and repeatedly achieved. The results suggest that with smaller etching masks even smaller features can be achieved in Si. It was found that in etching SiGe, lower pressures than those for etching Si are needed to reduce the undercutting.

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6. REFERENCES

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