Direct measurement of sidewall roughness on Si, poly-Si and poly-SiGe by AFM

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Abstract. In this paper the effect of the commonly used HBr/Cl₂ chemistry for dry etching on the line-edge roughness (LER) of photoresist patterned single crystalline Si (sc-Si), polycrystalline Si (poly-Si) and poly-Si₀.₂Ge₀.₈ sidewalls was characterized. Measurements were done by means of atomic force microscopy in combination with an elaborated sample preparation technique that allowed the LER at different depths of the sidewall to be measured. Samples were patterned by I-line lithography and etching was performed at an RF power of 200 W using HBr/Cl₂ (30/10 sccm) plasma. For sc-Si the photoresist and Si sidewalls had an LER of 0.8-1.4 nm and 1.5-2 nm, respectively. For poly-Si and poly-SiGe the photoresist sidewall roughness was, respectively, increased to 1.5-3 nm and 2-3.5 nm due to light scattering from the rough surface of the polycrystalline materials. The poly-Si film had a sidewall roughness of 3-4 nm. Poly-SiGe sidewall exhibited larger roughness with an LER of 5-12 nm which was not transferred from the photoresist. The results show that for sc-Si and poly-Si the sidewall roughness mainly originates from the photoresist process and little additional roughening is caused by the HBr/Cl₂ etching. However, for poly-Si₀.₂Ge₀.₈ the LER is considerably increased from that of the photoresist indicating that the HBr/Cl₂ etching is the main contributor to the LER.

1. Introduction
Low line-edge roughness (LER) in photoresist patterned and etched Si and SiGe thin films is important for several applications. LER affects light transmission in Si waveguides [1], reduces carrier mobility in FinFET devices [2] and increases leakage current in nanoscale MOSFETs [3]. Furthermore, sidewall roughness of poly-SiGe support material in the sidewall transfer lithography process [4,5] degrades the uniformity of the patterned nano-scale Fins or wires [6].

The LER in dry etched sidewalls is partially caused by the photoresist process but is further affected by the dry etching itself. Traditional atomic force microscopy (AFM) systems are not adequate for measuring LER since they only have a vertical feedback loop and thus have a limited accuracy in the lateral plane. Furthermore, the usual cone shape of the tip means that it cannot come in contact with the sidewall itself. One solution to this problem is to rotate the sample so that the normal of the sidewall is parallel to the feedback direction [7-9]. In this article the sidewall LER of photoresist masked and dry etched Si, poly-Si and poly-SiGe sidewalls is measured at different depths of the sidewall. Additionally, poly-SiGe sidewalls are measured when a Lift-Off-Layer (LOL) or an anti-
Reflective coating (ARC) is spun beneath the photoresist in order to clarify the origin of the sidewall roughness of poly-SiGe.

2. Experimental

The different test structures made can be seen in figure 1. The sc-Si sample was prepared on a (100) wafer with measured sidewalls along the [110] direction. The poly-Si and SiGe films were deposited on Si (100) wafers first covered with a 100 nm thick SiO\(_2\). Poly-Si\(_{0.2}\)Ge\(_{0.8}\) was deposited by LPCVD at 500 °C using SiH\(_4%/GeH_4\) (100/70 sccm) for 41 min which gave a layer thickness of 850 nm. The surface root-mean-square (RMS) roughness was measured to be 41 nm by AFM. The poly-Si was deposited by LPCVD at 650 °C using an SiH\(_4\) flow of 100 sccm for 90 min which gave a 1 µm thick layer with a surface roughness of 32 nm.

Photoresist (Shipley Megaposit SPR 700-1.2) was spun on at 5000 rpm (1 µm thick) and soft-baked at 90 °C for one minute. Patterning was done by an I-line lithography stepper with a dose of 170 mJ/cm\(^2\). Samples were subsequently post-exposure baked at 110 °C for one minute, developed (MF CD-26) for 20 seconds and hard-baked at 110 °C for 20 min. Dry-etching was performed in an Applied Materials Precision P5000 cluster tool equipped with a MxP Si etch chamber. Etching was performed at RF power 200 W and pressure 125 mTorr using HBr/Cl\(_2\) (10/30 sccm). The sc-Si sample was etched by time targeting a 1.2 µm depth while the poly-Si and poly-SiGe samples were etched until endpoint measured by optical emission spectroscopy at the wavelength 470.5 nm.

Additional experiments were performed using Lift-Off-Layer (LOL) and anti-reflective coating (ARC) spun beneath the photoresist on samples with a poly-SiGe layer. LOL (LOL-2000, Shipley Co.) was spun on at 2000 rpm (250 nm) and baked at 170 °C for 5 minutes. Photoresist was patterned on the wafer as described above except the developing time was decreased from 20 to 10 seconds which gave a 500 nm undercut. ARC (ARC-i-Con-16, Brewer Science Inc.) was spun on at 1000 rpm (260 nm) and baked at 180 °C for one minute. The sample was patterned and the ARC which was not removable by the developer was opened using a CHF\(_3%/CF_4%/O_2\) (5/8/5 sccm) plasma etch.

All AFM (Digital instruments, Nanoscope IV) measurements were done in tapping mode with standard silicon tips. To characterize the LER, an elaborated sample preparation procedure was developed. By exposing the wafer with a grating pattern and after etching the underlying layer, the wafer is cleaved and the sample is rotated 90 degrees. The AFM has full access to the sidewall surface and thus a direct comparison between photoresist and the etched film LER was obtained. The measurement error is estimated to be ±5% based on repeated measurements of the same area.

Figure 1. Schematic cross-section for the different samples made for sidewall AFM studies.
3. Results and discussion

The structures shown in figure 1 were characterized by means of the sidewall AFM technique developed for this work. Sidewall roughness was evaluated by calculating the RMS roughness of a 2 \( \mu m \) line horizontally along the sidewall. The results are shown in figure 2. The roughness for each sample was extracted from at least two measurements. The roughness variation between different measurements on the same sample was small and thus the spread in the data comes mostly from roughness variation at different depths of the sidewall.

On sc-Si, the photoresist and etched Si roughness were 0.8-1.4 nm and 1.5-2 nm, respectively. The poly-Si sample exhibited a larger photoresist roughness of 1.5-3 nm, likely due to light scattering of the rough surface onto the sidewall during the exposure. The dry etched poly-Si exhibited a 3-4 nm roughness. The photoresist roughness on poly-SiGe before and after dry etching was similar, showing the dry etch did not alter the photoresist roughness significantly. However, the poly-SiGe sidewall exhibited a significant increase in roughness compared to the photoresist. Figure 3 shows SEM micrographs of the poly-Si and poly-SiGe sidewalls.

The photoresist sidewall was not vertical but had an angle of 65-80 degrees which could cause it to extend farther into grooves than hills on the rough poly-SiGe surface. If present this effect would increase roughness in the dry etched layer. LOL was used to separate the photoresist from the rough poly-SiGe surface in order to isolate roughening caused by the plasma etching. The sidewall roughness was increased from that of the photoresist indicating that the dry etch itself was likely to cause additional roughening of the poly-SiGe. It is unclear why the dry etch induced roughening is greater for poly-SiGe than poly-Si, and it remains to be confirmed if the etch rate varies for different crystallographic orientations present in the poly-SiGe especially when the Ge concentration is high.

The photoresist roughness was decreased when ARC was used on poly-SiGe. The poly-SiGe roughness was also decreased but still significantly larger than the photoresist roughness. Figure 4 shows an AFM micrograph of this sample where it can be seen that the poly-SiGe sidewall exhibits a roughness transferred from the photoresist as well as progressively added roughening which starts at the beginning of the poly-SiGe layer and increases in amplitude with depth.

![Figure 2. Line-edge roughness (LER) of the different samples measured by AFM. Results are given as RMS values of lines drawn along the sidewall and the range is the variation of roughness at different depths of the sidewall.](image)

4. Conclusions

The sidewall roughness of sc-Si, poly-Si and poly-Si\(_{0.2}\)Ge\(_{0.8}\) patterns defined by a photoresist mask and dry etched by an HBr/Cl\(_2\) chemistry has been characterized. The measurements were performed using a specially developed sidewall AFM technique where the roughness at different depths is obtained. The results show that for sc-Si and poly-Si the sidewall roughness mainly originates from the photoresist process and little additional roughening is caused by the HBr/Cl\(_2\) etching. However, for
poly-Si$_{0.2}$Ge$_{0.8}$ films the sidewall roughness is considerably increased from that of the photoresist which indicates the HBr/Cl$_2$ etch chemistry causes a significant increase in roughness.

![SEM micrographs showing a bird's eye view of the photoresist and etched layer for (a) poly-Si and (b) poly-SiGe.](image)

**Figure 3.** SEM micrographs showing a bird's eye view of the photoresist and etched layer for (a) poly-Si and (b) poly-SiGe.

![AFM micrograph showing sidewall of an etched poly-SiGe using ARC. (b) Cross-sections through the photoresist (red) and the poly-SiGe (blue) showing an increase in sidewall roughness between the photoresist and poly-SiGe.](image)

**Figure 4.** (a) AFM micrograph showing sidewall of an etched poly-SiGe using ARC. (b) Cross-sections through the photoresist (red) and the poly-SiGe (blue) showing an increase in sidewall roughness between the photoresist and poly-SiGe.

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