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Roughness reduction of Si waveguides by KrF excimer laser reformation

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Abstract
Roughness reduction of Si waveguides by KrF excimer laser reformation is demonstrated. The root-mean-square roughness of the reactive-ion-etched Si surface is reduced from 13.95 nm to 0.239 nm with a laser intensity of 1.4 J/cm^2.

In Si photonics, fabrication of low-loss waveguides becomes more challenging as the waveguide size keeps shrinking for compactness [1]. The scattering loss of Si waveguides is proportional to the root-mean-square (RMS) roughness of the sidewall surface [2]. It is predicted to be less than 1 dB/cm if the RMS roughness is less than 1 nm [3]. Dry-etch processes to fabrication Si waveguides, however, create significant roughness. Therefore, post-etch processes to reduce roughness of the sidewall surface are indispensable for low-loss Si waveguides.

Many techniques are devised for roughness reduction of Si waveguides: hydrogen annealing [4], dry oxidation [5], and wet chemical etching [6]. Hydrogen annealing technique operates at 1100 ^{o}C and can reduce the RMS roughness to 0.11 nm [4]. Dry oxidation method also operates at 1100 ^{o}C and can reduce the RMS roughness to 0.5 nm [5]. These two methods have thermal budget concerns when Si photonics are to be integrated with Si electronics. IC foundries have constraints on wafer doping and flatness, which requires photonic structures to be fabricated after electronics. Therefore post-etch processes at high temperature may degrade the electronics. Wet chemical etching method can reduce the RMS roughness to 0.7 nm [6]. Oxidation methods, however, have a tradeoff between sacrificial oxide thickness and roughness reduction capability. Large roughness like ragged sidewalls by ICP-RIE is hardly reduced by these ways.

Here, we demonstrate KrF excimer laser reformation for roughness reduction of Si waveguides. It is capable of reducing the RMS roughness of reactive-ion-etched Si surface from 13.95 nm to 0.239 nm. This technique has no limitation on thermal budget during the integration of Si electronics and photonics as protective coatings can be used to prevent exposure of the electronics during laser illumination [7].

The principle of laser reformation is to illuminate the vertical sidewall of Si waveguides with a high energy pulse laser at an incident angle θ, as illustrated in Fig. 1. The KrF excimer laser has a wavelength of 248 nm, a pulse duration of 25 ns and a laser intensity of 1~2 J/cm^2. The absorbed light in Si converts to thermal energy. The illuminated surface Γ serves as a heat generation source and has different generation rates at the vertical sidewall and the ridge as the illumination intensity varies there. With an incident angle larger than 45^{o}, the vertical sidewall has a larger generation rate than that of the ridge. With appropriate intensities and incident angles, only the vertical sidewall melts. The molten sidewall, denoted by Ω, reforms due to the surface tension of liquid Si. It is this surface tension that flattens the roughness. After the laser pulse is gone, Si recrystallizes back to the surface and roughness reduction is done.

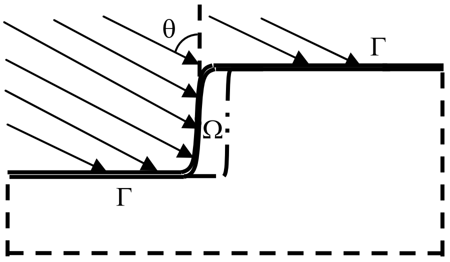

Fig. 1 Illustration of laser reformation of Si waveguides.

Two notable steps are taken in laser reformation. First, the incident laser illuminates vertically and the illuminated Si wafer is placed at an incline angle. This configuration allows the gravity acts on the molten Si along the direction of incident laser. The molten Si is pulled toward the ridge rather than the substrate and results in a less deformed ridge profile. This configuration fixes the direction of laser illumination and therefore avoids a complicated lens setup. Second, the illuminated wafer is placed in a vacuum chamber at a base pressure of 10^{-6} torr. This suppresses surface oxidation and impurity in-diffusion, which results in less increase of surface recombination velocity, about 25 cm/s.

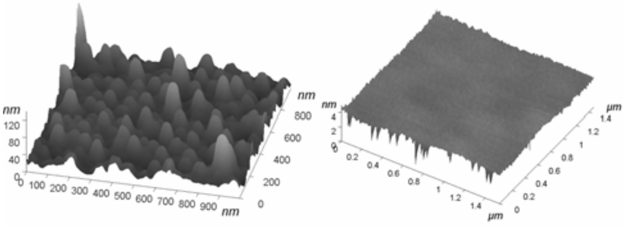

Fig. 2 AFM scans of an as-etched Si surface (left) and a laser reformed surface (right).

Reactive-ion-etched Si surfaces are investigated before and after laser reformation. A rough Si surface is prepared by reactive-ion-etch with a mixture gas of SF$_6$

and CHF_3. The as-etched Si surface has a RMS roughness of 13.95 nm, as shown in Fig. 2. It reduces to 0.239 nm after illumination of KrF excimer laser with an intensity of 1.4 J/cm^2. The relation of residual RMS roughness with respect to the laser intensities and the number of pulses is shown in Fig. 3. Obviously, the smaller RMS roughness requires the higher intensity and it does not depend on the number of pulses. To have a RMS roughness less than 1 nm, intensity higher than 1.2 J/cm^2 must be used.

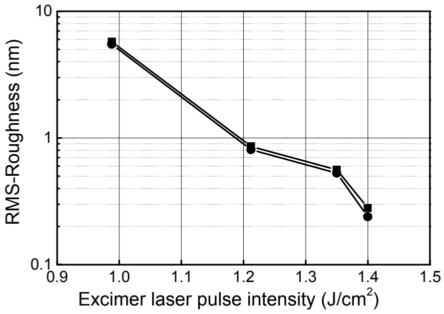

Fig. 3 The relation of residual RMS roughness of the as-etched Si surfaces by laser reformation with one pulse (square) and five pulses (circle).

Reactive-ion-etched Si ridge waveguides are examined before and after laser reformation. An as-fabricated ridge waveguide with a width of 400nm and a height of 500nm are shown in Fig. 4. The waveguide is etched with gas mixture of SF_6 and CHF_3, gas pressure of 10 mtorr and r.f. power of 50W [8]. Both of its sidewalls are illuminated by 5 pulses of KrF excimer laser. The illumination intensity is 1.4 J/cm^2 and the incident angle is 75^o from the normal of the Si substrate. The sidewalls experience a laser intensity of 1.37 J/cm^2. The shape of the ridge waveguide is deformed to be like a dome. The degree of deformation is comparable with that of the hydrogen annealing method [4]. In design of Si waveguides, the dimension and morphology has less influence on the scattering loss than the sidewall roughness does. Therefore, the deformation caused by laser reformation is not a tradeoff of roughness reduction capability if the optical mode change due to laser reformation can be predicted.

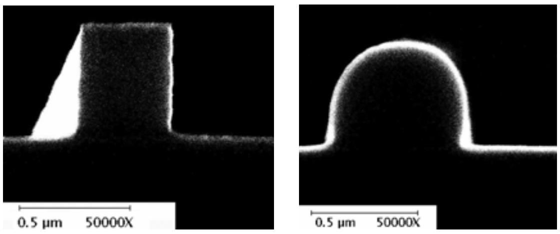

Fig. 4 SEM cross-sectional views of the as-fabricated Si ridge waveguides before (left) and after laser reformation (right).

Fig. 5 shows the SEM top-views of as-fabricated Si ridge waveguides before and after laser reformation. It has a width of 500nm and a height of 500nm. Obviously, the laser reformed ridge waveguide is smoother than the as-fabricated one. The standard deviation of linewidth of the as-fabricated waveguide is 13.6 nm. It reduces to 3.0 nm in the laser reformed waveguide, by a worst-case estimation from the SEM photos.

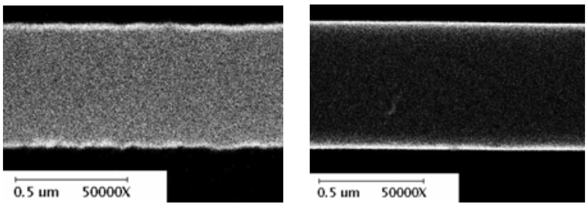

Fig. 5 SEM top-views of the as-fabricated waveguide (left) and the laser reformed waveguide (right).

The roughness of sidewalls in Si waveguides fabricated by dry-etch processes comes mainly from two origins. First is the roughness due to the dry-etch processes. In most cases, it exhibits as the variation of the waveguide linewidth along the vertical direction, as shown in Fig. 4. Second is the roughness due to the pattern transfer of masks. It exhibits as the variation of the waveguide linewidth along the lateral direction, as shown in Fig. 5. Clearly, laser reformation can reduce both kind of roughness and produce smoother Si waveguides. The roughness reduction capability of laser reformation is up to 13.95 nm and the ratio of the RMS roughness before and after this technique is about 58.4.

In conclusion, roughness reduction of Si waveguides by KrF excimer laser reformation is investigated. The RMS roughness of the reactive-ion-etched Si surface can be reduced to 0.239nm. This technique can be used as a post-etch processes for low-loss Si waveguides.

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