Fabrication of silicon microring resonator with smooth sidewalls

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Abstract. Fabrication of silicon microring resonators was optimized by using electron-beam lithography (EBL) and inductively coupled plasma (ICP) etching with different mask materials. Sidewall roughness of less than 10 nm was revealed by high-resolution scanning electron microscopy (SEM) without any post-etch process. The fabrication processes are described in detail, and comparisons are made in consideration of process complexity, process latitude, and sidewall roughness. © 2009 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.3258487]

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1 Introduction

Microring resonators have become a key building block for photonic integrated circuits due to their versatility in function and their capability of integration. They have been utilized in various applications including filtering,1,2 switching,3 modulation,4 wavelength conversion,5 and sensing.6 Silicon microring resonators, leveraging off the mature silicon-on-insulator (SOI) platform, provide silicon waveguides with strong lateral light confinement due to the large refractive-index contrast between silicon and air.
They can be realized with diameters of less than 10 \( \mu \text{m} \), with negligible bending loss, which is essential for integration of micro- and nano-silicon photonics.

Fabrication of silicon microring resonators has been realized using various methods, principally by nanolithography followed by silicon etch technology, but the process details have been only sparsely reported, especially aspects related to sidewall roughness control, which is crucial to suppress scattering loss in the resonators. Normally, sidewall roughness is induced by a combination of transfer of mask-edge roughness and etched surface roughness, the latter of which is the result of chemical reaction and ion bombardment on the silicon sidewall during the etch process. In the work discussed here, we present in detail the fabrication of silicon microring resonators. Electron-beam lithography (EBL) and a lift-off process were applied to form three different mask materials, chromium (Cr), negative e-beam resist maN-2403, and hydrogen silsesquioxane (HSQ), onto SOI wafers. Mask-edge roughness and its effect on the sidewall roughness of the resonators were characterized and are discussed in the following. Subsequently, inductively coupled plasma (ICP) etch processes for silicon etching with various mask materials were developed and optimized with the aim to minimize etched surface roughness without further post-etch process. Last, results obtained utilizing various mask materials were compared in order to achieve reduced process complexity, enhanced process latitude, and small sidewall roughness. In particular, silicon microring resonators with less than 10-nm sidewall roughness are demonstrated.

2 Experiment

Silicon microring resonators were fabricated on SOI wafers consisting of a 320-nm-thick silicon top layer and a 1-\( \mu \text{m} \)-thick buffer oxide insulator layer. Etch mask patterns of the negative e-beam resists maN-2403 and HSQ were formed using a JEOL JBX-9300FS EBL system set to 100-KV accelerating voltage and 2-nA exposure beam current. Exposure doses were optimized to achieve minimum linewidth fluctuation, while the Cr mask patterns were achieved by a lift-off process consisting of EBL and a subsequent metal deposition process employing a CVC e-beam evaporator. Cr evaporation occurred at a pressure of less than \( \frac{1}{10} \times 10^{-6} \text{ Torr} \) to ensure a sufficiently long mean free path of the Cr molecules for directional deposition.

The etch process for patterning the silicon microring resonators was developed using a plasma-therm ICP tool. Both the ICP coil power and bias power, which separately control generation and direction of reactive ions, respectively, operate at radio frequency. \( \text{Cl}_2 \) and optional \( \text{C}_4\text{F}_8 \) were used as etch gases. \( \text{Cl}_2 \) is a common silicon etchant under plasma. \( \text{C}_4\text{F}_8 \) helps to protect the phenolic resin polymer–based e-beam resist maN-2403, although it corrupts e-beam resist HSQ, which is a silicon-oxide-based material.

Fig. 1 Results obtained for fabricating silicon microring resonators using different masking processes. (a) Cr mask etching; (b) maN-2403 mask etching; and (c) HSQ mask etching.
In the lift-off process to create the Cr mask patterns, positive e-beam resist ZEP-520A was used as the sacrificial layer. Cr in the spacing areas other than the ring and the waveguides was intended to be removed in the resist strip process. Completely removing all the Cr at the edge of the ring and around the waveguide patterns proved very difficult, however, due to molecular forces. This results in severe edge roughness of the Cr mask, as shown in Fig. 2, and subsequently, the roughness is transferred to the etched silicon during the ICP process, which produces sidewall roughness on the silicon waveguides. The roughness is normally ~40 nm, determined by the roughness of the Cr mask. Figure 3 illustrates the sidewall roughness of the silicon waveguides transferred from the mask-edge roughness. In contrast, the mask-edge roughness of the negative e-beam resist maN-2403 and HSQ is relatively small, normally several nanometers, and is determined by the resist properties. Thus, the sidewall roughness results mainly from the etched surface roughness. The process with the Cr mask is slightly more complicated compared with the processes developed for the maN-2403 and HSQ masks, since an additional lift-off step was applied to produce the Cr mask patterns. There is, however, considerable process latitude because of the extremely large etch selectivity of silicon to Cr under plasma.

On the other hand, processes based on the negative e-beam resists, maN-2403 and HSQ, are the simplest because they comprise only EBL and ICP etching. The etch selectivity of silicon to HSQ is much higher than that of silicon to maN-2403 under Cl₂ plasma. This is because HSQ is a silicon-oxide-based material, while maN-2403 is composed of phenolic resin as a polymeric binder. Normally, the etch selectivity of silicon to maN-2403 is less...
than 1:1 under chlorine plasma, and it needs around 400-nm-thick resist for etching 300-nm-thick silicon. Moreover, we observed that in some runs, the e-beam resist became delaminated by the Cl₂ plasma, as shown in Fig. 4. Due to the higher etch selectivity of Si to HSQ than that of Si to maN-2403, thinner e-beam resist can be applied when using HSQ as mask material to improve EBL resolution and reduce mask-edge roughness. The etch selectivity of silicon to HSQ is higher than 5:1, so in our experiment, the thickness of HSQ is 90 nm, and that of maN-2403 is 300 nm for 320-nm-thick silicon etching by optimized ICP processes.

Using our Cr and maN-2403 mask etch process, the etched surface roughness of the silicon microring resonators is relatively low, normally less than 10 nm. This is due in part to the formation of the CFₓ polymer on the silicon sidewall, which tends to reduce striation roughness associated with ion bombardment. The process with the HSQ masks permits considerable process latitude due to the high selectivity of silicon to HSQ. However, it is worthy of notice that only Cl₂ was used as the etching gas since CₓFₓ corrupts HSQ under plasma, and the striation roughness induced by ion bombardment on the silicon sidewalls should be taken into consideration. Using the normal process, the etched surface roughness was 20 to 30 nm. In our process, we optimized the etch recipe based on HSQ mask etching and achieved etched surface roughness of less than 10 nm, as shown in Fig. 5, where Fig. 5(b) is a top view of the edge of the silicon waveguide, indicating roughness less than 10 nm. The roughness was demonstrated by inspecting the ripple edge fluctuation on top of the waveguide structure in a vertical etched profile with high-resolution SEM. Using this method, it is essential to make sure that the sidewall angle of the waveguide is close to 90 deg, and that there is no etch undercut below the etch mask, as shown in Fig. 6, so that the sidewall roughness can be demonstrated by the edge fluctuation on top of the waveguide. Since the edge fluctuation in Fig. 5(b) is around 5 nm, sidewall roughness less than 10 nm was achieved. The advantage of the SEM inspection is that it can provide an approximate value of the roughness for the whole waveguide structure, which is essential for evaluating the optical scattering loss, but the limitation is that the definite value of the roughness cannot be detected by this method.

A comparison was carried out for the preceding three processes considering process complexity, process latitude, and sidewall roughness of the resonator. The results are shown in Table 1.

Last, by controlling the mask-edge roughness and the etched surface roughness, silicon microring resonators were fabricated with an average sidewall roughness of less than 10 nm, as shown in Fig. 7, which was demonstrated by inspecting the edge fluctuation of the waveguide structure in a vertical etched profile with high-resolution SEM. These high-quality results could be achieved with both maN-2403- and HSQ-based processes, where the process with maN-2403 features the advantage of CFₓ sidewall protection etching, while that with HSQ takes advantage of the higher EBL resolution with thinner e-beam resist.

### 4 Conclusion

The process details of the fabrication of silicon microring resonators based on EBL and ICP etching were presented. Silicon sidewall roughness of less than 10 nm was achieved by accurate control of the mask-edge roughness and the etched surface roughness. Processes employing three different mask materials were discussed, analyzed, and compared to achieve reduced process complexity, enhanced process latitude, and low sidewall roughness of the fabricated resonators.

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<th>Table 1 Comparison of various fabrication processes.</th>
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<td>Process</td>
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<td>Cr mask</td>
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<td>maN-2403 mask</td>
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<td>HSQ mask</td>
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Fig. 6 Cross-section view of the fabricated silicon waveguide.
Fig. 7 Silicon microring resonator with smooth sidewalls.
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