Optimization of Plasma Etching Parameters and Mask for Silica Optical Waveguides *

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Abstract: Optical waveguides in silica-on-silicon are one of the key elements in optical communications. The processes of deep etching silica waveguides using resist and metal masks in RIE plasma are investigated. The etching responses, including etching rate and selectivity as functions of variation of parameters, are modeled with a 3D neural network. A novel resist/metal combined mask that can overcome the single-layer masks' limitations is developed for enhancing the waveguides deep etching and low-loss optical waveguides are fabricated at last.

Key words: reactive ion etching; silica-on-silicon optical waveguides; 3D neural network

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1 Introduction

Optical waveguides in silica-on-silicon have rapidly attracted the interest of researchers and industries due to their intrinsic potential to overcome speed limitation in future reduced scale of microelectronics and optoelectronics devices[1,2]. In addition, optical waveguides play a fundamental role in opto-electronics-integrated-circuits (OEICs) where many active and passive components such as array waveguide grating (AWG), $n \times m$ splitters, and directional couplers, require low-loss light transport lines and interconnects[3]. The superiority of silica-on-silicon optical waveguides to the other waveguides materials is dependent on many factors including the good mode match with standard single-mode optical fiber and the mass fabrication processes based on those currently available for silicon ICs. But this introduces a great challenge since in most cases the process considerations for OEICs are very different from those for silicon microelectronics. Film thickness for OEICs can be tenths of microns rather than hundreds of nanometer for current ICs. This makes it important in selectivity of etching masks and improves sidewall roughness to reduce scattering loss. Mostly, the silica waveguides are etched with a high-density plasma system, such as inductively coupled plasma etching (ICP), electron cyclotron resonance etching (ECR), and could be operated at the low neutral pressure with high plasma densities. Nevertheless, these apparatuses are expensive and appear in laboratories just in recent years. Most etchers are still the reactive ion etching system (RIE), which has high ion bombardment commonly resulting in high physical damage and poor mask resistance. Therefore, it needs more accurate control of the recipe parameters and a more effective mask used in the RIE deep etching process.

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In this paper, a silica etching process in a fluorine RIE plasma is characterized and process parameters varied in the design include RF power, work pressure, and gas ratio. We have studied and optimized a metal-photoresist double layer mask for deep (up to 6μm) silica optical waveguides. Our process introduces a Cr film as the mask bottom layer and an epoxy photoresist as the mask upper layer. At the same time, the difference of the etching results between the Cr film mask and epoxy resist mask is studied. This kind of combined layer mask has substantial advantages over the Cr film or epoxy resist used only as a single-layer mask; the low physical damage etching result with deep vertical profile of silica optical waveguides are reached with the optimized recipe.

2 Experiment

2.1 Apparatus and experimental design

The process was performed on a Unaxis 860L RIE plasma etching system. Before each set of the experiments, the chamber is cleaned by oxygen plasma[4] for 30min and then seasoned by the process conditions in the following experiment for 10min or longer, until the self-bias voltage has stabilized.

All experiments are carried out with a diode laser interferometer for in situ etching rate measurements. To reduce the potential influence of nonuniform temperature and/or nonuniform plasma conditions, the etching rate measured is always made at the same location on the wafer. For each test wafer, two fringes of typical interferometer signal are sufficient to calculate the SiO_2/Si waveguides (ER_{silica}) or epoxy resist mask (ER_{resist}) etching rate, so that each wafer can be used for several etch rate data points for SiO_2/Si waveguides and the epoxy resist mask. The Cr mask etch rate (ER_{Cr}) was measured by using a Tencor Alpha-Step 500 Surface Profiler with 0.1nm resolutions to test the film thickness variations with etching time. Expressions for the selectivity are given as below.

$$S_R = ER_{silica}/ER_{resist}$$

$$S_C = ER_{silica}/ER_{Cr}$$

The four parameters varied in the design are shown in Table 1 along with their respective ranges.

Table 1 Process parameters varied in the experimental design

Parameter	Value
RF power	80～300W
Work pressure	26.7Pa
O_2/CHF_3 ratio	0.05～1
O_2/CHF_3 total flux	30～150sccm

2.2 Preparation of etched samples

Test patterns were fabricated on 100mm commercial wafers of silica-on-silicon. Three different etching masks have been employed for the deep silica etching experiments. The first mask is Cr film, which was sputter deposition on the wafer for a thickness of a 200～300nm after a conventional photolithography process using the photoresist of a Clariant AZ6112. The waveguides layout was transferred into metal layer by etching in a $Cl_2/O_2/Ar$ plasma using the RIE system. Here, the RF power and pressure were set to 150W and 2Pa, respectively. The resist was then solvent stripped.

The second mask is an epoxy-based photoresist as it has high optical transparency and high contrast in the UV waveband, which makes it ideally suitable for vertical sidewalls and high aspect ratio features of the lithography pattern. The epoxy resist of MicroChem™ SU-8 was spun on the substrate for a thickness of 3000～4000nm. After the resist has been applied to the substrate, it was soft baked to evaporate the solvent and densify the film, and then exposed with near UV (350～400nm) mask aligner tools. The optimal exposure dose depends on the film thickness, the thicker film requires higher dosage. Following exposure, a post expose bake (PEB) is performed to selectively cross-link the exposed portions of the film. After PEB, SU-8 coated samples were developed at 20℃

in diacetone alcohol and rinsed briefly with isopropyl alcohol (IPA), and then hard baked at last.

The third mask is a resist-on-Cr double layer film. After a nearly 100nm Cr film first deposition on the wafer, an SU-8 resist with the same thickness was spun on the Cr film and patterned as in the second mask preparation process. The Cr film was etched as the first mask described above. An SU-8 film will be saved on the wafer after the Cr film is etched.

3 Results and discussion

3.1 Etching rate of SiO_2

Figure 1 shows the neural network of the variation of the epoxy resist masked silica etch rate with RF power and work pressure. In varying the parameters of interest, the other parameters are set to be a fixed value. As RF power increases, etch rate increases monotonically due to an enhanced concentration of F radicals and an increased ion density[5]. Etch rate increases at first and then decreases with increasing work pressure. In the design range of work pressure, there is a peak value of etch rate that is decreased with the RF power decreasing and disappears finally when the RF power is below 100W. For a fixed RF power, higher work pressure must result in a lower ion voltage at the wafer surface[6]. The data suggest that ion energy plays a significant role when the RF power is fixed at a low value, while etchant species density plays a significant role when the RF power is higher, the etchant species need is more.

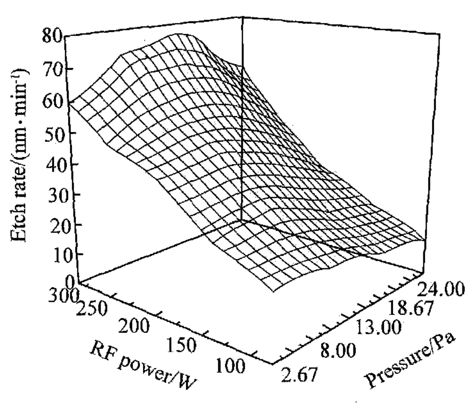


Fig. 1 SiO_2 etch rate as functions of RF power and work pressure O_2/CHF_3 ratio is 0.05, etch gas flow is 80sccm.

Figure 2 shows the neural network of the variation of the epoxy resist masked silica etch rate with O_2/CHF_3 ratio and total gas flow rate. It shows that, for a fixed total gas flux, the increase of O_2 concentration is to scavenge CF_x species that play a role in etching precursors through the reaction decarbongenation via both the gas phase and surface[7]. These mechanisms tend to lower the silica etch rate. In the low flux regime, higher flow rate tends to supply more etchant species and more species adsorption time that results in an increasing of etch rate. As total gas flux increases beyond a critical point for a given set of process conditions, the balance shifts from an etchant species-concentration limitation to a species adsorption-time limitation and the etch rate is decreased with gas flux increasing.

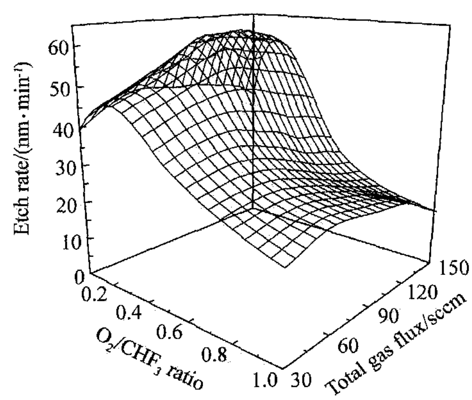


Fig. 2 SiO_2 etch rate as functions of O_2/CHF_3 ratio and total flow RF power is 220W, work pressure is 5.33Pa.

The other types of mask patterned Ge-doped SiO_2 etch rate are also studied and they have similar trends as the epoxy resist masked described above and have a close etch rate at the same etching conditions.

3.2 Selectivity

Figure 3 displays the variation of silica selectivity to the Cr film and epoxy resist versus bias voltage at different O_2/CHF_3 ratios, respectively. S_R curves in Fig. 3 demonstrate the existence of two etching regimes in which either the ion energy or the etchant character is the dominant factor governing the selectivity, and have been observed by many researchers[8,9]. This stems from the fact that the epoxy resist etching threshold is much higher than silica's. When the RF bias is below the bias voltage threshold for etching of the epoxy resist, the selectivity dramatically decreases with increasing ion energy. As the ion energy continues to increase, it enters the etchant reactive regime in which the S_R plateaus. In this regime, the etchant O_2/CHF_3 ratio plays a significant role.

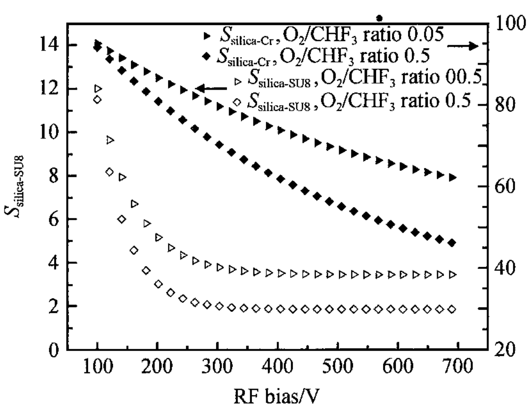


Fig. 3　Etching selectivity varying with RF bias and O_2/CHF_3 ratio　Work pressure is 2.67Pa, total etch gas flow is 80sccm.

From Fig. 3 we also can see that the S_C has very different behaviors from S_R. First, Cr film exhibits much better resistance in CHF_3/O_2 plasma than the epoxy resist flim; second, the selectivity is decreased with increasing ion energy no matter the ion energy in low region or high region. The etch rate of Cr film is always sensitive to the ion bombarding energy in our experience. O_2 concentration in etchant has similar influence to the S_C as to S_R. The infinite selectivities, S_C and S_R, can be achieved at a low RF selfbias voltage, however, the SiO_2 etch rates are quite low for these conditions.

3.3　SEM analysis of etching sample

From the above analysis, we can see that it needs high RF power, low work pressure, low O_2/CHF_3 ratio, and suitable gas total flow rate in order to get high silica etch rate and high selectivity at the same time, which is desired for deep silica etching. The samples etching results in the process conditions of 260W RF power, 2.67Pa work pressure, 70sccm total gas flux, and 0.1 O_2/CHF_3 ratio with the Cr masked and epoxy resist masked were presented respectively using a scanning electron microscope (SEM) in Fig. 4. Figure 4(a) displays that there exists huge destruction for the upper Cr mask layer under the high ion energy bombardment conditions and forms micro-masks on the etched silica areas as Cr film fragment redeposition is in result of extremely coarse bottom surface morphology. This also can be used to explain the reason that the selectivity S_C is decreased with increasing ion energy even in the high-energy region.

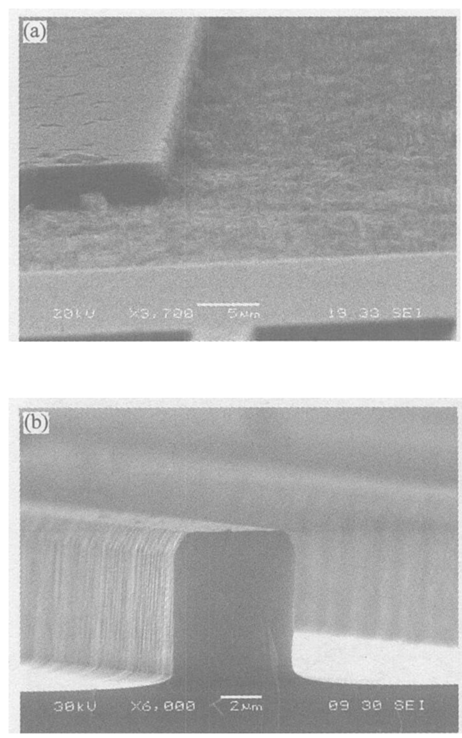
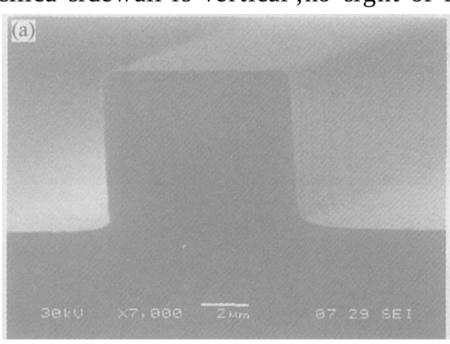


Fig. 4　SEM photographs of SiO_2 etched sample　(a) Cr masked sample; (b) Epoxy resist masked sample

From Fig. 4(b), the problem of using epoxy resist film as the etch mask can be found. As the etching is going on, the epoxy resist pattern figure's upper corner will facet more and more in result of enduring much more direction ion bombardment in plasma etch the process. This effect is most noticeable at high bias-voltage conditions[10]. And at last the edge of the facet propagates from the resist corner down to the etched silica layer, then the etching feature also exhibits a taper on the sidewall that is an expected vertical and smooth to reduce optical waveguides scattering loss. We can avoid this destruction of the SiO_2 sidewall when finishing the silica etching process before the edge of the epoxy resist taper facet arrives the silica upper surface and exerts an influence. While this means that a part of the epoxy resist film can not be used as a mask; and the selectivity in actuality is smaller than the behaviors mentioned as above, that thicker epoxy resist film is needed for a same thickness silica vertical etched, which will result in higher requirements for the epoxy resist photolithography process.

Figure 5 shows the SEM micrographs using the mask of resist-on-Cr double layer film. In Fig. 5, the silica sidewall is vertical, no sight of it being destroyed by the upper degenerated epoxy resist film, and it is also found that the silica etched bottom surface and the sidewall are clean and smooth. Believed to be due to the upper epoxy resist preventing the physical sputtering of the bottom Cr film and the high resistance of the underplayed Cr film can prevent the transfer of the epoxy resist degenerated facet to the etched silica layer. This can be confirmed from the Fig. 5(b) SEM picture in which the Cr film on the silica waveguides upper surface are undamaged and intact.



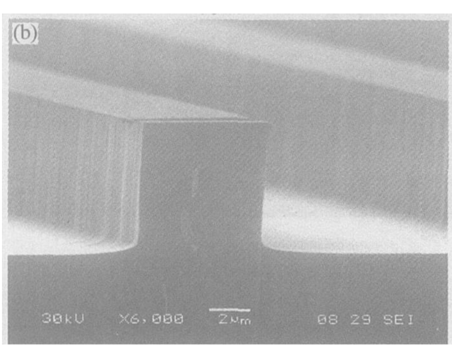


Fig. 5 SEM photographs of SiO_2 etched sample of patterned resist-on-Cr mask prior to (a) and after (b) residual epoxy resist stripped

The whole process of silica etching utilizing this new double layer mask is summarized briefly in Fig. 6. We can get deep, vertical, and smooth underlying etching until the upper epoxy resist film is consumed completely, depicted as Fig. 6 (d), it means that the higher utilization rate is for the epoxy resist mask, the thinner epoxy thickness is needed for resist film and smoother side wall etching can be gotten. Otherwise, it has to stop the etching process where the edge of the epoxy resist taper facet just arrives at the underlying upper surface as depicted in Fig. 6(c) if there is not a Cr film under the epoxy resist mask.

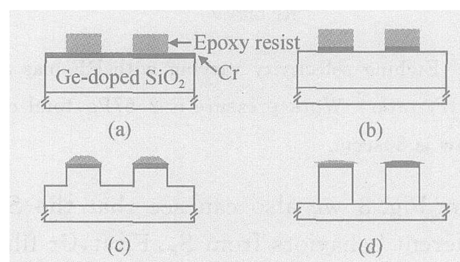


Fig. 6 Proposed process with resist-on-Cr mask (a) Photolithography; (b) Cr pattern; (c) SiO_2 RIE; (d) SiO_2 RIE continued

3.4 Propagation loss result

One of the most important properties for waveguides is their optical loss, which can be attributed to absorption and scattering. With recent advances in material technology, the absorption losses of SiO_2/Si waveguides have been dramatically reduced, so that transmission losses are largely the result of scattering by surface irregularities of the waveguide walls. We have measured the propagation loss of the 6μm ×6μm straight channel waveguides etched with epoxy resist ,Cr and resist-on-Cr film masks ,respectively. The upper cladding layer of 15μm of BPSG (B_2O_3-P_2O_5-SiO_2 Glass) deposited on the waveguides core by several times of PECVD and the anneal circle process after the core layer is etched and the residual masks material stripped. Figure 7 presents the relationship of fiber-to-fiber insertion loss with the propagation length of different waveguides at the wavelength of 1550 nm. From the fit lines ,the channel propagation loss of - 0. 07dB/ cm can be gotten with the combined mask , much better than the - 0. 25dB/ cm and - 0. 41dB/ cm achieved with the epoxy resist mask and Cr mask ,respectively ,which attribute to the better sidewall etched result with the double layers mask.

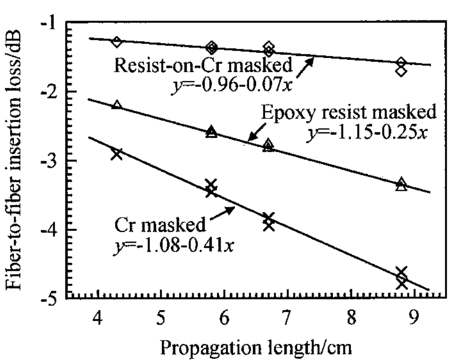


Fig. 7　Linear fit of measured fiber-to-fiber waveguides insertion losses as a function of channel waveguide length for different etched waveguides at 1550nm

4　Conclusions

We have investigated the behaviors of deep silica etching with a metal mask and polymer mask , respectively , in a CHF_3/O_2 reactive ion etching plasma. 3D neural networks of the silica etch rate and selectivity to different masks are constructed as functions of RF power ,work pressure ,CHF_3/O_2 ratio ,and total flow rate. Several trade-offs valuable to optimizing the process are identified. The etch rates exhibit the same behaviors for different masks ; however , selectivity S_R and S_C present different behaviors that the S_R has two different regions overruled by bias voltage and gas ratio , respectively ; the S_C with a very high value always has the same trend that is decreased with bias voltage and gas ratio increaseing.

In our optimized parameters of high etch rate and selectivity reactive ion etching conditions , rough bottom surface morphology is found in the Cr masked silica etch as a result of a micro-mask formed by Cr fragment. A tapered facet come into being in the silica sidewall of the epoxy resist masked samples when the etching process going on is attributed to epoxy resist film degeneration induced by ion bombardment effects. A novel resist-on-Cr double-layer mask is developed for overcoming the limitations of Cr film and epoxy resist used as single-layer masks. The upper epoxy resist film can prevent the physical sputtering of the bottom Cr film by ion bombardment ,and the high resistance underplayed Cr film acts as a stop layer to prevent the transfer of the epoxy resist degenerated tapered facet to the etched silica layer. Experimental results show that the etched silica roughness of the sidewall and bottom surface attained in the proposed process using resist-on-Cr mask is very low , which is also approved by the measured results of waveguides insertion loss with different masks. On the other hand ,the epoxy resist mask utilization is improved ,deeper vertical etch silica can be attained with a resist-on-Cr mask than the process using the same thickness epoxy resist single-layer as an etching mask. The Cr film thickness needed in this novel mask is only about ～100nm or less , which is much thinner than that used in the single Cr mask layer where the thickness is over 200nm. Therefore ,the newly developed process is easy to implement in the step of a fabrication process where a smooth and almost vertical silica profile is desired , like the optical waveguides process.

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二氧化硅光波导刻蚀参量及掩膜的优化*

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摘要: 硅基二氧化硅光波导是光通信中的关键器件. 采用光刻胶以及金属作为掩膜进行了反应离子刻蚀二氧化硅光波导的工艺研究, 获得了刻蚀速率及刻蚀选择比相对各工艺参数变化的三维神经网络模型. 利用一种新型的用于二氧化硅深刻蚀的复合双层掩膜结构, 克服了许多单层掩膜自身的限制, 并利用这一结构制作出低传输损耗的硅基二氧化硅波导.

关键词: 反应离子刻蚀; 硅基二氧化硅光波导; 三维神经网格

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