RIE lag in diffractive optical element etching

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Abstract

In this study, the pattern of a 4 mm diameter diffractive optical element with linewidth ranging from 12 to 0.5 μm was adopted. With the SiO_2 layer as the etch hard mask, silicon was etched based on HBr chemistry with additions of O_2 and SF_6. The effects of O_2 content on the sidewall anisotropy, etch rate, and etch selectivity over the SiO_2 mask were also examined. The RIE lag, where etching of a small trench (hole) lags behind a large trench (hole), was investigated to produce an optimum aspect ratio for each zone of the diffractive optical element. The regression relation of the etch depth versus zone width was determined as a guideline for the feasibility of this method. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: RIE lag; Diffractive optical elements; Anisotropic etching

1. Introduction

A diffractive optical element, e.g., diffractive microlens, is composed of zone structure by removing the multiple modulo 2π phase from the refractive lens technique. The diffraction efficiency is determined by the surface profile within a specified zone. However, the surface profile of this relief structure relies on the fabrication techniques, such as lithography, ion etching, etc. Due to the limitation of process equipment the diffraction efficiency of a binary surface profile is usually lower than the expected value. Specifically, the aspect ratio of each zone pitch is one of the main parameters determining the diffraction efficiency. How to control the aspect ratio under the limitation of various etching conditions is becoming a pursuing topic for most of the related research. In this paper, reactive ion etching (RIE) lag was used to obtain the existing optimum aspect ratio for each zone, i.e., the aspect ratio should be consistent throughout all zones. In other words, RIE lag may produce an

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optimum aspect ratio for each zone, then the diffraction efficiency of the diffractive lens can be optimized. Therefore, RIE lag where etching of a small trench (hole) lags behind a large trench (hole) [1,2] was investigated in this work. The regression relation of the etch depth versus zone width was determined as a guideline for the feasibility of this method. In this study, the pattern of a 4 mm diameter diffractive optical element with linewidth ranging from 12 to 0.5 μm was adopted. The silicon etching was based on HBr chemistry.

2. Experimental

The experiments were performed in an electron cyclotron resonance (ECR) reactor on 150-mm diameter wafers. To etch silicon deeply, a 1.2-μm thick silicon dioxide layer was deposited via thermally wet oxidation as the etch hard mask. After the lithographic process, the oxide layer was etched with a $CF_4/CHF_3/Ar$ mixture in a RIE process. Then, the photoresist was stripped. Afterwards, the pattern was transferred to the silicon substrate by the etch process based on HBr chemistry with additions of O_2 and SF_6. Finally, a 6:1 (NH_4F:HF)-buffered hydrofluoric acid dip was carried out to remove the remaining SiO_2 layer and the sidewall passivation film and the process was completed.

Feature width and etch depth measurements were made by scanning electron microscopy (SEM). SEM was also exploited to evaluate the sidewall anisotropy and the quality of the etched surface. The SiO_2 etch rate was determined from the thickness variation before and after silicon etching. Quoted etch rates were an average of several points across a wafer. The effects of O_2 content on the sidewall anisotropy, etch rate, and etch selectivity over the SiO_2 mask were explored. With appropriate O_2 concentration, SF_6 was added to achieve vertical sidewall and smooth surface.

A diffractive optical element, e.g., diffractive microlens, is composed of a zone structure, according to a standard modulo 2π phase technique to produce the zone structure. For example, the zone radius r_m of a zone plate is given by

$$r_m = (2m\lambda f)^{1/2} \tag{1}$$

where m is the zone index number, λ is the illumination wavelength, and f is the focal length. The phase profile is approximated by a discrete stepped profile with r_m getting narrower when close to the edge of diffractive microlenses. The diffraction efficiency of such a lens is strongly dependent on the profile of each zone pitch [3,4]. Specifically, the aspect ratio of each zone pitch, i.e., the ratio of depth/line width [5]. In other words, there is existing an optimum aspect ratio for each zone, i.e., the aspect ratio should be consistent throughout all zones. In our system, the aspect ratio of each zone of the diffractive lens is changing for fixed etch depth; therefore, the diffraction efficiency cannot be optimized if no RIE lag occurs. On the other hand, RIE lag may produce an optimum aspect ratio for each zone, then the diffraction efficiency of diffractive lens can be optimized. However, in this approach, various etch depths are required with the largest depth in the center and decreasing toward the boundary. Specifically, this leads to a lessening of the disadvantages of binary optics [6,7] for low diffraction efficiency. Therefore, RIE lag where high aspect ratio features have reduced etch rates [1,2] was investigated in this work. The regression relation of the etch depth versus zone width was determined as a guideline for the feasibility of this method. In this study, the pattern of a 4-mm diameter diffractive optical element with linewidth ranging from 12 to 0.5 μm was adopted.

3. Results and discussion

With the SiO_2 layer as the etch hard mask, silicon was etched by a bromine-based plasma. The etching parameters were as following: microwave power, 250 W; RF power, 90 W; He gas cooling, 10 sccm; $magnet_{main, sub}$, 21, 11 A; pressure, 3.3 mTorr for a total flow rate of 100 sccm, 2.2 mTorr for a total flow rate of 60 sccm.

The etch rates were calculated based on 10-min etching and averaged over the entire etch time. As depicted in Fig. 1, the etch rate of silicon strongly depends on the percentage of O_2 in HBr while that of SiO_2 is weakly dependent on the O_2 content. A small amount of oxygen (2%) enhances the concentration of etching species and thus increases the silicon etch rate. Nevertheless, the addition of 5% O_2 creates too much oxide on the sidewall and bottom surface and results in the dramatic decrease in the etch rate. This leads to the decrease of etch selectivity of silicon over SiO_2 with the O_2 addition. Accordingly, 2% oxygen content recipe was selected for further improvement of the sidewall anisotropy with the SF_6 addition. Fig. 2 shows the SEM micrographs of the etch profiles for various gas compositions. The feature size and etch depth are also displayed at the bottom of the figures. It was found through experimentation that a mixture of $HBr/O_2/SF_6 = 95/2/3$ sccm can yield a high degree of anisotropic etching with a good quality of etching surface.

To investigate the RIE lag effect, the diffractive optical element etching was conducted for a long duration. Fig. 3a illustrates the results of a 15-min etching with a total flow rate of 100 sccm corresponding to a pressure of 3.3 mTorr. Anisotropic etch profile is preserved. However, as presented in Fig. 3b, the sidewall of submicron features has concave contour near the top surface when the etch depth exceeds about 5 μm. This is caused by the deflected ions. As a result, the total flow rate was reduced to 60 sccm to decrease the pressure to 2.2 mTorr. Although the etch rate diminishes, the vertical sidewall recovers, as shown in Fig. 3c.

With depths and feature widths measured by SEM, Fig. 4a,b demonstrates the variation of depth with linewidth for total flow rates of 100 and 60 sccm, respectively. Since all Si zones were etched in a single run, one can interpret the depth variation as an etch rate variation, which increases with the linewidth. It is found that the depth variation is significant for submicron features while no notable depth change is observed for features above 3 μm. It also reveals that RIE lag will not occur until the aspect ratio is greater than about two. To obtain the regression relation of the etch depth versus zone width, a fourth-order polynomial was assumed:

$$d(w) = A + B*w + C*w^2 + D*w^3 + E*w^4 \qquad (2)$$

where d and w are etch depth and zone width in μm, respectively. The results for each condition are demonstrated in Table 1. Then, the equation is valid through the zone width of about 2.5 μm. It is discovered that the coefficients E of the fourth-order terms are very small compared to other coefficients. Thus, the data points can be fitted by a third-order polynomial in w.

4. Conclusions

With the SiO_2 layer as the etch hard mask, silicon was etched by a HBr-based chemistry. A small amount of oxygen (2%) increases the silicon etch rate while the addition of 5% O_2 results in a dramatic decrease in the etch rate, and the etch rate of SiO_2 is weakly dependent on the O_2 content.
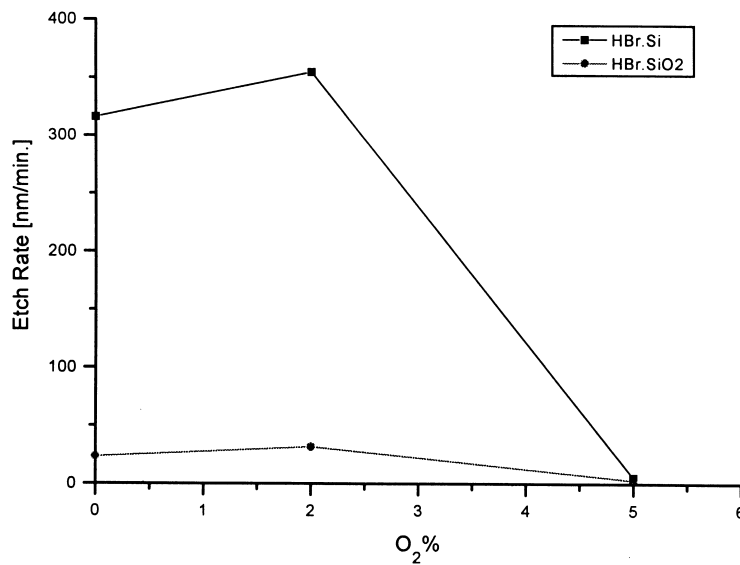
（a）Etch rate of silicon and silicon dioxide
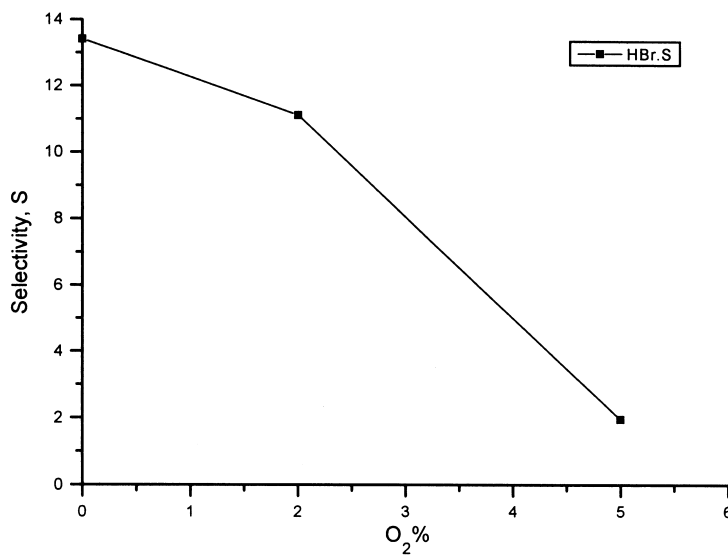
（b）Etch selectivity of silicon over silicon dioxide

Fig. 1. The effect of O_2 content in HBr on the etch rate and selectivity (total flow rate, 100 sccm). (a) Etch rate of silicon and silicon dioxide and (b) etch selectivity of silicon over silicon dioxide.

This leads to a decrease of etch selectivity of silicon over SiO_2 with the O_2 addition. A high degree of anisotropic etching of silicon can be achieved by a mixture of $HBr/O_2/SF_6 = 95/2/3$ sccm. To ensure vertical sidewalls for submicron features with depth larger than 5 μm, working pressure needs to be reduced, which is realized by decreasing the total flow rate to 60 sccm.
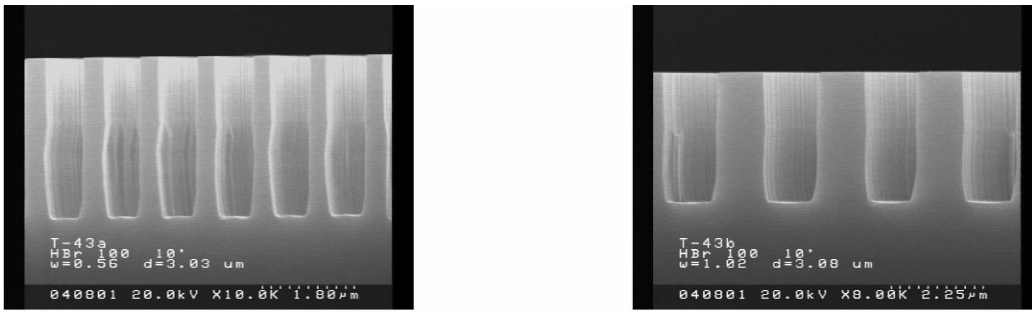
(a)   HBr＝100 sccm
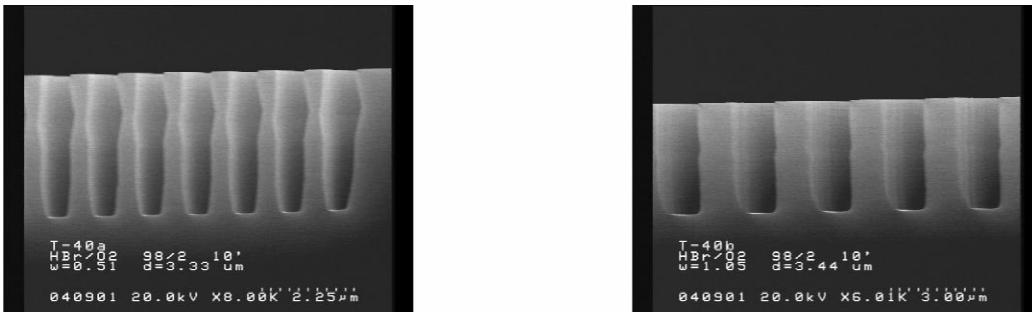
(b) HBr / O$_2$＝98/2 sccm
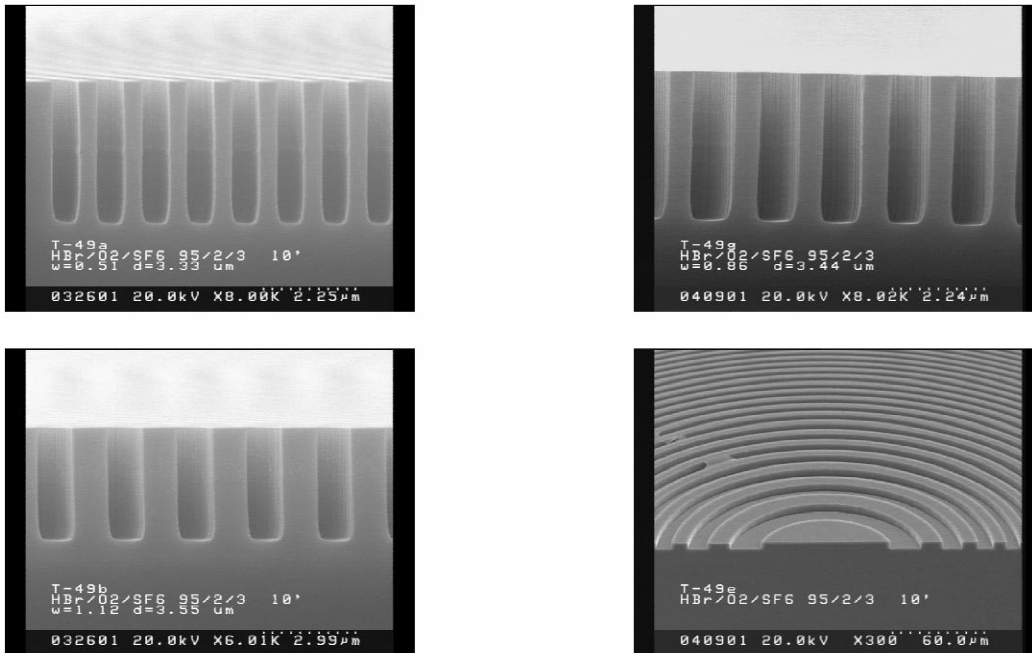
(c) HBr / O$_2$ / SF$_6$＝95/2/3 sccm

Fig. 2. Etch profile for various gas compositions: (a) HBr＝100 sccm, (b) HBr/O$_2$＝98/2 sccm and (c) HBr/O$_2$/SF$_6$＝95/2/3 sccm.
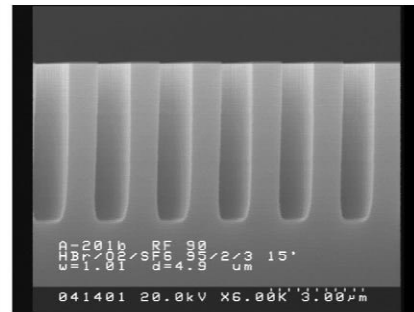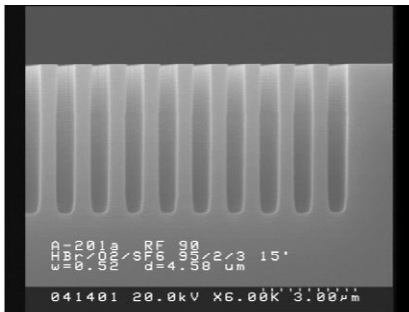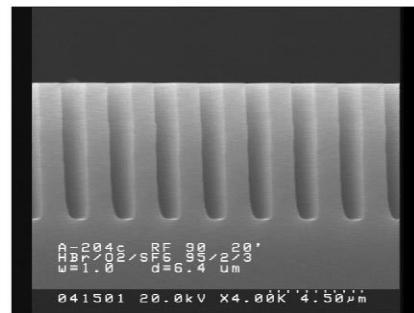
(a) HBr / O$_2$ / SF$_6$ = 95/2/3 sccm ; Time = 15 Min.
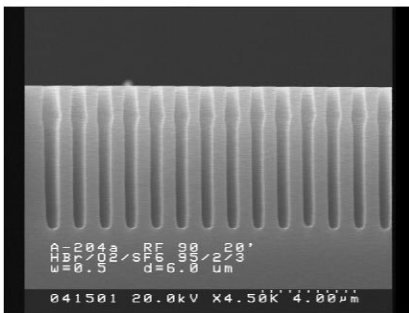
(b) HBr / O$_2$ / SF$_6$ = 95/2/3 sccm ; Time = 20 Min.
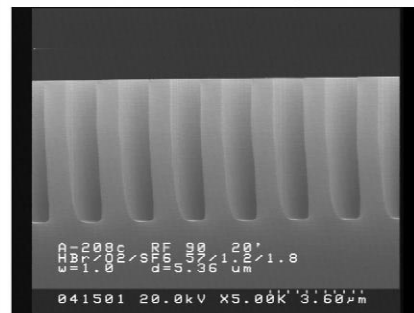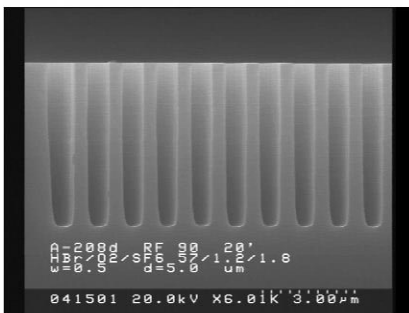
(c) HBr / O$_2$ / SF$_6$ = 57/1.2/1.8 sccm ; Time = 20 Min.

Fig. 3. Etch profile at different etch times and total flow rates: (a) HBr/O$_2$/SF$_6$ = 95/2/3 sccm, time = 15 min, (b) HBr/O$_2$/SF$_6$ = 95/2/3 sccm, time = 20 min; and (c) HBr/O$_2$/SF$_6$ = 57/1.2/1.8 sccm, time = 20 min.

RIE lag was observed for an aspect ratio greater than about two. It was found that the lag effect is significant for submicron features while no notable depth change is observed for features above 3 μm in this study. The regression relation of the etch depth versus zone width was proved to be a third-order polynomial in zone width.
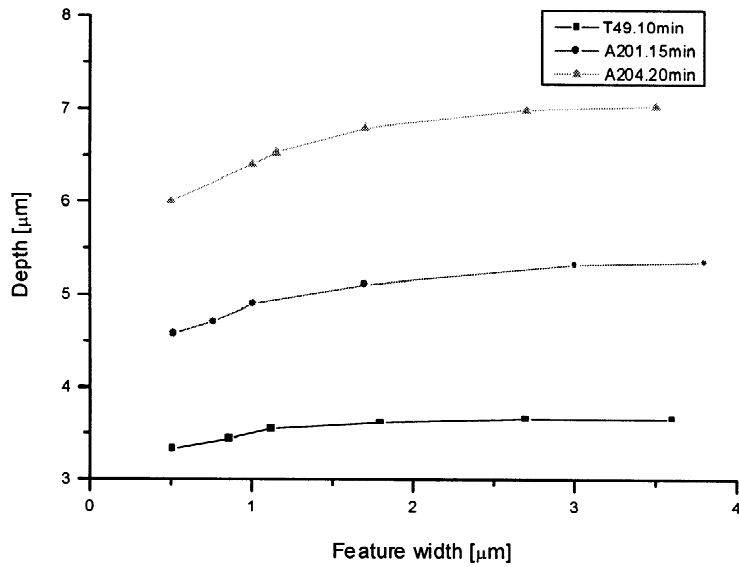
(a) HBr / O_2 / SF_6 ：95/2/3 sccm
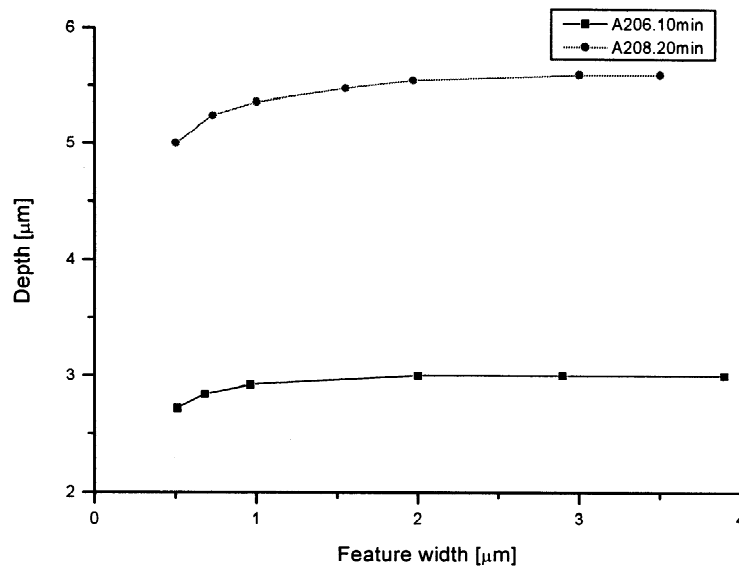
（b）HBr / O_2 / SF_6 ：57/1.2/1.8 sccm

Fig. 4. Variation of depth with linewidth for different total flow rates: (a) HBr/O_2/SF_6=95/2/3 sccm; and (b) HBr/O_2/SF_6=57/1.2/1.8 sccm.

Acknowledgements

Table 1
Regression relation of the etch depth versus zone width: $d(w) = A + B*w + C*w^2 + D*w^3 + E*w^4$, where d is etch depth and w is zone width in μm

Wafer no.	Flow rate (sccm) HBr/O$_2$/SF$_6$	Etch time (min)	A	B	C	D	E
T49	95/2/3	10	3.0189	0.7452	−0.3083	0.0453	−5.65E-06
A201	95/2/3	15	4.0515	1.2228	−0.4732	0.0716	−1.0E-05
A204	95/2/3	20	5.4713	1.1670	−0.2235	−0.0015	1.27E-05
A206	57/1.2/1.8	10	2.2721	1.1854	−0.6245	0.1071	−1.4E-05
A208	57/1.2/1.8	20	4.0611	2.6708	−1.7749	0.4155	−2.6E-04

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