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A NEW DRY ETCHING METHOD WITH THE HIGH ETCHING RATE FOR PATTERNING CROSS–LINKED SU–8 THICK FILMS

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Photo sensitive polymer SU-8, owing to its excellent mechanical properties and dielectric properties on polymerization, is widely used in MEMS device fabrications. However, the removing, stripping or re-patterning of the cross-linked SU-8 is a difficult issue. In this paper, CF_4/O_2 gas mixture provided by a plasma asher equipment was used for the patterning of cross-linked SU-8 material. The RF power, the temperature of the substrate holder, chamber pressure and gas concentration were optimized for the cross-linked SU-8 etching process. When the CF_4/O_2 mixture contains about $5\,\%$ CF_4 by volume, the etching rate can be reached at $5.2\,\mu$m/min.

K e y w o r d s: dry etching, plasma, SU-8 photoresist, etching rate

1 INTRODUCTION

SU-8 negative photoresist is widely used in variety of applications, which include masks [1], plating mold [2–4], packaging parts [5], cantilever sensors [6]. Due to its good mechanical properties SU-8 is an ideal material for fabricating the devices with high aspect ratio structures [7, 8]. By virtue of its dielectric nature such as water impermeability and excellent chemical resistance, SU-8 is suitable to fabricate micro-channels for microfluidic and bioMEMS (Micro-Electro-Mechanical Systems) devices [9]. Further patterning of the cross-linked SU-8 was needed for some applications after the initial photolithography, for example, micro-packaging structures and micro-channel devices.

It is difficult to remove or re-pattern fully cross-linked SU-8 by conventional methods, such as wet chemical agents. Oxidizing mixtures of sulphuric acid and hydrogen peroxide can provide preferable for stripping cross-linked SU-8 [10]. However, the wet chemical agents can attack metal structures and lead to lifting off the refined structure.

Plasma etching is an alternative approach for patterning cross-linked SU-8. The method of dry etching cross-linked SU-8 has been discussed by many researchers [11–14]. Dentinger *et al*. presented a study on plasma etching of cross-linked SU-8 thick films by using a gas mixture of CF_4/O_2 in RIE (Reactive ion etching) with the etching rate of 1–4 μm/min [11]. While Hong *et al* used a mixture of SF_6/O_2 to etch the cross-linked SU-8. The influence of fluorine on the etch rate of cross-linked SU-8 was investigated and the etch rate was 1.5–2 μm/min [12]. Mischke *et al* used the mixture gas CF_4/O_2 as the etching gas, and analyzed the influence of electron density and electron collision rate on etching rate of cross-linked SU-8, and the etch rate of cross-linked SU-8 was less than 1 μm/min [13]. Kristian discussed the influence of antimony on the etch rate of the cross-linked SU-8 by using RIE and used the mixture gas of SF_6/O_2. Etch rates up to 0.8 μm/min could be achieved [14]. However, etching rate of cross-linked SU-8 by using RIE equipment is low, and which is extremely time consuming and high expensive.

In this paper a novel CF_4/O_2 plasma etch method with the high etching rate and low cost is presented to remove or re-pattern fully cross-linked SU-8. The cross-linked SU-8 plasma etching process was optimized for high etching rate by using O_2 and CF_4 as the etching gases, while chamber pressure, individual gas flow rate, etching time and RF power are set as control factors. Plasma-asher (K1050X, Quorum/Emitech, UK) was used for plasma etching. Compared with RIE equipment, it will decrease the fabrication cost and shorten the fabrication cycles.

2 EXPERIMENT

All experiments were carried out on the 2 inch silicon wafer. At first, we need to verify the influence of each factor on the etching rate, and then determine an optimal etching parameter. The process flow for etching cross-linked SU-8 is shown in Fig. 1. The SU-8 was first spin-coated onto the substrate to form a thin SU-8 layer with thickness of approximately $50\,\mu$m. SU-8 was then processed with the standard procedure of pre-baking on a hotplate at $85\,^{\circ}$C for 30 min, followed by exposing to UV light at an intensity of $1.5\,$mW/cm^2 for 5 min. The SU-8 sample was then post-baked on a hotplate at $85\,^{\circ}$C

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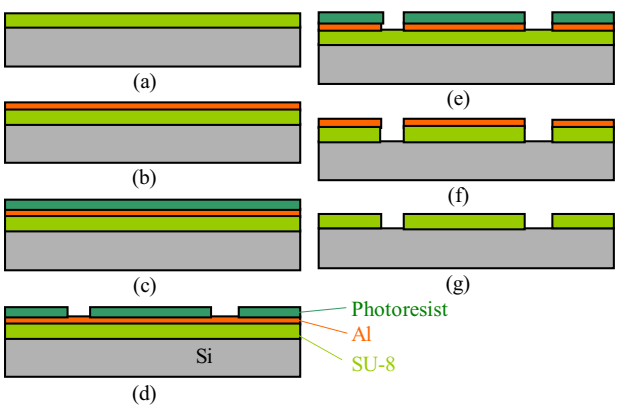

Fig. 1. The process flow of etching SU-8 (a) — SU-8 spincoating and exposure (b) — Deposition of Al mask material (c) — Photoresist spincoating (d) — Photoresist patterning (e) — Wet etching Al mask (f) — CF_4/O_2 plasma etching (g) — Al mask removing

Table 1. The parameters used for etching cross-linked SU-8 films

Etching duration(min)	2.5	4	5	6	7.5
Chamber Pressure (mbar)	0.9	10	20	30	
RF power (W)	60	70	80	90	100
$CF_4:O_2$ (ratio of flow rates)	1:1	1:4	1:10	1:20	1:30

for 1 min 30 s and slowly cooled to room temperature. By this stage the SU-8 resist was fully cross-linked.

In preparation for plasma etching, a metal etch mask was prepared by evaporation method on each sample. First, metal mask (200 nm Al) was deposited on the cross-linked SU-8 layer by evaporation coating. BP212 photoresist was spin-coated on the wafer at speed of 2200 rpm, and then soft-baked at 85 °C for 30 minutes. Finally, the resist was exposed by UV light at an intensity of 10 mW/cm^2 for 20 s, developed in 0.5 % NaOH solution for 30 s and then hardbaked at 85 °C for 30 min, the photo etch patterns were copied onto the photoresist to form the etching mask. Then the Al films was etched by H_3PO4 solution at 85 °C for 1 min, the Al mask with two rows of 30 μm holes was made out. Then plasma treatment was carried out under a certain process parameters. After plasma etching, the metal mask was stripped with H_3PO_4 solution.

Plasma-asher was used to etch cross-linked SU-8 layer. RF power up to 100 W at 13.56 MHz is available and can be controlled. In our experiments, the gas concentration (defined as the ratio of CF_4 flow rate to O_2 flow rate), the chamber pressure, the etching time and the etching power were selected to optimize the etching rate. To verify the effect of a certain parameters on etching rate, only one parameter was changed and the other three parameters were kept constant.

As shown in Table 1, the etching time was changed from 2 min 30 s to 7 min 30 s. The chamber pressure (p) was varied between 0.9 mbar to 30 mbar. The RF power change from 60 w to 100 w. The gas concentration was changed from 1:1 to 1:30. The system was operated under manual pressure control mode.

Optical microscope (Olympus STM6, Japan) and stylus profilometer (ET4000 M, Kosaka, Japan) were used to characterize the etched depth, the structure width and the morphology of the surface.

3 RESULTS AND DISCUSSION

The influence of plasma parameters on the etching rate of cross-linked SU-8 was investigated. The etching rate depended strongly on the process pressure, T_{SH} and gas concentration. After the measurements of etch depth were gathered, the mean depth and undercut at each level was calculated for every variable. An optimal etching parameter was obtained after understanding the influence of each factor.

3.1 The effect of etching time on the etching rate of cross-linked SU-8

The effect of etching time on etching rate was investigated in this experiment. Five cross-linked SU-8 samples with the same size and thickness were prepared and etched. The other etching parameters were fixed at 1 : 10 (CF_4 : O_2), 20 mbar, 100 W, respectively. Specific etching depths were obtained by controlling the etching time. As shown in Fig. 2 (a), the etching rate is increasing with the increase of etching time. However, when the etching time is larger than 5 min, the etching rate remains stable and keeps at 4 μm/min.

Figure 2(b) shows that the temperature of the substrate holder T_{SH} is increasing with the etching time. The T_{SH} was measured by using temperature indicating strip (THERMAX, England). Because of the high-frequency glow reaction, energetic particles of gas molecules collide with the cross-linked SU-8 polymer, which will generate a lot of heat and let T_{SH} rises. The higher T_{SH} temperature results in the high etching rate due to thermal activation and higher chamber pressure [14]. With the increase of T_{SH}, especially from 154 °C to 177 °C (4 min to 5 min) the etching rate increase fastest. However the etching rate maintains stable over 177 °C (after 5 min).

One possibility for such phenomenon could be due to the modified thermal and mechanical properties of SU-8 at high temperature. When etching time is longer than 5 min as shown in Fig. 2(b), TSH increases significantly and closes to the glass transition temperature of SU-8 (T_g, 200–240 °C) [15]. The Young modulus and hardness of SU-8 become decreased and the state of the cross-linked SU-8 changes from the hard glassy into the viscoelastic state at around T_g temperature, which could result in the slower plasma etching rate of SU-8 [16].

The etching time of 5 min was chosen as optimized plasma parameter in order to obtain a highest etching rate and relatively lower T_{SH}. At the etching time of 5 min, T_{SH} of 177 °C is far lower than the T_g of cross-linked SU-8. When etching for the thick SU-8 film, the sample should be cooled for a while after 5min etching to avoid the high T_{SH}.

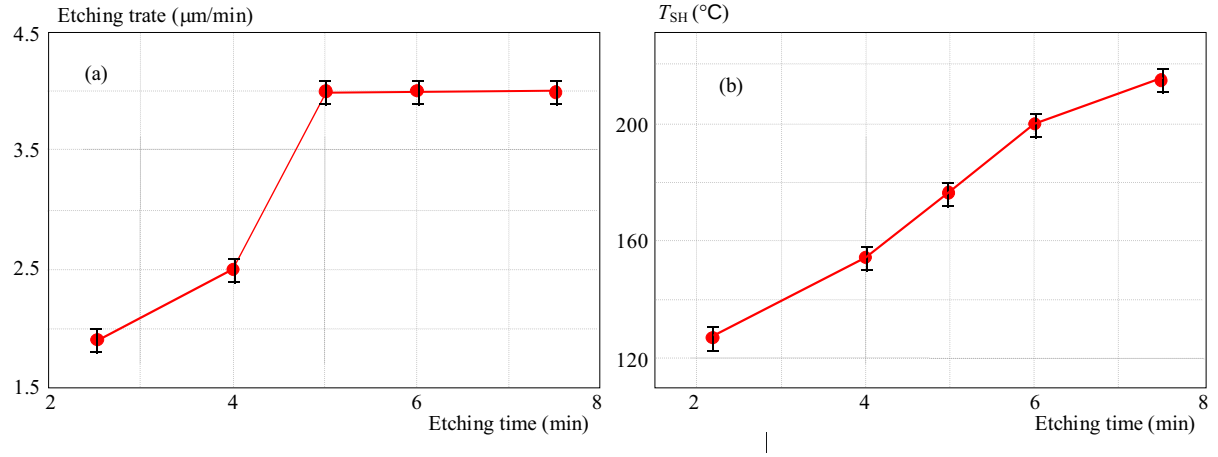

Fig. 2. The effect of etching time on the etching rate of cross-linked SU-8 (gas concentration of 1:10 ($CF_4 : O_2$), chamber pressure of 20 mbar, RF power of 100 W), (a) — dependence of etching rate on etching time, (b) — the curve of T_{SH} with the etching time

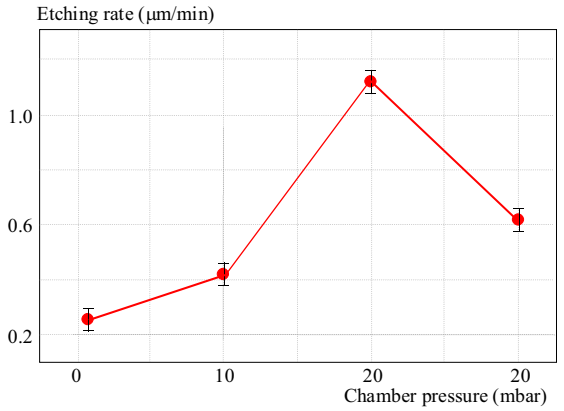

Fig. 3. The influence of chamber pressure on the etching rate of cross-linked SU-8. (gas concentration of $1 : 1(CF_4 : O_2)$, RF power of 100 W, and etching time of 5 min)

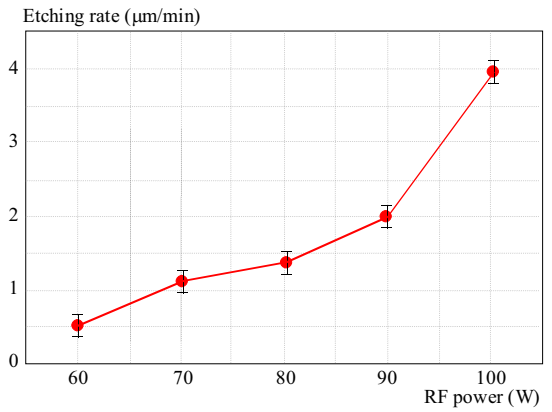

Fig. 4. The effect of RF power on the etching rate with gas concentration of $1 : 10(CF_4 : O_2)$, chamber pressure of 20 mbar, and etching time of 5 min

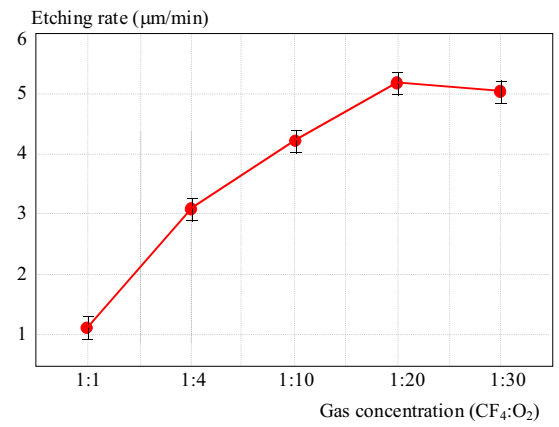

Fig. 5. The effect of gas concentration on the etching rate of cross-linked SU-8 (etching time of 5 min, pressure of 20 mbar, and power of 100 W)

3.2 The effect of chamber pressure on the etching rate of cross-linked SU-8

Figure 3 shows the influence of chamber pressure on the etching rate of cross-linked SU-8 while fixing the gas concentration, RF power, and etching time at $1 : 1$ ($CF_4 : O_2$), 100 W, and 5 min, respectively. As shown in Fig. 3, the etching rate of cross-linked SU-8 depends strongly on the chamber pressure. As chamber pressure rises, the number of oxygen and fluorine free radical participating in the chemical etching increases. Therefore, causing the etching rate increases with pressure increasing [17]. However, when the chamber pressure higher than 20 mbar, the etching rate decreases from 1.1 μm/min to 0.6 μm/min. As the gas pressure increases, the mean free path of plasma declines and the probability of ion collision increases. This will reduce the energy of ions and the etching rate of cross-linked SU-8 decreased. Based on the analysis above, the chamber pressure of 20 mbar was chosen as optimized plasma parameter in order to obtain a highest etching rate.

3.3 The effect of RF power on the etching rate of cross-linked SU-8

Figure 4 shows the effect of RF power on the etching rate of cross-linked SU-8 while fixing the etching time, gas concentration, and chamber pressure at 5 min, $1 : 10(CF_4 : O_2)$, and 20 mbar, respectively. The etch rate of cross-linked SU-8 is increasing with the RF power increasing. For a certain amount of gas (20 mbar in this paper), raising the RF power will increase both ion energy and active particle density in plasma. The physical

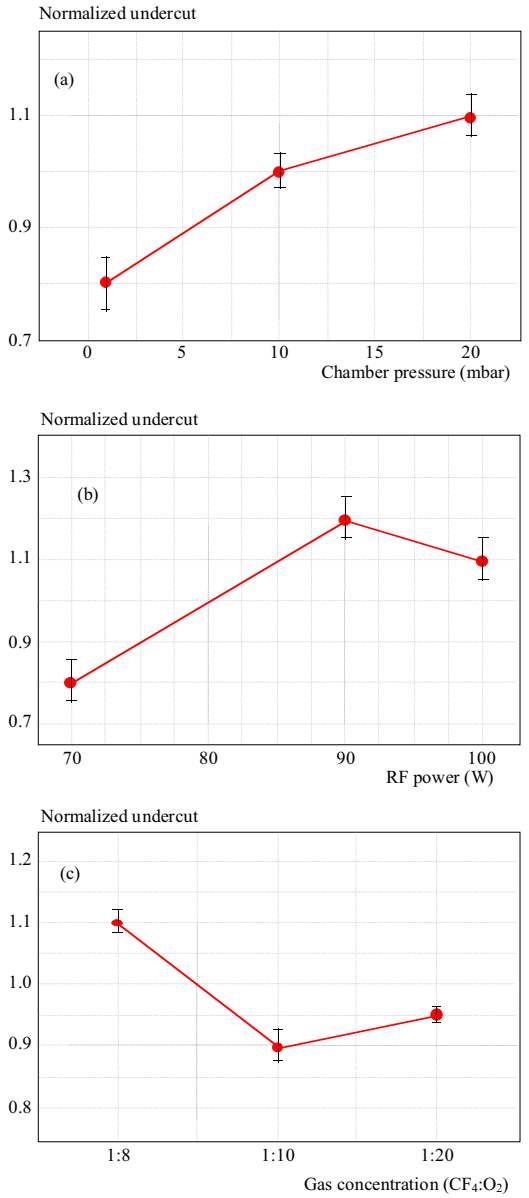

Fig. 6. The influence of different parameters on the normalized undercut. (a) — The influence of gas concentration on normalized undercut, (b) — the influence of RF power on normalized undercut, (c) — the influence of chamber pressure on normalized undercut

and chemical etching reaction with cross-linked SU-8 will therefore increases with the increase of etching power. The RF power of 100 W was chosen as optimized plasma parameter in order to obtain a highest etching rate.

3.4 The effect of gas concentration on etching rate of cross-linked SU-8

In order to investigate the effect of gas concentration on the etching rate of cross-linked SU-8, the parameters was fixed at 5 min, 100 W, 20 mbar, respectively. The gas concentration is defined as the ratio of O_2 flow rate and CF_4 flow rate. Figure 5 shows that with the increase of the gas concentration, the etching rate decreases. It indicates that CF_4 flow rate influence the cross-linked SU-8 etch rate significantly. With the gas concentration of $1:20$, the highest etching rate of $5.2\,\mu$m/min can be obtained. That might be explained by reactions between CF_4 radicals and O when the gas concentration of CF_4 is higher, which will reduce the amount of reactive oxygen available for the polymer etching. Therefore the gas concentration of $1:20(CF_4:\vee_2)$ was chosen as optimized plasma parameter in order to obtain a highest etching rate.

Based on the analysis above, we obtain that the optimized plasma parameter combination is gas concentration of $1:20$, RF power of 100 W, chamber pressure of 20 mbar and 5 min as an etching period.

3.5 The effect of etching parameters on the etching undercut

Figure 6 shows the normalized undercut obtained at each value for each of the three process variables. The normalized undercut is defined as the ratio of the undercut to the depth of etched cross-linked SU-8 film. It can be seen that the improvement of the undercut is limited. The normalized undercut remained at around 1.0. From Fig. 6(b) and (c), it can be seen that lower etching power and chamber pressure can reduce the etching undercut. This is in conflict with the optimized plasma etching parameter. Consequently there is a trade-off in situations where the cross-linked SU-8 is going to be patterned by plasma etching and both high etch rate and small undercut are needed.

Figure 7 shows the profile of cross-linked SU-8 structures patterned by optimal plasma etching with the gas concentration of $1:20$, RF power of 100 W, chamber pressure of 20 mbar and etching period of 5 min. The etching profile with an angular sidewall is attributed to the isotropic plasma etching. The loading effect of the sample, the machine type and configuration also have effect on the etching rate. In our experiments, where the etched area was about 3–10 % of the total area, the etching rate was about $5.2\,\mu$m/min in the plasma-asher machine.

4 CONCLUSION

The mixture gas of CF_4 and $\vee_2$ was used to increase the etching rate of the cross-linked SU-8. The influence of the RF power, gas concentration, and chamber pressure on the etching rate of the cross-linked SU-8 was studied. Experimental results show that a slightly increase of the concentration of CF_4 can dramatically increase the etching rate of cross-linked SU-8. When 5 % CF_4 (v:v) was added into the $\vee_2$ the etching rate of $5.2\,\mu$m/min was obtained. The optimal plasma parameter combination is gas concentration of $1:20(CF_4:O_2)$, RF power of 100 w, the etching time of 5 min and chamber pressure of 20 mbar which can lead to a highest etching rate of $5.2\,\mu$m/min.

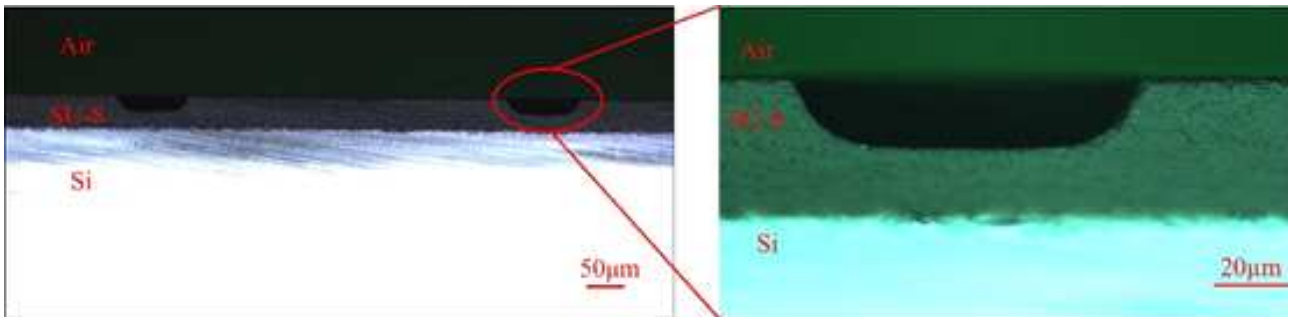

Fig. 7. Cross section image of cross-linked SU-8 structures etched by optimized plasma etching with the gas concentration of 1 : 20, RF power of 100 W, chamber pressure of 20 mbar and etching period of 5 min

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