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ArF Laser Enhanced Etching of Silicon

T.Fujii, R.Kawabata, H.Komiya, and H.Shimizu

VLSI Research Laboratories, SHARP corporation

2613-1 Ichinomoto, Tenri, Nara 632 JAPAN

The laser enhanced Si-SF6 reaction has been studied in the deep UV region. This reaction shows non-linear peak power dependence around 60MW/cm2. The etch rate is observed to depend on the Si structure in low power region. In high power region this structure dependence become to disappear. We think this non-linear laser power dependence of etch rate will achieve high spatial resolution etching.

1. INTRODUCTION

In recent years, photo-enhanced etching techniques have been intensively studied(1,2). The main purpose of this technique is to avoid damages that would be induced by plasma-ion process. Moreover, there is a possibility to realize the resistless projection image etching which simplify device fabrication process. The problem is to find a etching reaction which has enough spatial resolution for submicron patterning and high etch rate for acceptable process throughput.

Photo-enhanced etching reaction can be classified by the combination of light source and etching gas. One class is the photochemically active combination of light source and etching gas (photolysis), the other class is photochemically inactive combination of light source and etching gas (pyrolysis). In both classes, to achieve high spatial resolution, the etch rate should depend non-linearly on power density. In former case, etching gas molecule absorbs light in gas phase and photo-dissociated etching species diffuse from the light path before reaching substrate that will cause the degradation of the spatial resolution of etching pattern. In latter case, this type of reaction occurs on solid surface and etching profile is determined by beam profile on surface and etch rate depends on deposited power density. Therefore, we have been studying the latter case to expect high spatial resolution of this type of reaction.

In this work, we report the excimer laser enhanced Si-SF6 reaction. Surface reaction and non-linear power dependence of the etch rate was observed. The etching mechanism is also discussed.

2. EXPERIMENTAL

ArF(193nm) excimer laser was used as a light source and SF6 was chosen as a etching gas which shows only weak absorption of light around this wavelength in high pressure condition (621 Torr)(3). Fig.1 shows the schematic diagram of experimental apparatus. The laser beam was focused perpendicularly on the substrate in SF6 atmosphere. Etching gas was not flowed in this work. The incident laser peak power was varied 40-140 MW/cm2 (pulse duration 10 nsec) by optical attenuator and the laser average power was varied 4-140 W/cm2 (pulse repetition rate 10-100 Hz). All experiments was performed under the room temperature condition.

The different structure of Si, that is, single crystal(p(100), p(111)), polycrystalline, and amorphous, were used. And also, the different type of doping of polycrystalline Si, that is, undoped, n+ doped, and p+ doped which were doped thermally, were used. The sample was cleaned in diluted HF solution prior to the irradiation.

After substrate was exposed to laser irradiation, etched depth was measured with a mechanical stylus.

3. RESULTS

Laser enhanced Si-SF6 reaction is observed about laser peak power of 60 MW/cm2. Fig.2 shows the linear relation between etched depth and the number of deposited laser pulse. The etch rate can be calculated by the slope of this plot. It can be seen in Fig.2 the etch rate strongly depends on laser power.

Two types of power dependence of etch rate, average power dependence and peak power dependence, is examined. First, the average power dependence is shown in Fig.3. Here, the etched depth is normalized to deposited laser energy. Second, Fig.4 shows peak power dependence of the normalized etched depth. It is notable that etch rate is greatly accelerated about laser peak power of 60 MW/cm2.

The differences of etch rate between various structure of Si are shown in Fig.5. Three types of laser peak power dependence can be seen below and above laser peak power of 60 MW/cm2. Three structures of Si show different etch rate but slopes of etch rate against laser peak power are parallel in high power region above 60 MW/cm2. Etch rates are different and the slopes of curves are not parallel in low power region below 60 MW/cm2. The difference between n+, p+, and undoped polycrystalline was not observed in these region. The etch rates of p(100) Si and p(111) Si are the same in high power region but the difference in low power region is not clear.

Fig.6 shows that SF6 pressure dependence of etch rate at different laser peak power. The curves of the different peak power are parallel in this pressure region. The change of the pressure dependence of the etch rate is also observed above the etch rate of 2 Å/pulse.

4.DISCUSSION

The power dependence of the etch rate is non-linear as shown in Fig.5, and this type of dependence is similar to that of reported Ar+ laser experiment(4). To explain this power dependence, three types of the etching model corresponding to the peak power can be considered.

In low power region(A), weak surface activation seems to occur. Fig.7 shows that the peak power dependence of this surface reaction can be plotted by Arrhenius type. To estimate the activation energy, following assumptions are supposed. The surface temperature vould be proportional to the laser peak power and at the peak power of 60 MW/cm2 the surface would heat up to the melting point 1400°C. The reason of this temperature assumption will be discussed in high power region. The activation energy of this thermally activated surface reaction is calculated as 0.16eV, 0.19eV, and 2.6eV corresponding to amorphous Si, polycrystalline Si, and single crystal Si, respectively. This result shows that the reaction depends on the structure of Si.

In the medium power region(B) between low power region and high power region, the etch rate depends on the logarithmic peak power . We suppose that the etch rate is defined by the light penetration depth in region(B) to explain the result. This model is illustrated in Fig.8. Using the reported value of the absorption coefficient ($a=1.2\times10^{6}\ cm^{-1}$)(5) near this wavelength region, the calculated etch rate curve is shown in Fig.4.

In high power region(C), the etch rate are different with the Si structure. If the etch rate curves are shifted along the peak power axis, these curves would be overlap. This means that the elemental reaction mechanism would be the same for each Si structure in the (C) region and only the surface temperature would be changed. According to these result, the Si surface is supposed to melt in this region (60 MW/cm2).

In (C) region, the increase of the etch rate seems to be suppressed. Two mechanisms are considered to understand the suppression effect. One is the drastic increase of the effective absorption and the other is insufficient supply of the etching species.

Then we concern about the supply of the etching species. The supply of the reactive species can be seen in the pressure dependence of the etch rate. The etch rate is represented by the following formula.

$$(\text{ETCH RATE}) \propto (\text{SF6 SUPPLY}) * (\text{SF6 DISSOCIATION})$$

$$(\text{SF6 SUPPLY}) \propto (\text{SF6 PRESSURE})$$

$$(\text{SF6 DISSOCIATION}) \propto \text{EXP}(-Edis/kT)$$

From this relation following equation is obtained

$$\text{LOG}(\text{SF6 PRESSURE}) = Edis/kT + \text{LOG}((\text{ETCH RATE})/\text{const})$$

Here we assume that the reaction probability of the etching species and Si is constant. Following assumptions are used, dissociation probability is Ahrrenius type of temperature dependence and the supply of SF6 is proportional to SF6 pressure and surface temperature is proportional to laser peak power. Then SF6 pressure and peak power satisfy following equation

LOG(SF6 PRESSURE) = A/(PEAK POWER)

+LOG((ETCH RATE)/const)

The peak power and the pressure to give the constant etch rate are picked up from Fig.7 and are plotted to Fig.9. It shows linear dependence of (PEAK POWER) and LOG(SF6 PRESSURE) which is suggested in the model mentioned above. This result shows that the supply of etching species limits the etch rate in high power region. However, a simple model can not explain the change of pressure dependence of etch rate above 2 Å/pulse.

5.SUMMARY AND CONCLUSIONS

Three types of etching reaction correspond to laser peak power was observed.

Two of them correspond to medium and high power region. These are high etch rate reactions that correspond to reaction between highly activated layer of Si and SF6. the turning point of these two regions is 2-3 Å/pulse. In high power region, the insufficient supply of etching species suppresses the etch rate. The etch rate in this region is determined by surface temperature.

The other of them is low power reaction that corresponds to thermal surface reaction between weakly activated Si and SF6. The reaction shows surface structure dependence besides the temperature dependence.

Analyzing the pressure dependence by the simple etching model, the supply of the etching species were considered to limit the etch rate in high power region.

We think this non-linear laser peak power dependence of etch rate in both high and low etch rate region will give help to realize high spatial etching.

5.REFERENCES

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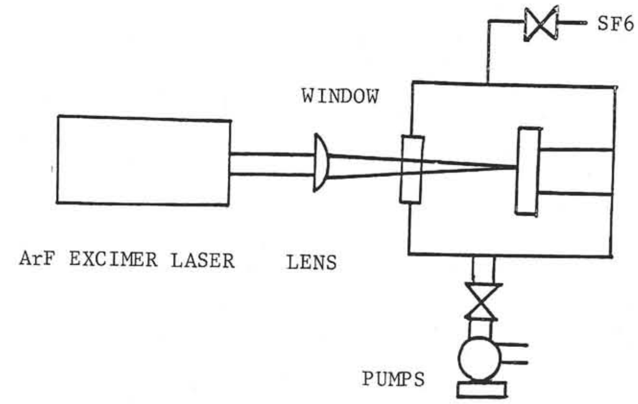

Fig.1 Schematic diagram of the experimental apparatus.

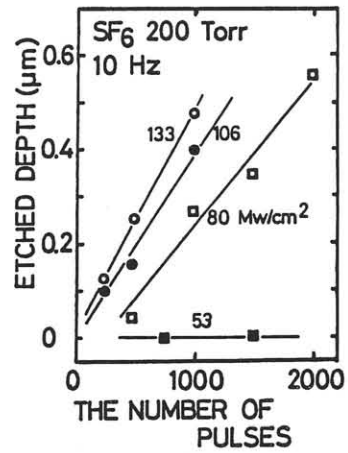

Fig.2 Plot of etched depth as a function of deposited laser pulse. Etched depth is proportional to the number of deposited laser pulse.

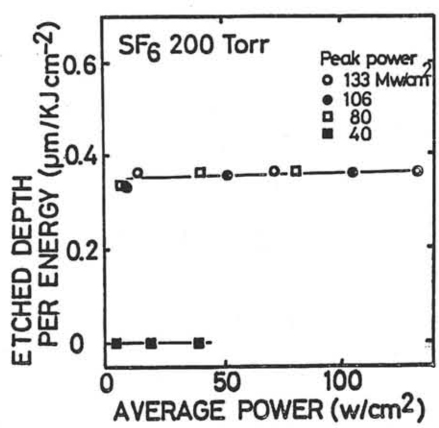

Fig.3 Laser average power dependence of the etched depth normalized to deposited laser energy. Laser pulse repetition rate was varied from 10 to 100 Hz.

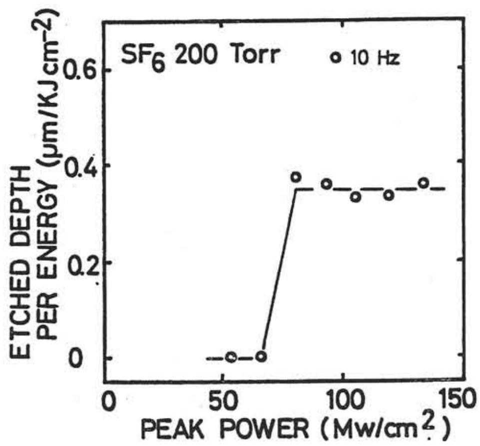

Fig.4 Laser peak power dependence of the etched depth normalized to deposited laser energy.

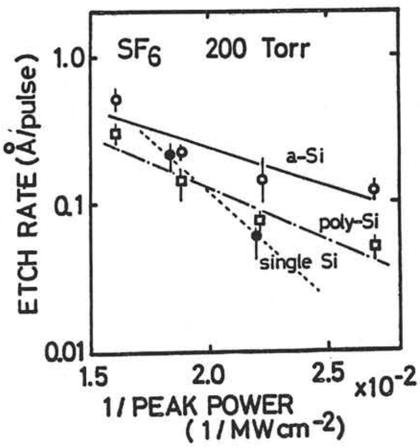

Fig.7 Plot of the etch rate as a function of laser peak power. The linear dependence can be seen.

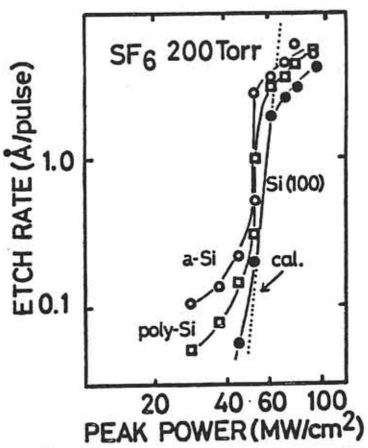

Fig.5 Laser peak power dependence of the etch rate. The differences between various structure of Si can be seen. The dashed line represents peak power dependence of the etch rate calculated by reported absorption coefficient.

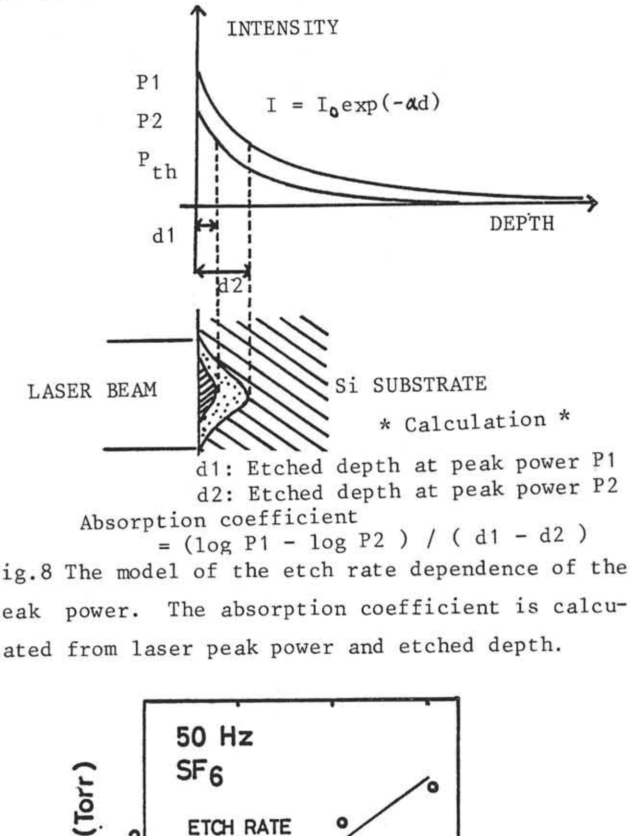

Fig.8 The model of the etch rate dependence of the peak power. The absorption coefficient is calculated from laser peak power and etched depth.

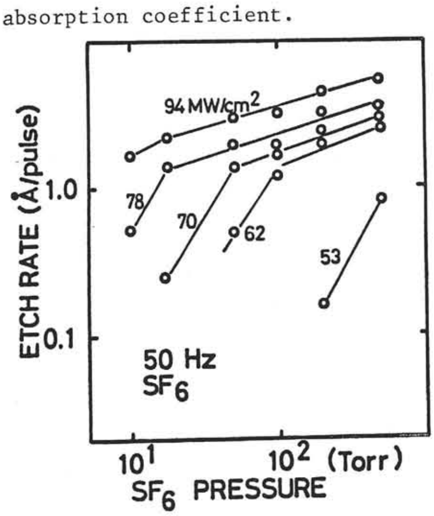

Fig.6 SF6 gas pressure dependence of the etch rate. The differences between various laser peak power can be seen.

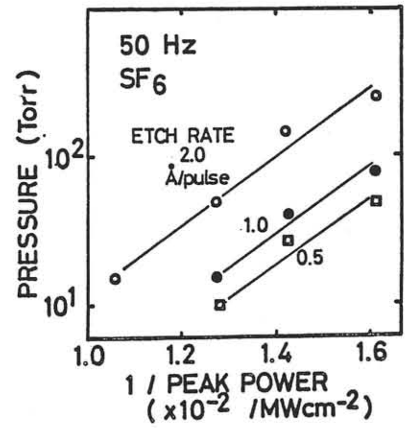

Fig.9 Plot of the pressure as a function of laser peak power under constant etch rate. The linear dependence can be seen.