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Effect of duty cycle on various etching widths during bosch process

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The effect of the duty cycle on the etching process and on the formation of silicon grass for different etching widths was investigated. As the duty cycle is defined as the chuck power application per second, it determines the etch rate and etching profiles. It was found that decreasing the duty cycle improves the etching profiles of the trench but it may also cause the formation of silicon grass at the bottom when the nominal width is significantly large. Therefore, for a large nominal width, lowering the duty cycle promotes the formation of silicon grass. Moreover, a large duty cycle induces undercut on the sidewall, which is deleterious to the etching profiles. Activation of the chuck power is controlled by the duty cycle and it also accelerates photo resist erosion or a bowing effect. Therefore, when the duty cycle becomes large, the etch rate is drastically enhanced. Finally, we can conclude that a low duty cycle is suitable for a Bosch process in order to prevent undesirable etching side effects, such as undercut or bowing.

Key words: Duty cycle, etch rate, Bosch process, silicon grass.

Introduction

The trend of miniaturization has been applied to the field of aerospace, especially for making micro rockets. Previously, the micro rocket was fabricated using mechanical micro machining techniques [1]. However, it is difficult to fabricate micro rockets with less than 1 mm resolution. Some other attempts using semiconductor processing were also used for micro rockets where a deep reactive etching technique was used [2]. A semiconductor processing technique is quite beneficial for mass production.

Deep reactive etching has been popular for years because it has many advantages such as a high etch rate to result in a high aspect ratio, process compatibility to photo resist masks and the capability to form deep trenches. Plasma etching is one of the important steps in semiconductor processing. Among various types of etching process, the Bosch process is one of the most promising etching techniques to obtain microstructures with high aspect ratios. An inductively coupled plasma (ICP), which is a high density plasma, is employed in the Bosch process, and a high etch rate can be achieved [3, 4].

The Bosch process uses SF_6 and C_4F_8 alternately to achieve anisotropic etching. C_4F_8 is deposited on the surface of the substrate to protect the sidewalls from the ion bombardment of SF_6 ions. There are many parameters in the processing: SF_6 pressure, source power, chuck power, etch/passivation time ratio, flow rate of etch/passivation gas, and duty cycle. For the past few years, many efforts have been made to study high aspect ratio structures in the Bosch process, by controlling these processing parameters [5-7].

Although the Bosch process is popular for semiconductor processing and MEMS (Micro Electro Mechanical Systems) fabrication, obtaining various shapes of microstructures is limited. Non-vertical or sidewall-tapering structures are often beneficial for some applications such as ink-jet nozzles and mass spectroscopy emitters [8]. There have been some research on the effect of the five parameters discussed above, but no precise study has been carried out on the duty cycle. The duty cycle is the time ratio of chuck power activation in one second. In this study, the effect of the duty cycle on etching characteristics is investigated.

Experiments

A general photolithographic process was used in these experiments. The size of wafer used was 6 inches (150 mm), and SC1 and HF solutions were used for cleaning. The wafers were then coated with photo resist, AZ4330, with a thickness of 5 μm. A deep reactive ion etching system (Alcatel Co.) was used. Helium gas was provided beneath the wafer for a cooling effect. Etching and passivation gases were alternately admitted into the chamber to make vertical trenches. After gases were admitted, a radio-frequency (RF) coil began to operate and generate a high-density plasma source for etching. Another power source was applied to control the substrate DC bias. The processing time for one wafer was 30 minutes. Table 1 gives the experimental parameters used in the ICP etching. In these experiments, the duty cycle was varied to observe its effect on the etching process and profile, while keeping the other parameters constant. The etched surfaces were observed using a Scanning Electron Microscope (SEM).

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Table 1. Parameter conditions used in this experiment.

No.1	Pressure (mTorr)	Chuck power (W)	Source power (W)	Etch/passivation time (s)	$SF_6 : C_4F_8$ (sccm)	Duty cycle (ms)
1						10
2	34 (4.54 Pa)	90	1800	7:2	200 : 125	20
3						30

Results and Discussions

Fig. 1 shows SEM images for each case taken as the duty cycle and width were varied. The images show that silicon grass tends to appear when the duty cycle is low and the nominal width is large. It is known that silicon grass is created by foreign particles or residues that may act as a micro mask against the ionic bombardment induced by the chuck power. In these figures, the silicon grass appears for a large pattern width or a low duty cycle. This implies that the duty cycle affects the etching behavior significantly with changes in the nominal width. Moreover, for a large nominal width, lowering the duty cycle promotes the formation of silicon grass.

Fig. 2 shows the etch rate variation in relation to the duty cycle. The curves show that the etch rate is continuously enhanced if the duty cycle is increased. Due to the fact that the duty cycle determines the activation time of the chuck power, more ions and radicals are attracted to the silicon wafer with an increase in duty cycle. Therefore, the etch rate for trenches with a small nominal width was the smallest.

The etch rate also depends on the nominal width. As the nominal width is decreased, the etch rate decreases because of the high aspect ratio. According to the Knudsen model, the etch rate tends to gradually decrease for an increase in the aspect ratio. When the depth becomes deeper and deeper, it needs more time for the etching products to escape the trench, slowing down the etch process. Fig. 3 proves that the etch rate is predicted correctly by the Knudsen model.

Fig. 4 shows the relation between the nominal width and the undercut. It shows that a high duty cycle causes a large undercut. As the duty cycle determines the chuck power duration per second, more plasma gases are attracted by the gas. The undercut becomes large when the duty cycle is 20 and 30 ms. This is also due to the erosion of the photo resist at the edges. Under the bombardment

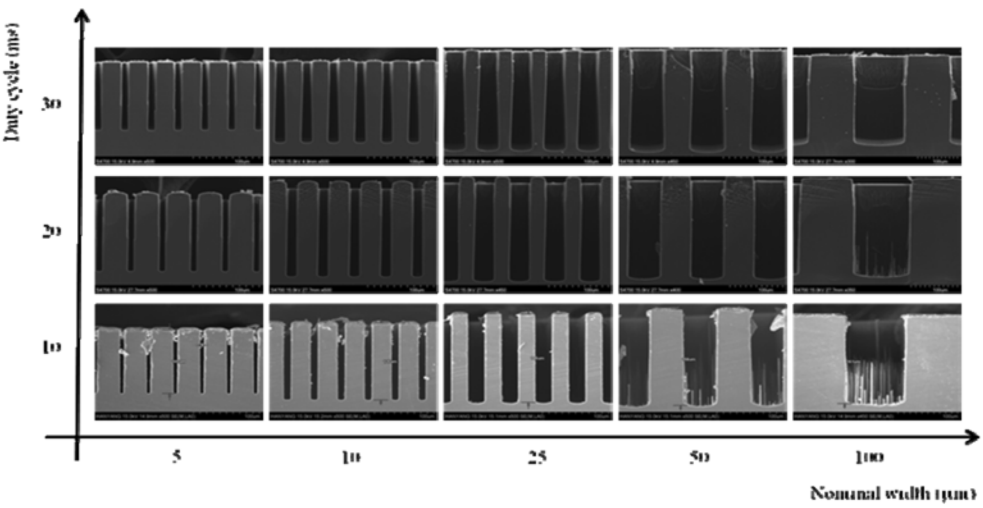

Fig. 1. SEM images of the cross-sectional area of silicon trenches as the duty cycle and width change.

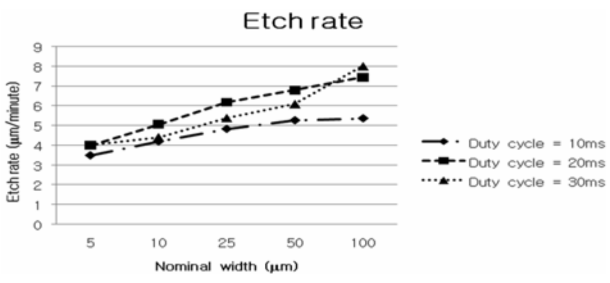

Fig. 2. Relation between the etch rate and duty cycle with changes in nominal width.

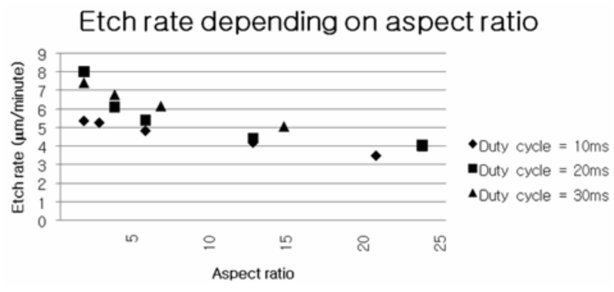

Fig. 3. Relationship between the etch rate and aspect ratio of trenches with various duty cycles.

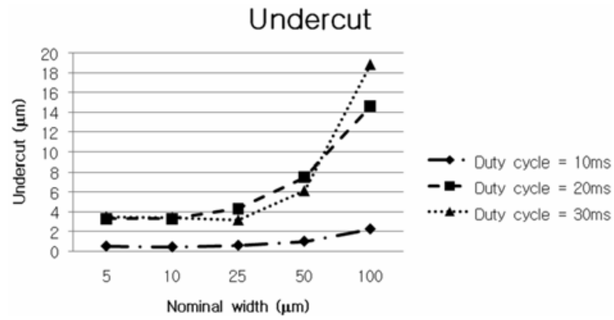

Fig. 4. Relationship between the duty cycle and undercut as the nominal width changes.

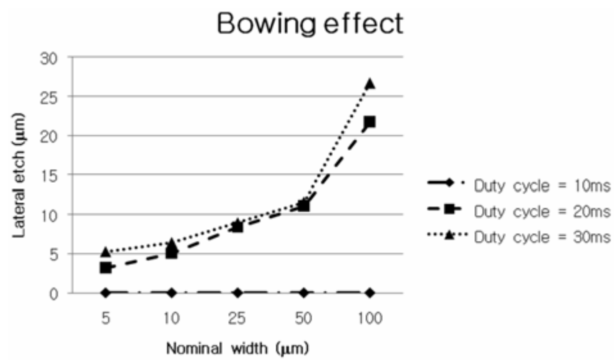

Fig. 5. Relationship between the bowing effect and duty cycle as the nominal width changes.

of ions attracted by a large duty cycle, the edge of the photo resist layer is recessed. This also indicates that the undercut is strongly affected by the nominal width. This is because many more ions arrive at the top of a large trench than at the bottom of the trench. By contrast, for small trenches, the undercut is small due to the small incident angle of ions.

A bowing effect was also observed (Fig. 5). The bowing effect becomes more significant with a duty cycle of 30 ms. The bowing effect is noticeable when the nominal width becomes large. It is known that excessive SF_6 ions reacting with a silicon substrate result in a bowing effect, increasing the bottom width of a trench.

The bowing effect suggests that the SF_6 contribution is more sensitive to the duty cycle than the C_4F_8 contribution. As the chuck power attracts ions to the silicon substrate and enhances the anisotropy of trench, increasing the duty cycle can be assumed to have the same effect as an increase in chuck power since the duty cycle determines the duration of the chuck power.

Conclusions

The influence of a variation of the duty cycle has been discussed. From the results mentioned above, several conclusions can be made. First, decreasing the duty cycle improves the etching characteristics of a trench but it may also cause silicon grass on the bottom when the nominal width is significantly large. The duty cycle helps strong etching reactions by inducing more ions to the substrate. Second, a large duty cycle induces an undercut on the sidewall, which is deleterious to the etching profiles. Activation of the chuck power is controlled by the duty cycle and it also accelerates photo resist erosion or a bowing effect. Finally, when the duty cycle becomes large, the etch rate is drastically enhanced. Therefore, we can conclude that a low duty cycle is suitable for a Bosch process in order to prevent undesirable etching side effects, such as undercut or bowing.

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