Small Plasma Space with a Small Plasma Source and Its Advantage in Minimal Fab

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We have developed an inductively-coupled plasma-reactive ion etching system (ICP-RIE) as a human-size tool of Minimal Fab for processing a half-inch wafer. The etching system has performed a Bosch etching process with a short switching cycle in a small chamber with a volume of 1/4 L. For the small chamber, we use a frequency of 100 MHz that is higher than the typical frequency of 13.56 MHz. The power consumption at 100 MHz is only ~ 40W. The Si etching rate of the Bosch process is ~ 2.5 μm/min. Moreover, residence times of deposition gas (C₄F₈) and etching gas (SF₆) are estimated to be ~ 0.2 second, and actually waiting times until feeding one of the gases into the chamber after the stop feeding the other gas are nominally set to be zero. The resultant Bosch cycle time of the alternative feeds of the two gases is only 2 sec. For the high-speed Bosch cycle of 2 sec, the resultant etching sidewall of Si structure becomes a scallop-less straight wall.

Keywords: Minimal Fab, MEMS, Deep RIE, Bosch process, Half inch wafer

1. Introduction

Semiconductor mega factories have problems of huge investment due to the increase in wafer diameter. Since the huge investment needs a mass market, low volume productions of devices become unsuitable for the mega fab. For the low volume production Minimal Fab [1-4] has been developed. Minimal Fab is a very small device production system with minimum investment using a φ 12.5 mm wafer. Minimal Fab is also a system very suitable for research and development and production of MEMS [5,6] (Micro Electro-Mechanical System) devices with a very large number of device types. To realize MEMS devices using Minimal Fab, it is important to establish a deep RIE process which is a basic MEMS technology. In order to fabricate a MEMS device with a Minimal Fab, it is necessary to develop a Minimal Fab standard tool with the width of 30 cm, resulting in limiting a chamber size to ~ 10 cm in diameter.

As for silicon deep etching today, a deep etching technique called Bosch process, which was patented in 1992 by F. Laermer of Robert Bosch GmbH, Germany, and A. Schilp et al. [7-10], is widely used in the field of MEMS. In the deep etching process, high-speed etching is essential, and as a plasma source for that, inductively-coupled plasma (ICP) [11,12] is generally used to generate high-density plasma.
Mounting ICP plasma on a Minimal Fab tool requires downsizing to adapt all the exhaust system, transport system, and supply system to the standard tool size of W296, D450, and H1440 [1-4]. However, the etching performance should not be degraded for the small tool size. In addition, an ICP plasma usually requires an ignition power, consuming a larger power than that during a plasma processing even in the small plasma of the small tool. Therefore, in the Minimal Fab small deep RIE it is needed that a plasma efficiency is raised to save the plasma power without lowering the etching rate while good etching uniformity and good surface morphology are obtained. For this serious issue, we optimized plasma size, plasma pressure, gas flow, and plasma density, and developed the tool to solve the issue. Also, we found that this small plasma tool makes a high-quality Bosch process. In this report, we give an overview of this tool and report its characteristics and phenomena.

2. Tool design of Minimal Fab ICP-RIE system

2.1. Tool overview

The schematic of the tool is shown in Fig. 1. ICP plasma is generated by applying an ultrashort wave (100 MHz, 20 to 40 W) to a coil. The RF (2 MHz, 0 to 400 V) bias with a rectangular wave cycle of 5 msec (f = 200 Hz) is applied to the wafer stage. The duty ratio of on and off RF bias in each rectangular wave period is changeable within 0 - 100%. A wafer is fixed to the stage by a mechanical clamp. There is a cavity inside the stage, and an air from outside is blown into the cavity to suppress the temperature rise of the wafer during the etching process. There is a slight vacuum gap between the wafer and the wafer stage. The cooling effect is enhanced by filling the gap with He gas. C₄F₈ gas is supplied from the top of the chamber to passivate the etched surface, and SF₆ gas is supplied from the top to etch the wafer surface. The two types of gas are alternately supplied.

One of features of the Bosch process tool in this study is that the ratio of pump evacuation speed Q to chamber volume V is 2 to 8 times larger than a tool for a mega fab. The effective chamber volume V of the minimal ICP-RIE is about 0.25 L, which is exhausted by a turbo molecular pump with a pumping speed S of 80 L/sec. This fast V/S = 3 msec could be realized by a huge pump of 13,000 L/sec for V = 40 L for a Mega fab tool. This kind of huge pump is unrealistic in the Mega fab. Thus, the Minimal Fab ICP-RIE has a relatively high exhaustion performance.

2.2. High frequency plasma

The efficiency of plasma energy for the input power of ICP plasma is determined by the ratio of reactance for resistance [13]. The resistance of the plasma circuit increases as the frequency increases mainly due to the skin effect, but at the same time, the reactance of the ICP coil also increases as the frequency increases. This power efficiency is determined by the competition between the resistance component and the reactance component. It is known that the ratio has an optimal value [13]. The usual ICP plasma generally uses 13.56 MHz RF. At this frequency, the resistance component is relatively large for a small plasma source. Then the power efficiency is getting lower [14]. For this reason, it is necessary to raise the frequency more and we used 100 MHz. Further, it was reported that the dissociation of C₄F₈ gas at 100 MHz was increased than that at 13.56 MHz because most of the dissociation and ionization is caused by electron collisions in weakly ionized gases.
plasma [15]. In other words, the Minimal Fab ICP plasma tool minimized the load loss because the coil wire length tends to be short, so a high frequency such as 100 MHz was able to be used. As a result, we obtained high density plasma with low loss for the small plasma.

2.3. Outline of Bosch process in this study

The etching picture of Bosch process cycle is shown in Fig. 2. In the Bosch process a passivation step using a gas such as C₄F₈ and an etching step using a SF₆ gas or the like are alternated.

In the passivation step, a CF-based polymerization layer is deposited on the whole surface as shown in Figs. 2 (1) and (2). Next, in the etching step, a voltage bias is applied to the wafer stage. Then, an electric field in the vertical direction is generated on the wafer surface. At the same time, fluorine ions drift and accelerate along the electric field direction. Those fluorine ions with this kinetic energy remove the passivation layer at the bottom of the etched hole, resulting in exposing the Si substrate surface. Here, the lateral sidewalls are protected by the passivation layer which is unetched as shown in Fig. 2 (3). The surface where Si substrate is exposed is isotropically etched with a round shape as shown in Fig. 2 (4). As a result, a periodical wavy shape by the isotropic etchings, which is called scallops, is formed on the side wall. Thus, one cycle of the Bosch process proceeds with an etching by the depth of one scalloped layer.

Figure 2 (4) is an advanced process added to the normal Bosch process mentioned above. This is a step of turning off the bias after the silicon substrate surface is exposed. The etching rate slightly decreases because the ion-assisted vertical etching component is suspended. This off-bias process is useful to suppress mask consumption and mask side etching in a long time etching to form a deep trench structure.

3. Experimental

The scallop-shaped side wall previously described above becomes a problem when the etched hole should be filled by a metallic material as a through via, or when a hole is used as an optical mirror wall. In order to eliminate or reduce the scallops, it is effective to perform fast replacement of the gases and to shorten the cycle time as shown in Fig. 3.

![Fig. 4. Plots of scallop heights corresponding with Bosch cycle times and illustrations of etching structures at each plot using Minimal Fab ICP etching tool.](image-url)
In the Minimal Fab ICP plasma tool, the gas replacement time of the passivation gas and the etching gas is relatively short as mentioned in section 2. Thus, in the small chamber configuration no mixing of the two gases occurs even in a faster cycle time than that of Mega fab.

In our experiment, we made a resist mask on a φ12.5 silicon wafer, and etched the wafer. In the whole experiments in this study, all the resist patterns were formed by Minimal Fab tools, which include RCA cleaner, piranha solution cleaner, coater, mask-less exposure, developer, dry asher, wet resist remover, etc. The wafer surface with a lithographic resist pattern was etched in the following conditions. (1 Bosch cycle time) × (number of cycles): 2 sec × 20 times, 4 sec × 10 times, 6 sec × 7 times, 13 sec × 3. Other conditions were a pressure during gas feeding of 10 Pa, an ICP RF power of 40 W, and gas flow rates of C₄F₈ = 8 sccm, SF₆ = 8 sccm. The processing times of the passivation and etching steps were equal with a ratio of 1:1. We evaluated the dependence between Bosch cycle time and scallop height. Here the scallop height was defined as a difference between the bottom and the top in a scallop.

4. Results and discussion
4.1. High-speed gas replacement
We measured scallop heights from SEM (Scanning Electron Microscope) profiles. In Fig. 4, scallop heights are plotted for Bosch cycle time. It was found that the scallop height tended to be shorter as the Bosch cycle time became shorter.

The height of the scallop became zero when the cycle time was 2 sec. In a SEM image with ×35,000 magnification, any periodical surface roughness on the side wall was not observed even at this resolution. In this sense, the etched side wall had a very smooth scallop-less surface.

Figure 5 shows the relationship between the Bosch cycle time and the etching rate of the Si substrate when the ICP power was fixed at 40 W. The etching rate simply should have no dependence of the Bosch cycle time since the total etching time is constant. In fact, the result was almost as it is. When the cycle time was shortened, the etching rate was slightly reduced because an etching loss time was increased due to the increase in the gas switching frequency.

4.2. Residence times of gases
In the Bosch cycle it is necessary to evacuate the two gases quickly so as not to be mixed. Otherwise, a side etching occurs in the mixed process time. The residence time of gases [16] is calculated using the following formula.

\[ \tau = \frac{V \times P}{Q} \]  

Here, \( \tau \) is residence time, \( V \) is a volume contributing to plasma (0.25 L), \( P \) is a chamber pressure, and \( Q \) is a gas exhaustion rate. The gas is exhausted in the form of \( P = P_0 \exp \left( -t/\tau \right) \). In this experiment, the inlet gas flow rate is equal to \( Q \). Substituting \( Q = 8 \text{ sccm} \) (0.1 Torr·L/sec), \( P = 10 \text{ Pa} \) (7.5×10⁻² Torr), and \( V = 0.25 \text{ L} \) into Eq. (1), \( \tau \) was estimated to be about 0.2 sec.

Thus, the gas was replaced at a time faster than the cycle time. In a spectral analysis of the plasma luminescence for the cycle time of 2 sec in Fig. 6, each spectrum from the gases disappeared at 0.2 sec after closing each gas feed valve.

This disappearing time is almost the same as the calculated residence value. This indicates that the two gases were alternately switched without
mixing of the gases every half cycle.

4.3. Etching characteristics
Here we evaluate whether or not the Bosch process using the Minimal Fab tool is functionally equivalent to the regular Bosch process. In a normal Bosch process, the passivation process and the etching process are basically not performed simultaneously, but are implemented separately (hereinafter referred to as Bosch mechanism). In the above-mentioned estimation of the residence time and the experiment of the luminescence, we have already analyzed that the two gases had no mixing. Even though it is useful to clarify no mixing also by other verification.

One experiment is to observe whether etching is occurred only during the etching step. When the etching time is half of one Bosch cycle, the etching rate at this time should be half compared with a continuous etching. In fact, the ratio of the passivation and etch process times in this study was 1:1. If the etching rate of the Bosch cycle is greater than a half of the continuous etching rate, then an etching is occurred also in the passivation step.

The etching rate using only SF₆ without using C₄F₈ was shown in Fig. 7. It was found that the continuous etching rate at 40 W was about 4.8 μm/min, which is over twice of 2.2 μm/min for the Bosch process cycle time of 2 sec shown in Fig. 5. Thus, this implies that the two gases were not mixed.

In addition, it is useful to verify whether a passivation film is formed or not. As an indirect experiment, we examined a continuous deposition rate using only C₄F₈. The deposition rate at 40 W was about 0.3 μm/min, which was 5 nm/sec indicating ~5 nm was deposited every passivation step with the passivation time of 1 sec. However, it has not been clarified that the deposited film in the Bosch process is polymeric Teflon.

From the above discussions, it was found that the etching and passivation are processed in each part of the cycle independently in terms of time, whose behavior is consistent with the Bosch mechanism.

4.4. Etched surface morphology
In the Bosch mechanism, the scallops should exist because there is an isotropic etching process that generates the scallop shape. However, in the actual process of this study, no scallop was observed in the cycle time of 2 sec as shown in Fig. 4. So, we use a SEM with a higher resolution to examine the surface morphology.

Figure 8 shows deeply-etched grooves when the Bosch cycle time was 2 sec and the total etching time was 600 sec after 300 cycles etching. The grooves were formed by etching a resist pattern of 2 μm line & space with 1 μm thickness. An etching depth was 13.3 μm.

The inset of Fig. 8 is a high-resolution SEM image with ×500,000 magnification. No scallop was observed. From the total depth of 13.3 μm and 300 cycles, a depth per cycles becomes 44.3 nm. In the inset, there is no periodical fluctuation with the period of 44.3 nm. Instead, uneven non-periodical fluctuations with a height of about 6 nm were observed. This fluctuation would be attributed to an etching inhomogeneity. At least, it is not due to a periodical effect of the Bosch mechanism.

Fig. 7. A plot of Si etching rate and polymer deposition rate dependent with ICP power while performing etching and passivation separately.

Fig. 8. A cross-sectional image of grooves formed by etching a line & spaced resist pattern with the period of 2 μm. The cycle time was 2 sec and the number of cycles was 300 times.
mechanism. From the above, it is found that the scallop actually disappeared for the etching with the cycle time of the 2 sec. In the Minimal Fab Bosch etching, it was found that the Bosch mechanism of sequential processes of passivation and etching is preserved while no scallop forms with the cycle time below 2 sec. The scallop-less smooth morphology is inherently caused by the short residence time of the gases in the small chamber.

5. Conclusion
In the minimal ICP-RIE plasma tool with the chamber volume of about 0.25 L, 100 MHz was used as a plasma frequency. Owing to the high frequency of 100 MHz, an ICP power of about 40 W was realized. In addition, the residence time of the gases for passivation and etching became very small of about 0.2 sec by reducing the volume of the chamber. This made it possible to switch the Bosch process with a high speed cycle of 2 sec. In the high-speed switching cycle, a scallop-less Bosch etching was realized.

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