Global pattern density effects on aluminum alloy etching for sub-0.25 μ m technology logic devices

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Global pattern density effects on aluminum alloy etching were quantitatively analyzed for sub-0.25 μ m technology logic devices. We found that etching the metal layer with one pattern density while applying the plasma activation parameters optimized for the other pattern density often results in inferior performance, even if the minimum design rules of both layers are the same. Additional studies show that the aluminum etch rate has an almost linear relationship to the pattern density of the etched metal layer when all the activation parameters are fixed. This evokes the necessity that the plasma activation parameters be optimized properly with the pattern density of each metal layer as well as with the minimum design rule. We speculate that these pattern density effects are caused by the variation of etching environment that is solely determined by effective etchants density and their effective residence time. Thus it may be possible to alleviate the global pattern density effects are independent of the pattern density. Based on the aforementioned speculation we controlled total pressure and feed gas flow rate and were able to achieve stable etching performance independent of the global pattern density. © 2001 American Vacuum Society. [DOI: 10.1116/1.1414114]

I. INTRODUCTION

Previous issues in aluminum alloy etching have mainly been related to design rule dependent etching performances or microscopic phenomena such as microloading effects. For example, local etch rate and profiles of patterned metal lines are strongly dependent on microscopic pattern density, and many studies have focused on alleviating these microscopically nonuniform phenomena.¹⁻⁵ With the advent of sub-half micron size aluminum alloy etching, global pattern density effects have also emerged as an important issue. That is, under the same plasma activation parameters, the overall pattern density of the etched layer strongly affects the etching environment and the resultant etching characteristics. The results of interaction between the etching environment and the etched layer were not serious when the pattern size was large. However, as the pattern size becomes smaller, it often results in a drastic variation in etching characteristics.

Different from memory devices, logic devices are destined to have metal layers with various pattern densities, even if they adopt the same design rule. If the general rule to cope with the pattern density variation is not found, much time and effort must be undertaken to optimize plasma activation parameters for each product. Thus it is necessary to illuminate the global pattern density effects on aluminum alloy etching and to find out a guideline to alleviate the pattern density effects.

In this work we analyzed the global pattern density of the metal layer for various 0.25 μ m technology logic devices using the tool developed within this company. Matching the pattern density with the resultant etching performance, we found that etching the metal layer with the nontypical pattern

density while applying the plasma activation parameters optimized for the typical pattern density results in quite different etching performance. In order to investigate the pattern density dependent variation of etching performances systematically, additional studies with the samples simulating various pattern densities were performed. Through these additional studies we clarified the pattern density dependence of etching characteristics and tried to present a possible way to alleviate the pattern density effects.

II. EXPERIMENT

The plasma etch system used in this study is a magnetically enhanced reactive ion etcher, MxP+TM, manufactured by Applied Materials, Inc. Among the major controllable activation parameters in this reactor, environmental temperatures, source power, magnetic field, and Cl2:BCl3:N2 gas ratio were optimized and fixed throughout this work. Chamber pressure (180 mTorr) and total gas flow rate (140 sccm) were adopted as based activation parameters; however, they were varied in order to cope with the pattern density effects.

We first analyzed the global pattern density of the metal layer for various 0.25 μ m technology logic devices, of which the typical pattern density ranges are shown in Table I. After the pattern density of each metal layer was analyzed, it was etched under the aforementioned base activation conditions, and the etching performance was compared matching each pattern density. We also prepared samples with the same layout, but with different pattern density, by controlling the exposure step in the lithography process. By doing this, samples with the macroscopic pattern density ranging from 15.2% to 89.2% were prepared, as shown in Table II. Silicon wafers with 200 mm diameter and Ti/TiN/Ti/Al-0.5 wt %Cu/ Ti/TiN metal stack deposited on oxide layer were used as

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TABLE I. Global pattern densities of metal layers for various 0.25 μm technology logic devices.

Products	Metal-1	Metal-2	Metal-3	Metal-4	Metal-5
А	30.4%	30.8%	31.3%	25.8%	25.7%
В	29.2%	30.4%	36.3%	20.6%	18.9%
С	40.6%	56.5%			
D	40.3%	32.7%	49.6%		
Е	24.2%	23.9%	30.1%	28.3%	27.2%

Note: Metal layers with nontypical pattern density are indicated by boldface.

sample wafers and *i*-line photoresist was coated on these wafers. These samples were etched using the same plasma activation parameters and their etching characteristics, such as etch rate, selectivity over photoresist, sidewall surfaces of patterned metal lines, and bottom residues, were investigated. After pattern density dependent variations of etching characteristics were illuminated under the fixed plasma activation parameters, the parameters such as total pressure or total feed gas flow rate were varied in order to find the basic rule for alleviating the pattern density dependent variation of etching characteristics.

Etch rate of aluminum and selectivity over photoresist were measured with a step-height measurement instrument Profiler P20HTM from Tencor. Three step-height measurements (before etch, after etch, and after strip) were made on the wafers with directly photoresist patterned aluminum alloy film and nine points per wafer were measured. Profiles of patterned metal lines and bottom residues were inspected with in-line scanning electron microscopes, JWS-7700TM from JEOL and S-8820TM from Hitachi.

III. RESULTS AND DISCUSSION

A. Etching performances related to the global pattern density

Table I shows the global pattern densities of each metal layer for various 0.25 μ m technology logic devices. Most metal layers have a pattern density ranging from 25% up to 40%, and a few layers have a pattern density well beyond this typical range. When the layers with a nontypical pattern density were etched using plasma activation parameters optimized for typical layers, unusual etching performance was observed. In the case of a metal-2 layer of product-C (with pattern density 56.5%), end point detection time decreased to half of that monitored for the typical pattern density. Etching

TABLE II. Samples prepared by controlling the exposure step in the lithography process.

Pattern density of layer	Normal exposed shot	Open exposed shot	Close exposed shot
15.2%	29 ea	29 ea	0 ea
30.4%	58 ea	0 ea	0 ea
65.2%	29 ea	0 ea	29 ea
89.2%	9 ea	0 ea	49 ea

Note: pattern density of open exposed shot: 0%; normal exposed shot: 30.4%; and close exposed shot: 100%.



FIG. 1. Pattern density dependence of aluminum (and photoresist) etch rate and consequential variation of end point detection time.

a metal layer with lower pattern density results in degraded performance. For example, when the metal-5 layer of product-B (with pattern density 18.9%) was etched, lots of bottom residues and sidewall attacks were observed. Considering that all of these layers have the same design rule, it can be concluded that the global pattern density of the etched layer strongly affects the etching environment and the resultant etching performance.

B. Global pattern density effects on etch rate and selectivity

The pattern density dependent etching performance described in the prior section seems to be closely related to the variation of aluminum etch rate. In order to investigate the pattern density effects systematically, samples with the same layout but with different pattern density were prepared and the etch rate of aluminum (and photoresist) was measured. Figure 1 shows this pattern density dependence of aluminum (and photoresist) etch rate and consequential variation of end point detection time when the samples listed in Table II were etched using the same plasma activation parameters. The aluminum etch rate shows an almost linear relationship to the global pattern density. The etch rate of photoresist also demonstrates a slight increase; however, its increasing tendency is much slower than the aluminum etch rate. The end point detection time is inversely related to the pattern density; end point detection time decreases when the pattern density becomes high, while it increases when the pattern density becomes low. The increase of end point detection time implies that the sidewall of a predefined metal line is exposed to the aggressive plasma longer. As a result, the metal sidewall is more susceptible to physical or chemical attack by plasma elements, which was observed in the metal-5 layer of product-B (with a pattern density 18.9%). Etch rate trends of aluminum and photoresist shown in Fig. 1 imply the process margin such as aluminum to photoresist selectivity or margin of over etch time may be lessened when the pattern density of the etched layer is decreased.



FIG. 2. Upper limits of over etch time for each metal layer of devices listed in Table I. Data in this graph is extracted for the base parameters described in the text (total pressure: 180 mTorr; feed gas flow rate: 140 sccm).

Based on the results in Fig. 1, the upper limits of over etch time were extracted for each layer of the device listed in Table I. As is shown in Fig. 2, metal layers with lower pattern density have a smaller margin of over etch time than those with higher pattern density. Sufficiency of over etch time implies a lower possibility of problematic etch performance than deficiency of over etch time, in the sense of robustness of patterned metal lines and bottom residues, as described in the prior section.

C. Alleviation of global pattern density effects

The pattern density dependences of etching characteristics described in the prior sections show that global pattern density must be considered when the plasma activation parameters are optimized. The dependence of etch rate on the amount of etchable surface (that is, global pattern density for a single-wafer etcher) was also reported in the literature, where the phenomena were usually explained in terms of loading effects.^{6,7} Some mathematical models were also developed to describe the procedures adopted to reduce the loading effects.^{6,8,9} However, their analyses seem to be insufficient in describing the phenomena related to the global pattern density effects.

We speculate that the pattern density dependent etching characteristics are caused by variation of the etching environment, which is solely determined by effective etchants density and their effective residence time. When all the other parameters are fixed, the etch rate of aluminum is determined by the effective etchants density, which is defined as etchants density within the reaction chamber divided by total etched area. Likewise, when all the other parameters are also fixed, the etching environment is determined by the ratio of raw etchants and etch by-products. The ratio of raw etchants and etch by-products is determined by the residence time of each etchant within the chamber divided by total etched area, which we define as effective residence time. Thus we believe that pattern density effects can be mitigated by keeping both the effective etchants density and effective residence time independent of the pattern density. When all the other acti-

Pattern density	Effective pressure/	Optimized pressure/
(etched area)	effective flow rate	optimized flow rate
15.2% (84.8%)	212 mTorr/165 sccm	219 mTorr/171 sccm
30.4% (69.6%)	259 mTorr/201 sccm	180 mTorr/140 sccm
65.2% (34.8%)	517 mTorr/402 sccm	90 mTorr/70 sccm

Note: effective pressure \equiv (180 mTorr)/(etched area); effective flow rate \equiv (140 sccm)/(etched area); optimized pressure \equiv (180 mTorr)×(etched area)/69.6; and optimized flow rate \equiv (140 sccm)×(etched area)/69.6.

vation parameters are fixed, the total chamber pressure and the feed gas flow rate together determine the etchant density and the residence time of each etchant within the reaction chamber.¹⁰ Thus it may be possible to eliminate the pattern density effects by controlling both the total pressure and the feed gas flow rate in such a way that these two effective values are constant regardless of the pattern density.

Table III shows the calculated effective pressure and effective flow rate for the pattern density 15.2%, 30.4%, and 65.2%. The effective parameters are calculated by dividing the pressure (or flow rate) by etched area, where both parameters are optimized for the pattern density 30.4%. Variation of the effective parameters according to the pattern density implies that the pressure and the flow rate optimized for the pattern density 30.4% do not always guarantee the best etch performance for other pattern densities. Therefore, the pressure and the flow rate should be reoptimized in such a way that the effective parameters for each pattern density are the same as those for the pattern density 30.4%. The optimized parameters for each pattern density also appear on the right column of Table III, which are calculated following the aforementioned speculation.

After the optimized parameters for each pattern density were calculated we checked the etch rates of aluminum (and photoresist) again for the each pattern density. As shown in



FIG. 3. Etch rate of aluminum (and photoresist) vs pattern density. The closed symbols represent the etch rates when the fixed parameters are applied (so the effective values are different). The open symbols represent the etch rates when the optimized parameters are applied in such a way that the effective values are kept constant.



65.2% Pattern Density

FIG. 4. Tilted view scanning electron microscopy photographs of the etched profile and sidewall of patterned metal lines: (a) pattern density 15.2% under fixed conditions, (b) pattern density 15.2% under optimized conditions, (c) pattern density 30.4% under optimized conditions, (d) pattern density 65.2% under fixed conditions, and (e) pattern density 65.2% under optimized conditions.

Fig. 3, the etch rate of aluminum (and photoresist) remains almost the same regardless of the variation of the pattern density of the etched layer under the optimized pressure and the feed gas flow rate.

The pattern density dependent variations of sidewall profile and bottom residue are also greatly reduced when the optimized parameters are applied (Fig. 4). Under the fixed conditions optimized for the pattern density 30.4%, attacks on the sidewalls of patterned metal lines are observed for the pattern density 15.2%, while robust and stable sidewall profiles are observed for other pattern densities. However, under optimized conditions, sidewall attacks of patterned metal lines virtually disappear even in the metal layer with a pattern density of 15.2%.

IV. CONCLUSION

The global pattern density of etched layers may affect the etching environment, which in turn results in a pattern density dependent variation in etching characteristics. The pattern density dependent etching characteristics are caused by the variation of effective etchants density and their effective residence time. Therefore, in order to alleviate the pattern density effects, plasma activation parameters should be optimized in such a way that these two effective values are independent of the global pattern density. Based on this speculation, we adjusted total pressure and feed gas flow rate based on global pattern density and were able to achieve stable etching performance independent of the global pattern density.

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