SINGLE WAFER PLASMA ETCHING OF ALUMINUM

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ABSTRACT

The processing conditions required for single wafer etching of aluminum films have been evaluated for the single wafer Tegal 702 system. This system has been specifically designed for aluminum etching. Etch rates up to 5000Å/min have been obtained on patterned wafers with high anisotropy and 20:1 selectivity over oxide. It was necessary to pretreat the photoresist prior to the etch to avoid severe resist damage. A CF_4 plasma pretreatment (PRIST) was found successful and is described.

1. INTRODUCTION

The use of plasma etching to define aluminum interconnects in the fabrication of integrated circuits is superior to wet etching because plasma etching can be anisotropic whereas wet etching cannot. In addition, the fine control inherent in single wafer processing provides some distinct advantages over batch processing. Two problems in the etching of aluminum films in a batch reactor can be solved by the one-wafer-at-a-time process. These are (1) the non-uniformity of film thickness and structure as a result of the deposition technique and (2) the non-uniform clearing of native surface oxides in a batch reactor.

The aluminum etching process itself consists of accomplishing four tasks during the etch: (1) removal of the native surface oxide from the aluminum, (2) uniform anisotropic etching with endpoint detection, (3) prevention of linewidth changes due to undercutting or photoresist damage during the etch, and (4) passivation of the wafer after the etch to prevent corrosion of the aluminum lines. Photoresist stripping is yet another consideration which can impact the etching process. Chapman (1980) has discussed some of these tasks in detail.

Unique safety problems occur in aluminum etching because carbon tetrachloride is used as an etchant. These are exposure to CCl_4 before processing and exposure to etching by-products. It is relatively easy to prevent operator exposure to CCl_4 by the proper design of a liquid delivery system. The more important safety problems are associated with the products of the CCl_4 plasma. These products include $AlCl_3$, HCl, and higher molecular weight chlorocarbons. Such materials are of unknown toxicity and must be treated with extreme caution. All are likely to be present on the reactor walls. Phosgene ($COCl_2$) and HCl have been measured in the vacuum pump effluent of an aluminum etcher (Bielle, 1981). The use of an oil filtration system with a neutralizing filter is expected to increase vacuum pump life and to reduce the toxicity of used pump oil. These safety problems can be reduced by proper hardware design and by developing proper maintenance procedures.

Apparatus: The etching system used consists of a gas mixing system which uses mass flow controllers to control flowrates, a Tegal 702 planar reactor, voltage, current and power probes, and a monochromator for optical emission analysis. The reactor is an 8-1/4" I.D. aluminum chamber with a shower-head gas inlet and outlet manifold. This manifold design decreases radial concentration gradients in the reactor and maintains good across-the-wafer etch uniformity. The lower electrode is RF powered and supports the wafer. The reactor has an area ratio of 4:1, and an electrode gap of 4.5 cm. Because the reactor is constructed of aluminum, all surfaces in contact with the plasma are passivated with an anodized Al_2O_3 coating. The chamber is designed to etch wafers up to 5 inches in diameter. For reasons discussed below, an atmospheric pressure dry nitrogen purged load lock was used to prevent room air from coming into contact with the reactor and wafers.

2. RESULTS AND DISCUSSION

Photoresist Pretreatment: All of the results discussed below were obtained with AZ1350J positive photoresist. A limited number of experiments with Hunt 204 positive resist showed similar behavior.

To maintain linewidth integrity during the etch, it was found necessary to pretreat the positive photoresist. A short hardbake (120°C for 20 min) permits etching at relatively low rates (up to 1000Å/min) without resist damage. However, this short bake is inadequate at higher etch rates. Figure 1a illustrates the photoresist damage which occurs with inadequately baked resist. The resist appears foamed and swollen. Small spaces are bridged because of the swelling. With a longer hardbake, this damage does not occur. However, the time required for this hardbake is greater than one hour if the bake temperature is kept below the glass transition temperature of the photoresist (125°C). The minimum bake times which prevent the type of resist damage shown in Figure 1a are listed in Table I.

Aluminum chloride, the volatile etch product, is one of the reactants responsible for the damage shown in Figure 1a. This is evident from the observation that CCl_4 can be used to plasma etch polysilicon without such damage. It is of interest to consider which component (or components) of the photoresist is responsible for the damage, and what the long hard bake actually does to this component.

The photochemistry of AZ1350J has been detailed by Pacansky and Lyerla (1979) Aspects of its thermochemistry are discussed by Shaw, et al (1977), and Dill and Shaw (1977). The resist system consists of a photoactive component (a naphthoquinone diazide), a Novolak-type phenolic resin, and a solvent system which consists of 70% cellosolve acetate (2-ethoxy ethyl acetate), 11% n-butyl acetate and 19% xylenes. The cellosolve acetate is the least volatile component of the solvent system. Show, et al have shown that the thermal desorption of the cellosolve acetate from a resist film is a complex process which involves up to three different binding energy states of this material in the film. They have also shown that the cellosolve acetate is driven off at temperatures lower than those required to thermally decompose the photoactive component. They measured the activation energy of the thermal decomposition of the diazide and found it to be 33 Kcal/mole in the photoresist film.

The data listed in Table I can be used to evaluate the activation energy of the hard bake process required to prevent resist damage during aluminum etching. The reciprocal of the minimum bake time is proportioned to the rate of the unknown process which occurs during the bake. An Arrhenius plot of this rate vs. the reciprocal of the bake temperature gives a straight line with a slope fo 28.4 Kcal/mole. This agreement with Shaw's value of 33Kcal/mole may simply be fortuitous but it suggests that the role of the hardbake involves the thermal decomposition of the diazide and not simply the removal of residual cellosolve acetate.

A number of other experiments were performed which also suggest that the purpose of the hardbake involves the decomposition of the photoactive component of the resist. Hard baked wafers that were soaked in cellosolve acetate for 36 hours at room temperature and dried for two minutes at 130°C could be etched without resist damage. Some photoresist samples supplied by the Hunt Chemical Corporation were formulated with dioxane, methyl cellosolve, and cyclohexanone instead of cellosolve acetate. All of these samples showed damage similar to that shown in Figure 1a if they were not hard baked. However, the minimum hardbake times were not evaluated for these materials. Hard bakes in dry nitrogen do not result in resist which does not foam during etching whereas hard bakes in room air do.

Attempts to track the baking reactions with transmission infrared spectroscopy were inconclusive. The transmission spectra of resist films spun on AgCl windows showed no changes after 15 minutes at 115°C. Consequently, the exact details of what occurs in the resist during the hard bake are unknown.

One method of photoresist pretreatment that permits higher hard bake temperatures without resist flow has been reported by Ma (1980). This process, called Plasma Resist Image Stabilization Technique (PRIST), consists of a short plasma pretreatment in fluorine containing plasma. This pretreatment permits bakes at temperatures as high as 280°C without photoresist flow. However, if the wafers are plasma treated for too long, excessive wrinkling occurs on the photoresist surfaces. Large wrinkles are not desirable because they are replicated on the aluminum sidewalls. This pretreatment process has been optimized in a Tegal 421 barrel reactor. The optimization involves balancing a strong loading effect against minimizing wrinkle size and maintaining good throughput. Optimal conditions are: 8 each 4-inch wafers, 0.4 torr of 25% CF_4, 75% N_2, 50 watts CW power for 6 min at 25°C.

Figures 1b and 1c show how resist profiles can be controlled with this treatment. In Figure 1b the unacceptable flow which occurs when an untreated wafer is hard baked is shown. This flow results in smaller spaces and sloping resist sidewalls. The PRIST-treated wafer is shown in Figure 1c. The wrinkling which appears on the resist surface occurs during the bake and is apparently caused by solvent loss through the fluorinated surface of the treated wafer. The magnitude of the wrinkling can be minimized by treating the wafers for the shortest possible time (depending on load) in the CF_4/N_2 plasma. Results similar to those shown in Figure 3c were obtained with SF_6 and SF_6/Ar mixtures as CF_4.

Oxide Removal: The removal of the native oxide from the aluminum surface is a necessary first step in the etching process. Heiman, et al (1980) have shown that in a low pressure Cl_2/Ar plasma, Al_2O_3 is removed by physical sputtering at room temperature. BCl_3 has been reported to etch oxide about six times faster than CCl_4 and is a potential dopant (Chapman, 1980). Since CCl_4 can remove the oxide at a rate of a few hundred angstroms per minute in the reactor used in this work, it was not necessary to use other gases for this step of the process.

One major difficulty in reproducibly etching a set of identical aluminum wafers is that the oxide etch times can vary considerably from wafer to wafer. This variable oxide removal time can result from the introduction of water vapor into the chamber during loading and unloading of wafers. The amount of time required to remove the native oxide from a wafer varies with the concentration of water vapor in contact with the reactor and the duration of exposure to this water vapor. Measurements here have shown that this time can vary from 15s for a dry reactor to 2700s (45 min.) for a reactor exposed to humid air overnight. A load lock is necessary to exclude ambient moisture from the reactor.

The criteria used to specify the required humidity control in the load lock are illustrated in Figure 2. A nitrogen purged interlock was quantitatively humidified and the reactor was exposed to this humid gas for 2.0 minutes. After this exposure, a wafer was etched and the time required to clear the oxide was measured. The error bars in the figure represent the scatter of five such experiments at each water vapor concentration. It is clear from the figure that the time required to remove the oxide varies linearly with humidity (in the range shown) and that the oxide removal time can be kept under 30s if the water concentration is less than 600ppm (dewpoint = -25°C; relative humidity at 22°C = 2.3%). This humidity control can be easily accomplished with an atmospheric pressure dry N_2-purged load lock.

Aluminum Etching: Once the surface oxide is removed from the wafer, the aluminum etching begins. The etch process can be monitored by observing the emission spectra of the plasma. Both the oxide removal and the aluminum endpoint can be monitored with a monochromator or a Type 2 CdS photodiode which has a maximum sensitivity at 515 nm. Figure 3 shows the emission spectrum of the plasma during the aluminum etch (2a) and at endpoint (3b). These spectra are similar to those reported by Curtis (1980) but the continuum from 350 to 550 nm is stronger here. Because the photocell spectral response increases linearly with wavelength in the wavelength region shown, the long wavelength region of the spectra is emphasized in the photocell output signal. The decrease in the above-mentioned continuum is responsible for most of the drop-off at endpoint that is shown in Fig. 2(c).

Etch rates were found to depend on gas composition, flowrate, pressure and power. Except for cases in which the etch rate was limited by the flowrate of CCl_4, the etch rate always increased linearly with net power. This was true for both pulsed and CW power. The etch rate variation with pressure is shown in Figure 4. The upper curve represents data taken by throttling the pump to change the pressure. The space time (reactor volume/volumetric flowrate) varied from 0.73 ms at 100 µm to 2.6 ms at 360 µm. The etch rate is seen to increase, remain constant from 140-260 µm, and then decrease. The lower curve in Figure 4 represents the etch rate variation which occurs if the pressure is varied by increasing the gas flowrate from 20 sccm at 100 µm to 125 sccm at 260 µm. This method of varying the pressure keeps the space time nearly constant at 0.7 ms. The curves illustrate two important points about the process. First, pump speed is a very important variable. Second, the pressure control required to keep the etch rate high is not too critical; the etch rate is virtually constant between 150 and 250 µm.

Etch Uniformity: Across the wafer etch uniformity was measured by etching wafers to 75% completion, stripping them, and measuring the amount of aluminum removed with a Dektak. For 3" wafers, the etch rate varies by less than ±5% inside the area bounded by a 2.6" diameter circle. The etch rate at the edge of the wafer is typically 10% higher than the mean etch rate. The etch rate varied with radial position only and not with angular orientation on the wafer. The uniformity of the etch increases with pressure in the 150 to 250 um range. The addition of 25% helium to the feed also increases the uniformity of the etch without decreasing the etch rate.

Selectivity: The selectivity of aluminum over SiO_2 was greater than 20:1 for all conditions examined. Photoresist selectivity varies with power and the resist to aluminum etch rate ratio varies from 10:1 at low power to 1.5:1 at high power. As mentioned earlier, the aluminum etch rate increases linearly with power and the ratio of the aluminum etch rate to the resist etch rate decreases with increasing power. Because the photoresist is etched anisotropically, little linewidth change occurs, even at an etch rate ratio of 1.5:1. A typical etch is illustrated in Figure 5 which shows (a) the PRIST treated resist, (b) the etched structure, and (c) the stripped aluminum lines. The underlying material is SiO_2.

Photoresist Stripping: Dry stripping of photoresist after aluminum etching is not always possible. After stripping, a residue that can be a few thousand angstroms thick often remains. Mattox and Tracy (1981) have Auger depth-profiled this residue and found that its surface is covered with aluminum oxide. This non-volatile oxide passivates the surface and stops the strip. The source of this aluminum is aluminum chloride which was trapped in the resist during the etch. Another common occurrence is a "picket fence" residue caused by accumulation of aluminum on the resist sidewalls. In this situation a thin, fence-like residue remains on the edges of the aluminum lines.

In Figure 5c, a dry-stripped line is shown. This wafer had been PRIST pretreated before etching at 4500Å/min and was stripped in a Tegal 415 barrel stripper. In order to dry strip the resist in a plasma stripper, the post-PRIST bake conditions must be carefully controlled. Failure to do so results in incomplete stripping of the resist. The reasons for this are not yet understood. Damaged resist such as that shown in Figure 1a has never been completely dry-stripped.

3. SUMMARY

This paper summarizes the aluminum etching process in a Tegal 702 in-line reactor and discusses some aspects of the photoresist damage that can occur during the etch. Details of the humidity control of the load lock, etch characteristics and the required photoresist pretreatment and wafer post-treatments are described. Work is continuing on modifying the reactor geometry to increase the etch rate, on minimizing resist wrinkling by using an in-line CF_4 pretreat and on developing a better understanding of what variables affect the photoresist stripping after the etch.

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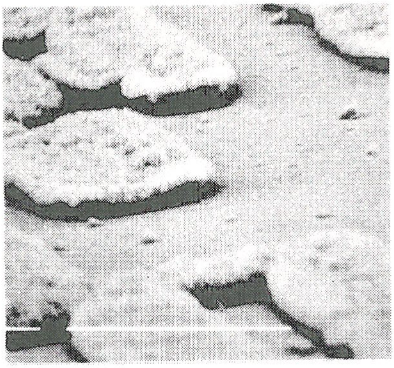
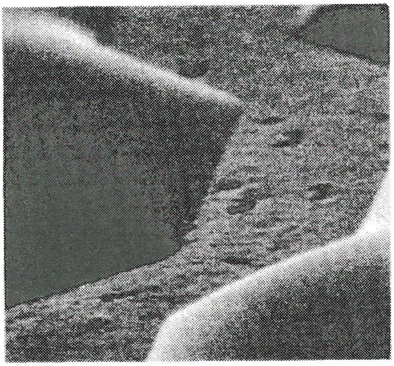
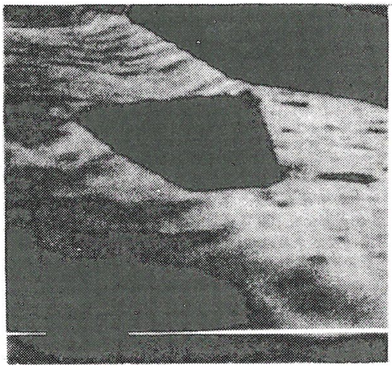


(a) UNTREATED AZ1350J
5000 A/min ETCH
5000X



(b) FLOWED RESIST
200 °C for 20 min.
10000X



(c) PRIST TREATED RESIST
200°C for 20 min.
10000X

FIGURE 1: PHOTORESIST PROFILES FOR ETCHED, BAKED AND PRIST TREATED AZ1350J

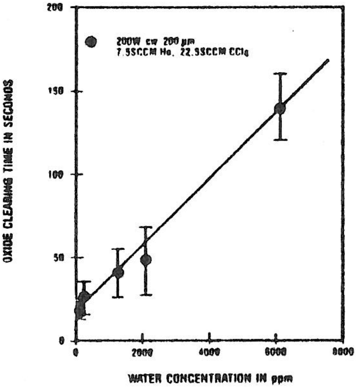


FIGURE 2 OXIDE CLEARING TIME VS HUMIDITY IN LOADLOCK

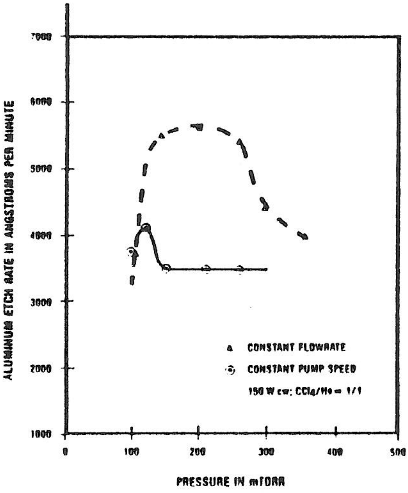
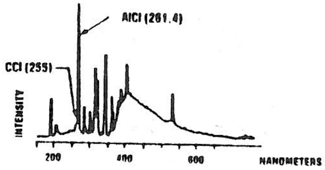
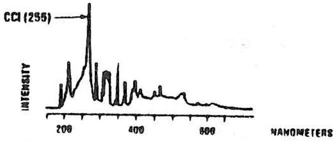


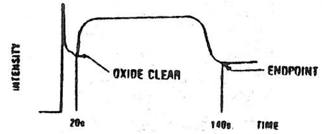
FIGURE 4 ALUMINUM ETCH RATE VS PRESSURE FOR CONSTANT FLOWRATE AND CONSTANT PUMP SPEED



(a) EMISSION SPECTRUM DURING THE ETCH



(b) EMISSION SPECTRUM AT ENDPOINT



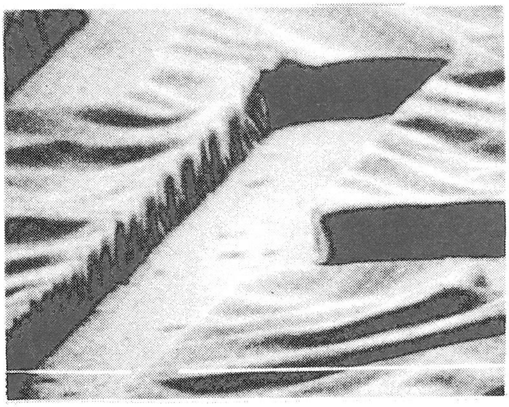
(c) PHOTODIODE OUTPUT DURING THE ETCH

FIGURE 3 EMISSION SPECTRA AND ENDPOINT CURVE FOR ALUMINUM ETCHING

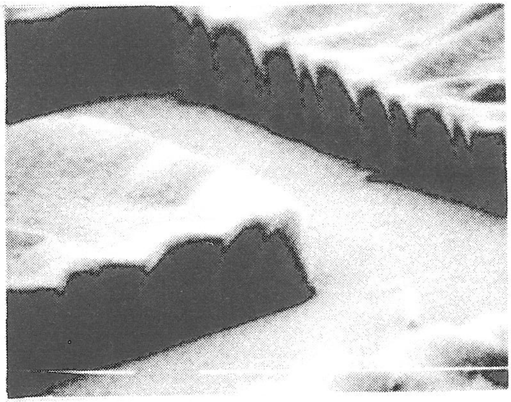
MINIMUM BAKE TIMES REQUIRED TO PREVENT PHOTORESIST FOAMING DURING ALUMINUM ETCHING

BAKE TEMPERATURE (°C)	MINIMUM BAKE TIME (minutes)
118	330
137	35- 60
150	15- 18

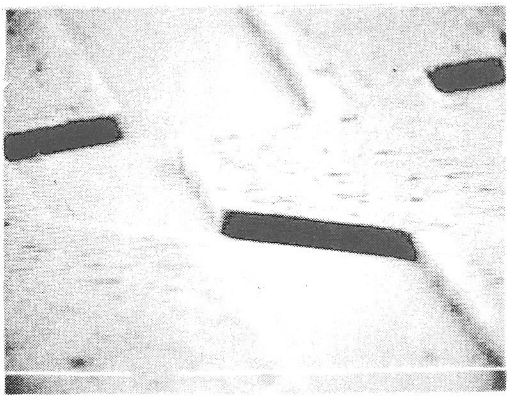
TABLE 1



(a) PRIST TREATED
AZ1350J



(b) ETCHED, NOT STRIPPED



(c) STRIPPED

FIGURE 5: SEM PHOTOS OF TREATED, ETCHED, AND STRIPPED ALUMINUM WAFERS.