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Plasma Etching of Aluminum Metallizations for Ultralarge Scale Integrated Circuits

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ABSTRACT

The metallizations which interconnect devices formed on silicon wafers have evolved from a single level of "broad" lines of aluminum to very narrow lines ($<1\ \mu\text{m}$ in width), often more than two levels per chip. Whereas broad lines may be satisfactorily defined by solution or "wet" etching, narrow lines must be defined by plasma etching to maintain dimensional and profile control. Moreover, simple aluminum metallization has become complex, generally consisting of a composite of barrier and antireflecting layers which sandwich the aluminum film. In addition, the aluminum film itself is probably "doped" with silicon and copper for solid solubility and electromigration considerations. Consequently, plasma etching of "aluminum" has become more complicated in the last few years. In this article, the issues confronting the process engineer in attempting to implement reliable metal etching processes are reviewed, emphasizing metallization layers employed for very advanced complementary metal oxide semiconductor integrated circuits.

Although various metallizations (*e.g.*, Ti-Pd-Au and Ti-Pt-Au)¹ have been used to interconnect devices of early integrated circuits and other materials such as metal polycides¹ and tungsten² have been used as well, aluminum has remained the overwhelming material of choice for this function. This is because aluminum has low resistivity ($<3\ \mu\Omega\text{-cm}$ at 20°C , which translates into low circuit resistance) and, despite its relatively low melting point (660°C),³ is compatible with other materials used in chip fabrication (*e.g.*, it adheres well to SiO_2 , may be readily etched selectively to SiO_2 , and acts as an etch stop for vias etched through SiO_2). Overviews of the evolution of plasma etching of aluminum and other metals for integrated circuit (IC) applications, as IC technology has unfolded, are presented in other publications (*e.g.*, Ref. 1, 4-9).

Typical Film Structures

As devices and features have become smaller and chips have become larger, aluminum has continued to be the primary interconnecting material. However, the nature of aluminum metallization has changed rather dramatically. For example, junction spiking problems¹ which are a consequence of the solubility of silicon (from source/drain or polycrystalline silicon lines) in aluminum at high-temperature processing steps were initially circumvented by the addition of a few percent of silicon to sputtered aluminum.¹⁰ Since aluminum is usually etched with chlorine containing plasmas, the addition of a small amount of silicon has no significant effect on the plasma etching of aluminum because Si-Cl compounds are volatile under these processing conditions (*e.g.*, SiCl_4 , boiling point = 58°C ; AlCl_3 , sublimation point = 178°C).³ A more satisfactory solution to this solubility problem has been devised by the insertion of a diffusion barrier metal layer between aluminum and the silicon substrate (see Fig. 1) which prevents migration of silicon into aluminum during normal thermal cycling¹¹⁻¹³ during fabrication. To date, the most effective barrier layers to be employed in the IC industry are Ti-W and TiN. However, satisfactory etching of these underlying layers requires process conditions which are different from those used for etching a single film of aluminum (or its Si or Cu containing alloys).

In contrast to the addition of Si to Al, the inclusion of Cu in aluminum to inhibit electromigration¹⁴ offers a more difficult plasma etching challenge.¹⁵ First, the volatility of Cu-Cl_x compounds (or any copper halide) is very low under

suitable processing conditions (the boiling point of CuCl_2 at 1 atm is 993°C ;³ second, the low volatility of Cu-Cl_x compounds results in an enrichment of the film in Cu (as a chloride) as the more volatile Al-Cl_x species are removed by etching; third, the combination of Cu enrichment and elevated wafer temperature ($>200^\circ\text{C}$) during deposition and/or etching leads to the segregation of Cu as CuAl_2 at metal grain boundaries; and fourth, the concentration of Cu as CuAl_2 may result in accelerated corrosion of aluminum in the presence of chlorine and moisture.¹⁵⁻¹⁷ Clearly, these properties of Al-Cu make (i) plasma etching of the bulk film, (ii) removal of metallic residue, and (iii) postetch processing more difficult than in the absence of copper.

Finally, to assist in forming well-resolved, fine-line circuit images in photoresist that are free of "necking" and "notching," a thin metallic antireflective layer (ARL) may be deposited over the bulk aluminum layer as the final step of a multistep metal deposition process. Several materials have been shown to be effective in significantly reducing the scattering of imaging light from the highly reflective polycrystalline aluminum surface, including Ti-W, TiN, and amorphous silicon.^{18,19} In addition, these layers suppress hillock growth¹⁸ along the upper surfaces of aluminum lines and may also prevent electromigration failure²⁰ within the lines during operation of the circuit. However, as in the case of barrier metallization, the use of a metallic overlayer complicates the metal etching task. These complications are not only due to the requirements of etching a narrow stack of dissimilar materials (see Fig. 1) with vertical profiles and of obtaining a dielectric surface free of metallic residue, but also for the need to minimize the loss of photoresist so that the tops of the metal lines are protected (for reliability considerations) during the final stages of etching.

As a consequence of these circuit reliability and processing requirements, a typical metal level of an advanced complementary metal oxide semiconductor (CMOS) IC has a film structure similar to that shown in Fig. 1. The aluminum layer which probably contains 0.5 to 4 atomic percent (a/o) copper (and possibly $\sim 1\%$ Si also) is $\sim 0.5\ \mu\text{m}$ in thickness for first and second levels of metal of a three-level metal circuit and is sandwiched between $0.1\text{--}0.2\ \mu\text{m}$ of underlying barrier layer metal (Ti-W, TiN, ...) and $0.04\text{--}0.1\ \mu\text{m}$ of overlying ARL metal, a total metal thickness of $\sim 0.7\ \mu\text{m}$. The third level of metal (used in most advanced logic chips) is generally composed of a thicker aluminum layer, $\sim 1.0\ \mu\text{m}$, but virtually the same ARL and barrier

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Composite Metallization for Advanced Circuits

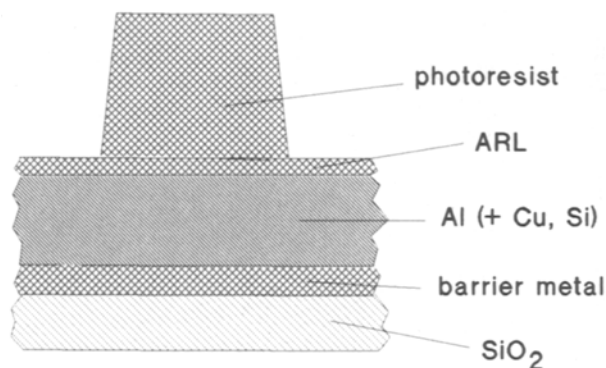


Fig. 1. Schematic representation of a composite metal layer, illustrating a top antireflective layer (ARL), the bulk aluminum layer, and the bottom barrier metal layer.

layer thicknesses as used for the first and second levels of metal (see Fig. 2 and 3).

Photoresist Issues

Although achieving adequate etch selectivity to photoresist during aluminum etching has always been challenging, it is even more challenging for very advanced circuits with submicron metal lines and spaces. This is because optical steppers with the resolution needed to define submicron features at a small pitch (e.g., $<2\ \mu\text{m}$) have high numerical aperture lenses that concomitantly have shallow depths of focus. Hence, transferring precise images of levels of large circuits from a mask plate into the photoresist on a large wafer which is not perfectly flat requires the use of thin photoresist.^{21,22} For features at a small pitch, this thickness may be only 1.0–1.5 μm , a reduction in thickness of more than 0.25 μm from that used for ICs with larger metal pitches. In contrast, for a third level of metal, since the pitch is usually larger than that at the lower levels, images may be satisfactorily resolved in thicker photoresist (e.g., $\sim 2\ \mu\text{m}$ in thickness), thereby providing greater etching process latitude.

To insure adequate protection of the metal lines during overetching, a photoresist thickness of $\sim 0.3\ \mu\text{m}$ is probably necessary at the end of etching, although this estimate varies with the degree of planarity of the underlying surface. To retain this thickness, an etch rate selectivity of $\sim 1.5:1$ (composite metal:photoresist) is required to etch the film structure shown in Fig. 1 with an overetch of 50% (which varies with topography as well as with the concentration and the distribution of copper in the film).^{16,17} Al-

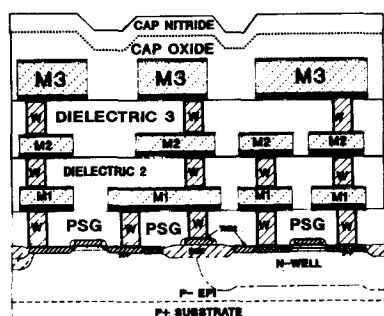
SUB-HALF MICRON INTERCONNECT STRUCTURE
(Three-Level Metal With W-Plug)

Fig. 2. Drawing of a portion of an advanced integrated circuit, showing three levels of composite metallization (e.g., see Fig. 1) which are interconnected by tungsten plugs.

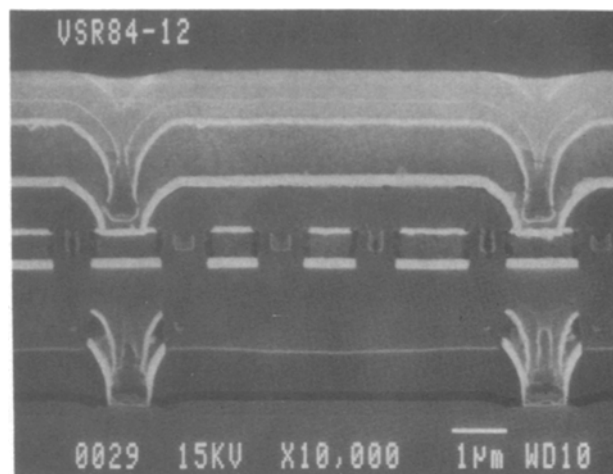


Fig. 3. Scanning electron micrograph of part of an advanced memory circuit, exhibiting three levels of composite metallization which consist of Al-Cu sandwiched between layers of Ti-W. The Ti-W layers are brighter than are the Al-Cu layers.

though this may seem to be a low etch ratio when compared to that for other plasma etching processes, it is typical of results obtained in IC production today and is unlikely to improve appreciably in the immediate future. For chips with high copper content in aluminum and perhaps also high aluminum deposition temperature ($\sim 400^\circ\text{C}$), the overetch requirement is usually greater than 50%, possibly greater than 80%. An overetch of this magnitude with thin photoresist may necessitate the use of an inorganic "hard mask" in conjunction with the conventional organic photoresist mask to offset the etching limitations with thin photoresist which are imposed by ICs with submicron lines and spaces.

Etching Requirements

A suitable metal etching process must fulfill several criteria: (i) form vertical or slightly sloped profiles of the composite metal structure to insure conformal step coverage of the interlevel SiO_2 layer that covers the metal lines, (ii) maintain cross-sectional dimensional control for circuit performance and reliability, (iii) remove residual "stringers" to prevent short circuiting between lines, and (iv) possess adequate etch selectivity to photoresist to prevent attack of metal lines at locations where photoresist is thin due to variations in topography. Since the processing is carried out with chlorine-based gas mixtures (except perhaps in etching some barrier layers as discussed below) and at low substrate bias voltages,²³ selectivity with respect to underlying SiO_2 is high ($\sim 10:1$) and thus easy to achieve. Fulfillment of these goals may be assessed by examining (i) scanning electron micrographs (SEMs) for profile and dimensional information and (ii) electrical test results for high leakage current (due to metallic residue) and high resistance (due to open circuits resulting from inadequate step coverage during metal deposition or postetch corrosion).

Plasma Process Gases

Unlike most silicon-based materials which are readily etched with fluorine-based plasmas, aluminum forms a nonvolatile polymeric film (AlF_x) upon exposure to fluorine containing plasmas. The reaction between aluminum free of its native oxide and molecular and atomic chlorine, however, is spontaneous^{6,9,23-25} and leads to the formation of Al-Cl compounds on the aluminum surface which sublime as AlCl_3 under plasma processing conditions. Thus, as illustrated in Table I, a variety of chlorine containing gas mixtures has been examined for this processing, since the desired etch product is AlCl_3 .

Table I. Plasma gas mixtures for bulk aluminum etching.

Gas mixture	Ref.
CCl ₄ /Ar	5, 16
Cl ₂ /Ar	24, 25
CCl ₄ /Cl ₂	6, 9, 26
BCl ₃ /Cl ₂	6, 9, 27, 28
BBr ₃	29
BBr ₃ /Br ₂	28, 29
BBr ₃ /Cl ₂	27
BCl ₃ /Cl ₂ /CHF ₃	19, 30
BCl ₃ /Cl ₂ /CF ₄	31
SiCl ₄	32

Although Cl₂ alone readily etches clean aluminum ($E_a \sim 0.2$ eV), it does not attack aluminum oxide unless the surface is subjected to ion bombardment.⁶ Originally, it was shown that although a CCl₄ plasma (with ion bombardment) provides a sufficient source of chlorine to etch aluminum and its native oxide, it also reacts with atmospheric moisture and O₂ in unloadlocked chambers. These competing reactions between Al₂O₃ and atmospheric gases led to irreproducible processing.³³ On the other hand, BCl₃ is a strong Lewis acid³⁴ and apparently reacts preferentially with H₂O and O₂ contaminants in the process chamber, thereby affording reproducible etching when added to Cl₂.⁶ As a result, plasmas based upon mixtures of BCl₃ and Cl₂ have become the basis for aluminum etching in the IC industry today, even though systems now use loadlock chambers to isolate the etching chamber from atmospheric contaminants. In addition to the processing reason cited above, BCl₃ mixtures have been chosen over CCl₄ mixtures because of health and environmental hazards associated with the use of CCl₄ and other chlorocarbons.

As the need to define submicron lines and spaces without undercutting of the photoresist mask has arisen, polymerizing agents such as CHF₃ or CF₄ have been added to BCl₃/Cl₂ plasmas to "passivate" aluminum sidewalls during etching. The accepted mechanism for this sidewall passivation is by the formation of carbonaceous polymers from species in the plasma and from photoresist which, in turn, inhibit etching on aluminum surfaces that are not subjected to ion bombardment from the plasma (*i.e.*, metal sidewalls).^{19,30} Interestingly, with a BCl₃/Cl₂/CHF₃ plasma, these passivating films are reported to contain carbon and chlorine only but not fluorine,³⁰ despite the sidewall etch protection which results upon fluorocarbon addition to this gas mixture.

As noted above, the two most common barrier metals used in the IC industry are Ti-W [30 atomic percent (a/o) Ti and 70 a/o W]³⁵ and TiN (which is essentially stoichiometric).³⁶ Both films are formed by sputtering. As shown in Table II, the Ti-W film may be etched with either chlorine or fluorine containing plasmas, although fluorine-rich plasmas may lead to undercutting. TiN etches readily in chlorine containing plasmas, in much the same manner as does bulk aluminum. Thus, the use of TiN may afford somewhat simpler processing and potentially lower SiO₂ loss during overetching with a chlorine-based plasma than does the etching of either film with a fluorine-based plasma. Since the dielectric layers for ULSI circuits must be planarized to accommodate high resolution steppers (see above), elimination of metallic residue and stringers is more easily achieved than with circuits with nonplanar topography. Finally, as in the etching of aluminum, profile

Table II. Plasma gas mixtures for ARL and barrier layer etching.

Barrier film	Gas mixture	Ref.
Ti-W	CCl ₄ /O ₂	37, 38
Ti-W	SF ₆ , +Ar, N ₂	39
Ti-W	SF ₆ /Cl ₂	40
TiN	CCl ₄ /N ₂	41
TiN	Cl ₂ /Ar	42
TiN	BCl ₃ /Cl ₂ /CHF ₃	43

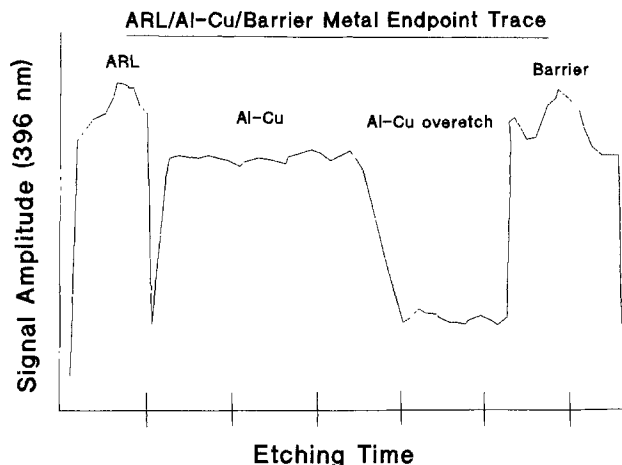


Fig. 4. An endpoint trace obtained during the etching of a composite metal layer consisting of 0.07 μm of Ti-W (=ARL), 0.5 μm of Al-Cu, and 0.15 μm of Ti-W (=barrier). The signal which was monitored as a function of time is the change in intensity of photoemissions from the plasma at 396 ± 5 nm (see text).

control is obtained, in part, by sidewall passivation during etching.

Endpoint Control

A typical endpoint trace obtained from etching a composite metal structure of ~ 0.1 μm Ti-W/0.5 μm Al-Cu/0.2 μm Ti-W on SiO₂ (see Fig. 1) is illustrated in Fig. 4 for a multistep process with a batch reactor. The endpoint trace shows changes in the intensity of photoemissions from excited species in the plasma which occur ~ 400 nm. This spectral region is useful for this composite structure because during etching excited gaseous aluminum, titanium, and tungsten atoms emit light at 396, 400, and 401 nm, respectively.⁴⁴ Hence, by monitoring the changes in intensity of light from the plasma with time in this spectral region, the progress of the etching process may be followed. For example, the declines in intensity in steps 1, 2, and 4 in Fig. 4, respectively, are associated with declines in the plasma of the concentration of excited Ti and W atoms from the top Ti-W layer, Al atoms from the bulk Al-Cu layer, and Ti and W atoms from the bottom Ti-W layer as etching progresses through this film structure. Step 3 is an aluminum overetch step to remove Al-Cu residue (and stringers) and thus produces a lower concentration of Al atoms (and presumably excited Al atoms) in the plasma, as indicated by the reduced intensity of the trace. Since the optical sensor can sample only a small region of the plasma, it is important for process control that the etching be uniform for both batch and single-wafer systems so that the region of the plasma that is sensed during etching is representative of the entire plasma.

Postetch Treatment

After etch, metallic surfaces must be free of residual chlorine (bound in any form to metal layers and photoresist) to prevent corrosion of the etched lines. Several techniques have been devised to remove residual chlorine including plasma passivation, water rinsing, immersion in an aqueous photoresist stripping solution, and O₂ plasma treatment. Of these methods, surface passivation by exposure of the etched wafers to a low ion energy, fluorine-rich plasma immediately after aluminum etching and prior to atmospheric exposure has become very successful. In this process, chlorine is removed from the surface of the wafer and a film of aluminum fluoride forms on the aluminum surface which, under these processing conditions, is unreactive (melting point of Al-F₃ is 1290°C).³ In addition, to insure corrosion resistance after plasma passivation, the remaining photoresist, which may still be impregnated with chlorine and Al-Cl_x compounds, must be stripped after removal of the wafers from the etch chamber. This is

accomplished by "ashing"⁴⁵ of the remaining photoresist in an oxygen plasma. During this process step, an oxide forms on the aluminum surface which helps to prevent corrosion of the aluminum lines.¹⁶ In a conventional barrel reactor, this oxide is 20–30 Å in thickness and is spectroscopically similar to native aluminum oxide.⁴⁶

Experience has shown that after plasma etching of aluminum, it may be necessary to carry out a more elaborate stripping procedure than is required after other plasma etching processes. For example, a three-step stripping process may entail (i) an immersion of the wafers in a hot alkaline solution (apparently) to dissolve Al-Cl_x species embedded in the photoresist that could be oxidized to unreactive Al-O compounds during O₂ plasma stripping, (ii) then stripping in an O₂ plasma, and (iii) completing the process with a second solution wet strip. There are a number of variations of this sequence which are successful in photoresist removal and corrosion prevention.

Particle Contamination

For ULSI circuits, particle contamination, principally from process chambers and processing solutions, is a major factor in limiting the yield of functional chips. Recently, it has been demonstrated^{47–49} that particles are produced in plasmas as part of the phenomena that also produce the reactive species that result in plasma etching. As described in these reports, particles form, grow, and remain suspended in the plasma until the discharge is extinguished. Once the plasma is extinguished these particles fall onto the surfaces of the reactor and the wafer(s). Clearly, minimizing these plasma-produced defects during etching is an intrinsic part of the etching process and adds another dimension to process control.

Generally, particle monitoring is part of reactor characterization which is performed at least once per day. Since reactor cleaning is tedious and time consuming, establishing acceptable particle levels ("specs") for an etching process with a particular metal structure is essential but not straightforward. Meaningful particle specifications can only be determined by experience with the etching system and the material being etched. The data listed in Table III were obtained from four different U.S. manufacturing sites, each of which uses a different Al-Cu film. As might be expected, there may be a trend in these data which suggests that higher concentrations of Cu lead to higher particle levels per wafer. Although these data are confounded by differences in barrier layer materials and plasma processes among the four sites, they may be used as a guide in establishing meaningful particle specifications for process control. With data such as shown in Fig. 5, a schedule for reactor cleaning can be set up to help insure optimal processing.

Summary

The metal etching process sequence for advanced ICs consists of several steps: (i) etching of the top antireflective layer, (ii) etching of any native aluminum oxide (a less stringent concern in current multichamber metal deposition systems which are loadlocked and operate at high vacuum), (iii) etching of bulk aluminum, (iv) overetching of aluminum to eliminate stringers and low volatility etch products of additives such as copper, (v) etching of a bottom barrier metal layer with sufficient overetch to insure stringer removal, (vi) surface passivation to prevent corrosion due to residual chlorine on the wafer, and (vii) photoresist stripping. The addition of copper to inhibit electro-

Table III. Particle levels for different Al-Cu sources.^a

Company	Film	Mean particles/wafer ^b
A	Al-Cu (0.5%)	10
B	Al-Cu (1%)	25
C	Al-Cu (2%)	22
D	Al-Cu (4%)	34

^a Data obtained with Applied Materials 8330 loadlocked systems.

^b 150 mm wafers; particles > 0.5 μm in diameter.

Particle Counts/Wafer vs Time

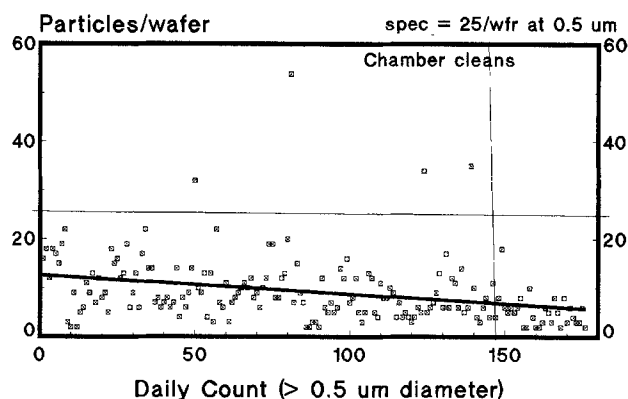


Fig. 5. Plot of number of particles of diameter >0.5 μm collected daily for a loadlocked batch system used to etch a composite Ti-W/Al-Cu/Ti-W metal layer. A small decline in number of particles, from ~12 to ~8/wafer (perhaps due to an etch process change), is shown by the heavy sloped line. An increase in particles/wafer, prior to chamber cleaning (vertical line at day 85 and day 150), indicates that chamber cleaning may be needed in order to maintain the particle count near 10/wafer.

migration presents several etching problems, including (i) removal of low volatility Cu-Cl_x compounds, (ii) potentially higher particle contamination with higher Cu content, and (iii) greater susceptibility to postetch corrosion. In addition, because of the reduced depth of focus with optical steppers with high numerical aperture lenses, thin photoresist must be used to resolve submicron lines and spaces. Since the etch selectivity between photoresist and multilayer metallizations used in advanced ICs is low, it may be necessary to use an inorganic hard mask in conjunction with a thin organic imaging mask to resolve submicron lines and spaces. In general, the processing challenges which have always existed in aluminum etching have become more critical in the ULSI era as the metallization has become more complex and the circuit requirements have become more stringent.

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