"Zero-Undercut" Semi-Additive Copper Patterning – A Breakthrough for Ultrafine-line RDL Lithographic Structures and Precision RF Thinfilm Passives

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Abstract

This paper presents the first demonstration of a "zero-undercut" precision formation of ultrafine-line copper conductor patterns for redistribution layers (RDL) and thin film RF passives. This is accomplished by using a highly-anisotropic and uniform copper plasma-etching process to remove the seed layer with no lateral etching of the copper patterns, unlike what is seen with traditional seed-layer removal by wet-etching. Application of this technical breakthrough for large-area panel processes allows demonstration of precision copper patterns demonstrated, for the first time, on organic laminates with no measurable lateral undercut. Two different plasma chemistries, one pure physical sputter-etching, and the other based upon chemical-physical processes with a hydrogen plasma, were investigated and compared.

Introduction

Integration of high-density memory and logic devices with fine-pitch interconnects is driving unprecedented advances in interconnections with interposers. The current approaches to high-density 2.5D and 3D interposers are either based on extension of organic substrate technologies to form interposers, or on silicon wafers. Traditional organic substrates are limited by coarse-wiring traces due to their poor dimensional and thermal stabilities and by high surface roughness. Low TCE and coreless organic substrates have been shown to improve electrical performance, but are limited in pitch due to their dimensional instability which affects layer-to-layer via-registration and in body size due to warpage during assembly. To address these limitations, the industry has been primarily focusing on silicon-based interposers with through-silicon vias (TSVs) and copper wiring with back end of the line (BEOL) wafer processes. However, silicon interposers face limitations due to their high electrical loss,high permittivity and small wafer size. They are also limited by their high cost resulting from small waferand reticle sizes. GT-PRC has recently proposed and began to demonstrate glass interposers with superior electrical properties and with 2-5 micron line lithography resulting in 30-50 micron bump pitch to address the limitations of silicon interposers [1].

Metal line patterning on package substrates is traditionally achieved with two approaches – subtractive and semi-additive processes. Subtractive processes limit the pitch because of undercut during the metal wet-etching process. For metals such as Al, dry or plasma etching is more effectively used to minimize the undercut. In this process, blanket Al films are deposited by evaporation or sputtering, and patterns formed by plasma-based etch processes using chlorine-containing gases such as BCl_3 and Cl_2 with photoresist as an etch mask. However, this approach has not been applied to copper etching because copper does not form volatile reactive compounds during plasma reactions. Therefore, fine-line copper patterning is accomplished with the damascene process. In this process, the need to subtractively pattern or etch Cu is avoided by first plasma etching trenches or vias in a dielectric layer to form the regions where Cu interconnects are to be placed. Cu films are then electroplated into the vias, followed by chemical mechanical planarization or polishing (CMP) to remove the Cu overburden that exists above the dielectric film [2].

In advanced high-density interposers and packages, copper trace patterns are traditionally formed by semi-additive processes (SAP). Such a process starts with a copper seed-layer that is either electroless plated or sputtered. This is followed by photolithography to create a mold for plating the copper. After the copper is plated to the desired thickness, the photoresist mold is stripped and the seed-layer is removed to complete the metal layer. This process flow is schematically illustrated in Fig. 1. The seed-layer is removed with a wet-etching process which is isotropic and not well-controlled. This creates a major process limitation called "undercutting", which, in turn, creates several challenges for fine-line and precision copper patterning. The high-density copper patterns can create "acid-traps" where the seed-layer etch rate is reduced. The electroplated patterns are thus exposed to the seed-layer etchant for an extended time. Therefore, in a large-area panel process, the high-density features are being over-etched while the seed-layer is being completely etched across the entire panel. This has been a major bottleneck in achieving fine lithographic structures. This process also limits the flexibility in panel design and layout. Several advances such as anisotropic wet etch or differential etch were recently explored to address this major challenge.

This paper addresses this challenge by using a novel copper dry etch to remove seed layer with no measurable lateral undercut. It discusses the pioneering advances in copper dry etching with various plasma chemistries and their applicability to semi-additive patterning. Two chemistries, one based on a physical process (Ar plasma sputtering) and the other on a chemical process using a hydrogen plasma, are explored. The linewidths before and after seed-layer etching are compared.

The advantages and disadvantages of both approaches are also assessed.

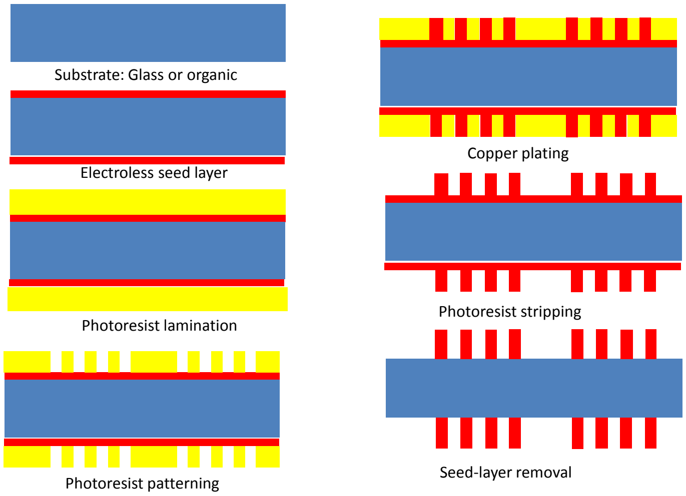


Fig. 1: Semi-additive patterning to form fine-line copper structures.

Dry-etching of metals

To address the limitations of acid or wet-etching, anisotropic metal plasma-etching has been widely investigated by the semiconductor industry over the past few decades. Metals such as Al and Cr are etched in Cl_2 or BCl_3 plasmas, while CHF_3 or SF_6-based plasmas are widely employed for etching Ti, Ta, W and Si or Si compounds. However, these processes are not directly extensible to metals such as Cu and Ni because they do not usually form volatile compounds with most halogenated plasma chemistries. A breakthrough in this regard has been recently achieved by utilizing a combination of Ar, Cl_2+Ar, Cl_2+H_2, H_2 or CH_4 with ICP (inductively coupled plasma). The mechanisms for copper dry etching are briefly discussed in this section.

Table 1: Plasma chemistries for Cu etching.

	Etch rate	Mechanism	Ref.
Ar	5-7 nm/min	Physical sputtering	
Cl_2 +Ar	500 nm/min	Chemical + physical	[3]
HBr	100-340 nm/min	Chemical+wet etch	[4, 5]
H_2	13 nm/min	Chemical+photon-assisted ion bombardment	[6]
Cl_2 + H_2	10-12 nm/cycle		[7]
CH_4	17 nm/min	Chemical	[8]

Lee et al. used high ion density-based electron-cyclotron resonance (ECR) Cl_2/Ar plasma for patterning copper [3]. With halide plasma-based etching [5], the copper is converted to a copper chloride. The chloride compound is then etched in an HCl liquid solution, thereby offering an alternative two-step approach to Cu patterning. This etching sequence requires a combination of dry and wet etching which can affect the throughput and create additional processing issues from multiple steps.

A two-step plasma etching process was developed by Hess et al. [7] The etching is based on solid-gas volatilization reactions in Cu-Cl-H system. The surface of copper is first chlorinated to form $CuCl_2$. It is suggested that the plasma reactions with hydrogen may convert $CuCl_2$ to the more volatile Cu_3Cl_3. This etching requires multi-step reactions. However, it yields reasonable etch rates of above 10 nm/min.

Fig. 2: Fine-line copper patterns on organic substrates.

H_2-based plasmas have been shown to yield the simplest gas-solid volatilization reaction, and was first demonstrated for copper etching by Wu et al. [6]. The plasma reaction is performed in an ICP reactor where copper reacts with H from the plasma to form CuH_x. This product is then desorbed by ion and/or photon bombardment. Therefore, ion- or photon-assisted desorption is proposed as the key mechanism in dry-etching of Cu using hydrogen plasmas.

Experimental Methods:

This paper explores Ar sputter-etching and H_2 plasma-etching processes to remove a copper seed-layer in a semi-additive process. In order to obtain the etch rates, the copper films were patterned into rectangular features using a subtractive process. Ti/Cu was sputter-deposited onto glass and silicon substrates. A positive liquid photoresist (Shipley 1827, Dow Chemicals) was used for this patterning process. The copper was etched with an etchant comprised of sulfuric acid and hydrogen peroxide. The thickness of the copper features was measured as a function of etch-time using a Tencor P-15 profilometer.

Advanced fine-line processes on organic substrates were used to demonstrate the process for 2.5D interposers. The substrate materials used in this study were composed of 100 µm thick halogen-free glass fiber-reinforced modified epoxy resin systems. The resin system was reinforced with one layer of glass fiber weave (average thickness of approximately 90 µm) and inorganic fillers for tailoring the modulus, CTE and for achieving flame retardant properties. For the test structure fabrication, a dry film photoresist was laminated on both sides, and patterned using UV lithography. An advanced projection mask aligner (Ushio UX-44101) was utilized for photolithograpy. Optical images of a part of the fabricated test vehicles are shown in Fig. 2. The copper dry-etch process is then applied to the test-vehicles for copper removal.

Results and Discussion:

Ar sputter-etching process: In the first part of this research, the etch rates with sputtered and electroless-plated copper seed-layers were investigated with pure physical process, Ar plasma sputtering. Etching occurs because of momentum transfer from the Ar ion bombardment due to its high atomic weight [6]. The copper thickness was measured periodically; the etch-rate was estimated to be ~ 4-5 nm/min. An SEM image of the patterned and thinned copper is shown in Fig. 3. The etched structures displayed some redeposit as seen in the SEM, indicating that the physical etching component is dominant over chemical etching as reported in the literature. Subsequent rinsing steps with H_2SO_4 showed cleaner edges with fewer redeposits.

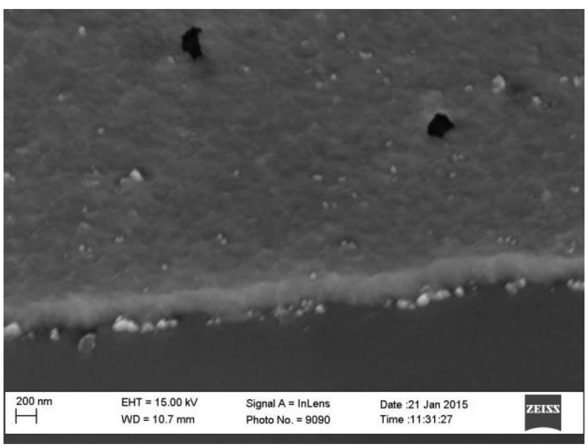


Fig. 3: Ar sputter-etching showing some redeposits.

H_2 plasma process: Cu films were also etched in H_2-based plasmas at temperatures of ~16 ^oC. Plasma etching of 270 nm Cu films was performed in an inductively coupled plasma (ICP) reactor (Plasma-Therm Inc). A flow rate of 50 sccm was used for hydrogen, leading to 20 mtorr pressure in the chamber. The plasma parameters were: RF1 = 100 W, RF2 = 500 W. RF1 is the power applied to the inductive coil. The second power supply (RF2) applies RF to the platen or lower electrode that provides a bias that extracts and accelerates the reactive species generated by the coil. The copper thickness as a function of etch time is plotted in Fig. 4. Based on the slope, an approximate etch rate of 4 nm/min is estimated.

The etching mechanism was described by Wu et al. [9]. The etching process involves both a physical and chemical component. The chemical component comes from the reaction between Cu and H_2 plasma to form copper hydrides, which then desorb from the surface to enable copper removal. The etch rates are dependent upon the sample temperature. The etch rates increase with temperature (from -150 ^oC to 10 ^oC) because of higher desorption rate of copper etch products. At temperatures above 10^oC, however, a reduction in etch rate was reported, and is attributed to the etch product instability. The resulting Cu is removed by sputtering which degrades the etch rates due to the pure physical removal process. Therefore, 10 ^oC is suggested as the optimum etch temperature. The etch rate at this temperature was measured to be ~12 nm/min by Wu et al. [9], higher than what is reported here, presumably because of the lower platen temperatures and oxygen-free copper surface preparation in Wu's work.

In comparison, an H_2 plasma has superior etch rates, improved selectivity to polymer or silicon substrates and less residue and redeposit. As a result, is highly preferred over an Ar-etching process for copper seed-layer removal.

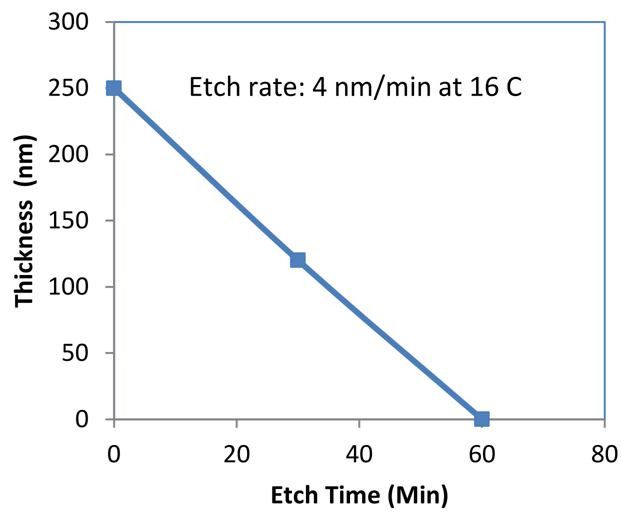
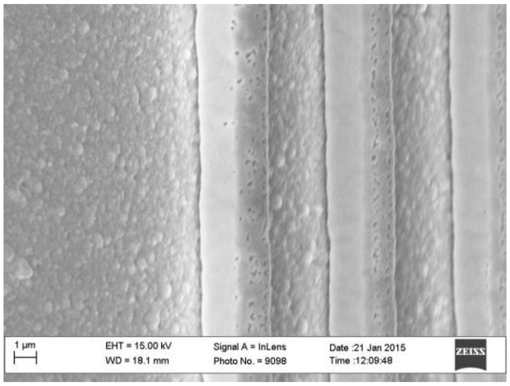
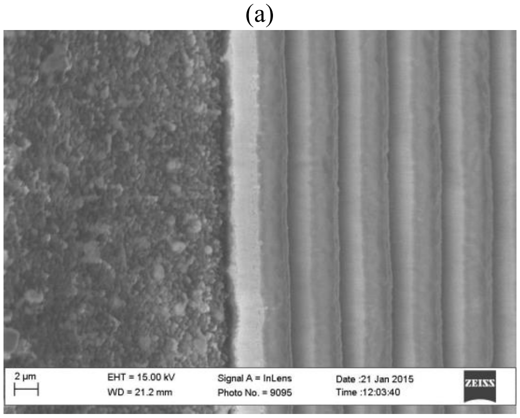


Fig. 4: Copper thickness as a function of etching time with hydrogen-based etching in inductively coupled plasma (ICP).

Seed-layer removal demonstration: In spite of the advantages of H_2 plasmas, Ar –etching was used for the test-vehicle demonstration in this initial study because of tool compatibility issues with organic packages. Fine lines were semi-additively patterned on organic substrates. The substrates were then placed in a plasma chamber at a power of 300 W, Ar flow rate of 50 sccm at 60 mtorr pressure for seed-layer removal. The copper seed layer was completely removed after 60 min, with an approximate etch rate of 5 nm/min. To eliminate any redeposit of the sputtered copper, a clean-step was performed with 10% H_2SO_4. The SEM images of copper fine-line structures before and after seed-layer removal are shown in Fig. 5. The line width and topography was extracted with a laser confocal microscope (Olympus – LEXT). Fig. 6 shows the line profiles after seed-layer removal. The line width was measured to be ~3.7 microns both before and after seed-layer removal, confirming that the dry-etch does not create any measurable undercut. Further improvements are expected with H_2 plasmas.



(a)



(b)

Fig. 5: (a) Fine lines on organic package with seed-layer, and (b) Seed-layer removal with Ar sputter-etching and cleaning.

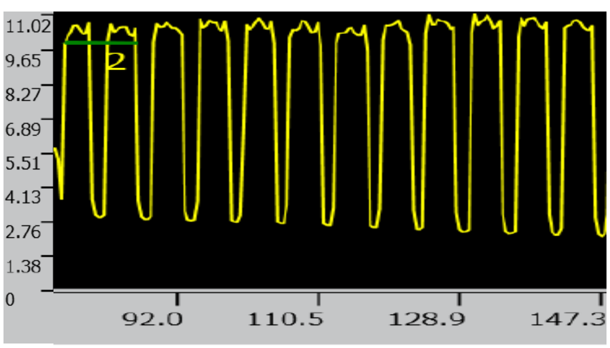


Fig. 6: Line profilometry with laser confocal microscopy after seed-layer removal. The width of the copper traces was 3.6-3.7 microns for both before and after seed-layer removal.

Summary:

This paper describes a solution to one of the biggest challenges in forming ultra-fine wiring technology for ultra-fine pitch interposers by demonstrating a zero-undercut seed-layer etch process in semi-additive copper patterning. The anisotropic nature and controlled etch-rates form the basis of seed-layer removal with no lateral etch. In the first approach, Ar plasma sputtering was used to etch copper as a purely physical process, followed by sulfuric acid clean. The plasma chamber and process design is much simpler with Ar sputtering. However, the etch rates are lower and the etch-selectivity needs to be improved. An alternative, hydrogen plasma etching process to form Cu patterns is a simple single-step plasma process. The high etch rates and selectivity achievable with H_2-plasmas result in improved manufacturability and process control. A representative process was demonstrated for seed-layer removal on organic laminates achieving 2-4 micron lithographic ground rules.

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