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Electrochemical mechanical deposition (ECMD) technique for semiconductor interconnect applications

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Abstract

A novel electrodeposition technique is described for deposition of conductors on non-planar surfaces of substrates in a planar manner. Electrochemical Mechanical Deposition (ECMD) technique involves simultaneous electrochemical deposition and mechanical polishing of the substrate surface. Copper layers deposited by the ECMD process grow preferentially in cavities on the wafer surface yielding flat profiles and much reduced overburden thickness. ECMD technology's potential to reduce cost of interconnect fabrication and some of its enabling features are discussed in this paper.

Keywords: Electrochemical mechanical deposition; Copper; Electroplating

1. Introduction

Electrochemically deposited copper is the material of choice for advanced interconnect applications due to its low resistivity, higher resistance to electromigration and good gap-fill capability [1–3]. Electrochemical deposition (ECD) employs copper plating electrolytes with organic additives to achieve bottom–up filling of small vias and trenches with high aspect ratios. However, for features with small aspect ratios, the ECD process yields conformal layers because the additives and the bottom–up fill mechanism are not operative in such large features. Fig. 1a schematically shows the filling behavior of small and large features with copper out of a plating electrolyte containing accelerator and suppressor species and chloride ions [4]. It should be noted that the barrier and seed layers that are traditionally deposited over the wafer surface before the electrodeposition step are not shown in Fig. 1a for brevity. As can be seen from this figure, deposition first initiates in a conformal manner in all features and on the surface (profile I). Then, relative accelerator concentration within the cavities of small features increases with respect to the top surface and bottom–up growth is initiated within these features as shown in Fig. 1a, profile II. Conformal growth continues in the large

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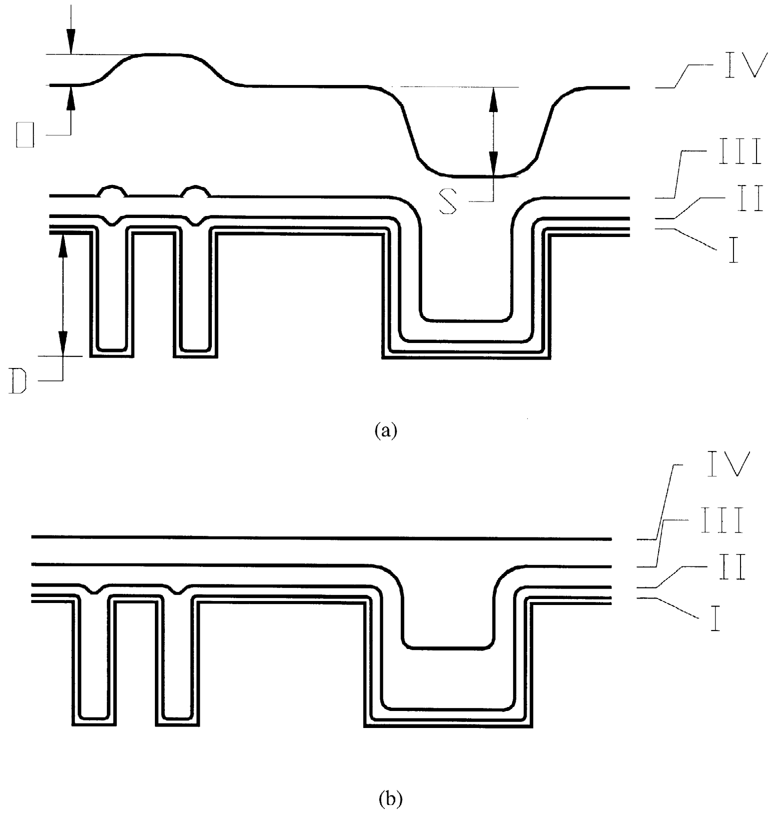

Fig. 1. (a) Evolution of copper thickness profile over small and large features in an electrochemical deposition (ECD) process. (b) Evolution of copper thickness profile over small and large features in an electrochemical mechanical deposition (ECMD) process.

features and at the top surface (field region) of the wafer during this stage since concentration distribution of accelerating and suppressing species on these surfaces are relatively uniform. As the small features are filled, bumps form over them due to the ‘over-plating’ phenomenon, which results from the relatively high accelerator concentration in those areas (profile III). The high accelerator content established within the small feature during the bottom–up fill stays over these small features even after the fill is complete giving rise to the bumps. Complete filling of the large features with conformally deposited copper requires a deposit thickness of greater than the depth, *D*, of the feature as shown in profile IV in Fig. 1a. Regions over small and dense features, on the other hand, are over-plated by the amount *O*. This copper over-fill can be avoided by using levelers in the plating bath. However, the large step, *S*, into the large features cannot be avoided.

A wafer surface topography with a thick and uneven copper film such as the one depicted in Fig. 1a presents challenges for processes such as CMP, chemical etching and electroetching, which may be used to remove the copper overburden from the field regions. For etching and electroetching techniques it is very difficult to planarize layers, especially over regions with large features. In CMP, over-plated dense arrays of small features require long over-polish times to clear, which in turn may cause dishing, erosion or oxide loss depending upon the hardware and consumable set employed. The thick overburden also requires long polish times and two-step/two-slurry removal processes with increased cost.

Electrochemical Mechanical Deposition (ECMD) is a newly developed technology that addresses some of the issues raised above. As the name suggests, ECMD employs both electrochemical and mechanical effects to achieve its results. The process may be carried out in regimes where effects are more mechanical than chemical or vice versa. As described in Refs. [5,6], the technique involves simultaneous plating and polishing/sweeping of the wafer surface. Sweeping is achieved using a pad or other means which can collectively be called 'Workpiece Surface Influencing Device' (WSID). Fig. 1b schematically shows the evolution of copper film profiles in an ECMD process. As can be seen from this figure, the first two stages of deposition (profiles I and II) are very similar to the conventional process of Fig. 1a. Once the bottom–up filling of high aspect ratio features is complete, however, the WSID is employed to initiate the mechanical action on the wafer surface. Initiation of ECMD mode arrests the over-plate phenomenon over the small features and at the same time accelerates growth within the large features as shown in profile III in Fig. 1b. Continuation of the ECMD process step eventually yields a flat copper profile IV and an overburden much smaller than the conventional ECD process.

2. Experimental details and discussion

NuTool® 2000 plating system with capability for both ECD and ECMD, and CUBATH® ViaForm™ copper plating chemistry with Accelerator and Suppressor were used for the reported work. The wafer was held by a wafer carrier, which could be rotated at various rpms and at the same time moved in lateral direction. During the ECMD process, wafer surface was contacted by the WSID surface as copper plating continued at a current density of 10 mA/cm2. Bath temperature was kept at around 20 °C.

Focused Ion Beam (FIB) cross-sections taken from three wafers coated with copper under various conditions are given in Fig. 2. These images show the evolution of the copper film profile on these wafers, which had 900 nm deep trenches etched into the dielectric. Columns A, B and C show copper deposition into 2-, 5- and 50-μm-wide trenches, respectively. Only one section of the 50-μm trench is shown in column C. FIB pictures in the top row (A1, B1 and C1) were taken from the first wafer after a conventional electrochemical deposition process step of 90 s. As expected, copper deposits in a conformal manner into all the trenches except at the bottom of the sidewalls where some super-filling can be observed. The middle row of the FIB cross-sections in Fig. 2 were taken from the second wafer which received, in addition to the 90-s electrochemical deposition step, an additional 40 s of ECMD. In other words, for this wafer, after the initial 90-s deposition, the WSID was brought to the wafer surface to initiate and sustain an ECMD process for an additional 40 s. As can be seen from the images of A2, B2 and C2, the 2-μm-wide trenches were completely filled as a result of a bottom–up accelerated growth initiated in the trenches by the ECMD process. This is evidenced by the larger increase of copper thickness in the 5- and 50-μm trenches compared to the wafer top surface. The third wafer used in this experiment was coated for 90 s under ECD and 80 s under the ECMD conditions and the results are shown in the FIB images of A3, B3 and C3. As can be seen from this data, accelerated growth of copper within the large features and planarization of the deposit continued

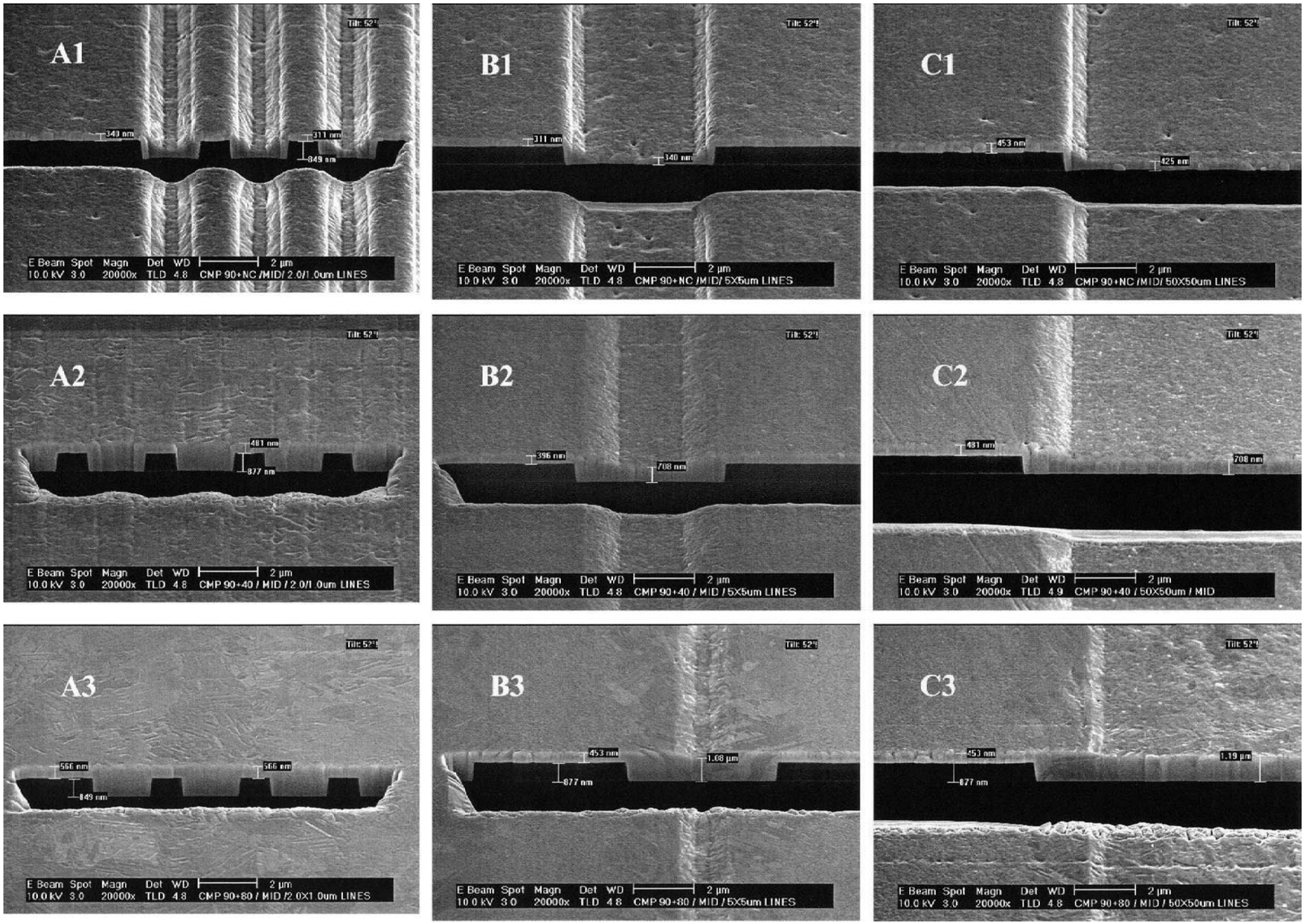

Fig. 2. Focused ion beam (FIB) images taken from three wafers after copper deposition for; 90 s by ECD (A1, B1, C1), 90 s by ECD + 40 s by ECMD (A2, B2, C2) and 90 s by ECD + 80 s by ECMD (A3, B3, C3).

during this additional ECMD period. Although not shown in Fig. 2, an additional 20 s of ECMD would completely planarize this wafer.

The evolution of copper thickness on the various portions of the wafers of Fig. 2 is graphically shown in Fig. 3. The three sets of data in Fig. 3 were taken from the 5- and 50-μm-wide trenches and they represent the copper layer thickness as measured from the bottom of the trenches, from the field region and from the wall of the trenches towards the trench center. The time axis represents the ECMD time period. As can be seen from Fig. 3, the copper thickness increases in a near-linear fashion with time on the field region as well as on the bottom surface of the trenches. The rate of growth, which is represented by the slopes of the curves in Fig. 3, is larger within the features compared to the field region. Comparison of the copper growth rate on the top surface and the trench bottom shows it to be about six times higher within the feature under the conditions that this experiment was carried out. This accelerated growth of electroplated metal into the large cavities of a substrate surface is a unique property of the ECMD technology.

It can be seen from Fig. 2 that the growth rate of copper on the trench bottom is about the same in both 5- and 50-μm-wide trenches. Furthermore, in addition to the bottom–up component of the film growth, there is also a growth front that moves in from the two walls of the trench towards its center. This growth front is quite symmetrical with respect to the two trench walls and its time evolution is the same irrespective of trench width. This can be seen from the comparison of the FIB images of B2 and B3 in Fig. 2 with the FIB images of C2 and C3, respectively. The copper thickness increase as measured from the sidewall of the large trenches is graphically shown in Fig. 3.

In a typical wafer plating process employing ECMD, a two-step approach may be used. During the first step of the process, traditional electroplating can be initiated on the wafer surface to obtain good gap-fill for the sub-micron size features. As is well known in the field and as discussed before in this

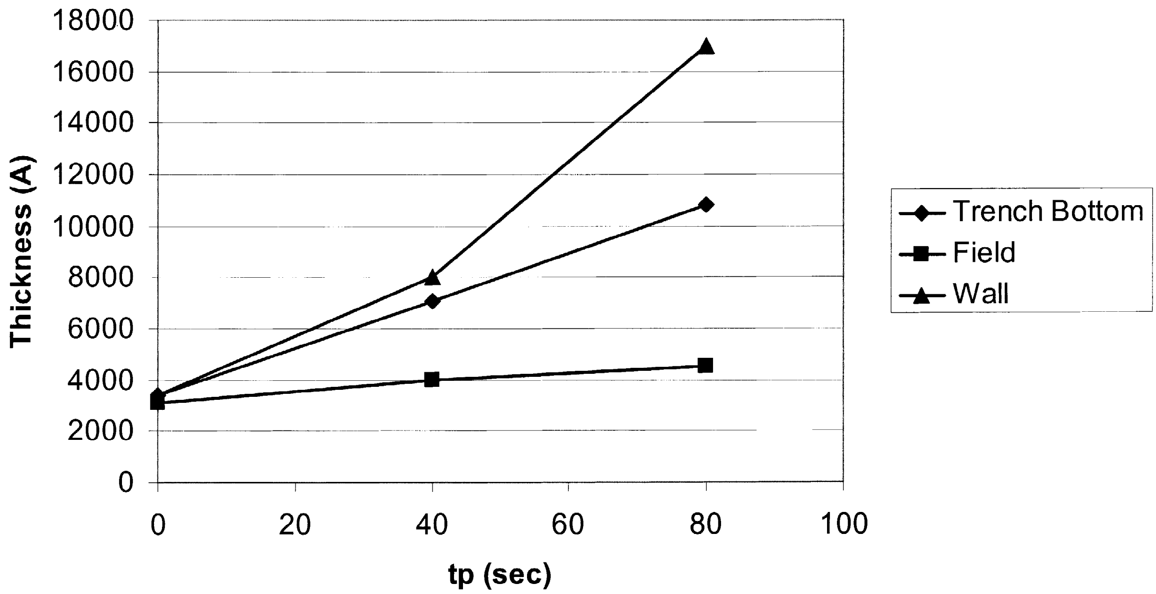

Fig. 3. Deposited copper film thickness as a function of ECMD time. Thickness measurements were made from the trench bottom, from the top field region and from the vertical wall of the trench.

manuscript, control of the plating chemistry, the waveform, and some of the process parameters such as the electrolyte flow and wafer rpm are all important factors that may influence the gap-fill performance. After accomplishing gap-fill through bottom–up growth in small features, ECMD process can be initiated to fill the large features as explained above.

Fig. 4 demonstrates the capability of the ECMD process for local planar deposition. In this FIB cross-section a 5-μm-wide trench and an array of about 550-nm wide trenches are shown as filled with ECMD copper. The trench depth is about 566 nm. A thin layer of W was deposited over the surface of the wafer before the FIB cut to sharpen the interfaces and measure the copper thickness more precisely. The thickness of the copper over the dense array of trenches is about 480 nm. The thickness of the copper overburden near the isolated 5-μm-wide trench is the same demonstrating the local leveling capability of the ECMD technique. Global planarization and uniformity was also evaluated for the same wafer where the overburden thickness was measured on dies at the center, mid-section and edge of the wafer. The results are listed in Table 1. As can be seen from this data, the copper overburden thickness values were all within 55 nm.

Under certain conditions, the thickness of the copper overburden can be controlled and adjusted in an ECMD process to minimize the overburden copper removal step. Fig. 5 shows a FIB cross-section

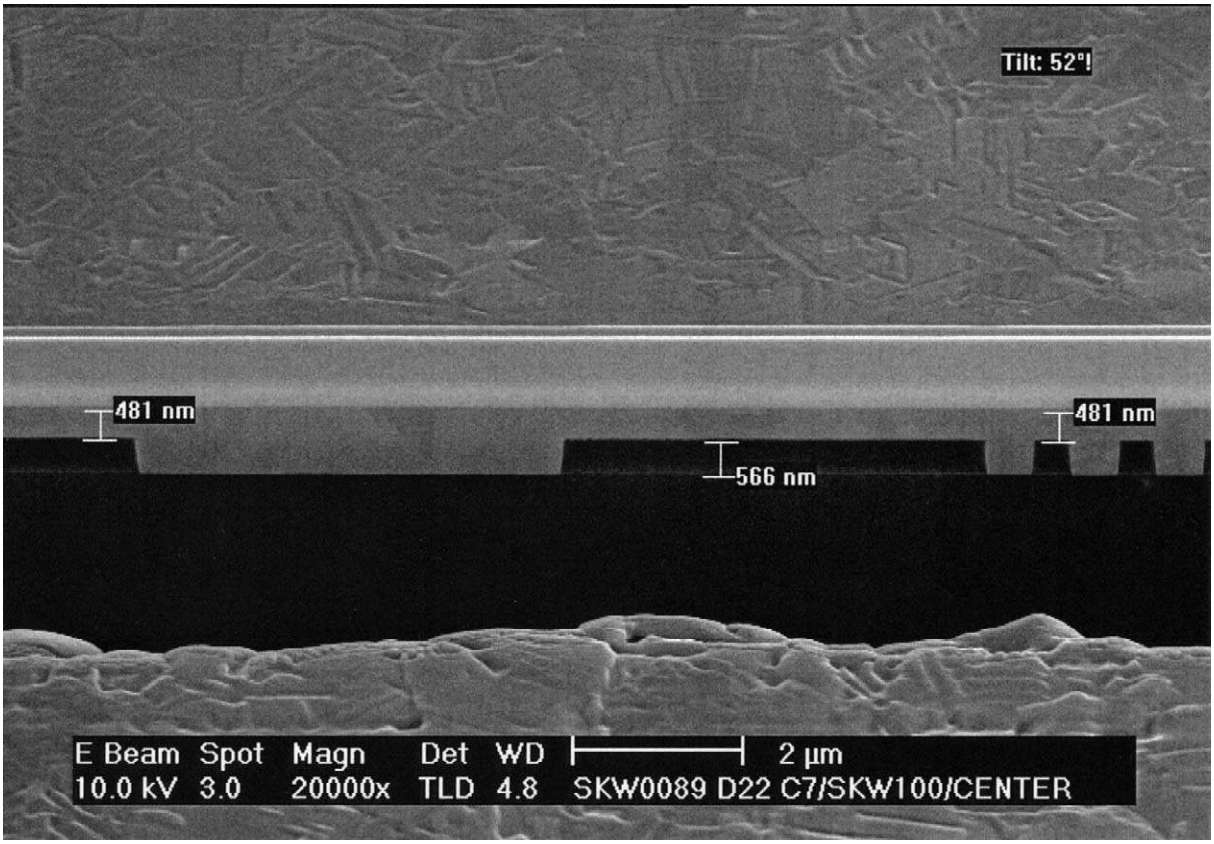

Fig. 4. Copper profile deposited by ECMD over an isolated trench and an array of small trenches.

Table 1
Copper overburden thickness measured at various locations after electrochemical mechanical deposition

	Center	Middle	Edge
Near-isolated trench	450 nm	480 nm	450 nm
Over dense array of trenches	425 nm	480 nm	480 nm

from a wafer similar to that of Fig. 4. However, this time ECMD process was initiated earlier, yielding a much thinner overburden. Considering the fact that the trench depth in this wafer is 566 nm and the seed layer thickness was 60 nm, the resulting 226 nm of copper overburden suggests that the ECMD process deposited about 160 nm of copper onto the top surface of the substrate while depositing about 720 nm of copper into the large trench. The ratio (720/160) = 4.5 is smaller than 6, which was the derived value from Fig. 3 as the ratio of copper growth rate within the feature to the growth rate on the field regions. This is due to the fact that the film of Fig. 3 was not fully planarized

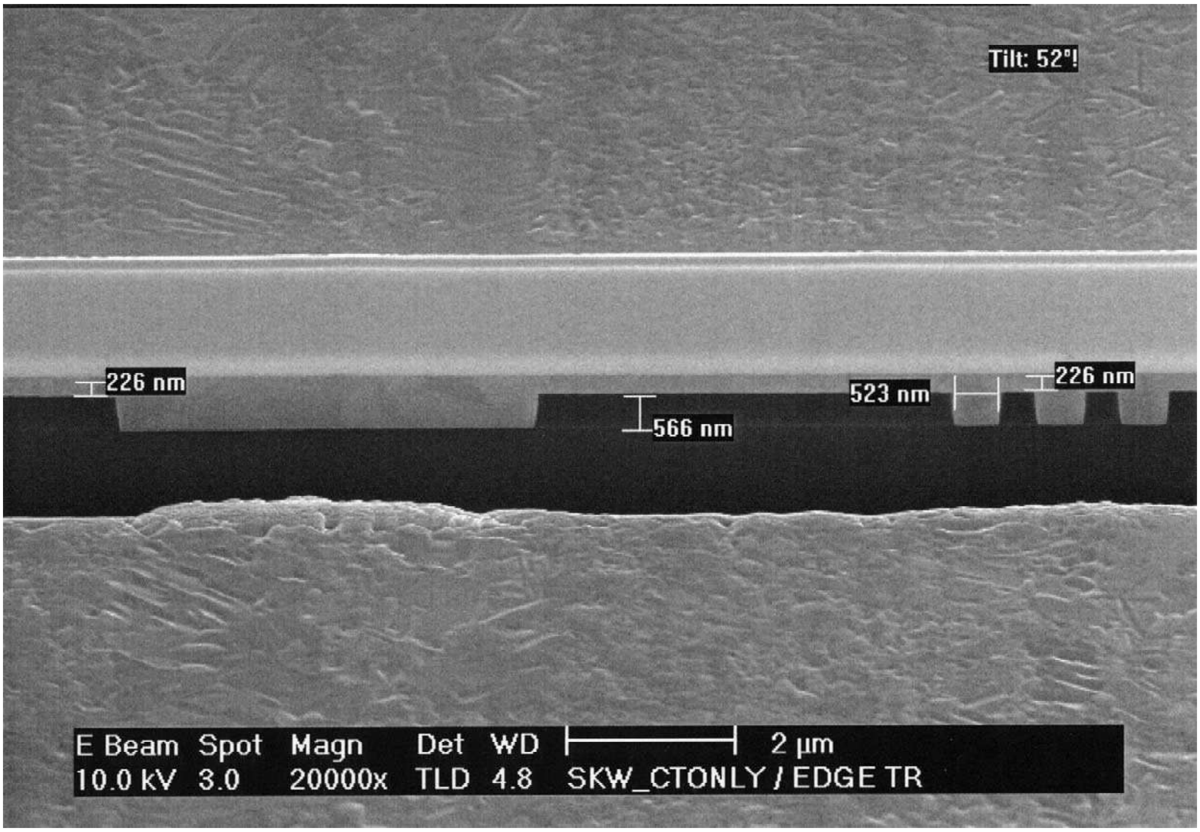

Fig. 5. Minimization of copper overburden by ECMD process.

and as the film fully planarizes the differential between the two growth rates is expected to decrease. It should be noted that several factors such as the additive concentrations, rpm of the wafer and the pressure at which the WSID makes contact with the wafer surface may influence the magnitude of the copper growth rate differential established by the ECMD process between the surface regions and the cavities.

Benefit of the ECMD process becomes more apparent as the feature depths increase. Fig. 6 is a FIB cross section taken from a 3.6-μm-deep, 5-μm-wide trench after plating with copper. The overburden thickness is only about 0.7 μm after ECMD. Traditional ECD would require more than 5 μm of copper deposition to fill such deep features.

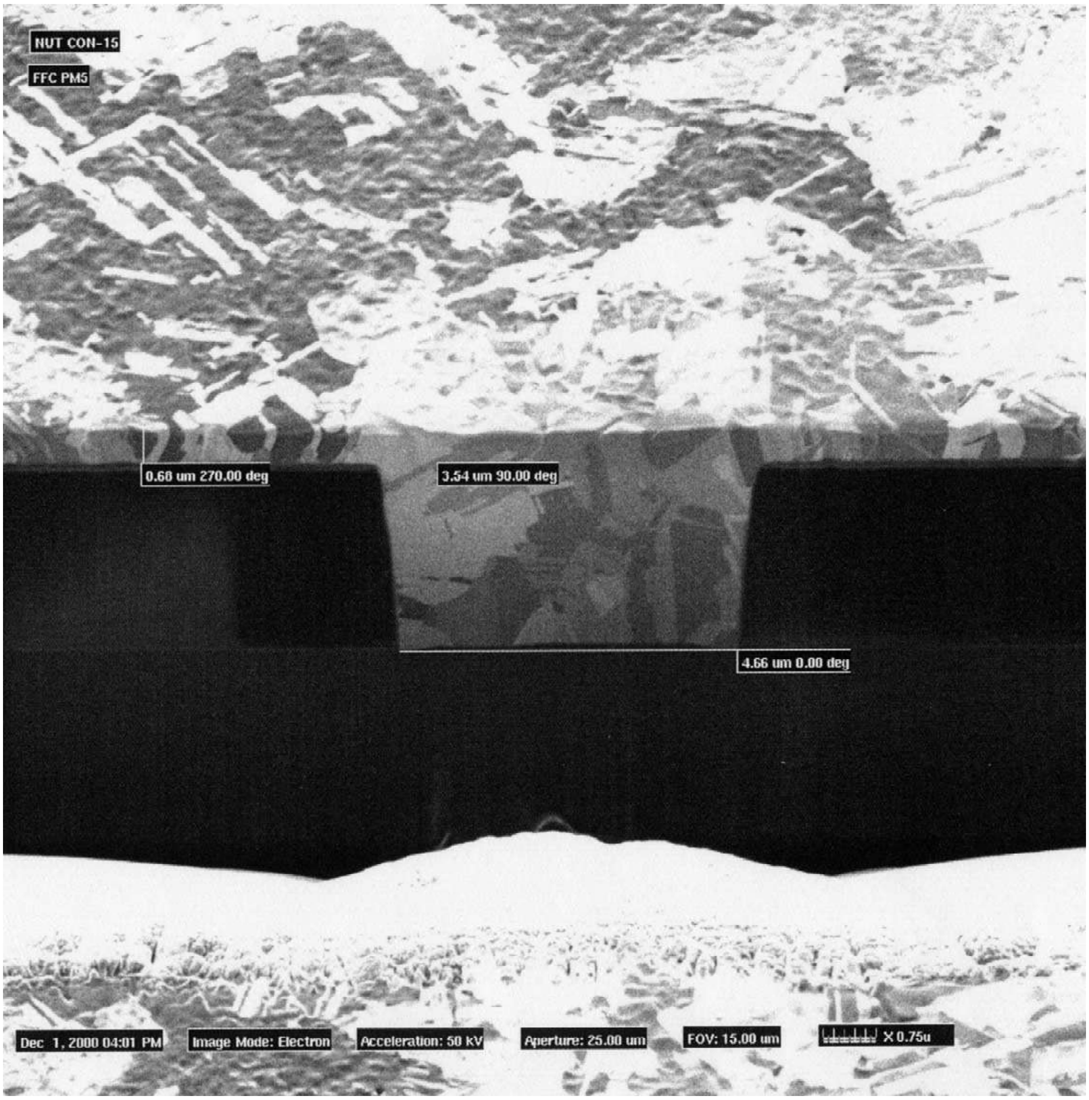

Fig. 6. A Trench (3.5 μm deep, 5 μm wide) filled with ECMD copper. Field thickness is about 0.7 μm.

3. Conclusions

A novel Electrochemical Mechanical Deposition (ECMD) technique has been described for the deposition of copper. It is shown that ECMD has unique capabilities as compared with the standard ECD process. Metal layers deposited by ECMD are planar and the thickness of the overburden is smaller than the films deposited by standard approaches. ECMD achieves this result by enhancing material deposition rate into the cavities while retarding or minimizing deposition on the substrate top surface. It should be appreciated that the thin and planar copper deposits such as those shown in Figs. 4 and 5 are very attractive for etching, electroetching and CMP. For etching and electroetching, a planar layer offers the possibility of removing the overburden in a planar manner without causing excessive dishing into the large features. For chemical mechanical polishing, ECMD offers significant cost advantage due to thinner copper to be removed. With planar and thin ECMD copper CMP times have been reduced by as much as 60% on wafers with dielectric thickness in the range of 0.35–0.55 μm. In addition to the increased throughput, CMP consumable costs are also drastically reduced.

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