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Engineering kinetic barriers in copper metallization

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In metallization processes of integrated circuits, it is desirable to deposit the metal lines (aluminum or copper) fast and at low temperatures. However, the lines (films) usually consist of undesirable columns and voids, because of the absence of sufficient diffusion—a direct result of large kinetic barriers. Following the proposal and realization of the three-dimensional Ehrlich-Schwoebel (3D ES) barrier, we present here a method to engineer this kinetic barrier so as to improve quality of deposited copper films. We deposit copper films by magnetron sputtering, characterize the film structure and texture by using the scanning electron microscope and the x-ray diffraction, respectively. Taking indium as surfactant during copper deposition, we have achieved much better density and bottom coverage of copper filled trenches. The characterizations show that the improvement is the result of the 3D ES barrier reduction caused by indium addition. Engineering the 3D ES barrier therefore leads to improved film quality. *© 2002 American Institute of Physics.* [DOI: 10.1063/1.1527226]

Thin films play a pivotal role in technology. For example, aluminum or copper thin films as interconnects of integrated circuits (ICs) affect or even dictate the ICs' performance. It is recognized that stronger ⟨111⟩ texture—with film surface primarily being {111}—leads to substantial improvement of electromigration resistance.[1] The ⟨111⟩ texture is thermodynamically preferred for face-centered-cubic metals, such as aluminum and copper. However, thermodynamically nonpreferred textures may be desirable; for example ⟨110⟩ texture of copper for better corrosion resistance[2] and ⟨111⟩ texture of TiN as barrier layers in ICs.[3] Understanding and being able to control the texture development are therefore crucial. Substantial effort has been devoted to both experimental and modeling studies of the texture developments.[3–5] The most common factors that control the texture development include deposition rate, substrate temperature, distribution of source particle (in energy and angle), substrate wetability, and stress/strain imposed on the film. For example, internal stress of moderate level developed during copper film deposition leads to predominant ⟨110⟩ texture.[6]

Adding to the complexity of texture development is the featured substrate in IC materials processing.[7] As part of the multilevel metallization, trenches and vias through the dielectrics need to be filled with metals, such as tungsten, aluminum, or copper. Because of geometrical shadowing effects during physical vapor deposition and limited diffusion, the metal films in trenches/vias may contain voids or nonpreferred textures—both lead to reduced electromigration resistance. The problems, at least the void formation problem, could be partially solved with increased substrate temperature. But this is at the expense of increased thermal budget, since high temperature may adversely alter structures of other IC components, such as $p-n$ junctions.

Moving away from the brute force approach, we have investigated the intrinsic kinetic barriers—diffusion activation energies. Recently, we have proposed and validated the three-dimensional Ehrlich-Schwoebel (3D ES) barrier.[8,9] Starting from this concept, we introduce surfactant to modify the 3D ES barrier, so as to deposit conforming films on featured substrate, with desired texture. In this letter, we present copper filled trenches, with substantially improved conformality but at no increase of substrate temperature, by introducing indium as the surfactant. It is worthy mentioning that we have also achieved the desired texture, ⟨111⟩ in the copper film at low temperatures; this aspect will be the subject of another publication.

The copper films are deposited by magnetron sputtering technique. The sputtering power is chosen to be 200 W for copper and 25 W for indium, and the chamber is filled with 99.999% Ar, flowing into the chamber at a rate of 8.5 sccm. During the deposition, the base pressure is about 5.0×10^{-8} Torr and the working pressure is about 2.5×10^{-3} Torr. The target includes a block of 99.995% copper and a block of 99.995% indium, which are sputtering cleaned in Ar gas for 10 min before deposition.

The substrate, which is 4 cm away from the target, is an n-type Si(111) wafer of resistivity 10–12 Ω cm, with a layer of SiO_2 formed on top. Using photolithography and Ar plasma etching, we pattern the substrate with a series of trenches, which are about 1.5 μm wide and about 1 in aspect

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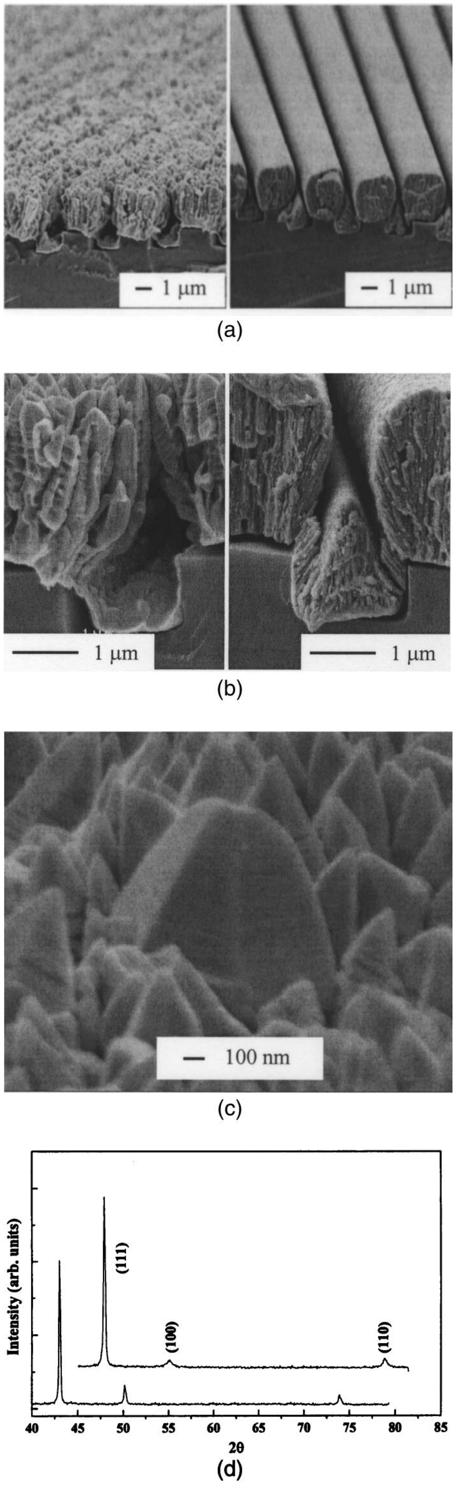

FIG. 1. (a) Overall morphology and (b) single trench view of copper films deposited at 200 W, without (left) and with (right) indium surfactant; (c) top view of the pure copper film, and (d) XRD of the copper film without (front) and with (back) indium surfactant.

ratio. Since the focus of this work is to demonstrate the effects of indium in trench filling in general, the small aspect ratio is sufficient. The deposition rate is estimated, based on the average film thickness, as 100 nm per minute, and the substrate temperature is maintained at $0.22T_m$ (22% of the melting temperature). The films are characterized using x-ray diffraction (XRD) and scanning electron microscopy.

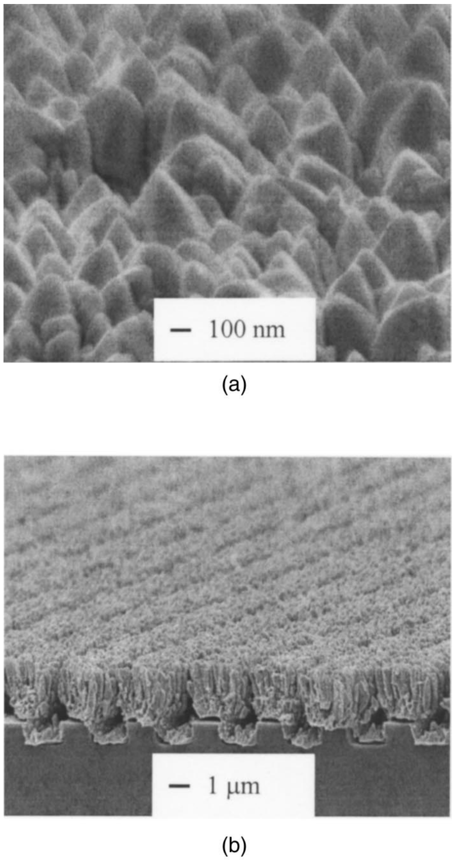

FIG. 2. (a) Top view and (b) overall morphology of copper films with indium surfactant introduced at half the frequency as in Fig. 1.

The overall morphology of copper filled trenches, with and without indium as surfactant, is shown in Fig. 1(a). To ensure sufficient surfactant floating on surfaces, we introduce about 1 nm indium at the beginning, and another 1 nm after depositing copper for 5 min—this alternating process repeats to the end. Zooming into a single trench, the microstructures are shown in Fig. 1(b). These two figures, Figs. 1(a) and 1(b), clearly show: (1) the density is higher, and (2) the bottom coverage or conformality is improved by the use of indium surfactant. Both improvements require enhanced mass transport—indium has served this purpose. Figure 1(c) provides a top view of the pure copper film (away from the trenches), and reveals many facets covering the surfaces of hillocks (or columns). We propose that indium atoms incorporated at edges separating the facets have reduced the 3D ES barrier, thereby enhanced mass transport between these facets. Once this interfacet transportation is facilitated, the on-facet diffusion barrier does not limit the mass transport anymore, since it is less than 0.1 eV.[9,10]

It is encouraging that the indium surfactant leads to better film density and conformality. It is also important to deposit the copper film with desired texture. Using the XRD technique, we have characterized the film as primarily of ⟨111⟩ textured, as shown in Fig. 1(d). For the pure copper film, the ratio of XRD intensities (111)/(100) is 6.3. When indium is used, this ratio is increased to 12.7. The indium surfactant has enhanced the desirable ⟨111⟩ texture in the IC metallization process, apart from enhancing the film density and coverage.

To ascertain that the observed improvements are caused by the indium surfactant, we have repeated the deposition process by varying the frequency of indium deposition. In-

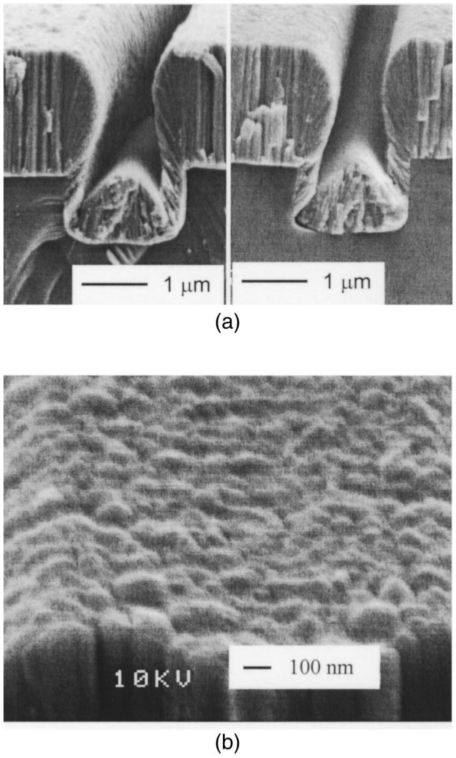

FIG. 3. (a) Single trench view of copper films deposited at 50 W without (left) and with (right) the addition of indium. (b) Top view of the pure copper film deposited at 50 W.

stead of depositing copper for 5 min between indium depositions, we deposit copper for 10 min each time—in effect reducing the amount of indium addition. As shown in Fig. 2(a), the surface facet size has been reduced, in comparison to Fig. 1(c), but facets still exist. The overall trench morphology [Fig. 2(b)] shows that the film is not as dense as in Fig. 1(a) (right), due to the lack of sufficient indium. Correlating the surfactant availability and the improvement (or enhanced diffusion), we conclude that the improvements are indeed caused by indium addition.

To further uncover the mechanism of enhanced diffusion by indium, we repeat the deposition at lower sputtering power (50 W), which corresponds to about 30 nm of copper per minute. Since the deposition rate is reduced by a factor of about 3, we keep the deposition time of copper between two indium depositions to be 10 min—the indium concentration is slightly higher here than in Fig. 1. The copper filled trenches, with and without indium as surfactant, are shown in Fig. 3(a). Comparison of these two trenches shows no visible difference. Further, the surface of pure copper film is smooth, and large facets are absent—as shown in Fig. 3(b). It is therefore unlikely for the 3D ES barrier to prevail. The indium is therefore not very effective, since there are no (or few) 3D ES barriers for the surfactant to alter. This evidence adds to the conclusion that the indium addition enhances diffusion by reducing the 3D ES barrier—which dominates when facets prevail; it is another indirect validation of the 3D ES barrier concept.

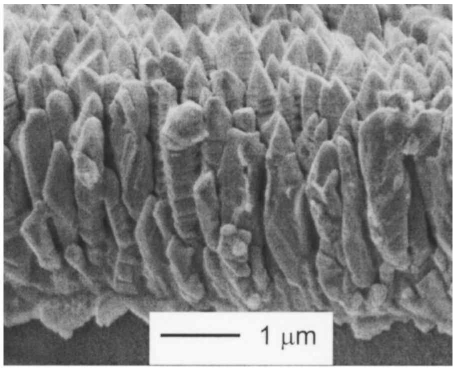

FIG. 4. Side view of $\langle 111 \rangle$ copper hillocks deposited at 200 W as in Fig. 1.

In summary, we have shown that indium addition during magnetron sputtering deposition of copper leads to substantially improved density and conformality (bottom coverage of trench in particular) of the film. Further, we have shown that the improvements (or enhanced diffusion) are due to the reduction of 3D ES barriers of copper by the introduction of indium.

Before closing, we show in Fig. 4 the hillock structures of the $\langle 111 \rangle$ copper film—the side view of trenches in Fig. 1. These hillocks (or columns) have very high aspect ratio, similar to the silicon columns reported in Ref. 11. Further details of the hillock development will be presented in a later publication.

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