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Directional deposition of Cu into semiconductor trench structures using ionized magnetron sputtering

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The primary metallization technique in the semiconductor industry for the past decade has been magnetron sputtering. The general industry trend towards damascene processing requires the capability to fill trenches and vias with sub-one-half micron widths and aspect ratios (AR) as high as 3:1. At these dimensions and geometries, the angular distribution of magnetron sputtered atoms results in the production of voids during deposition. A new approach to this problem is directional sputter deposition, where neutrals generated from magnetron sputtering are ionized through an inductively coupled rf plasma and accelerated towards the substrate via a small dc bias on the substrate, causing a significant portion of the flux to arrive at normal incidence. The experimental parameters of this process have been explored by depositing Cu on patterned Si wafers. The parameters have varying effects on the morphology of the deposited layer, which indicate relationships between the parameters and the ion-to-neutral ratio, the total flux, and the average ion energy. The ionized magnetron sputter deposition process has been used successfully to fill trenches of 600 nm width and 1.1 AR with Cu near room temperature, and appears to be extendable to more aggressive dimensions.

I. INTRODUCTION

The general trend in the metallization of interconnects for semiconductor wafers is away from blanket coatings [and subsequent reactive ion etching (RIE) patterning] and towards damascene processes, which utilize filling of embedded trenches and vias and subsequent planarization by polishing. The dimensions (sub-half-micron) and aspect ratios (>1) of these trenches and vias are generally incompatible with conventional sputter deposition due to the broad angular distribution of the sputtered atoms. Sputter deposition into these features results in significant overhang formation and eventual void formation, which causes increased resistance as well as reliability concerns.

A solution to this problem has been collimated sputtering, in which a physical filter is used with conventional low pressure sputtering to remove particles which are far from the normal direction.[1] However, deposition onto the collimators is significant, reducing the net deposition rate and limiting the effective lifetime of the collimator. Collimated sputter deposition has been applied successfully in manufacturing very thin films, primarily diffusion barriers and liners in trenches and vias, as well as low aspect ratio trench filling.

An alternative solution for plasma vapor deposition (PVD) based deposition technology for filling moderate aspect ratio features is to deposit films from metal ions, rather than neutrals. By setting up a simple sheath at the surface of the sample, depositing metal ions from a plasma are accelerated across the sheath at normal incidence, and their energy can be easily controlled.

This technique was first applied to the deposition of Cu on semiconductor features by Holber *et al.*[2] who evaporated Cu into an electron cyclotron resonance (ECR) plasma, and then condensed films from Cu ions on a nearby, negatively biased wafer. More recently, deposition with metal ions has been extended to a related technology using magnetron sputtering as the metal source and inductively coupled rf plasmas as the means of ionization.[3–6] This latter technique has the advantage of compatibility with existing manufacturing hardware and processes as well as the capability to deposit alloys [e.g., AlCu(0.5)] and compounds (TiN). This study describes the use of inductively coupled plasma ionization of magnetron-sputtered Cu to produce Cu ions which are then accelerated to wafer surfaces for trench-filling applications.

II. EXPERIMENT

The system consists of a conventional 200-mm-diam magnetron cathode with a 99.999% pure Cu cathode configured about 13 cm from a fixed sample holder. A two-turn, water cooled rf coil with a diameter of 200 mm was positioned 5–8 cm from the cathode (see Fig. 1). The substrate holder is equipped with quartz lamps for heating the substrate up to 400 °C and is biased by a dc supply from 0 to −300 V. The rf power capability is 3 kW and the magnetron is rated at 10 kW. The vacuum system is cryopumped with a base pressure below $6E-8$ Torr ($8E-6$ Pa). Prior to deposition, the magnetron cathode was always conditioned with the sample shutter closed. Samples were Si wafers with 600 nm, 1.1:1 aspect ratio (AR) trenches etched into a thick SiO_2 top layer. The quartz layer was precoated with a conformal 60 nm Ta layer for increased Cu adhesion. For measurement purposes, the samples were cleaved in air at room temperature and observed in a scanning electron microscope (SEM) at a 90° tilt.

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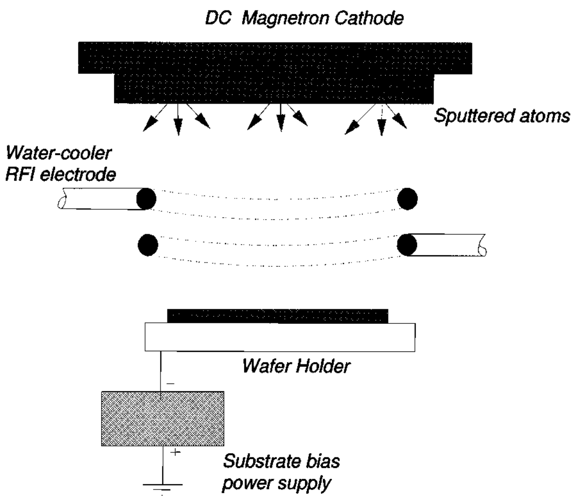

FIG. 1. Experimental configuration: the magnetron was 200 mm diam, 10 kW capacity; the RFI electrode was Cu tubing with a 3 kW power supply, and the sample power supply had a 1000 V, 1 A capacity. The vacuum system is not shown.

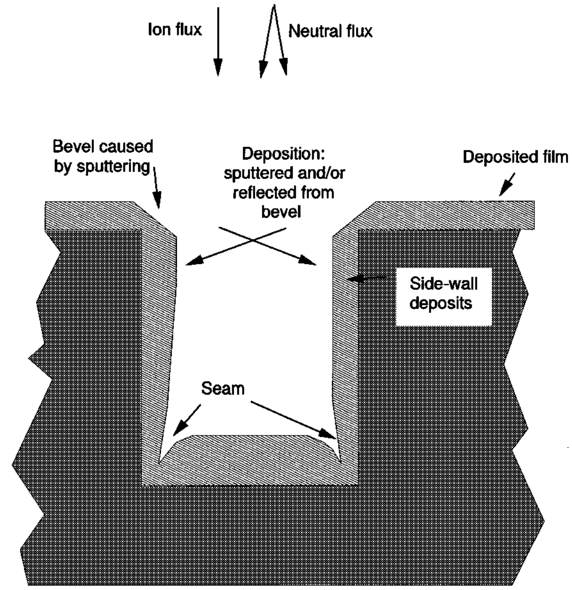

FIG. 2. Schematic of the cross section of the patterned wafers used in the experiment, and the primary features of the deposit.

III. RESULTS AND DISCUSSION

The distance between the Cu cathode in the magnetron and the substrate is approximately 13 cm and chamber pressures varied from 5 to 45 mTorr (0.67–6.0 Pa). At this distance, Ar pressures above 4–5 mTorr (0.53–0.67 Pa) place the experiments in a diffusion-dominated regime where the number of collisions between the sputtered Cu atoms and the Ar in the chamber is large enough to thermalize the Cu. Under these conditions, the sputtered Cu atoms have a nearly isotropic angular distribution[7] and essentially no residual kinetic energy.

In directed sputtering, the flux of neutral atoms passes through an inductively coupled rf plasma en route to the substrate. A significant fraction of the neutral Cu atoms becomes ionized, and these ions are accelerated across the sheath at an energy equal to the difference between the plasma potential (positive) and the potential of the substrate (negative). As a result, the ions arrive at the substrate at predominantly normal incidence. The deposition flux which reaches the substrate is a combination of mostly isotropic neutrals and directed ions (see Fig. 2). Therefore, the directionality of the net deposition is dependent on the ion-to-neutral ratio. A high ion-to-neutral ratio will produce a highly directional deposit, while a low ion-to-neutral ratio will produce a deposit which resembles deposits normally associated with conventional sputter deposition.

A distinction is made between the deposits at the top of the dielectric (also known as the overburden) and the bottom of the trench. The ratio of the thicknesses of the overburden to the deposit at the bottom of the trench is known as the top-to-bottom ratio, and is a good indication of how well the trenches are filled.

Because the Cu ions, as well as the Ar ions present in the plasma, are accelerated to the sample from the plasma potential, it is necessary to consider the effects of both sputtering and reflection of both species on the morphology of the deposit.

Sputtering will result in (a) a lower net deposition rate (b) the formation of bevels at high-angle edges or ledges on the surface (see Fig. 2), and (c) potential redeposition effects. Bevel formation is generally attributed to the angular dependence of the sputter yield which peaks around 45°–60°. Bevel formation is often desired, as it tends to reduce the lateral buildup of the overburden, including the overhang on the ledge. However, sputtering of the sample can also result in local redeposition effects which may result in unwanted changes in the overall morphology.

Ion reflection occurs across the surface of the deposit, but is most likely to occur when an ion is incident upon a moderate to high angle surface, such as a bevel or a steeply sloped sidewall. However, ion reflection is not specular due to the atomistic roughness of a surface. Instead, the reflected atoms (for ions are neutralized after interaction with a surface) have an angular distribution.[8] Reflection can result in two general effects: (a) the deposition of the reflecting particle (assuming it is a metal atom) at another location, and (b) the erosion by sputtering of material by the reflected atom at another location, which in this experiment could be either Ar ions or Cu.

The relative importance of sputtering and reflection on the deposit morphology is not clearly defined. Calculations, using a VF-TRIM-3D computer code, suggest that the reflection coefficient can significantly exceed the sputter yield at low energies.[9] Figure 3 shows plots of reflection coefficients (R_n) and sputter yields (Y_n) for relevant cases of Ar and Cu incident on Cu at 0° and 60°, as a function of ion energy. The sputter yields for Cu and Ar incident on Cu are roughly the same, as would be expected. However, the self-reflection coefficient (Cu ions on Cu) at 60° is significantly higher than the sputter yield, which suggests that the reflection and subsequent redeposition of the reflected Cu may be significant in determining the eventual film morphology. However because the exact Ar ion flux to Cu ion flux ratios were not measured

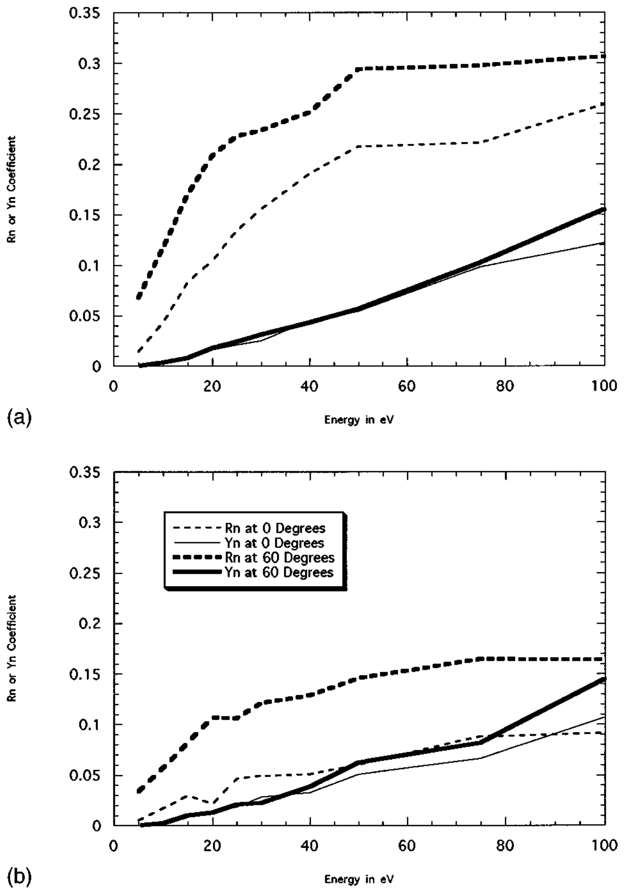

FIG. 3. Computer simulations of the reflection and sputtering yields for (A) Ar ions incident on Cu and (B) Cu ions incident on Cu.

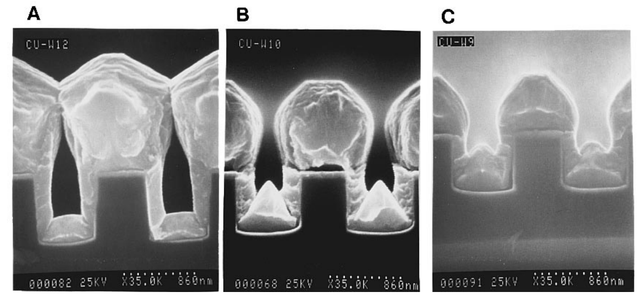

FIG. 4. Effect of increasing Ar pressure on deposit morphology at constant magnetron power (300 W), rf power (1000 W), time (24 min), and dc bias (−25 V). Shown are cross sections of patterned wafers at (A) 5 mTorr, (B) 20 mTorr, and (C) 40 mTorr.

in this experiment, the relation between the effects of Cu ion reflection and the effects of Ar and Cu ion sputtering, cannot be determined. Clearly, both can contribute to some of the observed results.

The formation of a bevel at the top edge of a trench can have both positive and negative consequences. On the positive side, the bevel eliminates the overhang formation and tends to keep the trench open for further deposition. On the negative side, for narrow trenches, redeposition of the material sputtered from the bevel along with the deposition of reflected metal ions can form local deposits on the other side of the trench. This lateral buildup can appear similar to the effects of isotropic, neutral deposition. The end result, however, is the same. The lateral buildup results in shadowing of the bottom of the trench and eventually will create a structure known as a pinch-off which results in closure of the trench and void formation.

Directional deposition can also result in the formation of slightly different deposits on the sidewalls of a trench as compared to the bottom of the trench. On the sidewalls, the primary deposition flux is at a grazing angle, which can result in a columnar, low density film [for an example, see Fig. 6(b)]. On the trench bottom, the films are generally denser due to the wider geometrical acceptance angle. Between these two types of deposits, if the sample temperature is kept cold (<100 °C) a seam or a cracklike void can often be observed. If overhangs from the overburden become large, shadowing effects may take place, reducing the number of particles that can fill the seam, and the seam becomes even larger. However, the formation of a seam can be influenced by local ion reflection, as well as redeposition of material sputtered from either the bevel or the trench bottom. The present work shows that ion reflections and sputtering events cause a redistribution of metal atoms within the trench. In some cases this can be useful to eliminate seams and voids as well as the columnar sidewall microstructure. (In the figures which show cross-sections of Si wafers, the seam may be exaggerated due to pull-out effects caused in sample preparation.)

The primary variables in the experimental setup were the Ar pressure in the chamber, the rf power applied to the coils, the magnetron power applied to the Cu cathode, the dc bias on the substrate, and the deposition time. Sample temperature was kept at or below 120 °C for all of the experiments. With the exception of time, each of these variables has a direct effect on one or more of the following fundamental quantities which determine the morphology of the deposit: the ion-to-neutral ratio, the overall depositing flux, and the average ion energy. The following sections show how these variables affect the fundamental quantities, and hence the deposit morphologies.

A. Ar pressure

Figure 4 shows a series of experiments in which the Ar pressure was varied. The magnetron power was set at 300 W, the rf power was set at 1000 W, and the dc bias was set at −25 V. Figures 4(A)–4(C) show the cross section of experiments carried out at Ar pressures of 5 mTorr (0.67 Pa), 20 mTorr (2.7 Pa), and 40 mTorr (5.3 Pa), respectively. The increase in pressure clearly results in both a decrease in the top-to-bottom ratio (from 3.92 ± 0.34 at 5 mTorr to 1.22 ±0.08 at 40 mTorr), as well as a decrease in the overall deposition rate [$51\%\pm2\%$ decrease from Figs. 3(A) to 3(C)].

Another trend that can be seen with increasing Ar pressure is the decreasing lateral dimension of the overburden. Figure 4(A) clearly shows the overburden creating a pinch-off which causes an effective void, but the progression to higher pressures results in smaller overburden widths for the same deposition time, allowing for greater amounts of trench deposition.

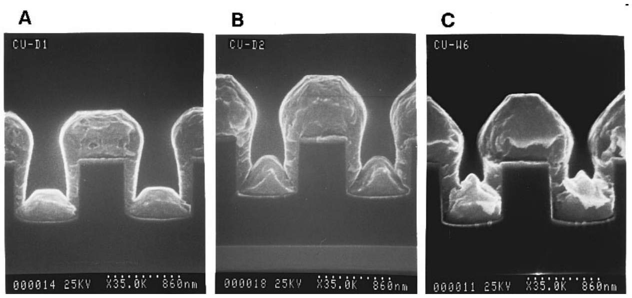

FIG. 5. Effect of increasing rf power on deposit morphology at constant magnetron power (300 W), Ar pressure (30 mTorr), time (24 min), and dc bias (−30 V). Shown are cross sections of patterned at (A) 300 W, (B) 600 W, and (C) 1000 W.

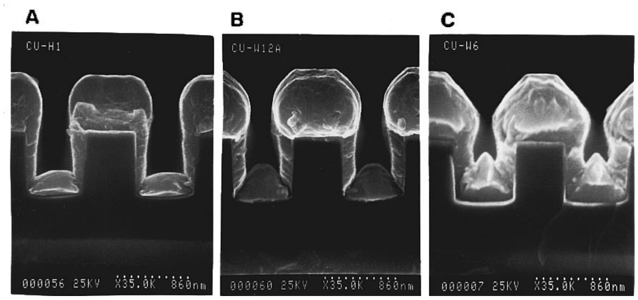

FIG. 6. Effect of decreasing magnetron power on deposit morphology at constant rf power (1000 W), Ar pressure (30 mTorr), and dc bias (−30 V). Deposition times are accordingly altered for comparison purposes. Shown are cross sections of patterned wafers at (A) 2000 W—3.6 min, (B) 600 W—12 min, and (C) 300 W—24 min.

Increasing pressures result in higher amounts of neutral Cu scattering, which lowers the overall Cu deposition rate. The scattering also results in a longer dwell time for Cu in the rf plasma, and therefore higher Cu ionization. The overall result is that increasing pressures cause an increase in the ion-to-neutral ratio. This conclusion is confirmed by earlier work with similar systems.[3,4] The relative increase of ions in the depositing flux translates into a higher degree of directed deposition, which allows the trenches to be filled to a greater extent, lowering the top-to-bottom ratio. The increased directionality can also be seen in the development of the bevels at the top of the deposit. Although Fig. 4(A) cannot really be used for comparison due to pinch-off, Figs. 4(B) and 4(C) show an increase in the bevel angle consistent with increases in sputtering and ion reflection [compare Fig. 4(B): bevel angle$=43°\pm4°$ and Fig. 4(C): bevel angle$=51°\pm3°$). Note that this higher scattering will also apply to the high energy Ar neutrals which backscatter from the magnetron sputtering target, causing them to lose energy in each scattering event. This energy loss will result in lower overall sputtering rates for the substrate, which contribute to the decrease in the overburden's lateral dimension, and an increase in trench deposition.

B. rf power

Figure 5 shows a series of experiments in which the rf power was varied. The magnetron power was set at 300 W, the dc bias was set at −25 V, and the Ar pressure was at 30 mTorr (4.0 Pa). Figures 5(A)–5(C) show the cross section of experiments carried out at rf powers of 300, 600, and 1000 W, respectively. The increase in rf power clearly results in a decrease in the top-to-bottom ratio (from 1.65 ± 0.15 at 300 W to 1.36 ± 0.07 at 1000 W). Furthermore, an increase in the overall deposition rate is present [$35\%\pm8\%$ over Figs. 6(A)–6(C)].

The increase in rf power also results in an increase in the relative ionization of Cu. The increase in the amount of ions increases both the overall deposition rate and the ion-to-neutral ratio. This also makes the deposition more directional, and the top-to-bottom ratio decreases. In addition, the increased number of ions leads to a higher incidence of ion reflections and sputtering, which can be seen in the increase in the bevel angle and lateral dimension of the overburdens, and the shrinking of the seams [see Figs. 5(A)–5(C)].

C. Magnetron power

Figure 6 shows a series of experiments in which the magnetron power was varied. The rf power was set at 1000 W, the bias voltage was set at −30 V, and the Ar pressure was at 30 mTorr (4.0 Pa). To insure the same deposited layer thickness for comparison purposes, the deposition times were scaled accordingly. Figures 6(A)–6(C) show the cross section of experiments carried out at magnetron power-deposition time values of 2000 W—3.6 min, 600 W—12 min, and 300 W—24 min, respectively. With the according time scaling, the thickness of the deposited layer is the same for the three experiments (within 140 nm of each other), but the top-to-bottom ratio noticeably decreases with decreasing magnetron power [from 2.18 ± 0.22 for Fig. 6(A) to 1.28 ±0.07 for Fig. 6(C)].

The decrease in magnetron power obviously decreases the rate at which Cu particles are generated (which was compensated for by appropriately scaling the deposition times) and thus the overall deposition rate. This lowers the average density of Cu particles in the rf plasma. Since the rf power is unchanged, the relative ionization of Cu increases due to an increased ionization rate. The increased relative ionization allows more directional deposition and, therefore, a decrease in the top-to-bottom ratios, as well as the development of bevels. Seams appear to fill between Figs. 6(B) and 6(C), but little to no seam appears in Fig. 6(A). This is due to the isotropic angular distribution effect of the neutrals dominating the deposition.

D. Sample voltage

Figure 7 shows a series of experiments in which the substrate voltage was varied. The magnetron power was set at 300 W, the rf power was set at 1000 W, the Ar pressure was at 30 mTorr (4.0 Pa), and the deposition time was 24 min. Figures 7(A)–7(D) show the cross section of experiments carried out at dc biases of −5, −20, −30, and −50 V, respectively. Across this range, the substrate voltage had only a limited effect on the overall deposition rate (experiments were within 90 nm of each other), and the top-to-bottom ratio was relatively unchanged [with the exception of Fig. 7(D), but a pinch-off had formed in that experiment]. The ion-to-neutral ratio had not changed—the ion energy had just

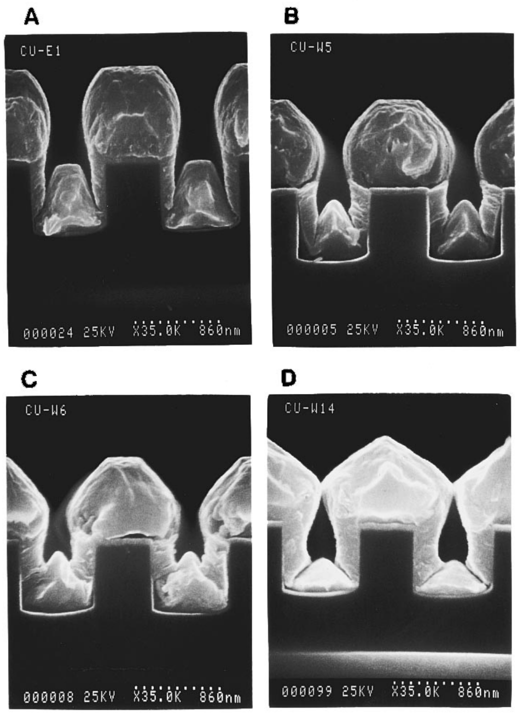

FIG. 7. Effect of increasing dc bias on deposit morphology at constant magnetron power (300 W), rf power (1000 W), Ar pressure (30 mTorr), and time (24 min). Shown are cross sections of patterned wafers at (A) −5 V, (B) −20 V, (C) −30 V, and (D) −50 V.

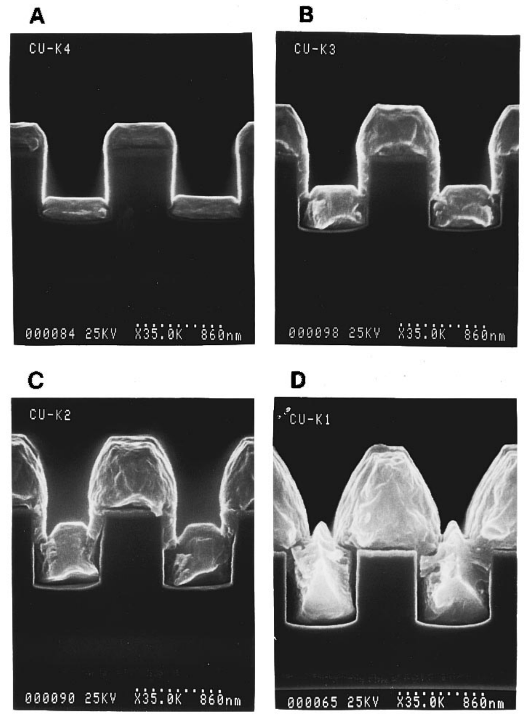

FIG. 8. Time evolution of Cu deposition into a 600 nm trench with an aspect ratio of 1.1:1. Deposition conditions were magnetron power=300 W, rf power=1000 W, Ar pressure=45 mTorr, and dc bias=−12 V. Shown are cross sections at (A) 10 min, (B) 20 min, (C) 30 min, and (D) 40 min.

increased. The increase in bias voltage resulted in an increase in the amount of reflection and sputtering [see Figs. 7(A)–7(D)], shown in the development of deep bevels and pinch-offs in the Figs. 7(A)–7(D) sequence. The increased reflection and sputtering helped fill the seams in the corners of the trenches, and caused growth of the trench wall deposit, but beyond −30 V, the reflections and sputtering events were creating detrimental pinch-offs.

E. Time evolution and trench filling

Figure 8 shows the time development of a deposition experiment in which the trenches are filled. For this experiment, the magnetron power was set at 300 W, the rf power was set at 1000 W, the dc bias was set at −15 V, and the Ar pressure was at 45 mTorr (6.0 Pa). Figures 8(A)–8(D) show deposition periods of 10, 20, 30, and 40 min, respectively. After 10 min, the Cu deposition appears to have come from normal incidence, but reflection and sputtering effects can be seen in the development of a slight bevel, and an angled sidewall deposit. After 20 min, the bevel becomes more pronounced, but reflection and sputtering in the trench seems to be causing slow and uniform growth of the overburden, and the seams are relatively small in comparison to the total trench deposition. After 30 min, the overburden is still growing at a rate that is small in comparison with trench growth, and the seams continue to be relatively small. Figure 8(D) shows the experiment which, after 40 minutes, has formed a completely filled trench, and an overburden which seems to be meeting up with the seams, rather than threatening to cause a pinch-off. (Throughout the entire sequence, the top-to-bottom ratio was approximately one.) This final result indicates that further deposition is possible without the occurrence of a pinch-off. This suggests that the experimental conditions are suitable for filling trenches with more aggressive aspect ratios.

IV. CONCLUSION

Directional sputter deposition has the promise of being an effective and useful metallization process in the semiconductor industry. An exploration of the experimental parameters which control this process reveal an interesting interplay between the flux of particles from magnetron sputtering that arrive at the substrate at a broad angular distribution, and the flux of ions from the rf plasma which arrive at or near normal incidence. The ion flux has an additional effect on the morphology of the deposit by redistributing the metal through Cu and Ar ion sputtering and Cu ion reflection. The morphologies produced on 600 nm semiconductor trenches are dependent on the ion-to-neutral ratio, the total flux, and the average ion energy. Ar pressure, rf power, and magnetron power affect the ion-to-neutral ratio and the total flux, and the bias voltage affects the average ion energy. By prior selection of these parameters, it has been shown that the morphology can be controlled to fill these trenches with an aspect ratio of one, and experimental evidence indicates the ability to fill smaller trenches with larger aspect ratios, indicating directional sputter deposition's promise as a damascene process.

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