Ionized physical vapor deposition of Cu for high aspect ratio damascene trench fill applications

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The ionized physical vapor deposition technique is used to fill high aspect ratio trenches with copper. This technique allows directional filling of embedded features, known as damascene, by sputtering metal atoms into a high density plasma. Large metal-atom ionized-flux fractions are achievable ($\approx$85%) leading to high directionality of deposition at the biased substrate. In this article, we report quantitative measurements of fill directionality of Cu using an inductively coupled plasma (ICP) high density source. Copper is deposited into fairly aggressive (depth/width $\leqslant 1.5$) damascene trenches. Metal ion flux fractions are estimated from direct measurement of the trench step coverage and compared to simulation. Estimates of the Cu+/Ar+ density ratios are also made to understand the influence of applied ICP power and Cu atom density (magnetron power) on fill directionality. It is found that at high magnetron powers (high copper atom densities) the plasma becomes "copper rich," where the flux of copper ions exceeds that of the argon ions. At low magnetron power and high ICP power, we find the trench fill to be highly directional. As magnetron power is increased, directionality suffers due to cooling of the plasma by higher copper atom flux.

I. INTRODUCTION

Current sputter-based metallization techniques were designed for blanket film deposition, followed by reactive ion etch (RIE) patterning, to produce interconnect lines and vias. However, the sputtering process produces a flux with a roughly cosine angular distribution. When attempting to utilize this technology to fill high aspect ratio vias and trenches embedded in the substrate, known as damascene features, significant voiding occurs due to the nearly isotropic flux (pinch off). The industry is currently studying metallization techniques that produce void-free fills.

A number of deposition methods are under consideration, or currently in production. These include chemical vapor deposition,[1] electroplating,[2] mechanical collimation[3,4] of sputtered species and ionized physical vapor deposition (I-PVD).[5–7] A review describing directional deposition techniques based on sputtering is available.[8]

The I-PVD technique involves sputtering metal atoms into an inductively coupled plasma (ICP) region, although Cu atoms have also been evaporated into an electron cyclotron resonance (ECR) plasma region,[9] producing high ionization fractions. The metal atoms are ionized in the high-density plasma, where they fall across a thin sheath at the biased wafer. These ions are thus electrostatically collimated to produce a highly directional trench (or via) fill. Ion energies at the wafer are easily controllable by wafer bias.

This method has been the focus of previous experimental characterization[5–7] as well as modeling.[10,11] In this study, we report evaluation of the directional deposition in fairly aggressive aspect-ratio (AR = depth/width $\leqslant$ 1.5) damascene trenches using I-PVD. The profiles achieved are compared to simulation[11] to assist in determining optimal process characteristics. This information is then used to qualitatively describe the synergistic interaction between magnetron and ICP powers, and their accompanying effects on fill directionality.

II. EXPERIMENT

A 28.5-cm-diam Cu target was used in an Applied Materials Endura rotating-magnet magnetron to sputter metal atoms into the high-density plasma region. Magnetron power could be varied over the range 0–3 kW. The rf power applied to the two-turn copper coil could also be varied to 3 kW. The wafer was mechanically clamped using a conventional Applied Materials perimeter clamp and substrate assembly, eliminating concerns with backside wafer electrical contact and conduction of current through the wafer. Substrate bias for these experiments was dc, variable from 0 to -100 V dc, although rf biasing could also be used. All experiments were performed at low bias voltage, $V_{\mathrm{bias}} = -10$ V dc. The substrate assembly was water cooled, with the maximum measured temperature for all experiments below 50 °C. The wafer position was 15 cm below the Cu cathode, and 5 cm below the two-turn ICP coil. The coil was constructed of 1 cm copper tubing to allow water cooling through the matching network. A schematic of the deposition tool appears in Fig. 1.

Although not shown in Fig. 1, the complete tool consists of two chambers, each outfitted with similar Endura class rotating-magnet magnetron sources. The first chamber is used to deposit a Ta adhesion layer at low pressure ($\approx$0.2 Pa). The wafer is then passed *in situ* to the ionized-PVD chamber for processing. This enables Cu to be deposited cleanly without a pre-deposition sputter clean that would be necessary following an up-to-air vent to transfer the wafer from the Ta chamber. This closely simulates the path a wafer would take to copper deposition in a production tool. The

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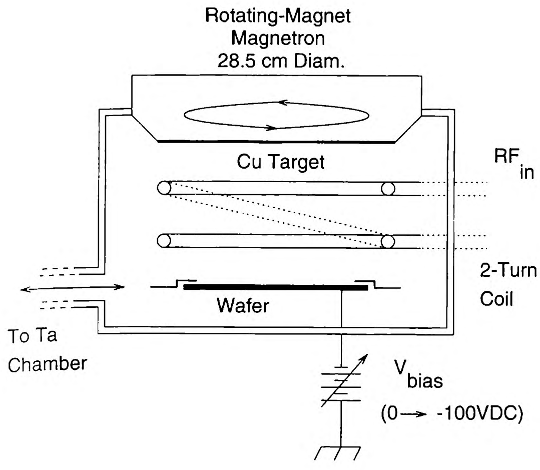

FIG. 1. Schematic view of I-PVD apparatus. Not shown is the Ta PVD chamber used to deposit an adhesive layer prior to Cu deposition.

complete system is capable of processing 20-cm-diam wafers. However, for this study, only small samples in the center of the wafer position are examined.

The samples were Si wafers prepared with a SiO_2 dielectric layer. Trenches and vias were etched into the dielectric layer, with a depth of 1.2 μ, presenting a variety of aspect ratios up to AR = 2.4 (width = 0.5 μ). Prior to Cu deposition, a layer of Ta was deposited *in situ* as an adhesion layer. The Ta layer was generally much thicker ($\approx$450 Å) than that normally used as an adhesion layer ($\approx$50–100 Å) to ensure good conformality. The thick Ta layer also served to assist in the analysis of each sample via high resolution scanning electron microscopy (SEM). Each sample was cleaved in air at room temperature.

Previous results indicate that metal-ion flux fractions (metal-ion flux/total metal flux) are highly dependent on background pressure.[5,6] This fraction ranges from $\approx$20% at 0.66 Pa to $\approx$80% at 6 Pa. In this study, we maintain a pressure of $\approx$ 6 Pa in order to ascertain the effect of varying ICP and magnetron powers on fill directionality.

Figure 2(a) shows a typical damascene trench fill as found in this study. Figure 2(b) gives the positions measured to quantify step coverage, which is defined as the relative thickness of the film on the sidewall, top, and bottom of the trench. The particular ratios used for the discussion of directionality are $r_1 = a/c$ (bottom trench thickness/top thickness) and $r_2 = b/a$ (sidewall thickness/bottom thickness). A higher value of r_1 indicates a highly directional deposition with an ideal value of unity. A lower r_2 value is also indicative of good directionality with an ideal value of zero. These ideal values of step coverage are required because the sidewall coverage at low bias ($\approx$10 V) and low temperature ($\approx$ RT) is generally columnar in structure leading to overall loss of trench conductivity. A completely directional deposition, $r_1 = 1$, would tend towards lower resistivity due to its large grain structure. The differences in bottom and sidewall film structure are evident in Fig. 2(a).

The step coverage can be used as an empirical indication of flux fraction, provided the deposition time is long enough

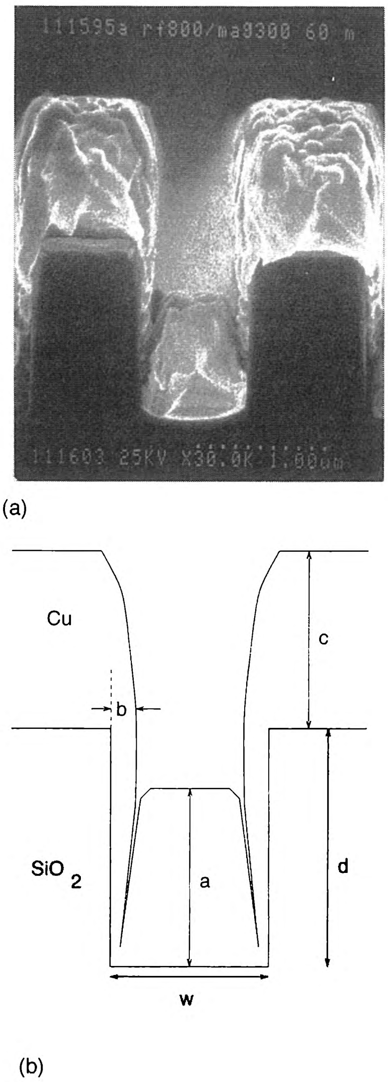

FIG. 2. (a) A representative trench fill (AR = 1.5). (b) The measurement points used for determination of step coverage.

to provide adequate shadowing of neutrals. The parameter r_1 is particularly useful in this regard because it is directly related to the ion-to-neutral flux fraction. At this high pressure (6 Pa), sputtered neutrals lose preferential direction after several collisions with the background, so deposition at the bottom of the trench is assumed mostly due to directed ions. Also, if the assumption of unity sticking coefficient is made, r_1 measures directly the ratio of bottom deposition rate[ions]/top deposition rate[ions + neutrals]. The quantitative nature of this assumption will be tested by comparison to simulation.[11]

In Fig. 3, the ratios r_1 and r_2 are shown as ICP power is varied for several aspect ratios. The magnetron power, and thus the metal-atom density, is kept constant at 600 W. Previous experiments[5,6] indicate that the metal-ion flux fraction saturates at $\approx$100 W to a value of $\approx$85%. For low rf powers, $\approx$400 W, the directionality is seen to be lower by comparing the r_1 and r_2 ratios. As rf power is increased above 800 W, directionality increases as well, indicating an increase in cop-

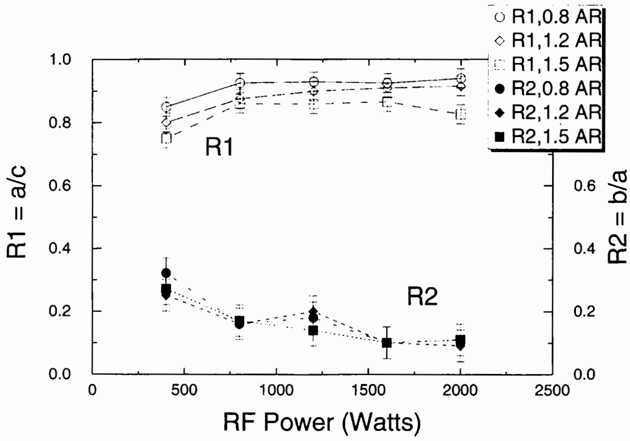

FIG. 3. Step coverage ratios, $r_1 = a/c$ and $r_2 = b/a$, shown as applied ICP power is increased. The magnetron power was kept constant at 600 W, pressure = 6 Pa, wafer bias = −10 V.

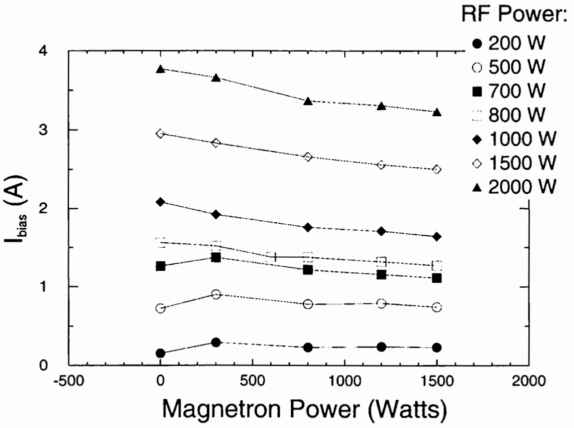

FIG. 5. Collected ion current vs magnetron power for several applied ICP powers. Wafer bias is −40 V, which is well into ion saturation.

per ion flux fraction. Since r_1 seems to saturate at a value somewhat less than unity, the Cu degree of ionization may have also reached saturation.

As rf power is increased even further, ⩾1500 W, direct measurements from the SEM become difficult. In this regime of high ion fluxes collected by the wafer, enhanced surface mobility for the Cu caused recrystallization of the film. This reduced the accuracy of the thickness measurements. However, taking r_1 and r_2 together suggests a dip in the directionality at 2000 W ICP power. More tests will be needed in the high ICP power regime.

Step coverage is shown for various magnetron powers at constant ICP power (800 W) in Fig. 4. We see that reduction of directionality by a decreasing r_1 and an increasing r_2 as metal-atom density is increased. Previous results[5,6] and modeling[10] have suggested that as metal-atom density is increased, flux fraction decreases markedly. This is primarily due to cooling of the high-density plasma by introduction of metal atoms where the ionization potentials ($IP_{Cu}=7.7$ eV) are much lower than the background gas ($IP_{Ar}=15.7$ eV). This cooling phenomena can be seen by the reduction of collected substrate current as magnetron power is increased, as shown in Fig. 5.

However, as magnetron power is increased, the local background gas density has been shown to decrease substantially.[12] This would have the effect of increasing the sputtered copper mean free path, which decreases the probability of ionization in the high-density plasma.[6] This gas rarefaction effect would also likely contribute to the decrease in collected ion current versus magnetron power in Fig. 5.

ICP sources have been shown to saturate with rf power due to neutral depletion by rarefaction[13] under certain conditions, but collected ion current at the wafer does not indicate saturation (see Fig. 6). In fact, as is generally the case for high-density plasma sources[5,6,10,13,14] the plasma density increases linearly with input power. This is seen in this experiment by the roughly linear increase in collected wafer current as ICP power is increased. Thus very little Cu ion flux

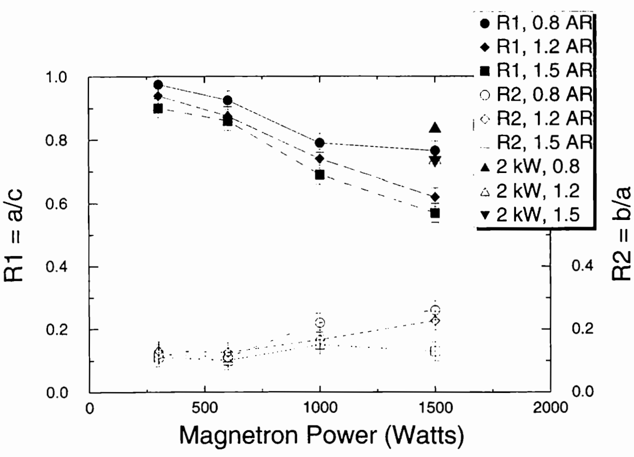

FIG. 4. Step coverage vs magnetron power. The applied ICP power was kept constant at 800 W, pressure = 6 Pa, wafer bias = −10 V. An additional run at higher ICP power (ICP = 2 kW, Mag power = 1.5 kW) is shown as triangles.

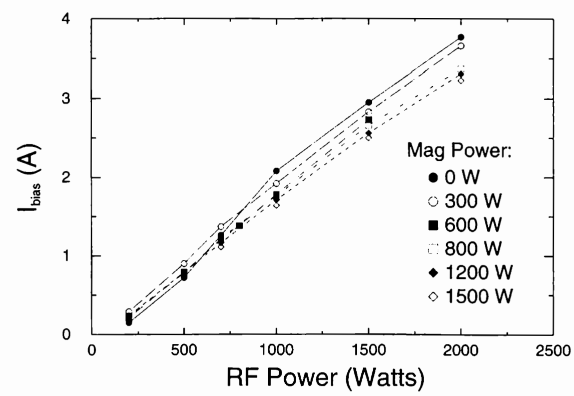

FIG. 6. Collected ion current vs applied ICP power for several magnetron powers. Wafer bias is −40 V.

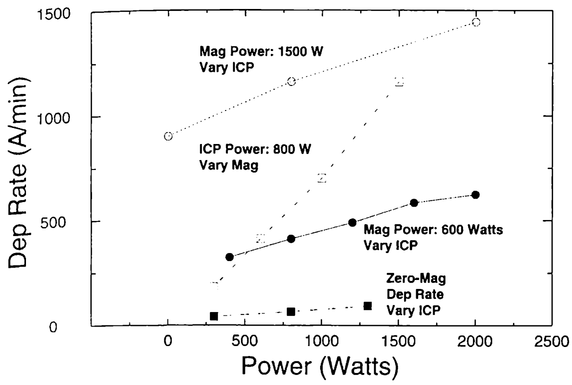

FIG. 7. Deposition rates vs magnetron and ICP power. The deposition rates for varying ICP power at zero magnetron power is also shown.

fraction is expected to be lost due to rarefaction of the background by the ICP, although this may be more important at higher powers.

A single run was completed at ICP power=2000 W and magnetron power=1500 W in order to determine if the plasma cooling effect seen upon introduction of Cu atoms could be compensated by increasing ICP power. These data points appear as triangles in Fig. 4, where we show the ratio r_1 for three aspect ratios. What we note is that increasing ICP power does compensate somewhat by increasing the Cu flux fraction to levels similar to that seen at ≈600–700 W magnetron power. This is probably due to the increasing temperature required to maintain a high argon ion density. This suggests that one method of increasing deposition rate while maintaining directionality is simply to increase ICP power with magnetron power. The higher power regime will be studied in the future.

The Cu deposition rates for the parameter space under consideration appear in Fig. 7. We note that the deposition rate is linear in magnetron power, which would be expected with a linear increase in Cu density. Also notable is the linearity in deposition rate with ICP power. This behavior is maintained for two constant magnetron powers, although the rate of increase is greater for the 1500 W case. The deposition rate for zero magnetron power is also shown in Fig. 7. Part of this increase in Cu deposition rate is presumed to be due to sputtering of the copper coil through capacitive coupling. However, the zero-magnetron deposition rate alone does not account for the increase in deposition rate with ICP power for the 0.6 and 1.5 kW magnetron powers shown.

We note that in raising the ICP power from 800 to 2000 W, the deposition rate increases by approximately the same factor as the increase in power, relative to the zero power case. The Cu ion current density also increases by a similar factor. This suggests that as applied coil power (plasma density) is increased, sputtering from the copper coil becomes more important. Because the copper ion density increases as well, ionization of coil species appears to be as efficient as for copper originating at the Cu target. The voltages on the coil were not measured for each run, but was found to be in the range of several hundred volts.

As is shown below, the plasma becomes ''copper rich'' at high magnetron powers. Thus the apparent rate of increase in deposition rate with ICP power should be larger at higher magnetron power due to the higher sputter yield of Cu on Cu over Ar on Cu. This is seen to be the case in Fig. 7 where the slope of the deposition rate versus ICP power is higher for 1500 W (269 Å/kW min) than 600 W (193 Å/kW min).

III. DISCUSSION

In order to test the assumption that r_1 directly represents the Cu ion flux fraction, we compare the data to a numerical model previously used to simulate I-PVD fill profiles.[11] We find that with the assumption of non-collimated, completely isotropic neutral flux, the Cu ion flux fraction and r_1 track fairly well. However, the simulation accounts for the fraction of Cu neutral flux that does reach the bottom of the features, while letting $r_1=\delta$ assumes only Cu ions are incident at the bottom of the trench. Thus we use the simulation value, matched to the SEM photographs, as the actual value of δ in the following discussion.

With an estimate of Cu ion flux fraction, we can also make estimates of the fraction of the total plasma density that is Cu ions. For this analysis we assume the directionality and deposition rate to be uniform over the entire wafer surface. This will not be true in general, but will be useful for qualitative estimates of global density fractions.

The deposition rate of Cu, R_T, and the total collected ion current, j_T, are given by

$$R_T=R_o+R_+, \tag{1}$$

$$j_T=j_{\mathrm{Ar}}+j_+, \tag{2}$$

where R_o=deposition rate due to Cu neutrals only, j_{Ar} =current density due to Ar ions only. The Cu ion current density, j_+, and the Cu ion deposition rate, R_+, can be related if we assume unity sticking coefficient. Further, this analysis ignores the effect of secondary electrons on the collected ion current, which is expected to introduce an error of less than 5%. Using the above assumptions

$$j_+=\frac{I_+}{A_w}=\frac{eR_+}{d_+A_+}, \tag{3}$$

where A_w=area of current collecting substrate [cm^2/], d_+=diameter of a single Cu atom (2.8 Å), and A_+=area of a single Cu atom [cm^2/atom].

The Cu ion flux fraction is defined in Eq. (4). Assuming unity sticking coefficient and using Eq. (1):

$$\delta=\frac{\Gamma_{\mathrm{Cu}_+}}{\Gamma_{\mathrm{Cu}_+}+\Gamma_{\mathrm{Cu}_o}}=\frac{R_+}{R_o+R_+}, \tag{4}$$

where Γ_{Cu_+} is the Cu ion flux and $\Gamma_{\mathrm{Cu}_+}+\Gamma_{\mathrm{Cu}_o}$ is the total copper flux. Equation (4) gives the copper ion deposition rate, $R_+=\delta R_T$ for a known δ.

Assuming that the collected current for each species is driven by Bohm presheath diffusion, we can write the ratio of Cu ion density to Ar ion density in the bulk of the high density plasma as

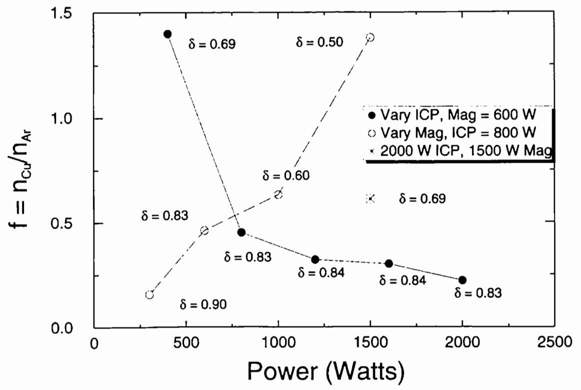

FIG. 8. Cu+/Ar+ ion density ratio vs. magnetron and ICP powers. The value of the Cu ion-flux fraction δ is shown for each case.

$$f=\frac{n_{\mathrm{Cu}}}{n_{\mathrm{Ar}}}=\sqrt{\frac{m_{\mathrm{Cu}}}{m_{\mathrm{Ar}}}}\frac{j_+}{j_T-j_+}, \tag{5}$$

where m_{Cu} and m_{Ar} are the masses of copper and argon (in amu), respectively, and n_{Cu} and n_{Ar} are the individual bulk ion densities.

Figure 8 shows the Copper density ratio, f, using the area of the wafer clamp (diameter = 31 cm) as the current collecting surface, and the simulation values of δ. We note that as we vary ICP power, while keeping magnetron power constant, the Cu/Ar ion density ratio, defined by Eq. (5) decreases rapidly in the beginning with a slightly less dramatic falloff past $\approx$800 W. This indicates that most of the extra ICP power is deposited in the argon background after the Cu ion density saturates. Coupled with previous results at lower rf power,[5,6] we find that rf coupling to Cu is very efficient, while a distinct cooling effect takes place upon introduction of Cu. But as power is increased, the electron temperature also increases to accommodate coupling to argon.

The effect of varying magnetron power is also seen in Fig. 8. Here the density of Cu increases with respect to the argon almost linearly in magnetron power. In fact, at higher magnetron powers, the copper ion density reaches almost $1\frac{1}{2}$ times that of argon at 1500 W, and may go even higher as magnetron power is increased. However the reduction in copper ion flux fraction with magnetron power suggests that while the copper density ratio, f, may increase, the accompanying decrease in electron temperature reduces the Ar ion density.

Over the range shown in Fig. 8, magnetron power is increased by a factor of 5, Cu deposition rate increases by a factor of 6, and the Cu+/Ar+ ion density ratio increases by a factor of 9. However, the Cu ion flux fraction decreases by $\approx$ 2 over the same range. From Bohm pre-sheath assumptions,

$$j_T=0.61e\left(\frac{n_{\mathrm{Cu}}}{\sqrt{M_{\mathrm{Cu}}}}+\frac{n_{\mathrm{Ar}}}{\sqrt{M_{\mathrm{Ar}}}}\right)\sqrt{T_e} \tag{6}$$

the ratio of total current density at power levels A and B from Figs. 5 and 6, and the Cu+/Ar+ ratios from Fig. 8 we can write as the ratio of Bohm currents for each species as

$$b_{+,\mathrm{Ar}}\equiv\frac{j_{+,\mathrm{Ar}_\mathrm{A}}}{j_{+,\mathrm{Ar}_\mathrm{B}}}=\sqrt{\frac{T_{e_\mathrm{A}}}{T_{e_\mathrm{B}}}}\frac{n_{+,\mathrm{Ar}_\mathrm{A}}}{n_{+,\mathrm{Ar}_\mathrm{B}}}. \tag{7}$$

In going from 300 to 1500 W magnetron power at 800 W ICP power, we get Bohm current ratios of $b_+=0.25$ and $b_{\mathrm{Ar}}=2.2$, i.e., we see a fourfold increase in Cu ion flux while Ar ion flux is halved. The decrease in Ar ion flux is likely due to a decrease in electron temperature which accompanies an increase in Cu atom density.[5,6,10] The reduction in Cu ion flux fraction is also likely due to reduced electron temperature.

We note that the increase in deposition rate due to the Cu ions is only a factor of 3.3, not the factor of 4 that we get for the increase in Bohm flux of Cu ions. This discrepancy can be understood by noting that the deposition rate and Cu ion flux fraction were measured at a single point (center of 20 cm wafer), while the ion current was collected over the entire surface. Thus any non-uniformities in the plasma would cause errors in this analysis. Because the above factors agree within 20%, this error is small and the general trends are uncompromised.

It was shown previously that increasing ICP power at high magnetron powers did indeed increase directionality (see Fig. 4). That same run (ICP power = 2 kW, magnetron power = 1.5 kW) is shown in Fig. 8. The Cu ion flux fraction is seen to increase to $\delta=0.69$, from 0.5, as the ICP power is increased from 800 to 2000 W. Further, the Cu ion density fraction decreases by a factor of $\approx$2.3. Over the same range, the total collected ion current, shown in Fig. 5, increases 2.5 times. We get Bohm flux ratios of $b_+=0.63$ and $b_{\mathrm{Ar}}=0.55$. The Ar ion flux is seen to increase slightly more than the Cu ion flux. Since the Cu ion flux fraction also increases, the electron temperature probably increases which promotes ionization of Ar and an increase in the Cu degree of ionization.

IV. CONCLUSIONS

The ionized-PVD method has been used to fill damascene trench structures with copper. The directionality of the fill, which is closely related to the trench microstructure and thus the interconnect resistivity, has been studied as a function of ICP power and Cu atom density. It is found that the cooling of the high-density plasma associated with an increase in metal-atom density (magnetron power) decreases the fill directionality. Conversely, increasing ICP power at low magnetron power tends to increase the Cu flux fraction to an asymptotic value of $\approx$85%, consistent with previous results.[6] Increasing ICP power at high magnetron powers can offset the loss of flux fraction somewhat but more work in the high power regime is needed. The effect of coil sputtering is shown to be important as ICP power is increased. The Bohm flux of Cu ions is found to increase as magnetron power is increased, while Ar ion flux decreases. Together with the Cu+/Ar+ flux ratio of Fig. 8, this suggests that copper becomes the dominant ionic species.

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