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Cu Deposition Using a Permanent Magnet Electron Cyclotron Resonance

Microwave Plasma Source

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Abstract

An electron cyclotron resonance (ECR) plasma has been used in conjunction with a solid metal sputter target for Cu deposition over 200-mm diameters. The goal is to develop a deposition process suitable for filling submicron, high aspect ratio features used for ultralarge scale integration. The system uses a permanent magnet for creation of the magnetic field necessary for ECR and is significantly more compact than systems equipped with electromagnets. A custom launcher design allows remote microwave injection with the microwave entrance window shielded from the Cu flux. Cu deposition rates up to 100 nm/min were observed and film resistivities were typically in the low to mid 2 $\mu\text{ohm-cm}$ range. Based on deposition rate measurements at two radial sample positions, uniformities of a few % over 200-mm diameters should be attainable.

Introduction

The properties of Cu make it a desirable material for connecting circuit elements of integrated circuits with submicron features. Compared to aluminum, its high conductivity leads to lower RC circuit delay times, and its higher melting point provides less susceptibility to electromigration. However, the technology for commercially attractive deposition of thin Cu films for this application is not presently available. The constraints on this technology include the need for low-temperature processing, less than about 300°C for compatibility with organic dielectrics, and the need for filling features with aspect ratios of 3:1.¹

W. Holber and colleagues at IBM's T. J. Watson Research Center developed a promising approach which met the technical constraints.² An electron cyclotron resonance (ECR) metal plasma fed by Cu vapor was used to fill features with aspect ratios approaching 4:1. Process temperatures were in the 200°–300°C range. Although the process appears desirable, the design of this deposition system did not have suitable manufacturing characteristics. In particular, the magnetic field needed for the ECR plasma source was produced by large electromagnets, and the metal vapor for feeding the plasma was produced by evaporation from a resistively heated molybdenum boat.

The use of a permanent magnet ECR source and of sputtered neutrals appeared to be a sensible approach to improving the production worthiness of the ECR deposition system. In this article, the uniformity and resistivity of blanket Cu films will be presented, together with initial results from filling submicron features. Inductively coupled plasmas (ICP's) are also candidates for plasma manufacturing processes,³ and other configurations using both ECR and ICP's have previously been examined for metal deposition.⁴⁻⁷ Additional simplification of these sources is still desirable for a production implementation.

Apparatus

A schematic of the deposition system is shown in Fig. 1. The principal elements are a permanent magnet ECR plasma source, a Cu sputter target, and a multipole-magnetic bucket. The ECR source uses a permanent magnet for production of the magnetic field as has been previously used by Mantei,⁸ and the multipole bucket has been previously described.⁹ A custom launcher¹⁰ allows production of plasma densities above the cutoff density^{11,12} even though microwaves are injected initially perpendicular to the magnetic field. This arrangement is essential for positioning of the microwave entrance window so that there is no line of sight path for the Cu flux. Cu deposits on the window thicker than about 10 nm would block microwave transmission.¹³ During operation, argon is injected into the system (~ 100 sccm for 5.0 mTorr), and an ECR microwave plasma is formed with microwave absorption occurring in the sputter target section. Plasma ions are then accelerated towards the Cu target by applying a bias (typically -200 to -300 VDC), and sputtered neutrals can be ionized by the same plasma. Both neutral and ionized Cu atoms contribute to deposition on substrates placed downstream of the sputter target section. At input powers of ~ 1000 W and pressures of 2–5 mTorr, plasma densities for Ar plasmas are typically in the mid 10^{11} cm⁻³ range with electron temperatures of 3–4 eV. The sputter target has an area of 150 cm² and operates at a current of up to 5 A for a target voltage of -300 V, yielding an average current density of over 30 mA/cm². The magnetic bucket has twenty alternating columns of ceramic magnets with a field of 0.08–0.1 T at the plasma boundary.

For the experiments discussed in this paper, Cu films were deposited on B-doped 100 Si substrates, roughly 1 cm by 2 cm. Several samples could be processed simultaneously on a 1.3 cm $\times$ 20 cm sample stage equipped with radio frequency (RF) and direct current (DC) bias and water cooling. The stage was inserted through a differentially pumped load lock, and samples were held in place by tantalum clips. Several samples could be processed at the same time, with locations corresponding to positions on an 200 mm (8") diameter wafer. Despite the cooled stage, evidence of Cu melting was seen for some process conditions, likely as a result of poor thermal

contact between the substrates and the sample stage. The experiments were performed in a portion of the available operating space where no sharp mode boundaries were observed (i.e., plasma characteristics varied smoothly).¹⁴

Resputtering

The previous work by Holber showed that the application of bias, either RF or DC, during the deposition was a necessary process step in successfully filling high aspect ratio features. Without bias, the incoming Cu flux had sufficient perpendicular energy to produce significant sidewall deposition. This sidewall deposition resulted in the feature necking off before it could completely fill. A moderate amount of bias preferentially sputtered the sidewall and allowed filling features up to 4:1 aspect ratio.

Figure 2 shows the net deposition rate as a function of induced DC bias for samples deposited in Ar plasmas with either RF or DC applied bias. Film thicknesses were measured with a Dectak stylus profilometer. Other conditions included a microwave power = 1000 W, Ar pressure 4.0 mTorr, and Cu target bias -260 V. The induced bias in the RF case is the DC component of the sample stage voltage and is measured with respect to ground. The DC bias is also measured with respect to ground. In both cases, the difference between the plasma potential V_p and ground must be added to obtain an indication of the ion energy. Since the floating potentials, V_f , were typically -5 to -9 V, and $V_p - V_f$ is about $3.5 T_e$, the plasma potential is likely 5–10 V above ground and the ion energy about 5–10 eV larger than that inferred from the bias potentials alone.

The RF curve indicates no net film deposition at a bias of about -60 V. The DC curves show no net Cu deposition at a somewhat higher bias, about -80 V, and have significantly lower sputter etch rates of the Si substrate for the larger biases. Profilometer measurements show higher rates adjacent to the clip for the larger DC bias values, suggesting poor electrical contact with the front

face of the sample. Indeed, uniform DC bias is unlikely when there is no net deposition (even with a front-facing contact) because of the low conductivity of the silicon in the absence of a metal film.

The results discussed above can be used to obtain a rough estimate of the ratio of argon ion current to the Cu ion and neutral fluxes. With no bias, the deposition rate is about 60 nm/min which is equivalent to a Cu flux, both ions and neutrals, of 1.4 mA/cm². This deposition is balanced by sputtering from both argon and Cu ions. Namely,

$$S(J_{Ar}^+ + J_{Cu}^+) = J_{Cu}^0 + J_{Cu}^+$$

where S is the sputter yield at the energy for no net deposition (assumed equal for Cu and Ar) and J_{Ar}^+ , J_{Cu}^+ , and J_{Cu}^0 are, respectively, the argon and Cu ion currents and the Cu neutral flux.

At an ion energy of 70 eV, the sputter yield of Ar on Cu is about 0.35.¹⁵ The ratio between the Cu ion and neutral fluxes is not known. However, by assuming that one or the other is dominant, an indication of the corresponding argon ion current may be obtained. For neutral dominated deposition, we find $J_{Ar}^+ = 1.4/.35$ mA/cm² $\approx$ 4 mA/cm², while for ion dominated deposition, we find $J_{Ar}^+ = .65/.35$ mA/cm² $\approx$ 2 mA/cm². Both values are consistent with argon ion densities of about 10¹¹ cm⁻³.

As discussed above there is no direct measure of the ratio of Cu ion to neutral flux, however two measurements suggest that there is a substantial ion flux. First, half micron, 3:1 aspect ratio features have been partially filled. For 5 mTorr argon pressures, the feature sidewalls and bottom typically have fairly uniform coverage with no evidence of necking or the preferential deposition that would be expected for isotropic deposition.

Second, a qualitative indication of the ion to neutral flux has been obtained by looking at deposition rates as a function of sample orientation. For 5 mTorr, the deposition rate at 90° is 1/5 that of normal incidence and at 2 mTorr the corresponding ratio is 1/10. At 5 mTorr, the ion-neutral or neutral-neutral mean free path is in the range 2–3 cm, some 5–7 mean free paths from the

sputter target. At this distance, the neutrals sputtered from the target should be nearly isotropic, which is inconsistent with the anisotropy observed.

While we do not have a complete understanding, the anisotropy is consistent with ions which are created and accelerated by ambipolar fields within a few mean free paths of the sample.

Blanket Properties

Table 1 summarizes film uniformity results for a fractional factorial experiment of the form 2^{4-1}_{iv} .¹⁶ Uniformities were derived using $[(\text{deposition rate at center}) - (\text{deposition rate at radius} = 10 \text{ cm})]/2$. A negative uniformity indicates a lower deposition rate at the center. While no particular attempt to optimize uniformity was made, it appears that obtaining one sigma uniformities in the range of a few percent should be attainable. With respect to deposition rates, analysis of this experiment indicated that the rate could be maximized by using the highest microwave power, target voltage, and pressure, while moving the sample to its closest possible position relative to the target. For these conditions, we observed a deposition rate of over 100 nm/min.

As a whole, deposition rates are significantly lower than desired for a commercially attractive process. Higher microwave power to increase the current density at the target and larger target areas are being investigated as a means of increasing deposition rates to a commercially interesting range. Sputtering rate increases of about a factor of ten should be possible for the source. In addition, the higher plasma density should increase the Cu ion-to-neutral ratio and result in improved fill characteristics.

Film resistivities were measured using a four-point probe. Shape and size correction factors were estimated from ref. 17 and resulted in resistivity values 5%–15% below uncorrected values. Resistivities were typically in the low- to mid-2 micro-ohm-cm range and were slightly below

2 micro-ohm cm for runs 2 and 6 in Table I. No attempt to reduce these resistivities through annealing was made.

Conclusions

A series of experiments to determine the blanket characteristics of deposited Cu films using a permanent magnet ECR plasma source have been completed. These experiments indicate that deposition uniformity over a 200 mm (8") diameter wafer is likely to be acceptable. Deposition rates are lower than desired, and several modifications are under way to significantly increase those rates. The resistivity of the as-deposited Cu films is in the low to mid 2 μ ohm-cm range, and preliminary runs investigating the ability to fill submicron features show straight side walls, which suggests that complete fills without significant void formation may be possible.

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TABLE I. Experimental Conditions and Results for Cu Deposition.

Run	Pressure (mTorr)	Power (Watts)	Cu Target Voltage (V)	Distance from Target (cm)	Average Deposition Rate (nm/min)	Uniformity (%)
CuExp1-1	2	750	-200	14.3	39.2	9.2
CuExp1-2	5	750	-260	14.3	61.8	-1.4
CuExp1-3	2	1200	-260	14.3	62.5	6.7
CuExp1-4	5	1200	-200	14.3	78.3	12.9
CuExp1-5	2	750	-260	21.9	27.1	15.1
CuExp1-6	5	750	-200	21.9	23.0	8.7
CuExp1-7	2	1200	-200	21.9	28.5	5.3
CuExp1-8	5	1200	-260	21.9	40.5	8.6

Figure Captions

Fig 1. Outline drawing of the ECR plasma processing system used for Cu deposition.

Fig 2. Cu deposition rate as a function of induced DC sample bias for both DC and RF applied bias. Plasma conditions were: net microwave power = 1000 W, pressure = 4 mTorr, and Cu target bias = -260 V.

Fig 1