Magnetron sputter deposition with high levels of metal ionization

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A new deposition technique has been developed which combines conventional magnetron sputter deposition with a rf inductively coupled plasma (RFI). The RFI plasma is located in the region between the magnetron cathode and the sample position, and is set up by a metal coil immersed in the plasma. A large fraction of the metal atoms sputtered from the magnetron cathode are ionized in the RFI plasma. By placing a negative bias on the sample, metal ions are then accelerated across the sample sheath and deposited at normal incidence. Results from a gridded energy analyzer configured with a microbalance collector and located at the sample position indicate the level of ionization is low at a few mTorr and rises to $>80\%$ at pressures in the 25–35 mTorr range. Optical measurements of metal ion and neutral emission lines show scaling of the relative ionization to higher discharge powers. Significant cooling of the plasma electron temperature is observed when high concentrations of metal atoms were sputtered into the plasma.

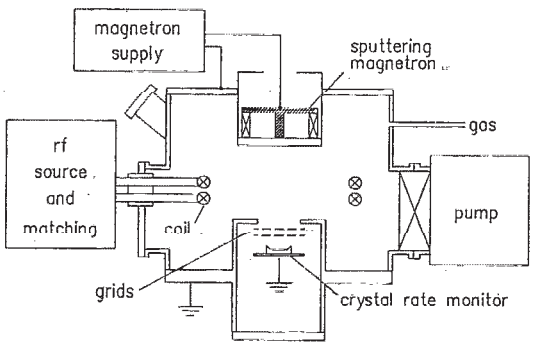
Magnetron sputter deposition is extensively used to produce thin films and hard coatings because of its high rate, ease of scaling, and the quality of the deposited films. As semiconductor linewidth dimensions have shrunk, and the aspect ratios of vias, studs, and trenches have increased (aspect ratio=depth/width of feature), it has become evident that magnetron sputtering cannot meet future technology needs. While one of the original strengths of magnetron sputter deposition was the ability to deposit continuous films over bumps or lines, known as step coverage, the mechanism behind this capability limits its applicability for higher aspect ratio features.

Sputtering is generally characterized by a spatial emission profile for the sputtered atoms which is roughly described as a cosine distribution. Significant variations from this distribution are observed depending on the incident ion energy,[1,2] surface crystallinity,[3,4] surface roughness, or topography, the presence of intentionally machined or textured surfaces,[5] as well as materials and gas choice, and gas pressure.[6] The details of the distribution are not critical: the obvious result is that atoms are emitted into a wide range of angles with respect to the surface normal.

The roughly cosine emission distribution, coupled with a large area cathode located only 5–10 cm from the sample results in a very broad angular distribution in the arrival of sputtered atoms at the sample surface. This provides good step coverage on low aspect ratio features, but fills deep features poorly due to the buildup of overhanging sidewalls.

Several attempts have been made to modify the metal deposition process. The presence of a physical filter, or collimator, between the cathode and sample limits the angular spread of the deposition.[7] Collimation also severely reduces the deposition rate. It is possible to use large levels of substrate bias to bombard the growing films[8] or substrate temperatures of 500 °C or more. This is limited to low aspect ratio features (1:1) and can be difficult to implement on heat- or charge-sensitive samples. A third technique makes metal films by direct deposition from a metal, or metal-rich plasma. Metal ions are accelerated across the sample sheath at normal incidence with little angular divergence. These metal ions then form the deposited film.[9–11]

The ionized magnetron sputter deposition experiment was configured as in Fig. 1. A 200 mm diam, circular planar cathode[12] was used, with high purity cathodes of AlCu or Cu. The inductively coupled rf plasma was set up by a two turn, water cooled metal coil with a diameter slightly larger than the cathode diameter. The coil was located in the region between the cathode and the sample, approximately 3–4 cm from each. The matching network was modified from an L configured matching network by removing the inductor, and placing the plasma coil in series with a third, grounded capacitor. The sample consisted of a gridded energy analyzer. Two grids of 300 mesh etched Ni were used to isolate the detector from the plasma and admit or repel ions. The collector was configured with a quartz-crystal microbalance which measured both the total ion current as well as the mass of the depositing film. This was necessary to differentiate between the ionized Ar working gas and the metal ions. An optical multichannel analyzer was also configured on a window port looking into the dense plasma region.



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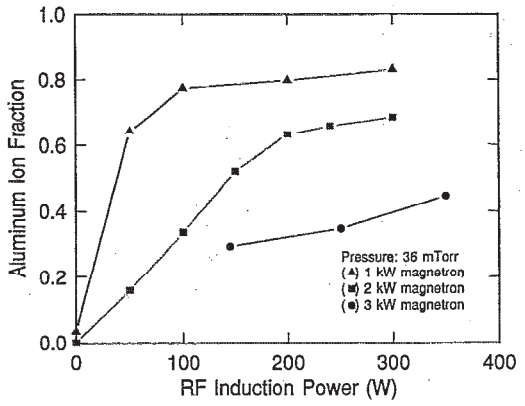

FIG. 2. Relative ionization levels for sputtered Al atoms in a 36 mT Ar discharge as a function of magnetron discharge power and rf inductive plasma discharge power. Data measured with gridded energy analyzer.

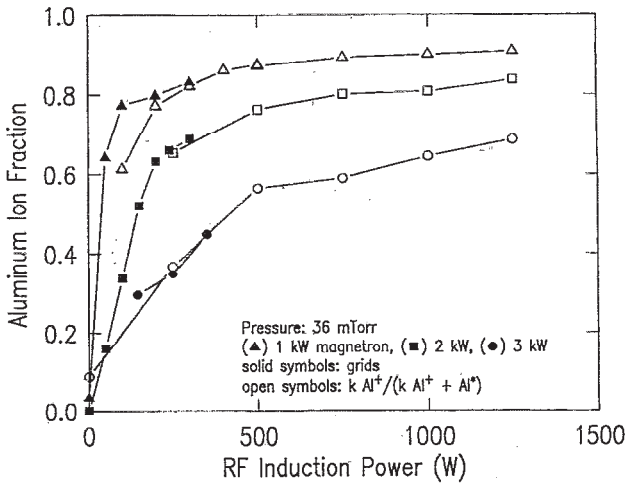

FIG. 3. Relative ionization levels for sputtered Al atoms in 36 mT Ar discharge as a function of magnetron and RFI powers. Solid data points taken using gridded energy analyzer. Open data points taken using optical emission.

By comparing the net deposition rate to the collector with and without ions, the ionization fraction of the metal can be determined. In Fig. 2, the relative ionization rate for Al atoms in Ar at 36 mTorr is shown at low RFI powers. At low magnetron power, the ionization level saturates at about 80%. Increasing the number of Al atoms by increasing the magnetron power results in approximately the same number of ions, but a higher proportion of neutrals. A similar behavior is observed as a function of working gas pressure, with the relative ionization level saturating at 30–40 mTorr for Al sputtering in Ar.

The energy analyzer technique was limited to low rf power (<500 W) because of the high plasma density in the RFI plasma. As the rf power was increased, the plasma was able to penetrate the grid assembly once the Debye length was smaller than the grid dimensions. To examine higher powers, the optical emission levels of the Al excited state and Al ions of similar energy were observed (Al*: 3944 A, 3.14 eV, Al^+: 3901 A, 10.6 eV). This technique is valid if the electron temperature is relatively constant. Since, in general, the electron temperature is a function of ionization potential and geometry of the plasma device–not rf power–the method can be used to extrapolate the ion fraction to high power levels. While this technique is clearly not quantitative, it is useful to observe the general trends in the ionization levels. In Fig. 3, optical data have been added to the gridded energy analyzer data of Fig. 2, matching points in the 100–300 W range. The qualitative behavior is similar: a saturation in the level of ionization is reached in the 65%–85% level.

By changing the working gas to Ne, the relative ionization level at 2 kW of magnetron power was generally 20% higher than for Ar. This may be indicative of increased Penning ionization in the plasma or increased electron impact ionization of the metal atoms due to an increased electron temperature. The use of Ne, as opposed to Ar, also results in a higher net deposition rate due to reduced sputtered atom-gas scattering, since Ne has a smaller collision cross section.

In general, the effect of increasing the level of metal atoms in the plasma through increased magnetron sputtering power was to reduce the relative ionization rate and cool the plasma. This was observed optically as a general reduction in the inert gas optical emission, as well as a reduction in the ion saturation current, which was observed in a related experiment.[13] The first case is complicated by the rarefaction of the gas atoms due to sputtered atom heating.[14] The ion saturation current is a simple function of the electron temperature. At constant RFI power, increasing the magnetron power from 1 to 5 times the RFI power results in about a $2\times$ reduction in ion saturation current, indicative of a $4\times$ reduction in electron temperature under the assumption that the electron and ion density is unchanged. Since the average ionization potential is decreasing as metal is added to the discharge, one might expect that the electron density would remain constant or increase. For example, when Kr substitutes for Ar in a RFI discharge, the density was found to increase by as much as $3\times$.[15]

Most inert gas processing-scale plasmas have a fairly low degree of ionization of the background gas, typically on the order of a percent or less. The plasmas are approximately Maxwellian, with an electron temperature in the eV range, and the rate of ionization by the tail of the distribution sustains the losses from the edges of the plasma. For an Ar plasma, the ionization potential is 15.76 eV. Metal atoms have an ionization potential generally much lower, in the 5–8 eV range. When a metal atom passes through a dense Ar plasma, its probability of ionization is much greater than a comparable Ar atom, and under ideal circumstances approaches 1.0.[16]

Magnetron sputtering can result in very significant particle fluxes into the RFI plasma region. For example, the sputter yield for Ar on Cu is about 2.5 at 500 eV. A 2 kW magnetron discharge at 500 V (4A) yields a Cu atom flux of 6×10^{19}/s, which is equivalent to 140 sccm. Each of these atoms has the capability to absorb (and emit) several tens of eV from the electron population through excitation and ionization. The effect, then, of significant metal fluxes

is to depress the electron temperature, even though the density may increase. Preliminary experiments using a Ti cathode in Ar indicate that approximately 50 eV of additional RFI power is required for each additional Ti atom to recover the same plasma conditions in terms of ion saturation current to a sample.

One application of this technique is the directional deposition of metal ions into high aspect ratio surface features. The net energy of the depositing metal ions is a function of the plasma potential and the sample bias. At moderate energies (10–200 eV) net deposition occurs. Higher energies result in erosion of the deposited films.[13]

It has been shown by Holber *et al.*[10] that directional fluxes of metal can be used to deposit metal films inside high aspect ratio (4:1) trenches and vias. The incident metal ion energy is sufficient to reduce any overhang formation (by sputtering) that might occur at the top of a trench or via. The current technique is slightly more versatile than Holber's work because metal is introduced by sputtering a cathode, rather than evaporation, and the RFI discharge is intrinsically simpler than an ECR plasma. These two features give greater control of film composition and system geometry, respectively, which is intrinsically valuable for such alloys as AlCu or TiW and for manufacturing applications.

This technique has also been scaled to dimensions consistent with semiconductor manufacturing. Typical parameters in this case are a cathode diameter of 30 cm, magnetron discharge power of 20 kW, load-locked sample handling and 200 mm wafer capability. Results from this work, as well as characteristics of the filling or lining of trenches and vias will be discussed elsewhere.[13]

It should be noted that this thin-film deposition device greatly extends the capabilities of thin-film materials science of large area films. The incident energy of the depositing particles can be easily controlled over a wide range of energies. This allows much wider latitude in the physics and chemistry of the deposited films, which was only previously available in small, ion beam experiments or unique, filtered arc systems.

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