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The microstructure of sputter-deposited coatings

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Microstructure is a critical consideration when polycrystalline or amorphous thin films are used for applications such as microcircuit metallization layers and diffusion barriers. The trend in device fabrication toward lower processing temperatures means that such coatings must often be deposited at substrate temperatures T that are low relative to the coating material melting point T_m. The structure of vapor deposited coatings grown under these conditions consists typically of a columnar growth structure, defined by voided open boundaries, which is superimposed on a microstructure which may be polycrystalline (defined by metallurgical grain boundaries) or amorphous. The voided growth structure is clearly undesirable for most applications. Its occurrence is a fundamental consequence of atomic shadowing acting in concert with the low adatom mobilities that characterize low T/T_m deposition, and its formation can be enhanced by the surface irregularities which are common to microcircuit fabrication. This paper reviews some of the recent developments in understanding the fundamental aspects of the relationship between the deposition conditions and the microstructure of sputter-deposited thin films, with particular emphasis on the origin of the growth structure and its suppression through energetic particle bombardment.

I. INTRODUCTION

An essential feature of thin films is that they are formed from a flux that approaches the substrate from a limited set of directions. Consequently, the metallurgical grains tend to be columnar. Furthermore, at low homologous temperatures (substrate temperature T, relative to coating material melting point T_m) a growth structure defined by voided boundaries that are also columnar is superimposed on the intrinsic grain structure as shown in Fig. 1(a). Thus thin film microstructures tend to have an anisotropic character which influences such properties as their magnetic anisotropy and their effectiveness for lateral current transport and as diffusion barriers. For example, the grain or growth boundaries present preferred diffusion paths which often extend through the entire coating thickness. (Activation energies for surface, grain boundary, and bulk diffusion are typically in the ratio 1:2:4 so that at $T/T_m < 0.5$ surface and grain boundary diffusion rates can be orders of magnitude larger than bulk diffusion rates.[1])

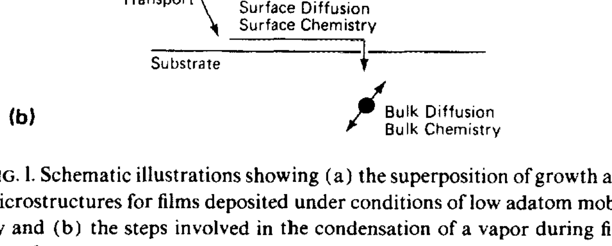

FIG. 1. Schematic illustrations showing (a) the superposition of growth and microstructures for films deposited under conditions of low adatom mobility and (b) the steps involved in the condensation of a vapor during film growth.

It is useful to envision coating growth as proceeding in three general steps as indicated schematically in Fig. 1(b). The *first step* involves the transport of the coating species to the substrate. The *second step* involves the adsorption of these species onto the surface of the substrate or growing coating, their diffusion over this surface, and finally their incorporation into the coating or their removal from the surface by evaporation or sputtering. The *third step* involves movement of the coating atoms to their final position within the coating by processes such as bulk diffusion. In the case of sputter deposition, the transport step is controlled by parameters such as the apparatus geometry and working gas pressure, while the diffusion steps are controlled largely by the substrate temperature, but may be significantly influenced by energetic particle bombardment.

Structure-zone models have proven very useful in providing an overview of the relationship between the microstructure of vacuum deposited coatings and the most prominent deposition parameters. The first such model was published by Movchan and Demchishin (MD) in 1969.[2] MD found that the microstructures of thick (0.3 to 2 mm) evaporated coatings of Ti, Ni, W, ZrO and Al_2O_3 could be represented as a function of T/T_m by three zones, each with its own characteristic structure and physical properties. The low temperature ($T/T_m < 0.3$) *zone 1* structure was columnar, consisting of tapered units defined by voided growth boundaries of the type shown in Fig. 1(a). The *zone 2* structure ($0.3 < T/T_m < 0.5$) consisted of columnar grains, which were defined by metallurgical grain boundaries and increased in width with T/T_m in accordance with activation energies typical of surface diffusion. The high temperature *zone 3* ($T/T_m > 0.5$) structure consisted of equiaxed grains, which increased in size in accordance with activation energies typical of bulk diffusion.

In 1973 the zone model was extended to magnetron sputtered metal films by adding an axis to account for the effect of the Ar working gas pressure as shown in Fig. 2.[3] The model was based on an examination of 0.025 to 0.25 mm thick coatings of Ti, Cr, Fe, Cu, Mo, and Al alloy deposited onto glass substrates using cylindrical-post[4] and cylindrical-hollow[4] magnetron sputtering sources. In this model, the MD zones were associated with conditions where the physics of coating growth was dominated in turn by mechanisms associated with each of the three steps shown in Fig. 1(b)—zone 1, atomic shadowing during transport; zone 2, surface diffusion; and zone 3, bulk diffusion. A fourth zone consisting of a dense array of poorly defined fibrous grains was identified in the region between zones 1 and 2 and termed *zone* T since it was believed to be a transition state between the two MD zones.

The purpose of this paper is to discuss some of the developments in our understanding of the microstructure of sputter-deposited coatings which have occurred since the zone models were proposed with particular emphasis on those aspects of the structure that are important to microelectronic metallization and diffusion barriers. The paper is not meant to be a complete review, but rather a discussion of some selected issues.

II. SOME GENERAL OBSERVATIONS

Although the original sputter-zone model was based on metal coatings deposited using cylindrical magnetron sources, its general features have been found to be rather universal, as one might expect because of the relationship between the zones and the fundamental processes of deposition.[5] Thus a detailed study of Cu coatings deposited with a planar magnetron yielded results in good agreement with the model.[6] General agreement was also found for Nb and Ta films deposited with a coaxial diode (no magnetic field)[7] and the low temperature zone 2/zone T range has been applied to sputtered amorphous materials.[8–10] Nevertheless, it is important to note that the universality, and indeed the utility, of the zone models comes from their simplicity. They were meant to provide general guidelines in selecting deposition conditions and not to be used in a detailed quantitative way. Several items relating to the use of the sputter-zone model for data interpretation are discussed below.

The voided growth defects that define the zone 1 structure are a consequence of atomic shadowing. Shadowing induces open boundaries because high points on the growing surface receive more coating flux than valleys, particularly when a significant oblique component is present in the flux.[3,5] Substrate surface roughness, or the step-like features encountered in microcircuit fabrication, promote zone 1 type behavior by creating oblique deposition angles. The inert working gas pressure in Fig. 2 is of course not a fundamental parameter. It enters the problem because collisional scattering by the inert gas atoms enhances the oblique component in the deposition flux. This scattering effect has a much greater influence on the coating structure than the adatom mobility reduction associated with adsorbed inert gas species on the substrate surface. This is shown by Fig. 3 which summarizes the results of an experiment designed to isolate the influences of the argon working gas and oblique deposition on the coating microstructure. It consisted of depositing Cu onto a water cooled substrate of complex shape in a hollow cathode sputtering source at relatively high Ar pressure (4 Pa). The coating on the outer surface was found to exhibit a classic zone 1 form. The coating on the side walls had the pronounced voided zone 1 structure found under conditions of extreme oblique deposition. However, the coating at the bottom of the 1 cm diameter by 1 cm deep hole exhibited a dense zone T structure with a mirror-like surface topography. This zone T structure developed on the protected surface because the oblique flux was removed and its formation was unaffected by the high Ar pressure.

Attempts to use the zone models to interpret experimental data may encounter situations where the observed structures are actually a combination of the structures normally associated with the individual zones. Thus a multiphase substrate may cause a coating to have significantly different structures in the region deposited over the different substrate phases.[11] Local substrate defects can cause preferential nucleation,[12] or enhanced shadowing effects, and result in lo-

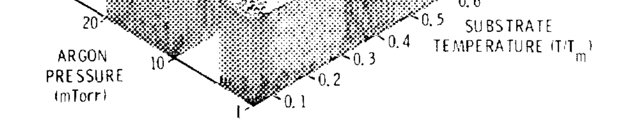

FIG. 2. Microstructure zone diagram for metal films deposited by magnetron sputtering. T is the substrate temperature and T_m is the coating material melting point. From Ref. 3.

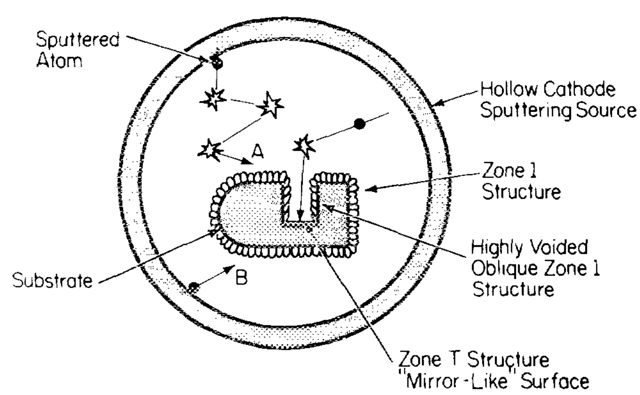

FIG. 3. Schematic illustration of hollow cathode deposition experiment which was designed to isolate the influences of the argon work gas pressure and an oblique deposition flux on the coating microstructure.

calized zone 1 crystallites[13] or modular defects,[14,15] growing out of a zone T, or even a zone 2 background.[5]

Gaseous impurities can have drastic effects on the microstructure and should always be a source of concern. It is well known that residual gas absorption can cause mobility variations over exposed crystallite surfaces.[16] Thus active species such as oxygen have been found to reduce adatom mobilities,[17,18] and therefore can promote zone 1 structures. Accordingly zone 1 structures are commonly encountered in reactive sputtering at low T/T_m in the absence of ion bombardment. The more insidious case is where the reactive species are introduced from chamber or substrate outgassing, in which case the resulting effects may appear to be associated with the substrate temperature, or in the inert working gas, in which case the resulting effects may appear to be associated with variations in the inert gas pressure. Oxidation of open zone 1 boundaries during growth, or after exposure to the atmosphere, is the reason why the resistivities of zone 1 deposits can be several orders of magnitude greater than bulk values. Similarly, Cu structures with columnar zone 1 boundaries were found to resist grain growth at relatively high temperatures ($T/T_m \sim 0.7$).[19] Conversely, room temperature recrystallization has been observed in sputtered Cu coatings which were deposited in the presence of modest energy ion bombardment and which did not possess zone 1 boundaries[20,21] (the ion bombardment was probably the source of the strain energy which drove the recrystallization).

III. ZONE 1/ZONE T MICROSTRUCTURES

The substrate temperature is probably the single most important parameter in thin film growth and becomes increasingly important as one moves to the right across Fig. 1(b). Thus, as a general rule, at sufficiently high temperatures bulk chemistry and diffusion dominate, so that a coating loses all memory of the earlier steps in its growth. Similarly, at intermediate temperatures, surface chemistry and diffusion can dominate over considerations such as shadowing that relate to the transport of the flux to the substrate. Thus it is in the low T/T_m regime where the coating microstructure is dependent on a plethora of parameters. These include the apparatus configuration, substrate surface morphology, and the working gas pressure, all of which influence the coating atom arrival directions and the energy and momentum delivered to the surface by the sputtered species and/or other energetic bombarding species. The low T/T_m region is of special interest in device fabrication because of the importance of refractory coating materials and of reducing processing temperatures. Therefore, as one might expect, it is the low temperature zone 1/zone T region which has been the primary focus of research and discussion during the past few years.

An important and still unanswered question concerns the fundamental nature of the zone T structure. It has been defined as the limiting form of the zone 1 structure at zero T/T_m on infinitely smooth substrates.[6] According to this view the zone T structure can be visualized as forming the internal structure of the identifiable zone 1 units. In the practical sense, the zone T structure is therefore a zone 1 structure with crystal sizes that are difficult to resolve and appear fibrous and with boundaries that are sufficiently dense to yield respectable material properties.

Computer simulation has contributed significantly to a recognition of the fundamental importance of atomic level shadowing and the manifestations of this phenomenon on the resultant microstructures. Figure 4(a) shows a computer simulation by Henderson, Brodsky, and Chaudhari in which hard spheres were serially launched so that they would travel in a straight line and intersect a substrate at an angle of 45°.[22] Intersection points in the x–y substrate plane were randomly selected. At the point of impact on the previously deposited spheres the incident sphere was assumed to stick, but was allowed to relax to the extent that it moved to the nearest "pocket" where it could make contact with two additional previously deposited spheres. The figure shows a slice parallel to the xz plane which is five sphere diameters thick. Figure 4(b) shows a similar two-dimensional simulation for normal incidence prepared by Dirks and Leamy.[23] The simulations show that the hard spheres tend to deposit into columns which lean in the direction of the incident flux and are interspersed with voids. Even at normal incidence the Henderson *et al.* simulations yielded a coating density which was only about $0.46\rho_c$, where ρ_c is the close-packed crystalline density. This density is considerably less than the value of about $0.9\,\rho_c$ that is obtained for actual amorphous silicon deposits.[24] Thus, Kim and Hen-

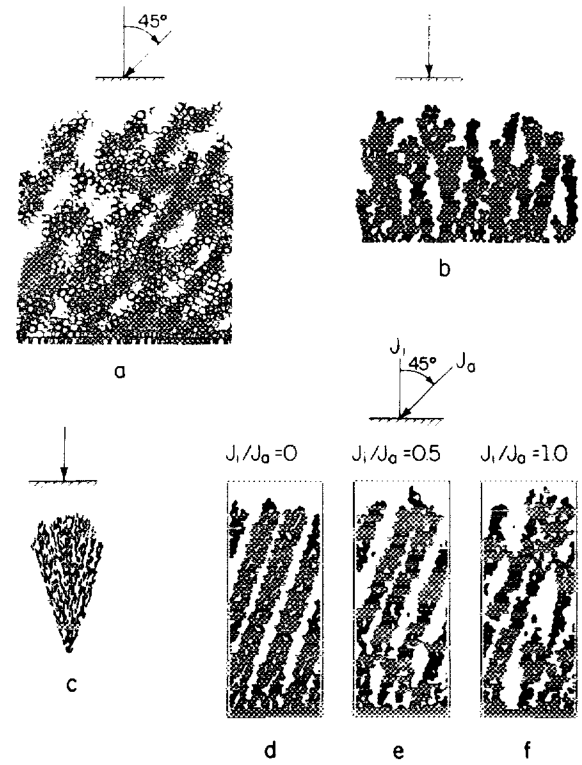

FIG. 4. Summary of several computer simulation experiments which illustrate the zone 1/zone T structure anisotropy which develops in thin films deposited under conditions of low adatom mobility. (a) Oblique incidence from Henderson, Brodsky, and Chaudhari (Ref. 22). (b) Normal incidence, from Dirks and Leamy (Ref. 23). (c) Ballistic aggregation on a point seed from Ramanlal and Sander (Ref. 36). (d) Influence of ion bombardment, from Müller (Ref. 69).

derson modified their simulation to include sticking coefficients of less than unity in order to demonstrate that the structural anisotropy was not an artifact of the low densities.[25] These modified simulations yielded denser coatings ($\rho = 0.67\rho_c$) in which it was difficult to identify the columnar growth visually (zone T structure). However, a plot of the distribution in directions of the contacting pairs showed that the model with the reduced sticking coefficient yielded an even higher degree of structural anisotropy than the lower density deposits. Thus, the computer simulation studies have provided additional support for the proposition that the columnar zone 1/zone T structure is a fundamental consequence of low mobility deposition.[18]

The identification of the zone T structure as a zone 1 structure on a smaller size scale, and as the internal structure of the zone 1 units, suggests the possibility of a repeating self-similar fractal array in which the geometrical properties defining the structures are indistinguishable as a function of a length scale. Messier and co-workers, using TEM and SEM methods, have identified at least four supernetwork structures with the following sizes in sputtered amorphous silicon: 5–20, 20–40, 50–200, and 200–500 nm.[26–29] The characteristic sizes within the overall structure and the surface roughness increased with coating thickness. Messier's group has accumulated considerable circumstantial evidence for self-similar fractal scaling in the repeating pattern within these structures; however, the question of true fractal behavior is still a matter of speculation.[30–32]

Computer simulations of diffusion-limited aggregation, where the aggregating particles approach their point of condensation by a random walk process somewhat similar to the high pressure deposition case, have yielded fractal behavior.[33,34] (A test for fractal behavior in such systems is that the amount of mass within a sphere of radius r varies as r^D, where the fractal dimension D does not depend on r over variations in r of perhaps three orders of magnitude.[35]) However, ballistic aggregation, in which the particles move in straight lines as in Figs. 4(a) and 4(b), is probably more closely associated with low T/T_m deposition on a flat surface. Figure 4(c) shows a ballistic aggregation simulation from a point seed.[36] A columnar structure with void streaks is observed. Early ballistic aggregation work seemed to show fractal behavior. However, more recent numerical[37] and analytical[38] studies suggest that the internal structure produced by these simulations is a nonfractal amorphous solid of fixed density which does, nevertheless, exhibit a surface roughness R that evolves with film thickness d according to $R \propto d^n$, where n is a constant.[39]

The above models address only the array of three-dimensional voided growth boundaries and the structure defined by these boundaries. Although these models do allow adatom relaxation and bouncing, they do not account for the surface diffusion which in crystalline materials can result in the formation of crystals and grain boundaries. Evidence for the importance of local surface diffusion was seen in the original structure zone work, where isolated zone 1 columns which appeared to consist of single crystals with (111) orientations were identified in low T/T_m Al deposits. Dahlgen and co-workers have used TEM, both parallel and perpendicular to the substrate plane, to examine the grain structure in thick (0.5 to 3 mm) Cu and Ni deposits formed at T/T_m values in the range from 0.1 to 0.4 by dc triode sputter deposition in Kr at low pressures (0.4 Pa).[21,40] The structures consisted predominantly of tightly packed long uniform columnar grains having a (111) orientation. The average grain width depended, as expected, on T/T_m and was about 400 nm at $T/T_m = 0.27$ for both the Cu and Ni. The grains had extremely high densities of stacking faults and twins oriented perpendicular to the grain axis. The average twin spacings were about 20 nm for Cu and 170 nm for Ni, and appeared to be randomly distributed. The Cu deposits at $T/T_m \sim 0.4$ also exhibited equiaxed grains which were believed to have resulted from recrystallization during deposition. Hentzell and co-workers also report evidence of equiaxed grains in the zone 1/zone T region ($T/T_m < 0.3$) for thick (9–14 μm) films of Ni and Ni–Al deposited by electron beam evaporation.[41]

Of particular interest is work of Nakahara and co-workers,[42–44] and more recently Fabris,[45] who have detected large numbers (10^{10}–10^{12} cm^2) of small (10–50 Å) voids in sputtered, evaporated, and electroplated thin films using transmission electron microscopy. These voids, which were seen in addition to the macroscopic growth voids of the clearly zone 1 type, were of two types, those that were bounded by grain boundaries and those that existed within grains. The voids were most pronounced adjacent to the substrate and were attributed to the nucleation and coalescence stages of growth. A uniform distribution of the voids was seen throughout the thickness of amorphous films. Evidence of microvoided structure is also seen in hydrogenated amorphous silicon films deposited by plasma-assisted chemical vapor deposition.[46]

IV. ENERGETIC PARTICLE BOMBARDMENT

It is well established that intense energetic ion bombardment during deposition can largely suppress the development of open zone 1 structures at low T/T_m. This has been demonstrated for both conducting[47,48] and nonconducting deposits.[49] The relevant parameters are the ion energy and the ion flux relative to the coating flux.[50–52] A systematic investigation of resputtered Cu at low T/T_m found that suppression of open boundaries required an ion flux adequate to resputter from 30% to 60% of the incident coating flux with the required resputter fraction increasing with the size of the substrate surface irregularities.[53]

In addition to bombardment by ions from the adjacent plasma, or an independent ion source, the surface of a growing coating during sputter deposition may be bombarded by sputtered atoms having average energies in the 10–40 eV range,[54] and energetic neutral working gas atoms (ions that are neutralized and reflected at the sputtering target[55]) having energies as high as several hundred eV. The reflected neutrals are particularly important and their influence can make the resulting structure dependent on the details of the apparatus configuration, which obviously adds complexity to the zone picture. Nevertheless, considerable progress has been made in at least qualitatively understanding some of the competing processes.

The energy flux carried to the substrate by the neutralized and reflected ions depends on the target mass relative to that of the working gas, the cathode shape (because of the scattering directions of the reflected species relative to the emission directions of the sputtered species), and the working gas pressure (because gas of scattering). At the low working pressures typically used in magnetrons, these reflected atoms can reach the substrates with a substantial fraction of their initial energy. The role of the reflected species on the coating structure has been elucidated by a series of studies of the internal stresses in films of Al, Cr, Cd, Fe, Mo, Ni, Rh, Si, Ta, V, W, and Zr deposited by cylindrical-post, cylindrical-hollow, and planar magnetron sources.[56–64] Typically, the experiments involved depositing coatings at constant T/T_m (typically about 0.2) and observing the changes in optical reflectance, resistivity, and internal stress as the operating conditions were passed from the zone T to the zone 1 region by increasing the working gas pressure. The zone T coatings were characterized by high optical reflectance, low resistivities, and compressive internal stresses, and often contained considerable entrapped working gas. The zone 1 coatings were characterized by decreased reflectances, increased resistivities, tensile stresses, and less entrapped working gas. The transition pressure (zone T/zone 1 boundary) was dependent on those parameters that influence the energy flux carried to the substrates by the reflected neutrals. Thus, it increased with the cathode operating voltage and the target-to-working gas mass ratio. Experiments in which shields were used to isolate the effects of reflected species emitted at various angles from the cathode surface unequivocally identified the role of cathode shape.[60–62] Thus, the transition pressure was greatest for cylindrical-post magnetrons, where the substrates are bombarded by species which are reflected at low scattering angles and preserve much of their initial energy, and least for hollow cathodes where the species scattered at small angles do not reach the substrates.

The zone 1/zone T boundary can thus be envisioned as resulting from a competition between the effects of energetic particle bombardment which tends to produce a dense microstructure, and oblique deposition which tends to produce an open structure. The oblique deposition can result from an extended source, or gas scattering as discussed previously. This behavior was further illustrated by experiments in which the basic zone 1/zone T transition was induced by increasing the bombardment dose per deposited atom in a Cr evaporation system in which the substrates were subjected to concurrent bombardment from an 11.5 keV Xe ion beam.[65] In the sputtering case, an increase in gas pressure also tends to promote the transition to zone 1 by reducing the discharge operating voltage and by scattering the energetic reflected species. Several of these points are illustrated by the planar magnetron data in Fig. 5. The transition pressure for Cr is seen to be about 0.04 Pa and to increase as the target mass is increased, finally reaching 2.5 Pa for Pt. The stress data at low pressures are anisotropic. Thus, tensile stresses indicative of a zone T structure are seen in the Cr films for a direction parallel to the long axis of the cathode, while the stresses in the direction perpendicular to the cathode axis are still compressive. Anisotropic reflectance was also observed. This behavior is believed to result from the oblique flux of atoms which originate from the ends of the cathode and promote an open zone 1 structure by atomic shadowing. It should be noted that it was also found that transition curves similar to those shown in Fig. 5 could be generated at low pressures by simply increasing the tilt angle of the substrates so as to increase the angle of incidence of the arriving deposition flux.[59]

Thus, we conclude that the existence of a zone T structure in films deposited by extended magnetron sources is largely a consequence of the bombarding effect of working gas ions which are neutralized and reflected at the cathode surface. It should also be emphasized that the zone T/zone 1 boundary shown in Fig. 2 is not unique, but depends on parameters such as the coating and working gas species, the size and shape of the target, and the position and orientation of the substrates relative to the target.

It is also important to consider the case of rf driven planar diode sputtering sources. These apparatuses are typically operated at working gas pressures (0.4 to 4 Pa), where gas scattering reduces the influence of reflected neutrals. However, the substrates are in contact with the plasma and are subject to bombardment by an ion flux which is often comparable to the sputtered flux and possesses average energies which are typically in the range from 5 to 100 eV, even in the absence of an externally applied bias.[66] This bombardment also promotes a dense structure of the zone T type. The ion energy varies inversely with the working gas pressure, so that the zone 1/zone T functional dependence resembles the form shown in Fig. 2, but for reasons that are quite different from the magnetron case. Messier and co-workers have considered the rf-diode case in some detail and have proposed a revised structure model in which the pressure axis is replaced by the floating bias potential of the substrates.[67]

The detailed atomic mechanisms by which energetic particle bombardment produces a more dense coating structure, and the degree to which this "zone T type" structure is iden-

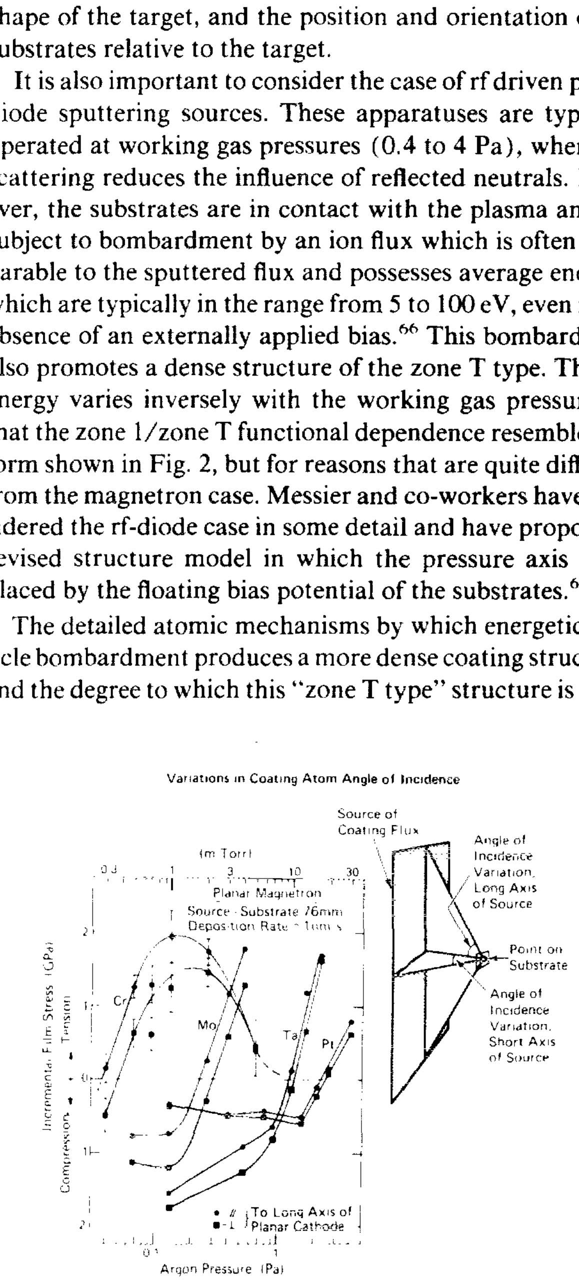

FIG. 5. Biaxial internal stress vs Ar working gas pressure for Cr, Mo, Ta, and Pt films deposited onto glass substrates using a rectangular planar magnetron source. Insert shows the effect of the oblique flux from ends of the source in promoting a structure that yields tensile stresses (from Ref. 63).

tical to the idealized zone T structures discussed previously, are a matter of speculation at this point. Again, computer simulation can be expected to provide insight.[68,69] In general terms the picture is fairly clear. Energetic particles incident on the surface of the growing coating must transfer energy and momentum to the atoms in the coating lattice as they slow down. Although resputtering may occur, the major thrust of momentum must be into the coating material. Thus, knock-on atoms of the coating material are driven further into the bulk where they tend to fill the microvoids that appear to be an inherent consequence of low T/T_m deposition.[18] Figure 4(d) shows two-dimensional microstructures formed by computer simulation under various degrees of ion bombardment in studies by Müller.[69] At high degrees of ion bombardment, bridging is seen to develop between the columns. Leamy and Dirks report similar bridging behavior in the absence of ion bombardment, when the mobility of their computer simulated adatoms was increased.[18]

When considering microstructure modification at low T/T_m by energetic particle bombardment, it must be remembered that working gas entrapment occurs. For example, the reflected neutral bombardment during cylindrical magnetron metal film deposition caused inert gas entrapment ranging from about 0.2 at. % for V sputtered with Ar to about 4 at. % for Mo sputtered with Ne.[70] High energy bombardment can also cause composition changes in multicomponents materials due to differences in sputtering yields.[52]

V. CONCLUDING REMARKS

The trends in microcircuit fabrication are toward the use of lower processing temperatures, often concurrent with requirements for depositing layers of refractory materials. Thus, deposition must frequently be done at low T/T_m, where the adatom mobility is limited. Vapor deposited coatings grown under such conditions exhibit a columnar growth structure defined by voided open boundaries. This growth structure is superimposed on a microstructure, which typically consists of columnar gains defined by metallurgical grain boundaries, but may also be amorphous. The growth structure is a fundamental consequence of atomic shadowing acting in concert with the low adatom mobility and tends to be exacerbated by the nonuniform surface topographics encountered in microcircuit fabrication. Suppression of the voided growth structure boundaries is an important consideration for most applications. There is considerable evidence that the superposition of an additional physical process, such as energetic particle bombardment or surface chemistry reactions, can dominate the low temperature growth process to the extent that a structure is formed in which there is no evidence of columnar growth structure at least on the size scales that can be studied by SEM and TEM.[71] Thus, the bombardment that results from ions that are neutralized and reflected at the cathode appears to be sufficient to suppress the growth structure in metallic coatings deposited using magnetron sputtering sources at low pressures. However, the compounds and surface topographies of interest in microcircuit fabrication generally require a more vigorous process, such as the intense ion bombardment that can be produced by bias sputtering.

The use of intense ion bombardment where the resputtered fraction is significant (30%–70%) can be expected to assume an increasing role in microcircuit fabrication for two reasons. The first is its ability to suppress the unwanted growth boundaries as discussed above. The second is its ability to produce planarized surfaces. The planarization mechanism is based on the fact that the deposition and resputtering rates on oblique surfaces depend in turn on the angles of incidence of the impinging coating atoms and the incident ions. Impressive results have recently been reported. Some of these are summarized in Fig. 6. Figure 6(a) shows computer simulations which clearly illustrate the influence of the angle of incidence dependence of the sputtering yield.[72] The upper drawing in Fig. 6(a) shows that sputtering by itself can gradually remove a square groove surface topography because of preferential sputtering of the side walls, but at the expense of etching away a considerable portion of the upper layers across the entire substrate. The lower drawing in Fig. 6(a) shows the result when sputter deposition is combined with the ion bombardment. Figure 6(b), which was sketched from SEM cross sections, shows the influence of increasing the resputtering fraction when Al films were deposited over 1.5 μm grooves at 250 °C ($T/T_m = 0.56$).[73] The ion bombardment suppressed open growth boundaries and at about 70% resputtering caused

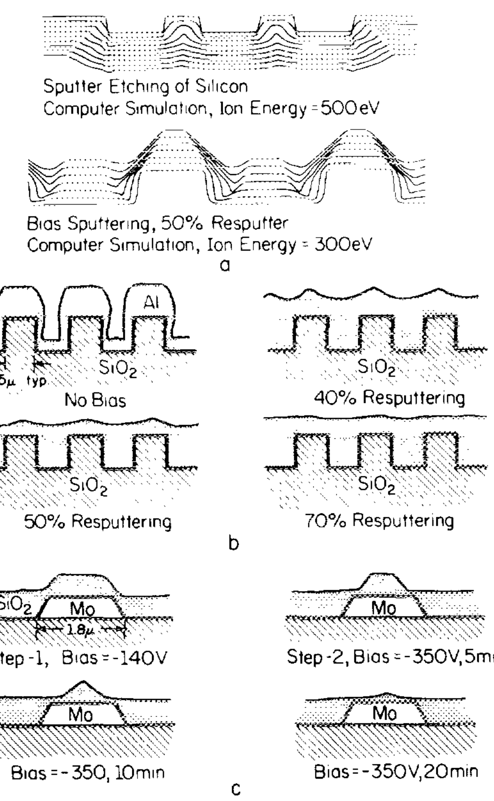

FIG. 6. Schematic illustration showing the effectiveness of ion bombardment in developing planarized structures. (a) Computer simulation of sputter etching of Si grooves (upper) and bias sputtered Al deposited onto Si grooves (lower) from Bader and Lardon (Ref. 72). (b) Planarization effect during bias sputter deposition of Al on Si grooves; drawn from experimental data reported by Homma and Tsunekawa (Ref 73). (c) Two-step bias sputter planarization of SiO_2 deposited onto Mo strip; drawn from experimental data reported by Mogami *et al.* (Ref. 74).

almost complete planarization. Figure 6(c) was sketched from data obtained by sputter depositing SiO_2 onto Mo strips using a two-step process.[74] In the first step, a bias sputtered layer similar to that shown in Fig. 6(a) (lower) was deposited. In the second step, the surface was planarized by increasing the bias voltage so that there was no net deposition on horizontal surfaces. The combination of planarization and microstructure control should permit sharply defined sidewall coatings of good integrity to be obtained by using photolithography to re-etch the grooves within the planarized material.

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