R. E. Jones, Jr.

Theories of the Distribution of Deposit from Sputtered Disk and Rectangular Electrodes

Abstract: Theoretical expressions for the distribution of deposits sputtered from disk-shaped and rectangular electrodes are derived for cases of 1) uniform emission obeying the cosine emission law, 2) distorted "under cosine" and "over cosine" emission, 3) additional emission confined to the peripheries of the electrodes and obeying the cosine emission law, and 4) distorted "inward" emission from the peripheries.

Introduction

The distribution of film deposit sputtered from a large disk or a rectangular electrode depends in a complicated fashion on the geometry of the electrode, its distance from the plane to be coated, and on the operating conditions of the glow discharge. The influence of the glow discharge is particularly complex, making it impossible to consider the sputtered electrode simply as an extended evaporation source. Sputtered material may be significantly scattered by collisions with gas molecules, and the cosine emission distribution, which is generally valid for evaporation, does not hold for sputtering emission except as a first approximation[1]. Furthermore, the ion bombardment intensity is never completely uniform, varying in intensity and direction particularly near the periphery of the electrode[1].

Despite these complications it is still useful to compare observed distributions to the predictions of simple models, considering the sputtered electrode to be one or more sources emitting with the cosine emission distribution and adding terms, when possible, to represent deviations from the cosine emission. We can, in principle, fit these theoretical expressions to observed distributions and determine how the intensity of the sources and the magnitudes of the deviation terms change with operating conditions. To a limited extent this approach has been used in studying the distributions of deposits rf sputtered from a disk-shaped electrode[2]. The results of this type of analysis should be useful in optimizing the uniformity of sputtered deposits and in understanding sputtering phenomena occurring at an extended electrode.

The simplest set of assumptions that could be made regarding the deposition of material from a large sputtered electrode is that 1) sputtering is uniform over the electrode, 2) emission obeys the cosine distribution, 3) the sputtered material is not significantly scattered by collisions in the gas and 4) the material sticks wherever it strikes a solid surface. These are the essential assumptions that were also made in deriving the deposit distributions from evaporation sources[3]. It will be shown that in the cases of the rectangular and the disk-shaped electrode the theoretical distributions that result can be expressed in simple, closed analytical forms.

These four simple assumptions, however, are not completely valid in practice. With the common shielding arrangements the dark space of the discharge will wrap around the edge of the electrode, providing more bombardment at the periphery. Furthermore, the ions that bombard the periphery impinge at oblique angles and have a high sputtering yield per ion. Both effects give rise to additional emission near the periphery.

It is clear that in any attempt to take these effects into account when deriving the distribution of sputtered deposit, one must either use complicated numerical methods for solution or resort to additional simplifying assumptions. We have taken the latter course and have derived expressions for thin planar sources at the periphery of the electrode. The other assumptions 2), 3) and 4) were retained. The superposition of these peripheral sources and a uniformly emitting electrode source (with properly adjusted intensities) have been shown to pro-

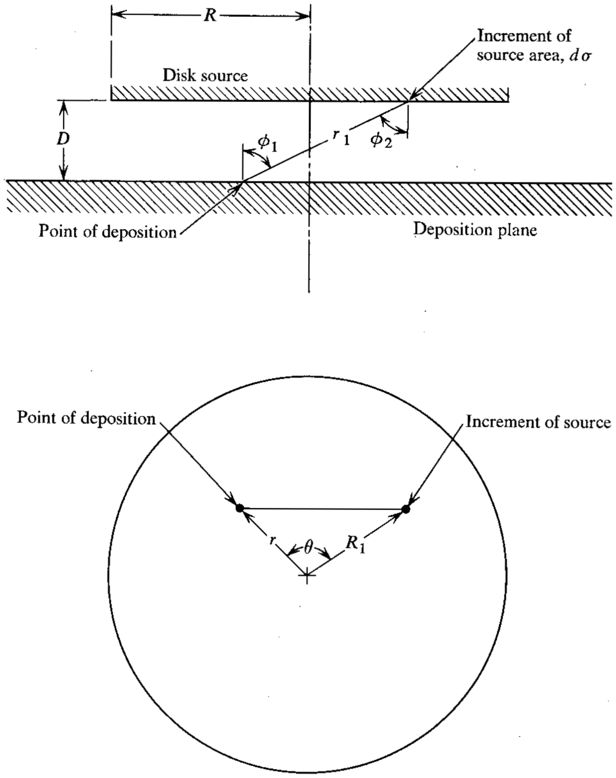


Figure 1 Geometrical definitions for a disk-shaped electrode.

vide a better approximation to observed distributions than was previously obtained[2].

In addition certain deviations from the cosine emission distribution [assumption 2) above] can be taken into account. A term can be added to the cosine emission law to represent diminished or enhanced ("under" or "over" cosine) emission perpendicular to the surface of the uniformly emitting disk or rectangular electrode. Fortunately, this gives rise to correction terms for the deposit distributions that are fairly simple, and the effects of "under" and "over" cosine emission can be traced easily.

Another type of asymmetry will exist at the periphery of the electrodes. Ions striking the periphery at oblique angles perferentially eject material in the direction of their momentum—inward toward the center of the electrode[4]. Correction terms that can represent this complication to a limited degree also have been derived.

The complications that arise when scattering in the gas and re-emission at the deposit surface occur [i.e., when assumptions 3) and 4) are invalid] have not been considered.

Analysis of disk electrode

We consider the emission for a disk or radius R positioned parallel to a deposition plane and separated from it by a distance D. This disk is first assumed to emit uniformly (i.e., independent of position on the disk) an amount of material m per unit area. The quantity m can be measured in a variety of rate units (Å $\sec^{-1}$, grams $\mathrm{cm}^{-2}\ \sec^{-1}$, gram atoms $\mathrm{cm}^{-2}\ \sec^{-1}$, etc.) or as a total material density (Å, grams cm^{-2}, etc.). The choice is immaterial provided a consistent set of units is used throughout. The basic equation governing the rate of deposition d^2i, at a point on the deposition plane due to an increment of source area $d\sigma$, may be written

$$d^2i = m\epsilon\, d\sigma \cos\phi_1/r_1^2 \tag{1}$$

where

d^2i = the rate of deposition at a point on the deposition plane due to an increment of source area
m = the amount of material emitted per unit area
$d\sigma$ = the increment of source area
r_1 = the magnitude of the vector between the increment of source area and the point of deposition
ϕ_1 = the angle between the vector $\mathbf{r}_1$ and the normal to the surface at the point of deposition
ϵ = the normalized geometrical factor giving the emission distribution from the increment of source area.

A schematic picture of the geometrical parameters is shown in Fig. 1.

- *Cosine emission distribution from a uniformly emitting disk*

If the emission from the disk obeys the cosine emission distribution, then

$$\epsilon = \pi^{-1}\cos\phi_2, \tag{2}$$

where ϕ_2 is the angle between the vector $\mathbf{r}_1$, representing the direction of emission, and the normal to the source increment $d\sigma$. The factor π^{-1} arises from the requirement that ϵ integrated over the total 2π hemisphere of emission directions be equal to unity. The geometrical quantities defined above also are shown schematically in Fig. 1. Combining Eqs. (1) and (2) and integrating over the entire source, we obtain for the total impingement rate I_0

$$I_0 = \int d^2i = \frac{m}{\pi}\int \frac{d\sigma\cos\phi_1\cos\phi_2}{r_1^2}. \tag{3}$$

To solve this integral it is convenient to introduce the additional parameters shown in Fig. 1. It follows from these definitions that we have

$$\cos\phi_1 = \cos\phi_2 = D/r_1$$
$$r_1^2 = R_1^2 + r^2 - 2rR_1\cos\theta + D^2, \qquad \text{and}$$
$$d\sigma = R_1 dR_1 d\theta.$$

The expression for the deposition rate at a distance r from the axis of the disk is, therefore,

$$I_0(r) = \frac{mD^2}{\pi} \int_0^R R_1 dR_1 \int_0^{2\pi} \frac{d\theta}{[R_1^2 + r^2 - 2R_1 r \cos\theta + D^2]^2} \tag{4}$$

The integral over the angle θ can be performed:

$$\int_0^{2\pi} \frac{d\theta}{[R^2 + r^2 - 2R_1 r \cos\theta + D^2]^2} = \frac{2\pi(D^2 + R_1^2 + r^2)}{[(D^2 + R_1^2 + r^2)^2 - (2rR_1)^2]^{3/2}} = \frac{2\pi(D^2 + R_1^2 + r^2)}{[(D^2 + R_1^2 - r^2)^2 + (2rD)^2]^{3/2}}$$

as can the integral of R_1, giving

$$I_0(r) = \frac{m}{2}\left\{1 + \frac{R^2 - r^2 - D^2}{[(D^2 + R_1^2 - r^2)^2 + (2rD)^2]^{1/2}}\right\}. \tag{5}$$

This expression, in a slightly different form, has been derived by von Hippel[5].

Other emission distributions

We now consider deviations from the cosine emission distribution [Eq. (2)]. Provided the emission distribution depends only on ϕ_2 (the angle of ejection relative to the normal to the surface) we can in principle represent it by a sum

$$\epsilon = \pi^{-1}[\cos\phi_2 + a_3 \cos^3\phi_2 + a_5 \cos^5\phi_2 + \cdots]. \tag{6}$$

We will consider the distribution under a disk when we include the first two terms of this expression. It is expedient to write the expression for ϵ in the form

$$\epsilon = \pi^{-1}[\cos\phi_2 + a \cos\phi_2\ (1 - 2\cos^2\phi_2)]. \tag{7}$$

The first term in this expression is the "cosine" emission distribution [Eq. (2)] analyzed above; therefore, we only need consider the effect of the second term. This particular form is used because the second term, integrated over the 2π hemisphere of solid angle, is equal to zero. Combining (1) and (7) and integrating, the contribution of the second term, $I_1(r)$, to the deposition rate is

$$\begin{aligned} I_1(r) &= \frac{ma}{\pi} \int \frac{\cos\phi_1 \cos\phi_2\ (1 - 2\cos^2\phi_2)\ d\sigma}{r_1^2} \\ &= \frac{maD^2}{\pi} \int_0^R R_1 dR_1 \int_0^{2\pi} \frac{d\theta}{[R_1^2 + r^2 - 2R_1 r\cos\theta + D^2]^2} \\ &\quad - \frac{2maD^4}{\pi} \int_0^R R_1\, dR_1 \\ &\quad \times \int_0^{2\pi} \frac{d\theta}{[R_1^2 + r^2 - 2R_1 r\cos\theta + D^2]^3}. \end{aligned} \tag{8}$$

The first integral in (8) occurred in (4) and its solution is given by (5). The integration over ϕ in the second term may be performed giving

$$\int_0^{2\pi} \frac{d\theta}{[R_1^2 + r^2 - 2R_1 r\cos\theta + D^2]^3} = \frac{2(D^2 + R_1^2 + r^2)^2 + (2rR_1)^2}{[(D^2 + R_1^2 + r^2)^2 - (2rR_1)^2]^{5/2}}\pi = \frac{2(D^2 + R_1^2 + r^2)^2 + (2rR_1)^2}{[(D^2 + R_1^2 - r^2)^2 + (2Dr)^2]^{5/2}}\pi.$$

The integral over R_1 can also be carried out so that the second term becomes

$$\begin{aligned} &\frac{2maD^4}{\pi} \int_0^R R_1 dR_1 \int_0^{2\pi} \frac{d\theta}{[R_1^2 + r^2 - 2R_1 r\cos\theta + D^2]^3} \\ &= \frac{ma}{4}\left\{1 + \frac{(R^2 - D^2 - r^2)}{[(D^2 + R^2 - r^2)^2 + (2Dr)^2]^{1/2}} + \frac{2D^2R^2(R^2 + D^2 - r^2)}{[(D^2 + R^2 - r^2)^2 + (2Dr)^2]^{3/2}}\right\}. \end{aligned}$$

Combining this result with (8), (4), and (5) we obtain

$$I_1(r) = -\frac{ma}{2} \frac{2D^2R^2(R^2 + D^2 - r^2)}{[(D^2 + R^2 - r^2)^2 + (2Dr)^2]^{3/2}}. \tag{9}$$

Rim source emitting the cosine distribution

To derive approximate expressions for the distribution of deposition rate from a "rim" source, we first assume that the sputtering is confined to a small width ΔR around the rim of the disk. Assuming the cosine distribution [Eq. (2)], we can derive from (3) an expression for the distribution of deposition rate I_{r0} from this type of source

$$I_{r0}(r) = \frac{(m\Delta R)\ RD^2}{\pi} \int_0^{2\pi} \frac{d\theta}{[R_1^2 + r^2 - 2R_1 r\cos\theta + D^2]^3} = \frac{m_r\, 2D^2R(D^2 + R^2 + r^2)}{[(D^2 + R^2 - r^2)^2 + (2rD)^2]^{3/2}}, \tag{10}$$

where we have relabeled the product $(m\Delta R)$ as m_r. This quantity will be the measure of the intensity of the rim source and have units of rate or quantity per unit length.

Rim source emitting an asymmetrical distribution

The emission distribution of material near the edge of a plate is not symmetrical around the normal to the surface but is preferential inward from the edge. We can represent this feature approximately by adding another term to the cosine distribution [Eq. (2)] so that the emission distribution becomes

$$\epsilon = \pi^{-1}[\cos\phi_2 + b\cos\phi_2\ (\cos\phi_2 \sin\phi_2 \cos\psi)]. \tag{11}$$

The definition of the newly introduced angle ψ is shown in Fig. 2. As indicated ψ is the angle, in the plane of the sputtered disk, between the projection of the vector $\mathbf{r}_1$ and the radius, R, directed to the increment of rim source. As a consequence of this definition we will have:

$$\cos \psi = (R - r \cos \theta)/(R^2 + r^2 - 2rR \cos \theta)^{1/2},$$

and as a consequence of definitions in the previous section we also obtain

$$\sin \theta_2 = (R^2 + r^2 - 2rR \cos \theta)^{1/2}/\mathbf{r}_1.$$

It should be noted that the assumed form of the asymmetrical emission distribution function (11) is limited in its ability to represent real emission distributions. The product ($\cos \phi_2 \sin \phi_2 \cos \psi$) will have its most negative value, $-1/2$, at $\phi_2 = \pi/2$, $\psi = -\pi$. It follows, that for ϵ in (11) to be always positive (as it must to remain physically realistic), we cannot have values of b greater than 2.

The reason for selecting the particular form of (11) is twofold. First, it will be shown that this form gives rise to a distribution on the deposition plane which can be expressed in a closed form, not requiring numerical integration. Second, it will adequately represent modest deviations ($b \leq 2$) from the cosine emission distribution.

The contribution to the distribution of the first term (corresponding to the cosine distribution) on the right-hand side of (11) is identical to the function I_{r0} given by (10). Therefore, we need only consider the contribution of the second term, which we label I_{r1}. This function can be shown to be

$$I_{r_1}(r) = \frac{b(m\Delta R)R}{\pi} \int_0^{2\pi} \frac{d\phi \cos \phi_1 \cos \phi_2 (\cos \phi_2 \sin \phi_2 \cos \psi)}{r_1^2}$$

$$= \frac{bm_r RD^2}{\pi} \int_0^{2\pi} \frac{d\theta}{[R^2 + r^2 - 2rR \cos \theta + D^2]^2} \times \frac{D(R - r \cos \theta)}{[R^2 + r^2 - 2rR \cos \theta + D^2]}.$$

The integration over θ can be performed giving

$$I_{r_1}(r) = bm_r R^2 D^3 \times \frac{2(D^2 + r^2 + R^2)^2 + (2rR)^2 - 6r^2(D^2 + r^2 + R^2)}{[(D^2 + r^2 + R^2)^2 - (2rR)^2]^{5/2}}. \quad (12)$$

Analysis of rectangular electrode

The coordinates used for the analysis of the rectangular electrode are shown in Fig. 3. Introducing the geometrical relationships implied in the figure, we have

$$\cos \phi_1 = \cos \phi_2 = D/r_1$$

$$r_1^2 = (x - X)^2 + (y - Y)^2 + D^2$$

$$d\sigma = dX\, dY.$$

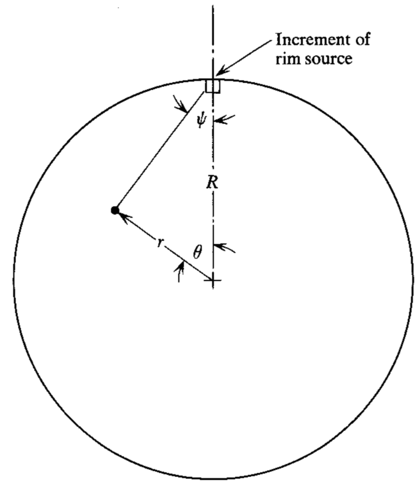


Figure 2 Geometrical definitions for a disk rim source.

- *Cosine emitter distribution from a uniformly emitting rectangle*

Assuming the cosine emission distribution, (1) and (2) can be combined and integrated to give the local deposition rate under the rectangle

$$J_0(x,y) = \frac{MD^2}{\pi} \int_{-x_0}^{x_0} dX \int_{-y_0}^{y_0} \frac{dY}{r_1^4}. \quad (13)$$

The integral over Y can be performed

$$\int_{-y_0}^{y_0} \frac{dY}{r_1^4}$$

$$= \frac{(y_0 + y)}{2[(x - X)^2 + D^2]\,[(x - X)^2 + D^2 + (y_0 + y)^2]}$$

$$+ \frac{(y_0 - y)}{2[(x - X)^2 + D^2]\,[(x - X)^2 + D^2 + (y_0 - y)^2]}$$

$$+ \frac{1}{2[(x - X)^2 + D^2]^{3/2}} \tan^{-1} \frac{(y_0 + y)}{[(x - X)^2 + D^2]^{1/2}}$$

$$+ \frac{1}{2[(x - X)^2 + D^2]^{3/2}} \tan^{-1} \frac{(y_0 - y)}{[(x - X)^2 + D^2]^{1/2}}.$$

Integration over X yields the final expression for J_0:

$$J_0(x,y) = \frac{m}{2\pi} \{f(x_0 + x, y_0 + y) + f(x_0 - x, y_0 + y) + f(x_0 + x, y_0 - y) + f(x_0 - x, y_0 - y)\}, \quad (14)$$

where

$$f(\alpha,\beta) = \frac{\alpha}{[\alpha^2 + D^2]^{1/2}} \tan^{-1} \frac{\beta}{[\alpha^2 + D^2]^{1/2}} + \frac{\beta}{[\beta^2 + D^2]^{1/2}} \tan \frac{\alpha}{[\beta^2 + D^2]^{1/2}}.$$

It can be shown that when $J_0(x,y)$ is integrated over the entire x-y plane the result is equal to $4\,mx_0\,y_0$. This is a necessary condition for the solution to be correct.

• *Other emission distributions*

The effects of deviations from the cosine emission distribution can be considered by assuming emission given by (7). The expression for the correction to the distribution which arises from the second term in (7) is

$$J_1(x,y) = \frac{ma}{\pi}\int \frac{\cos\phi_1 \cos\phi_2\,(1-2\cos^2\phi_2)\,d\sigma}{r_1^2}$$

$$= \frac{maD^2}{\pi}\int_{-x_0}^{x_0} dX \int_{-y_0}^{y_0}\frac{dY}{r_1^4} - \frac{2maD^4}{\pi}\int_{-x_0}^{x_0} dX \int_{-y_0}^{y_0}\frac{dY}{r_1^6}. \qquad (15)$$

The first integral in this equation is identical to that occurring in (13). It is equal therefore to a $J_0(x,y)$ (Eq. 14). The Y integration in the second double integral can be performed giving

$$\int_{-y_0}^{y_0}\frac{dY}{r_1^6} =$$

$$-\left\{\frac{(y_0+y)}{4[(x-X)^2+D^2]\,[(x-X)^2+(y_0+y)^2+D^2]^2}\right.$$
$$+\frac{(y_0-y)}{4[(x-X)^2+D^2]\,[(x-X)^2+(y_0-y)^2+D^2]^2}$$
$$+\frac{3(y_0+y)}{8[(x-X)^2+D^2]^2\,[(x-X)^2+(y_0+y)^2+D^2]}$$
$$+\frac{3(y_0-y)}{8[(x-X)^2+D^2]^2\,[(x-X)^2+(y_0-y)^2+D^2]}$$
$$+\frac{3}{8[(x-X)^2+D^2]^{5/2}}\tan^{-1}\frac{(y_0+y)}{[(x-X)^2+D^2]^{1/2}}$$
$$\left.+\frac{3}{8[(x-X)^2+D^2]^{5/2}}\tan^{-1}\frac{(y_0-y)}{[(x-X)^2+D^2]^{1/2}}\right\}.$$

The integration over X can also be carried out, giving finally:

$$J_1(x,y) = -\frac{aD^2}{4\pi}\{g(x_0+x,\,y_0+y)+g(x_0-x,\,y_0-y)$$
$$+g(x_0+x,\,y_0-y)+g(x_0-x,\,y_0-y)\}, \qquad (16)$$

where

$$g(\alpha,\beta) = \frac{\alpha\beta[\alpha^2+\beta^2+2D^2]}{[\alpha^2+D^2]\,[\alpha^2+\beta^2+D^2]\,[\beta^2+D^2]}$$
$$+\frac{\alpha}{[\alpha^2+D^2]^{3/2}}\tan^{-1}\frac{\beta}{[\alpha^2+D^2]^{1/2}}$$
$$+\frac{\beta}{[\beta^2+D^2]^{3/2}}\tan^{-1}\frac{\alpha}{[\beta^2+D^2]^{1/2}}.$$

This expression integrated over the entire x-y plane can be shown to equal zero—as is necessary for a valid solution.

• *Strip source emitting the cosine distribution*

To derive an expression for the distribution of deposit emitted from the periphery of a rectangle, we assume that the sputtering is confined to a small strip at the periphery which lies in the plane of the electrode. We first consider a single strip of width ΔY positioned at $y = y_0$ and extending $-x_0 \le X \le x_0$ (Fig. 4). Assuming the cosine distribution [Eq. (2)] we can derive an expression for the distribution of deposit, J_{s0}, from this type of source.

$$J_{s0}(x,y) = \frac{(m\Delta Y)D^2}{\pi}\int_{-x_0}^{x_0}\frac{dX}{[(x-X)^2+(y_0-y)^2+D^2]^2}. \qquad (17)$$

The product $(m\Delta Y)$ is relabeled as m_s. This quantity will be the measure of the intensity of the strip source and will have units of rate or quantity per unit length. Performing the X integration, we find

$$J_{s0}(x,y)$$

$$= \frac{m_sD^2}{2\pi}\left\{\frac{(x_0+x)}{[(y_0-y)^2+D^2]\,[(x_0+x)^2+(y_0-y)^2+D^2]}\right.$$
$$+\frac{(x_0-x)}{[(y_0-y)^2+D^2]\,[(x_0-x)^2+(y_0-y)^2+D^2]}$$
$$+\frac{1}{[(y_0-y)^2+D^2]^{3/2}}\tan^{-1}\frac{(x_0+x)}{[(y_0-y)^2+D^2]^{1/2}}$$
$$\left.+\frac{1}{[(y_0-y)^2+D^2]^{3/2}}\tan^{-1}\frac{(x_0-x)}{[(y_0-y)^2+D^2]^{1/2}}\right\}. \qquad (18)$$

This solution has been described previously by L. Holland and W. Steckelmacher[3].

When all four edges of the rectangular electrode are exposed to additional bombardment and emit at a high rate, three additional strip sources must be added. Assuming the geometries given in Figs. 3 and 4, expressions for the three additional distributions of deposit can be obtained from (18) by substituting: 1) $y \to -y$; 2) $y \to x$, $x \to y$, $y_0 \to x_0$, and $x_0 \to y_0$; and 3) the same as 2) except $y \to -x$.

• *Strip source emitting as asymmetrical distribution*

It has been observed that the ejection of material sputtered near the edge of a plate is not symmetrical around the normal to the surface but is preferential inward from the edge. This feature can be represented approximately by again assuming the emission distribution given by (11).

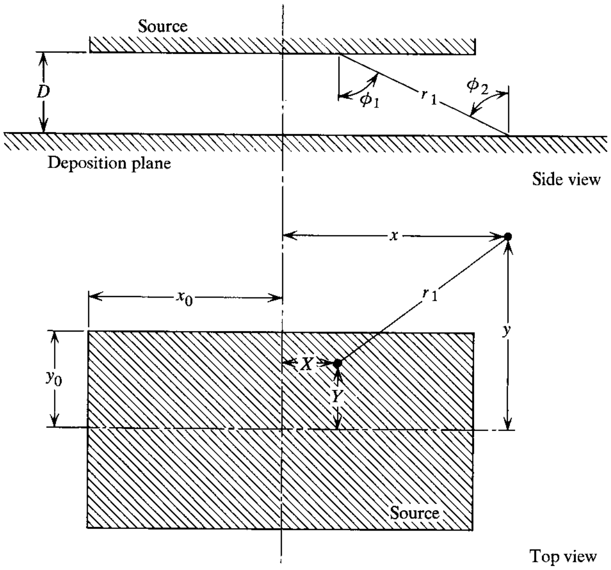
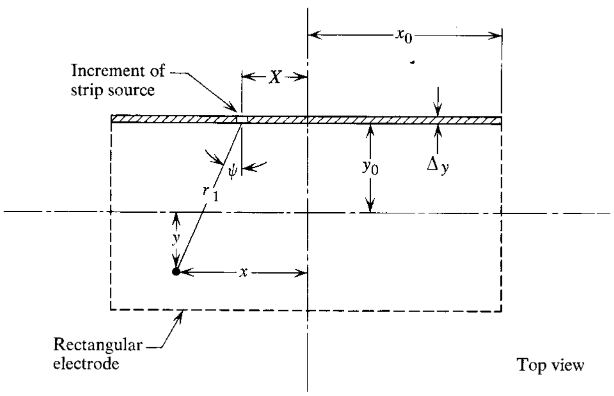


Figure 3 Geometrical definitions for a rectangular electrode.

Figure 4 Geometrical definitions for a strip source.



As a consequence of the definition of ψ (Fig. 4), we have

$$\cos \psi = -\frac{y_0 - y}{[(x-X)^2 + (y_0 - y)^2]^{1/2}}$$

and from previous definitions

$$\sin \phi_2 = [(x-X)^2 + (y_0 - y)^2]^{1/2}/r_1.$$

The contribution to the deposit distribution of the first term in Eq. (11) (corresponding to the cosine emission distribution) is identical to the function J_{s0} given by (18). The contribution of the second term, which we shall label J_{s1}, can be shown to be

$$J_{s1}(x,y)$$

$$= -\frac{b(m\Delta Y)D^3}{\pi} \int_{-x_0}^{x_0} \frac{(y_0 - y)\,dX}{[(x-X)^2 + (y_0 - y)^2 + D^2]^3} \qquad (19)$$

$$= -\frac{\mathrm{b}m_s(y_0 - y)}{4\pi}$$

$$\times \left\{ \frac{(x_0 + x)}{[(y_0 - y)^2 + D^2][(y_0 - y)^2 + D^2 + (x_0 + x)^2]} \right.$$

$$+ \frac{(x_0 - x)}{[(y_0 - y)^2 + D^2]\,[(y_0 - y)^2 + D^2 + (x_0 - x)^2]}$$

$$+ \frac{3(x_0 + x)}{2[(y_0 - y)^2 + D^2]^2\,[(y_0 - y)^2 + D^2 + (x_0 + x)^2]}$$

$$+ \frac{3(x_0 - x)}{2[(y_0 - y)^2 + D^2]^2\,[(y_0 - y)^2 + D^2 + (x_0 + x)^2]}$$

$$+ \frac{3}{2[(y_0 - y)^2 + D^2]^{5/2}} \tan^{-1} \frac{(x_0 + x)}{[(y_0 - y)^2 + D^2]^{1/2}}$$

$$\left. + \frac{3}{2[(y_0 - y)^2 + D^2]^{5/2}} \tan^{-1} \frac{(x_0 - x)}{[(y_0 - y)^2 + D^2]^{1/2}} \right\}. \quad (20)$$

When all four edges of the rectangular electrode are exposed to additional low angle of incidence bombardment, three additional terms similar in form to (20) must be added to represent the total deposit distribution. Assuming the geometries given in Figs. 3 and 4, these terms can be obtained from (20) by substitutions: 1) $y \to -y$; 2) $y \to x$, $x \to y$, $y_0 \to x_0$, and $x_0 \to y_0$; and 3) the same as 2) except $y \to -x$.

- *Emission from corners*

In the case of the sputtered rectangle, additional sources may need to be considered to represent additional emission from the corners of the electrode. The edges are subjected to more bombardment than the main portion of the electrode and the corners are likely to be even more exposed.

Expressions for the additional deposition for either the cosine distribution emission or the asymmetrical emission distribution may be formulated by taking (17) and (19) out of their integral form and using the quantity $(m\Delta Y\Delta X)$ as a measure of the intensity of the corner source.

Discussion

In the preceding sections expressions were derived for the deposit distributions for 1) uniformly emitting disk and rectangular electrodes with emission obeying the cosine distribution [Eqs. (5) and (14)], 2) terms that can be added to these solutions to represent distortions from the cosine distribution [Eqs. (9) and (16)], 3) thin strips emitting the cosine distribution along the periphery of the electrodes [Eqs. (10) and (18)], and 4) terms to be added to the solutions for the peripheral strips to represent asymmetric, inward emission from the edges [Eqs. (12) and (20)]. The total distributions corresponding to the superposition of peripheral and principle electrode sources and the terms that modify the cosine emission distribution may now be considered.

It is convenient to take the disk electrode as an example. The distribution in this case depends on only one parameter, the radius r.

The distribution from a uniformly emitting disk with emission obeying the cosine distribution is given by the curve labeled $a = 0$ in Fig. 5. The geometry used in this example ($R = 4.4375''$ and $D = 1.3125''$) is typical for large-scale sputtering systems. The calculated results show that the deposition rate is highest under the center of the disk, and is equal to about 92 percent of the emission rate from the disk in this case. Under the rim of the disk the deposition rate drops to slightly less than half the value at the center, as might be expected.

The effects of deviations from the cosine distribution (9) will now be considered. The distribution in this case will be given by the sum of I_0 [Eq. (5)] and the term I_1 [Eq. (9)] representing the effects of distortions from the cosine distribution. In Fig. 6, the emission distributions given by (7) are shown for $a = +0.3$, 0 (no distortion), and -0.3. The first case has been commonly referred to as a "under cosine," and the last as the "over cosine" emission distribution. In Fig. 5 the corresponding distributions of deposition rate are shown.

From Fig. 5 it is clear that large (30 percent in the direction normal to the surface) distortions of the cosine distribution have comparatively little effect on the distribution of deposition rate. In the center, the change is only about 2.5 percent, increasing to around 5 percent at 3 inches from the axis. Beneath the edge of the sputtered disk, the effects are nil and at still greater distances from the axis the effect changes sign.

Qualitatively the effects of the distortions are what might be expected from the shapes shown in Fig. 6. For example, with the "under cosine" ($a = +0.3$) distribution less material deposits under the disk and more to the "sides" (away from the disk). However, we can conclude that the effect of having a large disk at a close spacing is to largely compensate for the effects of the distortions by effectively averaging over-all emission directions.

The superposition of a rim source and a uniform disk source (both emitting in accordance with the cosine distribution) is shown in Fig. 7. The geometry assumed in this example is the same as before ($R = 4.4375''$, $D = 1.3125''$), and the emission of the disk is assumed to be unity ($m = 1$, Eq. 5). Total deposition rates for various intensities of the rim source $m_r = 0$, 2.5 and 5 cm^{-1} are compared. It can be shown that the rim source contribution to the deposition rate I_{r0} peaks near, but slightly inside, the radius of the rim. For a certain range of intensity of the rim source, this feature can give rise to an improved uniformity over the deposition plane. As an example, the curve in Fig. 7 for $m_r = 2.5\ \text{cm}^{-1}$ corresponds to a distribution uniform to within about ± 1 percent over a 4-inch radius. Values of m_r/m around 2.5 cm have been found to hold for disk-shaped targets rf and dc sputtered under a variety of operating conditions[2]. Means of enhancing and controlling the edge effects were also discussed in Ref. 2. Without the rim source ($m_r = 0$), the impingment rate drops about 35 percent over the same 4-inch radius. However, it is clear that the presence of a rim source may not always be beneficial. The curve for $m_r = 5.0\ \text{cm}^{-1}$ in Fig. 7 is an example of an over-intense rim source detrimental to the uniformity.

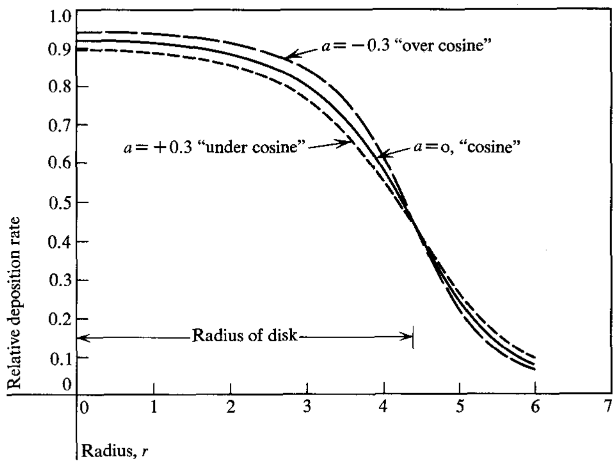
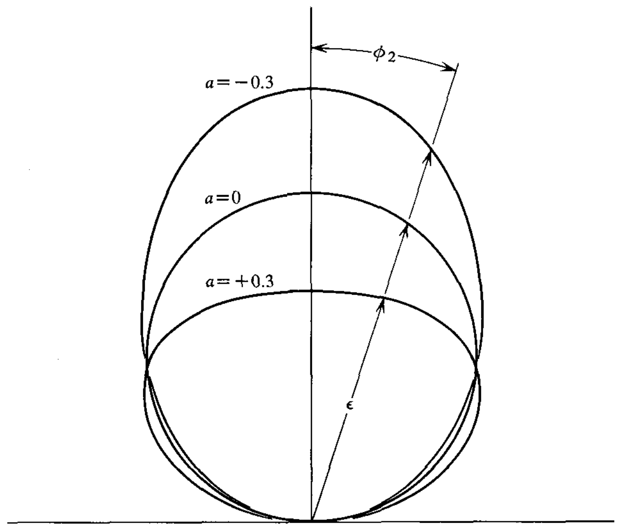


Figure 5 Deposit distributions from the uniformly emitting disk with and without deviations from the cosine emission distribution.

Figure 6 "Over cosine," cosine, and "under cosine" emission distributions.



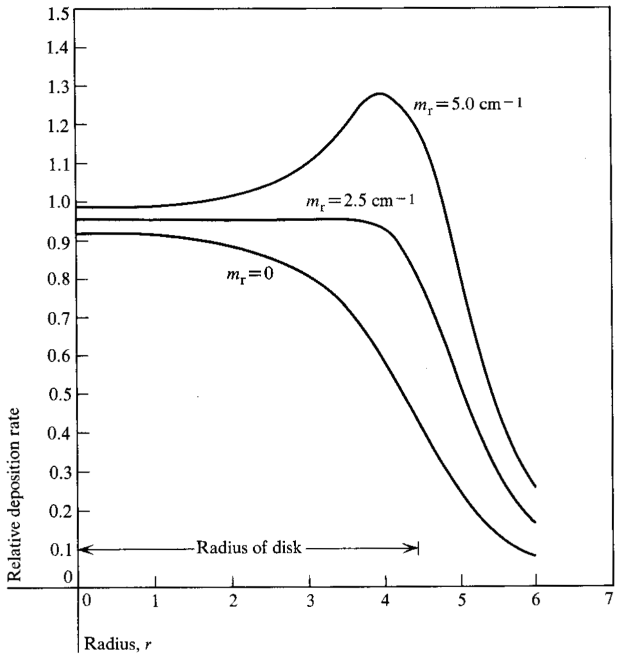
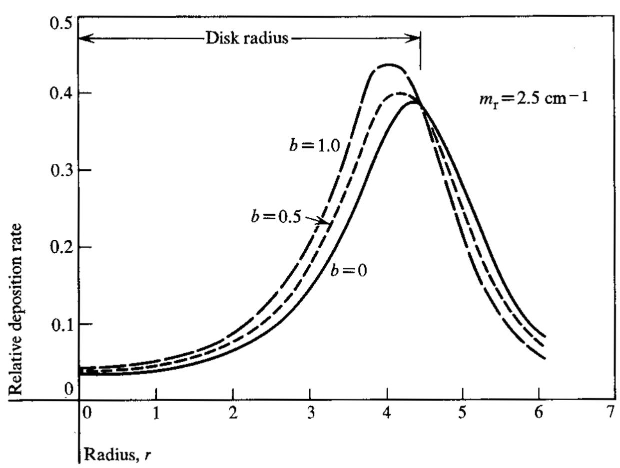


Figure 7 Superposition of the deposit distributions from a uniformly emitting disk and rim source of various intensities.

Figure 8 Deposit distribution from a rim source with various degrees of "inward" emission.



The effects of an asymmetrical emission distribution at the rim may be considered by adding I_{r0} and I_{r1} [Eqs. (10) and (12)]. Total deposition distribution for various degrees of asymmetry [$b = 0$, 0.5 and 1.0 in (12)] are shown in Fig. 8. The geometry assumed is the same as in the previous examples, and the intensity of the rim

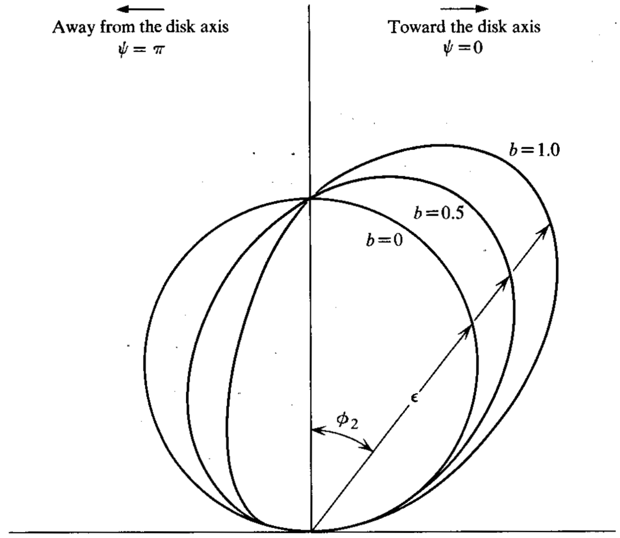


Figure 9 Cosine and asymmetrical "inward" emission distributions.

source, m_r, is assumed to be 2.5 cm^{-1}. The corresponding emission distributions are shown in Fig. 9.

One of the effects of introducing asymmetry into the rim emission is to shift the distribution of material inward from the rim. Another result, which is a less obvious consequence of the assumptions, is that the peak in the distribution increases as the degree of asymmetry increases. This relation is not due to an increase in the amount of material emitted from the rim since the net contribution of I_{r1} (the term which provides the asymmetry) is zero. Rather, the increase in peak height is due to the more "beam-like" shape of the asymmetrical distribution, as shown in Fig. 9.

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The author is located at the IBM Systems Development Division laboratory at San Jose, California 95114.