Thickness Distribution of Evaporated Films

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ABSTRACT

The emission distribution characteristics of an evaporation source can be used to define the correct geometry in the vacuum chamber for the production of uniform-thickness coatings.

We first measured the thickness of coatings on test pieces positioned at known radial distances on a single rotation flat rack in the vacuum evaporation chamber and used these data in a computer program which found the source emission function, in the form $\cos^Q \phi$, which provided the best fit to the data. ϕ is the emission angle of the evaporant stream from the source, measured from the vertical. The known emission function was then used to determine the source offset and calotte curvature which produced the best thickness uniformity over the diameter.

In one example, we found $Q = 1.31$ for Al_2O_3 evaporated from an electron beam source. This enabled us to predict a chamber geometry which yielded coatings across a calotte of diameter 81 cm with a thickness variation of +/- 0.3%. For $Si0_2$ $Q = 1.70$, but the uniformity was less excellent (+/- 3%) because this material is difficult to evaporate controllably. The technique is a powerful one for anyone setting up his coating chamber to produce a large number of coated substrates.

INTRODUCTION

Producing a coating of uniform thickness over a large aperture substrate, or over a rack loaded with many small substrates, can be done by making repeated trials with the rack loaded with test pieces. From one trial run to the next, the geometry is changed - the evaporation source offset increased for example - until the best arrangement is found. A more systematic way, and one generally more effective for a manufacturer, is to establish the intrinsic emission characteristics of the source (the source function) by a one-time experiment and to use this known source function to predict the best chamber geometry for good thickness uniformity. In this paper we present a scheme for doing this along with some practical examples for Al_2O_3 and $Si0_2$.

The source function can be used as data in a computer program which predicts the thickness uniformity over the rack; the accuracy of the simulation is only as good as the correctness of the source function used. It is important then to establish this function. It is equally important to contain the deposition angles (arrival angles) of the evaporant molecules at the substrate surface so that the molecules arrive from directions not far from the surface normal, otherwise the durability of the coatings will be poor. It seems to be generally true for practical substrates that good uniformity and small deposition angles have to be traded off against each other, that the price of good uniformity is poor deposition angles. There are ways out of this dilemma of course.

Additionally, the emission angles at the source must not be too large or else depletion or tunneling of the evaporant will perceptibly change the source function. But these topics are outside the scope of this paper; only thickness uniformity will be considered.

Let us reasonably suppose that the amount of material emitted by the source S (Fig. 1) in a given direction ϕ varies with ϕ, which is measured from some symmetry aids SS'. SS' will be taken to be the vertical through the source S: an error will exist if the source is tilted or some other asymmetry is introduced. We shall assume that the emission is independent of the azimuth, azimuthal variations being smoothed by substrate rotation. We shall consider only a single source of negligible extent. For the source function f (ϕ) we have used the even forms.

$$f(\phi) = A_0 + A_1, \cos\phi + A_2 \cos^2\phi + A_3 \cos^3\phi \quad \mathbf{(1)} \text{ or } \mathrm{Cos}^Q\phi \quad \mathbf{(2)}$$

The set of coefficients A, and Q, are parameters characteristic of the evaporant and its manner of evaporation. Neither form describes all possible source characteristics, although (1) is more general than (2). It is trivial matter to add more terms in the computation algorithm for (1) if necessary. We have found 4 terms enough.

We further assume that the arrival mass at the substrate follows an inverse square law, that the coating thickness varies with the cosine of the deposition angle and that all the arrival molecules stick. By integrating over one complete main revolution, we are thus able to compute the coating thickness from point to point on the substrate.

In (1), we have used exhaustive combinatorial search, or a fast spline routine', to select those coefficients which most closely predict the experimental thickness data. But for convenience we have generally used (2) and found the best-fit Q for a given set of experimental data by an interval-halving search routine: the process converges very rapidly.

We note that:

$A_0 = 1, A_1 = A_2 = A_3 = 0$

and $Q = 0$

represent one and the same source (point source). Likewise

$A_1 = 1, A_0 = A_2 = A_3 = 0$

and $Q = 1$

are identical and represent a Lambert source. It is easy to establish the following theorem, which provides the link between (1) and (2).

If $f(\phi) = A_0 + A_1 \cos\phi + \ldots + A_n \cos^n \phi$

is the source function for an evaporation source,

then $f(\phi) = \cos^Q \phi$, $Q =$

$$\frac{A_1 + 2A_2 + \ldots + nA_n}{A_0 + A_1 + \ldots + A_n}$$

is an equivalent function with errors existing only in the fourth order and higher.

EXPERIMENTAL APPROACH

We used the coating chamber arrangement shown in Fig. 1 with a centrally positioned source and a flat horizontal rack in single rotation. Other single rotation arrangements (curved racks, offset sources) would serve equally well, but note that the source function will be determined only over the range of ϕ employed, i.e. from zero to ϕ_m or 39 degrees in this paper. The source function may not be assumed valid outside this range. Planetary rotation is not appropriate for this calibration experiment since the solution for the source function will then be ill-conditioned, the coating thickness distribution across a planet being insensitive to source function.

Calibration runs were made for each evaporant under controlled process conditions. We placed glass test slides at intervals along the rack diameter and deposited half a dozen or so QW0T at 600nm. The normalized optical thicknesses were determined from spectrophotometric curves. Data pairs (rack position, thickness) were fed into a search program which returned the $\text{Cos}^Q\phi$ function (Table 2) which yielded a set of thicknesses most closely matching the experimental ones. We have thus built up a data bank of source functions for various evaporants and evaporation techniques.

$f(\phi)$ having been found, we then use a second program (Table 3) to find the optimum combination of calotte curvature and source offset for best uniformity (Fig. 2). This new geometry ought then to yield a rackful of coatings which are closely uniform in thickness.

We used a 112 cm chamber equipped for single rotation and evaporated Al_2O_3 from a centrally-placed electron gun. The experimental flat rack data of Table 1 were used to produce the computer output of Table 2 with the f (ϕ) valid over the range zero to 39 degrees. ϕ was found to be 1.31. This ϕ value was used to optimize the chamber geometry in a second program (Table 3) which this showed that if we used a spherically curved rack with R = 65.1 cm and with the source offset 34.3 cm. We should get good thickness uniformity. (The computer output of Table 3 is in one of our standard formats; we are interested only in the thickness information here.) Coating runs were made with this new geometry and produced the experimental results of Table 4.

Table 1

Radial Position	0.0	5.1	10.2	15.2	20.3	25.4	30.5	35.6	40.6
Normalized thickness	100.0	97.9	91.6	80.6	71.0	61.8	51.6	40.8	35.2

Table 2

Coating Distribution Program 99X:

A. Musset
Denton Vacuum LLC., Moorestown, NJ

Uses flat rack data to compute source function in form (COS (PHI))^Q
Load CTGDIST99A for fast computation by cubic splines
Single Source: inverse square and cosine deposition laws are assumed

Left offset of source	0
Rear offset of source	0
Height of rack center above source	51
Left offset of rack center	0
Tilt of rotation axis	0

Rack Positions (cm)	0.0	5.1	10.2	15.2	20.3	25.4	30.5	35.6	40.6
Thickness	100.0	97.9	91.6	80.6	71.0	61.8	51.6	40.8	35.2

Source function: (COS(PHI))^ 1.31
Validity range: 0 to 39 degrees

Table 3

Coating Distribution Program 6B:

A. Musset
Denton Vacuum LLC., Moorestown, NJ

Computes distribution over sphere rotating on its own axis in single rotation.
Single source: inverse square and cosine deposition laws are assumed

Left offset of source	34.29
Rear offset of source	0
Height of sphere center above source	51
Horizontal offset of sphere center	0
Radius of sphere	-65.054
Angle of rotation axis from vertical	0
Zone radius starts at	0
Zone radius finishes at	40.64
Zone radius increment	5.08

Source distribution: (COS(PHI))^ 1.31
Density of Coating: 4

RADIAL POSITION	THICKNESS	DEPOSITION DISTANCE	DEPOSITION ANGLE	EMISSION ANGLE
0	99.5	74 [74 74]	28 [28]	28 [28]
5.08	99.5	73 [71 76]	28 [29]	28 [31]
10.16	99.6	73 [69 78]	28 [30]	28 [35]
15.24	99.7	72 [66 80]	28 [30]	28 [38]
20.32	99.8	71 [63 82]	28 [31]	27 [41]
25.4	99.9	70 [61 85]	28 [31]	27 [45]
30.48	100	68 [58 87]	29 [32]	28 [48]
35.56	100	66 [54 89]	29 [32]	28 [52]
40.64	99.6	64 [51 91]	29 [32]	31 [56]

[   ] are extreme values

Maximum thickness of film is 129 nm per gram (for dimensions in cm)

Table 4

Radial Positions (cm) **Normalized Thickness**	0.0	5.1	10.2	15.2	20.3	25.4	30.5	35.6	40.6
Predicted	99.5	99.5	99.6	99.7	99.8	99.9	100	100	99.6
Run 1	99.8	99.6	99.6	100	99.6	99.8	99.6	100	99.4
Run 2	99.8	99.6	99.8	99.6	100	99.9	99.9	100	99.5
Run 3	100	99.6	99.5	100	99.3	99.0	100	100	98.8

For a rack diameter of 81 cm the thickness uniformity was very good. No test runs were needed to produce this excellent uniformity other than the initial data bank runs which permanently established the source function.

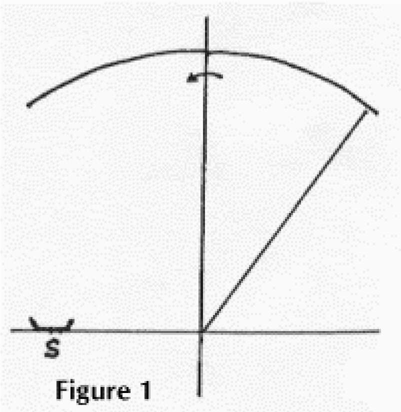

Figure 1

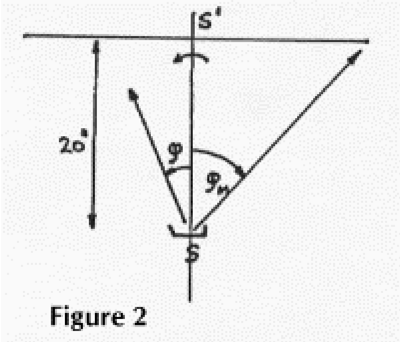

Figure 2

EXAMPLE SiO_2

This example is chosen for presentation in this paper because SiO_2 is a commonly used evaporant, but one which tends to be notoriously badly behaved in the e-gun crucible. The Q values found from the flat rack data ranged from 1.56 to 1.75. We used a mean value of 1.70 and obtained the following thicknesses of coatings on the calotte test pieces (Table 5). The geometry was identical to that used in the Al_2O_3 example except that the source offset was increased to 37.1 cm.

Radial Positions (cm) **Normalized Thickness**	0.0	5.1	10.2	15.2	20.3	25.4	30.5	35.6	40.6
Predicted	99.5	99.5	99.6	99.7	99.8	99.9	100.0	100.0	99.7
Run 1	93.9	93.4	94.3	94.8	95.0	96.2	97.5	98.6	100.0
Run 2	100	99.2	99.6	99.3	99.6	99.9	99.7	99.7	99.8

The Q value was found to be higher than for Al_2O_3 suggestive of a greater degree of evaporant tunneling, and the thickness uniformity more erratic though still good. Considerable operator skill (control of gun power, sweep pattern, beam position) was needed to achieve these results.

These cases are presented by way of examples only, but the procedure can be applied to a variety of substrate shapes, masking arrangements and to planetary rotation.

REFERENCES

1. "BASIC in Action", Chap 12, by A Musset and S. Dvorak, Butterworth (1984)