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PRODUCTION COATING OF VIAS IN ALUMINA SUBSTRATES WITH VACUUM EVAPORATED CHROMIUM AND GOLD

Conference Paper

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PRODUCTION COATING OF VIAS IN ALUMINA SUBSTRATES WITH VACUUM EVAPORATED CHROMIUM AND GOLD

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Summary

Design of a production vacuum deposition fixture for coating 3.75 inch by 4.50 inch (95 by 114 mm) alumina substrates with 50 nm of chromium and 6 μm of gold presented challenges in meeting geometry, mechanical, and cost constraints. The coated substrates had to meet unique requirements for via resistance, thickness uniformity, and backside metallization on hybrid microcircuits designed by Sandia Laboratories at Albuquerque, New Mexico, for the Energy Research and Development Administration and manufactured at the Kansas City Division of The Bendix Corporation.

The design required that vacuum evaporated chromium and gold thin films be used with a thru-hole maximum resistance of 25 milliohms on 0.025-inch-diameter (0.64 mm) vias in 0.027-inch-thick (0.69 mm) alumina substrates. A resistance of 10 milliohms was a highly desirable design objective. It was also highly desirable to coat both sides of the substrate and the via walls with chromium before depositing the gold rather than depositing the chromium and the gold on one side of the substrate and then turning the substrate over to deposit the chromium and gold on the other side. Depositing both the chromium and gold on one side of the substrate at a time would result in a layered chromium-gold-chromium-gold structure on the via wall.

Commercially available planetary fixtures could not deposit films which met all the design objectives. A study of fixture geometry versus the required film characteristics resulted in the design of a fixture which rotates the substrates 360 degrees about their long axis while simultaneously rotating them about the deposition source in a prolate cycloid motion.

The Requirement

The technique of plating through holes is old and well established in the manufacturing of conventional printed circuit boards. But plating through holes in thin film substrates is not so well established. A production process has been developed for metallizing through holes in thin film substrates using vapor deposition to coat both sides of the substrate without breaking vacuum. The metallized through hole is often referred to as a *via*, and that term will be used here.

The product and process specifications that triggered the development of this new process are outlined below.

- Alumina substrates 4.5 by 3.75 by 0.027 inches (114 by 95 by 0.69 mm) containing vias with diameters as small as 0.025 inch (0.6 mm) must be metallized on both sides with a 250Å (25 nm) chrome layer, followed immediately by a 60 kÅ (6 μm) thick gold layer. If the circuit uses resistors, the smooth side of the substrate is coated with a 500 Å (50 nm) Ta_2N film before the chromium is deposited.
- The two metallized planes on each side of the substrate are electrically interconnected with vias. Individual via resistances are required to be less than 10 milliohms and the via walls must have a film thickness uniformity that does not vary by more than three to one.
- The metallization process is specified as vacuum evaporation. Coating both sides of the substrate during the same cycle was preferred for two reasons: it prevented a Cr-Au to Cr-Au interlayering within the via, and it significantly reduced the labor content of the process.

Designing these product requirements into a low cost, high yield process becomes, to a large extent, a matter of fixturing and geometry design of the vapor deposition system. The surface condition of the via wall also plays an important role in determining via resistance.[1]

Fixture Design Considerations

A detailed search of the market was made to determine if standard equipment was available to meet Bendix needs. No manufacturer would guarantee standard equipment to meet Bendix requirements, so special design remained the most feasible alternative. Bendix developed the concept, set up the specifications, and then went to a vendor for a detailed design.

In via coverage, two major design criteria were required: hole shadowing must be controlled and, since the via wall always lies in a plane normal to the face of the substrate, step coverage must be considered and compensated for. Via shadowing and step coverage--as well as thickness uniformity on the surface and inside the via--are functions of the incident angle that the vapor stream forms with a normal to the surface at a point of interest. Various source geometries in conjunction with various manipulations of the substrate were considered as solutions to the problem. Integrated with these considerations was the problem of rotating the substrate 180° or subjecting it to a bisymmetrical source to achieve a uniform coating simultaneously on both sides.

Typical geometries and fixture configurations were reviewed for compatibilities that might lend themselves to design modifications that would result in workable fixturing. A rotating planetary fixturing concept with a centrally located electron gun source and a conventional bell jar system was selected for study. The plan was to choose a platen diameter large enough to meet capacity requirements, theoretically optimize the planetary geometry toward an acceptable via coverage, and evaluate the resulting thickness uniformity. If the via and thickness requirements were met, the necessary bell jar size and evaporant source capacity would be evaluated for compatibility with the fixture concept.

Minimum Thickness and Thickness Uniformity

In the typical planetary fixture, a platen carrying the substrates rotates in a concentric circle around the source (Figure 1). This style of fixture failed to meet Bendix requirements for two reasons: the substrate could only be coated on one side during a single deposition cycle, and the standard fixtures did not consider via coverage.

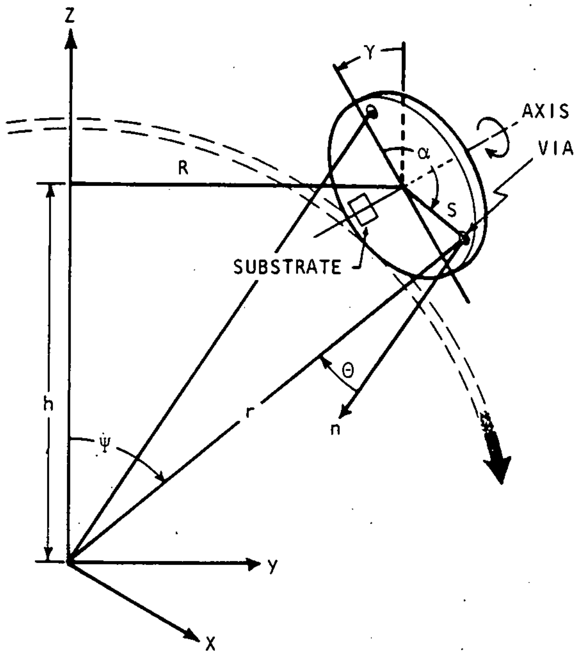


Figure 1. Typical Parameters for Planetary Fixture Assuming a Point Source

In a stationary position with an assumed point source, the thickness (Tp) at a particular point on the surface of the platen (Figure 1) is a function of the inverse square of the straight line distance (r) from the source to the point (Tp) and the cosine of the angle (Θ) formed by (r) and a normal to the surface at the particular point (Tp). This is expressed in the following equation[2].

$$Tp = \frac{B\cos\Theta}{r^2}$$

where:

Tp = thickness at point of interest (in mm),

$B = \frac{M}{4\pi\rho}$,

M = total mass of evaporated material evaporated (in grams),

ρ = density of evaporant metal,

r = straight line distance from source to Tp, and

Θ = angle formed between (r) and a normal with the surface of Tp.

If the thickness at a point that falls on the radius (Figure 2) such that it also lies on the vertical centerline of the platen is compared to the thickness that would have been deposited on the point had the platen been rotated, a difference in thickness may occur since the magnitude of r and Θ both may change with the platen rotation. When the platen is in continuous rotation, however, any thickness gradient appearing along the radius s would appear on circular contours around the center of the platen since each point on a given radius sees the same history of r and Θ magnitudes. The thickness of these contours can be defined with the following equation.[3]

$$Tp = B \int_0^{2\pi} (h\sin\gamma + R\cos\gamma)/r^3 \alpha,$$

where:

$B = \frac{M}{4\pi\rho}$,

M = Mass (in grams),

ρ = density,

$r = h^2+R^2+s^2+2s\cos\alpha(h\cos\gamma-R\sin\gamma)$,

γ = Angle of platen tilt,

α = Angle of platen rotation,

S = Distance from platen center to point of interest on platen radius,

R = Horizontal distance from platen center to vertical centerline of source, and

h = Vertical distance from horizontal centerline of platen to the source.

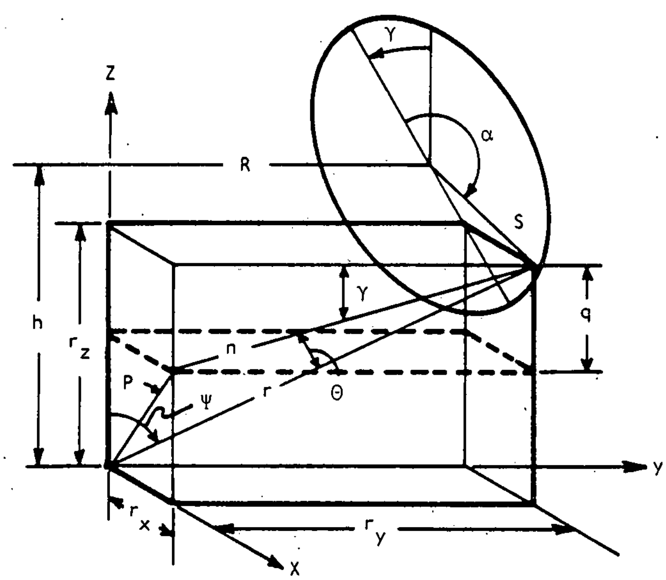


Figure 2. Three Axis View of Rotating Planetary Fixture[3]

The contour thickness and most of the dimensions shown in Figure 2 were computed and reviewed and particular data was selected for plotting. The variables and ranges of variance are as follows:

Tp = Contour thickness at any selected point on S,

γ = Angle of platen tilt from 0 to 90 degrees in increments of 10 degrees,

α = Angle of platen rotation from 0 to 360 degrees in increments of 20 degrees,

R = Horizontal platen-source distance held constant at 10 inches (25.4 mm),

h = Vertical platen-source distance from 16 to 22 inches (406 to 558 mm) in increments of 2 inches (50.8 mm), and

s = Platen center-platen radius distance from 0 to 10 inches (0 to 254 mm) in increments of 2 inches (50.8 mm).

The average thickness on the via walls does not follow the thickness of the surface since the via opening is sometimes shadowed during platen rotation and the via wall also lies at right angles to the platen surfaces. The platen orbit is not considered in thickness calculations since the vapor deposition is considered spherical and the orbit around the source is considered to be exactly concentric.

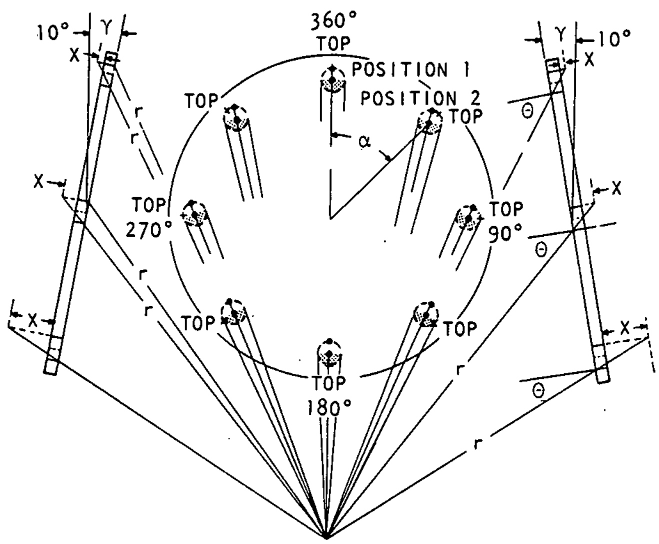


Figure 3. Via Shadowing Through 360° Rotation

Figure 3 shows a via that lies on the radius (S) of a platen as the platen rotates clockwise through 360 degrees. The zero reference for the angle of rotation (α) is defined as the platen position that places the via at the top of the platen and on its vertical centerline. The outermost section of the via (labeled *TOP* in Figure 3) is shadowed through the rotational angles of 90 to 270 degrees, while the innermost section toward the center of the platen is shadowed during the clockwise rotation of 270 through 90 degrees. The thickness ratio of film deposited at a point on the platen surface and the film thickness deposited on a via wall at the same reference point would vary with via position since the angle of vapor approach to the via opening changes. If the vapor stream is aimed more directly into the via opening, more vapor will pass through the via and less will condense on the via walls. The angle (Θ) in Figure 3 decreases as the platen rotates from its reference position at 0 degrees to a 180 degree position of the angle (α). The maximum depth of penetration into the projection of the via is labeled *X* and is a relative representation of the amount of vapor that would pass through the via.

The average thickness and the thickness uniformity inside the via will be a function of the relative differences in the values of Θ and *r* during the time periods that each section of the via is not shadowed.

In Figure 4, the centerline of a 0.027 inch (0.69 mm) diameter via is assumed to lie on a 2 inch (50 mm) radius from the center of the platen as the platen is rotated through 180 degrees. The magnitudes of the *r* and Θ components that fell on the centerline of the via were computed at each 20 degree increment through 180 degrees and the depth of penetration into the via or into a projection of the via was determined and plotted as the letter *X* on the ordinate of the graph against the angle of rotation (α) on the abcissa. The parameters *h* and *R* were held constant at 20 and 10 inches respectively.

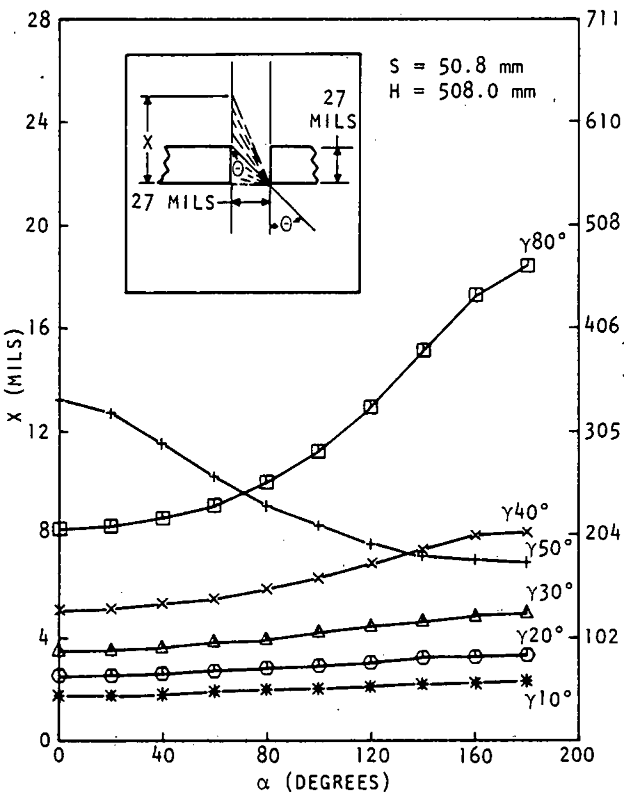


Figure 4. Maximum Depth of Vapor Penetration Through the Via Versus Platen Rotation With Various Platen Tilts

Six curves were plotted with platen tilts of 10, 20, 30, 40, 50, and 80 degrees. The lower angles of platen tilt are much flatter and tend to give much better step coverage because there is less variation in the angle during rotation and also because there is a reduced minimum value for the angle Θ. In Figure 5, three points on the substrate radius are examined at 180 degrees, and *X* is plotted against platen tilt.

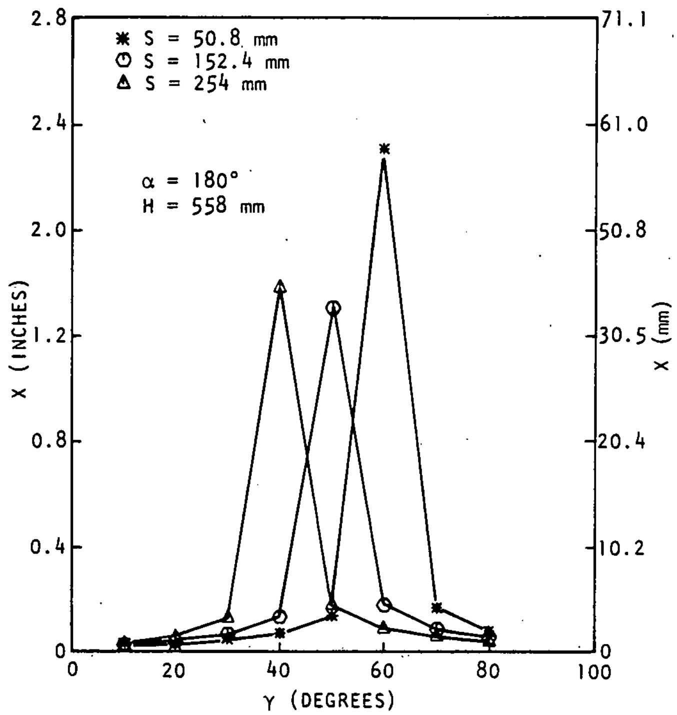


Figure 5. Maximum Depth of Vapor Penetration Through the Via Versus Platen Rotation With Various Platen Tilts

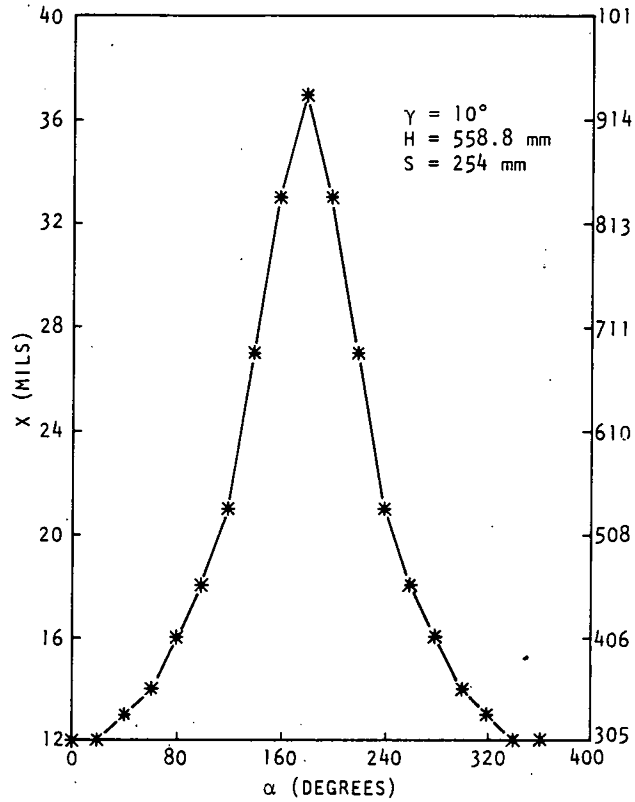


Figure 6. High Resolution Plot of Vapor Penetration Through the Via Versus Platen Rotation With Various Platen Tilts

These curves are much flatter for platen tilts from 10 to 30 degrees than for the higher tilt angles.

In Figure 6 the via has been moved out on S to a 10 inch (254 mm) radius point and the resolution of X on the curve has been expanded by an order of magnitude. The rotation of the platen was 0 to 360 degrees and the angle of platen tilt remains at 10 degrees.

In Figure 7, two planes are shown to intersect and a vector (r) is drawn from the source to their intersection. If r is held constant, the difference in thickness of a deposition that would occur on each surface would be a function of the difference in the angle Θ. The sketch shows that if either plane is chosen to be the platen position and the other the normal, then the angle Θ for the two cases will be complementary and T_H will be related to Tp by the function tanΘ. In Figure 7, T_H is defined as the thickness on a surface normal to the platen surface if a given thickness (Tp) is deposited on the surface at the intersection point.

Figure 8 plots the effect of the via wall lying in a plane 90 degrees to the platen surface. The same geometry was used in Figure 8 as was used in Figure 6, and the platen was again rotated through 360 degrees in increments of 20 degrees. It was assumed that sufficient charge was evaporated at each 20 degree increment to ensure a thickness of 60 kÅ (6 μm) on the platen surface at that point. Examining the thickness (Th) that would occur at the point if it lies in a plane perpendicular to the platen surface, it can be seen that on individual points on this platen radius the ratio of surface thickness to via wall thickness at worst case conditions may be as high as three to one.

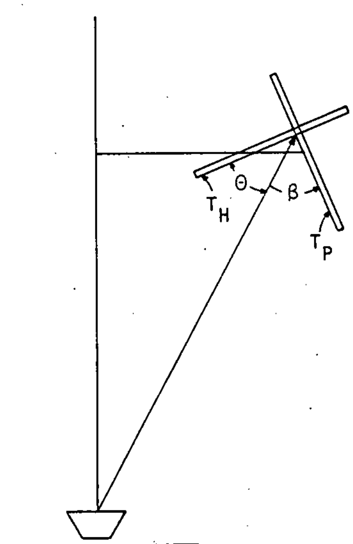


Figure 7. Comparison of Relationships of Θ With the Platen Surfaces and a Surface Normal to the Platen

In continual platen rotation, however, the thickness accumulation at a point on the via wall would be the result of a summation of the thickness values that the point on the via wall received at each position it experienced during the rotation of the

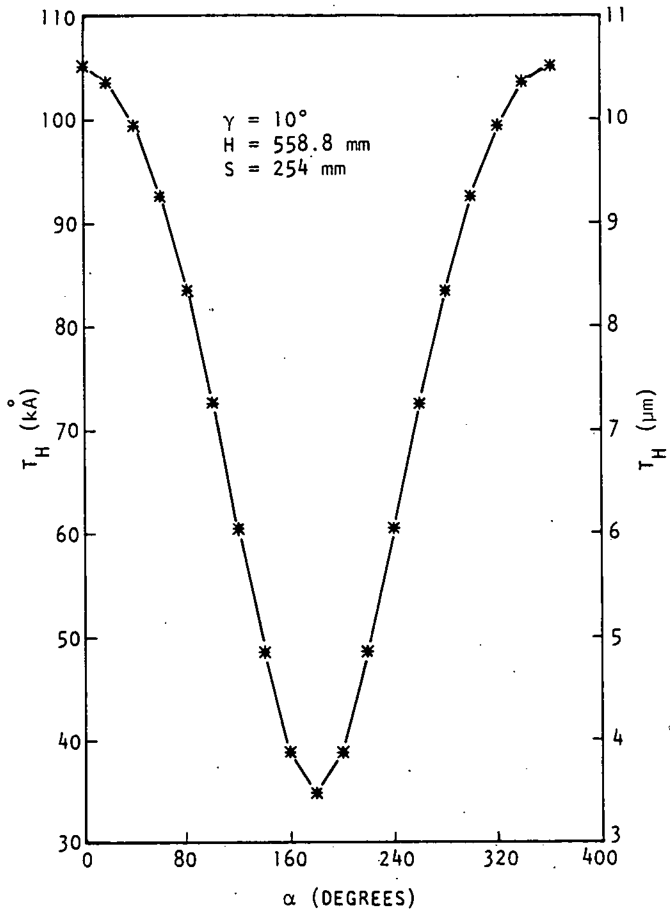


Figure 8. The Thickness (T_H) Occurring on a Surface Normal to the Platen Surface at 20° Points on the Platen, Assuming a Constant Thickness on the Surface

platen. The contour thickness on the platen surface will be a similar summation. The equations in Figure 9 make these summations for the conditions defined below.

Figure 9 is a sketch of a platen with the centerline of a 0.025 inch (0.64 mm) via located at a point on the platen radius 9.9825 inches (250 mm) from the platen center. The platen is considered to be in clockwise rotation around the center. The geometry associated with the platen is as follows.

- Constants

  Via diameter = 0.025 inch (0.64 mm)

  γ = 10 degrees

  R = 10 inches (254 mm)

  B = 250 grams/(4π)(19.2)

  h = 22 inches (558 mm)

- Variables

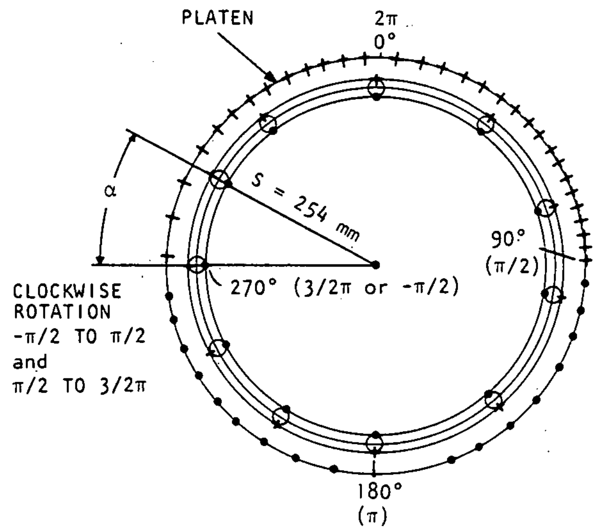
  $\alpha = -\pi/2$ to $+\pi/2$ and from $\pi/2$ to $3\pi/2$ radians in continuous clockwise rotation

$$\gamma = (h^2+R^2+s^2+2s\cos\alpha(h\cos\gamma-R\sin\gamma)$$

$$\Theta = \arccos(h^2\sin\gamma+R\cos\gamma)/\gamma$$

Two points on the via are considered: the outmost point on the radius is marked with a plus (+) and the shortest point on the radius is marked with a dot (·). The period of rotation through $-\pi/2$ to $+\pi/2$ is also identified with a + sign and indicates the period of rotation where the outermost point of the via is not shadowed. The dotted line indicates the rotation period ($\pi/2$ to $3\pi/2$) where the innermost point of the via (marked with a dot) is not shadowed.

The equation for T_{H+} calculates the accumulated thickness that would be deposited on a surface normal to the platen surface at the 10 inch (25.4 mm) radius point (marked with a + sign) while the platen is in continuous clockwise rotation with the stated dimension and shadowing condition. The term $T_{H\cdot}$ is the total thickness collected on the innermost section of the via at 9.975 inches (250 mm) from the platen center. The small changes in r and Θ that would occur if the platen was not rotated and points around the circumference of the 0.025 inch (0.64 mm) diameter via.



T_{H_+} = THICKNESS ON VIA WALL AT POINT MARKED +

$T_{H_\cdot}$ = THICKNESS ON VIA WALL AT POINT MARKED ·

Tp = THICKNESS CONTOUR ON PLATEN SURFACE AT VIA CENTERLINE

THEREFORE

$$T_{H_+} B \int_{-\pi/2}^{\pi/2} \tan\Theta\left[\frac{h\sin\gamma + R\cos\gamma}{r^3}\right] d\alpha = 88 \text{ kÅ } (8.8\ \mu m)$$

$$T_{H_+} B \int_{\pi/2}^{3\pi/2} \tan\Theta\left[\frac{h\sin\gamma + R\cos\gamma}{r^3}\right] d\alpha = 48.8 \text{ kÅ } (4.9\ \mu m)$$

$$Tp = B \int_{0}^{2\pi} \left[\frac{h\sin\gamma + R\cos\gamma}{r^3}\right] d\alpha = 114 \text{ kÅ } (11.4\ \mu m)$$

Figure 9. Total Thickness Accumulation at Two Points on the Via Wall That Lie on the Largest and Smallest Platen Radius (S)

were evaluated and considered insignificant. The worst case conditions at points + and • on the via wall were considered to be equal to the thickness around each half section of the via.

Via Resistance

Figure 10 shows the resistance calculations for theoretically perfect vias. A via with a uniform wall thickness (this assumes ideal wall surfaces) of 30 kÅ (3 μm) on a 0.025 inch (0.6 mm) diameter via will have a resistance of less than 10 milliohms. The via thickness calculations indicate achievable wall thickness that would yield resistances well below 10 milliohms at 60 kÅ (6 μm) surface thickness.

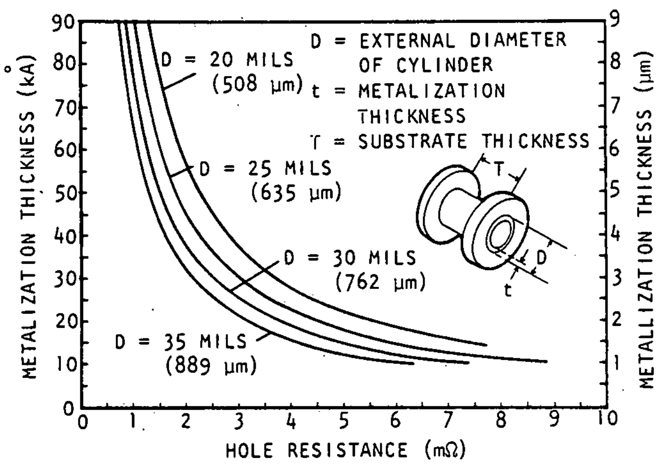


Figure 10. Theoretical Plating Thickness Versus Hole Resistance

Backside Metallization

To enhance thickness uniformity, maximize thickness inside the via, and to obtain metallization on both sides of the substrate within the same deposition run, Bendix chose the technique of rotating the substrate on its own axis. Making a complete deposition on the front side and then rotating the substrate and depositing the back side was considered, but this method did not adapt to the planetary mechanics as well as it did to drum configurations and did not have the advantage of improving via coverages by presenting the substrate to the source throughout the different angles generated by the third axis of motion. The mechanical complexity necessary to achieve this additional motion was realized to be a disadvantage. Preliminary bids were sent out to review the feasibility of designing a fixture of this type. After this review, the decision was made to require the extra axis of rotation.

Film Thickness Uniformity and Collection Efficiency

The best film thickness uniformity does not necessarily occur at the same point as best step or via coverage. For a given platen tilt and diameter in a planetary fixture using a point source, uniformity will reach an optimum at some ratio of h/r, although not all combinations of these variables result in practical dimensions. Figure 11 is a plot of h/r ratios versus uniformity on a 3-inch (76 mm) platen. Figure 12 shows the minimum point for the 20 inch (508 mm) diameter platen with tilt angles of 20 and 30 degrees at ratios above two to one. In Figure 13,

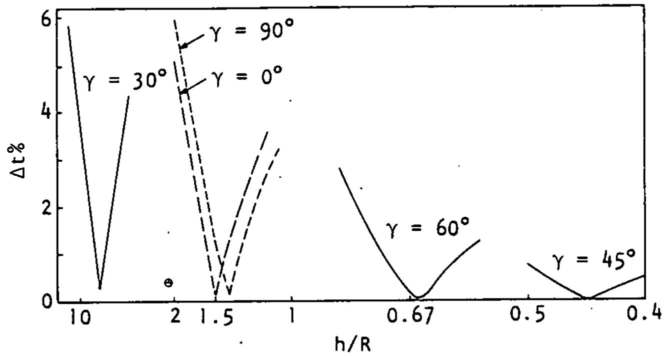


Figure 11. Thickness Variation as a Function of h/R for Various Angles of Tilt (Graph used with the permission of Grandville-Phillips Company, Boulder, Colorado[3])

the thickness is examined at a point on the vertical centerline of the platen located at 2, 6, and 10 inches (50, 152, and 254 mm) from the center of the platen. The tilt is held constant at 20 degrees and the vertical height is the variable on the graph. Collection efficiency is seen to be poor at the geometry described, but uniformity is near optimum.

The substrate was not considered rotating around its own axis. Rotation of the substrate around its own axis reduced the efficiency by an estimated 60 percent.

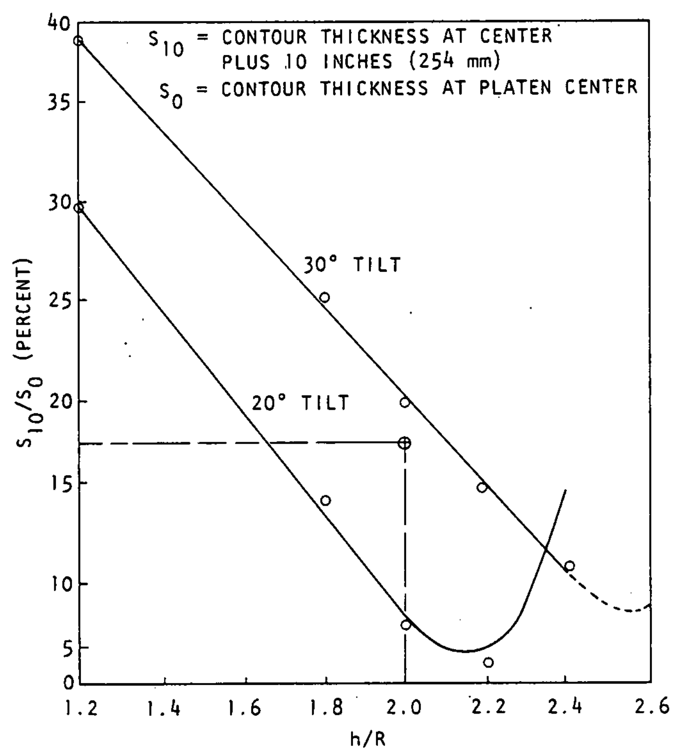


Figure 12. Percent Deviation of Thickness Across a 10-Inch (254 mm) Platen Versus Ratio of h/R for 20 and 30 Degree Platen Tilt

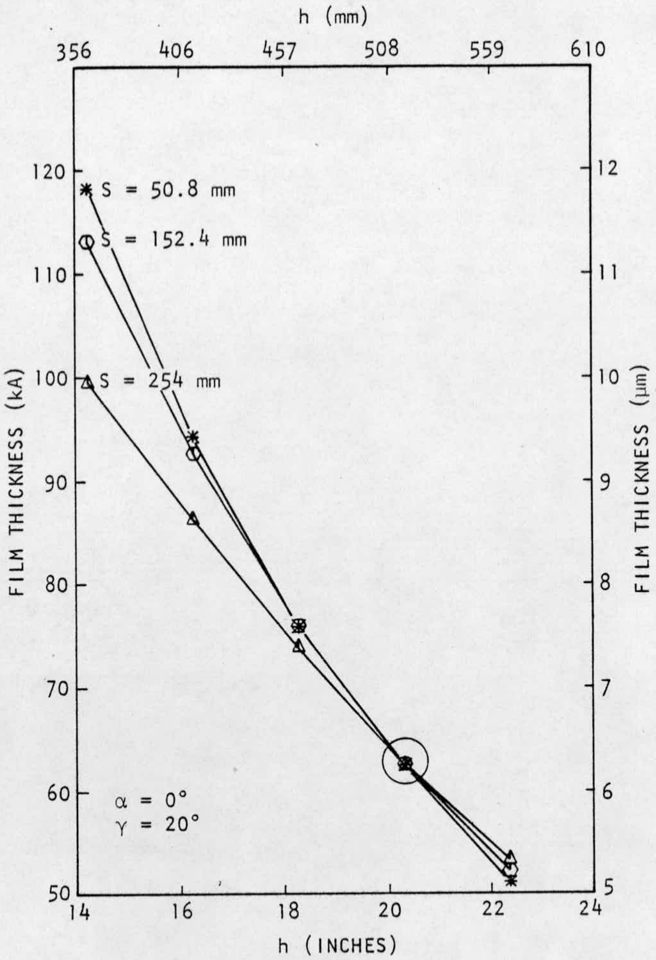


Figure 13. Film Thickness at Various Platen Points Versus Platen Heights

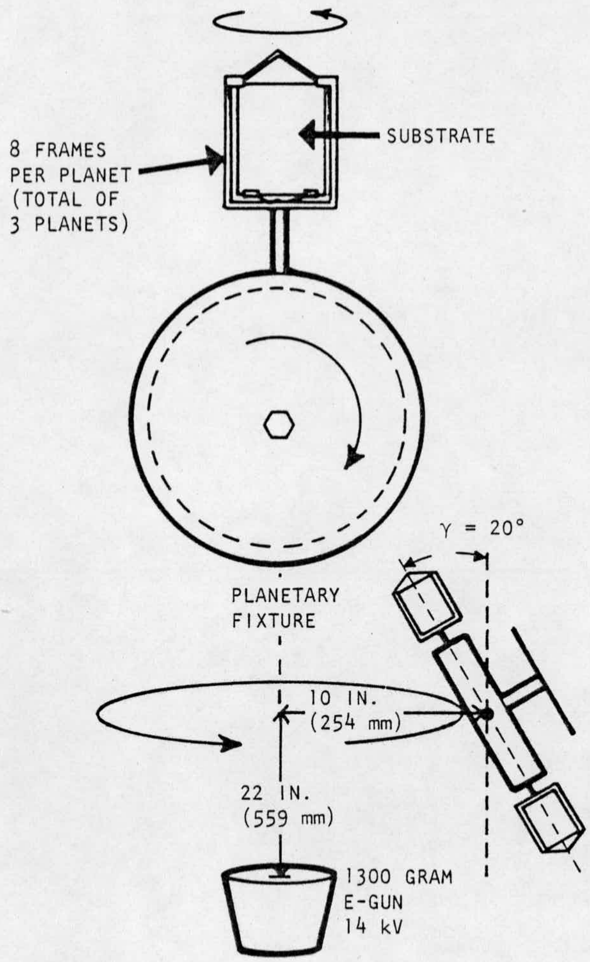


Figure 14. Specified Dimensions of Planetary Fixture

The specification for the machine geometry and fixture concept was written, and Davis-Wilder, Sunnyvale, California, won the bid and designed the fixture and vacuum system. Figure 14 shows the values for γ, R, and h, and indicates the third axis of motion. Figure 15 pictures the system. Davis-Wilder installed the Miessner pump at the top of the bell jar; substrate heat is furnished by infrared lamps. The substrate frame holds two substrates back to back if single side deposition without vias is required, or one substrate if both side metallization with vias is required. With a typical circuit size of 1 by 1 inch (25 by 25 mm), this represents 432 or 216 circuits per batch.

Film Properties

The rotation of the substrate on its axis and the relatively low angle of platen tilt were expected to influence film metallurgy to some degree, but not enough to keep the film from meeting Bendix production requirements.

Characterization of Design and Results

The characterization plan varies machine parameters such as evaporation rates, elapsed time between the end of the chromium deposition and the start of the gold deposition, deposition times, metal thicknesses,

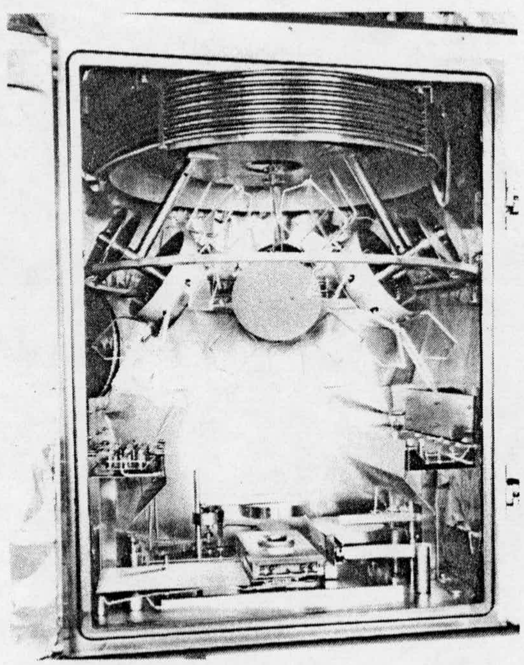


Figure 15. The Davis-Wilder System

fixture rotation speeds, geometry, substrate temperatures, and film properties to establish operating points and acceptable limits of variations.

Thickness Uniformity on the Substrate Surface

Evaluation of thickness uniformity across the substrate, including extreme measurements on both sides, indicates that a thickness uniformity of at least ±10 percent can be obtained.

Sheet Resistance of Gold

The sheet resistance of 40 kÅ (4 μm) of gold deposited in the machine averages 8 milliohms.

Surface Analysis

Surface analysis of the gold by Auger spectrometer shows no contamination except small traces of carbon. The carbon disappears when a few nanometers of surface is removed.

Bulk Purity

The bulk purity of gold was checked with electron microprobe and X-ray fluorescence to a penetration depth of 0.6 to 0.3 μm respectively and no contaminant was evident with the typical sensitivities of the technique.

Via Resistance and Uniformity

Via resistance of fourteen 50-mil (276 mm) holes evenly dispersed over a 4.5 by 3.75 inch (114 by 95 mm) substrate averaged 0.96 milliohms with a Σ of 0.03. A cross section of via holes shows thickness on the thick side of the via to be 100 kÅ (1 μm) and for the low side to be between 35 and 40 kÅ (350 and 400 nm) for surface thickness ranging from 66 to 75 kÅ (660 to 750 nm). Figure 16 shows a comparison of measured and calculated via resistance between the Davis-Wilder system and a typical planetary system. The capacity of the Davis-Wilder machine is three times that of the planetary system now in use at Bendix. High capacity with good via coverage is possible because of the special geometry design.

Bondability

Bondability of the film directly out of the machine is good. The ability of the film to withstand subsequent processing is now under evaluation.

Gold plated copper alloy leads 5.5 by 15 mils (139 by 381 μm) were thermocompression bonded to film directly out of the machine. Each lead was pulled at 90 degrees until the film adhesion failed or until the lead frame broke. The metal film was 60 kA (6 μm) thick. Typical results included the following:

- Number of pull attempts: 342.
- Percent film failures: 0.
- Percent lead failures: 100.
- $\bar{x}$ pull strength: 2.94 pounds (1.3 kg).

Conclusions

A specially designed planetary fixture has been built and is being characterized. Theoretical results agree

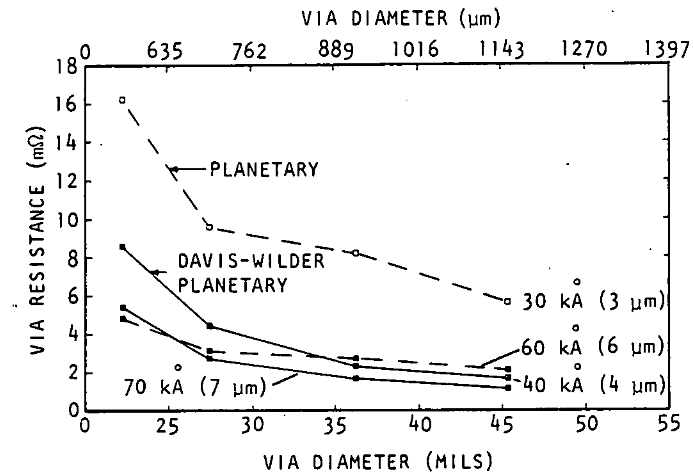


Figure 16. Measured Via Resistance Versus Hole Size in a Standard Planetary Fixture and the Davis-Wilder Fixture

with measured results within a range which permits the production of parts which meet specifications.

The planetary fixture gives good via coverage over a broad area without compromising other film properties. Additional bearings and moving parts had to be added to meet the mechanical requirements and these additional parts tend to increase machine down time. Some of the mechanical problems were solved by the installation of shielding against heat and contamination from the evaporant.

An evaluation is now being performed to determine the optimum bearing life versus bearing cost, but insufficient data is available at this time to permit recommendation of a specific bearing lubrication process.

The advantages and disadvantages of the fixture can be compared as follows.

Advantages

- Both sides of the substrate can be metallized during the same pumpdown.
- Via coverage is good with a large platen diameter.
- Surface uniformity and typical film properties are both consistently good.

Disadvantages

- The bell jar must be cleaned more often.
- The new fixtures are more complex mechanically.

A production cost study estimates a three to one reduction in labor costs for the process after all factors are considered.

[1]D. Norwood, *Manufacturing Processes for Hybrid Microcircuits Containing Vias* (Paper being presented at 26th Electronics Components Conference).
[2]L. Holland, *Vacuum Deposition of Thin Films* (Wiley, New York, 1956).
[3]Klaus H. Behrndt (Grandville Phillips Company, Boulder, Colorado), "*Thickness Distribution and Step Coverage in a New Planetary Substrate Holder Geometry*". (Submitted for publication to *J. Vac. Sci. Tech.*)