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MULTIPLE HYBRID MICROCIRCUIT PROCESSING

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Prepared by L. E. Schantz, D/842, under EP 4122659

Efforts were undertaken to study and select fabrication methods suitable for processing multiple hybrid microcircuits (HMCs) on 3.75- by 4.5-inch (95 by 114 mm) substrates through thin-film metallization and photolithography. Each fabrication method studied was based on its potential for multiple hybrid microcircuit processing. Thin-film deposition parameters were analyzed in terms of thin-film properties necessary to meet HMC electrical and component attachment requirements, and photolithography parameters were analyzed in terms of dimensional requirements on the circuit pattern. The objective of this effort was met, and the techniques developed are being used successfully in the production of multiple HMCs.

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SUMMARY

Activities started in March 1972 to establish economical vacuum deposition and photolithographic fabrication processes for thin-film hybrid microcircuits (HMCs). It had been previously determined that multiple HMC processing was the most economical method of producing HMCs in quantities sufficient to meet present and forecast production schedules.

To accomplish this, investigations via literature searches, SLA assistance, vendor publication reviews, and industrial contacts were planned to find processing methods and systems that could handle the larger substrates and also be capable of reproducing first generation technological achievements. Although this primary objective never changed, the project scope was expanded in August 1972 to initially set up a manual 3.75- by 4.5-inch substrate production capability for early (December 1972) implementation. To accomplish this intermediate task, major efforts were directed toward the following items pursuant to a non-automatic operation:

- Photoresist roller coating,
- IR photoresist drying,
- Batch developing and etching, and
- Electron-beam Cr/Au planetary deposition.

Efforts toward the primary objective were to resume upon completion of the intermediate objective. The primary objectives fell into the following categories:

- Electron-beam chromium/gold deposition (thin-film metallization characterization),
- Photoresist roller coating,
- Infrared photoresist drying,
- Automatic photoresist exposure, and
- Spray developing and etching.

The adhesion, resistivity, and thermocompression bondability characteristics of chromium/gold thin-films on tantalum-nitride-coated substrates were studied to establish an acceptable deposition process for microcircuit manufacturing. Best results were obtained at a 300°C substrate temperature. This data indicated that the

deposition rates must be controlled at 1 to 3 angstroms (0.1 to 0.3 nm) per second for chromium and at 20 to 30 angstroms (2.0 to 3.0 nm) per second for gold. Average film thicknesses were 250 angstroms (25 nm) chromium and 30,000 angstroms (3.0 μm) gold.

AZ1350J photoresist application by roller coating was investigated as an economical means of coating 3.75- by 4.5-inch (95 by 114 mm) substrates for multiple hybrid microcircuit fabrication. The most important aspect of the resist coating is thickness uniformity. The correlation between resist thickness and dimensional control of the photoresist image was established and a predicted distribution of thin-film line widths was made and verified.

The use of infrared heating to bake Shipley AZ1350 positive photoresist before exposure was investigated. The baking parameters which affect the substrate temperature were emitter temperature, conveyor speed, emissivity of the substrate surface, and the amount of air forced through the oven chamber. Single settings on the emitter temperature and conveyor speed held constant; however, the substrate emissivity was dependent upon the thin-film composition and photoresist thickness. When the volume of air forced through the oven remained stable, so was its effect on the substrate temperature. Through manipulation and control of these parameters, consistent prebaking of photoresist-coated substrates was achieved.

Automatic alignment and exposure of 3.75- by 4.5-inch substrates was investigated as a cost-effective HMC photolithographic procedure. Exposure light characteristics and automatic mask-to-substrate alignment process technology investigations were determined in terms of the physical parameters required to produce hybrid microcircuits.

Spray developing of resist and spray etching of thin-films was studied to establish the optimum dimensional control on photoresist and thin-film images. Both spray processes proved capable of holding ±1 to 2 percent dimensional control on a nominal 5.0-mil (127 μm) line even though several problems existed with the spray system. To solve these problems, a short term process development order was initiated to design spray processing equipment which would totally retain all vapors and would be economical to operate under both small and large production volume requirements.

All project objectives have been successfully completed, and the processing techniques have been implemented in production. No additional efforts on multiple HMC processing are foreseen at this time.

DISCUSSION

SCOPE AND PURPOSE

Activities were started on multiple hybrid microcircuit processing (fabrication of more than one HMC on a single ceramic substrate, Figures 1 and 2) to establish economical and technically improved vacuum deposition and photolithographic fabrication processes for thin-film hybrid microcircuits (HMCs). It had been previously determined that multiple HMC processing was the most economical method of producing HMCs in quantities sufficient to meet present and forecast production schedules.

Production schedules demanded a change from single HMC processing on 1.5- by 1.5-inch- (38 by 38 mm) square substrates to multiple processing on 3.75- by 4.5-inch (95 by 114 mm) substrates. Although the larger substrate size required totally new and different processing equipment from that previously used, it was estimated that such equipment would be approximately $500,000 less than the cost of duplicating current equipment and personnel, in addition to the associated cost of increasing the production facility size. Thus the project intent was to develop increased HMC production capacity and simultaneously to reduce the present cost of HMC fabrication by multiple HMC processing. However, several constraints were placed on the project:

- New processing equipment had to fit into the existing production facility without major rearrangements of walls, utilities, and production layout;
- The alignment and exposure machine, resist coater, and resist dryer had to be capable of processing 1.5- by 1.5-, 2- by 2-, and 3.75- by 4.5-inch (38 by 38, 50.8 by 50.8, and 95 by 114 mm) substrates;
- The tooling changes required for 3.75- by 4.5-inch substrate operation in the existing Randex tantalum sputtering system could not alter the established tantalum-nitride film characteristics; and
- The Cr/Au electron-beam evaporation system had to be able to process 1.5- by 1.5-inch and 3.75- by 4.5-inch substrates.

Technical efforts were to be directed toward establishing a process which would equal or improve the base line data developed on an earlier project (reported in BDX-613-1256). This base line data covered physical parameters of:

- Cr/Au thin-film properties (thickness, sheet resistivity, and bondability) and
- Photolithographic dimensional control (±2 percent).

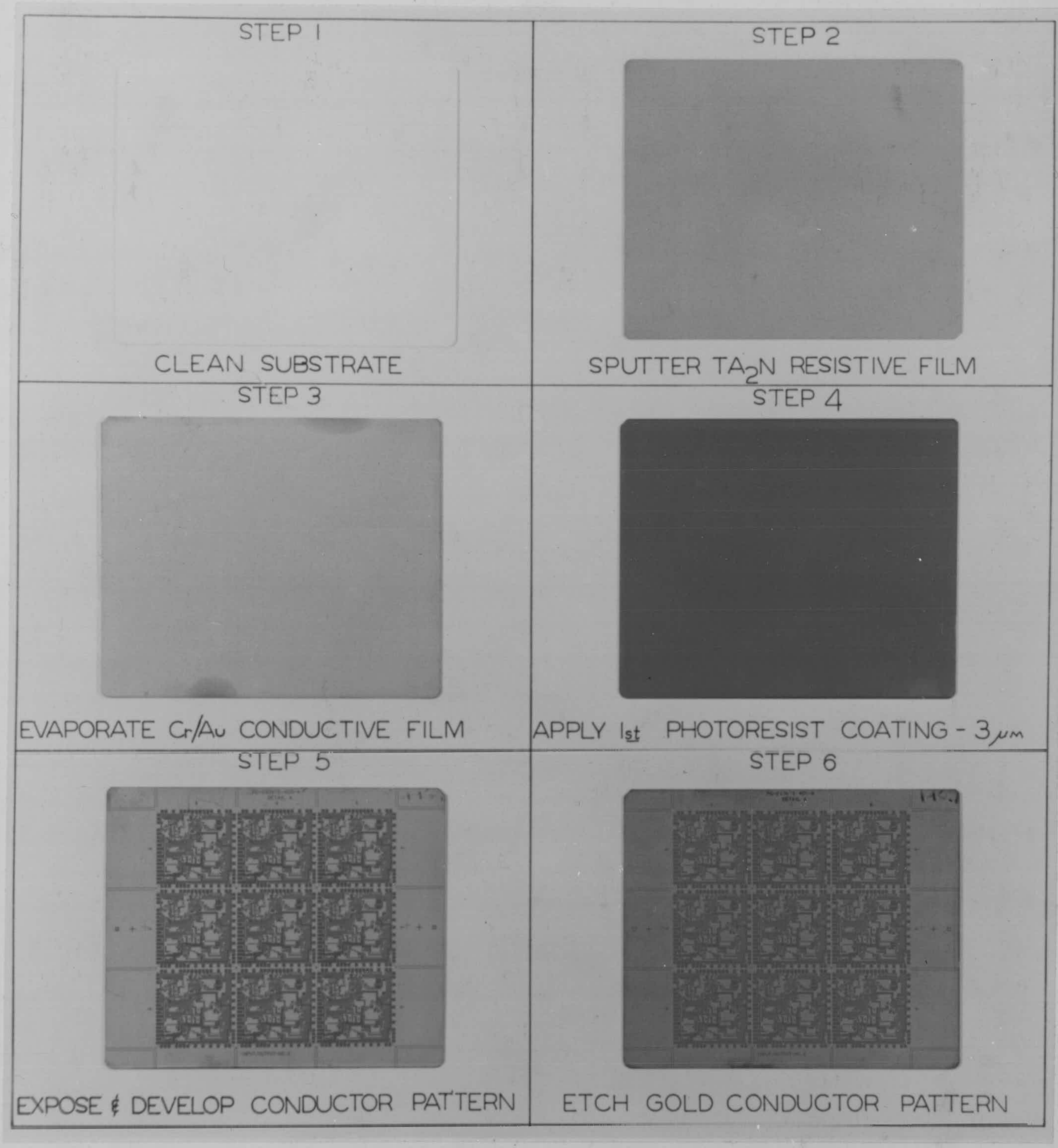

Figure 1. Multiple HMC Processing Outline, Steps 1 Through 6

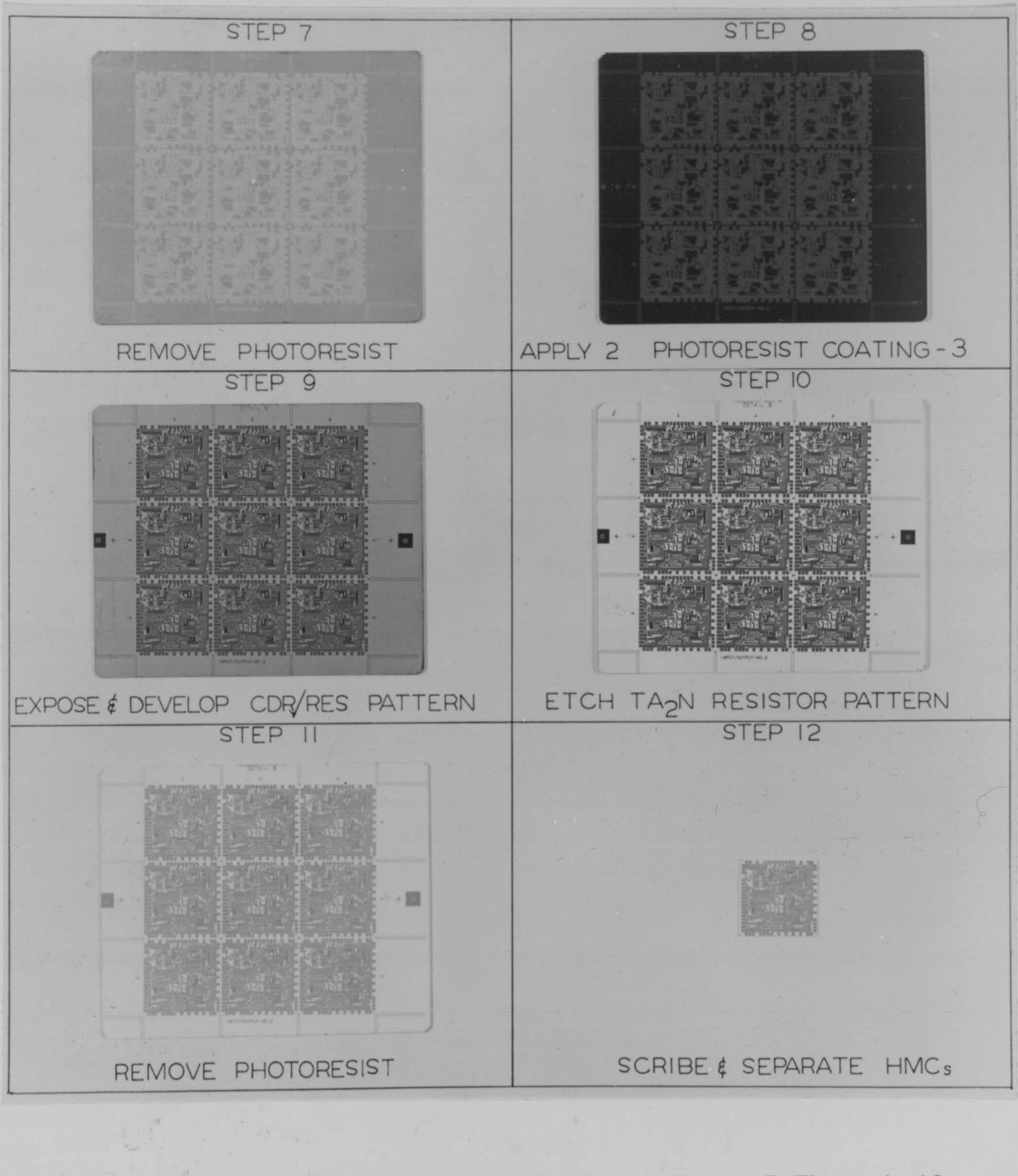

Figure 2. Multiple HMC Processing Outline, Steps 7 Through 12

Developmental efforts were to reproduce these parameters using the new processing equipment.

PRIOR WORK

There had been no work on multiple hybrid microcircuit processing prior to this endeavor; however, technical considerations and process requirements for thin-film hybrid microcircuits were established during a five-man residency program at Sandia Laboratories Albuquerque. These requirements have been expressed in terms of the physical parameters necessary for successful fabrication and product operation. The information resulting from the residency program represents the initial base line data available to Bendix Kansas City for HMC production. As such, development was on a laboratory basis and the processing technology necessary for multiple HMC fabrication was not developed. However, the base line data guidelines or first generation technology were to be used to direct and evaluate the results of multiple HMC processing.

ACTIVITY

Review and Selection of Process Techniques

Although insight and direction was obtained from the available HMC base line data, multiple HMC processing represented a major step forward in processing technology at Bendix. The single act of changing from 1.5- by 1.5-inch (38 by 38 mm) ceramic substrates, containing a single HMC, to 3.75- by 4.5-inch (95 by 114 mm) substrates with several HMCs necessitated a complete changeover in processing equipment and philosophies. None of the present processing equipment was suited to the larger substrate size. Although in certain instances available systems could process the larger substrate, the resulting physical parameters were not suitable for maximum use of available substrate area. It can be shown that maximum use of substrate area implies the HMCs be arranged in a matrix and must be near the substrate edges. Existing thin-film deposition and photolithographic systems were not capable of processing, with suitable parameter control, in the areas near the substrate edge. Therefore, the total quantity of HMCs processed per system operation-cycle could not be increased. Actually, in some cases, the throughput would decrease over existing capabilities.

It was therefore necessary to select new processing technologies which were most likely to meet the requirement of multiple HMC processing on 3.75- by 4.5-inch substrates. Since there has been some standardization on 3.75- by 4.5-inch substrates for HMC fabrication, particularly by Western Electric, there were several alternative processes available. The selection procedure will be described for each system and applicability to changing technological requirement will be reviewed for Cr/Au conductive film evaporation and photolithographic processing.

Substrate Material and Size

Selection of the substrate material was never a concern brought on by increase in size; however, the availability of the standard Al_2O_3 material to present specifications was considered. It was found that the 3.75- by 4.5-inch size was readily available from American Lava, Coors, and Materials Research Corp. The availability was mainly due to Western Electric's use of the same size substrate. Because of this standardization by Western Electric and other HMC manufacturers, the substrate material could be obtained at cost which was about $1.00 per HMC less than the previously used 1.5- by 1.5-inch size. The 3.75- by 4.5-inch size was also compatible with the existing Bendix 4- by 5-inch photomask capability. Any selection of a size either greater or less than 3.75- by 4.5-inch or in an alternate material other than Al_2O_3, would have resulted in a restricted and less economical source. The standardization of the substrate size has promoted commercial development of processing systems capable of handling it. The use of this equipment would be lost if an alternate size were chosen; however, with standardization comes the increased potential of incompatibility with changes in product requirements or basic process technologies.

The product requirements of vias was such a change in basic technology. Vias (holes in the substrate) are used to provide electrical conduction from circuit elements on the front side of the HMC to a ground plane on the back. The position of each via is rigidly fixed by the HMC layout; however, the via may move about on the substrate during the shrinkage phase of ceramic substrate firing. The typical locational uncertainty is about ±0.5 percent of the distance between the datum point and the desired location on the substrate. It can be seen that the larger the substrate, the greater location tolerance on the via position.

Chromium/Gold Conductive Film Deposition

When the preliminary requirement for vias was introduced, most conventional thin-film deposition systems were eliminated as possible processing systems. Deposition of chromium and gold on both sides of a substrate and also through small holes in the substrate during a single vacuum pumpdown required a special vacuum fixturing design. Due to the complexity of this requirement efforts on conductive vias were made a separate process development order effort.

This project continued investigation into single-sided Cr/Au depositions on 3.75- by 4.5-inch substrates. To do this a Veeco vacuum system with an electron-beam evaporator was chosen (on a least-cost basis) for development.

Photoresist Coating

Existing photoresist coating by spinning was not well suited for coating the 3.75- by 4.5-inch substrates. Four factors necessitated a changeover to a different technique:

- Danger of spinning large, rectangular parts,
- Non-uniformity of resist thickness on rectangular parts,
- Edge build-up of resist, and
- Slowness and waste of photoresist.

Two alternate techniques, roller coating and hot vapor spraying, have been used in the HMC industry for applying photoresist to larger, rectangular substrates. These two differ in method; however, each was judged to have an equal potential of coating the 3.75- by 4.5-inch substrate without the limitations of spinning.

A technical choice between spray and roller coating was not possible in terms of the requirements of first generation technology. The choice was based on economics, that is, purchase costs, operation costs, and projected development time required. In two of the three cases, the roller coating techniques proved to be less expensive (Table 1).

Based on economy, roller coating was chosen as the method to be developed first. This did not mean that roller coating was chosen as the ultimate method of HMC production; rather, it was chosen as the method to be investigated first, although hot vapor spraying was also kept in mind.

Photoresist Drying

Photoresists contain solvents which must be evaporated after application to the substrate surface. However, photoresist drying, commonly known as "baking," is not as straight forward as it might appear. The continuity, thickness uniformity, and light sensitivity of the film are affected during the drying operation.

It was learned from the previous work that conventional hot air ovens caused somewhat irregular properties in the photoresist. Primary among those were:

- Too rapid drying from top surface of resist,

Table 1. Comparative Cost of Photoresist Coating Systems

	Coating Method	
Factor	Roller	Spray
Purchase Cost	$4000	$32,000
Operation Cost (Ratio)	1	2
Development Cost (Ratio)	equal	equal

- Inconsistent time-temperature production on the substrate,
- Non-standardization of substrate carrier mechanism, and
- Non-uniform temperatures in the oven chamber.

Studies were made into various drying schemes and only infrared (IR) drying from a planar source, in an open-ended, conveyorized oven was judged suitable for HMC processing. IR baking affords a drying mechanism which proceeds from the interface of the substrate and photoresist outwards toward the resist surface. Since IR baking is open-ended and conveyorized, it provides the best possibility of obtaining a consistent time-temperature profile on the substrate. Because the substrates sit directly on the conveyor and pass beneath the IR source, the substrate carrier scheme is consistently non-interfering with the substrate temperature profile. No other alternative appeared as good as planar IR drying.

Automatic Mask Alignment and Exposure

Standard photolithographic processing requires the alignment of one or more photomasks to the thin-film pattern on the substrate. This alignment is presently accomplished manually and is therefore subject to operator error. The throughput is also operator dependent and is subject to operator fatigue. The alternative to manual alignment is automatic alignment which is operator free. Again, the requirement to increase throughput and to simultaneously reduce production costs dictated the use of automatic alignment. A manual approach would have required 4 or 5 times as many systems and operators.

Developing, Etching and Stripping

It was recommended from the results of earlier work (BDX-613-1256), that wet processing phases of photolithography; that is, resist developing, thin-film etching, and resist stripping, be accomplished by spray-type systems rather than by a batch emersion scheme. The technical advantages alone would justify this change. Further, the spray systems are about the only means of increasing throughput and reducing costs.

It was recommended that Bendix engineering staffs design and develop their own spray systems. This recommendation was based upon the lack of knowledge as to the less salient factors involved with HMC spray processing equipment. Most available information was principally related to printed circuit boards and was not directly applicable to HMC production. Due to limited availability of manpower and funding, it was decided to specify the system which was thought to be capable of spray processing HMCs and have it built by a commercial vendor. This was the approach most consistent with present work loads.

Thin-Film Chromium and Gold Deposition

Adhesion, electrical resistivity, and thermocompression bondability of chromium/gold films deposited on tantalum-nitride-coated aluminum-oxide substrates were studied to obtain optimum combination of film properties. The results indicate that substrate temperature must be maintained at 300°C, the chromium deposition rate must be controlled to within 1 to 3 angstroms (0.1 to 0.3 nm) per second, and the gold deposition rate must be controlled to within 20 to 30 angstroms (2.0 to 3.0 nm) per second.

Gold films produced by electron beam evaporation and chromium films sublimed from resistance-heated boats were used for the study. The films were deposited at gold evaporation rates of 20, 30, 40, and 50 angstroms (2.0, 3.0, 4.0, 5.0 nm) per second; chromium sublimation rates of 0.5, 1, 3, and 5 angstroms (0.05, 0.1, 0.3, 0.5 nm) per second; and substrate temperatures of 150, 200, and 300°C. The temperature profile and thickness uniformity of the deposition fixture were determined before the investigation was started. Thickness monitors were made from both glass and tantalum-nitride-coated aluminum-oxide substrates. Film thickness was measured by using both beta backscatter and a stylus profilometer. The gold films averaged 30,000 angstroms (3.0 μm) thickness, and the chromium films averaged 250 angstroms (25 nm). All bonding, resistivity, and adhesion samples used tantalum-nitride/chromium/gold coated aluminum-oxide substrates.

The adhesion of the chromium and gold films to the substrate was acceptable for all deposition conditions.

The electrical resistivity of the gold films was affected by substrate temperature during deposition. The resistivity ranged from a minimum of 2.59 microhm-centimeters for films deposited at 150°C to a maximum of 3.57 microhm-centimeters for films deposited at 300°C. Increasing substrate temperature had an opposite effect on the electrical resistivity of the chromium films. Chromium films deposited at the highest substrate temperature had the lowest resistivities.

Thermocompression bondability of both solid gold wire and gold plated lead frames was evaluated. Auger electron spectroscopy (AES) was used to monitor the surface of the film. The bondability of all as-deposited films was satisfactory in that there were no failures in the bond interface. Bondability was found to degrade on films that had been processed through a resistor stabilization cycle of 300°C for 2 hours in air. The stabilized films exhibited bond delaminations of 14.4 to 100 percent for lead frames, and 0 to 13 percent for fine wire, depending on deposition conditions.

Deposition Process and Analysis

An electron beam evaporation unit with planetary fixturing was used for depositing the chromium and gold. The system featured automatic pumpdown cycling and a 25-inch (0.635 m) belljar. The system pressure was maintained below 3.0 microtorr (0.4 mPa) for all depositions. The chromium and gold deposition cycle was monitored by an automatic deposition controller. This controller was calibrated to give the desired film thickness for a predetermined deposition rate. The gold was deposited from a 2-inch (50.8 mm) single-pocket electron beam source. A molybdenum crucible liner was used because the available power supply did not produce enough heat to evaporate the gold directly from the water-cooled source. The deposited film thickness and heat uniformity were optimized before starting the evaluation. The best thickness uniformity (±10 percent across the planetary fixture) occurred at 27 rpm. This speed was used for all work reported.

The substrates were heated by eight 1200-watt quartz lamps, which allowed substrate temperatures to be set at any point between 25 and 400°C. A temperature gradient (from top to bottom) of 13 percent was measured over the surface of tantalum-nitride-coated substrates in the static planet. Because of fixture rotation, an operating temperature gradient near zero was assumed.

A correlation was established between substrate temperature and a reference thermocouple located inside the planet to permit easy adjustment of the desired deposition temperature.

The chromium films were deposited at sublimation rates of 0.5, 1, 3, and 5 angstroms (0.05, 0.1, 0.3, 0.5 nm) per second. The gold films were deposited at evaporation rates of 20, 30, 40, and 50 angstroms (2.0, 3.0, 4.0, 5.0 nm) per second. The chromium films averaged 250 angstroms (25 nm) thickness and the gold films averaged 30,000 angstroms (3.0 μm).

Ceramic (99.6-percent pure Al_2O_3) and glass (Corning 7059) substrates were used in the evaluation. They were cleaned before deposition through a 10-step ultrasonic process. The ceramic substrates also were air fired at 900°C for 2 hours. The clean substrates were then sputtered with 500 angstroms (50 nm) of tantalum nitride before chromium/gold metallization. Eleven ceramic and four glass substrates were metallized in each deposition run; fourteen runs were made.

Three thin-film conditions were evaluated: as-deposited, as-stabilized, and prebond etched. The as-deposited condition refers to films immediately after removal from the vacuum deposition system. The as-stabilized condition refers to films which after removal from the deposition system are given a 300°C two-hour bake in air. This heat treatment is used to stabilize the exposed tantalum-nitride resistor network. The prebond etched condition refers to films which have been stabilized and then etched in ceric ammonium nitrate (CAN) for 10 minutes to improve bondability. All samples were cleaned with solvent immediately before bonding.

Chromium Film Characterization

The resistivity of the chromium film was calculated by using the sheet resistance and film thickness. The effects of substrate temperature and rate of deposition on chromium resistivity are shown in Figure 3. At all deposition rates, resistivity decreases with increasing substrate temperature and decreasing deposition rate. The lowest-resistivity films were produced at 1 angstrom (0.1 nm) per second and 300°C. This value is about twice that of the bulk resistivity for chromium.

Gold Film Characterization

The resistivity of the as-deposited and as-stabilized gold film was calculated from sheet resistance and film thickness (Figure 4). For substrate temperatures below 300°C, the resistivity of the as-stabilized film is greater than that of the as-deposited films. Stabilization produces no appreciable change in resistivity when the film is deposited on 300°C substrates; however, there is a change in resistivity during stabilization that is attributable to chromium diffusion. The absence of a resistivity change when the film is deposited at 300°C also can be attributed to chromium

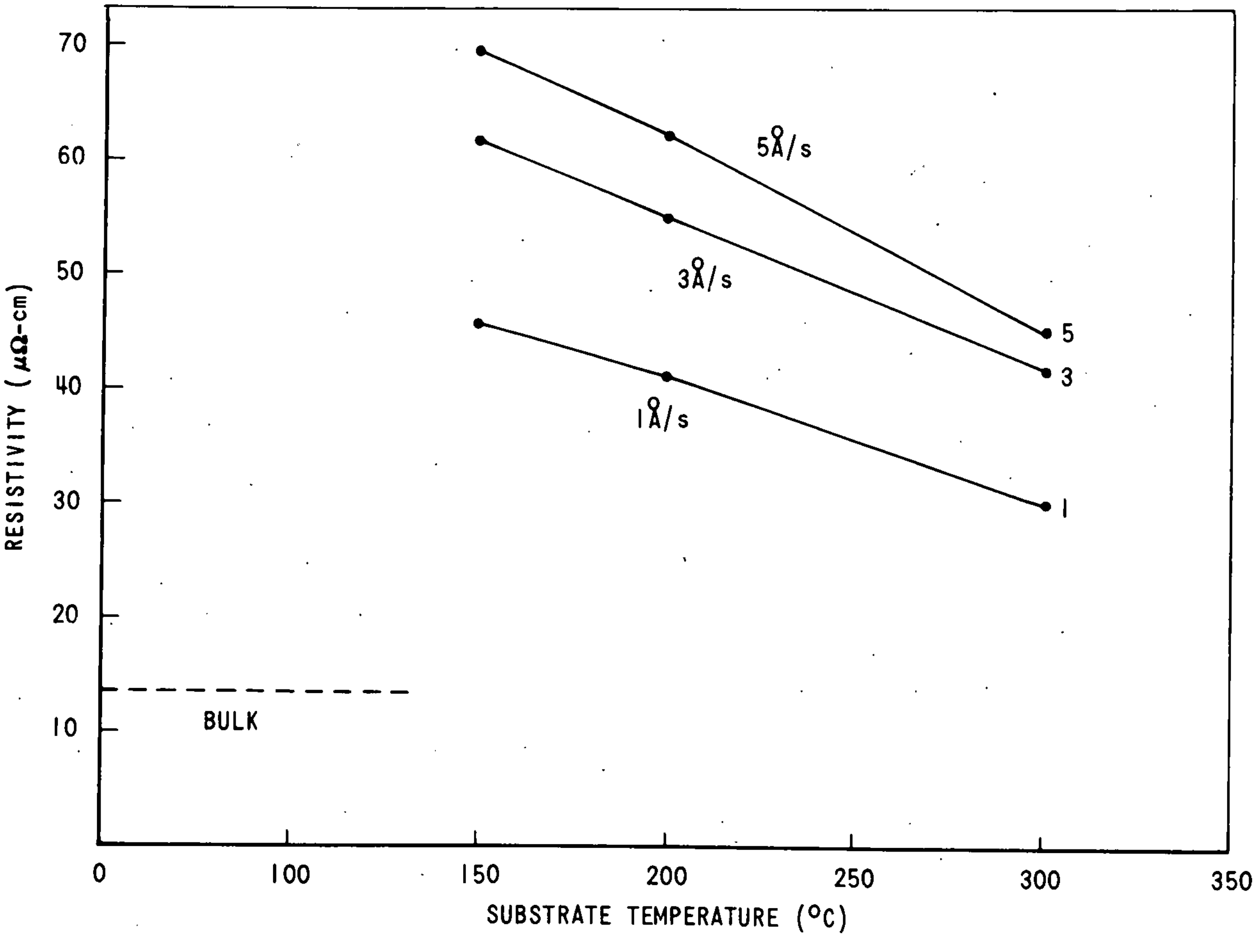

Figure 3. Chromium Film Resistivity Versus Substrate Temperature

diffusion during the metallization process. Since all films must be stabilized before use, any of the conditions investigated will produce a film with satisfactory resistivity.

The bondability of the gold films was evaluated on both 0.001-inch- (25.4 μm) diameter gold wire and gold-plated lead frames having a cross section of 0.005 inch by 0.015 inch (0.127 by 0.381 mm). They were thermocompression bonded to the substrates with conventional equipment and a predetermined bond schedule. The bonds were pulled to destruction, and the type of failure and the ultimate strength were used to determine bondability. Both wire and lead-frame bondability criteria must be met for a film to be considered bondable.

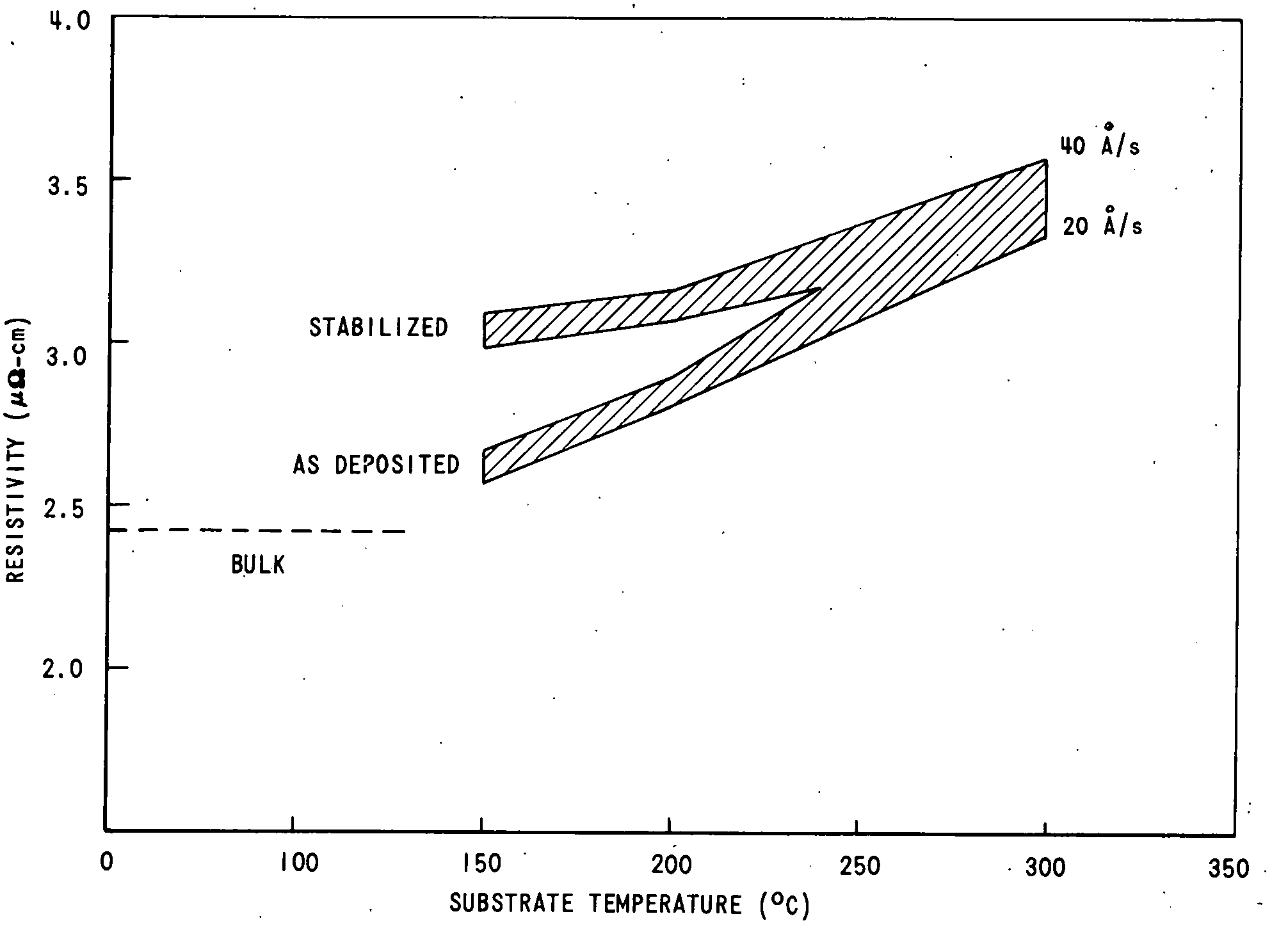

Figure 4. Gold Film Resistivity Versus Substrate Temperature

The bonded 0.001-inch (25.4 μm) wires were pulled in tension as shown in Figure 5. The films were defined as wire bondable if all bond failures were wire breaks. The films were considered not wire bondable if the failures were bond delaminations.

Lead-frame bonds were pulled to destruction in a 90-degree peel test, as shown in Figure 6. The films were defined as lead-frame bondable if the average of the peel strengths was equal to or greater than 1.0 pound (4.448 N), individual peel strengths were equal to or greater than 0.75 pound (3.36 N), and 60 percent or more of the total failure modes were heel failures. Films not meeting these criteria were judged not lead-frame bondable. If a bond failed in any other mode, it was considered no test.

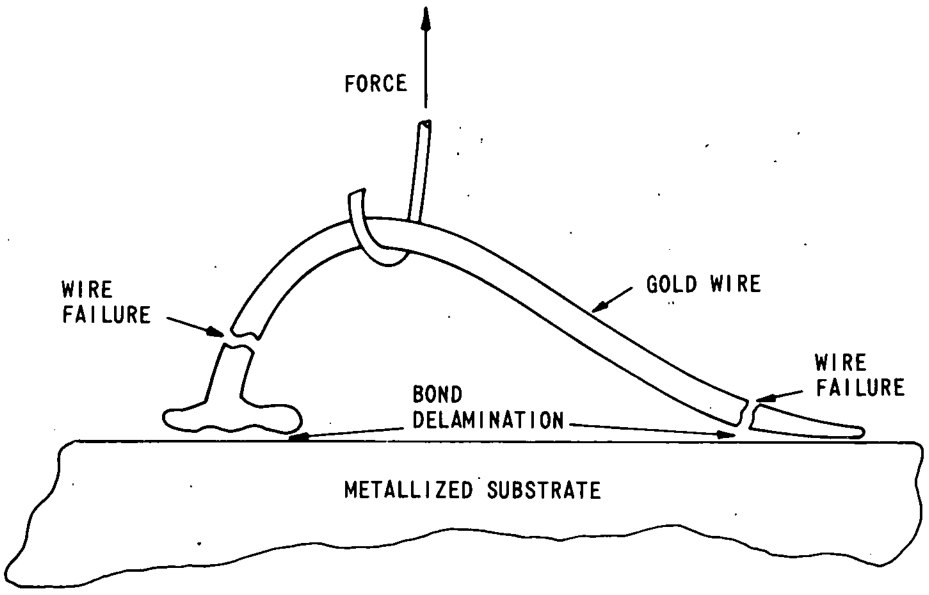

Figure 5. Wire Bond Failure

Bondability results are shown in Figures 7, 8, and 9. Only the data concerning as-stabilized films are shown because all of the as-deposited or prebond-etched parts showed no delaminations of either wire or lead-frame bonds and exceeded the minimum strength requirements.

Figure 7 shows the results of the fine-wire bonding evaluation for films deposited at varying substrate temperatures and gold evaporation rates. There was a trend toward fewer wire delaminations at higher substrate temperatures. Films deposited at a gold rate of 20 and 30 angstroms (2.0 and 3.0 nm) per second and 300°C had 100-percent wire breaks.

Figure 8 indicates that substrate temperature has a major effect on lead frame bondability. The lead-frame bond results show that a 300°C substrate temperature produced films having the fewest bond delaminations. Gold deposition rates of 20 and 30 angstroms (2.0 and 3.0 nm) per second resulted in lead-frame bonds that exceeded the 60-percent minimum heel failure requirement. They also exceeded the average and minimum strength requirements.

Figure 9 indicates that variations in chromium deposition rate affects lead-frame bondability for a 150°C substrate temperature.

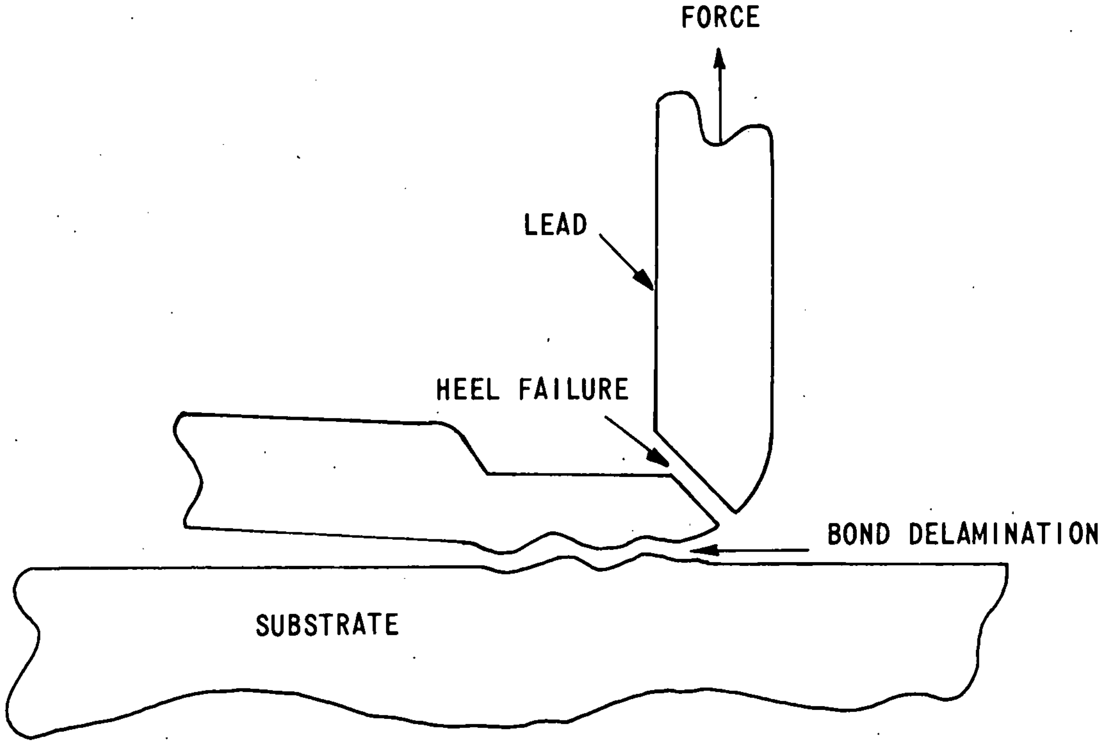

Figure 6. Lead-Frame Bond Failure

Both 0.5 and 5.0 angstrom (0.05 and 0.5 nm) per second rates caused complete loss of bondability on as-stabilized films. The effect of chromium rate variation was not studied at higher temperatures.

As-stabilized films deposited at a 1-angstrom (0.1 nm) per second chromium rate, 20 or 30 angstroms (2.0 or 3.0 nm) per second gold rate, and a substrate temperature of 300°C passed the minimum bondability requirements for both failure mode and strength. This indicates that a bondable as-stabilized film can be produced by controlling deposition parameters without the use of a prebond etch.

Photolithographic Processing

Roller Coating

The most important aspect of the photoresist coating is thickness uniformity, followed closely by the overall photoresist thickness. Three equipment variables--doctor bar pressure, roller/substrate

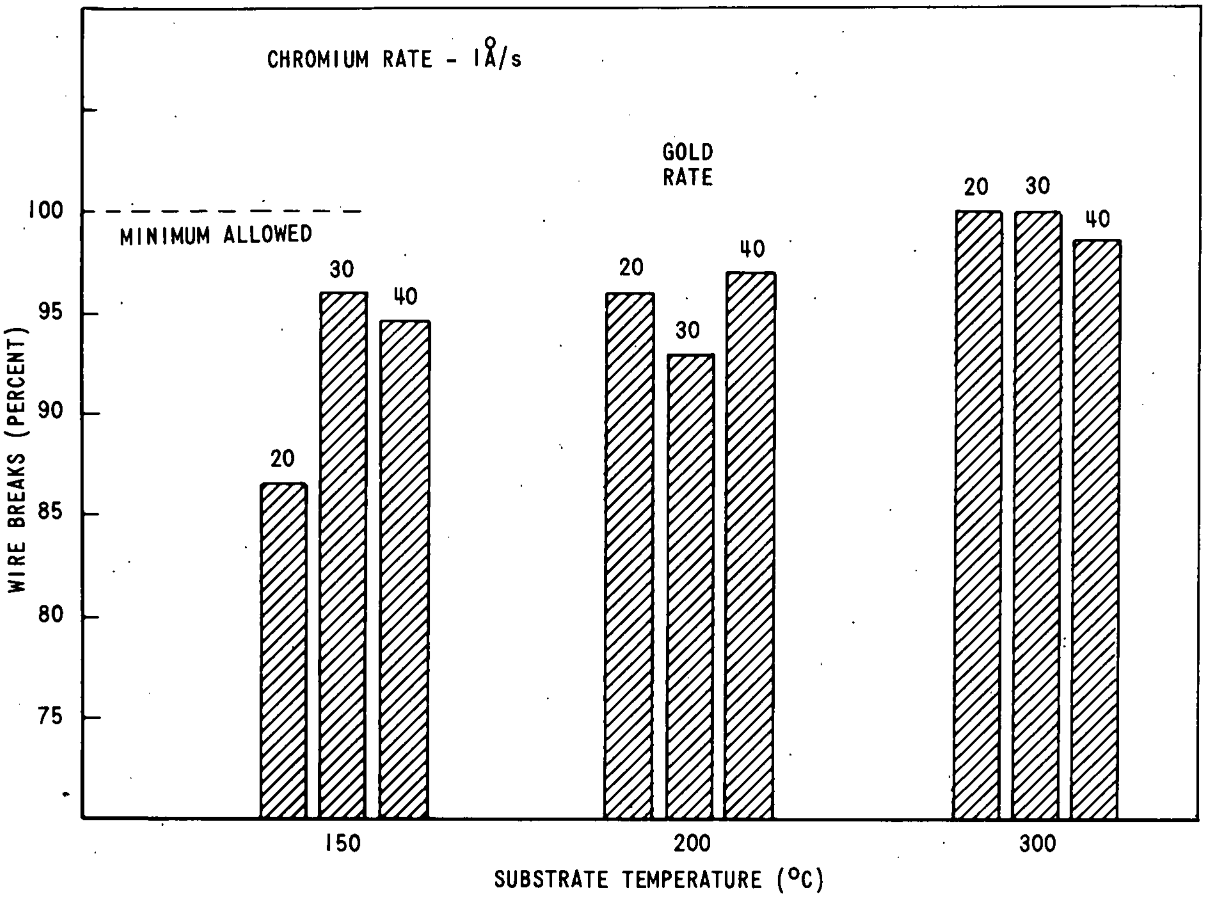

Figure 7. Fine-Wire Bondability

interference, and roller thread configuration--were found to control the overall resist thickness and thickness uniformity. Photoresist viscosity and its relation to the roller thread configuration have a direct bearing on thickness and thickness uniformity.

The doctor bar pressure is the most effective operational adjustment for the control of resist coating thicknesses, although, the relation between doctor bar pressure and resist thickness is not well behaved. Doctor bar pressure values are relative numbers and cannot be used universally as they depend upon the initial set-up procedures. Roller size and viscosity are fixed, measurable parameters. The viscosity is conveniently measured with a

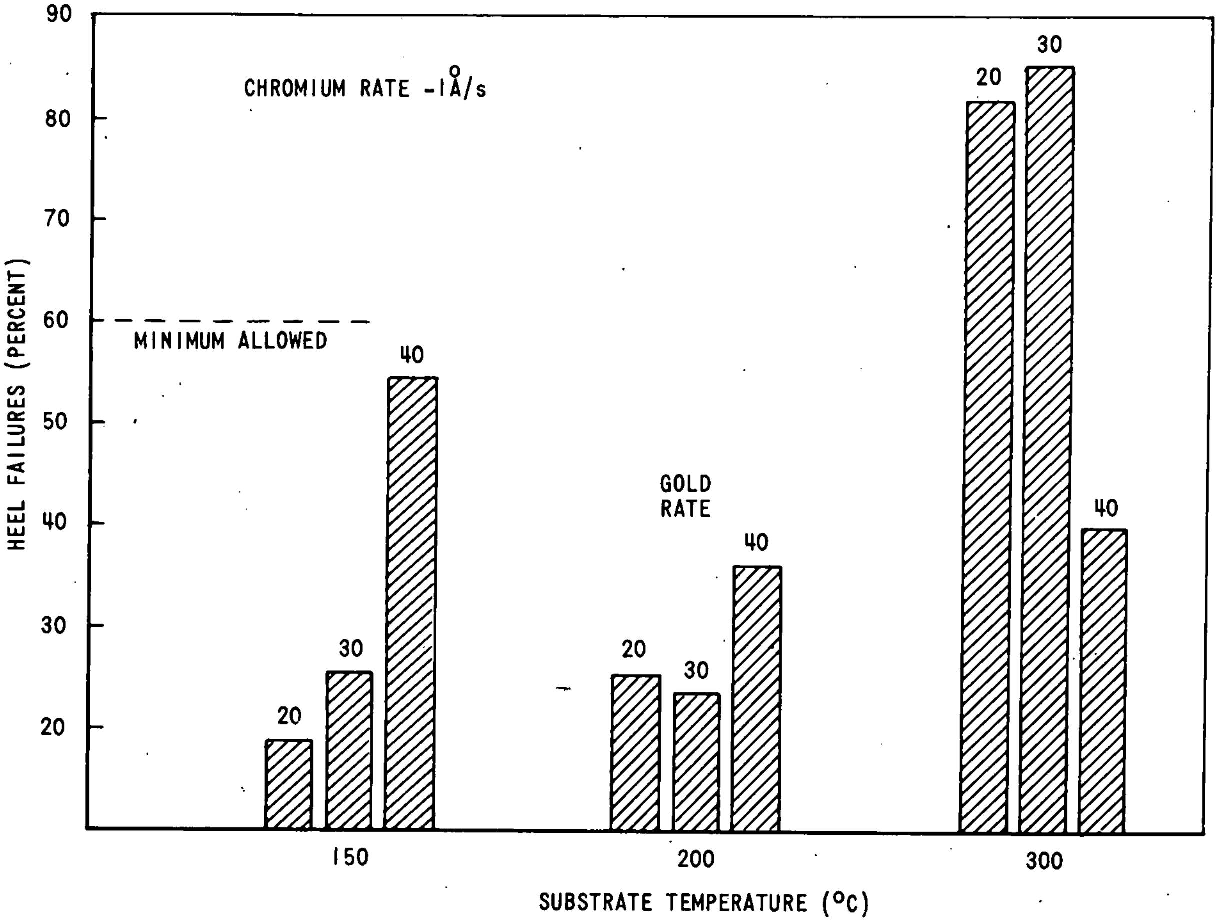

Figure 8. Lead-Frame Bondability

Zahn cup and the roller size is fixed by the manufacturer. There are four roller sizes available, representing successively larger thread sizes and, thus, coating thicknesses.

The determination of the proper resist thickness and thickness uniformity is largely emperical and related to the proper exposure energy and prebake conditions. However, the following general rules can be used as a guide.

- Increasing doctor bar pressures decreases the resist thickness on the substrate.
- Resist thickness is not predictably dependent upon the interference except at high interference levels, and any contributions it makes to overall thickness is decreased at higher doctor bar pressures.

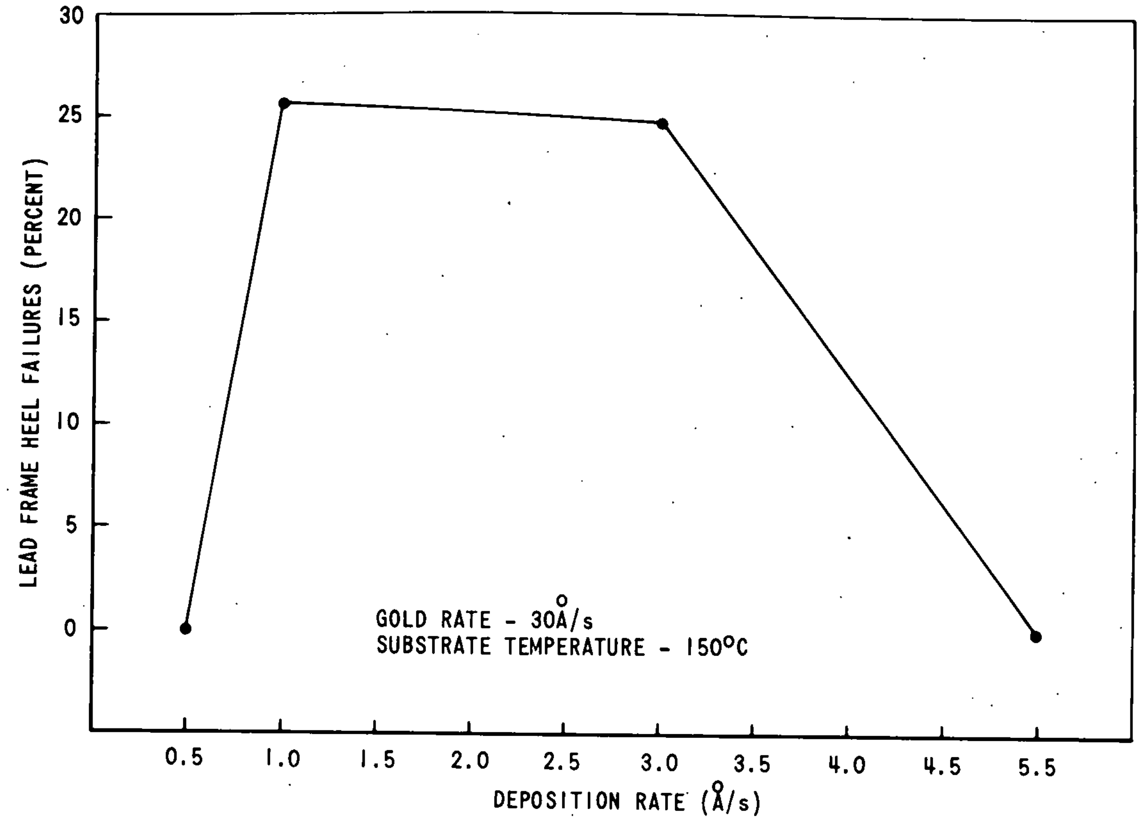

Figure 9. Chromium Deposition Rate Versus Bondability

- Increasing the roller thread size increases the overall resist thickness on the substrate.
- Increased resist viscosity provides for more consistent but generally thicker resist coatings.
- Consecutively smaller size rollers, which produce thinner overall resist coatings, are more consistent in repeating a specific coating thickness when all other parameters are held equal and constant.

<u>Resist Thickness and Expected Line Width Deviation</u>. The expected line width of the photoresist image is a function of the resist thickness and thickness uniformity. To achieve a line image with near zero line width deviation from the design value requires that the resist be exposed with the proper light energy for the particular resist thickness in use. Where there are variations in the resist thickness across the substrate, there will be

corresponding variations in the line widths at a fixed exposure energy. Figures 10 and 11 show the expected change in 5.0-mil (127 μm) and 3.0-mil (76.2 μm) lines for a variable resist thickness and a constant exposure energy. These figures consistently show a 0.2-mil (5.08 μm) change in line width per micrometer change in resist thickness. This is a rather significant change in line width; that is, 4 percent on the 5.0-mil line. Obviously, to minimize the variation in line widths it is necessary to maintain the most uniform resist thickness possible. This is done by high doctor bar pressures, interference levels, and by higher viscosity levels.

A second approach to line width control is to operate at a thickness level that is less sensitive to variations in the overall thickness. Figure 12 shows the required exposure energy for increasing resist thicknesses. It can be seen that at higher resist thicknesses, more exposure energy is required to properly expose the resist and that the required exposure range is strongly dependent upon small changes in the thickness. At lower thickness values the opposite is true; the proper energy required has only a limited dependence on the thickness. Therefore, resist thickness variations at the lower end of the thickness-energy curve have a far less significant effect on the line width. It may be concluded from the contributions of photoresist thickness and thickness uniformity to the dimensional distribution on line widths, that thinner resist coatings will afford tighter dimensional distributions than thicker resist coatings.

Line Width Distributions. Figures 13 and 14 are the respective line width distributions for the resist thickness distributions shown in Figures 15 and 16. As expected, the lesser resist thickness, by virtue of its tighter thickness distribution, produced a tighter line width distribution under proper exposure energy conditions for each average thickness.

In Figure 15, the thickness is skewed to the high side of $\overline{X}$ as is the line width distribution of Figure 13. For positive resist and exposure settings that are adjusted for proper exposure of the average resist thickness ($\overline{X}$), the higher than average resist thicknesses will be underexposed in proportion to the difference between that thickness and the $\overline{X}$ thickness. The underexposure condition will result in a line width proportionately higher than the $\overline{X}$ line width. The opposite is true for thicknesses less than the $\overline{X}$ thickness. This type correlation can be easily seen when comparing Figures 15 and 13 on a cell-for-cell basis.

Infrared Photoresist Baking. Infrared (IR) baking of photoresist was investigated as an improved processing method and as an integral part of an overall cost-effective photolithographic procedure. Process improvements in photoresist baking included:

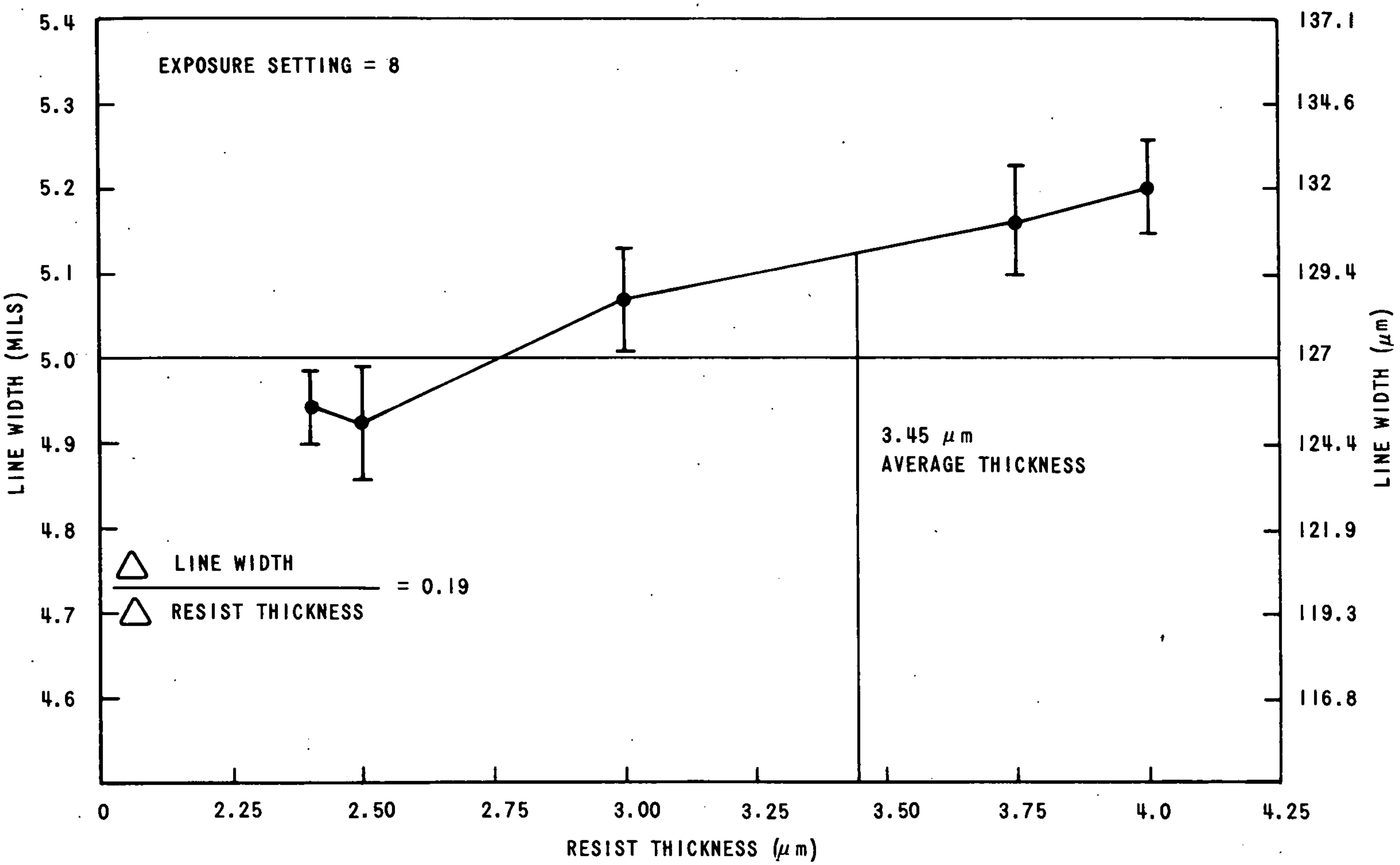

Figure 10. Line Width Change Versus Resist Thickness (5-Mil Lines)

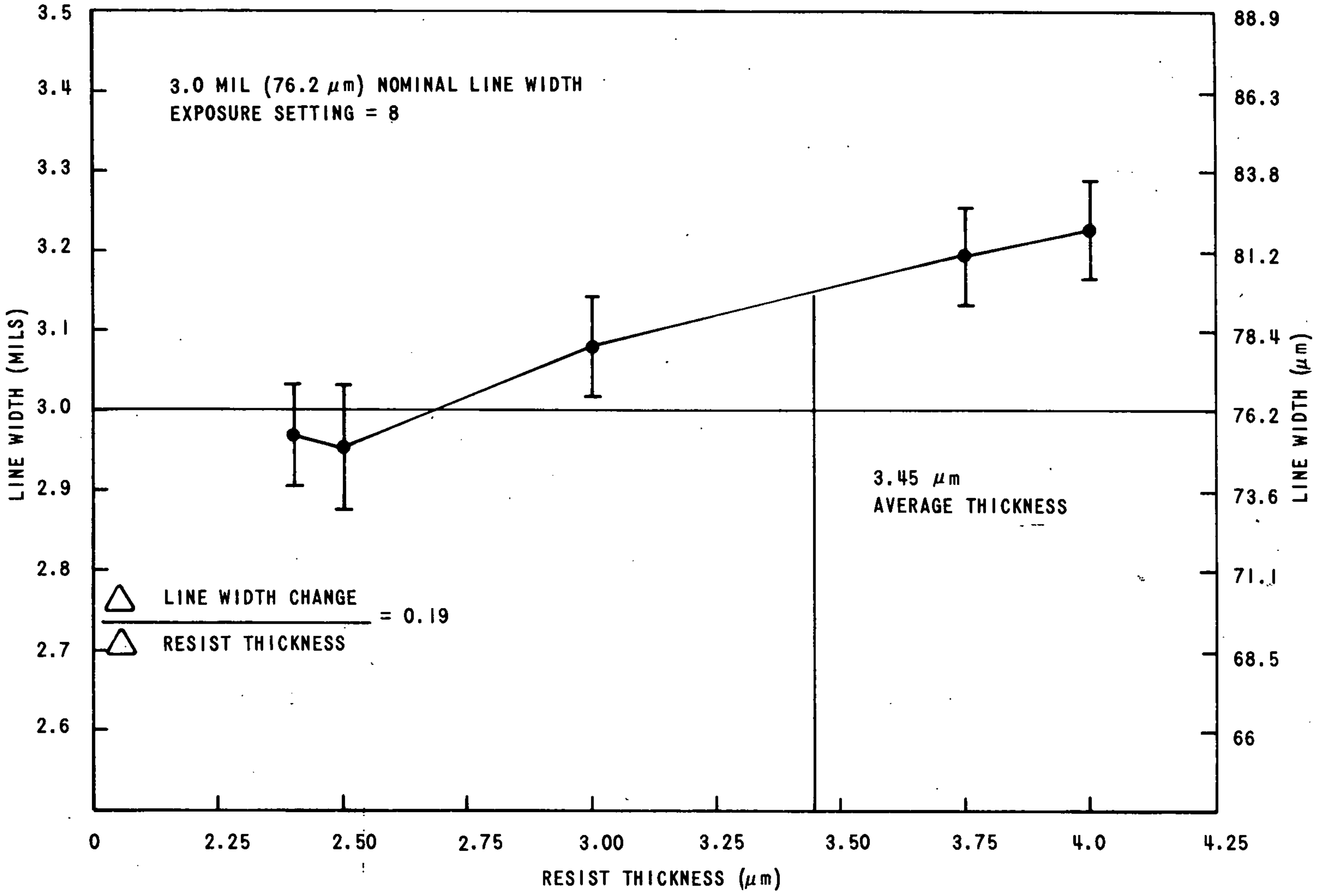

Figure 11. Line Width Change Versus Resist Thickness (3-Mil Lines)

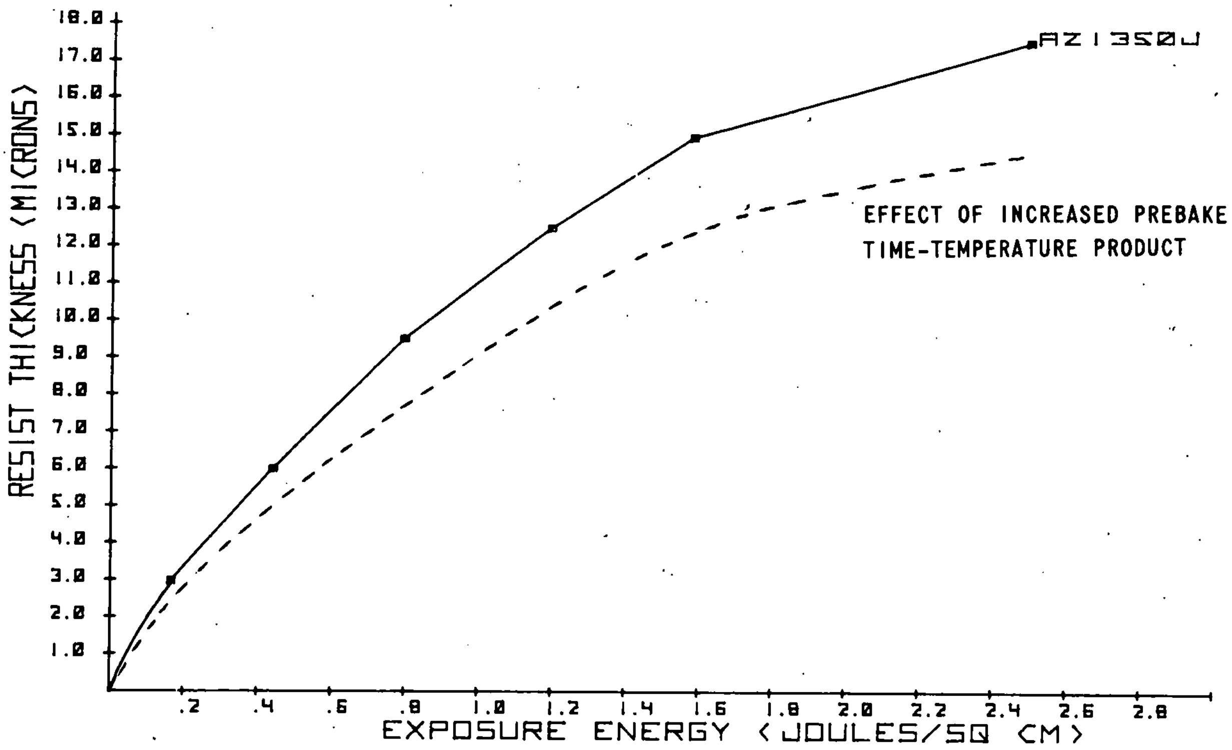

Figure 12. Exposure Energy Versus Resist Thickness

- More consistent time-temperature profiles from substrate to substrate and from day to day,
- Elimination of operator influence on photoresist baking conditions,
- Increased production capacity, and
- Automatic verification of substrate temperature for records control.

Separate experiments were performed to determine the substrate time-temperature profile consistency and its influence on product yields. In cases where the time-temperature profile was not consistent, examinations were made to determine if the IR oven system had failed or if other parameters were responsible. Variations in photoresist prebake conditions have been shown to influence the dimensional quality of the photoresist image and,

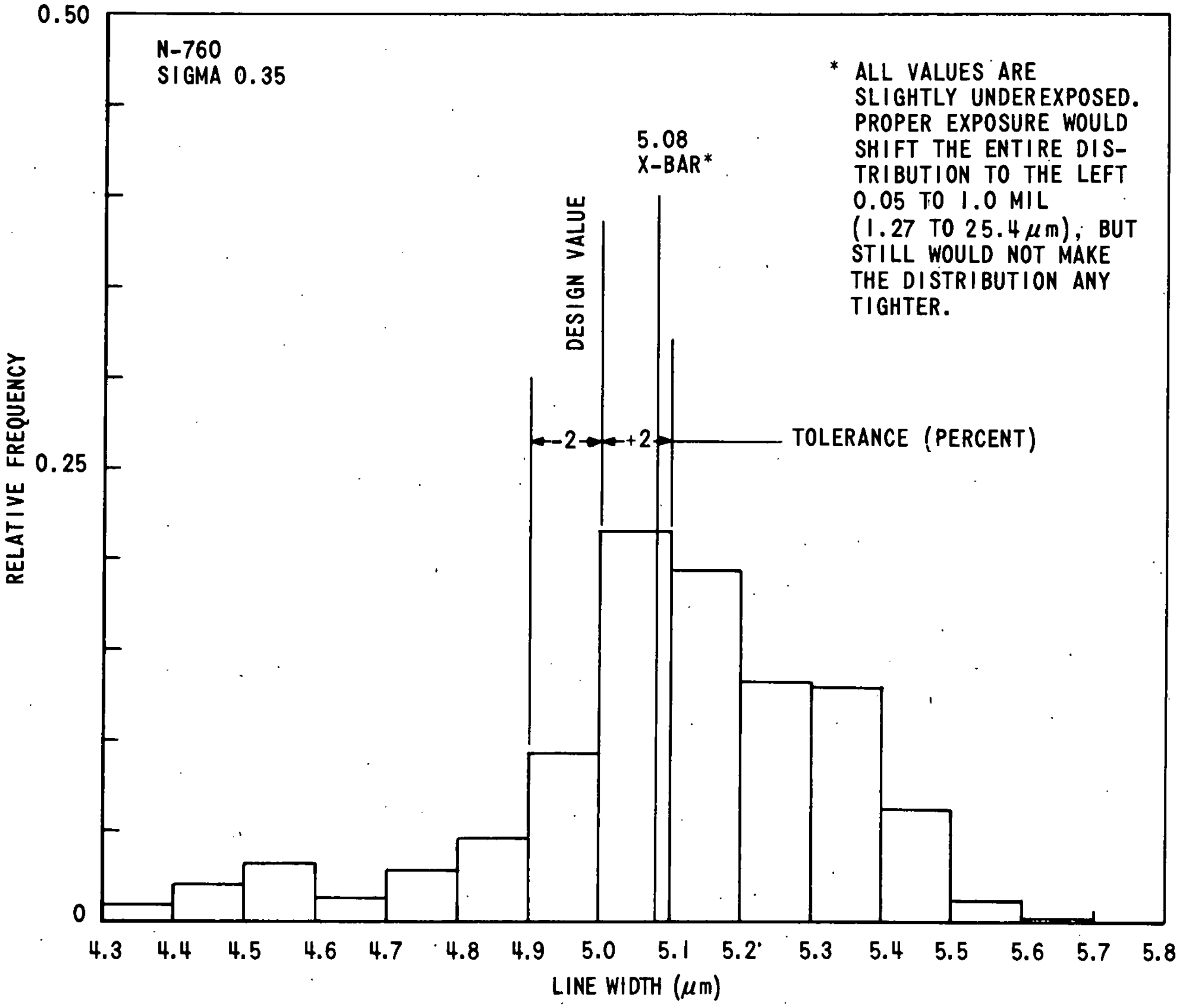

Figure 13. Line Width Distribution Measured at Nine Positions, Run-to-Run (>3.25 μm Resist Thickness)

thereby, the yield. Thus, the time-temperature profile became significant, and the development effort required to obtain a suitably consistent profile was essential.

<u>General Description of Zicon IR Oven</u>. The IR oven selected for evaluation was a Zicon Series 1100 Infrared Oven (Figure 17). The oven had a 16-inch-wide (406 mm) horizontal conveyor with a 24- by 24-inch (0.6 by 0.6 m) planar IR emitter above the conveyor.

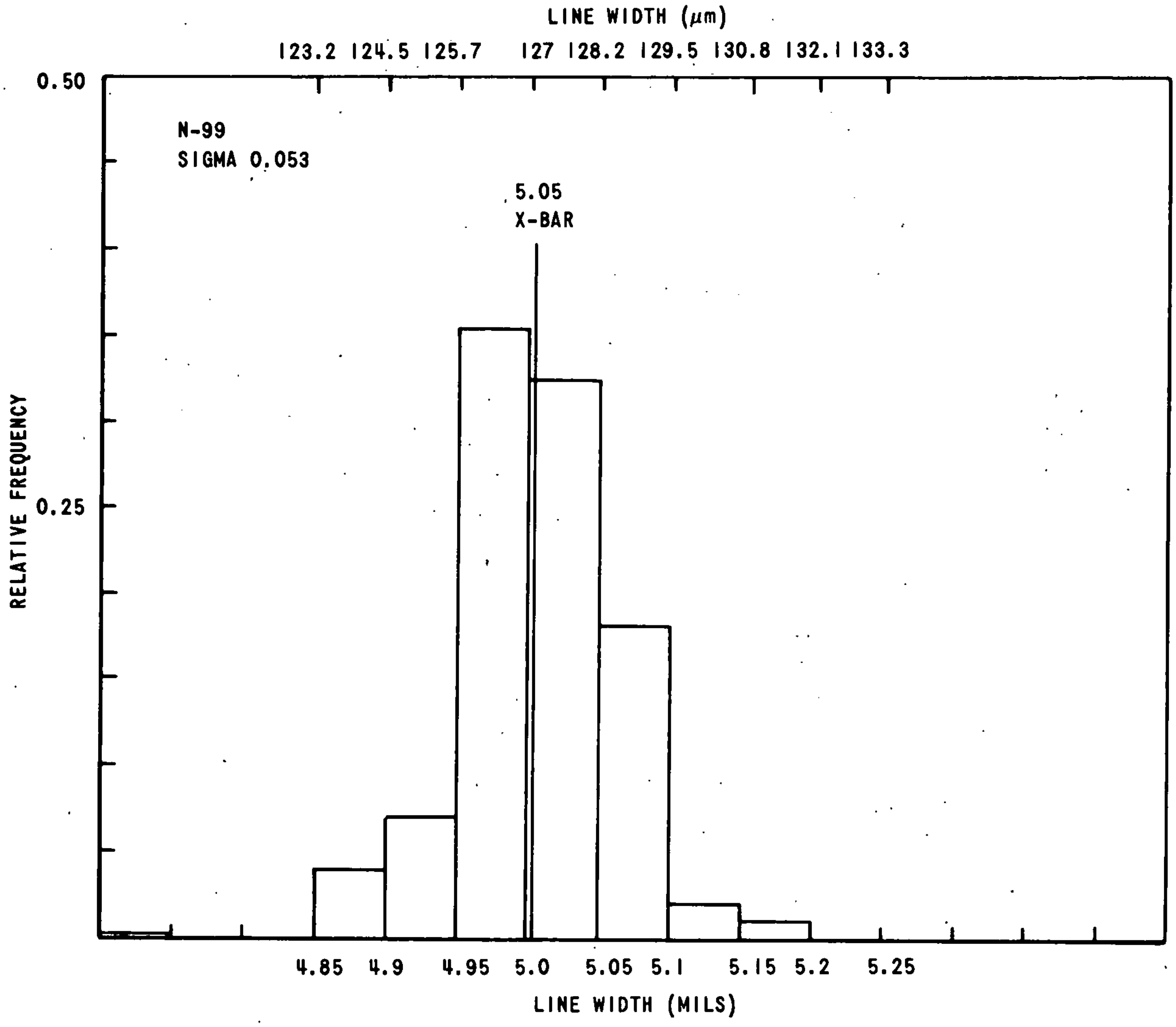

Figure 14. Line Width Distribution Measured at Center of Substrate, Run-to-Run (<2.0 μm Resist Thickness)

The emitter plane was parallel to the conveyor, was adjustable in height from 3 to 6 inches (76 to 152 mm), and had a selectable set point temperature control from 50 to 300°C. A chart recorder provided a record of the backside emitter temperature which was calibrated to the set-point controller sensor, also mounted on the backside of the emitter.

The conveyor was made of stainless steel mesh and had a variable speed from 0 to 6 feet per minute (0 to 30 mm/s). Class 100 air

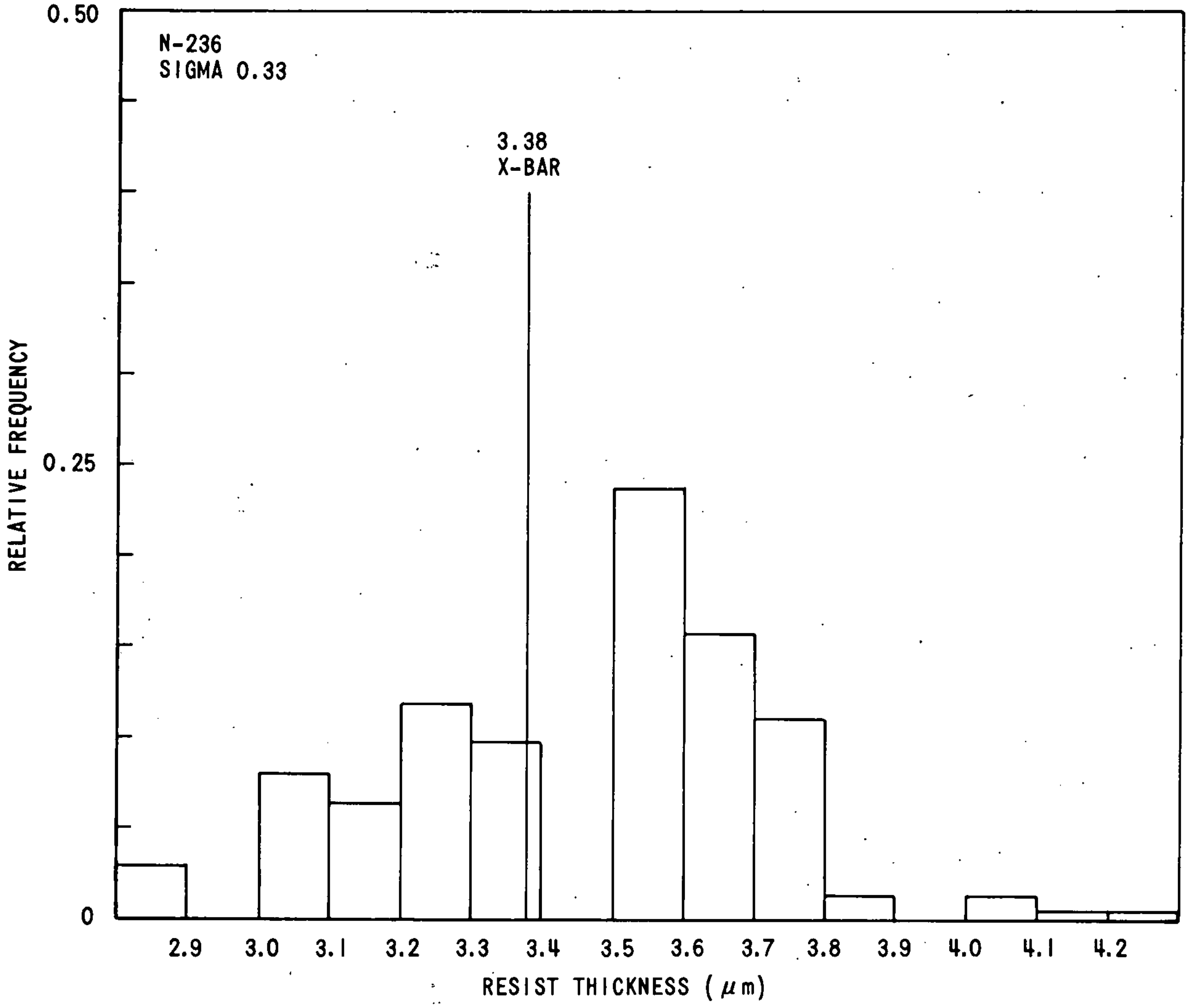

Figure 15. Resist Coating Thickness Versus Interference (Viscosity 21, Roller E-10)

was provided to flow across the conveyor and substrate surface. This kept the resist surface cool and allowed drying to proceed from the interface of the substrate and resist outward to the resist surface. The class 100 air also reduced the number of airborne particles contaminating the photoresist coating and carried the solvent fumes from the oven chamber. The air flow was horizontal from front to back in the oven chamber and vertical at the oven entrance and exit to prevent escape of solvent vapors. An exhaust port was provided at the rear of the system.

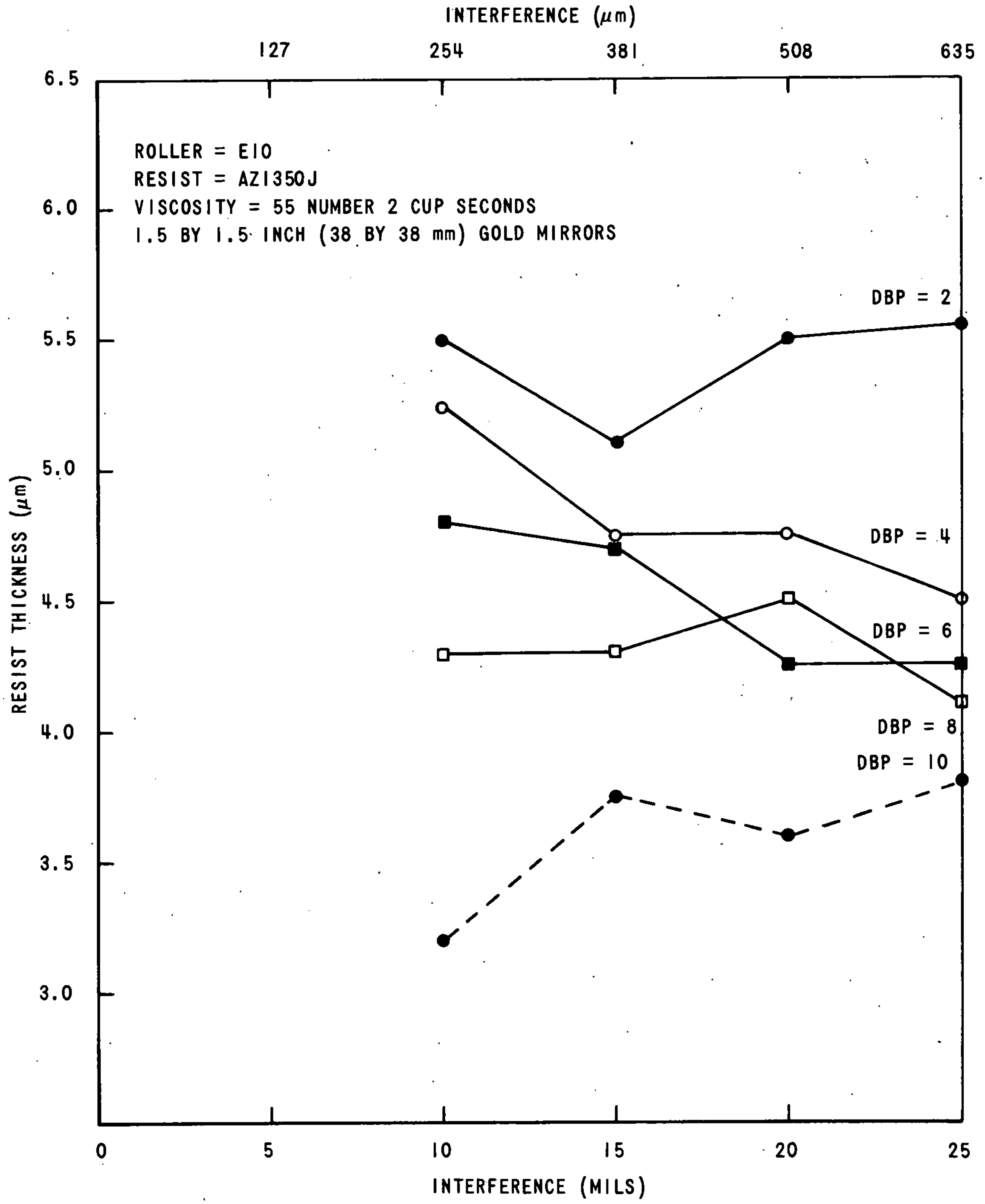

Figure 16. Resist Coating Thickness Versus Interference (Viscosity 55, Roller E-10)

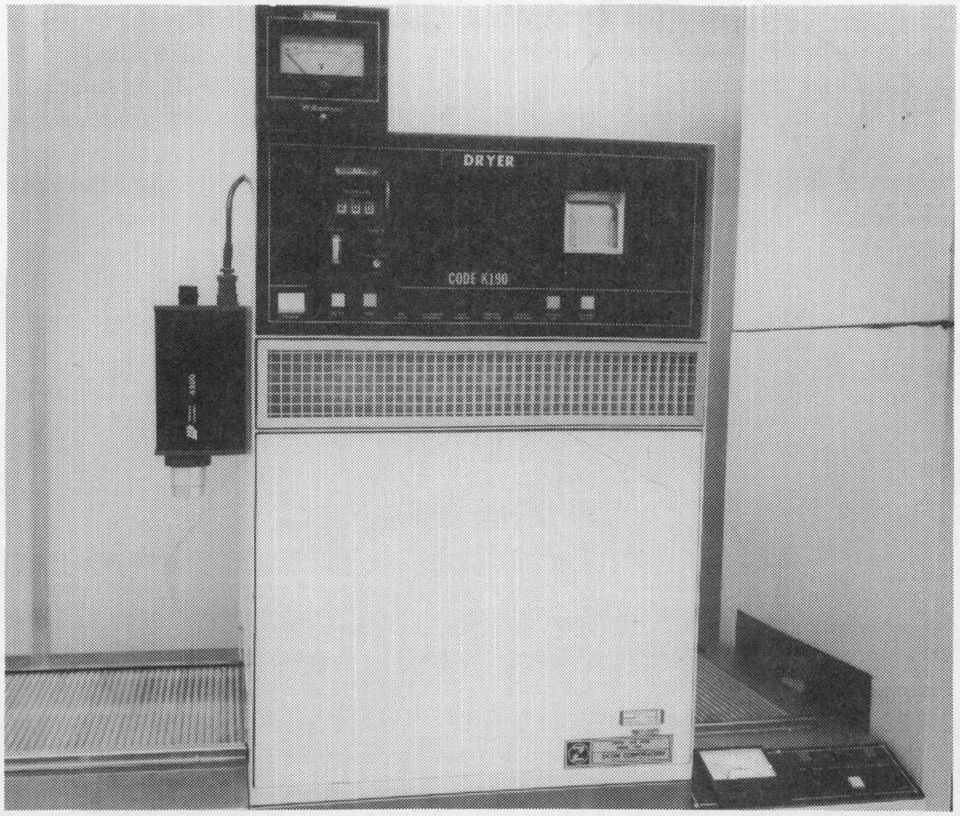

Figure 17. Zicon IR Oven With IR Temperature Sensor

An IR temperature sensor (Williamson Model 4212B) was added later to monitor the temperature of the substrate as it left the oven chamber. The sensor measures the average temperature over approximately a 1-inch-diameter (25.4 mm) circle and displays it on an analog meter. The meter has selectable upper and lower temperature limits which warn the operator when the substrate temperature is not in the selected range. An adjustment to set the emissivity to match that of the substrate surface was provided and has a range of 0.2 to 0.9.

Model of Heating Mechanism. Figure 18 shows a proposed model for heating a resist-coated thin-film substrate. IR energy emitted from the source strikes the resist surface where a fraction is reflected and the remainder is passed into the resist. A portion of this passed energy is absorbed by the photoresist directly (Point A) and that part not absorbed impinges the thin-film surface. Since substrates coated with 3.0 μm of gold or

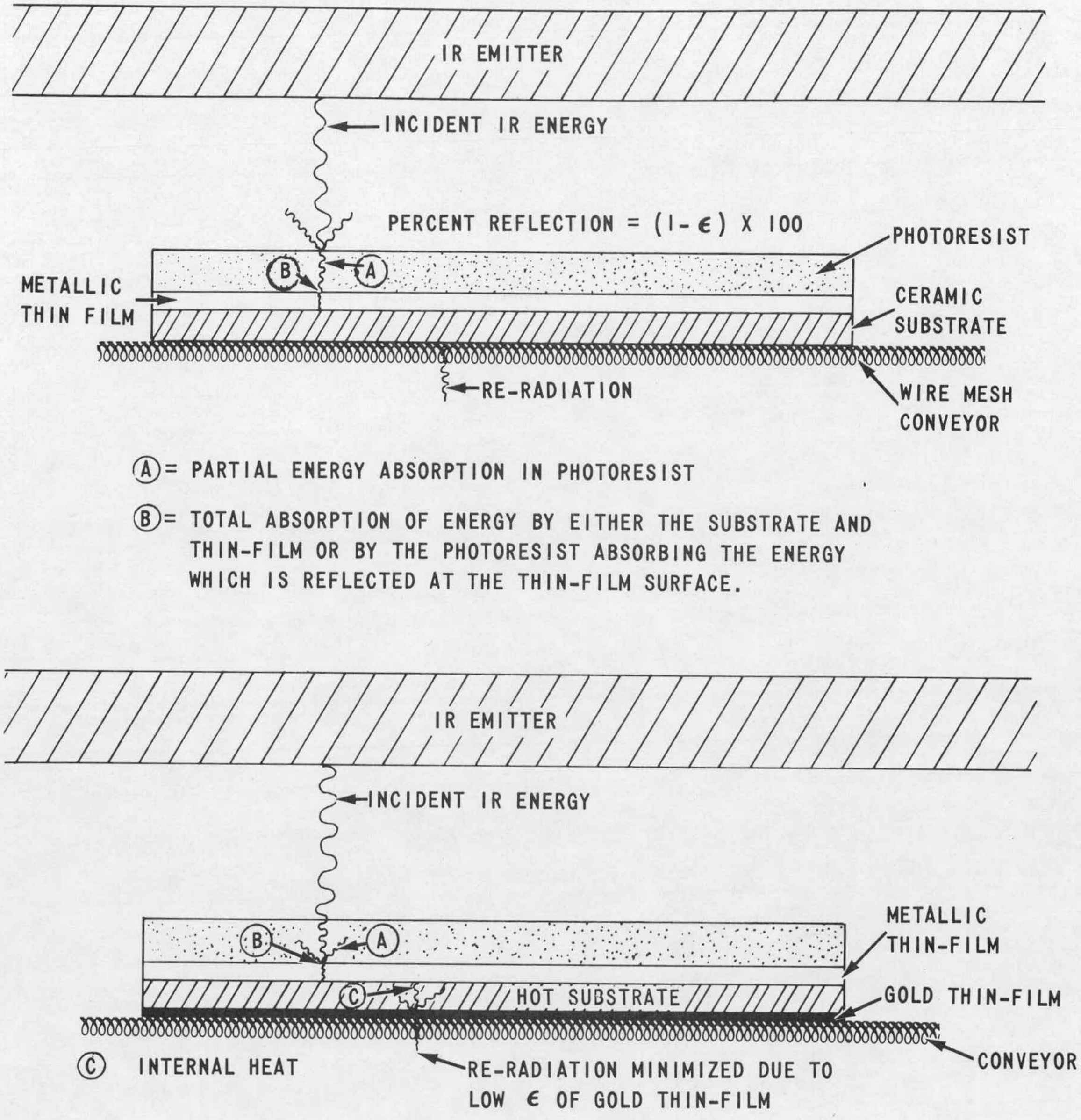

Figure 18. Heating Mechanism Model Without Backside Metallization (Top) and With Backside Metallization

0.05 μm of tantalum-nitride are opaque, no energy is transmitted through the substrate. All the remaining energy is either reflected or absorbed by the thin-film/substrate combination. That which is absorbed produces substrate heating which is the desired result. The majority of the reflected energy is absorbed by the photoresist. Since the gold surface is more reflective than the tantalum-nitride, photoresist heating (as opposed to substrate heating) is more predominant on gold-coated than on tantalum-nitride-coated substrates. In either case, the desired result of evaporating the photoresist solvent is achieved. The heating mechanism appears to make no difference in the quality of the photoresist coating.

As the substrate gets hotter, it begins to radiate its heat to the open area beneath the conveyor belt. When using backside metallization (ground planes) this radiation from the backside is significantly reduced (Figure 18) and higher temperature profiles and average temperatures are produced, thus altering the resist exposure characteristics.

Effect of Prebaking on Dimensional Control. Figures 19 and 20 display the dependence of line width on the emitter temperature settings and the average substrate temperature for various exposure energy settings. The average change in line width (ΔLW) to change in emitter setting temperature (ΔT) in the 150 to 300°C emitter setting range is as follows:

- For gold, ΔLW = 0.65ΔT, 200 to 300°C range at exposure setting equal to 14; and
- For tantalum-nitride, ΔLW = 0.30ΔT, 150 to 250°C range at exposure setting equal to 14.

Line width deviation is a first order function of exposure energy variations; however, the influence of light energy variations can be minimized by higher prebake temperature which makes the resist less sensitive to the light energy. (This subject is treated more thoroughly in BDX-613-1101.) The change in line width as a result of changes in average substrate temperature is also large as compared to the desired tolerance. Therefore, the contribution of variations in the photoresist prebake process to the overall change in line width distribution is significant, and the need for process control or baking parameters is obvious.

By applying design tolerance limitations on the line width, it is possible to determine the control necessary on the emitter temperature setting (or the average substrate temperature) to maintain the desired line width tolerance. The process limit on prebake temperatures, for a constant exposure energy setting, is the intersection of the tolerance limitation and the desired line of constant exposure energy. These lines have been drawn for exposure energy settings of 11 for gold mirrors and 14 for tantalum-nitride mirrors. The allowable temperature variation is shown in Table 2.

Since it is inconvenient to change oven conditions for gold and tantalum-nitride mirrors, a single set-point between 170 and 215°C must be used. This implies that at the zero line width deviation

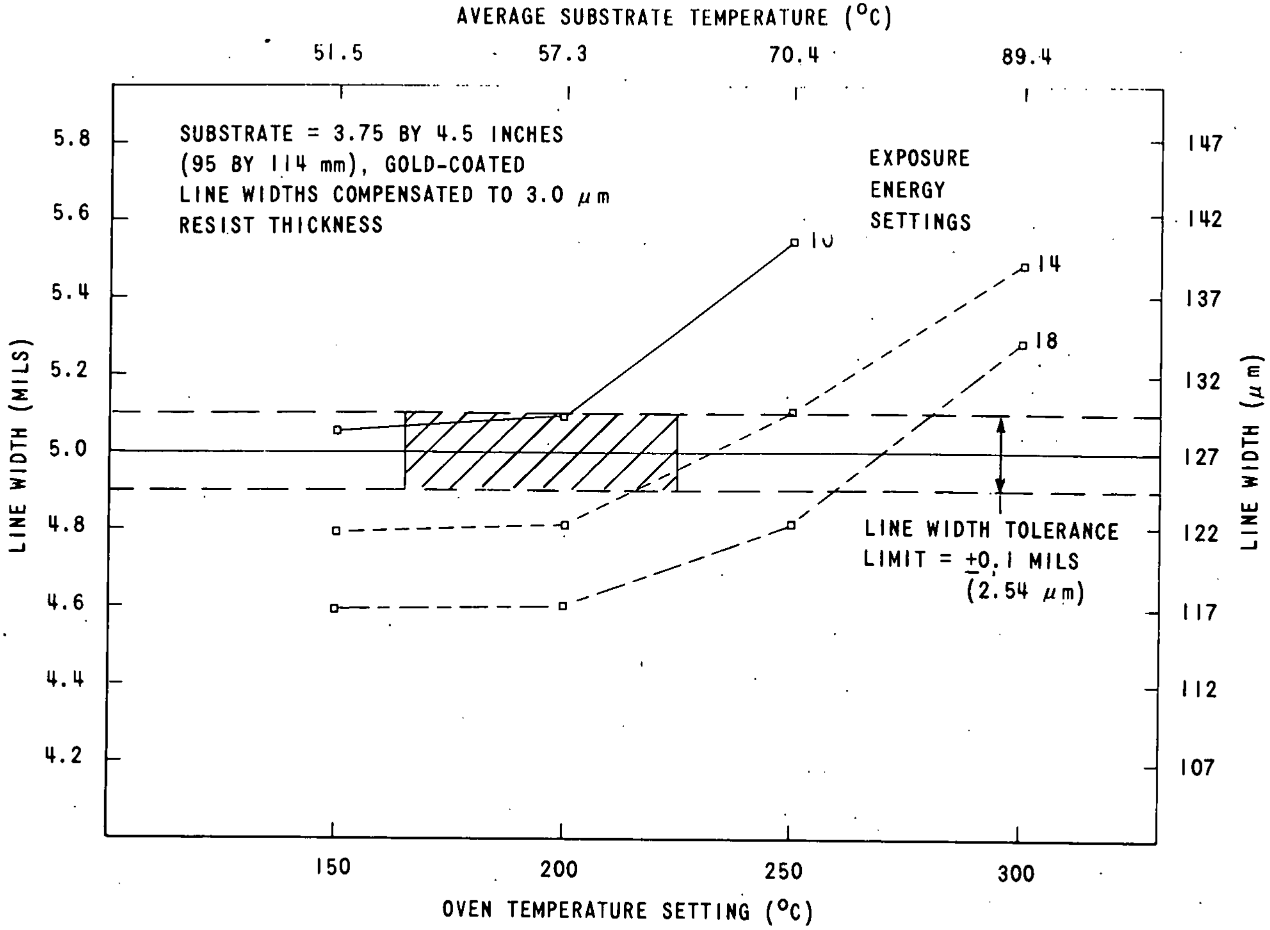

Figure 19. Prebake-Line Width Variations for Gold-Coated Substrates

point, the required exposure energies for gold and tantalum-nitride will be different. This is not troublesome, since the exposure energy is easily changed on the exposure system.

Photoresist Exposure

<u>Exposure Light Characteristics</u>. Proper exposure of photoresist is defined by PDO 6984719 as the amount of light energy per cm^2 required to reproduce the mask-image with a line-width deviation*

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*The dimensional difference between the mask image and the photoresist image, or the difference between the mask image and the final thin-film pattern.

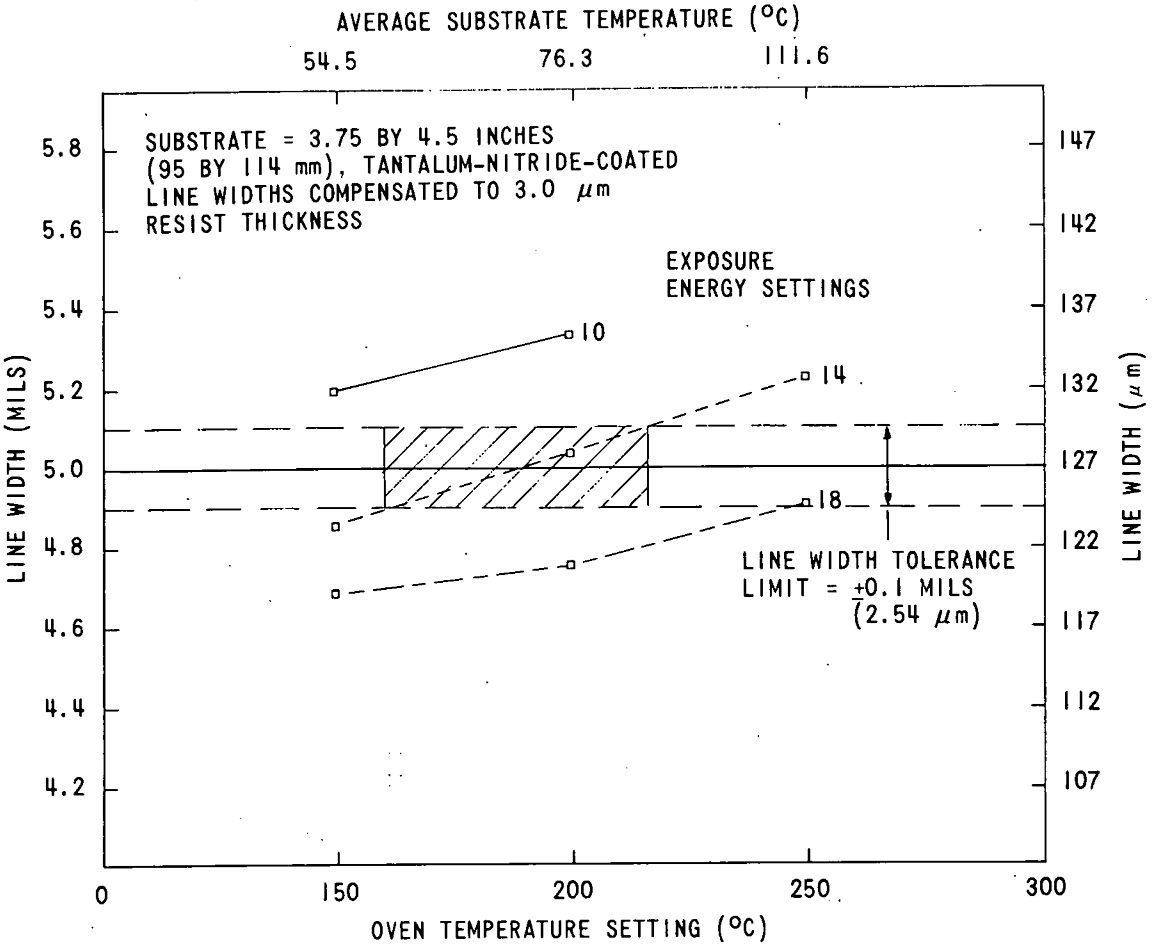

Figure 20. Prebake-Line Width Variations for Tantalum-Nitride-Coated Substrates

of less than ±50 microinches (1.27 μm). The ability to accomplish this becomes more difficult as the substrate size increases. Dimensional control is a first order function of exposure energy and energy uniformity and a second order function of photoresist thickness uniformity, prebake time-temperature product, mask-to-substrate separation, and developing times. The control of these parameters becomes more difficult as the substrate size increases and thus the dimension deviation distribution tends to become larger. However, this section will be limited to discussions of exposure light characteristics and effects of dimensional deviation.

Table 2. Process Limits on Prebake Oven Temperatures

Type of Substrate	Emitter Settings	Average Substrate Temperature
Gold	170 to 220°C	53.5 to 65°C
Tantalum-Nitride	165 to 215°C	60 to 91°C

The total light energy required to properly expose the resist is a function of the light intensity per cm^2 and the exposure duration, as given by

$$E = \int_{t_o}^{T} i(t)dt, \tag{1}$$

where

E = Energy density (joules/cm^2),

$i(t)$ = Instantaneous light radiance (watts/cm^2), and

$t_o - T$ = Exposure duration,

and is measured in the wavelength range of interest. It can be seen that there are two possibilities for controlling the exposure energy:

- Hold the instantaneous intensity constant and regulate the exposure time; or
- Actually integrate the instantaneous value of the light intensity over real time and compare it against a selectable value (T) for exposure termination.

Experience indicates that instantaneous light intensity regulation is difficult, especially when regulation compensation lags behind real-time intensity fluctuations. However, integration of the instantaneous light intensity over time in a particular wavelength region can be accomplished easily and with good accuracy. By selecting a wide band filter having a transmission consistent with the spectral response of the resist and a photosensor connected to an integrator which in turn controls the light shutter, a proper and consistent amount of light energy can be metered to the resist during each exposure. This type of setup assures that a consistent exposure energy will be given to each exposure. As the exposure lamp ages and the intensity changes the integrator automatically adjusts the exposure time to meter the same energy to the resist. For a long- or short-term variance in the light intensity, such as when the lamp is warming up, the integrator will compensate. The use of a wide band filter is adequate for controlling exposures, but will not accurately determine the quantitative amount of energy metered to the resist.

Light Intensity Determination. Determination of the actual light intensity and exposure energy to a high degree of accuracy can be accomplished by plotting the average* light intensity as a function of wavelength (Figure 21) and integrating the curve between the two wavelengths of interest. This integration can be accurately approximated by summing small incremental areas under the curve. By establishing the nominal exposure duration (in seconds) for proper exposure, the nominal exposure energy is simply the product of the integrated average intensity in the wavelength region of interest.

$$E = I_a T \tag{2}$$

where

E = Calculated exposure energy (joules/cm^2),

I_a = Integrated average intensity (watts/cm^2), and

T = Exposure time (seconds).

Equation 2 should not be confused with Equation 1 as they are applied to two separate things. Equation 1 represents the systematic approach to controlling the proper exposure energy delivered to the photoresist by integrating the instantaneous value of light intensity over time. Equation 2 is for calculating the exposure energy in J/cm^2 where I_a is considered to be constant (independent of time). Equation 2 comes from Equation 1 when $i(t) = I_a$.

The resulting exposure energy is shown in Table 3 as a function of the exposure duration in seconds.

Prebake and Exposure Relation. The connection between prebake temperature and the proper exposure energy was discovered during previous PDO efforts. It was determined that the relative light

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*Short term light intensity fluctuations (less than 10 milliseconds with an amplitude of 4 percent of the average value) exist in most exposure systems. These fluctuations can be seen by displaying the photometer output on an oscilloscope. The desired average intensity can be adequately displayed by an analog meter which responds to the average of the fluctuations.

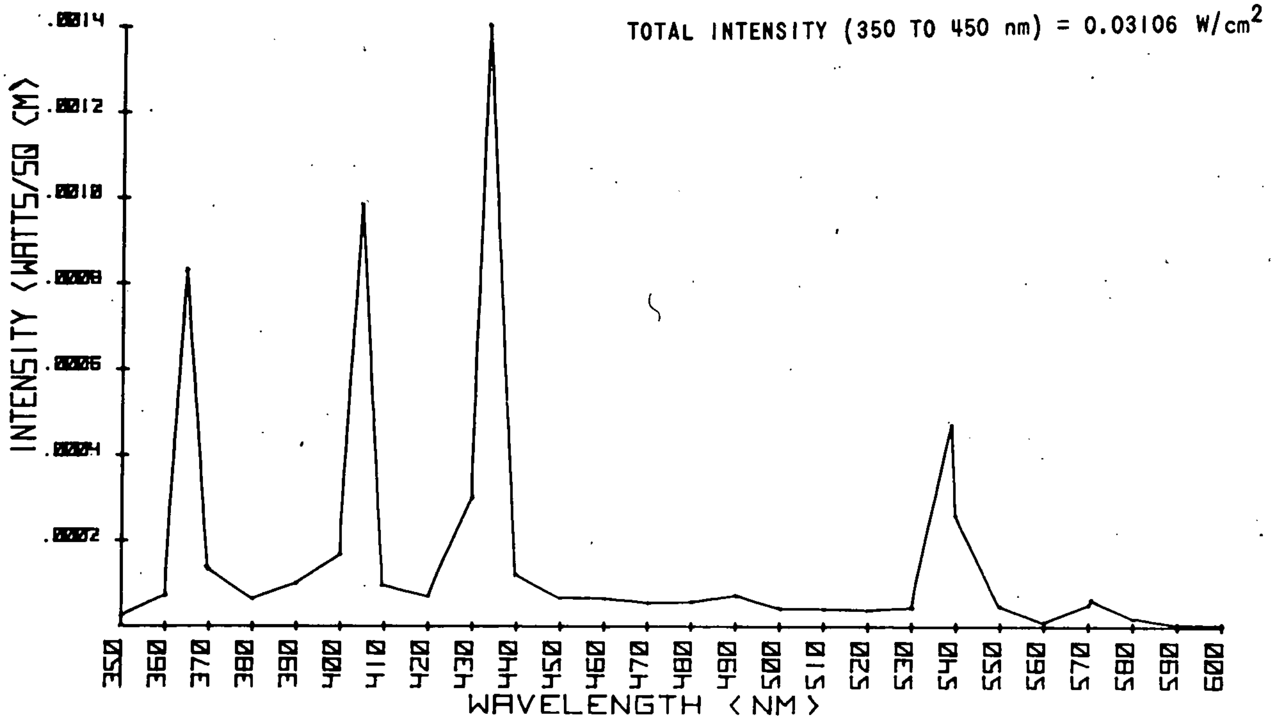

Figure 21. Light Intensity Versus Wavelength, Cobilt TF500

sensitivity of the photoresist could be decreased by increasing the prebake temperature. It was also shown that the relation was not firm; there was no particular prebake time-temperature product that gave optimum results on one oven and exposure system that could be applied to other ovens and exposure systems. What was shown was the method by which a single prebake oven and exposure system could be characterized collectively to establish a prebake/exposure schedule which would hold a predetermined dimensional quality.

Each prebake oven and exposure system would require concurrent characterization and these results would not necessarily correlate with other ovens and exposure systems. There is, of course, correlation between systems of the same model when set up and operated in the same manner, although such a correlation may not always be direct. Previous prebake ovens used at Bendix were convection air ovens and there exists no correlation between set-point temperature settings on the convection air ovens and the currently-used infrared ovens. Furthermore, when using the infrared ovens, there are differences in the average substrate temperature due to the relative emissivities of the substrate surface metallization and the photoresist coating thickness.

Table 3. Exposure Energy as a Function of Exposure Time

Exposure Time (s)	Average Intensity (W/cm^2)	Energy (J/cm^2)
1	0.03106	0.03106
2	0.03106	0.06212
3	0.03106	0.09318
4	0.03106	0.12424
5	0.03106	0.15530
6	0.03106	0.18636
7	0.03106	0.21742
8	0.03106	0.24848
9	0.03106	0.27954
10	0.03106	0.31060
20	0.03106	0.62120
30	0.03106	0.93180
40	0.03106	1.24240

Assuming the resist thickness to be constant, Figure 22 shows the average substrate temperature on a 3.75 by 4.5 inch (95 by 114 mm) substrate as a function of the oven set-point temperature and for continuous gold and tantalum-nitride thin films on the surface. Each substrate was also coated with ∿3.0 microns of AZ1350J photoresist. The relative emissivities of the gold and tantalum-nitride, 0.45 and 0.80 respectively, cause the average substrate temperature to differ as shown. It would not be expected that the proper exposure energy be the same for the two thin films at a given set-point oven temperature, except for set-point 150°C where the substrate temperatures are nearly equal.

Figures 23 and 24 show the prebake and exposure relation for gold and tantalum films. Besides the general prebake and exposure relation, the difference between the proper exposure energy for gold and tantalum-nitride thin-films is shown for a 200°C oven setting (Points A and A' on Figures 23 and 24). The difference in required exposure energy is principally the result of the difference in prebake conditions, although the relativity difference in ultraviolet reflection of gold and tantalum is also responsible. As a rule of thumb, the proper exposure energy

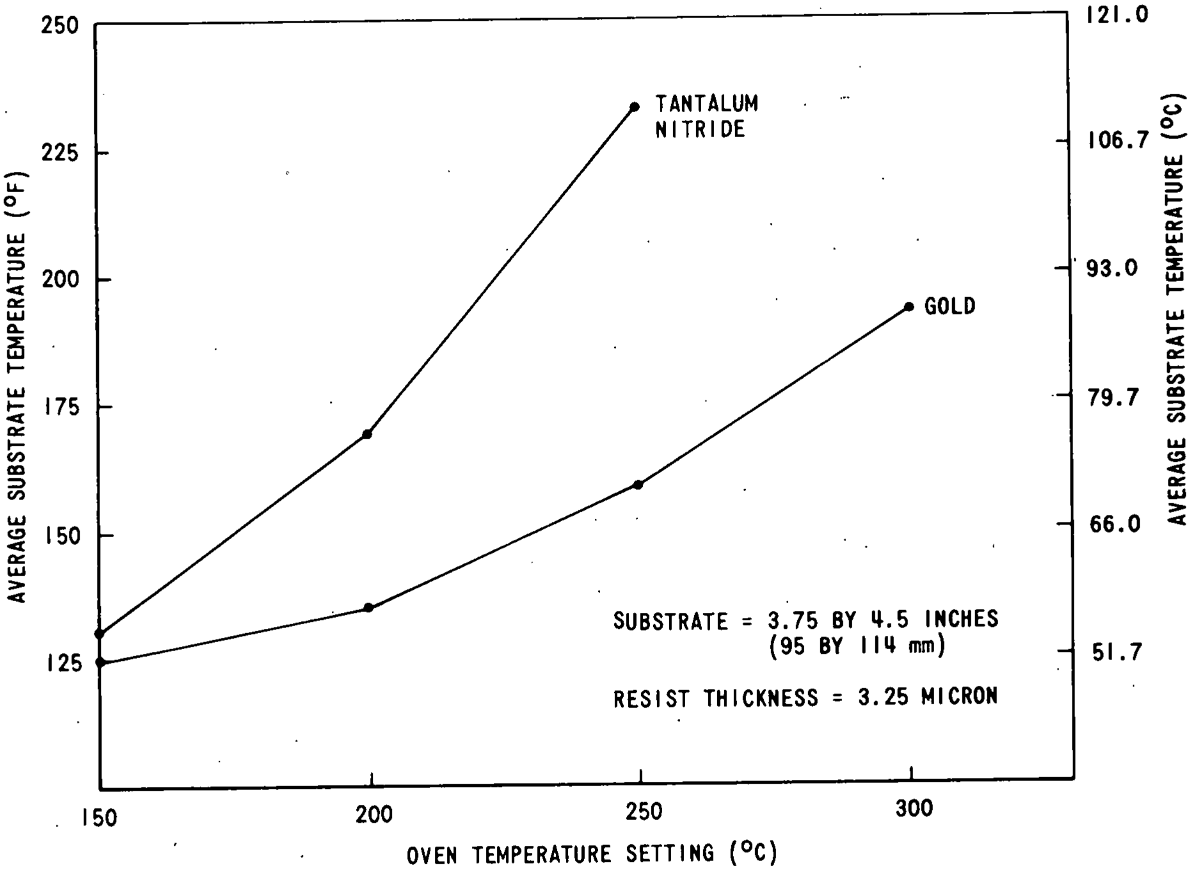

Figure 22. Average Substrate Temperature

can be expected to increase by 0.04 J/cm^2 for an increase of 50°C on the oven set-point controller. This value is only valid in the 200°C to 300°C setpoint temperature range.

Figures 25 and 26 show the application of tolerance limitations to the nominal design value of 5.0 mils (25.4 μm) and demonstrate the limits on the exposure energy which will hold the desired tolerance. These limits are the exposure energy schedule limits. By plotting the change in line widths for a constant exposure energy as a function of the oven temperature and applying the same tolerance analysis, the schedule limits on the oven temperature may be determined. As an example, using a ±0.1 mil (2.54 μm) tolerance and nominal 200°C prebake condition, the prebake and exposure schedule would appear as in Figure 27.

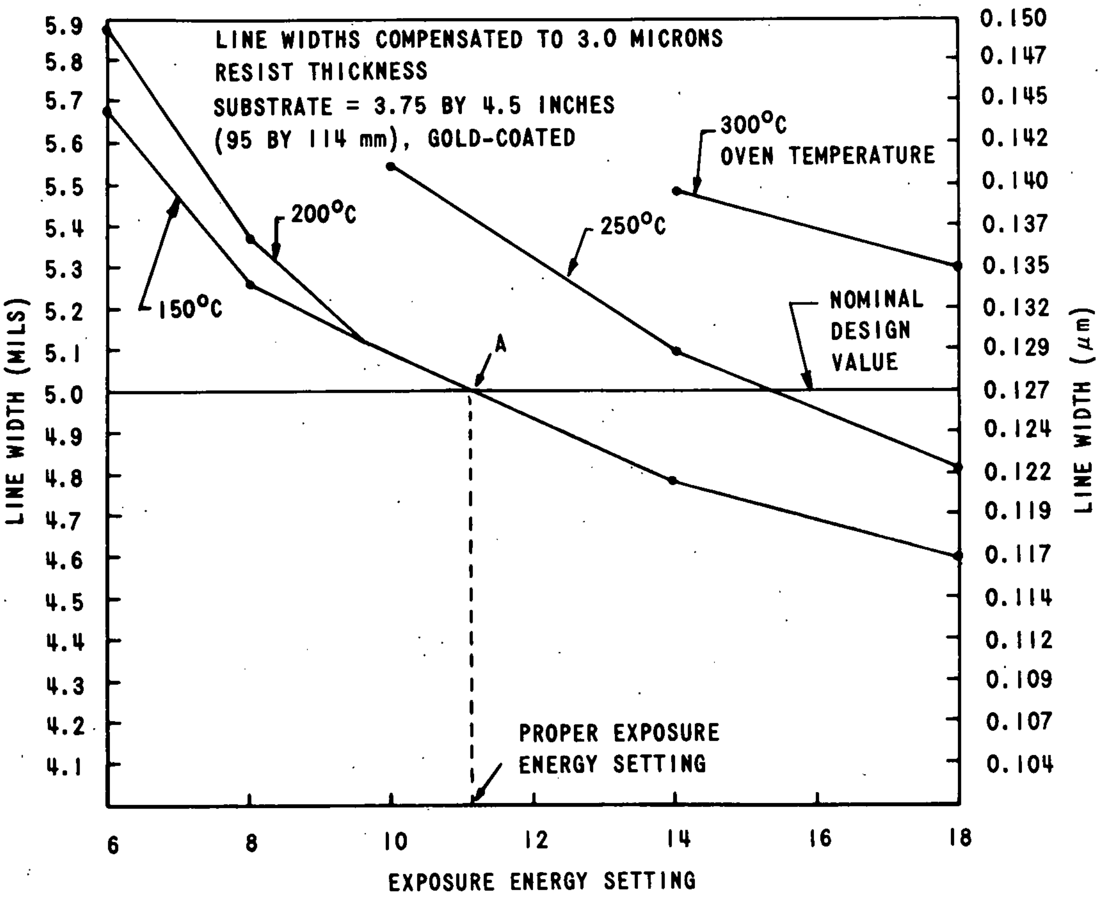

Figure 23. Exposure Relation for Gold-Coated Substrates

ACCOMPLISHMENTS

The primary objective of this project was to establish and characterize processing techniques for the production of multiple hybrid microcircuits on 3.75- by 4.5-inch (95 by 114 mm) substrates. This objective has been met and the techniques are successfully being employed in production. As a result of this activity, production capacity in metallization and photolithography has been increased by a factor of 9 to 12 times without corresponding increase in the number of parts handled by production operators, resulting in a reduction in the standard hours required to fabricate a thin-film network. Although actual cost savings depend on HMC complexity, an average savings of about $25 per HMC has been realized.

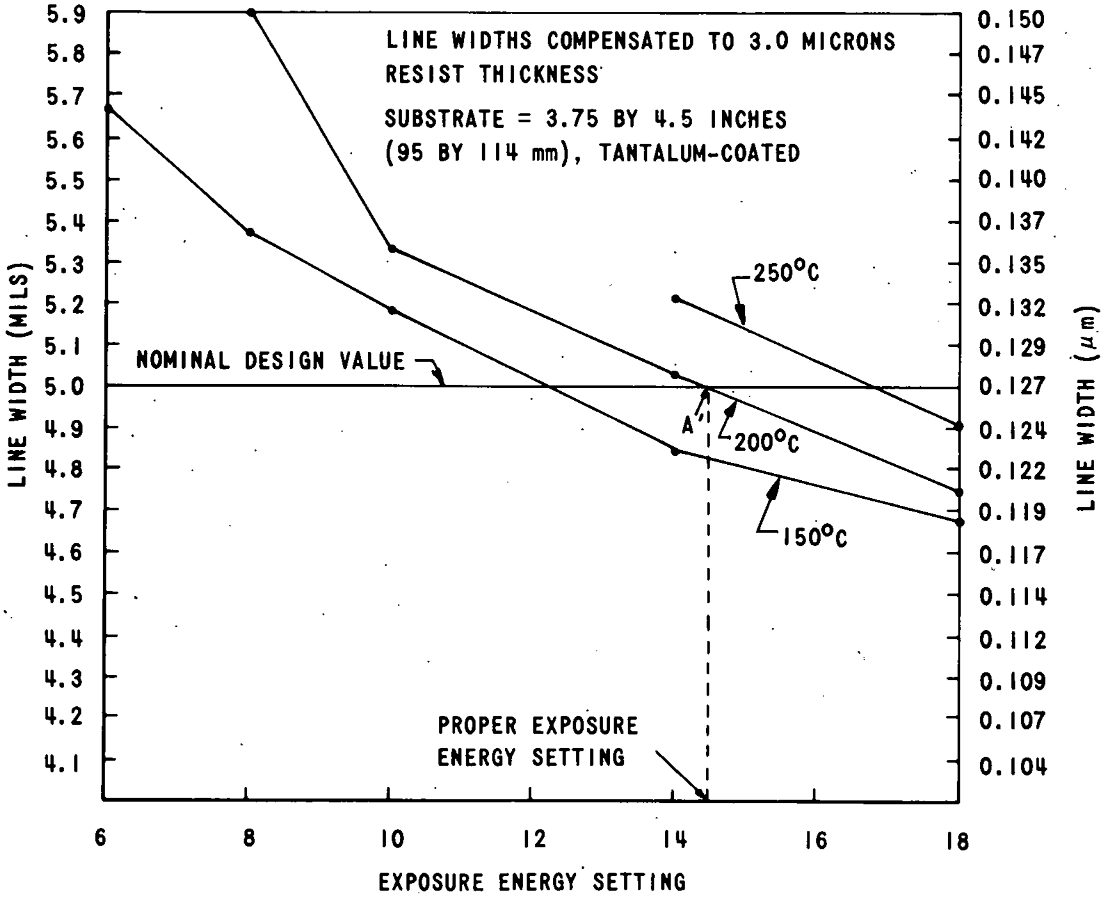

Figure 24. Exposure Relation for Tantalum-Nitride-Coated Substrates

Characterization of Cr/Au thin-films revealed that metallizing conditions affect the resistivity and bondability of these films. The rate of gold deposition has minor effects, but the effects of variations in substrate temperature and chromium deposition are major. All conditions investigated are capable of producing acceptable production films when CAN etched after stabilizing.

Films deposited at a 300°C substrate temperature have acceptable resistivity and are bondable in the as-stabilized condition. Although higher deposition temperatures might result in even better bondability for as-stabilized films, the conditions for a production process have been established.

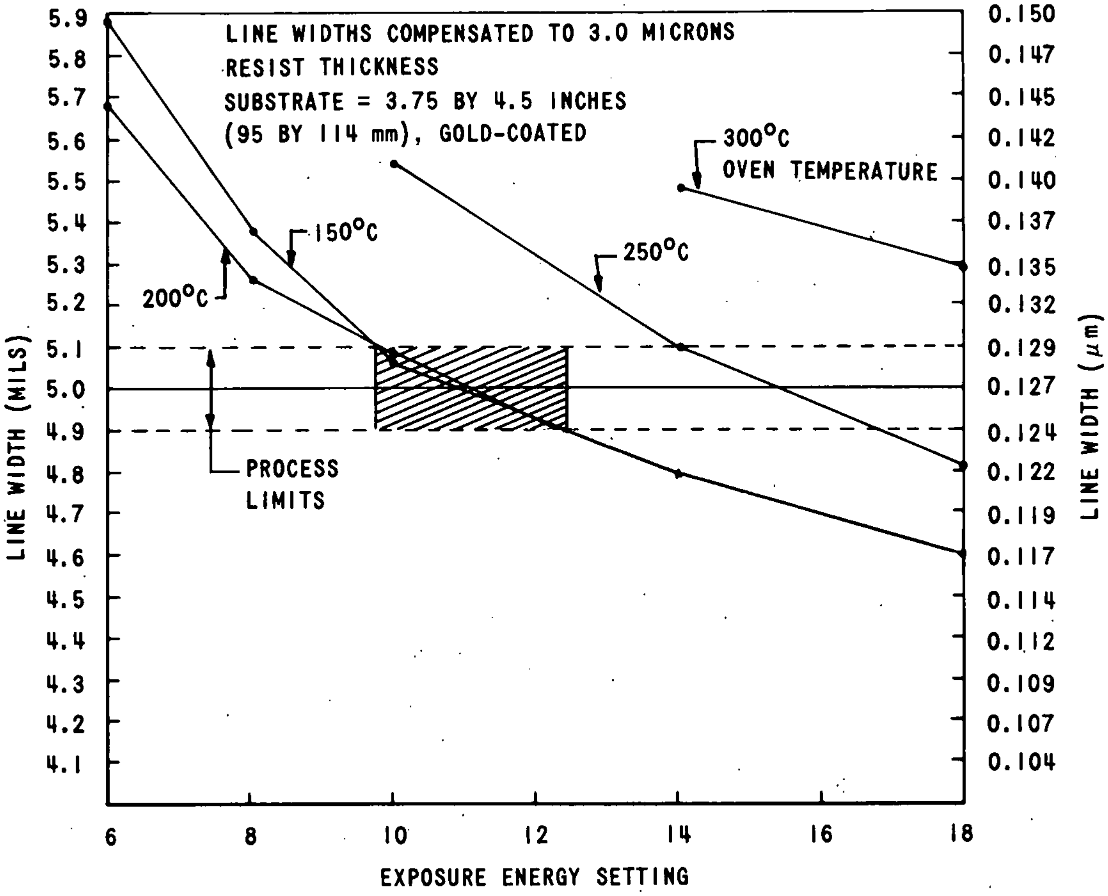

Figure 25. Expose Relation for Gold-Coated Substrates (Schedule Development)

FUTURE WORK

No future work on roller coating, IR baking, or alignment and exposure is required under present HMC product and processing requirements. If product or processing requirements are changed, then additional efforts may be required. Such changes in requirements might include:

- Smaller HMC geometries [less than 5.0 mils (127 μm)],
- Use of a photoresist besides AZ1350,
- Use of a substrate material other than Al_2O_3 unglazed ceramic, and
- Change in thin-films used for conductors, resistors, or both.

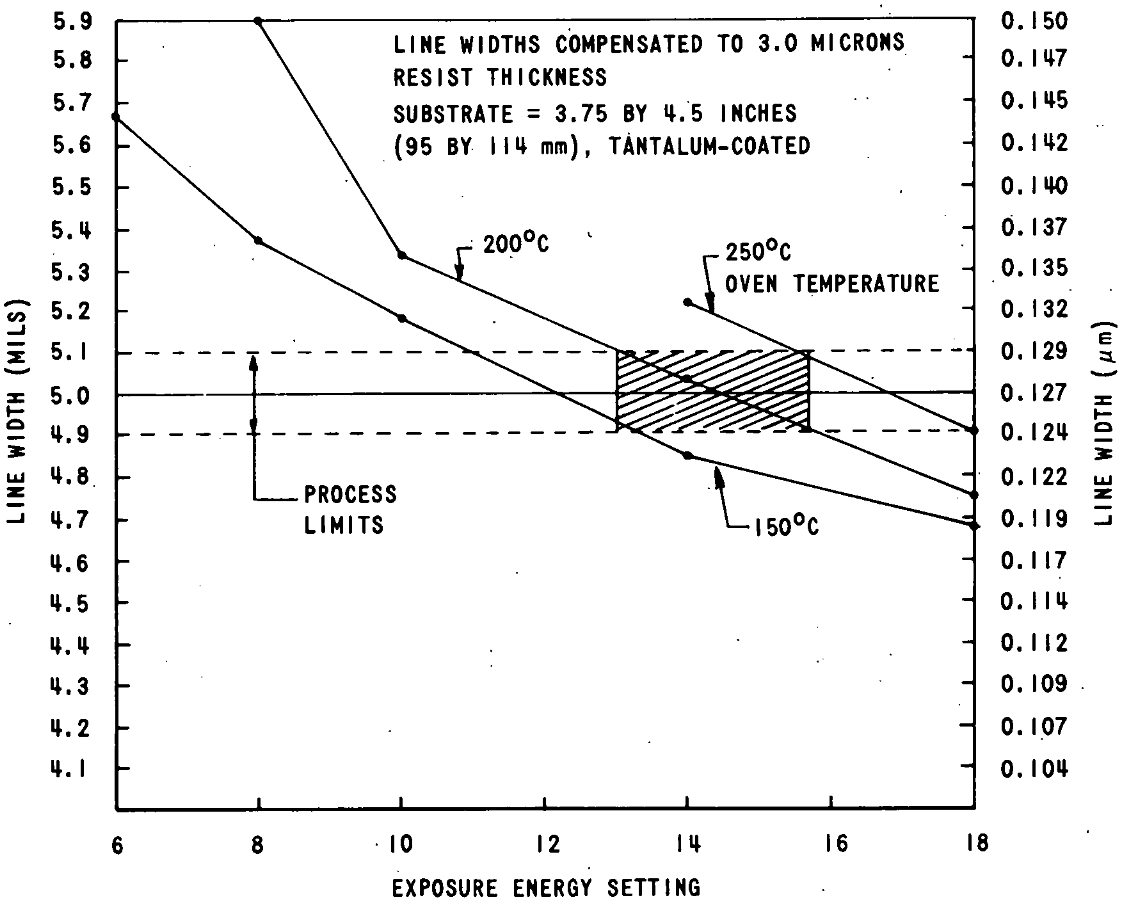

Figure 26. Exposure Relation for Tantalum-Nitride-Coated Substrates (Schedule Development)

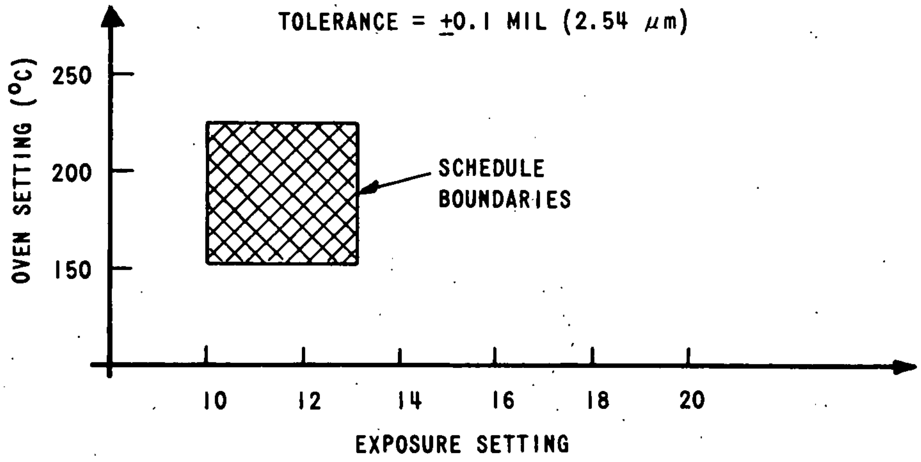

Figure 27. Prebake and Exposure Schedule

It is recommended that a back-up photoresist be developed for possible production use in the event that AZ1350 ingredients change or the resist becomes unavailable.

It is recommended that spray resist coating be investigated as an alternative to roller coating to achieve smaller HMC geometries and dimensional control. It is believed that, in the long run, spray coating may be more durable and economical than roller coating.

Higher emissivity gold surfaces, which are visually darker in appearance, may be more porous or have a coarser surface finish. In such a case, the surface reflection might be studied as a nondestructive process control monitor, that can be correlated to gold thin-film quality and, subsequently, to a prediction of bondability.

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