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INFRARED BAKING OF POSITIVE
PHOTORESIST FOR HYBRID
MICROCIRCUIT FABRICATION

PDO 6984726, Topical Report

L. E. Schantz, Project Leader

Project Team:
J. H. Pusch

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Topical Report

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INFRARED BAKING OF POSITIVE PHOTORESIST FOR HYBRID MICROCIRCUIT FABRICATION

BDX-613-1246, UNCLASSIFIED Topical Report, Published August 1976

Prepared by L. E. Schantz, D/842, under PDO 6984726

The use of infrared heating to bake Shipley AZ1350 positive photoresist before exposure was investigated as an integral part of a cost-effective hybrid microcircuit photolithographic procedure. The baking parameters which affected the substrate temperature were emitter temperature, conveyor speed, emissivity of the substrate surface, and the amount of air forced through the oven chamber. Individual settings on the emitter temperature and conveyor speed controllers were stable and repeatable; 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 did its effect on the substrate temperature. Through manipulation and control of these parameters, consistent prebaking of photoresist-coated substrates was achieved.

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SUMMARY

Infrared (IR) baking of photoresist before exposure was recommended as a result of preliminary tests during prior PDO activities. Using the previously derived information, an IR system was obtained which afforded the technical advantages of IR baking and was harmonious with economical photolithographic processing (Multiple Hybrid Microcircuit Processing, PDO 6984726).

Infrared baking is one of four process steps required to reproduce the hybrid microcircuit mask image in the photoresist. The photoresist image is required to have the same dimensions as the mask image; however, a ± 0.1 -mil ($\pm 2.5 \mu\text{m}$) variation is typically experienced. This variation is, in the major part, due to the variations in resist thickness and exposure energy while less than ± 0.01 mil ($\pm 0.25 \mu\text{m}$) is the result of process variations in prebake conditions. Programmed changes in the prebake conditions alter the image dimensions; however, once the image prebake conditions are set, there is very little effect.

The consistency in substrate temperature profiles as the substrates are conveyed under the IR emitter in the oven chamber is the primary technical advantage of the conveyORIZED IR drying system. This consistency is disturbed only by variations in the emitter set-point temperature, conveyor speed, and substrate surface emissivity. For all practical purposes the emitter temperature and conveyor speed are constant, while the surface emissivity is the largest single variable. Surface emissivity of the substrate is affected by photoresist thickness changes and the nature of the thin-film gold coating. Tantalum-nitride coatings appear to be more consistent in emissivity than gold. Even though the average substrate temperature changes with variations in the resist thickness, the effect on image dimensional quality is significantly less than the direct effect of variations in resist thickness and proper exposure* energy.

The average substrate temperature can be changed by varying the set-point emitter temperature, the conveyor speed or both. The emitter temperature principally controls the substrate temperature profile (temperature gradient), while the conveyor speed determines the maximum and the average substrate temperature. Changes in the average substrate temperature of 20 to 40°C can cause a change of 0.4 to 0.8 mil (10.1 to 20.3 μm) in the photo-

*Proper resist exposure is defined as the quantity of energy in joules/cm² required to reproduce the photomask image in the photoresist to ± 2 percent of the mask image dimension or ± 0.1 mil ($\pm 2.5 \mu\text{m}$) maximum.

resist image, depending upon the exposure energy used and the type of thin-film coating. Such planned changes to higher average substrate temperatures can be used to decrease the effect of exposure light variation on dimensional quality by decreasing the sensitivity of the resist to light.

The exact heating mechanism, although not important in terms of process control, is believed to be a combination of substrate and direct photoresist heating by IR irradiation. It is sufficient, in terms of process control, to identify the variables which influence the average substrate temperature and to determine the necessary restraint on each to achieve the required dimensional control of the photoresist image.

All objectives of the proposed development of IR photoresist baking have been met, transferred to Process Engineering control, and successfully employed in production. No future work is forecast under present product and processing requirements. If these requirements change, then short-term process development efforts will be required.

DISCUSSION

SCOPE AND PURPOSE

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:

- 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 consequently the yield.¹ Therefore, the time-temperature profile became significant and the development effort required to obtain a suitably consistent profile was essential.

PRIOR WORK

The feasibility of IR baking of photoresists was demonstrated during activities on PDO 6984719 where it was shown that time-temperature profiles from convection air ovens could be duplicated using IR irradiation. The convection air oven had the disadvantage of drying the outer photoresist surface and thereby trapping non-vaporized solvents. To prevent the outer surface of the photoresist from drying first, the substrates were irradiated from the non-resist coated side. The time-temperature profiles were measured on the front or resist coated surface. No other efforts were made besides demonstrating the feasibility and predicting the possible increase in process control and production quantities.

ACTIVITY

General Description of Zicon IR Oven

The IR oven selected for evaluation was a Zicon Series 1100 Infra-red Oven (Figure 1). 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. The emitter plane paralleled the conveyor, adjusted 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. Appropriate safety controls were provided as shown in Figure 2.

The conveyor (Figure 3) 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 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 air-borne 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 (Appendix A) to prevent escape of solvent vapors. An exhaust port was provided at the rear of the system. (Specific equipment purchase specifications appear in Appendix C).

An IR temperature sensor (Williamson Model 4212B) was added 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 (Figure 1). 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.

Oven Characterization

Photoresist-coated substrates are baked following the resist application to remove solvents and leave only the solid constituents (polymers and sensitizers). The baking operation, in some cases, is used to increase the photoresist adhesion to the metallized substrate surface. Therefore, the baking conditions may be determined predominantly by adhesion characteristics. The baking conditions may also be adjusted to decrease the photosensitivity

Figure 1. Zicon IR Oven With IR Temperature Sensor

of the photoresist and make the proper resist exposure condition* less sensitive to fluxuations in the exposure lamp and exposure controller. The later philosophy becomes less significant as a process control technique when integrating exposure controllers are used; however, it is well suited to help minimize dimensional fluxuations in the photoresist.

If the prebake conditions are to assist in dimensional control, it is necessary for the them to be consistent and repeatable from substrate to substrate regardless of where it is on the conveyor

*Proper resist exposure is defined as the quantity of energy in joules/cm² required to reproduce the photomask image in the photoresist to ± 2 percent of the mask image dimension or ± 0.1 mil (± 2.5 μ m) maximum.

Figure 2. IR Oven Control Panel

Figure 3. IR Oven Conveyor and Substrates

system. Figure 4 shows the isothermic plot of a 16- by 16-inch (0.41 by 0.41 m) static area beneath the IR emitter. The measured temperature variation of $\pm 10^{\circ}\text{C}$ becomes important when considering the heat transfer from the emitter to the substrate is proportional to the difference in the 4th power of the respective temperatures. Therefore, static use of the IR oven (substrates conveyed under the emitter and held there for a fixed time) would not afford the most consistent prebake conditions. The alternative is a dynamic operation where the substrates are conveyed under the emitter at a fixed speed.

Figure 5 shows a thermocouple temperature profile at various conveyor speeds as measured at the front, middle, and back edge

Figure 4. Isothermic Plot of Oven Chamber

of the conveyor belt. The temperature profile, at a single conveyor speed, is relatively constant with only a 2°C maximum difference. The profiles of Figure 5 do not actually represent the substrate condition that would exist in production; in fact, there are greater substrate temperature differences than 2°C. The cause of these temperature differences is discussed in the "Process Control" section; however, the important point here is that dynamic operation offers better consistency than static operation.

The dynamic consistency is a result of an averaging effect produced by allowing the substrate surface to "see" nearly all parts

Figure 5. Temperature Profile Versus Conveyor Speed

of the emitter surface to an equal extent rather than a single part as in the static condition. Only if the isotherm changes its pattern, will the profile change; however, it is unlikely that the profile will change dramatically. The heat transfer per unit time is given by²

$$H = \frac{dQ}{dt} = A\epsilon\sigma (T_e^4 - T_s^4), \quad (1)$$

where

t = time

T_s = substrate temperature

T_e = emitter temperature,

σ = 5.67 x 10⁻⁸ watts/m² (°K)⁴,

A = area of emitter, and

ε = emissivity of substrate surface.

Assuming the view factor equal to unity, the emitter temperature is the same as the isotherm temperature, and under dynamic operation can be averaged over the emitter width; (averaged over time) where the time is a function of conveyor speed. Therefore, Equation 1 could be written as

$$H = \frac{dQ}{dt} = A\epsilon\sigma (\bar{T}_e^4 - T_s^4), \quad (2)$$

where

$\bar{T}_e$ = Average emitter temperature.

Because $\bar{T}_e^4$ is relatively constant* for a given set-point emitter temperature, the profiles are consistent.

Consequently, characterization of the Zicon IR oven involves verification of the time-temperature profiles and, determining the correlation between these profiles and the exposure energy required for proper exposure.

Substrate Temperature Profiles

Temperature profiles were made on thin-film gold and tantalum-nitride-coated substrates at various emitter temperature settings and conveyor speeds by attaching a chromel-alumel thermocouple to

*See section on "Process Control".

the center of the substrate surface and recording the output on a chart recorder (Figures 6 and 7). The thermocouple referenced at 0°C made good thermal contact to the substrate surface and shielded less than 1 percent of the surface from the IR source. Profiles were made for 1.5- by 1.5-inch (38 by 38 mm) and 3.75- by 4.5-inch (95 by 114 mm) substrates. The spacing between the emitter and the substrate was also varied from 2.25 to 4.50 inches (57.1 to 114 mm). The substrates were coated with either continuous 3.0 μm gold or 0.05 μm tantalum-nitride thin films and approximately 3 μm of AZ1350J photoresist.

Figure 6. Temperature Profiles at Various Emitter Settings for Gold-Coated Substrates

Figures 6 and 7 show typical temperature profiles for 3.75- by 4.50-inch (95 by 114 mm) substrates. It is obvious that the substrate temperature gradient and the maximum temperature obtained is greater for each successively higher emitter temperature setting. However, the maximum temperature difference is not proportional to the predicted values from Equation 2; thereby correctly suggesting that additional heat transfer mechanisms are affecting the substrate temperature. It is also obvious that for a given emitter set-point temperature, the Ta₂N coated substrates

Figure 7. Temperature Profiles at Various Emitter Settings for Tantalum-Nitride-Coated Substrates

have higher temperature gradients and greater maximum temperatures. This variation is primarily due to differences in the relative surface emissivities. The most important aspect of the profiles is their consistency. Since the prebaking process is repeatable, consistent dimensional quality can be maintained in the photoresist image.

Through numerous temperature profile measurements, it was found that the profiles and therefore the average substrate temperatures were suitably consistent for hybrid microcircuit (HMC) production. Table 1 shows the average temperature gradient, the average maximum temperature, and the standard deviation for each on gold- and tantalum-nitride-coated substrates.

Although the maximum temperature range may appear large, the direct effect on the image dimensions is not significant. The photoresist responds to the average substrate temperature--a function of time and temperature--and not the maximum substrate

Table 1. Consistency of Temperature Profiles

Parameter	Type of Coated Substrate	
	Au	Ta ₂ N
Avg Max Temp* (°C)	80	93
Std Dev (°C)	5	3
Range (°C)	10	10
Temp Gradient** (°C/min) (°C/s)	22 (0.37)	29 (0.48)
Std Dev (°C/min) (°C/s)	2 (0.03)	2 (0.03)
Range (°C/min) (°C/s)	6 (0.1)	5 (0.08)
*Measurement accuracy $\pm 3^{\circ}\text{C}$ **Calculated between 60 and 80 seconds on temperature profile		

temperature. Since the substrate is at the maximum temperature for a short time, as compared to the overall baking time, the maximum temperature becomes less significant than the average temperature; however, if the maximum temperature is high enough, it can degrade the resist by melting, polymerization, and so forth.

Previously, photoresist prebaking was dependent on time and temperature. The conveyor speed fixes the prebake time and holds it essentially constant; therefore, it is now possible to speak of the average substrate temperature as the prebaking control parameter, because the average temperature is directly proportional to the prebaking time.

Average Substrate Temperature and Set-Point Emitter Temperatures

The calculated substrate temperature profiles for a fixed conveyor speed of 1 ft/min (0.50 mm/s) were determined by fitting equations to the curves of Figures 6 and 7. The data points and coefficients of the 3rd degree equations are shown in Appendix D. The resulting curves are shown in Figures 8 and 9. The average substrate temperature was calculated by integrating the equations for each emitter temperature setting and then dividing by the difference in the integral limits, or rather the total prebake time. This period corresponds to the time interval between the point when the substrate enters the oven (~ room temperature) and the point when it leaves the oven (maximum temperature). This interval at 1 ft/min (0.50 mm/s) is approximately 130 seconds. It does not include the cool down time which is not a significant factor below emitter settings of 200°C. In production, the substrates are

Figure 8. Calculated Substrate Temperature Profiles for Gold Mirrors

quickly cooled by conduction to the supporting surfaces (a condition not shown by Figures 6 and 7). Therefore, cool down time was not considered in determining average substrate temperatures.

Figure 10 shows the average substrate temperature for gold- and tantalum-nitride-coated substrates. From the significant difference between the two average substrate temperatures, it might be expected for each to react differently, and they do. These differences are the primary result of variations in surface emissivities.

Emissivity of Tantalum-Nitride and Gold Thin-Film Surfaces

The values given in Table 2 (determined by J. J. Cardarilli; Williamson Corp., Concord, MA) shows the ratio between the emissivity of the tantalum-nitride and the gold thin-film is 3:1; however, when covered with approximately 3 μm of AZ1350J photoresist, the ratio changes to about 2:1. Although a variance in temperature profiles is predicted by the difference in the

Figure 9. Calculated Substrate Temperature Profiles for Tantalum-Nitride Mirrors

emissivities, the exact profiles cannot be predicted due to heat transfer away from the substrate by multiple mechanisms.

Table 2. Substrate, Thin-Film, and Resist Surface Emissivities

Substrate Treatment	Bare Ceramic	Au Coated Ceramic	Ta ₂ N Coated Ceramic
Sprayed Black Without Photoresist	1	1	1
With Photoresist	0.4	0.2	0.6
	0.4	0.45	0.8

Figure 10. Average Substrate Temperatures

Apparent Emissivity of Photoresist

When the substrates are coated with photoresist, there is an apparent increase in emissivity. This increase implies there will be a greater heat transfer resulting from the photoresist being present. Without photoresist, the gold-coated substrate will barely become warm, while obtaining an average temperature of 135°F (56.9°C) with the resist coating. Since both the tantalum-nitride- and gold-coated substrates can be considered opaque in the 0.8 to 7.4 μ m range (Appendix B), it can be assumed that the IR energy not absorbed to heat the substrate is reflected. Since the emissivity increased and the substrates become hotter with the photoresist coating present, then it can be stated that some of the IR energy is being absorbed directly by the photoresist. The remainder (that which was not initially reflected from the resist surface) is absorbed, reflected, or both at the substrate surface.

Ideally, what is desired is for the IR energy to be transmitted by the photoresist coating and to be absorbed by the substrate; thereby heating the substrate and baking the resist from the substrate-resist interface out toward the resist surface. This

allows for an orderly drying process where the resist solvents are uniformly driven from the resist without trapping the solvents by allowing the resist surface to become hot and non-fluid. To provide for such a baking mechanism the resist should be predominantly transparent to the IR irradiation.

The AZ1350J photoresist does not appear to be transmissive to IR. This conclusion is derived from two facts:

- Greater resist thicknesses demonstrate greater emissivities and hotter average substrate temperatures, and
- IR spectroscopy shows a broad band absorbency in the resist from 2.75 to 10 micrometers.

Figure 11 shows the change in surface emissivity as a function of AZ1350J photoresist thickness. Assuming the metallic surface emissivity is constant regardless of the resist thickness, then any change in the total emissivity must be the result of the increased resist thickness; that is, increase in the emissivity means a greater absorbency by the photoresist. Likewise, if certain functional groups of the photoresist's constituents are excited by the IR energy (Figure 12) (that is, absorbing the IR to cause vibratory motion and thus heat), then the greater the thickness the larger the number of functional groups and thus more energy can be absorbed; hence an increase in the absorbency or emissivity.

Model of Heating Mechanism

The previous information now allows a proposal for a heating mechanism model. Figure 13 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 0.05 μm of tantalum-nitride are opaque, no energy is transmitted through the substrate. All 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, it is reasonable to propose that photoresist heating as opposed to substrate heating is more predominant on gold- than tantalum-nitride-coated substrates. Even if this proposal is true, the desired result of evaporating the photoresist solvents is achieved and the heating mechanism appears to make no difference in the quality of the photoresist coating.

Figure 11. Emissivity Versus Resist Thickness

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 13) and higher temperature profiles and average temperatures are produced, thus altering the resists exposure characteristics.

Emitter-Substrate Separation

The heat transferred from the emitter of area (A_e) to the substrate of area A_s is³

$$Q (A_e - A_s) = \int_{A_e} \int_{A_s} \frac{\cos^2 \theta}{r^2} dA_s dA_e, \quad (3)$$

where

θ = the angle between the incident radiation and the normal to the surface, and

r = the distance between the radiating emitter point and the substrate.

Assuming diffuse radiation from each incremental area dA_e on the emitter, which is a point source as dA_e approaches zero, then

Figure 12. IR Spectrum of AZ1350 Photoresist

(A) = PARTIAL ENERGY ABSORPTION IN PHOTORESIST

(B) = TOTAL ABSORPTION OF ENERGY BY EITHER THE SUBSTRATE AND THIN-FILM OR BY THE PHOTORESIST ABSORBING THE ENERGY WHICH IS REFLECTED AT THE THIN-FILM SURFACE.

Figure 13. Heating Mechanism Model

θ becomes a variable of the distance (X) from the oven center as the substrate moves through the oven and r is a function of θ (Figure 14):

$$r = \frac{s}{\cos \theta}, \quad (4)$$

where

s is the perpendicular separation between the emitter and substrate.

Figure 14. Tantalum-Nitride Substrate Temperature Profile

Therefore, the fraction of the radiant energy which leaves dA_e and is interrupted by A_s is

$$Q (A_e - A_s) = \int_{A_e} \int_{A_s} \frac{\cos^2 \theta \cos^2 \theta}{s^2} dA_s dA_e. \quad (5)$$

The integration of Equation 5 becomes particularly difficult as θ is given by Equation 6. It is easy to observe, however, that the total energy transferred to the substrate is directly proportional to the summation of the IR acceptance angle (θ) and inversely proportional to distance between the emitter and substrate.

Figures 14 and 15 show the temperature profiles of gold and tantalum-nitride substrates for 2.25- and 4.50-inch (57.1 and 114.3 mm) separations between the emitter and substrate. The closer the emitter, the hotter the substrate, as predicted by Equation 5.

If the planar IR source is thought of as a continuum of point sources, each of which radiates energy diffusely then the substrate accepts IR energy over an angle θ (Figure 16) which is a function of the separation (S) and the distance from the substrate center (X). This relation for a 3.75- by 4.5-inch (95 by 114 mm) substrate is described by

Figure 15. Gold Substrate Temperature Profile

$$\theta = 90 + \tan^{-1} \frac{(2.25-X)}{S} - \tan^{-1} \frac{S}{(X+2.25)}, \quad (6)$$

where

S = separation and

X = distance from center of emitter.

Figure 17 is a plot of the IR acceptance angle as a function of distance for separations of 2 and 4 inches (50.4 and 100 mm). Although Figure 17 is only a two-dimensional representation of the angle θ , it is sufficient to demonstrate that a greater amount of radiant energy is intercepted by the substrate as the emitter is brought closer. Furthermore, the space available for the

Figure 16. IR Acceptance Angle as a Function of Distance

Figure 17. IR Acceptance Angle

substrate to radiate to a cooler outside environment (Figure 16) is smaller with decreasing separation. It is not proposed that the increase in the substrate temperature is solely due to radiation as convection becomes more significant as the separation decreases. (The oven manufacturer believes that 30 percent of the heat transferred is by convection.)

Regardless of the mechanism, the desired temperature profile can be obtained by adjusting the set-point emitter temperature, the substrate to emitter separation, or both.

Average Substrate Temperature and Substrate Size

Equation 5 predicts the heat transfer per unit substrate area will be equal to:

$$\frac{\Delta Q_{e-s}}{\Delta A_s} = \frac{1}{s^2} \int_{A_e} \cos^2 \theta / 2 \cos^2 (\theta) dA_e. \quad (7)$$

Therefore, with all other parameters considered to be constant, the energy per unit substrate area is constant for a constant θ , and it would be expected that the profiles on different size substrates would be the same. That is, in fact, not the case. Figure 18 shows the time-temperature product and the average substrate temperature at an oven temperature setting of 200°C for a 1.5- by 1.5-inch (38 by 38 mm) substrate as a function of the oven conveyor speed. Comparing the value at 1 ft/min (5 mm/s) to that of Figure 10, it can be seen that the small substrate attains a higher substrate temperature by about 15°C.

This difference in temperature is believed to be caused by the difference in the radiation from the back side of the substrate and also by conduction losses. Again the exact mechanism by which the substrates differ in temperature is not important to the purpose of this project. It is sufficient to know how much they differ and that the profiles for each size substrate is consistent thus affording homogeneous processing and process control of production parts.

Conveyor Speed

Figures 19 and 20 show the actual temperature profiles on gold and tantalum-nitride mirrors as a function of conveyor speed at a constant emitter temperature. The profiles shown are for 1.5- by 1.5-inch (38 by 38 mm) substrates and the profile dependence upon conveyor speed for 3.75- by 4.50-inch (95 by 114 mm) substrates is exactly the same. The curves show the temperature profiles, during the period the substrate is in the oven, to be identical and independent of conveyor speed for all speeds greater than 1 ft/min (5 mm/s). For conveyor speeds less than 1 ft/min, there is a measurable temperature lag on the substrate caused by the air screen at the entrance of the oven. This cooling effect holds the initial substrate temperature near room temperature for the time period the substrate is under the air screen.

The temperature lag lowers the profile by shifting the substrate temperature in time; although the total effect is not significant when computing the average substrate temperature. At conveyor speeds less than 1 ft/min, the lag time is quite small compared to the total prebake time.

Figure 18. Time-Temperature Product on Substrates (Top) and Average Temperature on Substrates (Bottom)

Figures 19 and 20 show that the average substrate temperature, as determined by the profile and the maximum temperature, is controlled by the conveyor speed for a constant emitter temperature. Since temperature profiles for each conveyor speed setting follow the same curve, the maximum temperature is fixed by the amount of time the substrate is subjected to the IR emitter. This time and the maximum temperature is an inverse function of the conveyor speed. By fitting an equation to the profiles shown in Figure 21, the average substrate temperature can be calculated by integrating the curve over the time period the substrates are in the oven. The results are shown in Figure 18 and Tables 3 and 4.

Figure 19. Temperature Profiles Versus Conveyor Speed for Gold-Coated Mirrors

Table 3. Prebake Conditions on a 1.5- by 1.5-Inch (38 by 38 mm)
Gold Mirror Versus Conveyor Speed

Conveyor Speed		Average Temperature Gradient (°C/min)	Maximum Temperature (°C)	Average Temperature (°C)	Prebake Time (s)
(ft/min)	(mm/s)				
6	31.0	20	46	36.4	37
5	25.0	20	51	37.6	43
4	20.0	20	54	39.8	55
3	15.0	20	57	43.0	72
2	10.0	20	68	49.4	68
1	5.0	20	92	66.1	137
0.5	2.5	18	116	89.4	273
0.25	1.0	11	135	111.9	547

Table 4. Prebake Conditions on a 1.5- by 1.5-Inch (38 by 38 mm)
Tantalum-Nitride Mirror Versus Conveyor Speed

Conveyor Speed		Average Temperature Gradient (°C/min)	Maximum Temperature (°C)	Average Temperature (°C)	Prebake Time (s)
(ft/min)	(mm/s)				
6	31.0	27	50	39.7	37
5	25.0	27	54	40.9	43
4	20.0	27	57	43.2	55
3	15.0	27	62	46.4	72
2	10.0	27	75	52.8	68
1	5.0	27	95	69.9	137
0.5	2.5	23	113	94.2	273
0.25	1.0	18	133	118.4	547

Figure 20. Temperature Profile Versus Conveyor Speed for Tantalum-Nitride-Coated Substrates

Between conveyor speeds of 1 and 6 ft/min (5 and 30 mm/s) there is a 54°F (30°C) change in the average substrate temperature. The largest part of the change in average substrate temperature occurs with changes in the lower speeds of 1 to 3 ft/min (5 to 15 mm/s). Conveyor speeds greater than 3 ft/min (15 mm/s) have diminished effects when attempting to vary the average substrate temperature, and, as stated previously, conveyor speeds less than 1 ft/min (5 mm/s) are not sufficiently stable for use. This leaves the range between 1 and 3 ft/min (5 to 15 mm/s) for control purposes. The range is near the knee of the curve (Figure 18) and affords about a 36 to 54°F (20 to 30°C) latitude in control, de-

pending upon the emitter temperature setting. However, being on the knee of the curve also means less process control through possible instabilities in the conveyor speed and inability to repeatably set the conveyor speed. Although the latitude in the average substrate temperature as a function of the conveyor speed is limited to a 20 to 30°C range, such a range is sufficient to cause significant deviations in the photoresist image dimensions. (See section on "Effect of Prebaking on Dimensional Control.")

IR Temperature Sensor

An IR temperature sensor and indicator was added to monitor the substrate temperature as it leaves the oven chamber (Figure 1).

Figure 21. Curve Fitted Temperature Profiles

The substrate temperature is actually measured at a point about 6 inches (152 mm) outside the oven chamber. Therefore it does not represent the maximum temperature attained by the substrate, but rather a substrate temperature measured during the cooling

period. With all other parameters held constant, the IR sensor will monitor the consistency on the prebake process. However, the IR sensor is subject to several process variations including conveyor speed, emissivity of the substrate surface, and ambient room conditions.

Measurement of substrate temperature is not influenced by substrate size, emitter temperature, or emitter-to-substrate separation. It is obvious that slower conveyor speeds will allow more time for the substrate cool down in the 6 inches (152 mm) of travel outside the oven chamber, and that changes in conveyor speed will influence the distribution in measured substrate temperatures. The same arguments apply to variation in substrate emissivity and ambient room conditions. The most obvious change in emissivity is between gold and tantalum-nitride mirrors; while photoresist thickness variations also affect the measured temperatures. Ambient room conditions, such as room temperature and air flow velocities, affect the cool down cycles and thus the temperature distribution.

Once a temperature distribution, as measured by the IR sensor under a relatively fixed set of conditions, is established, then the upper and lower limit switches on the temperature indicators can be set to alert the operator if abnormal substrate temperatures occur during the photoresist prebake cycle. Such a distribution is shown in Figure 22 for a tantalum-nitride mirror with suggested limit settings. The limit settings are determined by the prebake and exposure relation in consideration of the distribution deviation. It should be emphasized that the distribution is valid only for the set of conditions for which it was derived. For example, in room D of the Process Capability Line with an average room temperature of 22°C, air flowing vertically at 80 ft/min (406 mm/s), and a conveyor speed of 1 ft/min (5 mm/s), the emissivity setting of the sensor equals 0.9 and the emitter setting equals 200°C.

Process Control

The key to process control is the consistency to which a particular procedure can be maintained. This ultimately resolves to control of the parameters involved in the process and to some extent the parameters of procedures preceding and following the particular process in question. Control in such ganged operations is more difficult than in a single, stand-alone operation. Photoresist prebaking is one of four processing steps necessary to produce an image in photoresist and it is interdependent upon both prior and post-processing steps.

As described earlier, the emissivity of the resist surface changes as a function of resist thickness. The resist thickness is a variable of the roller coating operation and has been found to

Figure 22. Tantalum-Nitride Substrate Temperature Distribution on IR Sensor

vary by $\pm 0.5 \mu\text{m}$ on a single substrate. The resulting local variations in heat absorption are dissipated to surrounding areas through conductivity of the substrate and produce no local dimensional effect. Nevertheless, variation in substrate temperature can and do occur from substrate to substrate due to overall differences in resist thickness. Such changes in average substrate temperature and the resulting effect on dimensional quality are normally small compared to the direct effect of variations in resist thickness on line dimensions.

It has been determined that each oven parameter can be controlled to a degree suitable to maintain ± 2 to 3 percent* deviation on line widths as small as 5.0 mils ($127 \mu\text{m}$). The IR oven parameters and the control maintained on each are given in Table 5.

Table 5. Parametric Control on IR Oven

Parameter	Setting Resolution	Stability	Calibration	Monitoring Methods
Emitter Temperature	1°C	$\pm 5^\circ\text{C}$	$\pm 2^\circ\text{C}$	Chart recording of back-side emitter temperature
Conveyor Speed	0.1 ft/min (0.5 mm/s)	$\pm 0.05 \text{ ft/min}$ (0.25 mm/s)	None	Analog dial with selectable high/low limit sets

The effect of emitter temperature and conveyor speed on the average substrate temperature was discussed previously. With the very good stability on these parameters, the average substrate temperature and thus the dimensional stability of the photoresist image should be quite good. However, the average substrate temperature does exhibit a variation which is due to changes in the substrates apparent emissivity. Such changes in emissivity are partly caused by variations in the resist thickness; but in the case of gold thin-film surfaces, such variations are caused by permutations in the actual gold surface. Wide variations in the surface character of the gold thin-film have been experienced. This is indicated by the larger standard deviation on the average maximum temperature of gold versus tantalum-nitride shown in Table 1. The photolithography processes have neither control

*IR oven baking is believed to contribute less than 1 percent of this 2 to 3 percent range.

over the gold surface emissivity, nor is it possible to predict and compensate for emissivity variations. As long as there are variations in the emissivity of the gold surfaces, there will be variations in the average substrate temperature and a subsequent deviation in the gold conductor line width on the HMCs.

Process control of IR prebaking of photoresists is the maintenance of a stable, average substrate temperature through control of critical parameters. All oven parameters are controlled sufficiently well to maintain ± 2 to 3 percent dimensional control on a 5-mil (127 μm) photoresist image. The variation between 2 and 3 percent* is partly due to the variation in gold surface emissivities.

Effect of Prebaking on Dimensional Control

Figures 23 and 24 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 follow.

- For gold, $\Delta\text{LW} = 0.65\Delta\text{T}$, 200 to 300°C range at exposure setting equal to 14, and
- For tantalum-nitride, $\Delta\text{LW} = 0.30\Delta\text{T}$, 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 as in Figures 25 and 26, it is possible to determine the control necessary on the emitter temperature setting (or the average substrate temperature) to maintain the desired tolerance. The process limit on prebake temperatures, for a constant exposure energy setting, is the intersection of the tolerance limitation

*IR oven baking is believed to contribute less than 1 percent of this 2 to 3 percent range.

Figure 23. Prebake-Line Width Relation for Gold-Coated Substrates

Figure 24. Prebake-Line Width Relation for Tantalum-Nitride-Coated Substrates

Figure 25. Tolerance Limits on Line Widths for Gold-Coated Substrates

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 6.

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 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.

Figure 26. Tolerance Limits on Line Widths for Tantalum-Nitride-Coated Substrates

Table 6. Process Limits on Prebake Oven Temperatures

Type of Substrate	Emitter Settings	Average Substrate Temperature
Au	170 to 200°C	53.5 to 65°C
Ta ₂ N	165 to 215°C	60 to 91°C

Applying the same analysis to the dependence of line width of exposure energy, a prebake and exposure schedule can be established. Such a schedule is shown in Figure 27 for thin-film gold substrates.

Figure 27. Prebake and Exposure Schedule for Gold Mirrors

Results and Conclusions

- The Zicon IR oven is an excellent system in design and construction. No down time has been experienced in over one year of operation.
- The Zicon IR oven is extremely well suited for pre-exposure drying of AZ1350 photoresist with a consistency adequate to produce hybrid microcircuits with a ± 2 to percent tolerance on a 5.0-mil (127 μm) photoresist line.
- Temperature profile gradients are independent of conveyor speed.
- Temperature profile gradients are directly proportional to emitter temperature, emitter-substrate separation, and substrate-thin-film-photoresist emissivity.
- Average substrate temperature is principally governed by the conveyor speed.
- Usable conveyor speed range is between 1 and 3 ft/min (5 to 15 mm/s).
- Variations in the average substrate temperature on photoresist coated, gold mirror substrates is due to variations in the emissivity of the gold thin-film.

- Emissivity of the photoresist surface increases with increasing resist thickness.
- For a constant emitter temperature, the maximum substrate temperature is fixed by the conveyor speed; that is, prebake time.

ACCOMPLISHMENTS

All work on the IR oven, as originally outlined,⁵ has been accomplished. Verification of the ability of the oven to prebake photoresist for HMC processing has been made. Processing technology for IR prebaking has been transferred to Process Engineering and the IR technique is successfully being employed in production.

Processing schedules have been developed to control the variation of a minimum 5.0-mil (127 μ m) line width to ± 2 to 3 percent, of which the IR oven contributes less than 1 percent.

FUTURE WORK

There is no future work predicted on IR baking of photoresist under the present product and processing requirements. As new product requirements, process requirements, or both are imposed, it may become necessary to perform a re-evaluation of IR prebaking. Such a change in requirements might include

- Smaller HMC geometries (less than 5.0 mils (127 μ m),
- 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.

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

REFERENCES

¹L. E. Schantz, *Hybrid Microcircuit Photolithographic Process* (Topical Report). UNCLASSIFIED. Bendix Kansas City: BDX-613-678, July, 1973.

²Francis W. Sears and Mark W. Zemansky, *University Physics Part 1*. Reading, MA: Addison-Wesley, 1963.

³Alan J. Chapman, *Heat Transfer*. 3rd edition. New York: Macmillan, 1967.

⁴L. E. Schantz, *Automatic Photoresist Alignment and Exposure on 3.75 by 4.5 Inch Substrates* (Topical Report). UNCLASSIFIED. Bendix Kansas City: BDX-613-1101, August, 1974.

⁵PDO 6984726 PERT Chart Schedule, data July 17, 1972.

Appendix A

ZICON TEMPERATURE PROFILES
AND AIR FLOW DIAGRAM

ZICON CORPORATION

BENDIX, KANSAS CITY

NOTES FOR AIR FLOW SCHEMATIC

Parts

1. Cover Plate
2. Side of Oven
3. Inner oven wall providing 1/2 inch slot between this wall and outside wall of oven
4. Chain conveyor
5. Perforated exhaust slot, 1/2 inch width
6. Exhaust plenum base, 2 inches deep
7. IR panel, not shown to simplify schematic.

Air Movement

Class 100 air from upper plenum at rate of 360 ft/min comes from slot (A) and is divided between exerting an outward pressure (C) and being carried into exhaust (D). Stream (C) is flowing at 100 ft/min linear minimum.

External air (B) trying to enter the oven will be pulled down by the exhaust slot, joining stream (D). Exhaust velocity at this slot is 200 ft/min linear.

Figure A-1. Air Movement at Oven Ports

ZICON CORPORATION

BENDIX, KANSAS CITY

DISCUSSION OF SOLVENT EVAPORATION INTO AMBIENT AIR IN USING THE IR OVEN

Consideration of the safety of the IR Oven raises the question of solvent evaporation into the air surrounding the unit. There are three basic positions of the substrates as they move along the conveyor entering the oven (see detail):

Position A - Prior to any part of the substrate being within the oven.

Position B - The substrate partially in and out of the oven.

Position C - The substrate fully in the oven.

Solvent given off to the atmosphere:

At Position A, evaporation rate would be related to the vapor pressure at ambient temperature, (about 2 mm) and the affected area, (S) of the substrate.

At Position B, the evaporation rate would be increased by the vapor pressure going up to correspond to the substrate temperature (maximum 48°C in Position B) to about 50 mm as the affected area goes down to zero. This dynamic situation is hard to evaluate, but a typical point, with half the substrate in, can be calculated to produce less than double the solvent vapor of the room temperature A Position.

Once Position C is attained no further solvent vapor is produced in the ambient air.

An adequate measure of vapor concentration can only be obtained through use of the proper gas detector for esters using an aspirator like the Mine Safety Appliance types.

Figure A-2. Substrate Positions and Solvent Removal

ZICON CORPORATION

BENDIX, KANSAS CITY

TEMPERATURE OF AIR IN OVEN EXHAUST AT EXIT PORT

At 4-1/2 panel height

<u>Oven Setting</u>	<u>Temp °C</u>
100°C	31
200°C	41
300°C	54

Solvent content of air leaving oven at 2u application

Full capacity

Top speed

.007 cc/min vapor

or $.26 \times 10^{-6}$ cfm vapor

air is 25-35 cfm so ratio is .01 ppm solvent by volume.

Appendix B

WILLIAMSON EMISSIVITY MEASUREMENTS

TELEX:92-3343

WILLIAMSON CORPORATION
PROCESS TEMPERATURE MEASUREMENT AND CONTROL SYSTEMS
1152 MAIN STREET, CONCORD, MASSACHUSETTS 01742
TEL:(617)369-9607; 259-9307

March 2, 1973

Mr. Lee Schantz
Bendix Corporation
Box 1159
Department 842N, XAG44
Kansas City, Missouri 64141

Dear Mr. Schantz:

I have enclosed the infra-red spectrums of the ceramic substrates, both coated and uncoated. As you can see, the uncoated ceramic (Spectrum #34B) begins transmitting energy at approximately 4.2 microns. When coated with gold or tantalum the material can be considered opaque.

The following chart shows the effect of emissivity due to the gold and tantalum coatings.

	<u>White Ceramic Substrate</u>	<u>Gold Coated Ceramic Substrate</u>	<u>Tantalum Coated Ceramic Substrate</u>
Portion Sprayed Black	(E=1)	(E=1)	(E=1)
Portion as received with photoresist	(E=.4)	(E=.45)	(E=.8)
Portion with photoresist removed with acetone	(E=.4)	E=.2)	(E=.6)

You did mention that in the actual application the instrument would be looking at the coated substrate with the photoresist removed in a grid pattern. This will have an effect on the instrument, as the above chart indicates, but the effect should not be very much. The indicated temperature will move to a lower indication when the target located within the field of view of the instrument moves from the photoresist coated surface to the cleaned coated surface. The amount of this change will depend a great deal on the size of the grid pattern. My feeling is that the amount of change in indicator temperature will be very small and could easily be averaged out.

If you have any additional questions, please feel free to contact me.

Very truly yours,

WILLIAMSON CORPORATION

/s/t/John J. Cardarelli

JJC/dlb

Figure B-1. IR Transmission for Uncoated Ceramic Substrates (0.9 to 2.5 micrometers)

Figure B-2. IR Transmission for Uncoated Ceramic Substrates (2.5 to 7.5 micrometers)

Figure B-3. IR Transmission for Gold- or Tantalum-Nitride-Coated Substrates (2.5 to 7.5 micrometers)

Appendix C

PURCHASE SPECIFICATION

SPECIFICATION
INFRARED DRYING SYSTEM

P. O. E-136893

1. REQUIREMENTS

1.1 General

- 1.1.1 The system specified herein will be used solely for baking commercially available photoresists on ceramic and glass substrates.
- 1.1.2 Processing Capacity. The drying system shall be capable of handling 400 substrates (up to 5" x 5" x 1/4") per each seven (7) hour period.
- 1.1.3 Operating Voltage. The system shall be wired for 208-240 volts AC, single phase, 60 Hz operation. The total power requirements shall be less than 4,000 watts. Only one power source will be furnished by Buyer where all other required voltages and frequencies shall be an integral part of the furnished system.
- 1.1.4 Safety High Voltage. Equipment requiring high voltages (in excess of 400 volts AC or DC) must be identified and protected with separate enclosures and with interlocks to cut-off power when the cover is opened.
- 1.1.5 Electrical Power Entrance. All power to the system shall enter at one point through a general duty safety switch or lockable plastic-case circuit breaker. Proper sized circuit breakers or fuses shall be used to protect components, subdistribution, and control circuits.

1.2 Basic Components

- 1.2.1 The system shall consist of the following five basic components:
- A. Conveyor feed-through system
 - B. Infrared planar source
 - C. Air flow system for solvent removal
 - D. Controls and indicators
 - E. Cabinetry

1.3 Conveyor Feed-Through System

- 1.3.1 Conveyor Belt. The stainless steel conveyor belt shall be continuous and shall be flat and level within the drying chamber and within the distance described per 1.3.2 and 1.3.3.
- 1.3.2 Conveyor Length-Entrance. At the entrance to the drying chamber the conveyor shall extend a minimum distance of ten (10) inches and shall not extend over fourteen (14) inches.
- 1.3.3 Conveyor Length-Exit. The length of the conveyor beyond the drying chamber exit shall be sufficient to allow the substrates (normally Al_2O_3) to cool to room temperature when the conveyor is running at maximum speed. In any case, the exit length shall not be less than 18 inches or greater than 24 inches..
- 1.3.4 Conveyor Speed Range. The conveyor speed shall be continuously adjustable from zero (0) feet per minute to five (5) feet per minute.

1.3.5 Belt Material. The belt material shall be compatible with solvents such as acetone, xylene, keytone, Freon, trichloroethylene, and ethylene glycol monomethyl ether acetate.

1.3.6 Work Area. The pass through openings shall be 18" wide minimum; belt width shall be 16".

1.4 Infrared Planar Source

1.4.1 Temperature Range. The planar IR source shall have a continuously adjustable temperature range from 50°C to 300°C.

1.4.2 Temperature Stability. The source shall be stable within $\pm 0.2^{\circ}\text{C}$ of any selected temperature setting and at maximum conveyor and air flow velocities. The same stability requirements apply to the work area described in 1.3.6.

1.4.3 Temperature Uniformity. The temperature uniformity of the source shall be less than $\pm 3.0^{\circ}\text{C}$ of any set point temperature. The corresponding work area (1.3.6) shall have a temperature uniformity of $\pm 3^{\circ}\text{C}$.

1.4.4 Warm-Up Time. The warm-up time to any set point temperature shall be less than 20 minutes. The requirements of 1.4.2 and 1.4.3 shall be met within the warm-up time.

1.4.5 Chamber Weight. The planar source height shall be adjustable above the conveyor belt from 2 1/4" to 4 1/2" inches.

1.5 Airflow System. Air of the following requirements shall be forced between the planar IR source and the conveyor belt.

1.5.1 Air Entrance-Exits. The air shall enter below the control chassis at the front of the unit and exit equally at the entrance and exit pass-throughs.

1.5.2 Air Class. The air shall be class 100 or better.

1.5.3 Air Volume. The air volume shall not be less than 65 cfm or greater than 100 cfm.

1.6 Controls and Indicators

1.6.1 Master On-Off. A single on-off control and indicator light shall be provided. This control shall supply power to all subsystems.

1.6.2 Temperature Control. Digital indicator and continuous set-point temperature controls shall be provided. A percent utilization meter for equilibrium status shall be provided. Accuracy and repeatability shall be within 2%.

1.6.3 Pyrometer. A pyrometer shall measure the center point of the IR source and shall be connected to an analog panel meter and the strip chart recorder of 1.6.4. The accuracy shall be $\pm 2\%$.

1.6.4 Chart Recorder. A strip chart recorder shall be connected via a manual engaging switch to the pyrometer of 1.6.5. The recorder shall be calibrated in degrees centigrade and have speeds of 0.7 and 4.7 inches per hour.

1.6.5 Conveyor Speed Controller and Indicator. An analog controller shall be provided to continuously vary the conveyor belt speed from zero (0) to five (5) feet per minute. An analog or digital indicator shall be provided to denote the conveyor speed in feet per minute. The controller and indicator shall be repeatable and accurate to within 2%.

1.6.6 Low Air Flow. An indicator - audio and visual - shall be provided to show a 50% decrease in air flow. The unit shall shut down within five minutes if manual assistance is not given.

1.6.7 Overheat. A flashing, visual indicator shall come on when the oven temperature exceeds $\pm 50^{\circ}\text{C}$ of the set point temperature. An additional audio alarm shall sound when the oven overheats dangerously and shall shut down the unit within three minutes if no operator assistance is given.

1.6.8 Conveyor Speed Alarm. An alarm - audio and visual - shall engage when the conveyor speed has deviated by $\pm 3\%$ from full scale on the indicating meter. Full scale will be five (5) feet per minute.

1.7 Cabinetry

1.7.1 Standing. The unit shall be self-standing and/or bench mounting.

1.7.2 Size. The unit shall not exceed: height 73", width 66", and depth 32".

1.7.3 Materials. All exposed construction material shall maintain class 100 air and shall be compatible with the solvents of 1.3.5.

1.8 Quality Verification

1.8.1 Work Area Thermal Map. The Seller shall thermally map the work area. A standard isotherm chart will be acceptable.

1.8.2 Thermal Profile. The Seller shall profile the work area at the middle temperature setting and at the lowest, middle, and fastest conveyor speeds. Three temperature indicators shall be used on each profile and shall be located at the edges and middle of the conveyor belt.

Appendix D

POLYNOMIAL FIT OF TEMPERATURE PROFILES

AU 3.75 X 4.5
150 C, 1FT/MIN

AU, 3.75 X 4.5
200 C, 1FT/MIN

AU, 3.75 X 4.5
250 C, 1 FT/MIN

DEGREE

3.00

X
Y

0.00
88.00

.33
106.00

.67
120.00

1.00
131.00

1.33
140.00

1.67
147.00

2.00
151.00

COEFFICIENTS

0.00
87.69

1.00
59.45

2.00
-17.48

3.00
1.79

DEGREE

3.00

X
Y

0.00
88.00

.33
120.00

.67
142.00

1.00
159.00

1.33
171.00

1.67
182.00

2.00
188.00

COEFFICIENTS

0.00
87.29

1.00
108.62

2.00
-44.61

3.00
7.79

DEGREE

3.00

X
Y

0.00
88.00

.33
130.00

.67
161.00

1.00
186.00

1.33
204.00

1.67
221.00

2.00
232.00

COEFFICIENTS

0.00
87.06

1.00
142.25

2.00
-52.67

3.00
8.95

TA, 3.75 X 4.5
150 C, 1 FT/MIN

TA, 3.75 X 4.5
250 C, 1 FT/MIN

TA, 3.75 X 4.5
200 C, 1 FT/MIN

DEGREE

3.00

X
Y

0.00
88.00

.33
96.00

.67
110.00

1.00
121.00

1.33
131.00

1.67
140.00

2.00
146.00

COEFFICIENTS

0.00
87.46

1.00
30.67

2.00
6.06

3.00
-3.41

DEGREE

3.00

X
Y

0.00
88.00

.33
122.00

.67
165.00

1.00
202.00

1.33
231.00

1.67
251.00

2.00
263.00

COEFFICIENTS

0.00
87.23

1.00
110.92

2.00
16.53

3.00
-14.23

DEGREE

3.00

X
Y

0.00
88.00

.33
108.00

.67
133.00

1.00
155.00

1.33
173.00

1.67
190.00

2.00
199.00

COEFFICIENTS

0.00
87.53

1.00
65.69

2.00
6.86

3.00
-5.95

HD - HIRBLA
3.75 X 4.5 SUB.
1'/MIN

OVEN SETTING =
150.00
TIME*TEMP =
270.27
1.00
AVE. TEMP =
124.74

OVEN SETTING =
200.00
TIME*TEMP =
292.84
1.00
AVE. TEMP =
135.16

OVEN SETTING =
250.00
TIME*TEMP =
343.95
1.00
AVE. TEMP =
158.75

OVEN SETTING =
300.00
TIME*TEMP =
418.27
1.00
AVE. TEMP =
193.05

IR - MIRROR
3.75 X 4.5 SUB.
1'/MIN

OVEN SETTING =
150.00
TIME*TEMP =
282.03
1.00
AVE. TEMP =
130.17

OVEN SETTING =
200.00
TIME*TEMP =
367.10
1.00
AVE. TEMP =
169.43

OVEN SETTING =
250.00
TIME*TEMP =
505.40
1.00
AVE. TEMP =
233.26

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