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DEVELOPMENT AND CHARACTERIZATION OF
A WAFER LEVEL UNDERFILL APPLICATION PROCESS

A Thesis
Presented to
The Faculty of the Department of Materials Engineering
San Jose State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

By
Chris Quentin
December, 2000

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ABSTRACT

DEVELOPMENT AND CHARACTERIZATION OF A WAFER LEVEL UNDERFILL APPLICATION PROCESS

By Christopher G. Quentin

Use of flip chip electronic packages is increasing because they offer better electrical performance than standard wire bonded packages. Currently, their use is limited mainly to expensive products such as microprocessors because of their high cost. One reason for the high cost is the die-level application of underfill adhesive.

A process for screen printing underfill directly onto a wafer before dicing was investigated. After a preliminary study of nine potential underfill materials, one was selected for detailed investigation of the printing process. Process parameters studied included screen thickness, snap-off height, and squeegee speed. The response parameters were film thickness and average surface roughness. The film thickness was found to be directly proportional to the screen thickness. It was also observed that the underfill materials tended to shear from the screen rather than flow from the screen as suggested by earlier theoretical studies.

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CHAPTER 1

INTRODUCTION

The most common type of integrated circuit package used in the microelectronics industry is the plastic leaded package. It consists of a silicon die mechanically bonded to a copper leadframe with an adhesive and electrically connected to the same leadframe by a series of small, 1~3 mil diameter, gold wires, as shown in Figure 1. The entire assembly is encapsulated in a silica-filled epoxy resin, except for the ends of the leadfingers, which are left exposed to form the electrical and mechanical connections to external circuits.

During the last several decades, these packages have undergone extensive development and have incorporated numerous technological advancements, such as fine pitch wirebonding. Despite these improvements, plastic leaded packages still have limitations. The foremost limitations are the die size and interconnect restrictions imposed by the wirebonding process. To eliminate interaction between interconnect wires during the encapsulation process, the length of the wires is minimized. This necessitates placement of the (wire) bonding pads at the perimeter of the die. This placement, in combination with bond pad size requirements, determines the minimum die size for a given number of interconnects.

New package types, such as the “flip chip”, have been developed to eliminate many of the problems associated with wirebonded packages. The chief advantage of “flip chip” packages over wirebonded packages is the direct attachment of the chip to the substrate,

where both the mechanical and electrical connections are formed using solder instead of wire interconnects and adhesive, as shown in Figure 2 and Figure 3.

Figure 1: Perspective view of standard wirebonded package.

Instead of bonding the die to a substrate and forming the interconnects in separate steps, the mechanical and electrical connections are created simultaneously. Solder is deposited directly onto the die's bonding pads and melted to form an array of "solder balls". The die is then "flipped", hence the name, and aligned with the substrate. When the solder balls are properly aligned with the substrate's bond pads, the entire package is heated above the solder's melting point to form both connections.

Figure 2: Cross-sectional view of flip chip showing interconnections.

Figure 3: Perspective view of flip chip package.

This type of interconnection provides several benefits, including higher interconnect density, smaller die, and faster circuit speeds. In standard leaded packages the circuit terminations, or pads, are arranged around the perimeter of the die to provide the shortest possible wire interconnects. Because of electrical and physical requirements, there is a minimum spacing between the pads that limits the minimum size of the die for a given number of I/Os. The flip chip design allows the pads to be arranged in an array rather than a perimeter configuration. This allows a larger number of connections for a given size die, as shown in Figure 4, or allows the same number of connections on a smaller die, as shown in Figure 5.

The flip chip design also results in shorter electrical connections between the circuits and the pads, as shown in Figure 6, resulting in circuits with faster clock speeds requiring less power than their leaded counterparts.

Figure 4: Comparison of I/O densities in flip chip and standard leaded packages with identical size die. Schematics are not to scale.

Figure 5: Comparison of die sizes in flip chip and standard leaded packages with identical numbers of I/O interconnects. Schematics are not to scale.

Figure 6: Comparison of electrical trace length on die with (a) bond pad arrays and (b) perimeter arrays. Schematics are not to scale.

Despite these improvements over previous package designs, the flip chip design still faces challenges. Its primary challenge originates in the difference between the coefficients of thermal expansion (CTE) of the silicon die and substrate. CTE values of common packaging materials, including silicon and two common types of substrates, are listed Table 1. Since these devices operate over a range of temperatures, the amount that the die and the substrate expand is not static. The expansion mismatch creates a variable shear force, which manifests itself as shear strain in the solder joints, as shown in Figure 7. Without reinforcement of the package, this cyclical shear force creates permanent and irreversible strains in the joints, and can lead to their premature failure.

Table 1: *Coefficients of thermal expansion for typical flip chip material.[1]*

Material	Coefficient of Thermal Expansion (K^{-1})	Temperature (K)
Silicon <100>	2.6×10^{-6}	293
Al ₂ O ₃ -based substrate	6×10^{-6} to 11×10^{-6}	298
PCB substrate	13×10^{-6} to 17×10^{-6}	298
Eutectic solder (37Pb-63Sn)	24.07×10^{-6}	298
Dexter FP4527 underfill	22×10^{-6}	273
Dexter FP4511 underfill	26×10^{-6}	313

The problem has been greatly reduced through the incorporation of high strength adhesives, known as underfills, between the die and the substrate, as shown in Figure 8. The underfill adhesive increases the bond area and absorbs a major portion of the thermally-induced shear forces. These underfill materials are comprised mainly of silica-filled epoxy resins, but also include other proprietary components such as surfactants and adhesion promoters, which enhance their process capabilities and reliability.

Figure 7: Schematic of thermally-induced shear strains in flip chip solder joints.

Figure 8: Cross-section of flip chip package showing underfill adhesive.

The underfill is dispensed directly onto each package where capillary action causes it to flow under the die. Once the gap between the die and the substrate has been completely filled, the package is placed in an oven, and the underfill is cured.

The underfill must meet many criteria. In its cured state, its elastic modulus must be large enough to withstand the shear forces generated by the thermal mismatch, but not so large that it transmits all of the shear forces from the substrate to the die. It must also adhere well to the die, the substrate, and the solder joints. In its uncured state, it must flow quickly and evenly under the die. Often, the chemical formulations which produce

the optimum mechanical properties degrade the flow characteristics. The final adhesive formulations represent a balance of the required mechanical properties and flow characteristics.

Although the use of underfill solves the CTE mismatch problem, it also creates additional manufacturing costs. Since the liquid underfill is dispensed onto each package individually, its application is costly and time-consuming. This “die level” process takes between 30 seconds and 2 minutes per die. When multiplied by the number of die on a single wafer, the cost escalates rapidly. The 15~30 minute batch cure of the underfill adds further time and expense.

Total process costs include not only time and materials, but also equipment costs. The standard underfill process requires costly dispensing equipment that is not present in many packaging lines, and is typically purchased at added expense.

One method to reduce costs is to replace the current die-level underfill process with a wafer-level process, in which the underfill is applied to an entire wafer in a single operation. Such a process will greatly reduce process times and costs by replacing multiple dispensing operations with a single underfill application, while simultaneously eliminating the need for costly dispensing equipment.

The proposed method of adhesive application for the wafer-level process is screen printing. Its use has been common in the electronics industry since World War II, when it was used to mass produce printed circuits.[4] Since then, it has been used for the application of dielectric materials, die attach adhesives, and conductive inks, among other materials. The related field of stencil printing is also a common method of applying the

solder paste used to form the flip chip's solder joints. It uses the same equipment as screen printing, but stencils are fabricated from sheet metal instead of the wire mesh used for screens.

Screen printing, is a relatively simple process, as illustrated in Figure 9. A patterned screen is placed at a specified height above the substrate - in this case a wafer. The material to be printed is deposited ahead of a squeegee, and a downward force is applied to the squeegee. The squeegee is then moved forward across the screen and forces material through the screen onto the substrate. As the squeegee passes, tension on the screen lifts it clear of the substrate behind the squeegee, leaving the patterned material.

Three of the reasons that screen printing was selected for the development of a wafer-level underfill process are industry familiarity, availability of the equipment, and simplicity of the process.

The remainder of the wafer-level underfill process will consist of soft curing of the underfill, dicing of the wafer, assembly of the package, and reflow of the solder. The underfill is gelled, or "soft-cured", to help it retain its shape. Once the underfill is gelled, the wafer is sawn into individual dice and assembled onto substrates. The assembled packages are then placed into an oven for simultaneous solder reflow and final adhesive cure. Depictions of the current and proposed process flows are shown in Figure 10.

Figure 9: Schematic of the screen printing process.

Proposed Process Flow (Wafer-level)

Current Process Flow (Die-Level)

Figure 10: Comparison of the current and proposed underfill processes.

CHAPTER 2

LITERATURE REVIEW

Screen printing has been the focus of many empirical studies, including those by Kobs et.al., and Haselhurst et.al [2,3], which focused on specific problems using specific materials and equipment, rather than screen printing in general. Theoretical analysis of the screen printing process has received far less attention than the empirical aspects of screen printing. A review of the current literature revealed only two theoretical treatments of screen printing, by Riemer and Huner.[4,5] Each of these treatments divided screen printing into two distinct processes, screen filling and material deposition. Both authors analyzed the screen filling process, but only Riemer analyzed the deposition process.

2.1. Riemer's analysis of screen filling and material deposition

Riemer began his analysis with the application of the Navier-Stokes equation to the flow of material between the screen and the squeegee. Realizing that an analytical solution of this equation was impossible without simplification, he assumed creeping flow¹ in a two-dimensional system. This allowed use of the Stokes simplification as shown in Equation (1).[4]

$$\partial p / \partial r = \eta(1/r^2) \partial^2 v_r / \partial r^2 + (1/r) \partial v_r / \partial r + \partial^2 v_r / \partial r^2 - (1/r^2) v_r - (2/r^2) \partial v_\phi / \partial \phi \quad (1)$$

where,

p = pressure in the fluid

¹ Creeping flow is defined as flow with a Reynolds number of less than 1.0.

r = radial distance from squeegee speed

η = material viscosity

$\phi = \alpha$ = squeegee angle

v_r = squeegee speed

Riemer noted that this equation had already been solved by Taylor for boundary conditions similar to those in screen printing[4], and extended this solution to include relations for both the pressure and the stream function. Assuming constant and infinite material volume under the squeegee and infinite screen length, Riemer generated numerical solutions for the stream function, shown in Figures 11 through 13, and pressure, as shown in Equations (2) and (3).

Figure 11 through Figure 13 depict the stream functions for squeegee angles of 30, 45, and 60 degrees, respectively. They were modified by Riemer to reflect a finite volume of material. Since the volume of fluid between adjacent streamlines is equal, closely spaced lines indicate high velocities, and widely spaced lines indicate low velocities. The velocity values can be converted to pressure using the Stokes equation, "... which relates viscous movement to pressure," and, "...states that the ink pressure is the highest where the ink velocity is reduced to a minimum." [4]

Riemer indicated a locus of maximum pressure on each plot, which occurred at one-third of the squeegee angle, α . This indicated that the pressure near the screen will increase with reductions in squeegee angle. Riemer inferred that higher pressure at the screen would enhance the flow into the screen, since the squeegee acts as a hydraulic pump.

Figure 11: Streamlines for screen printing solution at a 30 degree squeegee angle. (Reprinted with permission from "The Theoretical Fundamentals of Screen Printing Process," by D.E. Riemer. Originally published in the IMAPS periodical, Hybrid Circuits No. 18, 1989)

Figure 12: Streamlines for screen printing solution at a 45 degree squeegee angle. (Reprinted with permission from "The Theoretical Fundamentals of Screen Printing Process," by D.E. Riemer. Originally published in the IMAPS periodical, Hybrid Circuits No. 18, 1989)

Figure 13: Streamline solution for screen printing at a 60 degree squeegee angle. (Reprinted with permission from "The Theoretical Fundamentals of Screen Printing Process," by D.E. Riemer. Originally published in the IMAPS periodical, Hybrid Circuits No. 18, 1989)

He reasoned that high pressures are generated by the squeegee, and converted to shear stresses through the viscous properties of the material. These stresses cause the material to flow to lower pressure regions, i.e. openings in the screen. His solutions for pressure in the material are shown in Equations (2) and (3).

$$p_{\text{squeegee}} = 2\alpha \sin \alpha / (\alpha^2 - \sin^2 \alpha) \eta V (1/r) \quad (2)$$

$$p_{\text{screen}} = 2\alpha^2 \sin \alpha / (\alpha^2 - \sin^2 \alpha) \eta V (1/r) \quad (3)$$

where,

p_{squeegee} = material pressure at squeegee surface [Pa]

p_{screen} = material pressure at screen surface [Pa]

α = squeegee angle [radians]

η = material viscosity [Pa-s]

V = squeegee speed [cm/s]

r = radial distance from squeegee tip [cm].

The equation describing the material pressure at the screen is of primary importance, because it describes the system at the entrance to the screen apertures. Riemer assumed that flow through these apertures is pressure driven and is, therefore, proportional to the pressure at the screen, as described by Equation (3). By inference, the flow rate is also directly proportional to the squeegee speed, V , and inversely proportional to the distance from the squeegee tip, r , as shown in Figure 14. The relationship between the flow rate and squeegee angle, however, is more complex. The flow rate is directly proportional to the pressure of the underfill at the screen, and will exhibit the same response to squeegee angle as the pressure exhibits. The response of pressure to squeegee angle is shown in Figure 15.

Since the material viscosity during each print operation is constant, this theory predicts that the amount of material injected into the screen will be linearly dependent on the magnitude of the squeegee velocity and dependent on the complex function of squeegee angle, as shown in Equation (4).

$$\text{flow rate} \propto 2\alpha^2 \sin \alpha / (\alpha^2 - \sin^2 \alpha) \quad (4)$$

Equations (2) and (3) provide a general description of the material's behavior under the squeegee, but have inherent problems. They predict an infinite pressure at the tip of the squeegee, an obvious impossibility. Riemer stated that this problem arises from the laminar (creeping) flow assumption, which breaks down near the squeegee tip. Citing several references, he concluded that flow through a sharp angle, such as the angle at the intersection of the squeegee and screen, must be turbulent.

Figure 14: Pressure in printed material at surface of screen as a function of distance from squeegee tip. Viscosity of material is 1 Pa-s and squeegee angle is 50 degrees.

Figure 15: Pressure in printed material at surface of screen as a function of squeegee angle. Distance from squeegee tip is 0.1 cm and viscosity of material is 1 Pa-s.

He also derived Equation (5) to show that an increase in pressure increases the lifting force on the squeegee.

$$F_{\text{lift}} = 2\alpha \sin\alpha / (\alpha^2 - \sin^2\alpha) \eta V f(\text{ink qty.}) \quad (5)$$

The lifting force on the squeegee can be either a benefit or a problem. If the force causes the squeegee to hydroplane, it can create a coating thicker than the screen, but if the force is too large, the squeegee will pass over the material without the material filling the screen. According to Figure 16, coating thickness will increase (as a function of deposition weight) when the squeegee speed is increased.

Figure 16: Deposition thickness as a function of squeegee speed obtained by printing two viscosities of Dupont 4575 ink. (Reprinted with permission from "The Theoretical Fundamentals of Screen Printing Process," by D.E. Riemer. Originally published in the IMAPS periodical, Hybrid Circuits No. 18, 1989)

Though his initial derivations appear to recommend adjusting the process to maximize material pressure, Riemer cautioned that there are limitations. At some critical

pressure value, the associated shear stresses will exceed the shear strength of the material. At this point, cohesive failure between “layers of fluid” prevents transmission of the stresses between layers. The result is a sudden decrease in apparent viscosity, and failure of the creeping flow model. This type of behavior is displayed in Figure 17. The open circles represent the viscosity of a pseudoplastic suspension with a solids content of 76% by volume. At its critical shear rate, of approximately 60 sec^{-1} , the material exhibited a discontinuity in the viscosity gradient. After the addition of thinner reduced the viscosity and volumetric filler concentration to 74.5%, the discontinuity disappeared. The viscosity gradient remained continuous for the thinned material, up to shear rates from of 600 sec^{-1} .

Figure 17: Viscosity reduction associated with excessive shear. (Reprinted with permission from “The Theoretical Fundamentals of Screen Printing Process,” by D.E. Riemer. Originally published in the IMAPS periodical, Hybrid Circuits No. 18, 1989)

2.2. Huner's Analysis of Screen Filling

Another treatment of the screen filling process was proposed by Huner.[5] He characterized the process as the movement of a slider bearing over a porous walled stator, and chose to evaluate the process in terms of the flow rate of material past the tip of the squeegee. He theorized that this flow rate determined the final coating thickness, and that it was comprised of two components, as shown in Equation (6): the flow rate of material downward into the screen and the flow rate of material in the plane of the screen.

$$Q = Q_o + AHU \quad (6)$$

where,

Q = flow rate of material by the squeegee per unit width of screen

Q_o = flow rate of material in the plane of the screen per unit width

AHU = flow of material downward into the screen per unit width

A = porosity of the screen

H = height of the screen

U = squeegee velocity

This equation needed further derivation to quantify Q_o in terms of process variables. By combining equations that described the mechanical properties of the flexible squeegee blade, the downforce on the blade, and the pressure of the material under the blade, Huner derived a single relationship that described the effects of the variables on Q_o . This relationship is Equation (7)

$$\frac{d^2y}{d^2x} = \frac{6\mu U}{D \sin^5 \theta_R} \int_x^\ell (\lambda - x) \left[\int_x^\lambda \frac{(y - 2Q_o / U)}{12k_x H + y^3} d\chi \right] d\lambda + \frac{F}{D \sin^3 \theta_R} (\ell - x) \quad (7)$$

where,

$$D = Eh^3/12(1-\nu)$$

and,

D = flexural rigidity of the squeegee
 E = elastic modulus of the blade material
 h = thickness of squeegee blade
 ν = Poisson's ratio of the blade material
 y = height above screen surface
 x = distance (in plane of screen) from squeegee's point of attachment
 θ_R = angle of squeegee at screen
 U = squeegee speed
 μ = material viscosity
 $\ell \cong L \sin \theta_R$ = value of x at which squeegee contacts screen
 L = squeegee length
 F = contact force at squeegee tip
 k_x = in-plane Darcy (flow) constant
 H = height of the screen
 $\lambda = y_1/y_0$ = ratio of heights
 y_1 = height at leading edge of blade
 y_0 = height at squeegee tip
 χ = variable not specified by Huner

Unfortunately, the second order differential equation could not be solved analytically. Instead, Huner opted to evaluate the equation on a term by term basis. The first term on the right-hand side of the equation described the effect of viscous stresses on the curvature of the blade. It was described by the variable group, $\mu U/\ell$. The second term described the effect of the mechanical properties and geometry of the blade on its own curvature. It was characterized by the term D/ℓ^3 . Huner combined these groups to obtain the ratio of the viscous stresses to the mechanical properties of the squeegee. The result of this analysis was the dimensionless term shown in Equation (8).

$$\mu U \ell^2 / D \quad (8)$$

Based on this ratio, he proposed the existence of two operating regimes during the screen filling process, a squeegee-dominated regime and a fluid-dominated regime, represented by Equations (9) and (10), respectively.

$$\text{fluid stresses dominate} \quad \mu U \ell^2 / D \gg 1 \quad (9)$$

$$\text{elastic squeegee stresses dominate} \quad \mu U \ell^2 / D \ll 1 \quad (10)$$

When the dimensionless term, $\mu U \ell^2 / D$, is significantly less than one, the mechanical properties of the squeegee have a greater influence on the injection of the material into the wire mesh than the fluid properties. The flow of material past the squeegee in this regime is, “ ... independent of ink viscosity and squeegee speed, and is relatively insensitive to the squeegee angle of attack.”

When the dimensionless term is significantly larger than one, the opposite is true; fluid properties dominate the mechanical properties of the squeegee and the injection is dependent on the viscosity. The coating thickness, “...can be a sensitive function of all the setup and printing parameters.” Huner did not discuss the behavior of the process when the dimensionless term fell between the boundaries defined by Equations (9) and (10).

2.3. Riemer's analysis of material deposition.

The second half of the screen printing operation is the material deposition process. It occurs after the squeegee has filled a section of screen and continued moving along the screen. During this process, the screen is displaced downward by the squeegee, and the vertical component of the screen tension exerts an equal and opposite force to balance the

force exerted by the squeegee. As the squeegee passes the particular section of screen, the downward force exerted by the squeegee at that location is reduced, and the screen tension lifts the screen from the substrate, leaving the material on the substrate.

This portion of the screen printing process was analyzed only by Riemer.[4] He theorized that two distinct forces act in concert to remove the material from the screen during deposition. The first is the adhesive force between the material and the substrate. The second is the pressure difference across the material. According to Riemer, adhesion alone is insufficient to successfully remove the material from the screen. He stated that the adhesive forces between the material and the substrate "...are almost equal to ..." those holding the material in the meshes. He concluded that the extra force required to successfully empty the meshes is generated by the wires as they separate from the substrate. Their motion leaves evacuated, or low pressure, regions in their original locations, as shown in Figure 18.

Figure 18: Generation of a pressure differential across material as screen separates from substrate .

Since the pressure above the underfill and mesh is atmospheric, there will be a pressure difference between the air and the evacuated region. Rierner postulated that this pressure difference causes flow through the screen, similar to pressure induced flow through a pipe. He developed a relationship between process parameters, material properties, and screen geometry based on the Hagen-Poiseuille equation for steady-state flow through a circular pipe, which is shown in Equation (11).

$$Q = [\pi D^4 / (128 \eta)] \Delta p / L \quad (11)$$

where,

Q = volumetric flow rate
D = diameter of pipe
 η = dynamic viscosity of fluid
 Δp = pressure drop across pipe length
L = length of pipe

His relationship, shown in Equation (12), described the limiting value of ηV , in terms of the screen dimensions illustrated in Figure 19 and Figure 20, above which printing will fail to deposit material on the substrate,.

$$\eta V \leq (1/128)(D^2/d_w)(S-B/a)p_a \quad (12)$$

where,

η = material viscosity
V = squeegee speed
D = width of one mesh opening
 d_w = diameter of one wire
S = length of screen
B = length of printed pattern (centered on screen)
a = snap-off distance = distance between screen and substrate
 p_a = atmospheric pressure.

Riemer substituted atmospheric pressure, p_a , for the pressure differential, Δp , in Equation (12), because that was the maximum pressure drop that could develop across the screen. Thus, the relation indicated the maximum value of the viscosity for a given process.

Figure 19: Screen printing dimensions used by Riemer.

Figure 20: Schematic of screen aperture dimensions.

Figure 21: Cross-sectional view of printing process showing process dimensions.

In the derivation of Equation (12), Riemer made several other assumptions. The first was that the volumetric flow rate of the material from a screen aperture is, “...approximately equal to the screen snap-off velocity.” He incorporated this assumption into the derivation by using the relationship in Equation (13).

$$Q = V_a(\pi D^2/4) \quad (13)$$

where,

Q = volumetric flow rate from screen aperture

V_a = screen snap-off velocity

D = width of screen diameter

According to this assumption the flow rate, and thus the total volume of material deposited on the substrate, is proportional to both the screen snap-off velocity, V_a , and the square of the screen aperture width, D . The relationship between squeegee speed, V , and screen snap-off velocity, V_a , can be calculated using the dimensions shown in Figure 21. By equivalent triangles, the height of the screen above the substrate is given by Equation (14).

$$h = ax/(x+d) \quad (14)$$

Since the velocity of the screen is the first derivative of the height, the screen's snap-off velocity is given by Equation (15).

$$V_a = dh/dt = a(dx/dt)\{[(x+d)-x]/(x+d)^2\}$$

$$V_a = aV/d/(x+d)^2 \quad (15)$$

Since Riemer specified that the printing process is controlled by its upper bound, we are interested in the maximum screen snap-off velocity. This maximum occurs when the screen snap-off angle, θ_2 , is largest. For any given location, this occurs when the squeegee is directly overhead, i.e., $x=0$. Equation (15) then reduces to Equation (16).

$$V_a = aV/d \quad (16)$$

From Equation (16) it is obvious that the maximum screen snap-off velocity, and thus the flow rate of material from the screen, is directly proportional to both the snap-off height, a , and the squeegee speed, V . These relationships are illustrated in Figure 22 and Figure 23. The dashed lines indicate screen snap-off velocities at the back of the wafer and the solid lines indicate snap-off velocities at the front of the wafer, for a back-to-front printing stroke.

Figure 22: Maximum screen snap-off velocity as a function of snap-off height as predicted by Equation 16.

Figure 23: Maximum screen snap-off velocity as a function of squeegee speed as predicted by Equation 16.

Riemer's derivation indirectly predicts that the film thickness should respond linearly to changes in both the snap-off height and squeegee speed. It also predicts that the snap-off velocity and flow rate will be highest at the leading (back) edge of the wafer, and decrease linearly from that point forward. A comparison of snap-off velocities for nine print conditions at the front and back edge of the wafer is shown in Table 2.

Table 2: Comparison of screen snap-off velocities at front and back of wafers.

Squeegee Speed (in/s)	Snap-Off Velocity (in/s) at Back Edge of Wafer			Snap-Off Velocity (in/s) at Front Edge of Wafer		
	0.030 in	0.045 in	0.060 in	0.030 in	0.045 in	0.060 in
1.0	0.0043	0.0064	0.0086	0.0023	0.0035	0.0046
2.0	0.0086	0.0129	0.0171	0.0046	0.0069	0.0092
3.0	0.0129	0.0193	0.0257	0.0069	0.0104	0.0138

Since the derivation originated from the Hagen-Poiseuille equation, Riemer also assumed that the quantity of deposited material is inversely proportional to the length of the aperture, L . For most screens, this is approximately equal to twice the diameter of the wire used in the mesh, d_w . Thus, he substituted the value $2d_w$ for L .

Riemer included empirical data to support his theory that the product, ηV , has a maximum value that cannot be exceeded. Five sets of data from printing experiments performed with two similar inks of different viscosities are displayed in Figure 16.[4] The plots indicate that printing operations employing the higher viscosity material failed to deposit material above a certain squeegee speed, supporting his claims.

Sahay, et al. used a similar method to describe material deposition in the related field of stencil printing.[6] They also began with the assumption of steady-state flow in a circular pipe, but diverged from Riemer at that point. Sahay determined that the thickness of a stencil, which is comparable to that of a screen, was insufficient to allow fully developed flow. Instead of using the pressure-driven Hagen-Poiseuille equation, they developed a relation describing the fluid's velocity profile, $u(x)$, in the entrance region, and another relation for the shear stress, $\tau (= \mu du/dr)$, at the same location. By equating the shear stress equation to the shear strength of the material, Sahay derived Equation (17), which describes the shear diameter of the paste based on the material's shear strength and the stencil geometry.

$$r_d(x) = R - \delta + \frac{\delta^2(\delta^2 - 4\delta R + 6R^2)}{2\mu V(\delta_h^2 - 4R\delta_h + 6R^2)} \quad (17)$$

where,

r_d = detachment radius = radius at which shear strength of material is exceeded

R = radius of pipe

δ = boundary layer thickness

δ_h = boundary layer thickness at the stencil thickness, H

μ = Newtonian viscosity of material

R = Radius of stencil aperture

V = snap-off velocity of stencil

In addition, Sahay accounted for the partially developed flow by including Equations (18) and (19). The definition of the boundary layer thickness, described by these equations, is dependent on the location of the measurement relative to the entrance of the pipe. These dimensions are illustrated in Figure 24.

$$\delta = \frac{D}{L_e} x - \frac{D}{2L_e^2} x^2 \quad \text{for } L_e > x > 0 \quad (18)$$

$$\delta = \frac{D}{2} \quad \text{for } x > L_e \quad (19)$$

where,

x = distance along axis of flow

L_e = x value at which flow is fully developed (boundary layer thickness = R)

Figure 24: Diagram of boundary layer development at pipe entrance.

Sahay et.al. theorized that the material detaches from the screen in the boundary layer, because that is where the velocity gradient and, therefore, the shear stresses occur. Using Equation (16), the percentage of the stencil aperture's volume that would print for a given stencil geometry was calculated. Flow through a stencil aperture is not the same as flow through a screen aperture because stencil apertures are substantially larger than screen apertures. Because of this, Sahay's calculations are not directly applicable to screen printing, but this treatment is still important because it provides an alternate view of the driving forces behind the material deposition process. Sahay theorized that the

adhesive forces between the substrate and the material being printed drove the material deposition.

Riemer also theorized that under certain conditions, the viscous shear forces acting on the mesh wires and the pressure difference across the wires would prevent the screen from lifting off the substrate immediately behind the squeegee. Riemer stated that separation of the screen must occur immediately behind the squeegee to smoothly release the material from the screen. If the screen remained stuck in the printed material, it would not pull free until the squeegee was lifted from the screen to its resting position. This would cause an excessively fast separation between the screen and substrate, which would either cause cavitation and reduce print resolution or exceed the maximum product of ηV (specified in Equation (12)) causing print failure. Using terms describing the shear forces and pressure forces acting on the mesh, he generated Equation (20), which describes the value of μV that will result in immediate separation of the screen behind the squeegee.

$$\eta V > (\pi/256)(a/l_{SR})m\sigma_s 64-(l_{SR}/a)(m+d_R) p_a \quad (20)$$

where,

η = material viscosity

V = squeegee speed

a = snap-off distance = distance between screen and substrate

l_{SR} = distance from squeegee tip to screen frame

m = wire pitch

σ_s = screen tension

d_w = diameter of one wire

$d_R = m - d_w$ = effective mesh diameter

p_a = atmospheric pressure.

Values of ηV lower than the value generated by the right side of Equation (20) will cause the screen to stick in the printed film and create less than ideal coatings. The optimum operating conditions of a specific system can be determined by determining the process conditions that satisfy both Equations (12) and (20).

2.4. Review of Theoretical Treatments

Both Huner and Riemer assumed homogeneous Newtonian fluids for their analyses. Most screen-printed materials, such as dielectric inks and thermally conductive adhesives, are far from homogeneous. They contain substantial quantities of solid fillers, such as silica or silver, that are used to enhance the thermal, electrical, or mechanical properties of the material. The very nature of these particulate suspensions precludes the assumption of Newtonian behavior if their solids concentrations are large.

The screen printing process itself also precludes this assumption. It requires materials to exhibit high viscosity at low shear rates to prevent leakage of the material through the screen ahead of the squeegee, which would ruin the print resolution, as shown in Figure 25. Conversely, it requires materials to exhibit low viscosity at high shear rates so that the material can be forced through the screen as the squeegee passes. By definition, this behavior is pseudoplastic rather than Newtonian.

Riemer, himself, speculated that the filler particles enhance the material deposition process through non-Newtonian behavior. He claimed that resin rich layers are formed on the walls of tubes when particle suspensions flow through a tube. Based on this assumption he concluded that the resin rich layer acts like a bearing. This conclusion, by

itself, invalidates the assumption of a homogeneous fluid. These discussions remained on a purely conceptual level; no data were presented to support these conclusions.

Despite Riemer's seemingly contradictory assumption, he cannot be faulted. The complexity of the problem demanded simplification, and without the assumption of a homogeneous Newtonian fluid, an analytical solution was impossible. Since the intent of his analysis was to provide an understanding of the forces driving the printing process, not provide exact numerical solutions, the assumption was justified for his purposes.

2.4.1 Analysis of Screen Filling Treatments

Riemer's derivation of the squeegee-pressure relationship in Equation (3) provides valuable insight into the relationship between material properties and process parameters without providing critical values of operating parameters. The exact pressure in the material cannot be determined using Equation (3) because loss through the screen is not accounted for, but an upper bound on the material pressure for the process can be determined using this equation. Although it cannot be used to generate specific numerical information, Equation (3) allows us to gain insight into the mechanics of the screen filling process by specifying which variables affect the material pressure and their relative importance. As Riemer stated, the squeegee acts like a hydraulic pump by creating hydraulic pressure that drives the material into the screen. This knowledge was helpful in narrowing the focus of this study to a reasonable number of variables.

Newtonian behavior

Low viscosity at low shear rates allows material to flow before screen is in contact with substrate and ruins print resolution

Pseudoplastic Behavior

High viscosity at low shear rates allows material to flow only when screen is in proximity to substrate

Figure 25: Comparison of Newtonian and pseudoplastic behavior of screen printing materials.

Riemer also acknowledges the existence of an upper shear limit on the material, above which the material will not be deposited onto the substrate. The importance of this information is somewhat diluted because he did not include a method to calculate the shear rates in this complex system. Fortunately, Kevra has extended Riemer's work, and provided a simple method for the calculation of these shear rates.[10] He noted that the shear force is a function of the fluid's acceleration in both the x and y directions, and is given by Equation (21).

$$\tau_{xy} = \mu(\delta v_x / \delta y + \delta v_y / \delta x) \quad (21)$$

This equation does not lend itself to simple calculation of the shear rate, because of the complexity of determining the velocity gradients. Kevra noted that in Riemer's streamline plots, in Figure 11 through Figure 13, the velocity in the region below the pressure locus is almost solely a function of x. Therefore, he approximated $\delta v_y / \delta x = 0$ in this region, reducing Equation (21) to Equation (22).

$$\tau_{xy} = \tau_x = \mu(\delta v_x / \delta y) \quad (22)$$

Since $\tau = \mu\gamma$, the shear rate was given by Equation (23).

$$\dot{\gamma} = \delta v_x / \delta y \quad (23)$$

Further substitution for the velocity gradient in the vertical direction, $\delta v_x / \delta y$, yielded Equation (24),

$$\dot{\gamma} = (2V / r)[(\alpha - \sin \alpha) / (\alpha^2 - \sin^2 \alpha)] \quad (24)$$

where,

V = squeegee speed

r = distance from squeegee tip

α = squeegee angle

This equation allows estimation of the shear rates for comparison against the shear strength of the material, but with limitations. Because of the $1/r$ term, the shear rate increases asymptotically as r approaches zero. Obviously, the shear rate and pressure cannot increase to infinite values at the squeegee tip. At some distance from the squeegee, the material must shear free of the screen and flow up the face of the squeegee, creating the characteristic “roll” observed in screen printing. Since the shear rate is a function of material pressure, it is assumed that Kevra’s relationship also breaks down near the squeegee tip due to non-laminar flow, just as Riemer’s pressure relation did. While this expands the usefulness of Riemer’s derivation, critical information is still missing. What is the critical shear rate and how is it determined? Below what shear rate does the material fail to fill the screen? No insight into these questions was supplied by Riemer or Kevra.

Huner expanded knowledge of the screen filling process by analyzing the contribution of in-plane flow to the thickness of printed films. Inclusion of the effects of squeegee mechanical properties on screen printing had yet to be considered. Through his dimensionless number, he claimed to be able to predict whether these effects will deposit extra material on the screen, ultimately adding to the film thickness.

The remainder of Huner’s derivations, however, lacked sufficient detail to be useful for the prediction of coating thickness values. In comparison to his derivations for in-plane flow, the calculations for vertical flow through the screen were decidedly simple.

He included no derivations of flow resistance through the screen as a function of process parameters, but simply stated that the vertical flow was equal to the “AHU” term in Equation (6), where the porosity term, A , was a constant. He asserted that terms like this, “...have long been used to estimate the volume flow past the squeegee tip in a screen printing operation.”[14]

There was no discussion of flow resistance in the vertical direction because the derivation was based on the Morgan-Cameron approximation which only considers flow in the plane of the film.[14] According to Huner, the Morgan-Cameron approximation proposed that, “...if the porous matrix is in some sense thin ..., then there cannot be any large pressure drop normal to its surface,” and the pressure in the screen is solely a function of x , the direction of squeegee motion. Since the only appreciable pressure drop occurs in the plane of the screen, he proposed that the resultant flow of material in this plane could contribute significantly to the final film thickness.

This assumption might be valid under certain conditions, but his simplified treatment of the flow normal to the screen made it impossible to determine what these conditions might be. Various plots in Huner’s article showed that in most cases the terms accounting for in-plane flow account for substantially less than 15% of the total flow past the squeegee.[5] Since flow in both directions is pressure driven, if the in-plane flow is significant, logic dictates that the pressure drop normal to the screen is greater than the in-plane pressure drop if the porosity values in both directions are similar. The Morgan-Cameron approximation is typically used in paper coating operations, which are substantially different from screen printing operations. The porosity of the paper, and

thus, flow of material into the paper, is substantially less than in screen printing operations. The purpose of paper coating is, as the name implies, to coat the surface of the paper. The Morgan-Cameron approximation assumes that the tiny vertical pores in the paper fill instantaneously, creating backpressure and reducing the vertical pressure drop to a negligible value. This assumption is the basis for his neglect of the vertical flow term. His own derivations show that the vertical flow is substantially larger than the in plane flow, negating his own assumption. The purpose of screen printing is to fill the screen and then deposit the material on the substrate, not coat its surface.

It was obvious that Huner was only interested in the in-plane flows, analyzed in his earlier article[15], rather than a general analysis of screen printing. This article did not prove useful to the development of the underfill application process.

2.4.2 Review of Material Deposition Treatments

While the treatments of the screen filling process did not provide specific solutions, Riemer's treatment of the material deposition process provided specific process limits in terms of process variables, material properties, and equipment dimensions. His derivation of Equation (12), also included several assumptions, some of which were not elucidated in the text. His derivation began with the Hagen-Poiseuille equation, which was initially derived for fully-developed, steady-state, laminar flow in a circular pipe. Although the laminar flow assumption is valid, because of the high material viscosities and narrow apertures, the remaining assumptions are not.

Riemer used the fact that the hydraulic radii for both circular and square pipes are equivalent to conclude that the flow rate through square pipes could be described using

equations developed for round pipes. An equivalent hydraulic radius, however, means only that the mean wall shear stress is equal in both pipes, not that the flow rates are identical.[7]

White describes for flow rates through a circular pipe of radius r_o and a rectangular pipe of width $2a$ and height $2b$ using Equations (25) and (26).[7]

$$Q = \frac{\pi r_o^4}{8\mu} \left(-\frac{dp}{dx} \right) \quad (25)$$

$$Q = \frac{4ba^3}{3\mu} \left(-\frac{dp}{dx} \right) \left[1 - \frac{192a}{\pi^5} \sum_i \frac{\tanh(i\pi b/2a)}{i^5} \right] \quad (26)$$

The bracketed term in Equation (25) quickly converges to a value of 0.4. If this term is approximated as 1.00 and the width is set equal to the height, Equation (26) can be simplified to Equation (27).

$$Q = \frac{1.6a^4}{3\mu} \left(-\frac{dp}{dx} \right) \quad (27)$$

The ratio of the flow rate in a square pipe, of width D , to the flow rate in a circular pipe of diameter, D , is approximately 4.3 for a given material and fixed pressure drop when calculated using Equations (25) and (27). Therefore, use of this assumption will cause a gross underestimation of the flow rate through the square screen apertures.

The remaining assumptions are also invalid. The deposition process is obviously not steady state. The screen starts at rest and then accelerates away from the substrate. It also lacks the infinite supply of material required of a steady state system. This assumption, however, is also required for an analytical solution. Its use simply points out that the purpose of Riemer's investigation was to understand the forces that drive screen printing, not to calculate process parameters.

The third assumption of fully developed flow is equally invalid. According to White, fully developed flow occurs at a length, L_e , downstream from the entrance to a circular pipe, which can be estimated from Equation (28).[7]

$$L_e/D = 0.08Re + 0.7 \quad (28)$$

where,

L_e = entrance length = length at which fully developed flow occurs

D = hydraulic diameter of pipe = $4(\text{Area}/\text{Perimeter})$ = side length in a square pipe

$Re = Du\rho/\mu$ = Reynolds number

u = fluid velocity at entrance to pipe

ρ = fluid density

μ = fluid viscosity.

Since Riemer assumed creeping flow, the Reynolds number, Re , must be less than one, and therefore Equation (29) follows from Equation (28).

$$0.7 < L_e/D < 0.78 \quad (29)$$

Using his previous assumption, the flow length of the pipe, L , can be approximated by the thickness of the screen, t , since flow is perpendicular to the screen's surface. If the diameter of the "pipe", D , is approximated by the width of a single screen aperture, the

ratio t/D will be the maximum value of L_e/D that can occur in a screen. Based on these approximations, the data sheet from one of the largest screen manufacturers [8] indicates that nearly one-third (32%) of their screens have t/D ratios between 0.4 and 0.78. This means that fully developed flow will not occur in a large percentage of their screens even if the mesh apertures did approximate a circular pipe. A more accurate approximation would be to equate the flow length to the wire thickness, since only the wire is acting like the pipe wall, not the entire screen. Using this approximation, only 1 out of 31 screens has a t/D ratio greater than 0.78. Therefore, it is probable that fully developed flow will not occur in 30 of these screens.

Huner also criticized Riemer's unstated assumption of fully-developed flow, stating that the flow rates would be substantially different if the screen were treated as the entrance to a pipe.[9] He cited an equation for flow in a finite length capillary that indicated that the pressure drop for a given length of pipe is substantially larger in the entrance region than indicated by the standard Hagen-Poiseuille equation. The entrance effects require that the pressure drop term be corrected by the factor shown in Equation (30).

$$[1 + 3\pi/16(D/L)]. \quad (30)$$

Using the corrected equation, the flow rate through the aforementioned screens will be only 40% to 75% of the amount predicted by the uncorrected Hagen-Poiseuille equation. The ηV product predicted by Riemer's equation will also be reduced by a similar amount.

Even if the previous assumptions were valid, Riemer's approximation of the pressure drop across the screen at a constant one atmosphere will cause his equation to be inaccurate. Riemer estimated that $\Delta p \cong \Delta p_a$, without explicitly stating the assumption or the reasoning behind it. At no point in the process does the pressure drop across the screen equal atmospheric pressure. At the beginning of the process the pressure drop is zero and at the end it approaches, but does not equal, atmospheric pressure. At the start of material deposition, there is no flow through the screen, and no external forces acting on the material other than atmospheric pressure. Riemer's original assumption of a Newtonian fluid means that the pressure in the fluid is hydrostatic. Since the pressure in a hydrostatic fluid will be the same above or below the screen, no pressure drop can exist across the wire. As the screen pulls free of the printed film, the volume of the voided region under each wire expands. Assuming the voided region is not quickly filled with flowing underfill, the pressure in each voided region will drop in inverse proportion to its increase in volume. If the volume is large enough at the completion of the deposition process, the final pressure could approach zero and the pressure drop could be estimated as being atmospheric. Since the pressure drop increases from zero to one atmosphere during the process, the time-averaged pressure during the process will be closer to $0.5\Delta p_a$ than Δp_a . Riemer's assumption that $\Delta p \cong \Delta p_a$ will result in an error in calculation of the maximum product of ηV by a factor of nearly two. When combined with the previous invalid assumptions, this error renders Equation (12) unusable for the determination of process settings.

Riemer's second equation describing the material deposition process, Equation (20), also contains both mistakes and bad assumptions. A greater than symbol (>) was mistakenly included in the equation and should have been replaced by a less than symbol (<) as shown in Equation (31). Although one of Riemer's earlier papers includes the proper symbol, the equation is still not correct.[15] The derivation contained additional errors. The entire right hand side of the equation had the incorrect sign and the second term on the right hand-side of the equation was missing a 1/64 multiplier, which was also corrected in Equation (31). The complete derivation including corrections is shown in Appendix A.

$$\eta V < \left[-\left(\frac{\pi}{256}\right)\left(\frac{a}{l_{SR}}\right)m \sigma_s + \left(\frac{1}{64}\right)\left(\frac{l_{SR}}{a}\right)(m + d_R)p_a \right] \quad (31)$$

The basis of Riemer's derivation was Equation (32), which contained two terms, one for the shear forces acting on the wires in the screen mesh and another for the supposed force exerted on the wires by atmospheric pressure.

$$f_{mo} = 4\tau d_R(2d_w) + d_w(m+d_R) p_a \quad (32)$$

where,

- f_{mo} = forces acting on a single screen mesh
- τ = shear forces in material acting on screen wire
- m = wire pitch
- d_w = diameter of one wire
- $d_R = m - d_w$ = effective mesh diameter
- p_a = atmospheric pressure.

In the first term, it was assumed that the screen acted like a pipe of length $2d_w$. The interior surface area of the pipe equaled the surface area of the four supposed walls of the

aperture. According to Riemer, the surface area of each wall was best approximated by its length, d_R , of the wire that formed the wall times the screen thickness, $2d_w$. Use of this calculation will overestimate the surface area and the shear force, by at least 25%. If the wires were approximated as vertical walls, their heights should have been estimated as the one wire thickness, d_w , not the screen thickness, $2d_w$, because each aperture only contains a single wire in the vertical direction. If an approximation was not used, the surface area of aperture should have been calculated directly using the actual surface area of each wire, as shown in Equation (33).

$$\text{Surface area of a single wire} = (d_R) [1/2(\pi d_w)] \quad (33)$$

The second term in Equation (32) also contained a questionable assumption. Riemer, again, estimated that $\Delta p \cong \Delta p_a$, just as in his derivation of Equation (12), without explicitly stating the assumption or the reasoning behind it. Since the pressure drop increases from zero to almost one atmosphere during the process, the average pressure during the process would be better estimated by $\Delta p \cong 0.5\Delta p_a$.

Neither Riemer, nor Huner backed up their conclusions with empirical data. Huner acknowledged this fact, but Riemer stated his conclusions were fact, but only compared them to trends observed in second hand data. This lack of comparison to actual data prevented Riemer from identifying the errors in his derivations. A simple check of Equation (20) using all of the screens listed in Table 1 of Riemer's article[4] generated negative values of μV , up to snap-off distances of 0.3 inches, with the screen tension set in the recommended region ($\sim 0.15\%$ strain). Since many commercial screen printers

have maximum snap-off height settings in the 0.10-0.15 inch range, these screens would fail to print films under any circumstances if Equation (20) were valid. Obviously, the screens listed by Riemer must print at some set of conditions or else they would not be sold commercially. Neither of the articles provided useful equations for the calculation of preliminary process parameters, but they did provide some useful insight into the general process mechanics.

CHAPTER 3

RESEARCH OBJECTIVES

A successful wafer level underfill application process must produce uniform films of sufficient thickness to form continuous bonds between the die, underfill, and substrate. The thickness and uniformity of these films is determined by material properties, such as viscosity, and process parameters, such as snap-off height, squeegee speed, and screen thickness. Therefore, development of a successful process requires a detailed understanding of the effects of these factors on the printed film thickness and uniformity.

This study was undertaken to answer the following questions regarding the screen printing of newly developed wafer level underfill materials: 1) Which materials are capable of meeting the minimum film thickness requirements?, 2) What screen printing parameters have the largest effect on the thickness and uniformity of the printed films?, and 3) How do the film properties respond to changes in these parameters?

CHAPTER 4

EXPERIMENTAL METHODS

This study was divided into three distinct parts, the material selection phase, the parameter selection phase, and the response phase, as shown in the flow diagram in Figure 26. The test results from the material selection phase were used to narrow the list of proposed underfills from nine to two. The selected materials were subsequently used in parameter selection phase tests to determine which of six process parameters had the greatest effect on film thickness. Finally, these three parameters were tested in the response phase to determine the reaction of the film thickness to changes in these process parameters.

4.1. Materials

Nine underfill formulations were used in this study, each consisting of different (fused silica) filler particle sizes, filler percentages, and base resin polymers, as described in Table 3. The exact filler particle sizes and concentrations were unknown, with the exception of the filler concentration in the solids free materials. Three different resins were used in the underfills: two epoxy resins and one polyimide resin.

All nine formulations were employed in the material selection phase. Based on results of that phase, two materials were to be selected and employed in the parameter selection and response phases. Because of difficulties in obtaining raw materials, the manufacturer, National Starch & Chemical Co., elected to supply only one material: so the plans for those phases were altered to use a single material.

Figure 26: Flow diagram for experimental procedure.

Table 3: Proposed underfill materials tested in the material selection phase.

Material	Resin Type	Filler Type	Filler Concentration (vol%)	Filler Distribution
<i>A</i>	Epoxy A	Fused Silica	High(72)	Tri-modal
<i>B</i>	Epoxy A	Fused Silica	Medium-High(70.5)	Tri-modal
<i>C</i>	Polyimide A	Fused Silica	Medium(34.5)	Tri-modal
<i>D</i>	Polyimide A	None	None	-
<i>E</i>	Polyimide A	None	None	-
<i>F</i>	Polyimide A	Fused Silica	Medium(34.5)	Tri-modal
<i>G</i>	Epoxy B	Fused Silica	High(51)	Bi-modal
<i>H</i>	Epoxy B	Fused Silica	High(50.5)	Bi-modal
<i>I</i>	Epoxy B	Fused Silica	High(50.5)	Bi-modal

Figure 27: Typical six-inch diameter unbumped silicon wafer used for test printing.

These underfills were printed onto unbumped 150mm diameter, <110> silicon wafers, patterned with circuitry, that were identical to the wafer shown in Figure 27.

4.2. Equipment

4.2.1 Printing Equipment

Screen printing operations in each phase were performed using an MPM model SPM/AV semiautomatic screen printer equipped with dual trailing edge polyurethane squeegees. One squeegee was employed for the forward print stroke and the other was used for the backward stroke. The squeegees were 20.3 cm wide by 3.18 cm high and 0.64 cm thick.

The screens employed in the three phases were manufactured by Microcircuit Engineering Corporation. The screens, shown in Figure 28, consisted of stainless steel wire mesh stretched over a 50.8 cm x 50.8cm i.d. square aluminum frame and patterned with E10 polymer emulsion. The wire mesh was oriented so that the wires ran at a 45 degree angle to the direction of squeegee motion. The pertinent screen dimensions for the 31.5, 41.3, and 47.2 mesh count screens are listed in Table 4.

Figure 28: Stainless steel screens used to screen print wafers in
a) the material selection phase and b) the parameter selection and response phases.

Table 4: Screen dimensions.[8]

Mesh Count, 1/m, wires/cm (wires/in)	Wire Diameter, d_w, mm(mils)	Mesh Opening, d_R, mm (mils)	Open Area (%)	Screen Thickness, (mils)
31.5 (80)	0.094 (3.7)	0.22 (8.8)	49.5	0.20-0.23 (8.0 - 8.9)
41.3 (105)	0.076 (3.0)	0.18 (7.0)	46.9	0.15-0.17 (6.0 - 6.7)
47.2 (120)	0.066 (2.6)	0.17 (6.5)	47.3	0.13-0.15 (5.2 - 5.8)

The screens used in each test phase were nearly identical. The only differences among them, other than mesh count, were the patterns formed by the emulsion mask. The 80 mesh screen used in the material selection phase included a mask design, shown in Figure 29a, that allowed the entire wafer to be printed. The 31.5, 41.3, and 47.2 mesh screens used in the parameter selection and response phase incorporated the mask pattern shown in Figure 29b.

Figure 29: Mask patterns used on screens in a) the material selection test phase and b) the parameter selection and response test phases

4.2.2 Measurement Equipment

All weights were measured with a Sartorius Research model R200D scale, accurate to 0.001 grams. Film thickness and roughness measurements were made using a Tencor Alpha-Step 200 profilometer equipped with a 12.5 micron radius diamond stylus. Sections 4.3 through 4.5 provide the details of the measurement procedures used in each test phase.

4.3. Material Selection Phase

The objective of the material selection phase was to identify the two proposed underfill materials that were most likely to satisfy the wafer level process requirements discussed in Section 4.3.4. Selection of these materials was based on the results of screen printing tests performed under a limited number of typical screen printing conditions. The nine proposed underfill formulations, listed in Table 3, were printed onto wafers and the resultant films were measured and inspected. The resultant data were used to select two materials for the parameter selection phase.

4.3.1 Screen Printing – Material Selection Phase

Printing operations commenced with cleaning of the wafers. Each wafer was hand washed with a clean lint-free cloth and electronic-grade isopropyl alcohol and air-dried for 15 minutes. To ensure complete evaporation of any residual alcohol, the wafers were then dried in an oven for 30 minutes at 95°C, before being cooled to room temperature.

Upon completion of cleaning, each wafer was weighed to an accuracy of 0.001 grams. This established the tare weight required for subsequent wet film weight and thickness calculations.

The underfills were then printed at each of the printing conditions listed in the full factorial test matrix shown in Table 5. This matrix contained only two process variables, squeegee speed and snap-off height, because limited quantities of the materials prevented use of a larger test matrix. These two variables were selected because they are the most common adjustments on screen printers. The values of the remaining process parameters, which were held constant during the test prints, are listed in Table 6.

Table 5: Full factorial test matrix used in the material selection phase.

Squeegee Speed, cm/s (in/s)	Material #1	
	Snap-Off Height, mm (in)	
	1.3 (0.05)	2.5 (0.10)
1.3 (0.5)	Condition #1	Condition #5
2.5 (1.0)	Condition #2	Condition #6
5.1 (2.0)	Condition #3	Condition #7
7.6 (3.0)	Condition #4	Condition #8

Table 6: Constant value printing parameters used in the material selection phase.

Screen Printing Parameter	Value
Vertical Squeegee Force, N (lbs.)	71.1 (16)
Stroke length, cm (in)	35.6 (14)
Squeegee Rise Delay (sec)	30
Screen Rise Delay (sec)	30
Screen Mesh Count, wires/cm (wires/in)	31.5 (80)
Screen Aperture Width, mm (in) [8]	0.20 (0.008)
Screen Mesh Thickness, mm (in) [8]	0.02-0.23 (0.008-0.0089)

Three replications of the entire test matrix were originally scheduled, but again, limited quantities of material forced reductions in the number of wafers printed at each condition. The number of wafers printed at each condition is listed in Table 7.

The final step in the printing process was to weigh each printed wafer to obtain a gross printed weight. These weights were later used to calculate the net wet-film weight and the wet-film thickness.

Table 7: Number of repetitions of each set of screen printing conditions in material selection phase.

<i>Underfill</i>	<i>Number of repetitions</i>							
	<i>Print Condition</i>							
	<i>#1</i>	<i>#2</i>	<i>#3</i>	<i>#4</i>	<i>#5</i>	<i>#6</i>	<i>#7</i>	<i>#8</i>
<i>A</i>	1	1	1	0	2	2	2	0
<i>B</i>	1	1	1	1	3	0	1	1
<i>C</i>	1	1	0	1	3	1	3	1
<i>D</i>	1	1	1	1	1	1	1	1
<i>E</i>	3	2	3	1	4	1	3	3
<i>F</i>	0	0	0	0	0	1	1	2
<i>G</i>	1	1	1	1	2	1	1	1
<i>H</i>	3	3	3	3	3	3	3	3
<i>I</i>	3	4	3	3	3	3	3	4

4.3.2 Inspection and Measurements – Material Selection Phase

The weights used in this test phase for comparison of print conditions were net weights of the wet underfill films. This required two weights per wafer, a tare weight and gross weight. The tare weight was obtained by measuring the weight of the uncoated wafer, and the gross weight was obtained by weighing the freshly printed wafer.

The bare wafer weights were obtained two days prior to printing operations. Between the weighing and printing operations, the wafers were stored in a humidity-controlled environment. Since the gross weights were wet film weights, the printed wafers were weighed immediately after the print operations to minimize the loss of any volatile underfill components.

Each weight was obtained by performing the following operations: zeroing the scale, weighing the wafer, and then rechecking the scale's zero point. The inspection of wafers was performed visually without magnification under a bright fluorescent light.

4.3.3 Data Analysis – Material Selection Phase

The average wet film thickness of each material was determined indirectly from the wet film weight of the applied coating. First, the weight was calculated by subtracting the uncoated weight of the wafer from its coated weight. The thickness was obtained by dividing the wet film weight by the density of the underfill and the surface area of the wafer (174.3 cm²).

4.3.4 Selection Criteria – Material Selection Phase

The materials selected in this phase were chosen for their ability to consistently print defect-free films under typical screen printing conditions and print uniform films of sufficient thickness necessary for successful assembly. Since the wafer level underfill application process had not yet been developed, no specific criteria were available by which to judge the films. In order to rank the materials, preliminary criteria, which could be refined in the future, were created.

The success of underfills depends on their ability to form and maintain an uninterrupted bond with the interior surfaces of the die and the substrate. Formation of such a bond during package assembly requires a potential underfill to have three characteristics, namely, sufficient film thickness, film quality, and film uniformity.

4.3.4.1. Film Thickness

Film thickness was the most important of the three selection criteria. Insufficient thickness can lead to incomplete bonds and bondline voids during assembly, as shown in Figure 30. These defects will concentrate thermal stresses and could act as crack initiation sites. Overly thick coatings are less of a problem, because the excess underfill can be displaced by additional die pressure during assembly, as shown in Figure 31. Thicker films are actually preferred, because the displaced material will form a fillet around the edge of the die, enhancing its fatigue life.[13][14] Since a single flip chip package design was used in this study, the choice of the minimum coating thickness was simplified. The final (solder) bump height of the package, 85 microns (3.35 mils), was chosen as the minimum film thickness. The underfill would have to be at least that thick to form an uninterrupted bondline.

Figure 30: Assembly of substrate and die with insufficient underfill coating thickness.

Figure 31: Assembly of substrate and die with overly thick underfill coating.

4.3.4.2. Film Quality

Film quality is a subjective category that can encompass many different criteria. Since the wafer-level process had not been fully defined, many of the parameters that

could affect it were unknown. Defects that interrupt the bondline, however, were known to affect the quality of flip chip packages for the same reasons mentioned in the film thickness discussion. Inspection in the material selection phase focused solely on these types of defects.

Two types of these quality problems were observed in the films of the potential underfills: misprints and bubbles. Misprints were defined as regions where the underfill did not successfully adhere to the surface of the wafer. Bubbles are self-explanatory. Both types of defect harm the package by leaving uncoated areas on the wafer that could form voids and other bondline defects during package assembly. Eventually, specific frequency and size limits for defects will have to be based on reliability testing of assembled packages, however, since no wafer-level package assembly had been performed, no limits had been created. Instead, the film quality of each underfill was judged on a relative basis. The size of the largest defects and the percentage of each film's area containing defects were recorded. The size of defects was graded as small, medium, or large, and the percentage of the film's area containing defects was graded in 10% increments.

The presence of bubbles, however, was not cause for immediate rejection of a material. Small "microbubbles" quickly collapsed and did not affect the overall film thickness, so they only reduced the quality rating. Bubbles over the unused portion of the wafer also did not affect the process, so they were treated just like the microbubbles. Larger macroscopic bubbles or larger numbers of bubbles, however, were cause for

immediate rejection since they created regions of varied film thickness that would affect the process.

4.3.4.3. Film Uniformity

Uniformity was divided into two sub-categories: single wafer variations and wafer-to-wafer variations, otherwise known as repeatability. Uniformity across a single wafer was similar to film quality. It also involved variations in film thickness, but referred to repetitive variations across the entire wafer rather than localized defects. The principal uniformity problems were global variations in film thickness, such as “orange peel” texture and mesh imprints from the screen.

Orange peel was defined as localized variations in film thickness that created global textures similar to those of an orange rind, hence the name. This texture or roughness was a potential problem. If variations in thickness were severe enough, they would cause interruptions in the bondline, as shown in Figure 32, that would concentrate stresses and lead to premature failure of the bond.

Mesh imprints were, as the name implies, negative images of the screen in the underfill film. It was unknown whether the imprints would create a problem during package assembly. The materials were formulated to have some self-leveling capability at the elevated gel temperatures, so that a certain amount of non-uniformity could be tolerated. Without the insight provided by actual process, however, severe imprints were considered marginally acceptable or unacceptable.

Both the mesh imprints and the orange peel texture were graded according to severity and relative percentage of coverage. The severity had three levels: mild,

moderate, and severe. Severe uniformity problems were considered unacceptable. Moderate uniformity problems were considered marginally acceptable. Mild problems were considered acceptable. The relative coverage was graded in 10% increments.

Figure 32: *Effect of surface roughness on underfill bond.*

Wafer-to-wafer uniformity, also known as repeatability of coating thickness, is also important to the wafer level process. The ability to produce coatings of consistent thickness on every wafer is critical to the development of the wafer level underfill application process. It allows process variables, such as die placement pressure during assembly, to remain constant. This ability of each material to produce films of consistent thickness was graded by the range of film thickness values under specific printing conditions. Print condition #5 was the only condition at which multiple prints of each underfill were made; so it was the condition chosen for the comparison. In the case of a

tie, the ranking was based on a normalized value of the repeatability. This was calculated by dividing the range by the average thickness at the given set of print conditions.

4.4. Parameter Selection Phase

The objective of the parameter selection phase was to identify the process and material parameters that caused the largest variations in the printed films of underfill. During screen printing of underfill, these parameters will require the tightest control to produce films of consistent thickness and uniformity. Therefore, knowledge of their response is required to develop a wafer level underfill application process.

Initially, the test phase was designed to include two underfills and eleven process and material parameters. The response of the materials would be measured in terms of the average film thickness and roughness. The design was modified, however, when the underfill manufacturer chose to supply only one of the two materials. Without the second material, it was impossible to study the effect of material properties on the printed films. Therefore, the effect of material properties was eliminated. The final list of test parameters was reduced from eleven to six.

4.4.1 Screen Printing – Parameter Selection Phase

Printing operations again commenced with the wafer cleaning process described in Section 4.3.1. Each wafer was hand washed with a clean lint-free cloth and electronic-grade isopropyl alcohol and air-dried for 15 minutes. To ensure complete evaporation of any residual alcohol, the wafers were then dried in an oven for 30 minutes at 95°C, before being cooled to room temperature.

The thirty-two wafers were then screen printed according to the level III homogeneous fractional factorial test matrix, with six factors and two levels per factor, shown in Table 8. This design required eight distinct sets of printing conditions, as shown in Table 9. The values of the remaining printing parameters, which were not varied, are listed in Table 10. Four replications of the experiment were performed, two for each of the print directions shown in Figure 33, to minimize the effect of stroke direction on the data.

Table 8: *Printing parameters examined in the parameter selection phase.*

<i>Parameter</i>	<i>High Level</i>	<i>Low Level</i>
<i>Squeegee Speed, cm/s (in./sec.)</i>	7.6 (3.0)	2.5 (1.0)
<i>Snap-Off Height, mm (in.)</i>	1.5 mm (0.060)	0.76 (0.030)
<i>Squeegee Force, N (lbs.)</i>	71.1 (16.0)	35.6 (8.0)
<i>Squeegee Hardness (Durometer)</i>	90	70
<i>Mesh, wires/cm (wires/in)</i>	47.2 (120)	31.5 (80)
<i>Squeegee Angle(degrees)</i>	50	40

Table 9: Screen printing conditions for the parameter selection phase.

Print Condition	Squeegee Speed, cm/s (in/s)	Snap-Off Height, mm (in)	Squeegee Force, N (lbs.)	Squeegee Hardness (durometer)	Mesh Count, wires/cm (wires/in)	Squeegee Angle (degrees)
1	7.6 (3.0)	1.5 (0.060)	35.6 (8)	70	47.2 (120)	50
2	2.5 (1.0)	0.76 (0.030)	71.1 (16)	70	47.2 (120)	50
3	2.5 (1.0)	1.5 (0.060)	35.6 (8)	90	31.5 (80)	50
4	7.6 (3.0)	0.76 (0.030)	71.1 (16)	90	31.5 (80)	50
5	2.5 (1.0)	1.5 (0.060)	71.1 (16)	90	47.2 (120)	40
6	7.6 (3.0)	0.76 (0.030)	35.6 (8)	90	47.2 (120)	40
7	2.5 (1.0)	0.76 (0.030)	35.6 (8)	70	31.5 (80)	40
8	7.6 (3.0)	1.5 (0.060)	71.1 (16)	70	31.5 (80)	40

Table 10: Fixed value printing parameters in the parameter selection phase.

Screen Printing Parameter	Value
Squeegee Length, cm (in)	20.3 (8.0)
Stroke length, cm (in)	35.6 (14)
Squeegee Rise Delay (sec)	30
Screen Rise Delay (sec)	30

Figure 33: *Schematic of the two print directions in relation to the wafer.*

The difficulty associated with changing screens and squeegees, including full recalibration of the printer, necessitated the grouping of print operations by screen and squeegee type to minimize equipment changes. Therefore, the wafers were printed in a sequential order from print condition one to print condition eight, rather than the preferred random order. Four wafers were printed at each condition before any wafers were printed at the next print condition.

Upon completion of the printing operations, the coated wafers were baked in an oven for 60 minutes at 140°C to solidify the underfill. The resultant solid surface provided a solid surface for the subsequent film thickness and roughness measurements.

4.4.2 Measurements – Parameter Selection Phase

The two measurements used for comparison of print conditions in this phase were average cured film thickness and average film roughness. Film quality was not measured

in this phase, because it was assumed that potential quality problems were eliminated when the substandard materials were eliminated in the material selection phase. Both the thickness and roughness were measured with a Tencor profilometer at the nine measurement sites on each wafer shown in Figure 34. The profilometer scans were performed with the following settings: 10,000 μm scan length, 1 measurement per 5 μm , and a stylus force of 11 mg.

Each scan began with the stylus located over the underfill-free region and ended with the stylus located over the underfill, as shown in Figure 35. A reference height was obtained in the underfill-free region, marked “bare wafer”. The underfill film thickness was calculated by subtracting this reference height from the average film height obtained in the region marked “film measurement region”. The film height was not measured in the region in between, because the screen pattern altered the film thickness by creating an abnormally large “peak” of material at this location. The film measurement region began at a distance of 2000 μm past this peak and ended at the completion of the profilometer scan. This ensured that the screen pattern would have a minimal effect on the film thickness measurements.

The average film roughness, R_a , was also measured during the profilometer scan. The profilometer calculated the roughness by subtracting the average film thickness value of a scan from each of the individual measurements in the scan and averaging them, as shown in Figure 36.

Figure 34: Schematic of underfill film showing measurement locations.

Figure 35: Schematic of the measured region on the wafer and the profilometer readout.

Figure 36: Method of average roughness, R_a , calculation.

4.4.3 Data Analysis - Parameter Selection Phase

Comparison of the separate process parameters required film thickness and roughness data describing the wafers printed at each condition described by the test matrix. To obtain these values, the raw thickness and roughness data for the nine test locations on each wafer were averaged to provide an average thickness and roughness for each wafer.

These values were then analyzed using Analysis of Variance (ANOVA). The first step in the analysis was to determine whether the differences in average values of thickness and roughness produced by the different levels of each process variable were caused by systematic differences between the levels or by random error. This was accomplished using an F-test, which compared the variation between the means of the

two conditions to the variations of individual measurements within the conditions. If the variance ratio, or F-value, for the comparison exceeded a certain critical value, then the difference between the conditions was significant at the level indicated by the critical F-value. The level of significance for the parameter selection phase was $\alpha = 0.05$, which corresponded to a confidence level of 95%.

The second step was calculation of the estimated marginal mean values of film thickness and roughness based on the general linear model used in the analysis. These estimated means are the predicted values for the different levels of a variable, irrespective of the other variables.

4.4.4 Selection Criteria – Parameter Selection Phase

The two levels of each process variable used in the test matrix were chosen because they were the maximum and minimum values that would typically be used in a screen printing process. Therefore, difference between the estimated means at these levels is the maximum variation that would occur in the process.

The purpose of this phase was to select the process variables that, if changed, would cause the greatest variation in the printed films. Since film thickness was the primary film measurement, the variables were ranked by the difference in estimated mean thickness between their high and low levels. Those with the largest variation would require the tightest control to ensure consistent film thickness.

The surface roughness of the underfill, a specific measure of uniformity, was also important. Differences in roughness among the levels of each variable were also calculated and ranked from largest to smallest. Since specific criteria were not available,

the judgement was made on a relative basis. Large differences in roughness were less desirable than small difference and required the tightest control. Since roughness is the secondary criterion, it was evaluated only in combination with the results of the thickness measurements.

4.5. Response Phase

The objective of the this phase was to measure the response of the three process parameters selected in the parameter selection phase. This knowledge is required for successful development of a wafer level underfill application process, because consistent thickness and uniformity are necessary to minimize underfill bondline defects and the associated package failures. To obtain consistent film thickness and uniformity, the variables that have been demonstrated to produce the greatest variations require the tightest controls. Proper control of the variables cannot be achieved without knowledge of their response.

4.5.1 Screen Printing - Response Phase

Just as in the previous two phases, the wafers were cleaned with electronic-grade isopropyl alcohol, air dried for 15 minutes, and then baked at 95°C for 30 minutes to drive off any residual alcohol. Then, the one hundred and eight wafers were printed with the same batch of the same underfill used in the parameter selection phase. They were printed according to the homogeneous full factorial test matrix shown in Table 11.

A least squares linear regression was performed on the resultant mean values for the high, medium and low levels of the variables that had a significant response. If the correlation coefficient, R^2 , of the regression equaled or exceeded 0.95, the regression was

significant, and the response of the variable was classified as linear. If the correlation coefficient for a significant variable was less than 0.95, the response was classified as non-linear.

Table 11: Parameter response phase print conditions.

Print Condition	Squeegee Speed, cm/s(in/s)	Snap-Off Height, mm (in)	Mesh Count, wires/cm (wires/in)
1	2.5 (1.0)	0.76 (0.030)	31.5 (80)
2	5.1 (2.0)	0.76 (0.030)	31.5 (80)
3	7.6 (3.0)	0.76 (0.030)	31.5 (80)
4	2.5 (1.0)	1.1 (0.045)	31.5 (80)
5	5.1 (2.0)	1.1 (0.045)	31.5 (80)
6	7.6 (3.0)	1.1 (0.045)	31.5 (80)
7	2.5 (1.0)	1.5 (0.060)	31.5 (80)
8	5.1 (2.0)	1.5 (0.060)	31.5 (80)
9	7.6 (3.0)	1.5 (0.060)	31.5 (80)
10	2.5 (1.0)	0.76 (0.030)	41.3 (105)
11	5.1 (2.0)	0.76 (0.030)	41.3 (105)
12	7.6 (3.0)	0.76 (0.030)	41.3 (105)
13	2.5 (1.0)	1.1 (0.045)	41.3 (105)
14	5.1 (2.0)	1.1 (0.045)	41.3 (105)
15	7.6 (3.0)	1.1 (0.045)	41.3 (105)
16	2.5 (1.0)	1.5 (0.060)	41.3 (105)
17	5.1 (2.0)	1.5 (0.060)	41.3 (105)
18	7.6 (3.0)	1.5 (0.060)	41.3 (105)
19	2.5 (1.0)	0.76 (0.030)	47.2 (120)
20	5.1 (2.0)	0.76 (0.030)	47.2 (120)
21	7.6 (3.0)	0.76 (0.030)	47.2 (120)
22	2.5 (1.0)	1.1 (0.045)	47.2 (120)
23	5.1 (2.0)	1.1 (0.045)	47.2 (120)
24	7.6 (3.0)	1.1 (0.045)	47.2 (120)
25	2.5 (1.0)	1.5 (0.060)	47.2 (120)
26	5.1 (2.0)	1.5 (0.060)	47.2 (120)
27	7.6 (3.0)	1.5 (0.060)	47.2 (120)

The three levels of the three variables were arranged into twenty-seven distinct sets of print conditions. Four replications of each experiment, two for each print direction, were performed to ensure that variations in film properties, based on print direction, did not bias the data.

Just as in the parameter selection phase, the wafers were printed in three groups each corresponding to a particular screen, rather than in random order. Arranging the experiment in this manner minimized the number of printer recalibrations, which are required after every screen change.

The wafers were baked in an oven for approximately 60 minutes at 140°C to solidify the underfill. This operation created a solid surface for the film thickness and surface roughness measurements.

4.5.2 Measurement – Response Phase

The film thickness and average roughness of the resultant underfill films were measured using the same profilometer and method described in Section 4.4.2.

4.5.3 Data Analysis

Comparison of the separate process parameters required film thickness and roughness data describing each print condition in the test matrix. To obtain these values, the raw data from thickness and roughness measurements at the nine test locations on each wafer were averaged to provide an average thickness and roughness for each wafer.

These values were then analyzed using Analysis of Variance (ANOVA), as described in Section 4.4.3. This included an F-test on thickness and roughness data for

each process variable, to confirm the effects displayed by these variables in the parameter selection phase.

Values of the estimated marginal mean thickness and roughness were then calculated for each level of the significant independent variables, and compared against each other, i.e., high vs. low, high vs. medium, and medium vs. low, using an F-test. If the means of all three levels were significantly different, this indicated a significant response. If the means of each level were not significantly different, no response was present.

A least squares linear regression was performed on the resultant mean values for the high, medium and low levels of the variables that had a significant response. If the correlation coefficient, R^2 , of the regression equaled or exceeded 0.95, the regression was significant, and the response of the variable was classified as linear. If the correlation coefficient for a significant variable was less than 0.95, the response was classified as non-linear.

4.5.4 Selection Criteria – Response Phase

Selection of actual values of process variables was not performed in this study, because the final stage of process development, printing of underfill onto (solder) bumped wafers, was not performed. Further development of underfill material was required, so this final stage was delayed until the final underfill was formulated. Without film thickness and roughness data from bumped wafers there was no way to confirm that the thickness and roughness values would follow the same trends as observed with unbumped wafers.

CHAPTER 5

RESULTS AND DISCUSSION

The development of a wafer level screen printing process requires knowledge of the materials, the process parameters, and the process response. The experiments detailed in Chapter 4 were designed to gather that knowledge. The results of those experiments are presented here.

5.1. Material Selection Phase

The objective of this phase was to select the two materials that would perform best in a wafer level process. Performance of the materials was ranked according to their performance in three categories: film thickness, film quality, and film uniformity.

5.1.1 Film Thickness

Film thickness was the primary criterion, so it was analyzed first. Four of the nine underfills met the minimum thickness requirement of 85 microns (3.35 mils) at every print condition. The average wet film thickness values calculated for each of the underfills are listed in Table 12.

Underfills A and *B* films were consistently the thickest films produced at each of the eight print conditions. Both materials were formulated with the same resin, epoxy A, and filler particles; the only difference between them was the filler concentration. The material with higher solids content, *Underfill A*, consistently produced the thicker films. The same trend was observed with the three materials based on polyimide A resin. The

solids-filled material, *Underfill C*, produced thicker films under every set of operating conditions than the materials without fillers, *Underfills D* and *E*.

Table 12: Average wet film thicknesses of the underfills for all print conditions.

<i>Underfill</i>	<i>Resin Type</i>	<i>Average Film Thickness, mm (mils)</i>	<i>Minimum Film Thickness mm (mils)</i>	<i>Maximum Film Thickness mm (mils)</i>
<i>A</i>	Epoxy A	0.20 (7.7)	0.17 (6.6)	0.22 (8.7)
<i>B</i>	Epoxy A	0.12 (4.6)	0.099 (3.9)	0.14 (5.7)
<i>C</i>	Polyimide A	0.091 (3.6)	0.084 (3.3)	0.10 (4.1)
<i>D</i>	Polyimide A	0.076 (3.0)	0.058 (2.3)	0.099 (3.9)
<i>E</i>	Polyimide A	0.061 (2.4)	0.048 (1.9)	0.074 (2.9)
<i>G</i>	Epoxy B	0.079 (3.1)	0.069 (2.7)	0.091 (3.6)
<i>H</i>	Epoxy B	0.089 (3.5)	0.086 (3.4)	0.091 (3.6)
<i>I</i>	Epoxy B	0.079 (3.1)	0.069 (2.7)	0.086 (3.4)

Underfill F, also formulated with polyimide A resin, was not included in this comparison. It had a major problem, which caused its elimination from the study. After printing only four wafers with this material, the film of *Underfill F* that remained on the screen solidified and had to be removed using a solvent. The only solvent that would remove it dissolved the screen's emulsion coating and ruined the screen. Since a limited number of screens was available, the loss of additional screens would have jeopardized the research, and therefore, *Underfill F* was eliminated from the study.

No distinct trend was observed in the underfills formulated with epoxy resin B. *Underfills G* and *H*, which had identical tri-modal distributions of filler particles, produced average film thickness values of 79 and 91 microns (3.1 and 3.6 mils), respectively, and *Underfill I*, which had a similar tri-modal distribution but a slightly

lower filler particle content, produced films that averaged 79 microns (3.1 mils) thick. No conclusion could be made regarding the effect of the distribution of filler particles on the thickness of the underfill.

Based on the criteria stated in Section 4.3.4.1, the only materials that produced acceptable average film thickness were *Underfills A, B, C* and *H*. These four materials were deemed acceptable. Three of the other materials, *Underfills D, G, and I*, produced films at least 86 microns (3.4 mils) thick under certain conditions, so they were deemed marginally acceptable. *Underfill E* failed to produce acceptable films under any conditions. It was categorized as unacceptable. The rankings of the materials according to film thickness are shown in Table 13.

Table 13: Acceptability and rank of the underfills based on wet film thickness.

<i>Underfill</i>	<i>Acceptability</i>	<i>Rank</i>
<i>A</i>	Acceptable	1st
<i>B</i>	Acceptable	2nd
<i>C</i>	Acceptable	3rd
<i>D</i>	Marginal	7th
<i>E</i>	Unacceptable	-
<i>G</i>	Marginal	6th
<i>H</i>	Acceptable	4th
<i>I</i>	Marginal	5th

5.1.2 Film Quality

The next criterion used to evaluate the acceptability of the underfills was film quality, which was quantified in terms of two types of film defects, misprints and

bubbles. The type of film defects, the relative size of the defects, and the coverage (approximate percentage of the films which contained defects) are listed in Table 14.

Table 14: Description of film quality defects.

Underfill	Defect Type	Coverage (10% increments)	Size
<i>A</i>	Misprints	10-30%	Large
<i>B</i>	Bubbles	10-20%	Small
<i>C</i>	Misprints	<10%	Small
<i>D</i>	Bubbles	100%	Medium
<i>E</i>	Bubbles	100%	Medium
<i>G</i>	None	-	-
<i>H</i>	None	-	-
<i>I</i>	None	-	-

Only films printed with *Underfills A* and *C* exhibited misprints. Misprints were observed in films printed with *Underfill A* at every set of conditions. Most were between 2 mm and 7 mm ($\frac{1}{4}$ -inch) in diameter but the largest misprint was over 38 mm in largest dimension, as shown in Figure 37. The misprints observed in *Underfill C* films were much smaller. Although one was 5 mm in diameter, the remaining misprints were only a few screen apertures in diameter. *Underfill A* had the highest solids concentration of the materials that contained epoxy resin A, and *Underfill C* had the highest solids concentration of the materials that contained polyimide resin A.

The second type of defect, bubbles, was observed in the films of *Underfills B, D* and *E*. *Underfill B* films showed only a small number of microscopic bubbles at the end of the squeegee stroke, while those printed with *Underfills D* and *E* contained larger

bubbles distributed across the entire wafer. One of the *Underfill E* films is shown in Figure 38.

Figure 37: Major misprint in wet film of Underfill A.

Figure 38: Bubbles in wet film of Underfill E.

Only extremely minor quality problems were observed in Underfills G, H, and I films. On the unused edge of some of the wafers, they occasionally exhibited a few microscopic bubbles or a single aperture misprint. Since they were not over the active part of the wafer, the bubbles and misprints were not considered a problem; however, for the purposes of quality ranking, they were noted. Of the three underfills containing epoxy resin B, Underfill I produced the least number of minor quality problems on the fewest wafers, followed by Underfill H and Underfill G.

Both types of defects were caused by the inability of the screen to properly release from the printed adhesive film. The screen tension was insufficient to extract the screen from the highly viscous material immediately behind the squeegee. Instead of shearing the bond between the screen and the underfill and peeling free of the film, the screen remained stuck to the adhesive.

In the case of misprints, the screen remained stuck for the entire operation. As the screen was lifted to allow removal of the wafer, the forces exerted by the screen lift-off exceeded the adhesion strength of the underfill-substrate bond instead of the shear strength between the material and the screen. Therefore, when the screen was pulled free, it also pulled underfill from the surface of the wafer, leaving a misprinted area. The occurrence of misprints appeared to be related to the solids content of the material. Only materials with the highest filler content, *Underfills A and C*, exhibited misprints.

Bubbles were also caused by a failure of the screen to release from the material. Unlike misprints, the failure was not complete. Although the screen forces were unable to shear the underfill from the screen immediately behind the squeegee, they were

sufficient to cause the material to flow from the screen. This occurred at some distance behind the squeegee. The underfill remained attached to both the screen and substrate as the screen lifted free of the film. When the screen retracted away from the underfill, these “stringers” of underfill would stretch until they “necked down”, snapped, and fell back onto the wafer. Depending on the length of the stringer, it either settled straight back and formed a mound of material, or fell over sideways, trapped air, and created a bubble.

Bubbles were most prevalent at the end of the squeegee stroke, where the screen angle, and thus the vertical screen forces, were the smallest. In *Underfill B*, the forces at the beginning of the print stroke were large enough to shear the material from the screen, but the forces at the end of the stroke were not large enough. Therefore, the bubbles occurred only at the end of the stroke.

Bubbles were also most prevalent in the materials that did not contain fillers, *Underfills D* and *E*. It appeared that the solid particles aided the release of the solids-filled material from the screen by concentrating the shear in the region adjacent to the screen wires. The underfills without fillers flowed from the screen apertures rather than quickly shearing from the screen like the solids loaded materials. Given sufficient time, the underfill flowed from the screen until the stringer of material between the screen and film sheared. These short stringers would simply settle back onto the film. As the squeegee speed increased, the peel-off velocity between the screen and wafer also increased. Higher peel-off speeds stretched the stringers, making them more likely to fall

over and trap air. This is supported by the higher incidence of bubbles on wafers printed with higher squeegee speeds, i.e., 5.1 and 7.6 cm/s (2.0 and 3.0 in/s).

Based on these quality criteria, underfill A was classified as unacceptable because of misprints, and *Underfills D* and *E* were classified as unacceptable because of the large numbers of bubbles. *Underfills B, C, G, H, and I* were classified as acceptable. The quality ranking of these materials is listed in Table 15.

Table 15: Acceptability and ranking of underfill film quality.

Underfill	Acceptability	Rank
<i>A</i>	Unacceptable	-
<i>B</i>	Acceptable	5th
<i>C</i>	Acceptable	4th
<i>D</i>	Unacceptable	-
<i>E</i>	Unacceptable	-
<i>G</i>	Acceptable	3rd
<i>H</i>	Acceptable	2nd
<i>I</i>	Acceptable	1st

5.1.3 Film Uniformity

The third of the three underfill selection criteria was film uniformity, which was comprised of two subcategories: single wafer uniformity and wafer-to-wafer-uniformity. Single wafer uniformity described variations across the film on a single wafer. Wafer-to-wafer level uniformity described the ability of an underfill to repeatedly print films of uniform thickness.

5.1.3.1. Single Wafer Uniformity

Single wafer uniformity was quantified in terms of film variation type, severity of the variation, and coverage (percentage of the film exhibiting the variation). The results of this evaluation are shown in Table 16.

Table 16: Uniformity of films printed with the nine underfills.

Underfill	Problem Type	Coverage (10% increments)	Severity
<i>A</i>	Mesh Imprint	100%	Moderate
<i>B</i>	None	-	-
<i>C</i>	Mesh Imprint	100%	Moderate
<i>D</i>	Orange Peel	100%	Severe
<i>E</i>	Orange peel	100%	Severe
<i>G</i>	Orange peel	40-60%	Mild
<i>H</i>	Orange peel	30-50%	Mild
<i>I</i>	Orange peel	30-50%	Mild

Coatings printed using *Underfills A* and *C* were uniform and without noticeable orange peel. Due to their high solids content and high viscosity, however, the coatings retained an imprint of the screen mesh, as shown in Figure 39. *Underfill A* coatings had the most distinct imprints, which appeared to be the perfect negative of the screen. The imprints in the underfill *C* films were somewhat less distinct, since the material flowed slightly after printing.

Underfill B coatings were also uniform, but without the mesh imprint seen in the previous coatings. Instead, the resin flowed and erased all traces of the mesh. The resulting films were glossy and smooth, as shown in Figure 40. This material was classified as acceptable.

Underfill D and *E* films exhibited orange peel over the entire wafer, as shown in Figure 41. The condition was aggravated by the collapse of the bubbles, previously mentioned in Section 5.1.2, which popped and left shallow depressions, corresponding to their centers. When combined with the already thin coatings (as low as 48 microns), these depressions created unacceptably thin coatings.

Figure 39: Mesh imprint in *Underfill A* film.

Figure 40: Glossy film printed with Underfill B.

Figure 41: Orange peel in a cured film of Underfill D.

Films produced with the three remaining materials, *Underfill G, H, and I* contained varying levels of orange peel. Films printed with underfill G also exhibited a uniform coating of orange peel across the wafer at all conditions. Wafers printed with *Underfills H and I* exhibited regions with both glossy and orange peel textures, which occurred at the beginning of the stroke, while the glossy areas occurred at the end of the stroke. The slower squeegee speeds (1.3 and 2.5 cm/s) and the smaller snap-off height (1.27 mm) created the films with the worst orange peel. The wafers printed with the larger snap-off height left a uniform coating with a minimal amount of orange peel. The single wafer uniformity ranking of these materials is listed in Table 17.

Table 17: Acceptability and ranking of single wafer uniformity.

Underfill	Acceptability	Rank
<i>A</i>	Marginally Acceptable	6th
<i>B</i>	Acceptable	1st
<i>C</i>	Marginally Acceptable	5th
<i>D</i>	Unacceptable	-
<i>E</i>	Unacceptable	-
<i>G</i>	Acceptable	4th
<i>H</i>	Acceptable	2nd
<i>I</i>	Acceptable	3rd

Uniformity of the printed films was adversely affected by the same conditions that created bubbles and misprints. The “orange peel” texture and thin areas were brought about by the incomplete release of the screen from the underfill during printing. Certain conditions, such as a low screen snap-off velocity, created stringers of material that snapped back and created bubbles. If these stringers broke before they became

elongated, they settled backward into the film and formed localized mounds of thicker material. Alternating with the adjacent thinner areas, these mounds formed orange peel texture. During this process, a portion of the stringers remained attached to the screen, leaving less material on the wafer. Thus, areas with orange peel usually coincided with thinner coatings.

5.1.3.2. Wafer-to-Wafer Uniformity

Repeatability of the underfill, also known as wafer-to-wafer uniformity, was evaluated only at print condition #5, because there were insufficient quantities of each underfill to print multiple wafers at the other conditions. The repeatability of the underfills at print condition #5 are listed in Table 18.

Smaller values of repeatability indicated a more uniform film, and caused the underfill to be ranked higher. *Underfills H and I* had the first and second lowest repeatability values, respectively, followed by *Underfills I and B*. Although they had identical values of repeatability, *Underfill A* was ranked fifth, ahead of *Underfill E*, because it had a smaller value of normalized repeatability. *Underfill C* was ranked seventh because it had the largest value of repeatability. *Underfill D* was not ranked because only a single wafer was printed with this material at print condition #5.

5.1.3.3. Overall Uniformity Ranking

The overall ranking was calculated by summing the individual scores of the single wafer and wafer-to-wafer categories. Materials that received a rating of ‘unacceptable’ in either category were eliminated from the comparison. That eliminated *Underfills D* and

E, since they were rated as unacceptable in single wafer uniformity. The overall uniformity rankings are listed in Table 19.

Table 18: Repeatability of wet film thickness values for underfills at print condition #5.

Underfill	Qty. of Films	Repeatability, mm (mils)	Normalized Repeatability	Wafer-to-Wafer Rank
<i>A</i>	2	0.023 (0.9)	0.13	5th
<i>B</i>	3	0.015 (0.6)	0.15	4th
<i>C</i>	3	0.028 (1.1)	0.28	7th
<i>D</i>	1	*	*	-
<i>E</i>	4	0.023 (0.9)	0.38	6th
<i>G</i>	2	0.0051 (0.2)	0.09	2nd
<i>H</i>	3	0.0025 (0.1)	0.06	1st
<i>I</i>	3	0.010 (0.4)	0.13	3rd

Table 19: Overall uniformity ranking

Underfill	Single Wafer Rank	Wafer-to-Wafer Rank	Overall Rank
<i>A</i>	6th	5th	6th
<i>B</i>	1st	4th	2nd
<i>C</i>	5th	7th	5th
<i>D</i>	*	-	*
<i>E</i>	*	6th	*
<i>G</i>	3rd	2nd	3rd
<i>H</i>	2nd	1st	1st
<i>I</i>	4th	3rd	4th

*Material not ranked because of unacceptability

5.1.4 Material Selection - Discussion

Selection of the materials for use in the next stage of the process development was relatively straightforward. Materials with obvious quality problems or insufficient

thickness were immediately rejected. These included *Underfill A*, which (despite its impressive coating thickness) had insurmountable quality problems, and *Underfills D* and *E*, which had insufficient thickness. This left only *Underfills B, C, G, H*, and *I*. Of those five underfills, *G* and *I* had marginal thickness and *Underfill C* had marginal quality. Only *Underfills B* and *H* were acceptable in every category. The overall rankings, which supported this conclusion, were obtained by summing individual rankings in thickness, quality and uniformity. The rankings of the materials, in the individual and overall categories, are shown in Table 20.

Table 20: Overall underfill rankings from material selection phase.

Underfill	Film Thickness	Film Quality	Film Uniformity	Overall
<i>A</i>	<i>1st</i>	<i>*</i>	<i>6th</i>	<i>*</i>
<i>B</i>	<i>2nd</i>	<i>5th</i>	<i>2nd</i>	<i>2nd</i>
<i>C</i>	<i>3rd</i>	<i>4th</i>	<i>5th</i>	<i>5th</i>
<i>D</i>	<i>7th</i>	<i>*</i>	<i>*</i>	<i>*</i>
<i>E</i>	<i>8th</i>	<i>*</i>	<i>*</i>	<i>*</i>
<i>G</i>	<i>6th</i>	<i>3rd</i>	<i>3rd</i>	<i>4th</i>
<i>H</i>	<i>4th</i>	<i>2nd</i>	<i>1st</i>	<i>1st</i>
<i>I</i>	<i>5th</i>	<i>1st</i>	<i>4th</i>	<i>3rd</i>

*** Excluded from overall rankings because of unacceptability in one of the three individual categories**

For the two materials with an acceptable average thickness, uniformity and quality became the principal judgement criteria. *Underfill H* was the clear choice since it was ranked first in uniformity and second in quality. *Underfill B* placed second with a

uniformity ranking of second and a quality ranking of fifth. Therefore, *Underfills H* and *B* were the materials chosen for use in the parameter selection phase.

Two observations were made in this phase of the study. Both relate to the behavior of the underfill materials during the printing operation. The first observation is that films printed with materials with higher solids content were consistently thicker than films printed with the materials with lower solids content. A possible reason for this is a variation in viscosity across the flow profile. For simplification, flow through a screen aperture is usually approximated as steady-state Newtonian flow through a pipe, as illustrated in Figure 42a.[3,4] The assumption of a Newtonian fluid assumes a uniform viscosity across the diameter of the aperture. In the case of highly solids filled materials, such as the underfills used in this study, this assumption is not valid. Because of the variation in the filler content across the diameter of the aperture, there is also a variation in the viscosity across the diameter. The filler content of the underfill is substantially lower at the edges of the aperture than in the center of the aperture. Riemer mentioned that this was caused by interaction of the particles with the screen's wires.[4] He included a figure that displayed interactions similar to those typically used in discussions of the ideal gas law. These types of interactions will be limited by the viscous nature of the resin in screen printing materials. The lower packing fraction of particles at a solid interface is a more likely cause of the resin rich area adjacent to the wires. Whatever the cause, the solid particles in the center of the flow interact (or interlock) with each other, increasing the viscosity of this particle-rich "core". This is analogous to "plug flow" through a pipe, as shown in Figure 42b.

Figure 42: Flow of a) a homogeneous Newtonian fluid versus b) plug flow in a pipe.

The velocity gradient, and therefore the shear stress, across the core is small since,

$$\tau = \mu(du/dr) \quad (29)$$

where τ is the shear stress, μ is the Newtonian viscosity, u is the fluid velocity, and r is the radius of the pipe.[7] In contrast, the velocity gradient and shear stress in the resin rich layer adjacent to the wire are quite large. This larger shear stress will subsequently cause the underfill to release (or shear) from the screen near the wire. As the bulk particle content of the material and the particle content of the core increase so do the shear stress adjacent to the wire. This means that the shear limit of the material will be exceeded at a location closer to the wire, and more of the underfill from each screen aperture will be deposited onto the substrate, as shown in Figure 43. There are limits to this phenomenon. The printed volume will not increase indefinitely. As shown by the testing of material A, the underfill will not be deposited on the wafer under certain

conditions, namely higher squeegee speeds and screen snap-off speeds, if its solids content exceeds a specific limit. This was also noted by Riemer [4].

The second observation is that printing performed with viscous solids-free fluids produce thinner films with a higher incidence of bubbles and orange peel. In contrast to the solids-filled materials, these fluids behave more like the Newtonian fluid depicted in Figure 42. The velocity gradient across the diameter of the aperture is more uniform during their deposition, and the material flows from the aperture instead of shearing free of the screen. Eventually, the material attaching the fluid core to the screen ‘necks down’ enough so that its critical shear strength is exceeded, as depicted in Figure 44.

The location at which the materials will shear free will be closer to the center of the aperture than in the solids-filled material, leaving more material on the screen, as shown in Figure 44e. This explains the smaller print volumes (*i.e.*, lower film thicknesses) observed in *underfills D* and *E*. It also explains the occurrence of bubbles and orange peel in these materials. The elongated material breaks and the stringers fall back onto the film. Longer stringers are more likely to trap air when they fall to the surface. Those stringers that do not trap air will create localized thickness variations known as orange peel.

Figure 43: Printing sequence for solids-filled underfill.

Figure 44: Printing sequence for underfill that does not contain filler.

5.2. Parameter Selection Phase

The parameter selection phase was designed to use the materials chosen in the material selection phase to determine which three screen printing parameters had the greatest effect on the underfill film. Although *Underfills B* and *G* were originally selected, *Underfill B* was not used in this phase because the manufacturer discontinued its development. The film thickness and uniformity measurements for each wafer in the parameter selection phase are shown in Table 21 and Table 22.

The thickness and roughness data were evaluated using analysis of variance (ANOVA). F-tests were performed on both the average thickness and roughness data to detect statistically significant changes in the thickness and roughness of films printed using the high and low levels of the six parameters. The results of these tests are shown in Table 23 and Table 24.

Table 21: Average underfill film thickness values for individual wafers and print conditions used in the parameter selection phase.

Print Condition	Average Underfill Thickness (μm)				
	Wafer #1	Wafer #2	Wafer #3	Wafer #4	Avg. of Four Wafers
1	80.5	84.7	84.6	83.5	83.3
2	67.6	61.1	54.3	83.5	66.6
3	100.4	106.1	101.6	102.2	102.6
4	94.1	92.0	96.2	97.0	94.8
5	70.7	65.1	72.3	65.4	68.4
6	78.0	70.9	78.6	70.9	74.6
7	90.9	104.5	88.4	97.6	95.4
8	130.5	132.6	145.5	149.2	139.4

Table 22: Average roughness values of underfill surface for individual wafers and print conditions used in the parameter selection phase.

Print Condition	Average Underfill Roughness (μm)				
	Wafer #1	Wafer #2	Wafer #3	Wafer #4	Average of Four Wafers
1	2.3	2.1	3.1	3.0	2.6
2	3.5	5.3	4.9	3.0	4.2
3	3.5	1.2	3.5	3.6	3.0
4	7.2	5.0	7.5	5.2	6.2
5	5.0	4.6	4.8	4.4	4.7
6	3.8	3.3	3.7	3.2	3.5
7	6.6	8.5	7.0	8.4	7.6
8	5.6	6.0	4.7	6.6	5.7

The F-test for film thickness predicted that five of the six variables had significant effects. In the order of significance, they were mesh count, squeegee speed, snap-off height, squeegee hardness, and squeegee angle. They were significant at confidence levels between 96.5% and 99.9%. The squeegee angle failed to prove significant at the 95% confidence level.

The F-test for film roughness predicted a similar result. Four out of the six variables had significant effects including mesh count, squeegee angle, snap-off height, and squeegee force. They were significant at confidence levels between 98.6% and 99.9%. The significance of the squeegee hardness, 91.3%, fell just under the 95% significance level, but the significance level of the squeegee speed was far below that.

Table 23: *F-test results for average underfill film thickness data collected in the parameter selection phase.*

Variable(s)	Degr. of Freedom (df)	Sum of Squares (type I)	Mean Square	Variance Ratio, (F)	Significance Level, (α)
<i>Squeegee Speed</i>	1	1730.19	1730.19	18.657	0.001
<i>Snap-Off Height</i>	1	1680.55	1680.55	18.122	0.001
<i>Squeegee Force</i>	1	130.81	130.81	1.411	0.246
<i>Squeegee Hardness</i>	1	1018.13	1018.13	10.979	0.003
<i>Mesh Count</i>	1	10328.43	10328.43	111.37	0.001
<i>Squeegee Angle</i>	1	461.32	461.32	4.975	0.035
<i>Error</i>	25	2318.40	92.37		

Table 24: *F-test results for average underfill film roughness data collected in the parameter selection phase.*

Variable(s)	Degr. of Freedom (df)	Sum of Squares (type I)	Mean Square	Variance Ratio, (F)	Significance Level, (α)
<i>Squeegee Speed</i>	1	0.945	0.945	0.777	0.386
<i>Snap-Off Height</i>	1	15.263	15.263	12.548	0.002
<i>Squeegee Force</i>	1	8.508	8.508	6.995	0.014
<i>Squeegee Hardness</i>	1	3.850	3.850	3.166	0.087
<i>Mesh Count</i>	1	28.313	28.313	23.278	0.001
<i>Squeegee Angle</i>	1	15.540	15.540	12.777	0.001
<i>Error</i>	25	30.408			

Following the F-tests, the estimated marginal means of film thickness and roughness were calculated for each independent variable. These are shown in Table 25 and Table 26. Based on the estimated means, the parameters that showed the largest

deviation in film thickness were the screen mesh count, the squeegee speed, and the snap-off height. The three parameters that showed the largest deviation in estimated mean roughness were the screen mesh count, the squeegee speed, and the snap-off height. Since film thickness was the primary criterion used to evaluate the underfills, it will be discussed first.

Table 25: Estimated marginal mean thickness for screen printing parameters.

Screen Printing Parameter	Mean Thickness at Low Level (μm)	Mean Thickness at High Level (μm)	Difference in Means
Mesh Count	111.3	75.4	-35.9
Squeegee Speed	86.0	100.7	14.7
Snap-Off Height	86.1	100.6	14.5
Squeegee Hardness	99.0	87.7	-11.3
Squeegee Angle	97.1	89.5	-7.6
Squeegee Force	91.3	95.4	4.1

Table 26: Estimated marginal mean roughness for screen printing parameters

Screen Printing Parameter	Mean Roughness at Low Level (μm)	Mean Roughness at High Level (μm)	Difference in Means
Mesh Count	5.63	3.75	-1.88
Squeegee Angle	5.39	3.99	-1.40
Snap-Off Height	5.38	4.00	-1.38
Squeegee Force	4.12	5.21	1.09
Squeegee Hardness	5.04	4.34	-0.70
Squeegee Speed	4.86	4.52	-0.34

The relative aperture size of the two screens used in this phase is compared in Figure 45. Although the wire diameter, d_w , aperture width, d_R , and mesh size, m , are all

different, the relative ratio of open area to total screen area, d_R^2/m^2 , is approximately the same for both screens. Thus, the real difference between them is the screen thickness. Coincidentally, the ratio of estimated mean film thickness for the two screens is equal to the ratio of their screen thickness, as shown in Figure 46. A least squares linear regression, forced through the origin, yields a line with a correlation coefficient, R^2 , of 0.99, indicating a linear relationship between film thickness and screen thickness.

Figure 45: Schematic of 31.5 wires/cm (80 wires/in) and 47.2 wires/cm (120 wires/in) mesh screen dimensions.

Figure 46: Response of marginal mean film roughness to changes in screen thickness.

Although changes in squeegee speed and snap-off height had a lesser effect on film thickness than changes in the screen mesh thickness, they were still significant. Increasing the speed and snap-off height from their low levels to their high levels caused their estimated mean film thicknesses to increase by 17%.

The squeegee hardness and squeegee angle also had statistically significant effects (at the $\alpha=0.05$ level), causing reductions of 11.4% and 7.8% in the estimated mean thickness when changed from the low level to the high level.

Changes in the screen mesh thickness caused the largest variation (-33%) in the surface roughness, reducing the estimated mean from 5.63 to 3.75 μm . A linear least squares regression performed on the roughness data, also indicated a linear

correlation between the surface roughness and the thickness of the screen as shown in Figure 47.

Figure 47: Response of marginal mean surface roughness to changes in screen thickness.

Changes in the snap-off height, squeegee angle, and squeegee force also had statistically significant effects on the roughness. The larger snap-off height had a reduced roughness, and an increased thickness. An increase in squeegee angle also reduced the roughness, but decreased the film thickness. Lastly, the increases in squeegee force increased the surface roughness, while having no significant effect on film thickness.

The squeegee hardness and speed also showed variations, but they were not significant at the 95% confidence level. The hardness did exhibit decreased surface roughness with the harder (90 durometer) squeegee, but it was significant only at a 92% confidence level.

Ideally, changes in the six parameters would result in beneficial changes in both the film thickness and film roughness measurements. This behavior only occurred with changes in the snap-off height. An increase in film thickness and a decrease in film roughness were observed when the snap-off height was increased. Two of the other parameters, squeegee speed and squeegee force, caused statistically significant changes in only one of the two measured film properties, i.e. thickness or roughness. Changes in the remaining variables, screen thickness, squeegee hardness, and squeegee angle had opposing effects on the two measurements: an increase in the variable would produce a beneficial change in the film thickness and a detrimental change in film roughness.

In the parameter selection phase of the testing, the screen (mesh) dimensions had the largest effect on the selected film properties. Changes in screen thickness produced the largest variations in both film thickness and roughness. Increases in screen thickness caused increases in both the film thickness and roughness. While increases in film thickness are beneficial, increases in film roughness are not. If the increase is too large, the film roughness may cause an incomplete bondline during assembly, resulting in an unacceptable part. Because the changes in these two criteria produce contrasting effects, it is especially important to select the proper screen - one that is thick enough to meet the minimum film thickness requirement, yet thin enough to minimize film roughness.

The differences in predicted film thickness values between levels of snap-off height and between levels of squeegee speed were nearly identical. The differences in predicted film roughness values between levels of snap-off height and between levels of squeegee angle were also similar. Since the film thickness increased and the roughness decreased

with increasing snap-off height, the problem of selecting a snap-off height is much easier than selecting the screen thickness. Larger snap-off heights produced beneficial changes in both criteria.

Increases in the squeegee speed from 2.5 to 5.1 cm/s (1.0 to 3.0 in/s) produced a 17% increase in the estimated mean film thickness and a statistically insignificant reduction in roughness. Since only the thickness varied, the squeegee speed can be adjusted to optimize the film thickness without significantly altering the roughness.

The harder (90 durometer) squeegee produced an 11% thinner film than the softer (70 durometer) squeegee, but also produced a 14% decrease in roughness. These opposite effects mean that selection of a squeegee is not straightforward. It is dependent on the other parameters. The harder squeegee can be used to provide smoother films if the other parameters are set to values that allow the thickness requirements to be met. A softer squeegee may be required, however, if the settings of the other parameters do not provide sufficient thickness.

The squeegee angle produced the smallest significant effect on thickness, an 8% decrease, and the second largest decrease in roughness, a 26% decrease. Just like the squeegee hardness, the angle chosen for a process will depend on the other parameters. The angle can be used to reduce roughness, but may adversely impact the film thickness.

The increase in squeegee force from 35.6 to 71.1 N (8 to 16 lbs.), during this phase of testing, produced a statistically significant increase in film roughness, but a statistically insignificant increase in film thickness. Since only the roughness was affected, the force

can be used to counteract the negative effects other parameters have on film roughness, when they are adjusted to increase film thickness.

The conclusions from this phase are that changes in screen thickness, squeegee speed, and snap-off height create the largest response in film thickness and roughness. These conclusions are based on a level III fractional factorial experiment and do not account for interactions among the parameters.

5.2.1 Comparison with Riemer's Derivations - Parameter Selection Phase

Most analyses of the screen printing process divide it into two distinct processes: screen filling and material deposition. According to Riemer the screen filling process is linearly dependent on the squeegee speed and dependent on a complex function of the squeegee angle.[4] If these theories hold true, a plot of the marginal mean film thicknesses for squeegee speed and squeegee angle should yield a straight line with a constant slope and an intercept of zero when plotted against squeegee speed and against the complex function of squeegee angle. As can be seen from Figure 48 and Figure 49, the marginal mean film thickness values do not correspond to the expected values. The intercept of both graphs is significantly substantially larger than zero, indicating that the printed film thickness data do not support Riemer's relationship for screen filling, as described by Equation (3). There are three possible reasons for the failure to prove this relationship: 1) this process is not limited by screen filling; 2) the process is dependent on both screen filling and material deposition; or 3) the derivations are not accurate representations of the screen printing process.

The first reason is the correct one. If the screen does not fill, there will be no contact between the underfill and substrate, and no material will be deposited on the substrate. All of the screen printing operations in the parameter selection phase were successful; therefore, logic dictates that the screen filled successfully. Riemer's relationship predicts only the material pressure, not whether the screen will fill successfully. It only proves useful in the event that the print fails. Even then, it only suggests that the squeegee speed or squeegee angle be reduced. It does not indicate the magnitude of the reduction.

Figure 48: Response of marginal mean film thickness to squeegee speed.

Figure 49: *Response of marginal mean film thickness to the function of squeegee angle.*

According to Rierner, the material deposition process is dependent on the snap-off height and the squeegee speed.[4] It was already shown in the analysis of screen printing, that the thickness should not be proportional to the squeegee speed, because Rierner theorized that **both** the screen filling process and the deposition process are dependent on the speed. If the process is dependent on both screen filling and deposition, the thickness should be directly proportional to the square of the squeegee speed. Plots of the marginal mean film thickness as a function of the snap-off height and the square of squeegee speed are shown in Figure 50 and Figure 51. Linear regressions on these data failed to yield lines with constant slope that intersected the origin, and therefore the data failed to support Rierner's derivations.

Figure 50: Response of marginal mean film thickness to snap-off height.

Figure 51: Response of marginal mean film thickness to the square of squeegee speed.

5.3. Response Phase

The objective of this phase was to determine the response of two variables, namely cured film thickness and roughness, to changes in the three parameters selected in the parameter selection phase. The two dependent variables were measured in the manner as they were measured in Section 4.4.2. The raw data are listed in the Appendix B. A full factorial experiment was selected because it allowed determination of the primary effects of the independent variables and the interactions among them.

The first step in analyses of the response phase data was the performance of a single factor F-test on the underfill thickness data to ensure that significant variations had occurred between print conditions. The results of the F-test for the 4 replications and 27 conditions are listed in Table 27. The F-value of 4.860 easily exceeded the critical value of $F_{\alpha=0.05} = 2.29$ [16] confirming that there was a statistically significant difference in the thickness data between at least two of the conditions, at the 95% confidence level.

Table 27: Results of F-test for underfill thickness response to the total population in response phase printing tests.

<i>Variance Ratio, F</i>	<i>Variance Ratio at $\alpha=0.05$, $F_{\alpha=0.05}$</i>	<i>Degrees of Freedom between conditions, df_1</i>	<i>Degrees of Freedom, error, df_2</i>	<i>Significance, (α)</i>
4.860	2.29	26	81	0.001

Additional F-tests were performed on the individual and grouped variables shown in Table 29. Each of the independent variables and all of the grouped variables exhibited

significant variance ratios, F , at the 99.9% confidence level, indicating a significant difference between at least two of their levels. Further analyses were required to determine whether significant differences existed among all levels of the variables.

Table 28: Results of F-test for underfill thickness response to changes in specific variables.

<i>Variable(s)</i>	<i>Degr. of Freedom (df)</i>	<i>Sum of Squares (type I)</i>	<i>Mean Square</i>	<i>Variance Ratio, (F)</i>	<i>Signif. Level, (α)</i>
Mesh Count	2	27428.31	13714.15	869.050	0.001
Snap-Off Height	2	1873.62	936.81	59.365	0.001
Squeegee Speed	2	1248.02	624.01	39.543	0.001
Mesh Ct.-SnapOff Ht.	4	2783.33	695.83	44.094	0.001
Mesh Ct.-Sq.Speed	4	104.09	26.02	1.649	0.170
Snap-Off Ht.-Sq.Speed	4	411.56	102.89	6.520	0.001
Error	79	1246.67	15.78		

5.3.1 Response Phase – Thickness Main Effects

The estimated mean thickness values of the primary variables, shown in Table 29, were calculated for comparison of the different levels. Although each of the variables appeared to exhibit a significant change between all three levels, pairwise F-tests were necessary to confirm that the differences between the level were significant. The results of these tests are shown in Table 30, Table 31, and Table 32.

Table 29: Estimated marginal mean film thickness for the three levels of each independent variable.

Variable	Level	N	Mean Thickness, μm	Std. Error, μm
Mesh Count, wires/cm (wires/in)	31.5 (80)	36	105.3	0.67
	41.3 (105)	36	76.6	0.67
	47.2 (120)	36	67.8	0.66
Snap-Off Height, mm (in)	0.76 (0.030)	36	87.0	0.67
	1.1 (0.045)	36	77.6	0.67
	1.5 (0.060)	36	85.1	0.66
Squeegee Speed, cm/s (in/s)	2.5 (1.0)	36	78.9	0.67
	5.1 (2.0)	36	80.4	0.67
	7.6 (3.0)	36	87.4	0.66

Table 30: Comparison of the difference in mean underfill film thickness between levels of screen mesh count using F-tests.

Mesh Count, 1st level, wires/cm (wires/in)	Mesh Count, 2nd level, wires/cm (wires/in)	Difference in Mean Thickness, 1st - 2nd level, μm	Std. Error, μm	Signif. Level, α	95% Confidence Interval	
					Lower Limit, μm	Upper Limit, μm
31.5 (80)	41.3 (105)	28.7	0.95	0.001	26.8	30.6
	47.2 (120)	37.5	0.95	0.001	35.6	39.4
41.3 (105)	31.5 (80)	-28.7	0.95	0.001	-30.6	-26.8
	47.2 (120)	-8.8	0.95	0.001	6.9	10.7
47.2 (120)	31.5 (80)	-37.5	0.95	0.001	-39.3	-35.7
	47.2 (105)	-8.8	0.95	0.001	-10.7	-6.9

Table 31: Comparison of the difference in mean underfill film thickness between levels of snap-off height using F-tests.

Snap-Off Height, 1st level, mm (in)	Snap-Off Height, 2nd level, mm (in)	Difference in Mean Thickness, 1st – 2nd level, μm	Std. Error, μm	Signif. Level, α	95% Confidence Interval	
					Lower Limit, μm	Upper Limit, μm
0.76 (0.030)	1.1 (0.045)	9.4	0.95	0.001	7.4	11.3
	1.5 (0.060)	1.8	0.95	0.056	-4.9e-02	3.8
1.1 (0.045)	0.76 (0.030)	-9.4	0.95	0.001	-11.3	-7.4
	1.5 (0.060)	-7.5	0.95	0.002	-9.5	-5.6
1.5 (0.060)	0.76 (0.030)	-1.8	0.95	0.056	-3.8	4.9e-02
	1.1 (0.045)	7.5	0.95	0.002	5.6	9.5

Table 32: Comparison of the difference in mean underfill film thickness between levels of squeegee speed using F-tests.

Squeegee Speed, 1st level, cm/s (in/s)	Squeegee Speed, 2nd level, cm/s (in/s)	Difference in Mean Thickness, 1st – 2nd level, μm	Std. Error, μm	Signif. Level, α	95% Confidence Interval	
					Lower Limit, μm	Upper Limit, μm
2.5 (1.0)	5.1 (2.0)	-4.4	0.96	0.001	-6.4	-2.5
	7.6 (3.0)	-8.5	0.95	0.001	-10.4	-6.5
5.1 (2.0)	2.5 (1.0)	4.4	0.96	0.001	2.5	6.4
	7.6 (3.0)	-4.0	0.95	0.001	-6.0	-2.1
7.6 (3.0)	2.5 (1.0)	8.5	0.95	0.001	6.5	10.4
	5.1 (2.0)	4.0	0.95	0.001	2.1	6.0

The results of the pairwise F-tests showed that significant differences existed between all pairings of the three levels of each primary variable, except one. The confidence level ($1-\alpha$) for these differences was between 99.6 and 99.9%. The only

exception occurred between the 1.5 and 0.76 mm (0.060 inch and 0.030 inch) snap-off heights. The 95% confidence interval encompassed zero, indicating that their mean thickness values were not significantly different at this level. The small difference, 1.531 μ m, between the means of these two levels was only significant at a 94.4% confidence level. Despite the high level of significance, the magnitude of the difference between these levels was not large enough to warrant further attention.

The most noteworthy aspect of this analysis was the effect of mesh count, or really screen thickness, on the film thickness. While the significance of this difference was not statistically larger than most of the others, the magnitude of the difference was substantially larger. The changes in film thickness between the underfill applied with the 80 mesh screen and the underfill applied with the other screens was at least 3 times greater than the next largest change. Screen thickness will obviously have the largest effect of any primary variable on the final thickness of the underfill film.

Control of this variable is straightforward because the thickness is linearly proportional to the thickness of the screen. This relationship is shown in Table 33 and Table 34. The ratio of the film thickness values for the screens are within 3% of the screen thickness ratios. The results of a linear least squares regression of the marginal mean film thickness data are shown in Figure 52. As expected, the correspondence was excellent with a correlation coefficient (R^2) value of 0.9947, reinforcing the observation first made in the parameter response phase that the film thickness was directly proportional to the screen thickness.

Table 33: Screen thickness data and estimated marginal film thickness for comparison.

Screen Mesh Count, wires/cm (wires/in)	Screen Thickness Range [8], mm (mils)	Nominal Screen Thickness, mm (mils)	Marginal Mean Underfill Thickness Printed with Screen (microns)
80	0.20-0.23 (8.0-8.9)	0.21 (8.45)	105.3
105	0.15-0.17 (6.0-6.7)	0.16 (6.35)	76.6
120	0.13-0.15 (5.2-5.8)	0.14 (5.5)	67.8

Table 34: Comparison of screen thickness versus film thickness.

Ratio Description	Screen Mesh Ratio		
	80/105	80/120	105/120
<i>Ratio of screen thickness</i>	1.33	1.54	1.15
<i>Ratio of mean thickness' printed with corresponding screens</i>	1.37	1.55	1.13

Figure 52: Response of marginal mean film thickness to changes in screen thickness.

According to the results of the F-test, of changes in film thickness caused by changes in the snap-off height were also significant. The largest change in film thickness, 9.4 microns, occurred between the (0.030 and 0.045) inch settings. A similar, but slightly smaller change, 7.5 microns, occurred between the 1.1 and 1.5 mm (0.045 and 0.060 inch) settings. The film thicknesses produced by the 1.1 mm (0.045 inch) setting were smaller than those produced using the larger and smaller settings. This non-linear response is a possible indication in a change in the mechanics of deposition.

At small snap-off heights, it was observed that the screen stuck in the film, as predicted by Riemer, and was not pulled free until later, when the screen was physically lifted by the screen printer. At larger snap-off heights, the larger angle between the screen and the wafer increased the vertical component of the screen tension, and usually resulted in a clean release of the screen during printing. In either case, the separation velocity between the screen and the wafer was large. At the intermediate snap-off height, however, the separation velocity was much smaller. Therefore, the screen adhered to the film for a time after the squeegee passed. Unlike at the smallest snap-off height, however, the screen slowly peeled free of the film during the ensuing delay before screen removal. The screen typically released from 70-95% of the film before the entire screen was physically removed. At the slower separation speeds created by this slow peel, there was a higher incidence of orange peel, indicating that the material flowed from the screen apertures rather than shearing free of the screens. As observed in the parameter selection phase, flow of the material from the screen usually resulted in larger amounts of underfill film left on the screen because the material sheared closer to the center of the aperture.

Consequently, flow of the material resulted in thinner films. No correlation between snap-off height and film thickness was observed because the method of screen release at each of the snap-off heights was not consistent. When the screen was quickly sheared free of the films at the 0.76 and 1.5 mm (0.030 and 0.060 inch) snap-off heights the film thickness was statistically identical. The film thickness only varied at the 1.1 mm (0.045 inch) snap-off height when the screen was removed through a combination of slow peeling and shearing from the film.

The final main effect concerned the increase in film thickness with increases in squeegee speed. The magnitude of the changes was approximately half of those observed with changes in the snap-off height, but unlike those responses, the effect was roughly linear. The results of a linear least squares regression of the marginal means as a function of squeegee speed is shown Figure 53. The R^2 value of 0.8775, was below the 0.95 value that signified a linear response, therefore, the response was classified as non-linear. In addition, the intercept of the linear fit was substantially larger than the expected value of zero. Adjustment of the data points to account for the standard error ($0.96\text{ }\mu\text{m}$), however, can increase the value as high as 0.9465 as shown in Figure 55. Further testing at higher and lower squeegee speeds is required to determine whether a linear correlation is present or whether this is simply random variation of data.

The response phase data failed to support Riemer's equations for screen filling or material deposition. The printed film thickness was not directly proportional to either squeegee speed or snap-off height. The film thickness was only directly proportional to the screen thickness.

Figure 53: A comparison of marginal mean film thickness with squeegee speed. Dashed line indicates position of linear fit.

Figure 54: A comparison of marginal mean film thickness with squeegee speed after adjustment of data with the standard error.

Although the mean film thickness data did not indicate a truly linear relationship between film thickness and squeegee speed, it can still be used to as a process control. Within the bounds of the test parameters employed in this test phase, the squeegee speed can be adjusted to provide a roughly linear adjustment of the film thickness. It cannot be used to print films with specific thickness values, but can be adjusted to increase or decrease the film thickness from the thickness of a previous print operation. Further testing at higher and lower squeegee speeds is required to determine whether a correlation is present or if this is simply the random variation.

5.3.2 Response Phase – Thickness Interactions

The next step in the analysis was investigation of possible secondary effects, caused by the first order interaction of two primary variables. The F-test results from Table 28 indicate that there are no significant interactions among levels of the grouped variable *mesh count-squeegee speed*. That leaves only two other grouped variables, *mesh count-snap-off height* and *snap-off height-squeegee speed* which had possible interactions. The mean film thickness values and 95% confidence intervals produced by each level for these grouped variables are listed in Table 35 and Table 36. An interaction between levels of these variables will not exist unless the 95% confidence intervals for the adjacent levels do not overlap. An inspection of the data shows numerous cases where they do not overlap. This does not mean interactions are present, merely that one might be present. No clear interactions are present in the data.

The data was plotted in Figure 55 and Figure 56 to determine whether a graphical representation would make any trends would more visible. The main effects of screen

thickness, snap-off height, and squeegee speed are clearly visible, but no obvious interactions appear other than the main effects discussed previously. It is possible that effects between pairs of non-adjacent conditions exist. Additional data points or a more sophisticated statistical approach, or both, are required to discover the interactions in this data.

Table 35: Mean film thickness values for the combination of mesh count and snap-off height.

Mesh Count, wires/cm (wires/in)	Snap-Off Height, mm (in)	Mean Film Thickness μm	Std. Error, μm	95% Confidence Interval	
				Lower Limit, μm	Upper Limit, μm
35.1 (80)	0.76 (0.030)	110.6	1.147	109.4	111.8
	1.1 (0.045)	100.3	1.147	99.1	101.5
	1.5 (0.060)	105.0	1.147	103.8	106.2
41.3 (105)	0.76 (0.030)	76.7	1.209	75.4	77.9
	1.1 (0.045)	65.0	1.147	63.8	66.2
	1.5 (0.060)	88.1	1.147	86.9	89.3
47.2 (120)	0.76 (0.030)	73.6	1.147	72.4	74.8
	1.1 (0.045)	67.5	1.209	66.3	68.8
	1.5 (0.060)	62.3	1.147	61.1	63.5

Table 36: Mean film thickness values for the combination of snap-off height and squeegee speed.

Snap-Off Height, mm (in)	Squeegee Speed, mm (in/s)	Mean Film Thickness μm	Std. Error, μm	95% Confidence Interval	
				Lower Limit, μm	Upper Limit, μm
0.76 (0.030)	2.5 (1.0)	81.5	1.209	80.2	82.8
	5.1 (2.0)	85.4	1.147	84.2	86.6
	7.6 (3.0)	94.0	1.147	92.8	95.2
1.1 (0.045)	2.5 (1.0)	74.3	1.147	73.1	75.5
	5.1 (2.0)	80.3	1.209	79.1	81.6
	7.6 (3.0)	78.2	1.147	77.0	79.4
1.5 (0.060)	2.5 (1.0)	81.1	1.147	79.9	82.2
	5.1 (2.0)	84.4	1.147	83.2	85.6
	7.6 (3.0)	90.0	1.147	88.8	91.2

Figure 55: Plot of film thickness data for the grouped variable mesh count-snap-off height.

Figure 56: Plot of film thickness data for the grouped variable snap-off height-squeegee speed.

5.3.3 Response Phase – Roughness Main Effects

The same method used to determine the variables that affected film thickness was also used to determine the variables that affected the film roughness. First, an F-test was performed on all levels of the primary and secondary variables. As shown in Table 37, the only significant effects on film roughness occurred with variations in the snap-off height, the squeegee speed, and the grouped variable *mesh count-snap-off height*.

A comparison of the estimated marginal means in Table 38 indicated an expected effect with changes in the snap-off height. It was confirmed with a t-test on the marginal mean film roughness, as shown in Table 39. The largest values of roughness occurred at the intermediate snap-off height (1.1 mm). As mentioned in Section 4.1, orange peel is produced when the screen is slowly removed from the substrate and the underfill flows from the screen apertures. Since a slow screen peel-off was already observed with the

wafers printed using the intermediate snap-off height, higher roughness values were expected. A significant change in film thickness was also detected between the wafers printed at the high and low snap-off values, possibly because separation of the screen occurred during screen liftoff rather than during the printing process. The faster screen lift-off speed, 0.25 cm/s (0.1 in/s), would create a higher shear force and cause the underfill to separate more cleanly from the screen - hence the reduced roughness.

Table 37: Results of F-test for underfill roughness response to changes in specific variables.

Variable(s)	Degrees of Freedom (df)	Sum of Squares (type I)	Mean Square	Variance Ratio, (F)	Significance (α)
Mesh Count	2	2.952	1.476	1.848	0.164
Snap-Off Height	2	49.956	24.978	31.266	0.001
Squeegee Speed	2	6.483	3.242	4.058	0.021
Mesh Ct.-SnapOff Ht.	4	68.803	17.201	21.531	0.001
Mesh Ct.-Sq.Speed	4	0.549	0.137	0.172	0.952
SnapOff Ht.-Sq.Speed	4	6.526	1.632	2.042	0.096
Error	81	63.13	0.799		

The other main effect occurred with changes in the squeegee speed. The results of an F-test on the estimated marginal means, shown in Table 40, showed no significant difference between the slower squeegee speeds of 2.5 and 5.1 cm/s (1.0 and 2.0 in/s), but indicated an increase in roughness with the higher squeegee speed of 7.6 cm/s (3.0 in/s).

This was counterintuitive. It was expected that the slower squeegee speeds and corresponding slow screen separation speeds would not be fast enough to shear the underfill from the screen. This would cause the underfill to flow from the screen and result in orange peel with its corresponding roughness. The higher squeegee speed and corresponding higher screen separation speed were expected to quickly shear the underfill from the screen causing less orange peel and reduced roughness. This rationale was not entirely incorrect. A check of the data reveals that it was skewed by the extremely high roughness values measured on wafers that were printed with squeegee speeds of 7.6 cm/s (3.0 in/s) and a snap-off height of 1.1 mm (0.045 in). The roughness value observed under those print conditions was 30% larger than the next largest roughness value. It was also 90% and 45% larger than the roughness values at the same speed and the 0.76 and 1.5 mm (0.060 and 0.030 inch) snap-off heights, respectively. The range of roughness values exhibited by coatings printed at the 0.76 and 1.5 mm (0.030 and 0.060 inch) snap-off heights varied by only 12% and 5%, respectively. The results were skewed by the values produced at this one set of print conditions.

The correlation between the screen thickness and screen thickness observed in the parameter selection phase was not observed in this phase. No significant differences were observed between any pair of screen thickness levels.

5.3.4 Response Phase – Roughness Interactions

The F-test on the roughness data for the grouped variable *mesh count-snap-off height* indicated possible interactions among conditions. The data, shown in

and Figure 57 were analyzed for evidence of such an interaction. They appeared more random than the thickness data. No definitive interactions were observed, except for the main effect of the 0.045 snap-off height.

One interesting feature of the graph was the roughness value for the film printed with 47.2 wires/cm (120 wires/in) screen and the 1.5 mm (0.060 inch) snap-off height. Its roughness value went against the observed trend. It was larger than the roughness measure on the film printed with the 47.2 wires/cm (120 wires/in) screen and 1.1 mm (0.045 inch) snap-off height. No statistical inferences could be made regarding this observation.

Table 38: *Estimated marginal mean film surface roughness for the three levels of each independent variable.*

<i>Variable</i>	<i>Level</i>	<i>N</i>	<i>Mean Roughness, μm</i>	<i>Std. Error, μm</i>
<i>Mesh Count, wires/cm (wires/in)</i>	31.5 (80)	36	3.4	0.152
	41.3 (105)	35	3.2	0.152
	47.2 (120)	35	3.6	0.149
<i>Snap-Off Height, mm (in)</i>	0.76 (0.030)	35	3.4	0.152
	1.1 (0.045)	35	3.8	0.152
	1.5 (0.060)	36	3.1	0.149
<i>Squeegee Speed, cm/s (in/s)</i>	2.5 (1.0)	35	3.2	0.152
	5.1 (2.0)	35	3.3	0.152
	7.6 (3.0)	36	3.8	0.149

Table 39: Comparison of mean underfill film surface roughness between levels of snap-off height using F-tests.

Snap-Off Height, 1st level, mm (in)	Snap-Off Height, 2nd level, mm (in)	Difference in Mean Roughness, 1st – 2nd level, μm	Std. Error, μm	Signif. Level, α	95% Confidence Interval	
					Lower Limit, μm	Upper Limit, μm
0.76 (0.030)	1.1 (0.045)	-1.63	0.215	0.001	-2.06	-1.20
	1.5 (0.060)	-0.66	0.213	0.003	-1.08	-0.23
1.1 (0.045)	0.76 (0.030)	1.63	0.215	0.001	1.20	2.06
	1.5 (0.060)	0.97	0.213	0.001	0.54	1.40
1.5 (0.060)	0.76(0.030)	0.66	0.213	0.003	0.23	1.08
	1.1 (0.045)	-0.97	0.213	0.001	-1.40	-0.54

Table 40: Comparison of the mean underfill film surface roughness between levels of squeegee speed using an F-test.

Squeegee Speed, 1st level, cm/s (in/s)	Squeegee Speed, 2nd level, cm/s (in/s)	Difference in Mean Roughness, 1st – 2nd level, μm	Std. Error, μm	Signif. Level, α	95% Confidence Interval	
					Lower Limit, μm	Upper Limit, μm
2.5 (1.0)	5.1 (2.0)	-3.38e-02	0.215	0.875	-0.47	0.40
	7.6 (3.0)	-0.54	0.213	0.013	-0.97	-0.11
5.1 (2.0)	2.5 (1.0)	0.38e-02	0.215	0.875	-0.40	0.461
	7.6 (3.0)	-0.51	0.213	0.020	-0.93	-8.23e-02
7.6 (3.0)	2.5 (1.0)	0.54	0.213	0.013	-0.12	0.97
	5.1 (2.0)	0.51	0.213	0.020	8.23e-02	0.93

Table 41: Mean film surface roughness values for all combinations of mesh count and snap-off height. Mean values are estimated marginal means.

Mesh Count, wires/cm (wires/in)	Snap-Off Height, mm (in)	Mean Film Surface Roughness, μm	Std. Error, μm	95% Confidence Interval	
				Lower Limit, μm	Upper Limit, μm
31.5 (80)	0.076 (0.030)	2.84	0.272	2.57	3.12
	1.1 (0.045)	4.27	0.258	4.01	4.53
	1.5 (0.060)	3.16	0.258	2.90	3.42
41.3 (105)	0.076 (0.030)	3.36	0.258	3.10	3.62
	1.1 (0.045)	5.32	0.272	5.04	5.59
	1.5 (0.060)	2.22	0.258	1.96	2.48
47.2 (120)	0.076 (0.030)	1.79	0.258	1.53	2.05
	1.1 (0.045)	3.29	0.258	3.03	3.55
	1.5 (0.060)	4.57	0.258	4.31	4.83

Figure 57: Plot of film thickness data for the grouped variable mesh count-snap-off height.

CHAPTER 6

CONCLUSIONS

The three phases of this study each yielded valuable information regarding the screen printing of underfill adhesive. The material selection phase yielded two subjective conclusions regarding the screen printing of underfills. The first conclusion was that solids-filled materials produced thicker printed films than unfilled materials. The second was that materials that did not contain fillers produced films that contained larger quantities of bubbles and orange peel.

The conclusions derived from the remaining phases were quantitative in nature. The parameter selection phase thickness measurements proved that screen thickness, snap-off height, and squeegee speed had the largest effect on the thickness of films printed with highly solids-loaded materials. Of these three variables, screen thickness had the largest effect.

The response phase data confirmed these effects. It also confirmed the supposition, made in the parameter selection phase, that the printed film thickness was directly proportional to the screen thickness. The effect of changes in squeegee speed was also linear, although not directly proportional. Unlike the other variables, the response of the film thickness to changes in snap-off height was more complex, varying not only as a direct function of snap-off height, but also with first order interactions of snap-off height with screen thickness and squeegee speed. As in the previous phase, changes in screen thickness produced the largest changes in film thickness followed by changes in snap-off height and squeegee, respectively.

Statistical analysis of the parameter selection and response phase data failed to confirm either of Riemer's derivations. The film thickness was not directly proportional to the squeegee speed or the complex function of squeegee angle, as predicted by Riemer's derivation for screen filling. Nor was the film thickness directly proportional to snap-off height or the squeegee speed, as predicted by his equations for material deposition. Based on this lack of correlation, the approximation of screen printing operations as steady-state flow through a pipe is invalid for solids-filled materials. Based on observations the material appears to shear from the screen rather than flow from the screen.

CHAPTER 7

RECOMMENDATIONS FOR FUTURE RESEARCH

It is recommended that this research be expanded to include an analysis on the effects of material properties on the printing process. The study should evaluate the response of printed films to changes in resin properties, such as viscosity and molecular weight, and filler properties, such as size, content, and distribution. The final formulation of the wafer level underfills will depend on the results on additional tests, including long term reliability tests. Changes in material properties of the adhesive resin or filler particles may be required. Knowledge of the effect of these changes on the screen printing process would reduce the amount of testing required to optimize the screen printing process for new adhesive formulations.

CHAPTER 8

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APPENDIX A

DERIVATION OF EQUATION 20

Riemer's derivation of Equation (20) is recreated in this appendix to explain some of the assumptions that he made. Because of the limited space available in the original article, Riemer did not include the entire derivation, and many of the assumptions went unstated which made the derivation hard to follow. This step-by-step derivation also show the errors that were made in the derivation.

Riemer began his derivation by stating that two forces acted on each screen aperture to resist the snap-off of the screen.[4] The two forces, he concluded were caused by viscous friction between the paste and screen and by the pressure differential across the wires.

$$f_{mo} = \text{viscous forces} + \text{pressure forces}$$

$$f_{mo} = (\text{viscous shear stress})(\text{shear area of wires}) + \Delta p(\text{cross-sectional area of wires})$$

$$f_{mo} = \tau(\text{interior wall area of wires}) + \Delta p(\text{horiz. surface area of wires})$$

As shown in Figure 58, Riemer defined the total wall area in one aperture that is subjected to the viscous shear forces as equal to the height of the screen times the length of the four wires that formed the sides of the aperture, as described by Equation (34).

$$\begin{array}{l} \text{Total wall area} \\ \text{subjected to shear} = 4(d_R)(2d_w) \end{array} \quad (34)$$

Riemer defined the area that was subjected to the pressure differential as the maximum horizontal area of the wires that formed a single aperture, as described in Equation (35). The length of one wire was m and the length of the other was d_R . The width of both wires was d_w .

$$\text{Cross-sectional area subjected to pressure} = d_w(m + d_R) \quad (35)$$

Figure 58: Schematic of a single mesh aperture.

Using this information, Riemer derived Equation (32).

$$f_{mo} = \tau(4d_R)(2d_w) + d_w(m + d_R)\Delta p \quad (32)$$

Riemer then included an unstated assumption that Δp was approximately equal to the maximum pressure differential, as shown in Equations (36) and (37)

$$\Delta p \approx p_a \quad (36)$$

$$f_{mo} = 8\tau d_R d_w + d_w(m + d_R)p_a \quad (37)$$

where,

τ = shear stresses between paste and wire mesh surface

d_w = wire diameter

m = wire pitch

$d_R = m - d_w$ = effective mesh diameter

p_a = atmospheric pressure

The definition of shear stress was defined by Equations (38), (39), and (40)

$$\tau = \eta \frac{dV_m}{dr} \quad (38)$$

$$V_m = \left(\frac{32}{\pi} \right) \left(\frac{Q}{d_R^4} \right) \left[\frac{d_R^2}{4} - r^2 \right] \quad (39)$$

$$Q = \left(\frac{d_R^2 \pi}{4} \right) V_a = \text{volumetric flow rate through aperture} \quad (40)$$

$V_m = f(r)$ = paste velocity in aperture during screen snap-off

V_a = screen snap-off velocity

r = effective radius from center of aperture

Substituting Equation (40) into Equation (39) yielded Equation (41).

$$V_m = \left(\frac{32}{\pi} \right) \left(\frac{V_a d_R^2 \pi}{4} \right) \left(\frac{1}{d_R^4} \right) \left[\frac{d_R^2}{4} - r^2 \right]$$

$$V_m = \left(\frac{8V_a}{d_R^2} \right) \left[\frac{d_R^2}{4} - r^2 \right] \quad (41)$$

The derivative of Equation (41) was given by Equation (42).

$$\begin{aligned} \frac{dV_m}{dr} &= \frac{d}{dr} \left\{ \left(\frac{8V_a}{d_R^2} \right) \left[\frac{d_R^2}{4} - r^2 \right] \right\} \\ \frac{dV_m}{dr} &= \left(\frac{8V_a}{d_R^2} \right) \left\{ \frac{d}{dr} \left[\frac{d_R^2}{4} - r^2 \right] \right\} \\ \frac{dV_m}{dr} &= \left(\frac{8V_a}{d_R^2} \right) \{-2r\} \\ \frac{dV_m}{dr} &= -\frac{16V_a r}{d_R^2} \end{aligned} \quad (42)$$

Substitution of Equation (42) into Equation (38) for dV_m/dr resulted in Equation (43).

$$\tau = \eta \frac{dV_m}{dr} = -\frac{16\eta V_a r}{d_R^2} \quad (43)$$

Substitution of Equation (43) into Equation (32) for τ resulted in Equation (44).

$$\begin{aligned} f_{mo} &= \left(-\frac{16\eta V_a r}{d_R^2} \right) d_R 8d_w + d_w (m + d_R) p_a \\ f_{mo} &= \left(-\frac{128\eta V_a r}{d_R^2} \right) d_R d_w + d_w (m + d_R) p_a \end{aligned} \quad (44)$$

Riemer, however, specified that screen snap-off velocity V_a is related to the squeegee velocity V by Equation (45)

$$V_a = V(l_{SR}/a) \quad (45)$$

$$f_{mo} = \left(-\frac{128\eta V \left(\frac{a}{l_{SR}} \right) r}{d_R^2} \right) d_R d_w + d_w (m + d_R) p_a$$

$$f_{mo} = d_w \left[\left(-\frac{128\eta V r}{d_R} \right) \left(\frac{a}{l_{SR}} \right) + (m + d_R) p_a \right] \quad (46)$$

Substituting the relationship $r = (d_R/2)$ yielded Equation (47)

$$f_{mo} = d_w \left[\left(-\frac{128\eta V \left(\frac{d_R}{2} \right)}{d_R} \right) \left(\frac{a}{l_{SR}} \right) + (m + d_R) p_a \right]$$

$$f_{mo} = d_w \left[-64\eta V \left(\frac{a}{l_{SR}} \right) + (m + d_R) p_a \right] \quad (47)$$

Riemer defined the force acting on the portion of the screen stuck in the printed film as Equation (48).

$$F_{mo} = \left(\frac{1}{2} \right) n_K f_{mo} \quad (48)$$

where,

$$n_K = \# \text{ of apertures in the printed film} \\ = (1/m)(\text{length of screen in the film})$$

l_K = length of screen in the film(at very small angles)

so,

$$n_K = (1/m)l_K \quad (49)$$

Riemer used similar triangles, as shown in Figure 59, to obtain Equation (50).

Figure 59: Schematic of similar triangles.

$$l_K = (l_{SR}/a)(2d_f) \quad (50)$$

where it is assumed that,

$d_f = d_w$ = wire diameter

$2d_f = 2d_w$ = thickness of printed film before screen snap-off
= thickness of screen

This definition is assumed because Riemer failed to define this term in either of his articles. The number of wires in the film, n_K , is given by Equation (51).

$$n_K = (1/m)(l_{SR}/a)(2d_f)$$

$$n_K = (2d_f/m)(l_{SR}/a) \quad (51)$$

The force acting on the screen per unit width is further defined by Equation (52).

$$F_m = (1/2) n_K f_{mo}$$

$$F_m = (1/2) (2d_f/m)(l_{SR}/a)f_{mo}$$

$$F_m = \left(\left(\frac{d_f}{m} \right) \left(\frac{l_{SR}}{a} \right) \right) f_{mo} \quad (52)$$

Substituting Equation (47) into Equation (52) produced Equation (53).

$$\begin{aligned} F_m &= \left(\left(\frac{d_f}{m} \right) \left(\frac{l_{SR}}{a} \right) \right) \left\{ d_w \left[-64\eta V \left(\frac{a}{l_{SR}} \right) + (m + d_R) p_a \right] \right\} \\ F_m &= \left(\left(\frac{d_f}{m} \right) \left(\frac{l_{SR}}{a} \right) \right) \left\{ d_f \left[-64\eta V \left(\frac{a}{l_{SR}} \right) + (m + d_R) p_a \right] \right\} \\ F_{mo} &= \left(\frac{d_f^2}{m} \right) \left[-64\eta V + \left(\frac{l_{SR}}{a} \right) (m + d_R) p_a \right] \end{aligned} \quad (53)$$

Riemer theorized that the screen will be lifted free of the printed film when the vertical component of the screen tension exceeds F_m . where the screen tension is defined by Equation (54).

Screen Tension = (tensile force)(wire cross-sectional area)(tangent of snap-off angle)

$$\text{ScreenTension} = \sigma_s \left(\frac{\pi d_f^2}{4} \right) \tan \alpha \quad (54)$$

At small angles $\tan \alpha \approx \sin \alpha$ and $\sin \alpha = (a/l_{SR})$ so Equation (54) is transformed into Equation (55).

$$\text{ScreenTension} = \sigma_s \left(\frac{\pi d_f^2}{4} \right) \sin \alpha$$

$$\text{ScreenTension} = \sigma_s \left(\frac{\pi d_f^2}{4} \right) \left(\frac{a}{l_{SR}} \right) \quad (55)$$

Thus, the screen lifts free of the film when Equation (56) is satisfied.

$$\sigma_s \left(\frac{\pi d_f^2}{4} \right) \left(\frac{a}{l_{SR}} \right) > F_M \quad (56)$$

Rearranging Equation (56) and substituting Equation (53) for F_M gives Equation (57).

$$\begin{aligned} \sigma_s &> \left(\frac{4F_M}{\pi d_f^2} \right) \left(\frac{l_{SR}}{a} \right) \\ \sigma_s &> \left(\frac{4}{\pi d_f^2} \right) \left(\frac{d_f^2}{m} \right) \left[-64\eta V + \left(\frac{l_{SR}}{a} \right) (m + d_R) p_a \right] \left(\frac{l_{SR}}{a} \right) \\ \sigma_s &> \left(\frac{l_{SR}}{a} \right) \left(\frac{4}{\pi m} \right) \left[-64\eta V + \left(\frac{l_{SR}}{a} \right) (m + d_R) p_a \right] \\ \sigma_s &> \left(\frac{l_{SR}}{a} \right) \left(\frac{1}{\pi m} \right) \left[-256\eta V + 4 \left(\frac{l_{SR}}{a} \right) (m + d_R) p_a \right] \\ \left(\frac{a}{l_{SR}} \right) (\pi m) \sigma_s &> \left[-256\eta V + 4 \left(\frac{l_{SR}}{a} \right) (m + d_R) p_a \right] \\ \left(\frac{a}{l_{SR}} \right) (\pi m) \sigma_s - 4 \left(\frac{l_{SR}}{a} \right) (m + d_R) p_a &> [-256\eta V] \end{aligned} \quad (57)$$

$$\left(-\frac{1}{256}\right)\left[\left(\frac{a}{l_{SR}}\right)(\pi m)\sigma_s - 4\left(\frac{l_{SR}}{a}\right)(m + d_R)p_a\right] > \eta V$$

$$\eta V < \left(-\frac{1}{256}\right)\left[\left(\frac{a}{l_{SR}}\right)\pi m \sigma_s - 4\left(\frac{l_{SR}}{a}\right)(m + d_R)p_a\right] \quad (58)$$

$$\eta V < \left[-\left(\frac{\pi}{256}\right)\left(\frac{a}{l_{SR}}\right)m \sigma_s + \left(\frac{1}{64}\right)\left(\frac{l_{SR}}{a}\right)(m + d_R)p_a\right] \quad (59)$$

Equation (59) varies substantially from Riemer's final result, Equation (32). It appears that Riemer was not careful when deriving his equations. Although not included in the article, it is clear that he failed to include the negative sign in Equation (42) when he inserted it into Equation (37). He also failed to multiply both terms on the right hand side of Equation (57) by the preceding 4, and failed to multiply both terms in the right side of Equation (58) by the preceding 1/256. Thus, the entire right side of Equation (32) has the wrong sign, and its second term is missing a 1/64 multiplier.

$$\eta V < \left[\left(\frac{\pi}{256}\right)\left(\frac{a}{l_{SR}}\right)m \sigma_s - \left(\frac{l_{SR}}{a}\right)(m + d_R)p_a\right] \quad (32)$$

The result of Riemer's derivation should have been Equation (59).

APPENDIX B

RESPONSE PHASE RAW DATA

Table 42: Raw film thickness data for response phase print conditions 1-6.

Print Cond.	Average Thickness (mm)									
	Wafer ID	Test Site #1	Test Site #2	Test Site #3	Test Site #4	Test Site #5	Test Site #6	Test Site #7	Test Site #8	Test Site #9
1	RP25	124.15	103.74	114.43	77.98	106.50	126.60	90.32	100.32	101.14
1	RP26	106.00	103.90	114.91	76.87	102.40	111.90	83.73	109.58	87.13
1	RP27	126.35	110.24	114.43	76.43	110.10	116.10	89.96	104.44	94.24
1	RP28	108.00	98.60	112.19	67.38	101.90	114.00	92.31	115.20	85.68
2	RP21	111.20	115.00	124.27	80.99	112.00	116.57	97.12	113.34	107.67
2	RP22	113.50	110.30	113.90	73.43	105.50	113.30	83.67	114.95	91.85
2	RP23	120.10	115.90	151.60	80.40	111.80	138.77	86.71	108.04	103.52
2	RP24	114.45	104.10	100.40	81.12	104.70	113.08	84.38	110.87	84.90
3	RP1	135.08	130.10	130.20	110.03	123.10	141.91	139.48	121.42	138.40
3	RP2a	122.90	114.19	126.20	108.81	115.50	131.20	138.80	116.32	127.63
3	RP3a	126.83	123.95	133.29	105.15	120.20	135.80	140.23	110.27	124.10
3	RP4	133.13	139.42	137.50	96.39	126.50	138.40	92.47	110.80	90.33
3	RP2	119.60	105.40	130.65	57.12	108.30	145.50	102.20	107.70	104.97
3	RP3	119.57	105.17	116.64	67.53	113.60	126.85	81.44	117.84	82.08
4	RP13	89.89	81.19	121.76	79.68	119.10	117.10	125.25	104.01	110.23
4	RP14	106.72	104.45	109.54	63.78	85.37	75.18	85.82	76.38	90.98
4	RP15	103.98	75.89	121.76	73.56	113.90	118.70	123.05	99.73	97.75
4	RP16	105.67	106.41	112.19	64.04	83.65	88.54	92.39	73.60	92.89
4	RP17a	84.60	76.70	100.97	75.29	114.40	124.49	121.98	102.10	102.70
4	RP16a	102.30	88.12	113.40	64.54	73.59	79.74	80.57	66.22	78.86
5	RP5	93.61	84.30	137.69	78.84	122.40	136.21	118.04	106.73	109.43
5	RP6	118.90	128.00	124.40	80.13	124.60	102.09	98.40	80.31	93.87
5	RP7	95.68	81.31	132.39	95.94	117.30	128.41	143.24	106.53	82.96
5	RP8	119.57	119.94	123.20	72.49	114.60	100.75	86.43	79.39	93.20
6	RP17	75.02	65.18	92.73	64.45	113.80	116.70	113.21	106.19	112.67
6	RP18	111.40	121.20	121.81	72.78	112.70	103.47	83.27	82.43	84.05
6	RP19	68.50	80.96	98.69	76.63	126.00	127.30	118.21	110.49	115.87
6	RP20	108.50	118.53	127.39	68.32	88.03	77.39	85.80	76.82	82.96

Table 43: Raw film thickness data for response phase print conditions 7-13.

Print Cond.	Average Thickness (mm)									
	Wafer ID	Test Site #1	Test Site #2	Test Site #3	Test Site #4	Test Site #5	Test Site #6	Test Site #7	Test Site #8	Test Site #9
7	RP33	113.11	101.38	103.50	98.43	101.90	107.07	110.52	97.82	75.35
7	RP34	106.41	96.70	115.10	91.19	98.71	103.86	116.70	*	105.10
7	RP35	117.41	104.38	104.90	102.20	103.90	102.37	103.72	94.07	101.84
7	RP36	107.90	97.82	103.41	97.59	103.27	105.69	108.47	99.60	106.50
8	RP29	106.20	100.00	108.82	96.47	107.10	114.86	109.05	96.02	73.93
8	RP30	109.00	102.56	113.00	92.12	109.20	116.97	117.94	107.10	111.70
8	RP31	82.78	104.30	106.82	96.65	109.20	115.86	115.25	90.63	76.93
8	RP32	103.90	101.80	107.69	97.32	106.30	109.00	112.50	105.30	108.90
9	RP9	109.14	110.91	119.61	105.96	106.60	119.48	115.28	110.30	89.65
9	RP10	115.97	113.58	130.09	107.70	125.30	119.99	118.90	108.70	113.53
9	RP11	121.14	122.81	114.71	94.88	112.30	117.18	112.28	97.63	61.50
9	RP12	109.73	105.30	112.11	103.48	106.80	109.50	115.33	118.75	112.87
10	RP97	*	*	*	*	*	*	*	*	*
10	RP98	84.99	69.44	91.03	47.70	80.63	94.00	81.08	53.43	53.30
10	RP99	61.03	72.23	84.43	54.33	79.48	92.07	80.80	53.13	52.57
10	RP100	88.79	68.37	88.29	50.13	84.05	90.59	78.64	50.20	95.14
11	RP93	58.25	68.84	95.34	56.02	88.24	101.03	86.67	55.94	58.82
11	RP94	79.96	66.29	103.50	46.80	87.28	96.71	84.42	53.15	51.93
11	RP95	69.09	76.58	80.84	51.76	89.92	99.55	85.18	56.63	57.74
11	RP96	96.86	86.92	92.52	49.80	83.14	90.28	87.71	60.43	52.63
12	RP73	80.22	81.16	105.26	58.78	92.44	106.10	95.67	60.93	57.63
12	RP74	93.70	91.58	112.53	46.36	90.30	103.20	95.08	64.64	61.49
12	RP75	79.27	82.74	96.33	49.35	89.34	100.90	93.53	64.32	60.28
12	RP76	87.31	84.62	103.00	47.52	92.17	104.40	91.13	56.54	55.49
13	RP85	56.64	47.40	45.53	46.08	48.23	60.83	86.15	56.70	87.50
13	RP86	57.18	56.79	61.91	56.08	66.02	69.86	56.55	68.98	61.92
13	RP87	54.59	46.19	76.15	44.40	54.96	61.34	83.60	63.71	85.13
13	RP88	66.70	51.62	68.58	54.26	53.20	64.20	56.73	63.19	62.94

*unable to take measurement at this location because of damage to wafer

Table 44: Raw film thickness data for response phase print conditions 14-21.

Print Cond.	Average Thickness (mm)									
	Wafer ID	Test Site #1	Test Site #2	Test Site #3	Test Site #4	Test Site #5	Test Site #6	Test Site #7	Test Site #8	Test Site #9
14	RP81	58.90	46.47	53.58	50.24	55.04	60.93	92.31	55.37	92.58
14	RP82	91.36	51.54	65.93	48.25	54.37	65.95	54.36	74.68	66.52
14	RP83	53.76	48.17	58.11	45.07	54.47	78.20	91.70	64.39	90.16
14	RP84	99.44	52.94	71.88	53.89	53.12	71.48	63.31	70.70	67.28
15	RP89	63.56	59.07	69.69	59.97	67.78	73.94	99.12	67.23	97.55
15	RP90	101.82	58.14	89.78	46.11	53.02	64.77	60.78	69.64	68.38
15	RP91	60.53	45.74	64.13	46.28	52.36	69.86	97.79	69.57	103.70
15	RP92	97.48	56.94	75.01	53.95	55.72	68.58	58.79	71.23	72.57
16	RP105	82.49	74.90	89.54	67.81	79.90	94.62	83.32	88.47	86.79
16	RP106	86.04	74.33	93.19	65.56	82.22	94.46	90.27	84.48	89.80
16	RP107	84.09	77.98	87.19	71.56	81.41	90.80	81.35	82.09	82.27
16	RP108	90.10	78.44	82.61	84.28	79.66	82.91	89.93	80.72	81.91
17	RP101	93.25	80.61	84.64	77.95	82.44	91.78	92.77	91.51	89.18
17	RP102	94.30	81.56	91.64	77.75	85.37	93.96	92.42	90.14	89.59
17	RP103	86.77	81.48	89.60	81.55	83.36	96.12	79.55	90.71	94.35
17	RP104	91.38	81.69	91.74	77.04	86.06	101.30	81.70	89.79	92.68
18	RP81	92.17	90.51	95.60	91.40	93.54	107.49	98.16	98.76	97.78
18	RP82	86.20	91.72	99.45	84.69	94.21	95.09	87.64	91.75	89.25
18	RP83	94.18	90.21	100.46	89.49	95.88	115.63	91.20	95.06	91.46
18	RP84	85.88	80.44	96.02	83.41	86.93	100.40	96.84	92.89	91.04
19	RP61	67.82	66.99	70.72	62.22	67.09	77.42	75.51	71.96	69.74
19	RP62	68.36	64.47	72.20	57.74	63.92	77.81	67.93	74.16	72.16
19	RP63	70.25	65.92	73.22	63.62	67.86	81.02	70.56	70.03	67.53
19	RP64	64.76	61.22	69.68	55.57	66.01	70.66	62.33	75.70	73.09
20	RP57	75.69	72.73	75.03	72.69	72.99	86.70	77.09	74.12	71.03
20	RP58	71.27	67.89	73.75	64.26	68.87	76.77	80.46	78.58	75.56
20	RP59	75.56	71.54	77.53	85.78	74.57	85.15	78.79	74.37	73.18
20	RP60	74.02	70.30	77.82	62.48	72.45	81.71	80.58	79.02	77.46
21	RP37	75.82	70.90	79.23	74.44	73.08	86.85	80.09	80.68	76.39
21	RP38	74.26	71.15	80.74	73.51	73.14	65.66	81.01	76.65	78.66
21	RP39	74.88	72.77	78.52	81.69	72.92	78.17	77.19	74.66	76.68
21	RP40	84.69	72.09	78.71	76.67	72.88	83.10	79.26	73.73	79.27

Table 45: Raw film thickness data for response phase print conditions 22-27.

Print Cond.	Average Thickness (mm)									
	Wafer ID	Test Site #1	Test Site #2	Test Site #3	Test Site #4	Test Site #5	Test Site #6	Test Site #7	Test Site #8	Test Site #9
22	RP49	60.54	66.30	71.41	57.76	69.19	79.98	74.20	65.78	65.42
22	RP50	69.87	66.62	74.25	55.17	69.53	77.18	68.35	47.22	40.94
22	RP51	65.07	63.28	70.32	54.02	68.91	77.50	73.39	64.84	62.28
22	RP52	65.73	61.84	71.58	58.72	65.62	73.14	66.06	45.21	38.71
23	RP41	59.83	72.75	79.29	62.95	75.27	85.31	70.29	76.48	68.88
23	RP42	74.78	69.21	83.41	56.49	75.05	84.68	75.78	49.38	44.76
23	RP43	73.25	70.74	80.38	33.75	76.38	83.10	70.74	74.04	63.13
23	RP44	*	*	*	*	*	*	*	*	*
24	RP53	56.12	61.83	85.87	51.14	82.44	94.84	81.69	64.40	57.80
24	RP54	74.76	64.25	82.53	47.27	75.26	70.68	64.26	51.18	45.70
24	RP55	61.65	60.82	85.97	56.87	83.60	92.34	88.55	66.28	62.74
24	RP56	71.42	60.01	81.16	49.27	75.91	75.51	66.95	54.68	42.12
25	RP69	57.59	57.24	61.53	52.56	60.47	63.62	56.01	49.92	50.83
25	RP70	45.00	64.84	70.88	59.94	67.19	69.68	76.73	73.69	69.69
25	RP71	53.27	34.93	61.70	43.61	56.67	60.49	48.44	48.30	62.63
25	RP72	46.00	58.85	66.53	57.74	62.59	66.10	74.90	69.90	68.41
26	RP65	63.86	69.13	63.11	51.43	58.99	58.49	51.04	49.24	48.50
26	RP66	46.00	55.38	69.85	58.27	64.82	74.00	65.11	76.42	76.61
26	RP67	63.18	58.09	60.76	49.06	55.80	61.92	64.41	48.01	54.46
26	RP68	44.17	59.62	67.21	67.11	67.15	69.69	74.70	73.80	70.21
27	RP45	67.79	56.92	59.70	46.61	52.08	58.74	61.35	60.69	86.00
27	RP46	45.10	68.30	70.81	61.50	70.93	75.54	74.63	81.66	76.68
27	RP47	67.24	59.27	60.70	40.77	53.44	61.96	67.21	51.90	91.27
27	RP48	44.43	66.51	77.42	62.52	77.92	83.75	73.92	81.06	75.59

*unable to take measurement at this location because of damage to wafer

Table 46: Raw film thickness data for response phase print conditions 1-7.

Print Cond.	Average Roughness (mm)									
	Wafer ID	Test Site # 1	Test Site #2	Test Site #3	Test Site #4	Test Site #5	Test Site #6	Test Site #7	Test Site #8	Test Site #9
1	RP25	4.11	2.03	1.36	4.16	0.97	3.44	5.40	0.69	3.52
1	RP26	3.37	2.03	4.18	4.91	1.50	0.86	7.41	0.46	4.10
1	RP27	1.33	1.56	1.26	4.84	1.00	1.78	3.82	1.08	5.14
1	RP28	2.51	0.60	2.27	4.17	0.77	0.41	9.53	2.80	6.94
2	RP21	1.75	1.10	0.90	4.08	0.99	2.70	5.70	1.79	4.19
2	RP22	1.10	0.70	0.93	6.44	0.70	1.55	4.27	0.71	5.70
2	RP23	2.35	1.42	3.20	3.46	1.24	3.41	3.65	1.33	4.54
2	RP24	1.52	1.51	2.50	4.72	0.79	1.52	6.08	0.75	5.72
3	RP1	0.72	1.32	0.84	4.88	0.99	4.12	7.61	1.13	1.63
3	RP2a	2.76	0.80	1.27	1.19	1.90	3.29	4.59	1.26	1.82
3	RP3a	1.71	1.52	2.99	1.90	1.91	4.10	3.85	0.74	1.58
3	RP4	2.72	3.28	5.96	8.84	3.49	3.49	6.87	1.37	7.59
3	RP2	2.54	1.81	4.07	6.80	0.47	6.96	12.00	1.02	5.82
3	RP3	1.31	1.02	2.95	6.97	0.78	1.09	7.64	1.13	7.63
4	RP13	4.14	2.27	0.98	2.55	1.43	1.47	2.28	0.87	1.33
4	RP14	1.15	1.90	3.22	8.88	2.05	3.61	7.20	5.11	9.71
4	RP15	6.08	4.66	4.27	5.76	2.32	1.90	1.28	1.41	0.79
4	RP16	0.80	1.78	2.63	3.29	2.20	8.55	12.35	10.02	11.84
4	RP17a	4.95	4.55	2.11	4.62	1.42	1.36	0.81	1.89	0.83
4	RP16a	1.52	9.69	1.95	8.17	6.23	5.09	12.50	9.36	11.60
5	RP5	3.02	3.29	2.31	7.64	1.15	1.85	5.31	1.09	0.88
5	RP6	1.94	2.13	2.84	3.96	1.83	4.45	3.89	4.78	14.13
5	RP7	3.83	5.02	1.33	9.26	0.79	3.50	4.31	0.61	0.67
5	RP8	0.62	3.44	1.16	8.30	2.16	4.61	10.40	6.41	8.52
6	RP17	7.27	10.02	8.25	5.78	0.80	8.11	4.99	0.99	1.78
6	RP18	1.88	0.98	4.09	4.57	6.32	1.10	8.33	8.98	10.26
6	RP19	7.32	7.74	8.52	6.12	0.68	0.85	2.55	2.09	1.74
6	RP20	5.19	3.20	0.50	3.32	4.51	3.27	11.70	7.09	6.34
7	RP33	2.49	2.17	2.76	1.52	2.39	2.42	3.33	5.25	9.07
7	RP34	2.20	0.95	1.42	3.21	1.90	1.74	5.59	0.00	2.32
7	RP35	3.15	1.25	3.44	2.80	2.40	3.38	1.86	3.34	7.48
7	RP36	3.33	2.13	1.47	0.92	1.86	2.14	2.22	2.08	2.03

Table 47: Raw film roughness data for response phase print conditions 8-14.

Print Cond.	Average Roughness (mm)									
	Wafer ID	Test Site # 1	Test Site #2	Test Site #3	Test Site #4	Test Site #5	Test Site #6	Test Site #7	Test Site #8	Test Site #9
8	RP29	3.37	1.92	3.65	3.10	1.76	3.75	3.04	4.85	6.03
8	RP30	5.94	1.80	1.80	2.79	1.30	2.20	4.68	1.29	3.92
8	RP31	4.19	2.58	2.61	1.52	2.23	2.12	1.70	8.33	11.75
8	RP32	3.19	1.30	2.51	0.76	1.03	2.05	2.96	1.47	2.70
9	RP9	2.37	1.58	1.50	2.66	2.13	4.13	4.25	8.33	7.88
9	RP10	7.33	4.23	2.56	1.41	2.12	1.74	1.82	1.76	2.66
9	RP11	1.95	6.08	4.51	3.33	2.25	5.24	2.12	15.04	5.31
9	RP12	5.08	0.34	3.29	0.88	2.30	3.47	2.69	2.28	2.44
10	RP97	*	*	*	*	*	*	*	*	*
10	RP98	2.75	7.46	3.28	3.45	1.40	2.84	0.74	4.95	3.85
10	RP99	3.42	6.10	2.20	4.05	1.00	2.66	0.75	3.67	2.88
10	RP100	2.31	5.63	5.10	4.29	1.83	2.28	1.69	5.80	5.04
11	RP93	3.54	6.45	3.78	3.57	1.73	1.77	1.43	5.83	5.36
11	RP94	3.92	4.79	3.17	3.49	1.39	2.29	1.35	4.66	5.68
11	RP95	3.22	6.61	4.11	5.05	2.43	2.64	0.86	4.65	4.32
11	RP96	1.63	0.93	2.27	3.95	1.21	1.41	0.83	4.42	3.58
12	RP73	4.17	7.45	3.02	5.67	0.93	1.26	0.55	7.63	3.51
12	RP74	3.07	2.75	2.59	4.51	1.27	3.01	0.83	5.76	6.39
12	RP75	6.79	2.67	3.19	5.34	1.33	2.91	0.79	2.49	4.25
12	RP76	4.31	7.43.5	3.86	3.03	1.88	2.84	0.39	4.75	4.21
13	RP85	9.11	6.50	5.44	6.29	5.82	4.57	3.20	7.80	1.94
13	RP86	4.36	4.09	5.84	6.96	4.88	4.73	4.79	4.53	3.61
13	RP87	9.34	7.08	4.25	3.46	2.31	3.56	1.28	3.40	2.19
13	RP88	3.94	7.43	2.52	2.98	4.91	3.19	6.36	4.60	5.45
14	RP81	5.60	5.72	5.65	6.51	6.09	6.15	1.37	5.31	1.06
14	RP82	1.37	2.32	3.72	6.77	6.23	3.97	7.59	7.97	5.80
14	RP83	7.76	3.15	3.62	6.21	3.24	6.63	2.80	5.50	1.96
14	RP84	2.51	4.63	5.71	2.98	7.33	7.63	9.41	4.47	6.63

*unable to take measurements at this location because of damage to wafer

Table 48: Raw film roughness data for response phase print conditions 15-21.

Print Cond.	Average Roughness (mm)									
	Wafer ID	Test Site # 1	Test Site #2	Test Site #3	Test Site #4	Test Site #5	Test Site #6	Test Site #7	Test Site #8	Test Site #9
15	RP89	6.09	6.28	6.93	3.10	4.59	4.27	2.69	2.75	2.18
15	RP90	1.75	3.34	6.91	6.00	6.98	5.62	9.58	7.61	12.69
15	RP91	11.49	5.64	6.99	6.24	3.95	6.71	1.34	4.17	3.95
15	RP92	1.86	3.90	4.27	7.85	10.86	8.31	13.43	9.94	9.99
16	RP105	2.85	1.67	4.99	3.62	2.47	3.95	1.80	2.78	1.93
16	RP106	1.79	1.78	4.17	3.00	2.59	4.53	4.15	1.56	3.68
16	RP107	3.03	2.05	3.20	1.05	3.55	3.93	2.73	1.26	0.78
16	RP108	1.04	1.88	2.43	1.31	2.35	1.32	1.34	2.29	1.04
17	RP101	0.99	0.99	2.45	1.16	1.65	2.47	1.79	2.99	3.32
17	RP102	0.97	0.90	2.43	0.80	1.39	2.73	1.08	3.01	2.05
17	RP103	2.44	1.28	3.30	1.82	2.005	3.58	1.07	2.89	1.31
17	RP104	1.94	1.32	4.17	1.47	1.90	2.98	1.23	3.27	1.02
18	RP81	2.09	1.67	2.84	1.81	1.74	2.43	1.77	2.46	2.25
18	RP82	3.61	2.03	4.95	1.42	1.42	1.73	1.42	1.57	1.64
18	RP83	2.33	1.64	5.31	0.87	2.91	3.35	1.49	2.54	0.59
18	RP84	1.41	3.52	3.57	1.33	1.86	1.55	0.85	3.05	1.05
19	RP61	1.56	1.69	2.14	1.18	2.48	2.70	1.30	2.95	1.02
19	RP62	1.68	0.63	3.71	0.59	1.48	2.50	1.12	3.24	1.99
19	RP63	1.01	1.76	3.82	1.22	1.91	2.09	0.61	1.82	1.55
19	RP64	1.00	0.85	2.38	1.13	2.52	2.35	1.90	1.89	2.61
20	RP57	1.14	1.81	3.87	1.70	2.55	2.92	1.13	2.28	1.79
20	RP58	0.73	0.61	3.13	1.24	1.39	1.43	1.22	3.24	3.05
20	RP59	1.73	1.16	4.15	1.23	2.74	3.61	0.80	1.98	0.92
20	RP60	1.64	1.12	2.18	1.00	0.98	1.65	0.72	2.30	1.75
21	RP37	1.16	1.09	3.23	1.21	1.84	2.75	2.15	0.73	1.69
21	RP38	2.09	0.84	5.08	1.07	1.10	0.88	2.59	0.88	0.96
21	RP39	1.98	1.08	3.35	1.23	1.64	0.51	2.27	0.64	2.08
21	RP40	1.20	1.27	3.51	0.91	1.72	1.19	2.03	1.06	1.32