Wet-recess Process Optimization of a Bottom Antireflective Coating for the Via First Dual Damascene Scheme

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ABSTRACT

The via-first process is unique by the fact that a material is needed to fill the vias to some arbitrary value, with little or no isolated-dense via bias so that the underlying layer underneath the via is protected from the trench etch step. Secondly, this material may have to coat over the surface of the wafer with some chosen thickness again with minimum or no bias to maximize the trench photolithography process window. Finally, the material must be easily removed from the via after the trench etch with no residue, crowning, or fencing. The ideal via fill material would be able to perform all the above listed parameters, but no perfect solution exists yet. The etchback process that is discussed herein, called the solvent etchback (SOLVE) process bypasses these lengthy modules, will fit within today's manufacturing processes and will have little impact on throughput of the photobay coating tools.[1] The process utilizes industry standard photoresists solvents such as PGMEA, Ethyl Lactate, PGME and existing solvent prewet dispense nozzles in the BARC coater module. Also, this process only requires one material that can both fill the via and act as a BARC during the trench photo step with a user defined thickness on top the wafer that will minimize light reflections coming from the substrate. The process flow for the SOLVE process is:

1. Coat a wafer with a thick BARC to planarize the wafer and minimize isolated-dense bias.
2. Bake the BARC so that it is partially crosslinked.
3. Apply a solvent to the wafer and etchback the BARC to a thickness that suits the trench photo step.
4. Bake the BARC to fully crosslink the BARC.

Process variables that can have an affect on the SOLVE process are the softbake temperature and time to modify the BARC thickness on the wafer. Dispense parameters that will modify the post-etch uniformity of the wafer include the dispense time, dispense spin speed and the IDI M450 dispense pressure. The repeatability of the process can be modified by changing the solvent spin off speed and acceleration.

Keywords: DUV, photolithography, bottom anti-reflective coating, BARC, via fill, gap-fill, via-first, dual damascene

1. INTRODUCTION

The mantra "smaller, faster, cheaper" has been used in the semiconductor industry for some time and is used to denote the increasing speed, decreasing size and decreasing price for integrated circuits. To succeed with this idea companies are implementing new technologies and process flows such as copper interconnects, low-k dielectrics, smaller gate sizes, metal gates, extremely low-energy implants, etc. A subset of the copper interconnect technology is the dual damascene architecture or process flow. In the dual damascene process the contact via and overlying metal layer are deposited simultaneously which removes at least one interface, a deposition, and an etch step. The process is a simple design but has been a challenge to implement in production environments. Various schemes to pattern the vias and metal layers have been proposed such as the via-first, and trench-first.

The via-first process is unique by the fact that a material is needed to fill the vias to some arbitrary value, with little or no isolated-dense via bias so that the underlying layer underneath the via is protected from the trench etch step. Secondly, this material may have to coat over the surface of the wafer with some chosen thickness again with minimum or no bias to maximize the trench photolithography process window. Finally, the material must be easily removed from the via after the trench etch with no residue, crowning, or fencing.

The ideal via fill material would be able to perform all the above listed parameters, but no perfect solution exists yet. Today various material manufacturers and integrated device manufactures use a variety of materials to accomplish the via fill process. One process uses a thick material that is transparent to the exposure wavelength that is coated on the wafer to fill vias with minimal bias and the transparent material is

etched back by RIE, CMP or TMAH developer flush to the surface of the wafer. Then a bottom anti-reflective coating (BARC) is coated onto the wafer and the trench photo process is accomplished. A similar process uses a thick BARC that is coated onto the wafer again to reduce bias then a RIE or TMAH process is used to etch back the BARC to the correct thickness for the trench photo process.

All these process have one thing in common and that is they use process modules that are lengthy in time. The RIE or CMP methods will require transport to the correct process bay of the fab, there the process occurs which may take several minutes, then another wafer cleaning step is needed. Finally returning to the photolithography bay to coat a BARC and complete the trench lithography step. The TMAH developer process use the developer module of the coater track, the longest process module within the photobay and may slow down throughput in coating tools and also the overall throughput of the photolithography bay unless more coater tracks with more developer modules are purchased.

The etchback process that is discussed herein, called the solvent etchback (SOLVE) bypasses these lengthy modules, will fit within today's manufacturing processes and will have little impact on throughput of the photobay coating tools.[1] The process utilizes industry standard solvents such as PGMEA, Ethyl Lactate, PGME and existing solvent prewet dispense nozzles in the BARC coater module.   Also, this process only requires one material that can both fill the via and act as a BARC during the trench photo step with a user defined thickness on top the wafer that will minimize light reflections coming from the substrate. The process flow for the SOLVE process is:
1. Coat a wafer with a thick BARC to planarize the wafer and minimize isolated-dense bias.
2. Bake the BARC so that it is partially crosslinked.
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4. Bake the BARC to fully crosslink the BARC.

A diagram of the process is shown in Figure 1. What will be shown is the viability of this process along with optimization results for the solvent dispense and bake parameters to gain the most uniform coating after etchback.

2. EXPERIMENTAL

Screening experiments were performed to prove the concept of the SOLVE process. First, small silicon substrates that had 700nm deep vias of various diameters and pitches were coated with DUV52N at a thickness of 200-250nm. Next, a bake matrix was performed on the partial crosslinking bake step to find were the BARC was removed by the three solvents PGMEA, PGME, and Ethyl Lactate. The solvent etch time was set at 30 seconds so that the entire dispense, etch, spin off, and EBR process would last a maximum of 60 seconds. The solvent was in contact with the BARC for 30 seconds then removed by spinning the substrate at 2000rpm for 30 seconds. Once the solvent etch and spin off process was complete it was followed by a hardbake at 205°C for 60 seconds. The hardbake would fully crosslink the material so that further testing with photoresist would not result in intermixing and give poor results. The substrates were cross-sectioned so that the via fill and surface coating properties could be investigated

Once a softbake temperature was defined, full size 200mm wafer optimization tests were performed. Here the dispense and spin off process for the solvent was defined to give the best results for BARC thickness uniformity across the wafer. A screening Design of Experiment (DOE) was defined so that the important parameters that would affect the uniformity of the BARC coating after the solvent etch and hardbake process steps could be found and investigated further. The DOE factors look at both the dispense and spin off of the solvent. The factors are listed in Table 1 and a graphical representation of each factor is shown in Figure 2.

The design for the DOE was a 54 run two level factorial with midpoints. This many experimental runs allowed for the software to have enough degrees of freedom to find the main factors that would affect the uniformity of the post-solvent etch BARC coating. Three coated wafers were used for each experimental run to check the repeatability of the solvent etchback process. The responses for the DOE were the median and mean thickness post-etch and the average standard deviation across the three wafers.

3. RESULTS AND DISCUSSION

3.1 Screening Experiments
To discover the feasibility of the SOLVE process, a BARC, Brewer Science DUV52N, was coated with a thickness of 250nm on small substrates that had via arrays of varying pitches and diameters. These coated substrates were then used in a test matrix consisting of changing the partial crosslinking bake step,

herein called the softbake. The factors tested were the softbake temp, softbake bake time, and solvent. Table 2 lists the test sequence for each of the three factors. The substrates were then cross-sectioned and the via fill and surface coating properties were evaluated.

It was found and shown in Figure 3 that the bake temperature could vary 180-190°C to show no fill to full fill irregardless of the solvent. It was assumed initially that the BARC would have different reactions to a particular solvent. With the fill properties independent of the solvent, the SOLVE process may allow the use of any mixture of EBR solvents and still give the same results as a pure solvent, this increases flexibility of the process and allows a much faster testing program

Bake time comparisons show that identical fill results and BARC surface thickness can be obtained if the temperature is adjusted properly depending on the bake time. The trend that has appeared is that the lower the temperature the longer bake time that is needed to remove the same amount of BARC as a high temperature short time bake. The interesting aspect of this test is that it may show a different crosslinking rate within the via compared to on the wafer surface. This change in crosslinking rate may be driven by the amount of residual solvent left in the material after spin coating prior to the softbake. This can be seen by looking at the BARC surface thickness after etchback with Ethyl Lactate in Figure 4. As the softbake time is reduced, at a given temperature, the thickness is reduced in a linear fashion. Comparing that to the via fill properties in Figure 5 with Ethyl Lactate, there is a dramatic non-linear break or bend in the data as the bake time is decreased. At the point where the via fill makes the sharp bend is the point at which the crosslinking starts. If there is more solvent left in the via than compared to the BARC on the surface then the heat energy coming from the hotplate would be directed into removing the solvent before the crosslinking reaction began. With the bake time fixed then, the crosslinking reaction in the via would not proceed as far as the crosslinking reaction on the surface. This different crosslinking rate would manifest itself in the solvent etchback process by removing the material faster in the via than the material that is on the surface.

The via crosslinking reaction may also contribute to fill bias. In Figures 4 and 5 the dotted lines represent the fill bias in nanometers, when the crosslinking is not as complete, during the shorter softbake times, the bias increases. Again heat transfer may play a role because the isolated vias will always have more BARC in the via after the solvent etchback, assuming equal fill in the case of extremely thick coatings such as in this case. The crosslinking rate may be dependent on the volume of the substrate surrounding the via. Simply, the more substrate that is surrounding the via the better the heat source.

3.2 Uniformity Optimization

Etchback uniformity testing consisted of a two-level factorial design with eight factors; these factors are listed in Table 2. When the DOE was designed it was assumed that the best uniformity would be achieved if the coater module used to dispense solvent in the TEL Mk8 could mimic the developer module dispense. With that assumption made the DOE was designed to have a radial dispense for the solvent. Also, the volume of solvent dispensed onto the wafer would be around 20mL so typical low-volume diaphragm pumps can not dispense that amount so an IDI M450 pump was chosen. The volume the pump dispenses depends on the pressure of the nitrogen in the reservoir, the time of dispense and the dispense valve setting. When the pump is dispensing the M450 pressurizes the airspace above the fluid in the reservoir and opens the dispense valve to a predetermined point. The fluid in the reservoir then flows in the dispense line for the user-defined dispense time. If the dispense time is too long or the dispense valve is opened too much the liquid in the reservoir can be removed such that the filter is uncovered and induce air into the dispense line. The maximum volume that can be dispensed is then the amount of liquid that can be removed from the reservoir without the filter being uncovered. Though not tested in this screening DOE the M450 has the capability to vary the dispense rate during the dispense. Variable rate dispense could adjust for the change in volume per unit area that occurs from center to edge of the wafer when a radial dispense occurs. The M450 was setup such that under maximum pressure (15psi) and longest dispense time (2.2sec) of the DOE the pump would dispense 20mL. This setup was chosen because the dispense valve is the most difficult to change in the DOE and remained at that setting throughout the DOE while varying the dispense pressure and the time, which by the nature of the pump design will change the dispense volume. A 20mL dispense volume will keep sufficient solvent above the filter so that it is not uncovered during the dispense.

Since solvent is being dispensed on the wafer the uniformity of the post-solvent etch process would be directly related to how fast and how uniform the solvent could be dispensed over the entire wafer, considering that a typical photoresist dispense nozzle is being used. The other dispense factors that were then chosen were dispense spin speed, arm start location, and arm direction. The dispense speed was held to spin speeds below 250rpm so that the solvent would not be removed by centripetal forces. The arm start location and arm direction was chosen so that the radial dispense could be evaluated. The locations that the arm could

start or end the dispense were center, edge, and halfway between center and edge of the wafer. Arm direction was chosen so that the arm would move from either the center to the ending location or vice versa. If the DOE indicated a center to edge direction with the edge as the ending location, the arm would start dispensing at the center, move to the edge and end dispense. Conversely, a edge to center dispense with the start location as the edge the arm would start dispense at the edge, move to the center of the wafer, and end dispense. It is possible from this setup that a center only dispense could occur if the ending location was the center of the wafer and the arm direction was center to edge. Since the arm speed is controllable on the Mk8 it was decided that the dispense time and the distance the arm must travel across the wafer based on the location of the arm would dictate the speed of the arm, removing the possibility that the arm would stop at a particular location and the dispense would continue.

Once the solvent is dispensed and the solvent etch complete the solvent must be removed from the wafer efficiently and quickly to remove the solvent etch byproducts, so various factors were chosen to also investigate the spin off process. It was decided to keep to an upper limit of speed and acceleration that would be compatible with 300mm wafer processing. The factors that were chosen to investigate the spin off process were spin speed, time and the acceleration between the etch step and the solvent spin off.

Once all the data from the DOE was analyzed the variance caused by each factor was analyzed to determine which factors would have the greatest effect on the uniformity of the post-etch coated wafer. Because of the size of the DOE it was possible to look for interactions between factors such as dispense spin speed and dispense time. The mean and median thickness standard deviation was calculated for the three wafers in each experimental run to investigate the uniformity of the post-solvent etch wafer. Also, the range of the standard deviation from the three wafers was calculated and analyzed to find the factors that would yield the most repeatable etch process.

With only three wafers of data a significant difference in the factors between the mean and median would indicate a problem with the data and/or analysis of the data because the median and mean should agree when many data points are taken. The ANOVA analysis of both the mean and median standard deviation indicted that the dispense speed, and the interaction between the dispense spin speed and dispense time have the dominant role in determining the uniformity within a wafer. The dispense pressure was another dominant factor that contributes to uniformity within the wafer but to a lesser extent compared to the dispense spin speed and time. As noted earlier the arm speed is adjustable and was adjusted such that the arm would move the correct distance in the time allotted and dispense only during that arm movement. Given that it may be possible that the interaction between spin speed and time could be attributable to the arm speed. Further investigation should uncover the solution to this problem. The differences predicted between the mean and median standard deviation were weak interactions between other factors and are being attributed to the noise in the data.

To achieve a reproducible process the DOE indicated that the solvent spin off process can be optimized. The most dominant factor was the interaction between the solvent spin off speed and acceleration. Followed by arm direction during dispense and the interaction between the arm start/end location and the spin off acceleration. This final interaction might be attributed to the definition of how the arm moved in the DOE. It was possible to have a center dispense which may have clouded the results with faulty data, rather than have only radial arm dispense.

Confirmation runs of the DOE predictions set at the maximum uniformity and minimum uniformity were carried out. The bake temperature was 175°C for 60 seconds for this test, which is lower than the early screening test with smaller substrates. This is most likely due to the change from the manual process with the smaller substrates to the automated process on the TEL Mk8. With the bake temperature defined for the TEL Mk8 the processes were input as shown in Table 3 and five wafers were run for each process. The average thickness for the minimum and maximum uniformity process was 114.8nm and 108.8nm respectively. The uniformity data for the minimum and maximum process is 15.2nm (1σ) and 17.1nm (1σ), a 12% percent difference between the two processes. The DOE had predicted a minimum uniformity of 15.6nm and a maximum of 24.2nm, a 54% difference. From this it is possible to conclude that the model is not accurate for absolute numbers but the confirmation runs did show a reduction in the uniformity when changing the process.

4. CONCLUSIONS

Process variables that can have an affect on the SOLVE process are the softbake temperature and time to modify the BARC thickness on the wafer. Dispense parameters that will modify the post-etch uniformity of the wafer include the dispense time, dispense spin speed and the IDI M450 dispense pressure.

The repeatability of the process can be modified by changing the solvent spin off speed and acceleration. Confirmation runs of the minimum and maximum uniformity processes that were generated by the DOE indicated a 12% reduction in uniformity across the wafer.

As dual damascene continues its integration into manufacturing processes, difficulties arise that require unique solutions. The SOLVE process will fix several problems that exist in today's dual damascene processes. The first is decrease the time it takes to complete the trench photolithography step. Today, many processes require the gap or via fill material to be coated onto the wafer and then sent to the etch area for a full wafer etch that removes the unwanted material. Then the wafer comes back to the photo bay for the trench photolithography step. The SOLVE process keeps the wafer in the photo bay and can be 40% shorter than a RIE etch process. The SOLVE process only uses one material for both gap fill and reflectivity control. Compared to the develop etchback method the SOLVE process is both faster and does not utilize the longest process module of the coater track. Isolated-dense bias typically is about 30-70nm the BARC thickness on the surface of the wafer.

REFERENCES

1. Brakensiek, Nickolas, *et. al.* "Novel BARC Etchback Method for Via First Dual Damascene Process." Interface 2003

Factor Name	Factor Low / Mid / High Settings (unit)	Responses (3 wafer calculation)
Dispense Pressure	5 / 10 / 15 (psi)	Median Thickness
Dispense Spin Speed	50 / 150 / 250 (rpm)	Mean Thickness
Dispense Time	1 / 1.6 / 2.2 (sec)	Mean Standard Deviation (1 sigma)
Arm Start Location (measured from center)	0 / 45 / 90 (mm)	
Spin Off Speed	1000 / 1500 / 2000 (rpm)	
Spin Off Time	10 / 20 / 30 (sec)	
Spin Off Acceleration	1000 / 3000 / 5000 (rpm/sec)	
Arm Direction	To Center / To Edge	

Table 1. List of factors and responses for uniformity screening DOE.

Factor	Factor Settings
Solvent	PGME / PGMEA / Ethyl Lactate
Bake Temp	150°C – 200°C
Bake Time	15sec – 120sec

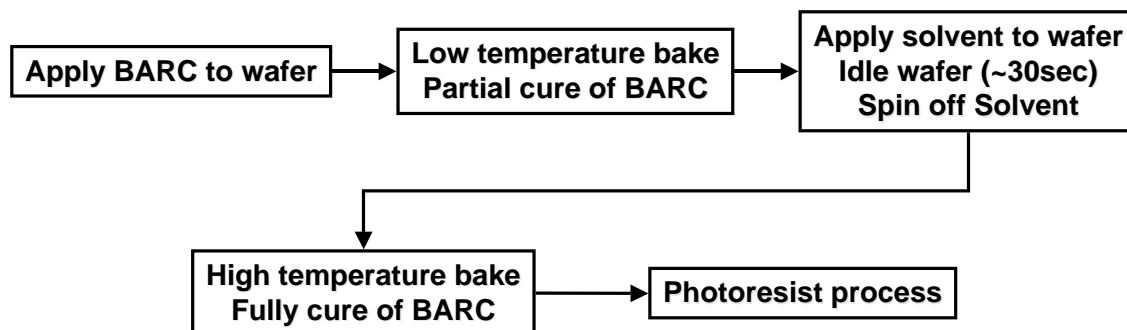**Table 2.** List of screening factors for process viability.

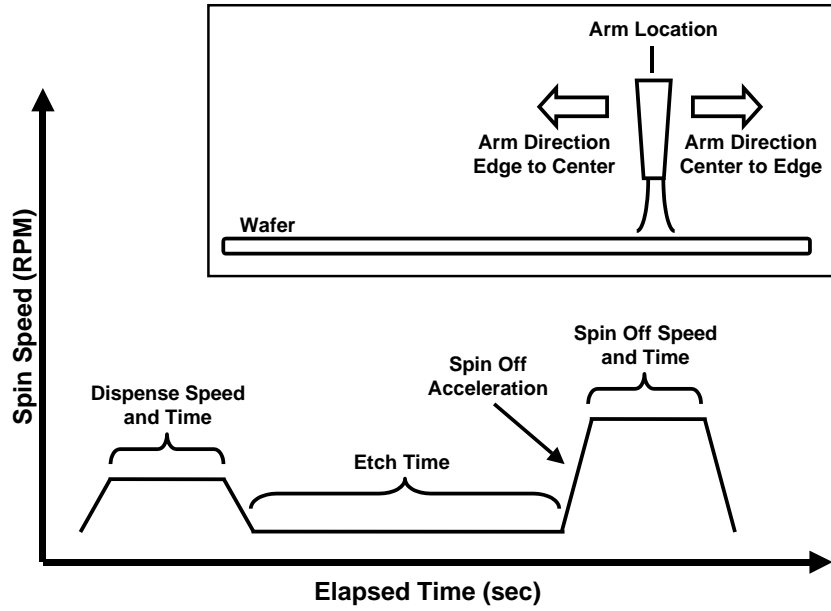**Figure 1.** Flowchart for the SOLVE process.

Figure 2. Graphical representation of the factors for the optimization DOE. Inset represents the dispense arm factors.
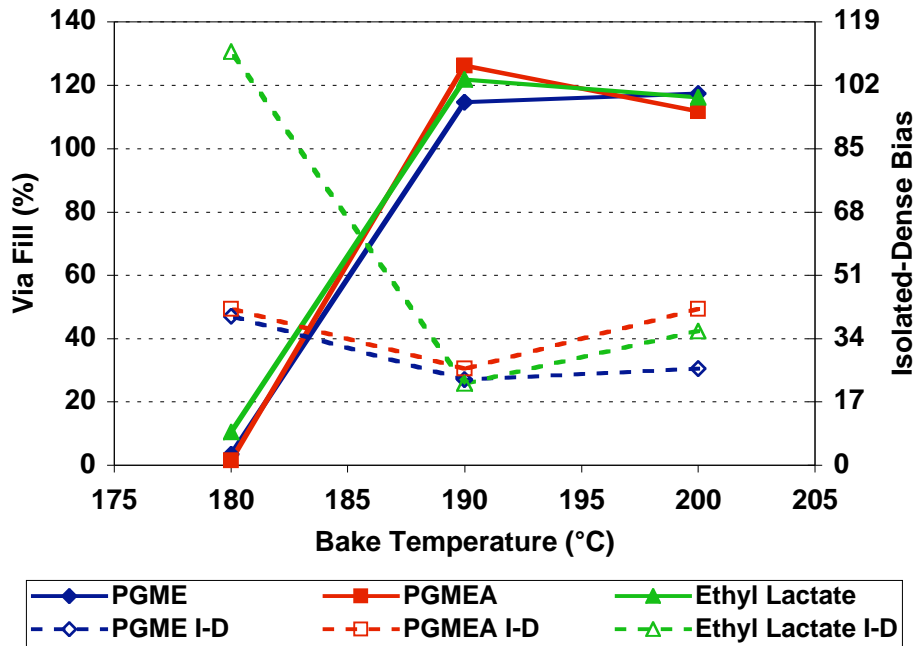

Figure 3. Via fill results varying softbake temperature and solvent. Solid lines represent the via fill. The dashed lines represent the isolated-dense bias in nanometers
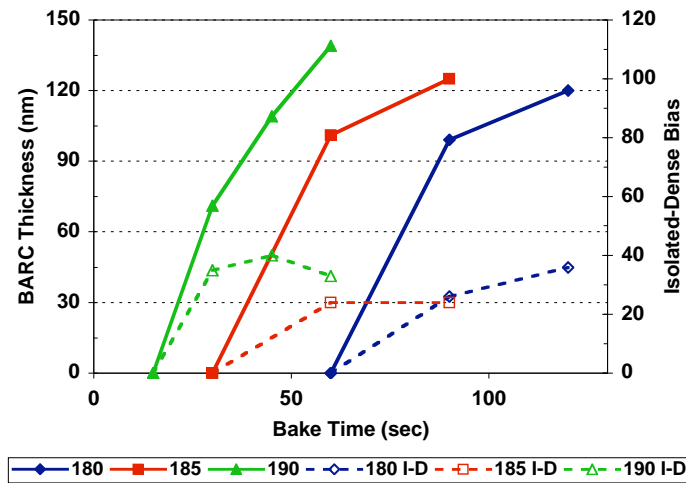
Figure 4. BARC thickness on the surface of the wafer after etchback varying softbake temperature and softbake time, using the solvent Ethyl Lactate. The dashed lines represent the isolated-dense bias in nanometers.
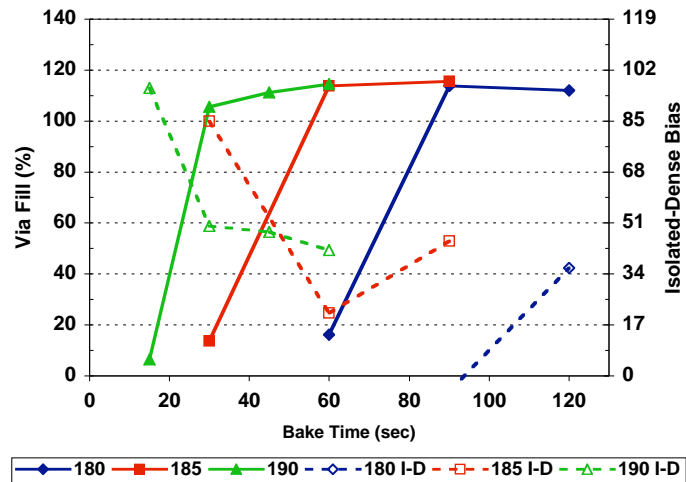

Figure 5. BARC via fill after the SOLVE process varying the softbake temperature and softbake time. The dashed lines represent the isolated-dense bias in nanometers.

Process	Dispense Pressure (psi)	Dispense Speed (rpm)	Dispense Time (sec)	Arm Location (mm)	Spin Off Speed (rpm)	Spin Off Time (sec)	Spin Off Acceleration (rpm/sec)	Arm Direction
Best	13	250	2.0	90	2000	30	1000	Center to Edge
Worst	7	50	1.2	0	1040	30	1200	Edge to Center

Table 3. Processes used for DOE conformation runs.