Determination of New Deep Ultraviolet Photoresist Targets and Interchangeable Processes on Coating Equipment at Marvell Nanofabrication Laboratory

Allison Dove and Emily Beeman
Marvell Nanofabrication Laboratory, UC Berkeley, June 14, 2018

1. 2024 Update

1.1. The standard thicknesses listed in this document are no longer current, following changes to the soft bake procedure made in 2024. This document is left as-is for reference.

2. Introduction

2.1. Background & Motivation

In 2017, Marvell Nanofabrication Laboratory upgraded two of its photolithography tracks to provide capacity for more resists, increase recipe flexibility, and add 200 mm wafer capability. This document reports on the experiments performed to define and characterize the new photoresist standard processes on the lithography tracks.

Historically, the lab has supported two deep ultraviolet (DUV) resists -- Rohm & Haas UV210GS-0.6 and Rohm & Haas UV26-3.0. UV26GS-3.0 is a thick DUV resist and was not tested in this work. UV210GS-0.6 is intended to be spun to thicknesses between 0.55 µm and 0.95 µm [1]. Before the upgrade this resist was spun at 7000 rpm to get a 0.42 µm layer which is thin enough to resolve 200 nm features. With the new tools, the lab has now added UV210GS-0.3, a DUV resist that is intended to be spun to thicknesses between 0.25 µm and 0.50 µm [1]. In this report, we characterize both UV210GS-0.3 and UV210GS-0.6, paying special attention to the thickness overlap between the two resists. We show that the two resists can be used interchangeably given the same thickness.

In reviewing the manufacturer's recommended procedure [1], we also determined that we were using a non-optimal developer process. We programmed new developer recipes in line with the manufacturer's recommendation. Differences between the old developer recipe and new developer recipe are documented in a separate report. Finally, we also tested the impact of using Bottom Anti-Reflective Coating (BARC) on our process. We show that the variation in required exposure dose with varying thicknesses is virtually eliminated, as expected.

2.2. Theory

Photolithography is highly sensitive to the photoresist thickness used in processing. The needed dose-to-clear (E0) goes up linearly with resist thickness but superimposed on that linear increase is a sinusoidal interference effect. At particular thicknesses of resist, the light reflects off the substrate to constructively/destructively interfere which increases/decreases the amount of energy absorbed by the photoresist. This interference effect diminishes as the resist gets thicker and can be modelled as a damped harmonic oscillation [2]. The entire resist sensitivity model is a damped harmonic oscillator plus a linear increase with thickness, as shown in Figure 1.

Determining the periodicity of the process allows us to target the extremes of the swing curve. Operating at the extremes of the swing has two benefits: better sidewall profile control and less process variability with thickness variation [2]. Wafers typically have 1-2% uniformity variation, which translates to a 100-200 Å thickness variation across the wafer. Choosing a thickness in the middle of a swing means that

inherent thickness variation would span a wider dose-to-clear range. By choosing the extremes, the same energy will clear a broader range of thicknesses. Of the extrema, the maxima are chosen so that the exposure energy will always be sufficiently high to clear, even if the thickness variation is out-of-spec.

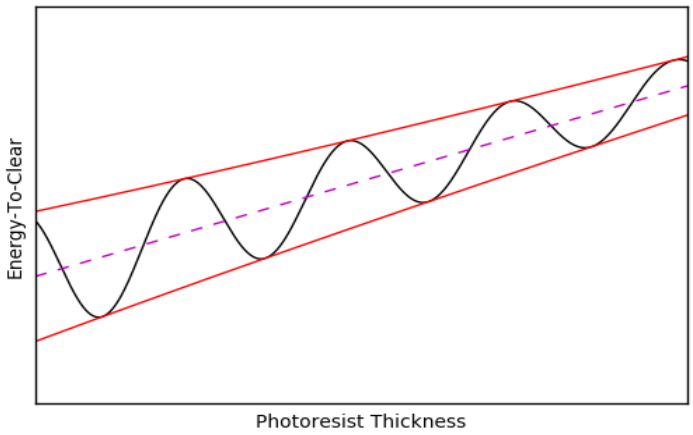

Figure 1. Simulated swing curve (black solid line). The linear shift is shown as the dashed pink line. The decreasing amplitude of the damped harmonic function are shown using the red lines which define the envelope of the swing curve. The simulated parameters were chosen to exaggerate the damping and linear effects for clarity.

Since the underlying cause of the interference pattern is reflections at the substrate interface, the periodic dependence can be nearly eliminated by an anti-reflective coating prior to photoresist application. A bottom anti-reflective coating (BARC) is a polymer with a *k* value chosen to attenuate the incident light and prevent these interference effects. Applying a BARC with the appropriate *n* and *k* values should nearly eliminate any swing effect.

2. Bare Silicon Experiment

2.1. Swing Curve Procedure on Bare Silicon

Testing was done using standard p-type, prime-grade <100> CZ silicon wafers, with resistivity between 10 - 50 ohms/cm^2. Wafers were reused throughout the experiment with thorough cleaning between experimental runs. The cleaning process was a solvent clean and a series of acid dips. The solvent clean was 10 minutes of Microposit 1165, a N-Methyl-2-pyrrolidone-based solvent, at 80℃; this step removed the bulk of the photoresist from the wafers. The first acid sequence was 10 minutes of piranha at 120℃, followed by a water rinse and then 1 minute in a bath of 10:1 49% hydrofluoric acid; the sulfuric acid removed photoresist residue and the hydrofluoric acid removed any native oxide. These two cleaning steps were typically done the night before the photoresist was applied. Immediately before the wafers were coated, they were re-cleaned in 1 minute of 120℃ piranha, water rinsed, then 1 minute of 25:1 49% hydrofluoric acid, before a final rinse and spin dry. This final clean ensured a pristine wafer surface before coating started.

After cleaning, wafers were run on one of two tracks: either the Picotrack PCT-200CRS or the SVG 8800 track. Wafers run on PICOTRACK were primed on track with 30 seconds of hexamethyldisilazane (HMDS) vapor at 100℃ to promote adhesion. Due to time constraints, wafers run on the SVG track were primed in a standalone YES Primeoven LP-5 with two minutes of HMDS vapor. Since the E0 tests were

clearing featureless areas, any differences in priming between the two methods was not a concern for this work.

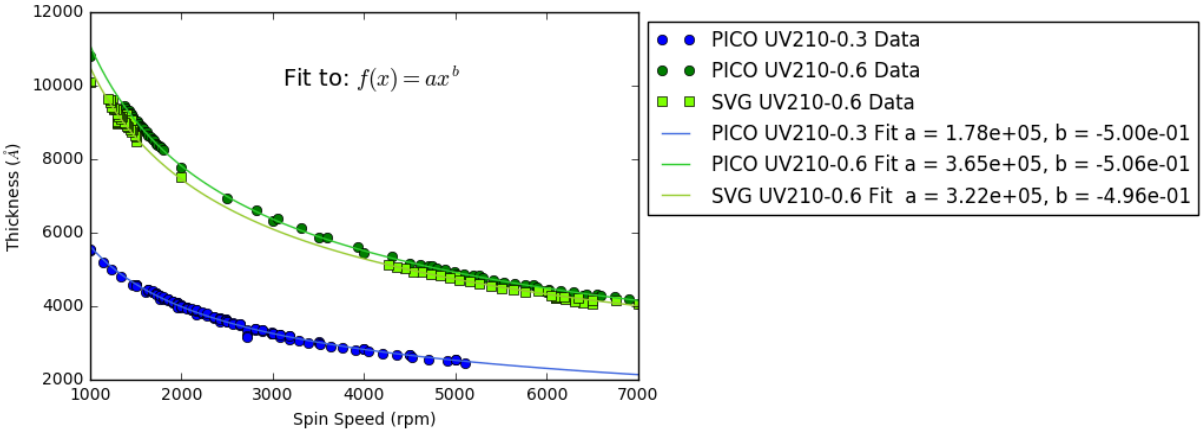

Figure 2. Spin Curves for the UV210 resists. Blue circles show UV210GS-0.3 on Picotrack. Dark green circles show UV210GS-0.6 on Picotrack. Light green squares show UV210GS-0.6 on SVG. The solid lines show the fits for each curve, and the fit coefficients are shown in the legend.

After priming, the photoresist was dynamically dispensed onto a slowly spinning wafer and then the wafer was spun up to a set speed to give the desired thickness. Historically in the Nanolab, only two thicknesses have been supported for UV210GS-0.6: 0.42 µm and 0.90 µm. The 0.42 µm resist thickness has been used to resolve features as small as 200 nm. A thinner resist, spun out to 0.38 µm allowed for features as small as 150 nm [3]. These values determined our regions of interest. For the thin coatings we varied thicknesses from 0.240 µm to 0.500 µm, targeting thicknesses every 50 Å. Thick coatings started at 0.850 µm going up to 0.950 µm, again with targets every 50 Å. Backside edge bead removal was performed to ensure wafer cleanliness. The wafers were then proximity baked for 60 seconds at 130℃.

The thickness of each wafer was measured by spectroscopic reflectometry on a Nanospec/AFT Model 3000 at 9 points across the wafer. The thicknesses reported here are averages of these nine measurements. The same measurement recipe was used for all wafers and assumed an index of refraction of 1.56. The thickness is plotted versus the spin speed to generate a spin curve, seen in Figure 2. The spin curve can be fit to the equation $f(x) = ax^b$. The fit coefficients are shown in the legend in Figure 2. The fit is then used to determine the spin speed required to hit individual thickness targets for the swing curve.

The wafers were exposed in an ASML 5500/300 deep ultra-violet (248 nm KrF laser) stepper. A clear reticle was used for the imaging with 25 individual dies. Each die was shot with a different exposure energy, starting from 3 mJ/cm^2 and increasing in steps of 0.5 mJ/cm^2. Wafers were grouped in batches of 3 or 5 for efficiency; no variation across batches was observed.

After exposure, the wafers were developed on the same track system where they were coated. The development process consisted of a contact bake at 130℃ for 90 seconds, then a puddle develop in MF-26A for 45 seconds, followed by a water rinse before finally being spun dry. E0, the dose-to-clear exposure energy, was measured by examining the wafers and identifying the exposure dose required to fully clear the die.

2.2 Bare Silicon Results

The resulting swing curve is shown in Figure 3. The area where UV210GS-0.3 and UV210GS-0.6 overlap shows excellent agreement, as expected given that only the solvent content differs between the two resist. Measurements were made over the course of 4 months with excellent agreement between different data sets. Lab humidity varied dramatically (10% in February, 43% in May) between data runs, but no impact is seen on the swing curve behavior. We observe no difference in exposure behavior based on which tool is used to coat/develop.

The data was fit to a damped harmonic oscillator with a linear shift, shown in Equation 1.

$$f(x) = Ae^{-x/d}\cos\left(\frac{2\pi x}{\lambda} + \phi\right) + mx + b \qquad \textbf{(Equation 1)}$$

The fit coefficients are: $A = -1.56\,mJ/cm^2$, $d = 8.24 \times 10^{15}$ Å, $\lambda = 727$ Å, $\phi = -2.75$radians, $m = 9.71 \times 10^{-5}\,mJ/(cm^2\,\text{Å})$, and $b = 6.65\,mJ/cm^2$.We then solve for the extrema, taking the first derivative of $f(x)$. As d is very large, the damping term $e^{-x/d} \to 1$and can be neglected. Similarly, since $m \approx 0$, this term can likewise be dropped, leaving us with the relatively simple equation

$$f'(x) = -\frac{2\pi A}{\lambda}\sin\left(\frac{2\pi x}{\lambda} + \phi\right) \qquad \textbf{(Equation 2)}$$

To find the extrema, we set the derivative equal to zero; since sine waves are periodic there are zeros every $n\pi$ radians, where *n* is an integer. Solving for x, we find

$$x = \frac{\lambda(n\pi - \phi)}{2\pi} \qquad \textbf{(Equation 3)}$$

To find the maxima only, we take the second derivative and solve for those x where $f''(x) < 0$. The thickness values are listed in Table 1. Note that for the 4320 Å thickness resist, this resist can be spun with either product -- on PICOTRACK, we achieve this thickness using the 0.3 formulation. On SVG, where the spindle design allows for higher spin speeds, we achieve this thickness using the 0.6 formulation.

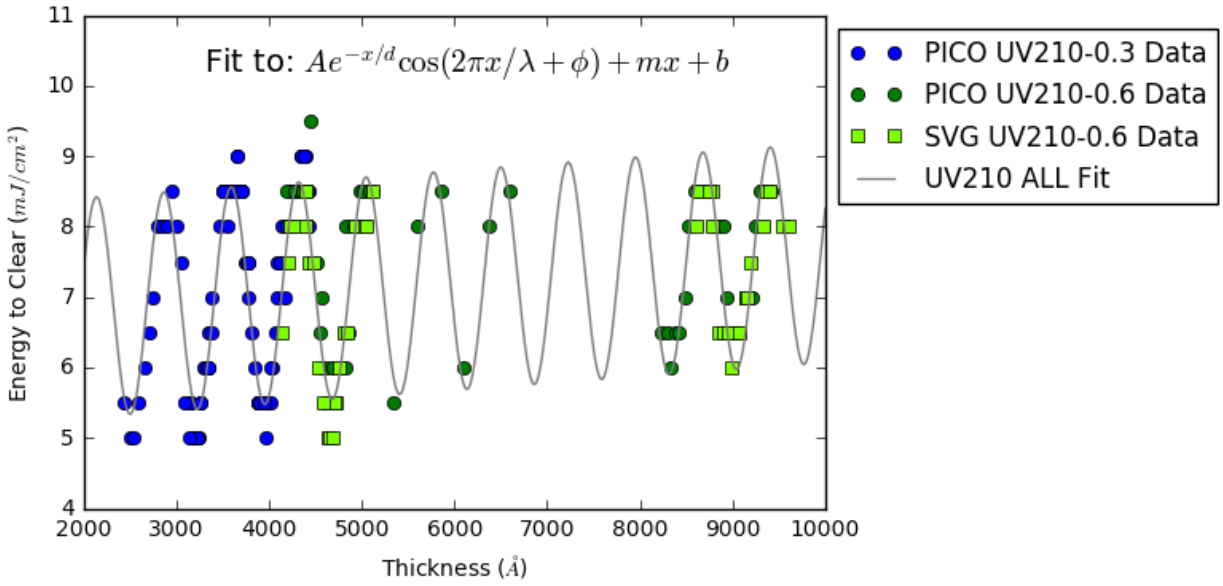

Figure 3. UV210 Swing Curve. PICOTRACK (PICO) UV210GS-0.3 is shown in blue. PICOTRACK UV210GS-0.6 is shown as dark green circles. SVG UV210GS-0.6 is shown as light green squares. The fit is shown as the solid gray line.

Thickness (Å)	PICO Spin Speed (RPM)	SVG Spin Speed (RPM)	Photoresist Product Name	Staff Monitoring
2865	3855		UV210GS-0.3	No
3590	2450		UV210GS-0.3	Yes
4315	1690	5995	UV210GS-0.3/UV210GS-0.6	Yes
5045	5200	4375	UV210GS-0.6	No
5770	3615	3335	UV210GS-0.6	No
6500	2860	2625	UV210GS-0.6	No
7225	2320	2120	UV210GS-0.6	No
7955	1920	1745	UV210GS-0.6	No
8680	1615	1465	UV210GS-0.6	Yes

Table 1: Fitting the spin curve for UV210GS-0.3 and UV210GS-0.6 we determined the spin speed for the listed maxima. UV210GS-0.3 is listed in blue. UV210GS-0.6 is listed in green. Staff will run regular process monitors on 4 variants: UV210GS-0.3 at 0.36 µm, UV210GS-0.3 at 0.43 µm, UV210GS-0.6 at 0.43 µm, and UV210GS-0.6 at 0.87 µm.

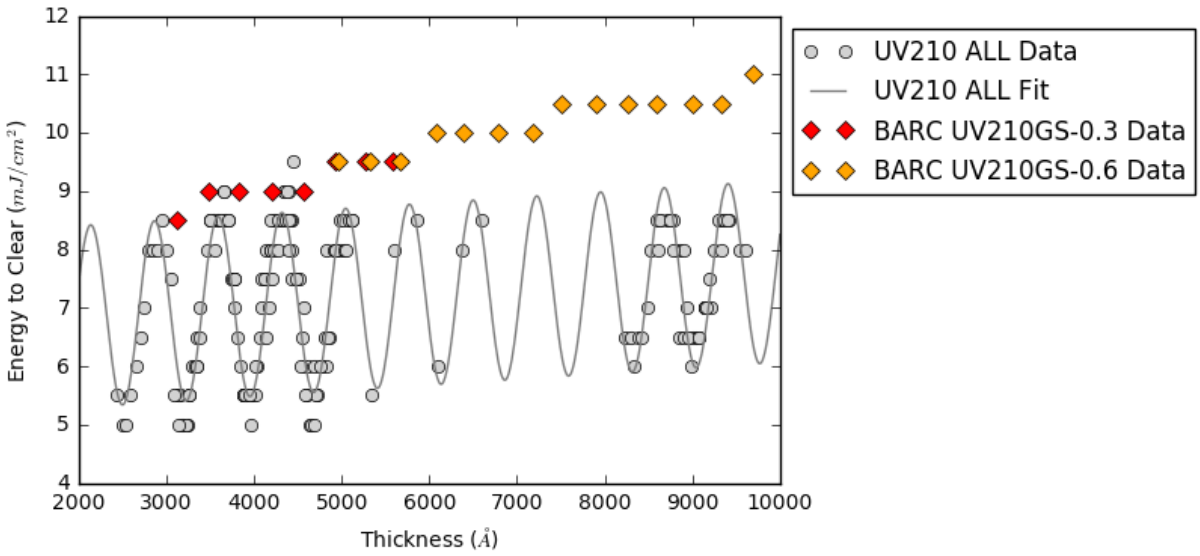

Figure 4. The dose-to-clear for UV210 on BARC is shown. UV210GS-0.3 with BARC is shown in red. UV210GS-0.6 with BARC is shown in orange. For comparison, all the data on bare silicon wafers is shown as gray circles and the fit is the gray line.

3. BARC Experiment

3.1. BARC Swing Curve Procedure

The cleaning procedure for the BARC-coated wafers was identical to the standard silicon wafer preparation described in section 2.1. These wafers were not treated with HMDS, per the manufacturer's recommended procedure. BARC was dispensed on a spinning wafer and spun to a thickness of 600 Å. Wafers were contact baked at 190℃ for 60 seconds. The BARC itself is kept in a warm bottle (temperature is in the range of 30 - 35℃) which lab members have observed helps prevents aging of the polymer. After the BARC application, photoresist was applied at varying spin speeds to achieve the desired thickness. Both 0.6 and 0.3 formulations of UV210 were used. Softbake, deep UV exposure, and developer processes were identical to processes for bare silicon wafers.

3.2 BARC Results

The resist thicknesses for the BARC experiment targeted the extrema points from the bare silicon swing curve -- if any swing effects occurred, we theorized that we would capture the effect at these thicknesses. As Figure 4 shows, we see no swing effect for BARC coated wafers; the required exposure energy rises monotonically with thickness. We expect that if a smaller exposure step had been used, we would see a more linear behavior rather than series of steps.

Data from the manufacturers of BARCs state that there will still be some swing effect with thickness [4] [5]. Our experiment did not capture these swings because the steps between our thickness targets were too broad and because we were not looking at the critical dimension of a feature but at a broad clearing of a featureless area.

4. Conclusions

Based on the swing curve on bare silicon, we have selected new photoresist targets for deep UV processing on the lithography tracks. We have measured no difference in exposure depending on the coat tool in use. We found spin speeds to get equivalent thicknesses on the two tools. We also showed that use of BARC greatly reduces any thickness-dependent swing in exposure dose.

Acknowledgements

All work was performed at the Marvell Nanofabrication Laboratory. The authors wish to thank all Nanolab members, who we know were inconvenienced during our long 6-hour runs throughout the course of this experiment when we had all the tools in the litho bay tied up; we truly appreciate your patience!

References

[1] *UV™ 210 Positive DUV Photoresist for Microlithography Applications.* (Rohm & Haas Electronic Materials, 2005). Retrieved from http://www.microchem.com/PDFs_Dow/UV210GS.pdf

[2] Dammel, R. *Diazonaphthoquinone-based Resists*, Tutorial Texts in Optical Engineering, v TT11. SPIE Optical Engineering Press: Bellingham, Washington, 1993.

[3] Calderon, F. and J. Clarkson. *Critical Dimension Enhancement of DUV Photolithography on the ASML 5500/300.* Berkeley Nanolab High School Intern Project Final Report. Retrieved from https://docs.google.com/document/d/1nScb52O9kPOfd7_YD38jNID4oX17xq7FSfhjwslrcC8

[4] *Introduction to Bottom Anti-Reflection Coating (BARC) Technology.* (The Dow Chemical Company, 2013). Retrieved from https://www.youtube.com/watch?v=fGrL2gAuklI

[5] *Understanding Brewer Science ARC Products. (*Brewer Science Corp., 2002). Retrieved from https://people.rit.edu/deeemc/reference_13/arcs/understanding_arc.pdf

Source Code and Original Data

The analysis was done in Python 3.5; the original data files and source code are available here.

Appendix -- Overview of Process Steps

	Chemical/Tool	Process	Notes
Solvent Clean	-------- MSINK1 -------- Microposit 1165	80°C, 10 minutes	Remove photoresist
Acid Clean	-------- MSINK8 -------- Sulfuric Acid + Hydrogen Peroxide (Piranha) Hydrofluoric Acid	120°C, 10 minutes Ambient temperature, 1 minute	Remove any photoresist residue Remove native oxide
Acid Clean	-------- MSINK6 -------- Sulfuric Acid + Hydrogen Peroxide (Piranha) Hydrofluoric Acid	120°C, 1 minute Ambient temperature, 1 minute	Remove any organic residue Remove native oxide, leave surface hydrophobic for better photoresist adhesion
HMDS or BARC	Picotrack Wafers SVG Wafers BARC Wafers	30 seconds on track 2 minutes in standalone primer 600 Å spun on SVGCOAT3	
Coat	PICOTRACK1 SVGCOAT6	UV210GS-0.3 UV210GS-0.6 UV210GS-0.6	Spin speed varied to give different thicknesses
Measure Thickness	NANOSPEC	198 STAFF-ASCOAT_UV210-0.6(1.56)	
Expose	ASML300	3.0 mJ/cm^2 - 15.0 mJ/cm^2 in steps of 0.5 mJ/cm^2	
Develop	PICOTRACK2/ SVGDEV6	90 second PEB 45 second puddle develop in MF-26A	