Solutions to Resist Pattern Collapse for 45 nm Lithography.

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Abstract—**Two approaches to prevent pattern collapse of 45 nm photoresist features were explored to create a process which minimizes the forces attributed to collapse while increasing adhesion forces. Two different bottom anti-reflective coatings (BARC), a first and second reflectance minimum were examined in conjunction with the experimental approaches. An initial characterization of pattern collapse was performed to act as a control to gauge the effectiveness of the experimental approaches using an exposure matrix. The first approach implemented a surfactant added to the de-ionized (DI) water rinse after develop to decrease the capillary forces between the features. The second approach created more topography to the surface of the BARC in order to provide more surface area for the resolved feature to adhere to.**

Index Terms—**pattern collapse, 45 nm half pitch, immersion lithography, interferometry, surfactant rinse, bottom anti-reflective coating etch, capillary forces, adhesion forces, 1st minimum BARC, 2nd minimum BARC**

I. Introduction

The reduction of lithographic feature sizes has allowed continuous growth for the semiconductor industry. Yet even with new technologies there are certain physical limits to current resist processes and technology. Trying to image features below 100 nm leads to compromised integrity of the resolved resist features and results in a problem known as pattern collapse. Features begin to topple over and in some cases become severely deformed. It has been realized that there are at least three forces that can be attributed to pattern collapse [1]:

1) The capillary forces that act on the structures during development.
2) The adhesion between the resist features and the underlying films.
3) The resists thermo-mechanical properties.

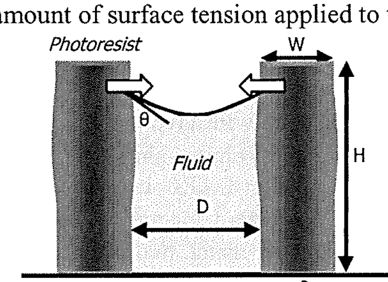
This study focuses on the capillary and adhesion forces and demonstrates two experimental approaches to decreasing pattern collapse of 45 nm equal lines and spaces in conjunction with a comparison of a 1st and 2nd minimum anti-reflective coatings (BARC). This first approach will be to implement a surfactant into the development process to decrease capillary forces to strengthen the resist. The second approach involves etching the BARC film by a small amount in order to create more topography to the surface so that there will be more surface area for the resist to adhere. These two approaches were experimented on separately to optimize process parameters before implementing them both into a final process, minimizing the amount of pattern collapse that can occur.

II. Theory

A. Capillary Forces

The majority of the forces acting on the resist that cause the features to collapse occurs when the liquid from the develop and rinse process remaining between the resolved features. When the liquid level is below the height of the surrounding features, a meniscus forms with some amount surface tension. The actual amount of surface tension is dependent upon the chemical components of the liquid. This is the point where the force is greatest on the surrounding features. Figure 1 describes a maximum amount of stress allowable for a resist feature with mechanical properties matching common polymer based resists.

In order to decrease surface tension, the properties of the liquid must be altered. For this study, an approach will be used which adds a surfactant to the de-ionized water rinse post wet develop. The addition of the surfactant will decrease the contact angle of the liquid to the feature sidewall which is related to the amount of surface tension applied to the feature.



$$\sigma = 6\gamma\cos\theta/D \times (H/W)^2 \quad [2]$$

σ: maximum stress γ: surface tension θ: contact angle
H: height of feature D: pitch of pattern W: width of feature

Fig 1. Maximum allowable stress between photoresist features.

B. Adhesion Forces

The adhesion between the resist and the undying film helps to strengthen the integrity of a feature. In this case, the underlying film is an organic based BARC. Adhesion is directly related to the amount of surface area between the resist and the BARC [3]. In standard processes, the BARC is hard-baked, commonly at temperatures between 200°C and 215°C. This step cures the BARC and so any mixing of chemistry between the photoresist and BARC is kept to a minimum. Therefore, the adhesion between the BARC and the resist is purely a physical property.

The BARC is spun on which provides a fairly uniform coating. The hard-bake drives off much of the solvents and by doing so leaves the surface with some slight topography. In order to increase this topography, a dry etch was used. A low power Argon (Ar) based plasma etch was explored as a means to increase the surface topography. An illustration of the process can be seen in Figure 2.

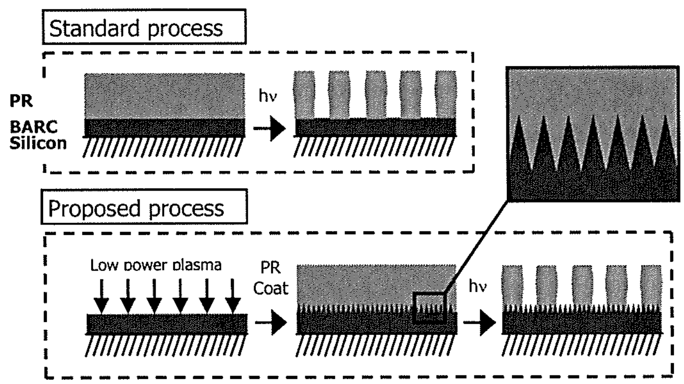


Fig 2. Process flow for standard coat/expose/develop process and the proposed process that includes the dry etching of the BARC.'

The use of a BARC helps to minimize constructive nodes that form due to the interference effects of incoming and reflected radiation off of an underlying interface between different materials. These nodes result in resist features with uneven profiles where there are portions of the resist with different widths. The basic principle is that the BARC is coated at a specific thickness, namely a multiple of a ¼ wavelength of the exposing radiation. Radiation that makes it through the resist-BARC interface and then reflects off of the BARC-Silicon interface will have had an optical path length ½ wavelength longer (phase shift of π) than radiation reflecting off of the resist-BARC interface. These two beams will deconstructivly interfere due to the π phase shift.

This study compared using two different BARC's, a 1st reflectance minimum and a 2nd reflectance minimum. Since these coatings are dependent on thickness and optical properties of the materials themselves such as the refractive index, simulation was done to find the optimum thickness (T_{crit}) for each BARC. An initial study was performed to obtain spin speed curves fro both the 1st and 2nd minimum BARC's so that the critical thicknesses could be obtained consistently.

Although both BARC's were designed to minimize the reflectance off of the Silicon substrate, the 1st minimum was far more effective (Figure 3). The purpose for looking at the different BARC's was to investigate whether the two approaches to minimizing pattern collapse would have varying efficiency depending on the resist profiles caused by the difference in the resulting reflected intensities between the BARC's.

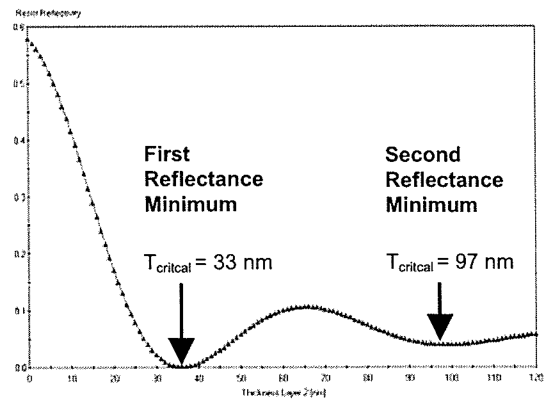


Fig 3. Thickness vs. Reflectivity of a bottom anti-reflective coating.

III. EXPERIMENT

A. Tools and Materials

For each approach, the Rochester Institute of Technology system for immersion lithography (Figure 4) [4] was used to expose 45 nm half pitch features (lines and spaces) with 2:1 aspect ratios, varying the exposure dose in a 6 x 6 matrix. The reasoning for using an exposure matrix was to gauge the effectiveness of the approaches on preventing pattern collapse which is more prevalent when the features are either under or over-exposed. If the number of exposure fields without pattern collapse above and below a known good exposure level increases, the approach can verified. From here on, percent Exposure Latitude (%EL) will be used to describe this range and its value is seen in equation 1.

$$\%EL = \frac{E_{\max} - E_{\min}}{E_{best}} \times 100 \qquad \text{[Equation 1]}$$

The Immersion lithographic system uses interferometry to expose the lines. The 193 nm goes through a chromeless phase shift mask which acts as a diffraction grating. The ± 1st diffraction orders are collected and reflected to interfere with each other using a Smith-Talbot prism setup. Using water as the immersion fluid, an effective numerical aperture (NA) of 1.05 is achieved.

The 1st minimum BARC used for this study was supplied from Rohm & Haas and the 2nd minimum BARC from Brewer

Science. The resist and a top coat were both supplied from JSR Micro. The top-coat helped prohibit any absorption of the immersion fluid into the resist.

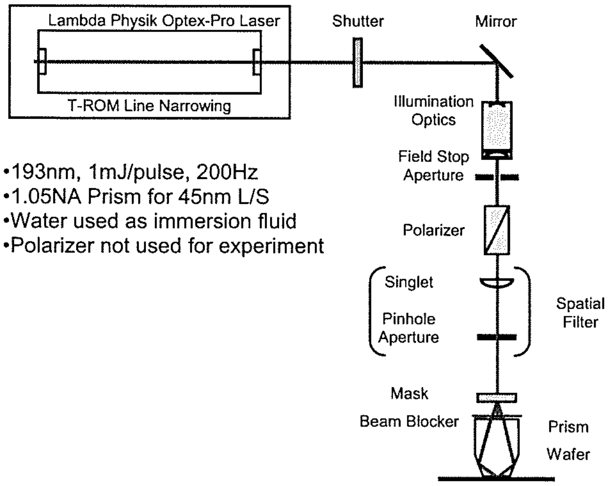


Fig 4. Schematic of R.I.T. system for Immersion lithography research.

B. *Characterization*

An initial control experiment was performed in order to have a standard process in which pattern collapse routinely occurred. This process was used as a comparison to gauge the effectiveness of both approaches at minimizing the amount of collapse. To ensure there would be a process that would result in pattern collapse, each BARC was not only coated at T_{crit}, but also 15% above and below that thickness. This was to diminish the canceling effect on the constructive nodes formed in the resist profiles, making the features less robust.

With each BARC coated, a 6x6 exposure matrix was used to observe pattern collapse in the under and over-exposed regions. Four levels of pattern collapse were characterized in order to have a standard to compare all treatment combinations to.

Collapse Levels:

1) GL- Good lines with no collapse (Figure 5).
2) 2L- Adjacent lines collapsed into each other (Figure 6).
3) 3L- Groups of 3 lines collapsed into each other (Figure 7).
4) 4L- Four or more lines collapsed into each other, no good lines anywhere in exposure field (Figure 8).

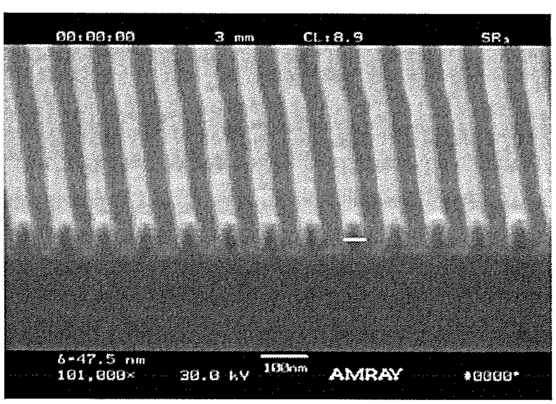


Fig. 5. Good lines with no collapse.

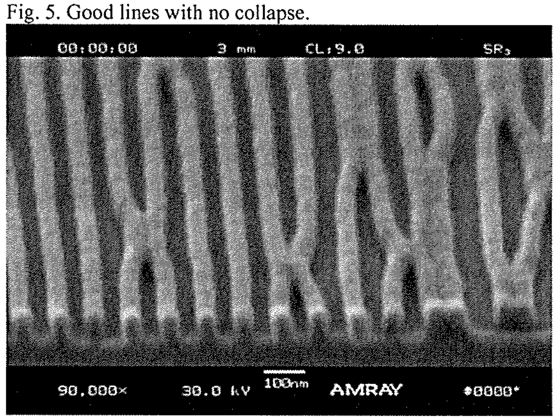


Fig. 6. Adjacent lines collapsed.

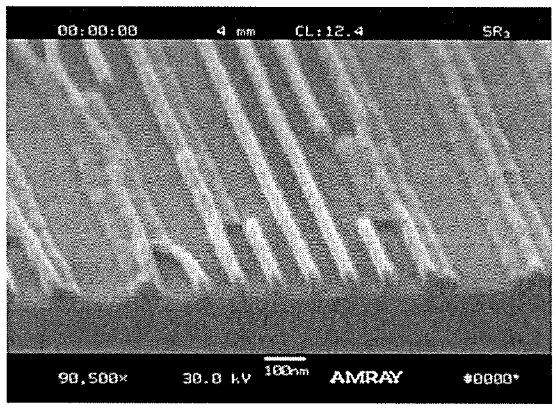


Fig. 7. Groups of 3 lines collapsed.

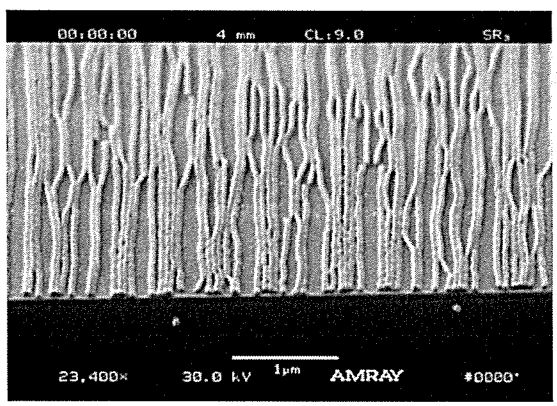


Fig. 8. Four or more lines collapsed.

The characterization showed that pattern collapse did occur for both BARC's. Not only was it prevalent for the samples with BARC thickness above and below T_{cirt}, but also in the samples coated at T_{cirt}. With pattern collapse demonstrated the study continued next with implementing the two approached to minimize the amount of pattern collapse that did occur.

C. Surfactant Added DI Water Rinse

Isopropyl alcohol (IPA) was used as the surfactant due to its availability in most semiconductor fabrication laboratories. Although it is a solvent, it has been used successfully as a surfactant [5]. The IPA was added to DI water at three different percentages by volume. It was assumed that high concentrations off IPA would begin to damage the features by dissolving them away so only 10%, 25% and 50% concentrations were used.

Multiple samples using both BARC's (with no etch) were coated and exposed. Directly proceeding development, the different IPA:DI water mixes were used to rinse the developer away, then the samples were then air dried. After inspection, it was seen that there was only a slight decrease in pattern collapse with increasing concentration of IPA. For the 1st minimum BARC, the 50% IPA treatment eroded away the BARC and cause complete collapse of all exposures on that sample while the 2nd minimum BARC sample showed further improvement over the 25% sample.

D. BARC Etch Study

Due to the tight constraints on the thickness of the BARC, an etch recipe had to be found which had a very controllable (predictable) etch rate with good uniformity. Since the goal was not to remove much material, a low power physical etch using Ar was experimented with. A study was done varying power, pressure, and flow. Before and after each etch, the surface was examined using atomic force microscopy to analyze the difference to the topography (Figure 9). The process parameters that were concluded upon were; 50 sccm of Ar, 75 W at 125 mtorr. The etch rates were approximately 13 Å/min and 27 Å/min for the 1st and 2nd minimum BARC's respectively.

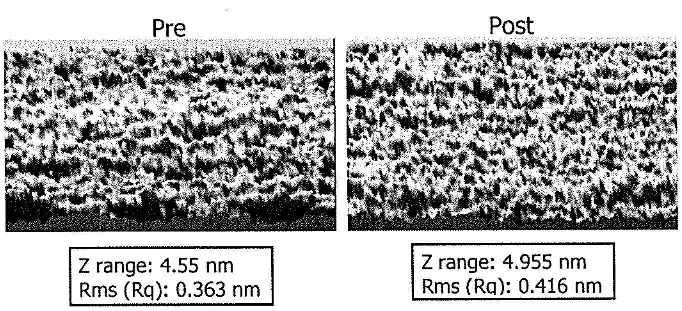


Fig. 9. AFM analysis pre and post dry etch.

Once the surface was etched there was a concern about the ability to spin coat a uniform layer of photoresist on the rough surface. Initially, when an etched sample was coated using the same process (spin speed and amount of photoresist) there where some visible striations on the surface of the sample towards the outside of the wafer. Due to the fact that the exposure matrix only took up a small portion in the center of the six inch wafer where the photoresist was fairly uniform, the striations did not create a problem.

After a brief experiment varying spin speed and using a greater volume of photoresist when coating, the striations were minimized at the cost of some uniformity. It is believed that a further study could optimize this process.

With multiple samples coated at T_{cirt}, the exposure and develop was done using the standard development process used for the control experiment. After development, the samples were analyzed using scanning electron microscopy. Even in under and over-exposed regions, no pattern collapse occurred. This was an obvious improvement over the standard process.

The only issue observed from this process were some random areas where there appeared to be footing at the base of the feature (Figure 10). Resist had not been fully developed away making the base of the feature much wider than the middle and top. With that type of structure, the feature is very stable and would not likely collapse but are not desired due to the inconsistent widths. As expected, these areas where the features exhibited this footing were mostly in the underexposed regions. A longer time in the developer could compensate but for this study the time was kept constant.

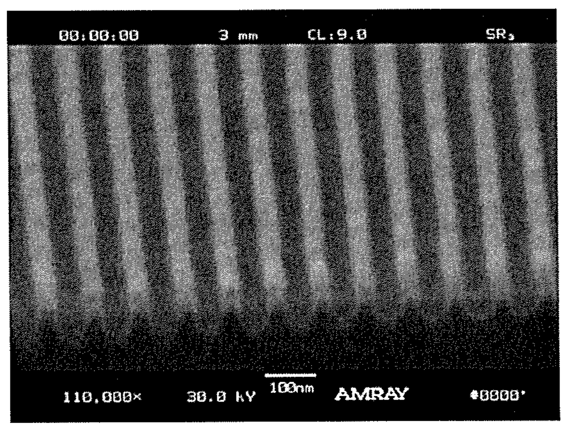


Fig. 10. Footing observed on BARC etched sample.

E. Combined Process

Both the BARC etch approach and the surfactant added DI water rinse approach was combined into one process to see if there were any interaction between the two approaches. The BARC etch recipe was used for both BARC's and the 10% IPA was used for the post develop rinse. Through out the exposure matrix, the 2L type of pattern collapse was observed. This was thought to be from the IPA dissolving away the BARC from under the features causing the features to topple into one another. This was seen for both BARC's (Figure 11).

From the analysis it was theorized that there was a mechanism associated with the rough surface of the BARC that accelerated absorption of the IPA and the dissolving away of the BARC. One reason might be an increase in small crevices in the BARC at the base of the feature due to a poor coat of the photoresist. Essentially, a void at the resist-BARC interface which opens up when the exposed areas between the resist are developed away.

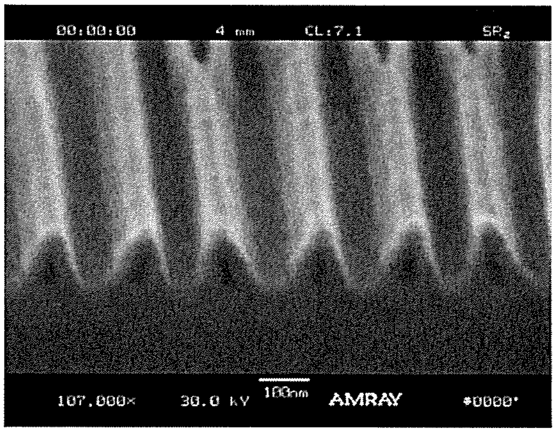


Fig. 11. Collapse due to interference effects of the surfactant and BARC approaches.

F. Final Comparison

As seen in Table 1, both approaches decreased the amount of pattern collapse by increasing exposure latitude, and in the case of the BARC etch eliminates collapse. The surfactant rinse did decrease the amount of pattern collapse but there is a maximum concentration of the IPA where collapse begins to occur. Another issue was that higher concentrations of IPA dissolved away some of the resist in the under and over-exposed fields.

The combination of both approaches revealed that the use of IPA does in fact start to dissolve away the BARC and can cause pattern collapse by eating away the BARC from under the feature. This combined with the capillary forces when the liquid is evaporating caused the features to topple into each other.

BARC	**Control**	**Surfactant Approach**			**BARC Approach**
		IPA			**BARC Etch**
		10%	**25%**	**50%**	
1st Min. R.	±15 %EL	± 22 %EL	± 26 %EL	0	No collapse
2nd Min. R.	0	0	± 4.3 %EL	± 14 %EL	No collapse

Table 1. Comparison of % EL between control, surfactant approach and BARC approach.

IV. Conclusion

Both the surfactant added rinse used to decrease capillary forces and the BARC dry etch used to increase adhesion did in fact appear to decrease pattern collapse. The BARC etch appears to be the most promising approach since it can passively eliminate pattern collapse without distorting any of the features as the IPA rinse tended to do. Of note is that there are many other surfactants that can be used to decrease capillary forces and would likely perform better than the IPA in a similar study. This study quantified improvements by looking mainly at under and overexposed features where pattern collapse occurs more regularly. Therefore, it can be inferred that both of these approaches might appear to work equally as well if all fields were exposed at the appropriate dose for the process.

References

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