Novel high sensitivity EUV photoresist for sub-7 nm node

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ABSTRACT

Extreme ultraviolet lithography (EUVL) has been recognized as the most promising candidate for the manufacture of semiconductor devices for the 7 nm node and beyond. A key point in the successful introduction of EUV lithography in high volume manufacture (HVM) is the effective EUV dose utilization while simultaneously realizing ultra-high resolution and low line edge roughness (LER). Here we show EUV resist sensitivity improvement with the use of a photosensitized chemically amplified resist PSCARTM system. The evaluation of this new chemically amplified resist (CAR) as performed using EUV interference lithography (EUV-IL) is described and the fundamentals are discussed.

Keywords: EUV, 14 nm HP, 7 nm node, resolution, sensitivity, CAR

1. INTRODUCTION

The history of the semiconductor device industry dates back to 1948 when William Shockley from Bell Laboratories invented the first transistor using a solid semiconductor which was also found by him in 1946.¹ Then, Texas Instruments invented the first integrated circuit (IC) in 1958.² From this point on, IC scaling has driven not only the semiconductor industry, but many other industries for almost half a century. Needless to say, advances in lithography have been key in this aggressive scaling. Tool and process improvements have partially been responsible for making this aggressive scaling possible. Undoubtedly nonetheless, materials used in these processes are also important, especially photoresists. Important discoveries in photoresists development as the exposure wavelength is reduced in order to improve the resolution have continuously been proposed in the history of lithography. For example, the breakthrough invention of CARs by Willson from IBM Almaden Research Center allowed us to overcome the low sensitivity problem when using “dark” excimer laser sources.³⁻⁵ Today, the semiconductor industry is facing a similar situation. We have again a low sensitivity problem using “darker” EUV sources, so another discovery is needed to reduce the cost of ownership which is now skyrocketing due to 193i multiple patterning.⁶ Tagawa of Osaka University had previously presented initial results with regards to this new multi-exposure lithography concept that involves the use of a *photosensitized chemically amplified resist*TM. This process has the potential not only for EUV sensitivity enhancement but also for the simultaneous chemical gradient improvement.⁷ In this study, we investigate this new photoresist system by EUV interference

lithography (EUV-IL) at the Paul Scherrer Institute (PSI).⁸ In this work we have also investigated several positive tone resists and a negative tone resist by electron beam lithography (EBL).

2. EXPERIMENTAL

2.1 Material

Resist samples were prepared by mixing resin, photo-acid generator (PAG), quencher, photosensitizer precursor (PP) and solvent. A metal containing additive was also mixed in for the metal containing positive tone PSCAR resist. The resist solution was filtered using 0.2 μm PTFE filter prior to evaluation.

2.2 Electron Beam Lithography Evaluation

Contrast curves were obtained by first spin-coating the different resists solutions on silicon wafers treated with an organic under layer, and pre-baked at 100 °C or 130 °C for 60 seconds to give 50-100 nm film thickness. EBL was performed using a Hitachi HL-800D tool. After the EB exposure, the wafer was irradiated with a UV-LED lamp ($\lambda = 365$ nm, the tool was assembled by Tokyo Electron Kyushu Ltd.) baked at 110 °C for 60 seconds. Finally, the wafers were developed for 30 seconds. To investigate the patterning capabilities of the resists, the different material solutions were spin-coated on silicon wafers treated with a silicon containing layer on top of an organic underlayer. The rest of the procedures were the same above.

2.3 EUV-IL Evaluation

For the EUV-IL study, the film thickness was reduced to about 30 nm. The rest of procedures were the same as in EBL patterning study experiment.

3. RESULT AND DISCUSSION

3.1 Mechanism of the PSCAR system

As described previously by Tagawa, the PSCAR process consists of a 1st pattern exposure (by EUV, EBL etc.) and 2nd UV flood exposure while using a new type of CAR. In order to realize the sensitivity improvement with this process, the resist needs to contain a PP as well as a PAG. Figure 1 illustrates PSCAR mechanism briefly. At the pattern exposure stage, a small amount of acid is generated by the decomposition of the PAG. This small amount of acid catalyzes the transformation of PP to PS. Since the acid generation occurs only at exposed area, PS generation also only happens in that region. Therefore when the UV flood exposure is carried out a huge amount of acid generation takes place in the 1st pattern exposure area only. Through this process, sufficient acid is obtained to make dissolution contrast even though the 1st pattern exposure dose amount is limited like in EUV lithography case.

Figure 1. PSCAR Mechanism illustrated.

An example of PP and PS is shown in Figure 2 with their corresponding UV-Vis absorption spectra. In this example, an aromatic acetal compound is applied as a PP (PP-1) and is transformed to ketone (its PS form) via acid catalyzed

hydrolysis. As shown in the spectra, PS has strong absorption at 365 nm which is one of the useful flood exposure wavelengths while PP-1 does not have absorption at the wavelength at all.

Figure 2. Example of PP & PS and their UV-Vis spectra.

3.2 PSCAR study with efficient sensitization material

Aiming for a very efficient sensitization with the PSCAR process, a new PP material, PP-2, was developed. Figure 3 shows the EBL contrast curves of the PP-1 and a PHS based positive resist containing PP material, PP-2 (left and right respectively). PP loading concentration was kept constant for each resist (5 wt% to resin). It is obvious that PP-2 has much higher potential of sensitization with UV flood exposure. As much as $12 \mu\text{C}/\text{cm}^2$ sensitivity enhancement was observed for PP-2 when $0.5 \text{ J}/\text{cm}^2$ 365 nm UV-LED dose was applied while only $2 \mu\text{C}/\text{cm}^2$ change was monitored for PP-1.

Figure 3. EB Contrast curve of positive resist containing PP.

Since PP-2 was found to have very efficient sensitization potential, further PSCAR study was conducted with this PP. For the next step, EBL patterning was investigated. Although multilayer reflectivity control is not necessary for ordinary EUV or EB lithography, is required for PSCAR process since a UV flood exposure, here 365 nm, is applied. The importance of multilayer optimization is clear from Figure 4. The reference stack (Si-sub/AD layer 60 nm/resist 60 nm) was not appropriate as can be seen from both, the reflectivity simulation and our patterning results. According to the simulation, too much 365 nm light is converged at the interface between AD layer and resist. This was thought to be the cause of severe peeling of the pattern when UV dose was increased. On the other hand, the use of an optimized stack (Si-sub/UL 160 nm/Si anti-reflective coating ARC 33 nm/resist 60nm) was shown to be efficient in the prevention of pattern collapse even though UV dose was high. A 2.7 times faster photospeed was found for this LS pattern. This optimized multilayer stack was applied for both the EB and EUV patterning evaluation.

Figure 4. Multilayer dependency byreflectivity simulation and PSCAR results (150 nm HP LS by EBL).

From the material point of view, resists for the PSCAR system can be prepared very easily since only the addition of a PP material to existing CARs is needed. As various CARs have potential to be utilized for this purpose, here we exhibit PSCAR demo with metal containing positive tone resist and negative tone resist by EBL.

Recently, metal additives have been reported to improve EUV resist sensitivity while maintaining high resolution and low LER values at sub-20 nm HP.⁹ Therefore a dual sensitivity improvement can be accomplished by the combination of a metal additive and PSCAR system. As shown in Figure 5, 1.4 times sensitivity enhancement was achieved in comparison to the baseline resist by this method.

Figure 5. PSCAR Demo with Metal Containing Positive Tone Resist (150 nm HP LS by EBL).

Negative tone CARs are not excluded from the PSCAR application. Figure 6 proved that sensitivity enhancement was made with that platform and 1.7 times faster photospeed was gained when 1.5 J/cm² UV flood exposure was conducted.

Figure 6. PSCAR Demo with negative tone resist (150 nm HP LS by EBL).

3.3 PSCAR demo with EUV-IL

PSCAR lithography performance was evaluated for one of the current best CARs using the EUV-IL set-up at the Swiss Light Source (SLS) synchrotron facility located in PSI. Figure 7 shows SEM images of 18 nm HP LS patterns obtained at best dose. In this figure, a table with the calculated dose-to-size (DtS), LWR, and Z-factor¹⁰ values from multiple EUV dose shot images is also shown. Here, Sample-A, one of the best CARs developed by JSR Corp. was chosen as a base resist. Two different PSCAR samples were prepared: (1) Sample-A with PP-2 additive (JEUXS80001)¹¹ and (2) Sample-A with PP-2 and an increased amount of quencher (JEUXS80002). For JEUXS80001, simple sensitivity enhancement by UV flood was of interest, while resist performance comparison with base sample-A at the same EUV DtS by UV flood was of interest for JEUXS80002.

For JEUXS80001 as expected, good sensitivity enhancement was seen and 1.7 times faster EUV photospeed was gained at 0.5 J/cm² UV flood exposure dose. However, the LWR increased and resist performance was not improved in terms of the Z-factor with increasing UV flood exposure dose. The reason for this Z-factor deterioration with UV-flood exposure dose is not clear at the moment and the details are now under investigation. For JEUXS80002, the DtS value was high without UV-flood due to the additional quencher loading, but decreased to the same sensitivity when 0.75 J/cm² UV flood dose was applied. From the stochastic point of view, increased quencher loading should be advantageous for better resist performance, but the LWR and Z-factor at 0.75 J/cm² UV dose were comparable with base resist Sample-A. Further investigation that will help us understanding this behavior and help us improve the resist formulation is on the way.

Sample-A	JEUXS80001 (Sample-A + PP-2)				JEUXS80002 (Sample-A + PP-2 + Quencher)	
28.5mJ 19nm	27.8mJ 17.95nm	23.3mJ 18.6nm	16.9mJ 19.2nm		36mJ	27mJ
EUV only	EUV only	UV flood 0.25J	UV flood 0.5J		EUV only	UV flood 0.75J

Material	UV flood	18nm hp LS			
		DtS	Sen. Up	LWR	Z-Factor
Sample-A	None	29.7mJ	-	3.7nm	1.19E-08
JEUXS80001 (Sample-A + PP-2)	None	29.5mJ	-	3.9nm	1.31E-08
	0.25J	24.4mJ	x 1.2	4.6nm	1.51E-08
	0.50J	17.3mJ	x 1.7	6.1nm	1.88E-08
JEUXS80002 (Sample-A + PP-2 + Quencher)	None	37.0mJ	-	3.4nm	1.25E-08
	0.75J	29.0mJ	x 1.3	3.7nm	1.16E-08

Figure 7. PSCAR demo with EUV IL -Sample-A base- (18 nm HP LS)

We also tested another CAR by JSR, Sample-B, for PSCAR evaluation. Sample-B has photosensitizer PP-2 and an increased amount of quencher (JEUXS80003) like JEUXS80002 above. Figure 8 shows the patterning results at 16 nm HP LS pattern. In this experiment, the sensitivity enhancement with UV-flood exposure dose was not so vivid and a 2.0 J/cm² UV flood exposure dose was not sufficient to achieve the base resist DtS. Nevertheless, it is worth mentioning that the LWR and Z-factor values were not deteriorated with UV-flood sensitization until 2.0 J/cm² and the resist performance was found comparable to the base resist Sample-B.

Figure 8. PSCAR demo with EUV IL -Sample-B base (16 nm HP LS)

4. CONCLUSION

In this paper, the mechanism, material examples of PP and PS, the importance of a multilayer system were discussed and evaluation results with new a new type of PP were shown for the PSCAR method. A new PP material PP-2 enabled good UV flood sensitization with various CAR systems as shown experimentally by EBL. A PSCAR demonstration by EUV-IL was also carried out and the results showed that faster EUV photospeed was achieved with UV-flood exposure but overall further improvement in the resist performance is still required. PSCAR material improvement can be enabled by new PP material development and further resist formulation optimization. This has the potential to accelerate the implementation of EUV lithography for mass production at the 7 nm node and beyond.

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