Comparative study of line roughness metrics of chemically amplified and inorganic resists for EUV

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ABSTRACT

We present a comprehensive study of the roughness metrics of different resists. Dense line/space (L/S) images of polymethyl methacrylate (PMMA), hydrogen silsesquioxane (HSQ), different chemically amplified resists (CARs), and metal oxide based resists have been patterned by extreme ultraviolet interference lithography (EUV-IL). The three line width roughness metrics: r.m.s. value σ_{LWR} , correlation length ξ and roughness exponent α , were measured by metrological analysis of top down SEM images and compared for the different resists imaged here. It was found, that all metrics are required to fully describe the roughness of each resist. Our measurements indicate that few of the state-of-the-art resists tested here can meet the International Technology Roadmap for Semiconductors (ITRS) requirements for σ_{LWR} . The correlation length ξ has been found to be considerably higher in polymer-based materials in comparison to non-polymers. The roughness exponent α , interpreted using the concept of fractal geometry, is mainly affected by acid diffusion in CARs where it produces line edges with a higher complexity than in non-CAR resists. These results indicate that different resists platforms show very different LWR resist metrics and roughness is not only manifested in the σ_{LWR} but in all parameters. Therefore, all roughness metrics should be taken into account in the performance comparison of the resist, since they can have a substantial impact on the device performance.

Keywords: line roughness, LER, LWR, PSD, HHCF, correlation length, roughness exponent

1. INTRODUCTION

Line width roughness (LWR) of the resist image is of crucial technological importance because it directly transfers i.e., to gate length dimensions variations – during plasma etching pattern transfer – ultimately impacting device performance. Early studies have found that the threshold voltage and other electrical characteristics in Fin field effect transistors (FinFETs) are affected by the LWR due to fluctuations in the gate length, width and related geometrical interfaces¹. Similar effects are estimated in other parameters such as cut-off frequency, gate capacitance, off current (I_{off}), etc.

There are several LWR sources such as aerial image quality, mask roughness, photon shot noise, secondary electron blur, acid diffusion, statistics of deprotection and quenching events, molecular size, thickness, development, etc. Although some of these causes are systematic and others are stochastic, the measured roughness is eventually a stochastic one-dimensional spatial signal. As such, the analysis of roughness in the domain of spatial frequency was introduced and these descriptors were defined: the power spectral density (PSD), the σ vs. line length curve and the height-height correlation function (HHCF).² These descriptors provide three metrics that altogether define the LWR. These metrics are the total root mean square roughness (σ_{LWR}), the correlation length (ξ) and the roughness exponent (α). With these metrics it possible to quantify the roughness contribution introduced at each spatial frequency. This methodology brings advantages from the metrology point of view of the device reliability. For instance, critical dimension (CD) variations and low frequency LWR are known to affect intra-transistor performance, while high frequency LWR is known to affect inter-transistor performance. Furthermore, device performance has been found not to be affected by the roughness contributions above a specific technology-node dependent frequency (equal to the reciprocal of the pitch) owing to the spatial averaging effects of the device dimension.

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The ITRS sets the target requirements for the maximum total LWR that can be tolerated per technology node in an integration process. These LWR targets are summarized in Table 1 for the years of 2011 to 2017. The σ_{LWR} limit is set to 1.6 nm for year 2016³ (not taking into account resist smoothing techniques before and during edge transfer). The maximum LWR according to ITRS specification is technology node-dependent and, for the reasons mentioned above, it is calculated in the spatial frequency range from 0 to the cut-off frequency (1/pitch).

Table 1. ITRS target specifications for dimension and line width roughness of devices.

Technology		2011	2012	2013	2014	2015	2016	2017
DRAM	Half pitch (nm)	36	32	28	25	23	20	18
	LWR (nm)	2.8	2.5	2.2	2	1.8	1.6	1.4
Flash	Half pitch (nm)	22	20	18	17	15	14.2	13
	LWR (nm)	2.8	2.5	2.2	2	1.8	1.6	1.4
Logic	Half pitch (nm)	38	32	27	24	21	19	17
	LWR (nm)	2.8	2.5	2.2	2	1.8	1.6	1.4

Besides the total σ_{LWR} , it is agreed that the correlation length and the roughness exponent also play a role in the performance of devices, although their effect is not yet fully understood. Nevertheless, novel EUV resist platforms will undoubtedly employ radically different approaches to patterning, which will likely result in different characteristic LWR metrics. It is worth mentioning that the roughness transfer from the photoresist during plasma etching affects the spatial components of LWR in different ways,^{4, 5} which is of course of technological interest for process integration. For these reasons, this work provides a comparative study of the LWR performance of various photoresists according to the abovementioned metrics and an interpretation is proposed.

2. EXPERIMENTAL

2.1 Samples preparation and description

Photoresists materials were patterned by EUV-IL at the XIL beamline of the Swiss Light Source (SLS) using diffraction transmission gratings as described elsewhere⁶. Densely packed L/S patterns with pitch ranging from 100 to 36 nm have been investigated here. Each photoresist was processed according to the manufacturers' specifications: coating conditions, thermal treatments, development, post processing. The list of samples is shown in the table below (Table 2). The PMMA (950k molecular weight, 1% in chlorobenzene) and HSQ (FOX16 diluted in methyl isobutyl ketone 1:6) were chosen as reference systems because of their very well-known properties. The HSQ was also developed in two different alkaline solutions (tetramethylammonium hydroxide TMAH and sodium boron hydroxide). We tested three state-of-the-art chemically amplified resists specifically designed for EUV lithography based on organic polymer backbones, from undisclosed manufacturers. Finally, we tested two different formulations of a photocondensed, negative tone, molecular oxide resist, that is non-chemically amplified and is synthesized by Inpria Corp. All photoresists were patterned using the same transmission mask and under the same illumination conditions.

Table 2. Description of samples for comparative LWR study.

Resist	Manufacturer	Type	C.A.	Thickness [nm]	Development
PMMA	Sigma Aldrich	organic	N	40	MIBK:IPA
HSQ	Dow Corning	inorganic	N	35	TMAH
					NaBOH
CAR 1	undisclosed	organic	Y	35	undisclosed
CAR 2	undisclosed	organic	Y	35	undisclosed
CAR 3	undisclosed	organic	Y	25	undisclosed
YABA	Inpria Corp.	metal-oxide	N	32	undisclosed
YF	Inpria Corp.	metal-oxide	N	25	undisclosed

2.2 Analytical metrology

The patterned resists were inspected using a scanning electron microscope (SEM) Zeiss Supra VP55, using the following settings: EHT 1 keV; beam current 21 pA; frames per picture: 1; frame integration: none; pixel aspect ratio 1:1. The obtained top-down SEM images were then analyzed using SuMMIT software suite to extract the LWR r.m.s. value, correlation length and roughness exponent. These metrics were calculated using both the power spectral density (PSD) and the height-height correlation function (HHCF) descriptors. The results shown in the following sections are based on the HHCF descriptor because it provided the most consistent output when analyzing noisy images. For the calculation of r.m.s. value according to ITRS, a cut-off frequency equal to the reciprocal of the pitch was used. The measurement and analysis of the parameters are performed using the same tool and SEM conditions, to ensure a consistent quantitative comparison of the results.

3. RESULTS AND DISCUSSION

3.1 Total r.m.s. LWR

For comparison purposes, in here we consider the total r.m.s. roughness of lines patterned at dose-to-size (also known as Best Energy or E_{size}). As a matter of fact, resist densely L/S patterned produces the lowest total roughness when the exposure dose used is equal to the dose-to-size because the slope of the quasi-beam profile is highest⁷. The total LWR for each resist at every pitch tested is shown in Figure 1. From this figure it is clear that the roughness is not significantly affected by the pitch size. This is due to the fact that the produced aerial image by interference lithography has a constant normalized image log slope (NILS) independent of the pitch. As a result, EUV-IL is a powerful technique to compare the roughness of L/S images at different pitches.

In this study we have found that HSQ yielded the lowest σ_{LWR} among all these resists, regardless of the development used. We ascribe this to the small molecular size of the HSQ silicon cage structure and to the highest dose required to pattern it which has a beneficial effect on the shot noise-induced roughness. The performance of the chemically amplified resists varied considerably depending on the specific formulation. The metal oxide based materials YABA and YF produced relatively low roughness lines (also possibly owing to the small molecular block size). PMMA showed quite remarkably high roughness, which is attributed to large molecular size of the polymer.

Figure 1. Total r.m.s. LWR measured for each resist at the dose-to-size for pitches 100 to 36 nm.

In the framework of the ITRS requirements, let us consider now the σ_{LWR} measured up to a cut-off spatial frequency equal to the reciprocal of the pitch. The resulting σ_{LWR} is shown in Figure 2. The ITRS-relevant σ_{LWR} is clearly lower than the full σ_{LWR} because it is measured in a smaller frequency range. Nonetheless it is remarkably smaller in the case of non-polymer resists (-40% to -54%) than it is for all others resists (-25% to -37%). This observation leads us to conclude that the chemical composition affects the frequency components differently and should be taken into account for the device performance. Finally, we note that the ITRS specification is at present quite challenging to be met for all EUV resists, unless additional smoothing techniques are employed.

Figure 2. σ_{LWR} calculated according to the ITRS specifications and at the dose-to-size for each resist per pitch from 100 to 36 nm. The dashed orange line indicates the ITRS requirement for year 2016. The numbers indicate the percent difference between the full LWR and the ITRS-LWR (averaged throughout pitches).

3.2 Correlation length ξ

The ξ metrics represents the boundary between the low frequency regime (plateau of the PSD) and the high frequency regime (self-affine geometry). It is agreed that the size of the molecule, the acid diffusion and the development mainly affect the correlation length. The statistical distribution of measured ξ values of each resist is shown in Figure 3.

Figure 3. Statistical distribution of the correlation length for all samples. Boxes indicate the median and top/lower 25th percentile, while caps indicate the top/lower 5th percentile.

The general trend seems to indicate that polymer-based resists (PMMA, CAR 1, CAR 2, CAR 3) have larger ξ than non-polymers (HSQ, YABA, YF). In fact, the molecular size of the former resists is defined by the radius of gyration of their backbone polymer. In PMMA of molecular weight 950k, the radius of gyration can be as large as 30 nm⁸, while for these CAR resists it is estimated < 10 nm. Moreover, the acid diffusion also plays a role in CARs and adds to the ξ , which explains why their correlation length (≈ 10 to 12.5 nm) is comparable to that of the non-chemically amplified, but larger polymer PMMA.

3.3 Roughness exponent α

The slope of the power spectral density in the fractal regime (spatial frequency $f > 1/\text{pitch}$) is usually discussed in the framework of fractal geometry⁹. In fact, several studies found that sub-micrometric surfaces and structures exhibit self-affine morphologies typical of fractals¹⁰. For line edges, the fractal dimension d is then defined in relationship to the roughness exponent α according to the relation $d=2-\alpha$. In self-affine geometries, the fractal dimension d is always larger than the topological dimension (1 for edges) and it is larger when the edge complexity is higher.

The statistical distribution of roughness exponent α (and corresponding fractal dimension d) of all samples is shown in the following Figure 4.

Figure 4. Distribution of the roughness exponent α (and corresponding fractal dimension $d=2-\alpha$) for all resists investigated in this work. Boxes indicate the median and top/lower 25th percentile, while caps indicate the top/lower 5th percentile.

In the fractal regime, all CAR resists yielded the line edges with the most complex contour, which we attribute to the effect of acid diffusion. In addition, smaller α might indicate that the dissolution process is more homogeneous in CAR

resists than it is in PMMA (which is a larger polymer and not as uniformly dissolved along the resist sidewalls)¹¹. The HSQ yielded different roughness depending on the development process, which seems to affect α much more than it does with the other metrics. In this regard, it is proposed that the slower developer (NaBOH) might form higher complex contours than TMAH does. Finally, the metal oxides materials (YABA and YF) formed lines with the lowest complexity among all examined here.

3.4 Summary of results

Different resist platforms showed remarkable differences in their roughness metrics due to the diverse chemical properties of each formulation. The summary of the results is shown in Figure 5.

Figure 5. Summary of the results for the three metrics of resists investigated in this work.

4. CONCLUSIONS

We have measured the LWR metrics of different resist platforms using a unified metrological approach. The LWR metrics change considerably depending on the lithographic process and according to the specific physicochemical properties, molecular size, and development of each material.

It was found that the correlation length is mostly affected by the combination of polymer size and acid diffusion. The roughness exponent of lines is mostly affected by the development process and by the acid diffusion.

From the point of view of device manufacturing and reliability, the effect of ξ and α on the device performance are of great technological interest. In this regard, theoretical calculations indicate that lower ξ , α , minimize the detrimental effect on performance of devices¹². Further studies are required to experimentally assess these effects on manufactured devices.

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