LER White Paper for the IRDS

Introduction

Key dimensions and process control parameters from the IRDS More Moore technology tables, relevant to patterning, are listed in Table 1. Line-edge roughness (LER) or line-width roughness (LWR) values are given, depending upon which of these two metrics is considered by the More Moore IRDS International Focus Team (IFT) as being more critical for the feature of interest. LER values < 0.5 nm are required in 2022, and LWR values < 1.0 nm are required for later nodes. The technical challenges associated with achieving these levels of roughness will be discussed in this white paper, starting with the origin of roughness in semiconductor patterning, including interactions with layers under the resist. This will be followed by an overview of the trade-offs among roughness, resolution, exposure dose, and defects. Finally, potential solutions will be presented.

The origin of roughness in lithographically-generated patterns

Roughness in lithographically-generated patterns is the result of statistical variations at the nanometer level. In the lithographic process, energetic quanta, typically photons or electrons, impinge on films of resist according to the intended pattern and drive radiation-induced chemical reactions in the resist. It is a theorem of statistical mechanics that the number of quanta N in a beam that passes through a cross-sectional area will vary according to a Poisson distribution with standard deviation given by

$$\sigma \approx \sqrt{\langle N \rangle} \tag{1}$$

where $\langle N \rangle$ is the average number of quanta. The implications of this for lithography can be appreciated from a specific example. Currently, the throughput of EUV exposure tools is set at a standard exposure dose of 20 mJ/cm^2. This means that ~54 photons pass through a 2 nm × 2 nm cross section, which will fluctuate ± 14%, effectively a dose variation at the nanometer level. Such variations can be reduced by increasing the exposure dose, but this will lower exposure tool throughput, thereby adversely affecting the cost-effectiveness of EUV lithography. More about this will be discussed later.

In addition to quantum fluctuations in photon or electron beams, there are also variations in resists at the molecular level. Chemically amplified resists are commonly used in DUV and EUV lithography, and these are multi-component systems. There can be random fluctuations in the concentration of each component, at the molecular level in mixtures (Fig. 1), but there can also be aggregation[1] and/or segregation[2] of components (illustrated in Fig. 2). These considerations apply to the concentration of photoacid generators and base quenchers in the polymer matrix. The polymers that make up the bulk of resist films also contribute to nano-scale resist variation. These polymers will not have a single molecular weight but instead the molecular weight varies around an average value and the exact monomer ratios and ordering in the polymer composition again vary from polymer to polymer. Briefly stated each polymer in the resist is as different to each other as are snowflakes and for the same reasons of unique growth. Roughness in resist patterns is a consequence of variations at the nanometer level (often referred to as stochastic variations), which have become relevant for the sizes of features in current and future nodes.

Diffusion processes in resists, such as the diffusion of photoacids during post-exposure bakes, can reduce feature-edge placement variations over distances comparable to diffusion lengths. Extensive diffusion can reduce roughness and is also associated with lower exposure doses in chemically amplified resists, but it will also limit resolution. As a rule of thumb, the diffusion length should be < 8% of the ½-pitch;[3] otherwise, there is insufficient chemical gradient to form small features after the bake-induced diffusion.

Table 1. Key dimensions and process control parameters relevant to patterning. HP = high performance, GAA = gate-all-around.

YEAR OF PRODUCTION	2020	2022	2025	2028	2031	2034
Logic industry node (nm)	"5"	"3"	"2.1"	"1.5"	"1.0 eq"	"0.7 eq"
Mainstream device for logic	finFET	finFET	LGAA	LGAA	LGAA-3D	LGAA-3D
Overlay (mean + 3σ, nm)	3.0	2.4	2.0	1.6	1.6	1.6
Minimum metal ½- pitch (nm)	15	12	10	8	8	8
Contacted poly ½-pitch (nm)	24	22.5	21.0	20	19	19
Physical gate Length - HP (nm)	18	16	14	12	12	12
FinFET minimum ½- pitch (nm)	14.0	12.0				
FinFET fin width (nm)	7.0	6.0				
Lateral GAA ½-pitch (nm)			11.0	10.0	10.0	10.0
LGAA minimum width (nm)			7	6	6	6
LGAA CD control (3σ, nm)	r		0.7	0.6	0.6	0.6
Gate LER (nm)	0.7	0.6	0.5	0.4	0.4	0.4
Metal CDU (nm)	2.3	1.8	1.5	1.2	1.2	1.2
Metal LWR (nm)	2.3	1.8	1.5	1.2	1.2	1.2
GAA LER (nm)			0.49	0.42	0.42	0.42

The radiation-chemistry of EUV resists is mediated through the photoelectrons generated by absorption of EUV photons, as well as subsequent secondary electrons.[4] [5] [6] [7] There is further image blur from the ranges over which these electrons travel before initiating a chemical reaction.[8] [9] With interferometric lithography, line/space patterns with 10-nm half-pitches have been obtained in metal-oxide resists, indicating that EUV lithography can be extended to such dimensions without being limited by photoelectron blur.[10]

Over generations of scaling, feature sizes have become so small that the finite sizes of molecules have become relevant. Shown schematically in Fig. 3 is the molecule, adamantane, which is often appended to resist polymers in order to improve etch resistance. The width of adamantane is ~6% of the width of 10 nm features and is a very large fraction of the LER and LWR requirements in Table 1.

In addition to causing LER and LWR, it has been found that stochastic effects can lead to the formation of defects.[11] Although there are no explicit requirements for stochastic-induced defects in the IRDS, clearly the defect rate must be sufficiently small as to enable good yield of highly-integrated circuits.

It has been observed that roughness in resist patterns often increases when the resist becomes very thin.[12] This may be due, in part, to the segregation of components in spin-cast chemically amplified resists.[13] The tendency towards increased LER as resist thickness decreases is problematic, because resist films need to be thin when patterning small features, in order to avoid pattern collapse. In this regard, inorganic resist platforms may be advantageous, since the resist materials may have greater rigidity than organic materials. Dry development may also be useful for addressing the problem of pattern collapse.

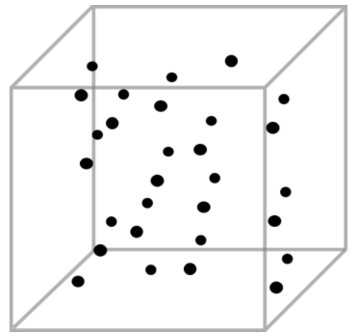

Figure 1 Illustration of the non-uniform distribution of the constituents of multi-component resists.

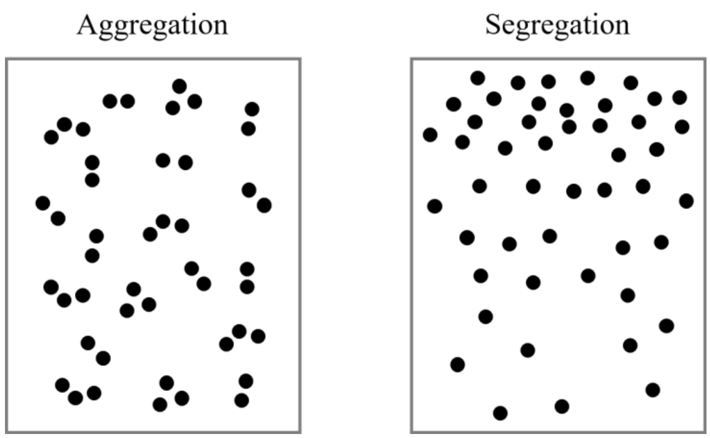

Figure 2. Illustration of aggregation and segregation

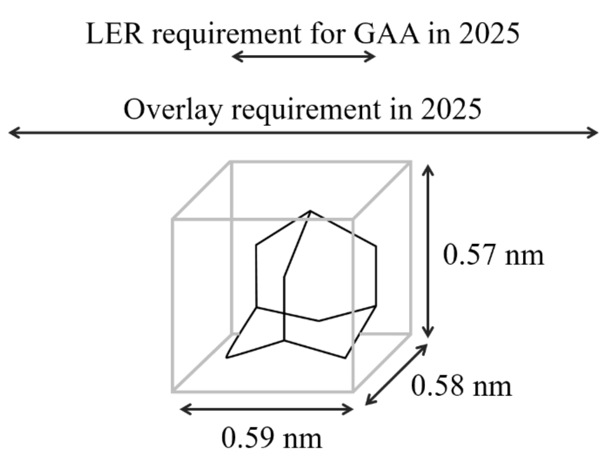

Figure 3. The molecule adamantane and some representative dimension from the roadmap. The requirements are from the IRDS 2021 values for high performance logic.

Metrology

In recent years, it has become recognized that SEM noise needs to be considered in the measurement of LER.[14] [15] [16] Moreover, the finite resolution of electron microscopes must be taken into account when considering LER at the requirements listed in Table 1.[17] With LER requirements < 1 nm, roughness needs rigorous definition that makes sense at molecular dimensions and is consistent for application to device physical modeling and measurement of feature roughness on wafers. That is, it is important that measurements of physical-edge roughness reflect the same electrical-edge roughness conditions as assumed by people doing device modeling.

Trade-offs among line-edge roughness, resolution and resist sensitivity

As listed in Table 1, low roughness is a requirement for advanced transistors. Because of photon shot noise, this cannot be achieved at very low exposure doses. Accordingly, strong source of EUV light are needed in order for LER requirement not to limit exposure tool throughput. Roughness can be mitigated through the diffusion of components such as photoacids, but diffusion limits minimum feature sizes. This trade-off is often referred to as the RLS triangle, for resolution (R), line-edge roughness (L) and resist sensitivity (S),[18] as shown in Fig. 4. This trade-off has been captured in a single metric, the Z-factor:[19]

$$Z\ (\text{mJ-nm}^3) = R^3 \times L^2 \times S. \tag{5.2}$$

where R represents the resolution, in terms of ½-pitch (nm), L represents LER (in nm) and S is the exposure dose in units of mJ/nm^2. Small values of Z are desirable, with values ~2×10^{-8} mJ-nm^3 being typical.[20]

Underlayers

It has been observed that LER for a given resist will vary when coated on an assortment of underlayers. It was eventually recognized that it is necessary to account for high-frequency noise in SEM measurements of LER, and such noise has a strong substrate dependency. More recently, LER has been seen as dependent on substrate, but with a much smaller dependency than thought previously, once the SEM noise is accounted for properly.[21,22]

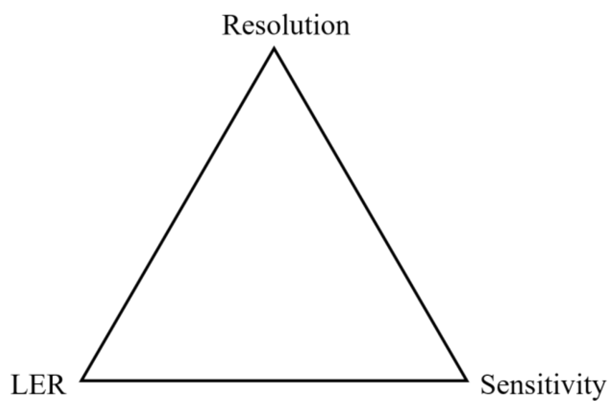

Fig. 4. The RLS triangle. Reducing one parameter necessarily requires an increase in one or both of the other parameters

Potential solutions

Considerable effort has gone into improving chemically amplified resists so that they meet the resolution and roughness requirements in Table 1. Much of this activity has involved resists based on a conventional approach, with resists consisting of polymers, photoacid generators and base quenchers. More complex types of chemically amplified resists have also been considered, but these are immature.

In addition to statistical variation caused by photon shot noise, optical absorption is a process subject to stochastic effects. Higher exposure doses will reduce both photon shot noise and the statistical variations of absorption, but at the expense of scanner throughput and lithography costs. The incorporation of elements with high optical absorption at EUV wavelengths can be used to reduce the statistical variation in absorption while permitting the use of lower exposure doses, so long as the benefits of greater absorption are not offset by increased photon shot noise.

Because of some fundamental concerns with chemically amplified resists, alternative platforms are being developed for EUV lithography. (Table 2) Because of mask blank defects, it is important to maximize the areas on masks that are covered by absorber. This implies a need for both positive and negative tone resists.

Table 2. Types of EUV resists

EUV Resist Platforms	**Tone**
Chemically amplified resists	Positive and negative
Metal-oxide resists[23]	Negative
Multi-trigger resists[24]	Positive
Photo-Sensitized Chemically Amplified Resist™ (PSCAR™)[25]	Positive
Scissioning resists	Positive
Vacuum-deposited resists[26]	Negative

In application, the LER that matters is the roughness of features after etch. It has been noted that the morphology of etched surfaces differs from that of developed resist films. In particular, the roughness appears to acquire a 2D aspect after etch. Many descriptions of LER have noted a decrease in LER following etch, but much of these reductions may have been a consequence of lower SEM noise when measuring features composed of materials other than photoresist.

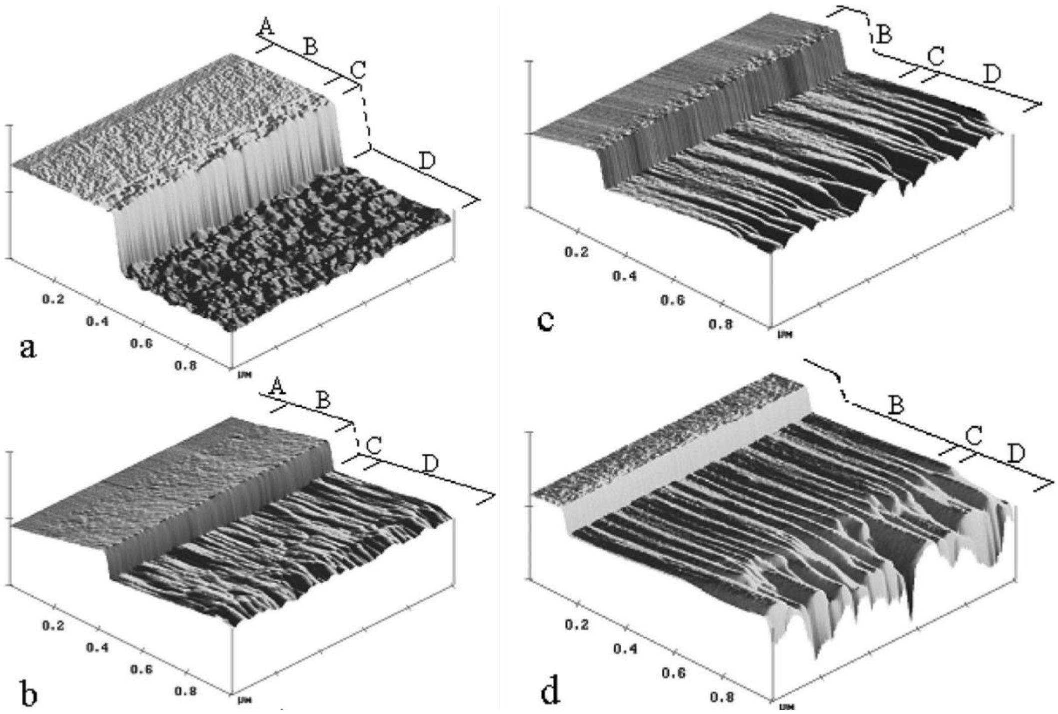

Fig. 4. Sidewalls of patterned KrF resist, measured using atomic force microscopy. a) After development. b) following etch of a bottom antireflective coating. c) and d) 200 nm and 500 nm oxide etch in a CF_4-CHF_3 plasma. Layer designations: A—silicon substrate; B—silicon oxide; C—antireflective coating; D—photoresist. Height scale: 200 nm/div.[27]

Long-term Outlook: The Extendibility of Subtractive Patterning

The semiconductor industry has used functional precursors of today's resist materials for subtractive patterning of device layers practically since its inception. Over that time span, these materials have been improved both incrementally and through fundamental innovation, enabling them to support leading edge patterning to this day. Key constraints are determined from device specifications (Table 1). In order to meet future LER/LWR requirements, it is worth considering new paradigms for patterning, such as non-subtractive patterning, where building the desired device geometries is achieved by selective modification of the surfaces on which patterns will reside. An example of this is selective deposition, which might be used to reduce constraints imposed by resolution limits and edge placement errors.

Other approaches, inspired by chemical biology, while highly speculative, merit consideration. For example, technologies such as CRISPER CAS9[28] today allow targeted and precise cut and paste operations to modify DNA. Conceivably, scientists and engineers could develop proteins such as CAS9 to cut molecular line and space patterns in a controlled way. It may also be possible to grow molecular building blocks and assemble them on a surface as larger pattern pieces guided by molecular anchors put on the surface through a preceding lithography step. While any such achievements are far from reality today, the tools to develop such capabilities do already exist.

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