FAST EVALUATION OF NEXT-GENERATION LITHOGRAPHICAL PATTERNS BY SMALL ANGLE X-RAY SCATTERING

Tengjiao Hu[1], Ronald L. Jones[1], Wen-li Wu[1], Christopher Soles[1], Eric K. Lin[1], Arpan Mahorowala[2], Diego M.Casa[3]
1 Polymers Division, National Institute of Science and Technology, Gaithersburg, MD 20899-8542
2 IBM T. J. Watson Research Center, Yorktown Heights, NY 10598
3 CMC-CAT, Advanced Photon Source, Argonne National Lab, Argonne, IL 60439

Introduction

Lithography has been widely used in semiconductor industry, bio-sensors, etc. As the lithographic process moves to smaller size of the patterns (sub-100 nm), there are more stringent demands both in manufacture and characterization.[1] Detailed characterization of the patterns includes the average quantities such as periodicity, feature size, feature profile, and their variations within the total pattern. Our group is developing a method to characterize small lithographical features by means of small angle X-ray scattering (SAXS).[2] In our earlier experiment, we have demonstrated that it is possible to measure periodicity and feature size from diffraction patterns. More than six scattering peaks allowed an accuracy of the periodicity to be on the scale of nanometer.

Broadening of the peaks and the decrease of the peak intensity contain useful information on the irregularities of the patterns. By careful alignment of the optics, we successfully suppressed the instrumental smearing effect and highlighted the diffuse scattering due to the irregularity of the patterns, which reveals other useful information on the samples.

Experimental

A set of samples was prepared on silicon wafers by the means of optical lithography using a 193 nm photoresist. The difference among samples is the designed size of the patterns. The silicon oxide lines were designed to be evenly spaced within a sample and with different periodicity among samples.

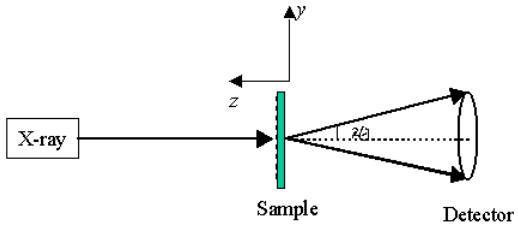

Figure 1 Schematic of small angle X-ray scattering.

SAXS measurements were performed at the ID-9 beamline of the Advanced Photon Source (Argonne National Laboratory) using a two-dimensional detector. The X-ray wavelength is 0.95 Å and the full width at half maximum (FWHM) of the beam profile is 81 µm in both *x* and *y* directions. All samples were measured in the transmission mode as shown in Figure 1. X-ray can penetrate silicon wafers (≈1 mm) with sufficiently high scattering intensity so that each measurement required only a few minutes.

Results and Discussion

Figure 2 shows the scattering patterns for samples. The gradually increasing clarity of the diffraction peaks indicates an increasing quality of the samples. This is a simple way to examine the patterns even without modeling. Thus, pattern quality can be qualitatively estimated prior to data reduction and analysis.

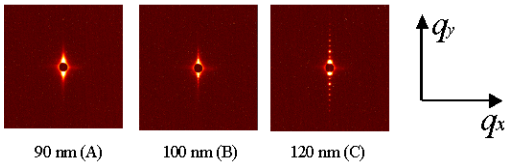

Figure 2. Small angle X-ray scattering patterns of evenly spaced silicon oxide lines.

Similar to the diffraction of crystals, the distance between neighboring peaks in q (wave vector, $q=4\pi Sin\theta/\lambda$) is related to the periodicity by the Bragg diffraction equation: $2dSin\theta = n\lambda$, where d is the periodicity of the pattern, 2θ the scattering angle, n the diffraction order and λ the X-ray wavelength. Figure 3 is a typical linear fit of the peak positions versus the diffraction order for sample C, which shows a periodicity of (237 ± 2) nm. In this paper, the standard uncertainty is estimated to be three standard deviation.

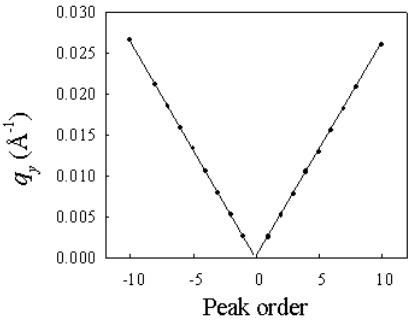

Figure 3. SAXS diffraction peak position as a function of diffraction order. The standard uncertainty of the data is smaller than the symbol's size.

Relative scattering intensity at different q values reveals information on the feature size and its profile. The measured scattering intensity is compared to models with varying degree of complexity in Figure 4. First, we only include the smearing effect due to the instrumental resolution, i.e., only of the wavelength spread, the detector resolution and the collimation condition.[3] In order to catch the feature of a broader experimental scattering peak, we have to incorporate an arbitrary constant standard deviation into the resolution function. It is one order magnitude larger than the instrumental smearing. This fact indicates that the line width spreading is not only due to the instrumental smearing, but more importantly, also due to the sample (*i.e.*, the defects in the sample). Constant broadening of the peaks is a characteristic of random deviation in the line position from its average lattice.[4] Even with the added arbitrary deviation in the resolution function, there are still some features of the peaks not fully captured by these simple models. This subtle difference is an indication of other kinds of imperfections in the sample.

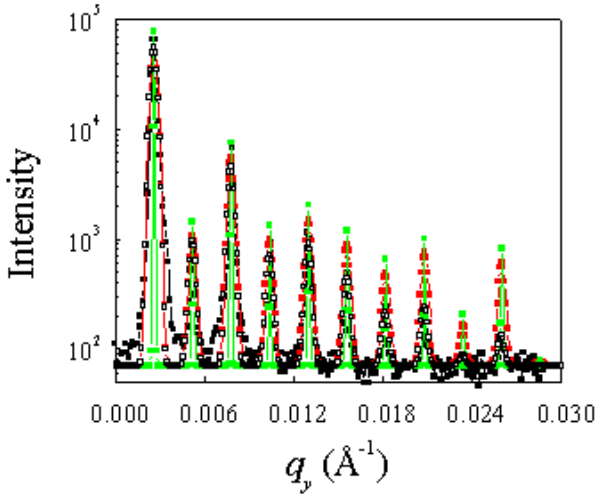

Figure 4. Experimental scattering data and fitting results of Sample C. The black filled square is the experimental data. Simple rectangle model was used to fit the data with (red filled square) and without (blue filled square) an arbitrary resolution standard deviation. The best fitting (black empty square) has incorporated both the Debye-Waller effect and an arbitrary standard deviation in the resolution function.

In order to account for the faster decrease of the measured scattering intensity than the modeled one at higher q's, we have incorporated the Debye-Waller effect ($I_{exp}=I_{model}exp(-4\pi^2\sigma^2q^2/3)$, where I_{exp} is the measured scattering intensity, I_{model} the modeled scattering intensity for ideal patterns and σ the root-mean square displacement of the lines from their undisturbed positions) in the fitting as shown in Figure 4. The Debye-Waller effect was originally used to account for the small random deviations of atomic positions from their undisturbed sites on a lattice. In our case, it is an indication of the random deviation of the distance between neighboring lines from their average value. The fitting indicates that there is ≈2.2 nm deviation from its average periodicity.

Since the instrumental smearing is smaller than the smearing due to the samples, we can further distinguish the difference of the peak spreading in the two dimensional scattering patterns. To a first order approximation, the FWHMs of the peaks in both q_x and q_y directions are characteristics of the irregularity of the patterns in each direction. We have shown in Figure 4 that the FWHM in q_y directions can be roughly described by a constant standard deviation in the resolution function. Figure 5 shows that the FWHM of the peaks in both directions have some difference.

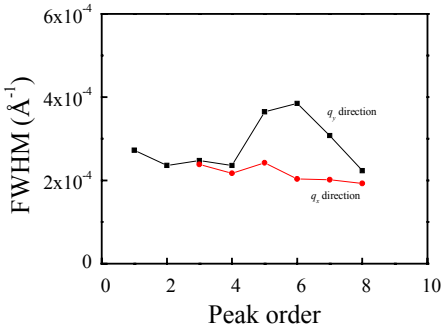

Figure 5 The FWHMs of the peaks in both q directions of Sample C. The standard uncertainty of the data is smaller than the symbol's size.

Conclusions

Using SAXS, we have demonstrated a precise characterization of the pattern periodicity and average line width. In addition, the random deviation of the distance between neighboring patterns is described by the Debye-Waller factor. A smaller contribution of the instrumental resolution to the peak broadening makes it possible to probe other useful information such as peak width in different directions, which is an indication of the line edge roughness in the respective directions.

Acknowledgements. This work was funded in part by the NIST Office of Microelectronic Programs. Additional funding was provided by the DARPA Advanced Lithography Program under contract N66001-00-C-8083. The Advanced Photon Source and D. M. C. are supported by the U.S. Department of Energy under contract W-31-109-Eng-38. R. L. J. is supported by a NIST National Research Council postdoctoral fellowship.

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