Critical Dimension Metrology in Microelectronic Test Patterns by Using CD-SAXS

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Introduction

Microelectronic fabrication requires precise control over feature dimensions and placement during the construction of as many as seven layers of circuitry, each involving multiple processing steps that may result in a loss of pattern fidelity. The complexity of this process is increasingly controlled by evaluating the quality of test patterns included in a nonfunctioning region of the die. The need to quickly and cheaply identify reduced pattern quality is complicated by the continuing reduction in the smallest feature size of a circuit, termed the "critical dimension." While 30-nm gate lengths are already common [1], these structures are relatively isolated and can be evaluated with traditional techniques such as scanning emission microscopy (SEM) and light scatterometry. For dense patterns, such as those used in dynamic random access memory (DRAM), the fabrication of compact discs (CDs) of ~50 nm in the next two years will demand control of CDs to ~1 nm [1]. Existing metrologies based on SEM (CD-SEM) and light scatterometry face significant technical hurdles in quantifying pattern dimensions and defects in this regime. Atomic force microscopy (CD-AFM) offers sufficient resolution but is relatively slow and challenged by dense high-aspect-ratio features.

We are developing a method based on transmission x-ray scattering capable of subnanometer precision in critical dimension metrology over large (50×50 μm) arrays of periodic structures. In contrast to light scatterometry, small-angle x-ray scattering (SAXS) is performed in transmission by using a subangstrom wavelength. With a wavelength that is more than an order of magnitude smaller than the pattern size, the patterns are characterized by using traditional methods employed in crystallographic diffraction. Using a relatively high-energy x-ray beam (>13 keV), an unmodified Semiconductor Equipment and Materials International (SEMI)-standard silicon wafer is measured in transmission without the need for a high-vacuum cell.

Quantities of particular interest are average values and the associated distributions of periodicity, or pitch, and pattern width. In addition, we hope to develop the technique in future experiments to routinely provide a 3-D description of the pattern shape, including height and sidewall angle.

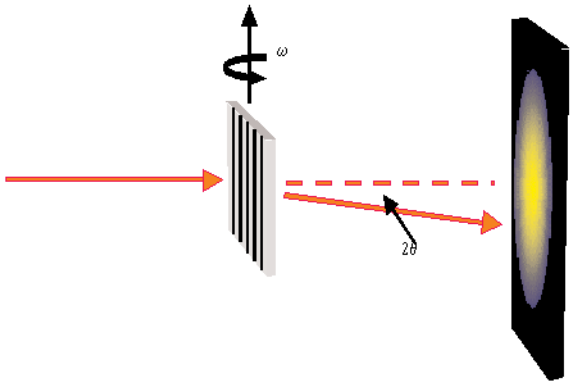

FIG. 1. Schematic of CD-SAXS transmission geometry, showing incident and scattered x-ray beam (solid lines), scattering angle 2q, rotation axis of patterened sample (middle), and 2-D detector (right).

Methods and Materials

Samples were prepared by using standard photolithographic processing on SEMI-standard silicon wafers. Initial patterns used to develop dimensional capabilities were provided by Shipley Co. (Marlborough, MA) [2]. Line edge roughness studies were performed in collaboration with the IBM T.J. Watson Research Center (Yorktown Heights, NY) [3]. Studies of "via pad" metrology were performed in collaboration with International SEMATECH (Austin, TX) [3].

SAXS was performed at beamline 9-ID (CMC-CAT) at the APS. The beam energy was set to 13 keV (wavelength of approximately 0.095 nm) by using a monochromator, and the beam size was set to approximately 40×40 micrometers by using three sets of rectangular slits. Intensity at the sample was increased by using a pair of focusing mirrors. X-ray transmission intensity through a SEMI-standard wafer was determined to be 0.07. Data were collected on a 2-D charge-coupled device (CCD) and background-subtracted by using standard methods.

Results

In Fig. 2, a top-down SEM image displays a typical photoresist test grating, consisting of a regular array of lines with a height of ~250 nm and a target width of 120

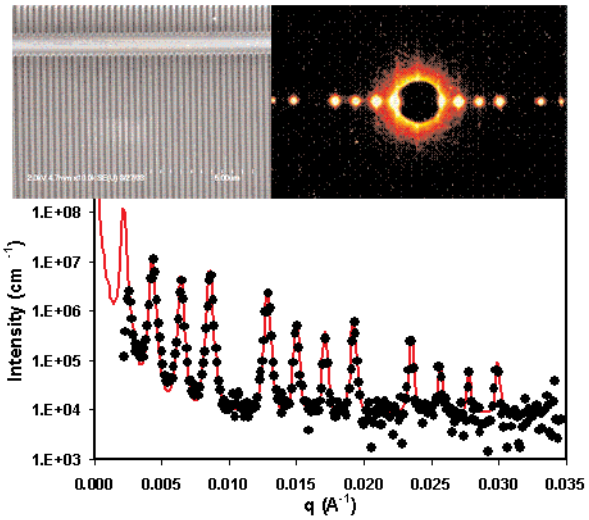

FIG. 2. Data collected along the diffraction axis (bottom) compared to top-down SEM image (top left) and the full 2-D detector image (top right).

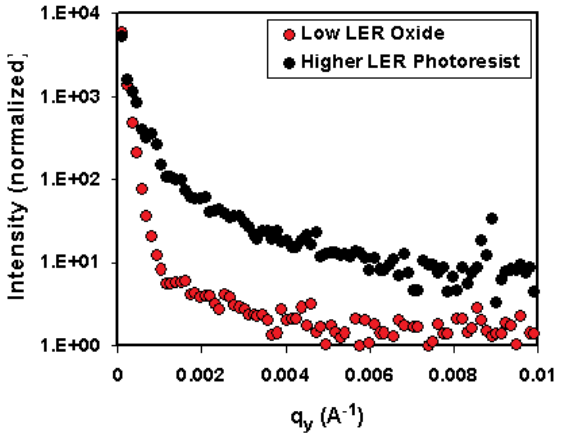

FIG. 3. Data comparing intensity as a function of q_y (perpendicular to the diffraction axis) at similar values of q_x for an oxide grating with a very low LER (open symbols) and a photoresist grating with a higher LER (filled symbols). Intensities are normalized to have the same value at $q_y = 0$.

nm based on the mask dimensions and optical configuration. The resulting 2-D CD-SAXS detector image is primarily characterized by a series of diffraction spots running perpendicular to the orientation of the line grating. The scattered intensity along the diffraction axis can then be modeled by using standard diffraction analysis techniques. In particular, the data in Fig. 2 are modeled by using a form $I_{ideal}(q) = B^2 |S^2(q) P^2(q)|$, where B is a q-independent prefactor used to place the data on an absolute scale, S(q) is a structure factor describing the underlying pattern lattice, and P(q) is a form factor describing the shape of the average pattern. The lattice spacing, or the pattern repeat period, is then obtained from the structure factor. In the limit of independent S(q) and P(q), S(q) can be represented as a series of evenly spaced delta functions occurring on lattice points $q = 2\pi n/d$, where n is an integer and d is the real space lattice factor. The form factor P(q) is then the Fourier transform of the average line shape. In Fig. 2, the data are modeled with a line possessing a rectangular cross section. The resulting pattern is characterized as a series of delta functions occurring at the inverse lattice positions, with relative intensities determined by the intensity "envelope" of P(q). The peak width is then determined through a combination of resolution smearing and small deviations from the ideal model provided above.

One measure of defects is obtained directly through the monotonic decay of intensity at higher values of q by using a Debye-Waller factor, where $I(q) = I_{ideal}(q) \exp(-2\pi\sigma^2 q^2)$ and σ is the average deviation of a pattern from its lattice position. While preliminary studies indicate that the values of s track increases in line edge roughness (LER), extracting values from power law relationships over a limited q range is inherently model dependent. As an example, preliminary calculations of the effects of typical sidewall angles on the form factor P(q) are likely to produce a similar effect over the same q range. Therefore, the Debye-Waller factor will incorporate several effects that must be systematically deconvoluted before quantitative estimates of σ are meaningful. While σ is not currently a direct measure of a specific defect, increases in s are still a direct measure of overall defect density.

While average dimensions are readily provided by CD-SAXS in sub-100-nm patterns, the ability to characterize defects in the patterns is of great interest. Recent studies on a series of photoresist patterns have demonstrated the ability to measure correlations in the sidewall morphology in gratings. As shown in Fig. 2, these correlations result in intensity "streaks" propagating parallel to the line edge. Industrial measurements of variations in sidewall position are typically referred to as LER. The lack of a standard definition of LER has stirred significant debate and activity directed toward roughness standards and standard definitions. The "streak" intensity observed here is, in principle, a measure of the frequency spectrum of LER. In Fig. 3, the q-dependence of the streak from a photoresist sample with a larger LER, as observed qualitatively from SEM images, is compared to a sample with relatively straight line edges. The magnitude of the spectrum is significantly larger in the photoresist sample; however, it is clear that a precise measurement will require a reduction in background. Efforts to measure these samples in lower-background

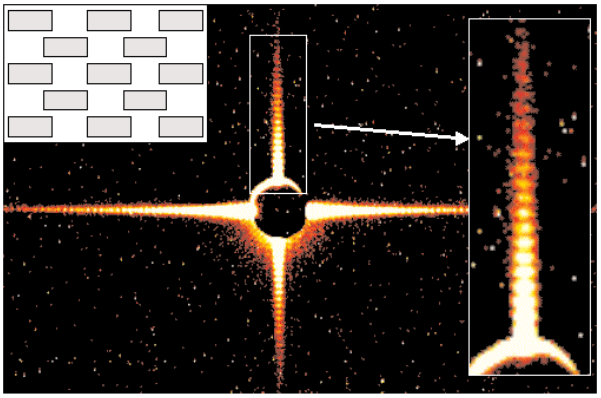

FIG. 4. Detector image resulting from CD-SAXS measurements of an array of via pads, shown schematically in the inset (top left). Also shown is a magnified view of the diffraction peaks (right).

environments are currently underway; however, the demonstration of a metrology of the LER frequency spectrum by using CD-SAXS represents a significant accomplishment.

The wide range of applicability of the CD-SAXS technique is immediately demonstrated in Fig. 4, where a via pad structure, consisting of essentially a checkerboard pattern of rectangles, is etched into a thermally grown oxide layer on a SEMI-standard silicon wafer by using standard photolithographic processing. In contrast to light scatterometry, the entire "top-down" shape is simultaneously captured on the 2-D SAXS detector as a series of diffraction peaks along perpendicular directions. In contrast, light scatterometry measures only a single dimension. The ability to capture data over the full 2-D detector provides faster metrology of 2-D structures such as via pads and interconnects; however, it is also key to the measurement of LER, as described previously.

Finally, the ability to scale the CD-SAXS technique to a laboratory-scale device is critical to making the technique relevant to industry. By using a standard sample with a known x-ray cross section, the data in Fig. 2 can be placed on an absolute-intensity scale. With known fluxes from commercial tube sources, we have established that a series of diffraction peaks should be observable by using a laboratory-scale device with adequate resolution and in reasonable time scales. Continued studies on the most appropriate instrumental configuration and on the relative importance of different data analysis techniques are ongoing.

Discussion

We used beamline 9I-D at CMC-CAT to demonstrate a procedure for measuring critical dimensions and defect structures common in current and future microelectronic circuitry labeled as CD-SAXS. By using standard diffraction analysis in the small-angle regime, CD-SAXS has demonstrated the capability of subnanometer precision in pattern periodicity and pattern width. In addition, a Debye-Waller factor was found to indicate defect density, while sidewall morphology produced a measurable "intensity streak" perpendicular to the diffraction axis. The applicability of CD-SAXS in a production environment has also been investigated and is considered feasible.

Acknowledgments

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