Assessing Electron-Optical Uniformity in Multi-electron Beam Arrays

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The recent commercial availability of miniature electron columns and multibeam electron optics enable the prospects of both analysis and electron beam processing of large areas at high throughput and high spatial resolution. Examples of such applications include multi-ebeam lithography, defect inspection for semiconductor and other nanoscale manufacturing processes, and additive manufacturing via electron beam induced deposition/etching. While these diverse applications span a wide range of operating conditions (accelerating voltage, beam current, spot size, dose per pixel), any robust manufacturing process, whether fabrication or quality control, will require the individual beamlet characteristics to be uniform within some specification determined by the desired manufacturing tolerances. Depending on the application, these characteristics might include astigmatism, information limit, and noise level (fluence), in addition to spot size and beam current. We have developed a protocol for extracting quantitative assessments of electron-optical performance of massively parallel electron beam arrays, which could be used either in tool development, routine alignments, or performance monitoring.

The contrast transfer function (CTF) provides a semi-quantitative assessment of the fidelity with which a scanning electron microscope reports the structural details of the imaged object as a function of spatial frequency. Briefly, the method involves producing a radial integration of the Fourier transform of an image from a test structure. If the distribution of spatial frequencies in the test structure is known and homogenous, variations in the electron-optical parameters will manifest as differences in the transforms. In this paper, we demonstrate the use of a random dot array, consisting of 12 nm radius dots written on a silicon wafer substrate using electron beam lithography with hydrogen silsesquioxane (e.g., HSQ) resist, as shown in Figure 1. By writing the array from a GDS file, the exact spatial frequency distribution of dot positions is known, controllable, and homogeneous.

At low frequencies, the fidelity is very high, nominally 100%, however, at higher frequencies, the fidelity decreases due to factors contributing to the point spread function, including aberrations and image collection artefacts. At very high spatial frequencies the CTF is dominated by the noise floor, as shown in Figure 2. Beam-to-beam variations in noise level can be extracted directly by comparing their noise floors, as illustrated in Figure 3. The information limit is indicated from the intersection of the high-frequency roll-off of the CTF with the noise floor. Finally, the sensitivity of the information limit to noise variations can be assessed from the slope of the high frequency roll-off.

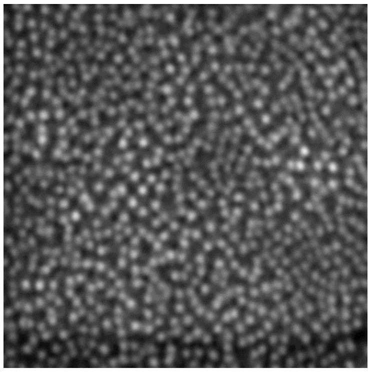

Figure 1: Random dot array(RDA) test structure: 12 nm dots of SiO_2 printed on a silicon wafer. The full die size is approximately 10 micrometers, ensuring that any stitching errors and pattern replication issues are minimized in the frequency range of interest.

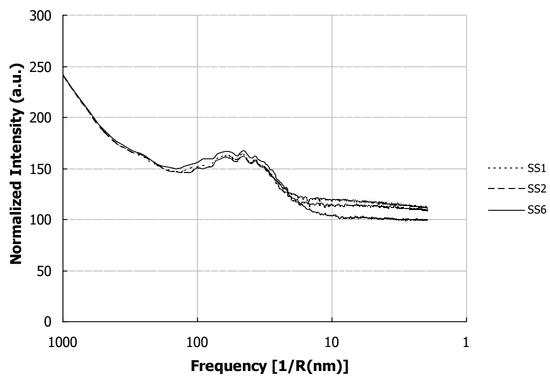

Figure 2: Fourier transforms of RDA test structure: The RDA was imaged using three different scan speeds (SS1 is the fastest, SS6 is the slowest) to illustrate the sensitivity to electron dose per pixel. Predictably, increasing the dose improves the signal to noise ratio, indicated by lowering the noise floor. The mid-range frequency hump is due to the shape factor of the individual dots.

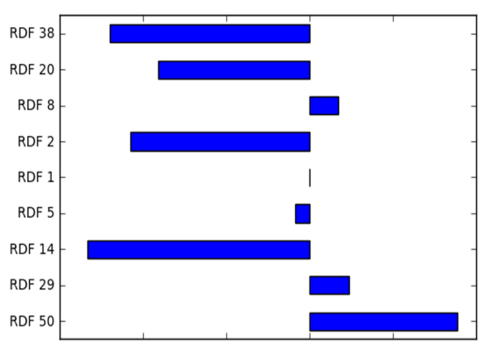

Figure 3: Variation in noise level in a multi-ebeam system: Noise levels of several beams in a 61 beam system are compared to the central beam (RDF 1), allowing the uniformity of the array performance to be assessed.