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Evidence for the Gaussian Scattering of Electrons in a Gas

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The unique benefits of the variable pressure scanning electron microscope (VP-SEM) are the result of the interaction of the incident electron beam with the low-pressure gas that surrounds the sample. This interaction, however, also results in the scattering of the incident beam so that the focused beam becomes surrounded by a skirt of scattered electrons. The diameter of this skirt, and the intensity profile across it has been the subject of considerable research and simulation because of its importance in interpreting images and micro-analytical data. While numerous experimental studies and simulations have been described none of them provide a convenient way of describing the profile in either magnitude or shape.

To remedy this deficiency a new measurements of the skirt size as a function of pressure has been performed by X-ray mapping. The sample was a cleaved silicon wafer, with a straight, sharp, and opaque edge extending over a distance of hundreds of micrometers, placed on an aluminum sample stage in a Hitachi S4300 SE/N, a Schottky emitter variable pressure scanning electron microscope (VPSEM). The fluorescent X-ray signal generated by the beam was collected by a Röntec XFlash Silicon Drift Detector (SDD) (RÖNTEC GmbH, Schwarzschildstraße, Berlin) and beam currents in the range 1-10nA were used, giving X-ray count rates of 20,000 to 40,000 cps in the silicon K-line peak. Since X-rays will be generated wherever the scattered beam strikes the wafer a map recorded in the silicon K-peak shows the integrated intensity of the scattered beam as a function of its position relative to the wafer edge. When no beam scattering occurs the transition from silicon to aluminum (sample holder) will be abrupt on the scale of the interaction volume. The X-ray image (typically 800×600 pixels) was set so that the silicon edge was vertical. The intensity of the line profiles was then obtained from the digital map by integrating several hundred line-scans perpendicular to the edge using the routines provided in ImageJ allowing an excellent signal to noise ratio to be achieved [1]. A line profile across the map normal to the edge then plots the variation of silicon X-ray intensity, and hence of the amplitudes of the scattered electron beam, with position relative to the edge.

Typical profiles obtained from the silicon map in the vicinity of the edge for a range of gas pressures are shown in figure (1). These traces were found to accurate fit an "error function (erf)" distribution a result which implies that the scattered profile is Gaussian (or a close approximation to Gaussian) in form. The suggestion that the scattered profiles are Gaussian is not immediately evident from any of previous work because that was mostly concerned with estimating the effective width of the distribution rather than its functional form. It could reasonably be expected that when the electrons in the beam suffer multiple scattering events then the profile might acquire the characteristic "bell shaped" Gaussian form but for the conditions examined here the mean number "m" of scatters per electron trajectory is between 0.5 ~ 1.5 which would seem to be too low to result in a Gaussian distribution. However, recent work on the scattering of electrons in thin films, under conditions which closely approximate those used in the gas, have also demonstrated that the edge profile data is a good fit to an error function [2]. This is a convenient result because the form of the scattered beam can now be described by a single parameter 'σ', the standard deviation of the Gaussian, and can be well expressed in terms of the functional variation derived by Danilatos [3]

$$\sigma = (C/E).Z.(P/T)^{1/2}.GPL^{3/2} \qquad (1)$$

where E is the beam energy (in eV); Z is the atomic number of the gas; P is the gas pressure in Pascal; T is the temperature in degrees K; GPL is the beam path length in the gas in meters; and C is a constant.

In some regimes such as at lower gas pressures, however, there are some discrepancies between the experimental profile and an simple "erf" curve. A better fit can be obtained by assuming that the beam broadening profile could more accurately be described as consisting of two components, both of which are Gaussian: a background or "skirt" with a larger value of σ_1 (consisting of the elastically scattered electrons from the gas interaction), and the central, focused probe, region with a smaller value of σ_2 (comprising both inelastically scattered and unscattered electrons). In the high gas pressure environment the value of σ_1/σ_2 is larger than at low gas pressures so the deviation of the edge profile from the ideal error function curve is a measure of the relative contribution of these two components. The relative percentages of focused beam and background contribution at different gas pressures could therefore in principle be separated by curve-fitting the experimental error-curve profiles recorded across a range of pressures.

References

[1] ImageJ developed by Wayne Rasband can be downloaded from http://rsb.info.nih.gov/ij/
[2] E Urgiles, R Toda, and J Z Wilcox, Rev.Sci.Instr. (in press), (2006)
[3] G.D.Danilatos, Advances in Electronics and Electron Physics, **71**, (1988), 109

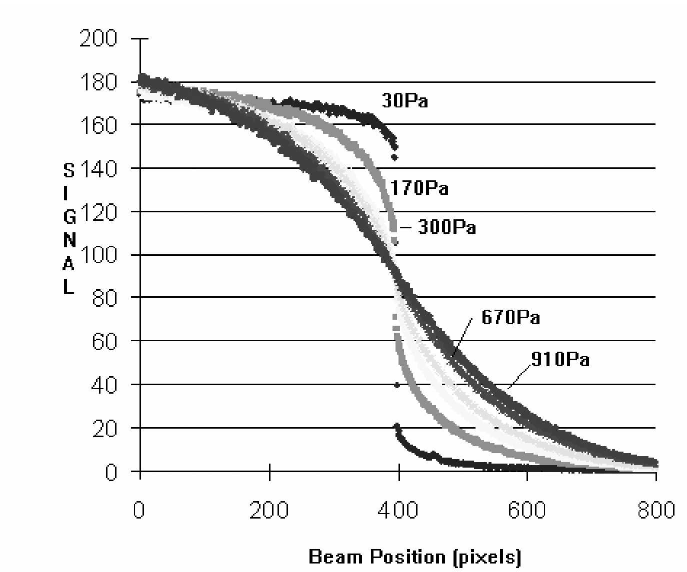

Figure 1. Typical line profiles obtained from X-ray images recorded over an edge as a function of pressure. Data recorded in a Hitachi S4300 SE/N with a Rontec SiDD detector at 20keV.