

Progress in secondary electron yield mapping in charged particle microscopy

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Charged particle microscopy techniques including scanning electron microscopy (SEM) and helium ion microscopy (HIM) are widely used for nanoscale characterization. In these techniques, a focused beam of particles scans across the sample, initiating the emission and detection of secondary electrons (SEs) at each scan position. A major source of noise in this technique is the Poisson nature of the incident beam. This source shot noise [2], along with lack of knowledge of the internal detector gain and efficiency, creates ambiguity in the interpretation of the detected SE intensity, which prevents mapping of the SE yield η on an absolute, calibrated scale. The reduction of noise with quantitative SE mapping would enhance the information content of such images.

Time-resolved measurement (TRM) has been proposed as a way to mitigate source-shot noise and enable quantitative η mapping [3,4]. With TRM, one can use the number of SE detection events to estimate the number of incident particles at each pixel, thereby enabling η estimation. Previous works have assumed that SE counts are directly available for the implementation of TRM [4]. In this work, we discuss methods for the implementation of TRM on a real charged particle microscope and quantify the reduction in imaging noise made possible by TRM.

Figure 1 shows our setup for TRM implemented on a Zeiss Orion Plus HIM, operating at a beam energy of 30 keV and current of 0.1 pA. We coupled the signals from the detector and the beam scan coils onto an oscilloscope and processed these synchronized signals on a computer [5]. Figure 1(b) shows an example of both the scan waveform (top) and the ET detector voltage (bottom). The detector voltage consists of a series of pulses; each pulse corresponds to SEs excited by one incident ion. The large variation in pulse heights is due to the high value of η for helium ions for most samples and the consequent variation in number of SEs per ion [6]. To estimate the number of SEs per pulse, as required for TRM, we must determine the mean c_1 and variance c_2 of the one-SE voltage response of the detector. For this purpose, we imaged several featureless samples and fitted the distribution of detected pulse heights using a linear-Gaussian detector response model [3] to form maximum likelihood estimates for η , c_1 , and c_2 . Figure 1(c) shows an example of this fitting for a silicon sample. For this case, the extracted $\hat{\eta} = 1.67$, $\hat{c}_1 = 0.17$ V and $\hat{c}_2 = 0.011$ V².

To quantify the potential gains from TRM, we performed Monte Carlo simulations to calculate the mean-square error (MSE) in η estimation using conventional and TRM schemes. Figure 2 shows MSE for three η estimators for an average pixel dose of 20 ions. Figure 2(a) shows an example of the simulated ET detector voltage response. The conventional estimator (blue curve in Figure 2(d)) is analogous to conventional SE imaging – the ET detector voltage signal is sampled at a fixed time interval of 100 ns as shown in Figure 2(b), and the resulting voltages are summed and scaled to estimate η . The oracle (red curve in 2(d)) is an idealized η estimator that uses both the SE count

and the number of incident ions; it represents a generally unachievable lower bound on the MSE of η estimation. The time-resolved estimator (yellow curve in 2(d)) uses the estimated detector parameter values and the exact values of detector voltage peaks (Figure 2(c)) to estimate SE and incident ion counts. The TRM estimator has lower MSE compared to conventional imaging, especially in the range of SE yields common in HIM ($\eta > 1$). The lower MSE for TRM arises from both exact measurement of each peak height instead of constant sampling, as well as estimation of the number of incident ions. With the detector parameter estimation schemes described here, we are now working to implement TRM and demonstrate improved imaging [7].

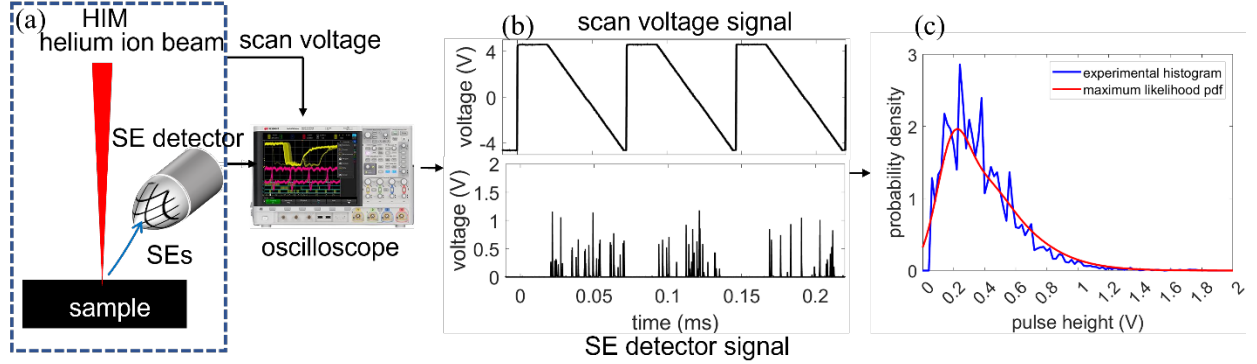


Figure 1: Time-resolved imaging scheme. (a) Imaging setup (b) Outcoupled scan (top) and detector (bottom) waveforms (c) Maximum-likelihood estimation of mean SE yield and detector parameters from detected pulse height distribution.

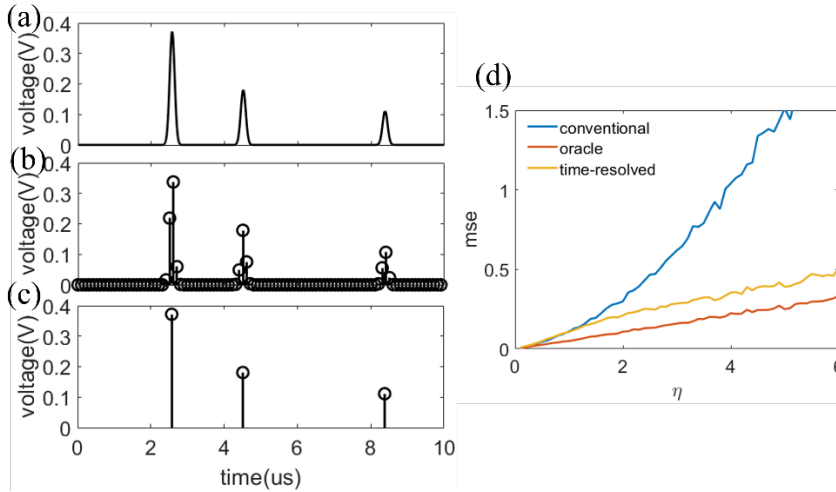


Figure 2: Monte Carlo simulation of SE imaging (a) Simulated ET detector voltage (b) Constant-rate sampling for conventional imaging (c) Peak detection for time-resolved imaging (d) Mean-squared error for different estimators.

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