How to count electrons for Scanning Transmission Electron Microscopy

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BIOGRAPHY

Dr. Grigore (Greg) Moldovan is the Chief Technology Officer at point electronic GmbH – a supplier of electronics and software for electron microscopy, from standard parts to high-performance bespoke systems. Greg is a scientist and a microscopist with an experience of some 20 years, he has previously worked for Oxford Instruments, University of Oxford and University of Cambridge, and he holds a PhD from University of Nottingham on Materials Science and Electronics Engineering. At point electronic, Greg manages technology development and new product introduction.

ABSTRACT

Gaps in established patterns of work and equipment are best revealed by asking unexpected questions that seem simple at the beginning, but which end up illuminating points of view that stand undeservedly ignored in the routine of everyday work. How to count electrons? is such a question that aims to bring into focus how to best to detect and acquire signals in electron microscopy. A practical implementation is described here, illustrating that such open questions can be put to action and that counting electrons is just a few steps away from everyday work.

ACKNOWLEDGEMENTS

J.P.P. and L.J. acknowledge SFI grant 19/FFP/6813, L.J. acknowledges SFI/Royal Society Fellowship grant URF/RI/191637. turboTEM is supported by funding from Enterprise Ireland and the European Regional Development Fund.

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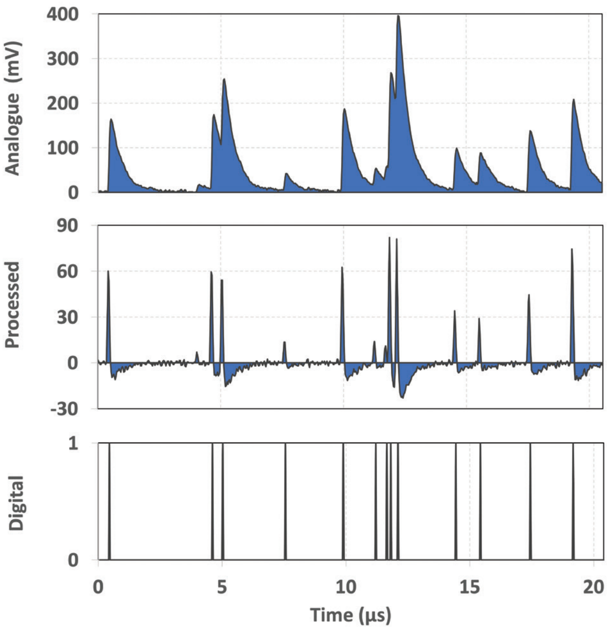

FIGURE 1 *Experimental analogue, processed and digitised signals from single electrons. Note that single electron pulses are narrowed in the processed signal and then set to the same high in the digital signal.*

INTRODUCTION

It stands to reason that modern Scanning Transmission Electron Microscopes (STEM) are able to count the electrons they use for imaging. Electron microscopy has had such great improvements in detection over the last few years, with direct imaging cameras, fast readout electronics and new processing algorithms, that just counting electrons seems an easy task. So easy in fact that perhaps none of these recent advances are necessary - the conventional answer in electron microscopy to pixel value questions is quantification. In this mindset, if a conversion constant can be determined between raw pixel values and electron counts, then a simple operation should give electron counts per pixel. However, scattering of electrons during detection has a stochastic character, and therefore such a conversion constant can only have a statistical nature. At best, quantification could therefore give a probability or likelihood of electron count, which is unfortunately insufficient for low count values, where statistical assumptions break down.

But single electrons are not out of reach, and the more experienced readers will remember that single electron signals can be observed even with budget indirect CCD cameras optimised for high efficiency. Just drop the beam current enough that single electrons are sparse on the camera, then single electrons clusters are easily observed. One could therefore attempt to drop the beam current, record many fast frames with single electron clusters and then process each frame for counting. However, a staggering number of frames is needed to count in this fashion, simply because electrons must be sparse in each frame, which in turn means that total acquisition time becomes too long for practical count rates. Certainly, no live counting is possible with slow cameras in STEM.

Perhaps the latest imaging detector technology is required after all, and indeed the new high-end direct cameras can have not only much higher framerates, but also embedded logic in the hardware for single particle counting. At the readout chip level, each pixel can compare the incoming analogue signal with a configurable threshold value to decide if a new electron has arrived, and then several neighbouring pixels can also check with each other to decide if they have been triggered by the same electron, so as to prevent double counting. The counting process is not without limits, but certainly a good way to count electrons. However, whilst this pixel counting and frame readout is fast enough for TEM mode, such counting imaging cameras are still several orders of magnitude too slow for live STEM, as STEM requires counting at each beam position on the sample. Perhaps new operation modes will be developed to enable faster operation, but in the meantime this frame-based approach is also not appropriate for STEM electron counting.

In principle, the same sparse counting approach can be applied directly to standard STEM scans, whereby the beam current is reduced, and the scan speed increased such that single electron clusters are recorded

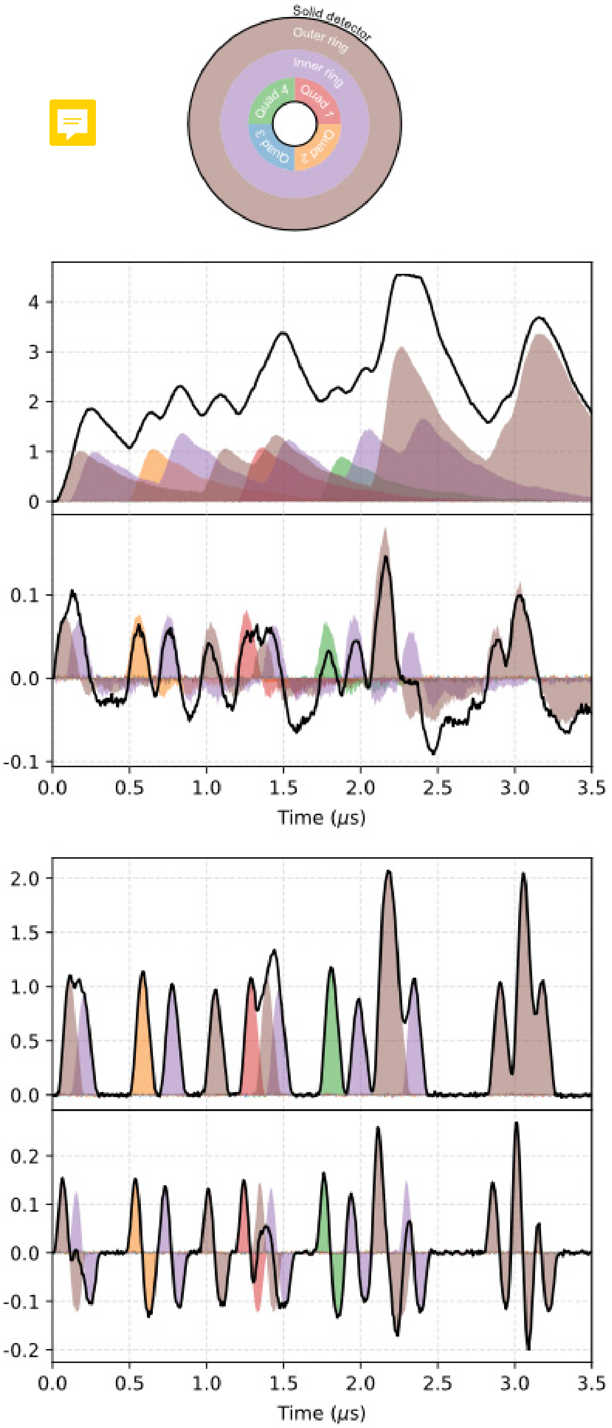

FIGURE 2
Simulated analogue and processed single electron signals for scintillator (top) and Si-diode (bottom) detectors. Colour plots show signals for respective detector segments, black plots show signals for unsegmented detectors. Note that best maximum count rate is obtained for the segmented Si-diode detector.

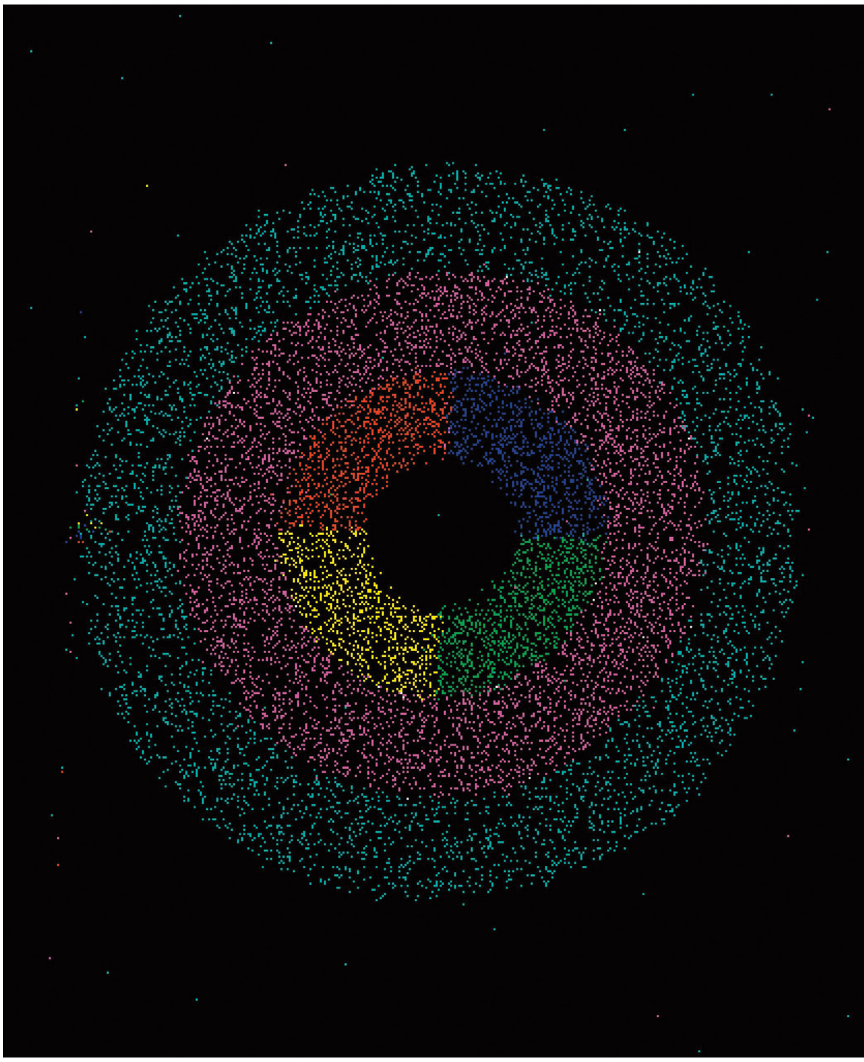

FIGURE 3
Colourised experimental annular dark field detector map, showing simultaneous counting of single electrons with each detector segment.

in conventional scans. The acquired analogue pixel values can then be compared with a threshold to identify and count single electrons, and finally all counts can be accumulated into a final image. Whilst speed of beam scanning is now not limited by detection speed, counting electrons after acquisition of the analogue signal again requires very many frames with very sparse electron signals and it's simply too inefficient. To illustrate this, even if single electrons arrive at a spacing of every ten pixels in the scan, hundreds of frames are still required to count tens of electrons per pixel in the accumulated image and, unfortunately, scanning speeds of hundreds of frames per second are not practical.

These introductory points are worked out here to illustrate that as advanced as STEM may be today, it lacks the basic ability to count electrons – without additional equipment. Particle counting is such an essential and enabling function for so many low-dose techniques, that it's absence so far in STEM may come as a surprise.

HARDWARE FOR COUNTING

Given that standard detectors and beam scanning are too slow or inefficient to count after analogue acquisition, a common solution in particle detection is to use a pulse processor that converts the live analogue signal into live digital pulses. A scan controller is then used to read these digital pulses and thus count electrons for each pixel in the scan.

As an example, a similar approach is used for EDX where a similar pulse processor is used between the X-ray detector and the scan controller. Pulse processors for EDX also have the additional task of measuring the area underneath each single X-ray signal in order to determine its energy. Unfortunately measuring energy of single electrons in a similar fashion is not useful because resulting energy resolution would be on the order of several kV, again due to the stochastic nature of single electron interaction with the detector. The practical approach is therefore to use a pulse processing algorithm optimised for the required particle type and detector.

PULSE PROCESSING

Similar with counting single electrons inside each pixel in imaging cameras for TEM, a basic counting pulse processor needs to compare incoming analogue signal to a set threshold. When threshold is exceeded, then a digital output is switched to high to transmit the new count to the scan controller. In practice, even such basic comparator hardware is already much faster than conventional STEM detectors, which need a few microseconds to fall back down to their dark level after each single electron signal. This means that maximum counting rate with such a basic comparator, or the maximum beam current that can be used, is given by single electron pulses piling up on top of each other, which prevents the digital output from returning to zero and therefore prevents counting.

Short of replacing the slow conventional detectors with new faster detectors, it is possible to increase counting rate to practical STEM beam currents by processing the raw analogue signal into much narrower single particle profiles. This can be done by live digital signal processing within the pulse processor firmware, which includes digitisation of the analogue signal at much higher speeds than used by the scan controller. A live gradient-based signal processing algorithm is sufficient to narrow down and separate such piled-up single electron events, and therefore enable counting for live STEM workflows (Figure 1).

The TurboTEM Pulse is such a generic device that can be added to any conventional detector to obtain digital counting signals for any STEM, including the gradient signal filter necessary to compensate for detectors with slow fallback.

SEGMENTED DETECTOR

To bring the maximum counting rate towards even higher beam currents, it is necessary to use a detector better suited for counting. Whilst a faster detector with a shorter fallback for single electron events can already bring a significant improvement, a detector with multiple independent segments for parallel acquisition can provide an even greater increase to the maximum count rate.

For example, if conventional STEM detectors could be segmented as illustrated in Figure 1, first in quadrants then in rings, then single electron signals that would pileup in an unsegmented detector, could be conveniently separated in different outputs, and therefore piling up could be significantly avoided. Geometry of detector segments should be optimised for STEM, with fewer and larger segments further away from to the optical axis, accounting for a decreasing rate of single electron events at higher scatting angles.

Conventional STEM detector technology is based on scintillators and photomultipliers tubes and, unfortunately, cannot be easily segmented in this fashion. However, new STEM detectors can be based on solid-state Si diodes with in-situ preamplification, which can be segmented into the complex geometry required for counting. Not only that this detector technology is able to reduce pileup trough optimised segmentation, but also reduces it further dues to its inherent faster fallback. Whilst conventional scintillator-based detectors tend to have a fallback on the order of microsecond, Si-based detectors can reduce this ten-fold to much below a microsecond (Figure 2).

One such detector is the Opal STEM detector, with a Si-diode segmented into multiple BF, ADF and HAADF areas for parallel counting. The detector may be configured with/without a central hole for simultaneous bright field with a conventional detector.

SCAN CONTROL

To complete electron counting for STEM, digital outputs from the pulse processor must be counted by the scan controller to record counts for every pixel in the scan. Scan controllers embedded with the microscope are not designed for such digital signals and therefore an external scan controller needs to be added to the microscope. External scan interfaces on STEMs are designed for such open scan control architecture, with the user required only to switch from internal to external scans.

The DISS6 TEM scan controller is used here, which provides the necessary scan outputs to the microscope, digital inputs for counting from the turboTEM Pulse, a control interface for the Opal STEM detector and a Python library for custom development. To match the high count-rate architecture of the pulse processor with multiple sensing segments, simultaneous acquisition from multiple digital inputs must also be used with the external scan controller (Figure 3). These simultaneous signals can then be mixed in the software to obtain desired detection geometries, for example the four quadrants could be kept independent for Differential Phase Contrast (DPC) or added for maximum signal count.

SUMMARY AND CONCLUSIONS

To answer the question in the title, add a pulse processor to a standard STEM detector. This requires connections to the detector and an external scan controller with digital inputs, both of which can also be added if missing. If maximum count rate is important, for example to work a higher beam current, then use a segmented detector and a scan controller with multiple simultaneous inputs.

Article, and references available online at: analyticalscience.wiley.com/publication/microscopy-and-analysis