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Improving the Noise Floor and Speed of Your Detector: A Modular Hardware Approach for Under $1000

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Scanning transmission electron microscopy (STEM) has cemented itself as a powerful and pivotal characterization method in the materials scientist's toolkit. Combined with spectroscopy and aberration correction, a wealth of information can be simultaneously acquired. High-angle annular dark field (HAADF) is perhaps the most popular imaging mode of STEM due to its ready interpretability and atomic number contrast. This has given rise to quantitative studies examining chemical and thickness/3D information without the need for time consuming tomographic techniques. Previous studies have shown this to be an effective approach for a range of materials, for example in heterostructure interfaces [1] or catalytic nanoparticles [2]. However, a full and accurate quantification of HAADF images requires an extensive calibration of the STEM and use of simulation. Calibration is required because of the imperfect detection systems and digitization. For example, detector non-uniformity results in individual electron events contributing differently to the image intensity [3]. Similarly, analog to digital conversion results in arbitrary data values in the final image, often with a non-zero dark signal. These effects combine to limit HAADF STEM as a routine quantitative technique.

Whilst newer generations of solid-state electron detectors are improving in areas such as uniformity or adding new capabilities through 4D-STEM [4], these can often be limited in their speed, cost, or collection angles. We recently demonstrated the capability to use existing detectors, including those based on scintillator technology, to perform single electron counting inside the electron microscope [5]. Each electron impinging on a detector results in a voltage peak that, in typical detection modes, is integrated to form the pixel value. Instead, the raw signal data can be processed to detect each peak as one electron. Previous studies used simple intensity thresholding from fast image scans but had poor dynamic range [6], creating an upper limit on dose and specimen atomic number. By differentiating the raw detector signal before applying a threshold, multiple rapid electron events (electron pile-up) can be distinguished to maintain a high detection efficiency (Fig. 1). The result is images with pixel values in units of integer electrons and with a true zero-level background, improving image quantification, and allowing for the summing of large numbers of frames without noise accumulation (Fig. 2). However, our earlier approach required oversampling of data combined with a posteriori processing and manual syncing with the image scan [5].

To provide a more practical electron counting solution, we have developed a modular hardware system to perform digital pulse readout (Fig. 3). This can be retrofitted to existing systems or installed on new instruments. This device performs all the signal processing *in hardware* and interfaces with existing scan controllers such as Gatan's Digiscan II/III and point electronic's DISS. The signal of any electron detector can be digitized to electron counts by simply selecting a new signal source in the existing

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software. To achieve this, we use an off the shelf field programmable gate array (FPGA) single board computer combined with signal conditioning electronics to maximize the dynamic range. The use of FPGAs provides the necessary speed for signal processing and hardware syncing, but also retains flexibility to customize and expand capability should it be needed. All of this can be achieved with components that cost under $1000 in total. Our hardware therefore provides a modular, accessible and sustainable approach to extend the capabilities and lifetime of any microscope.

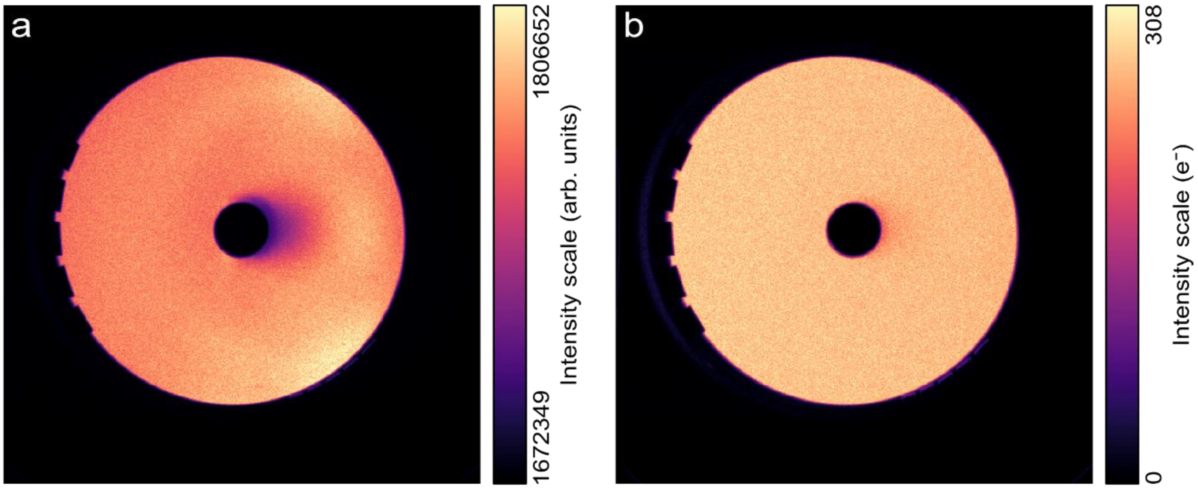

Figure 1. Simultaneously acquired Fischione ADF detector maps using analog, **a**, and counted signals, **b**. Note the difference in intensity variation and scale limits. Data was recorded using a 300 kV Titan G2 equipped with a point electronic scan controller.

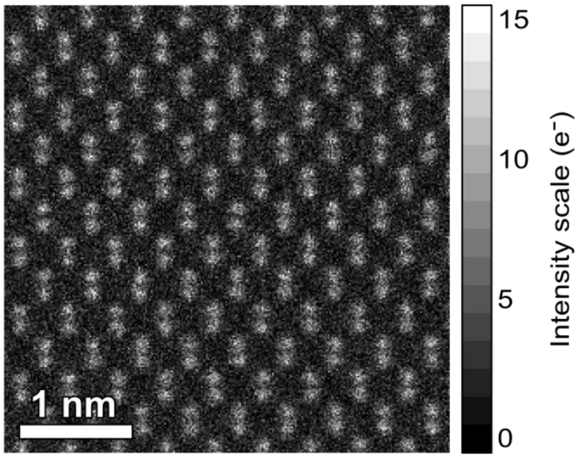

Figure 2. Digital atomic resolution image of Si $\langle 110 \rangle$ created from 40 summed frames each with a dose of ~3.23 $e^{-}\text{Å}^{-1}$. Data was acquired using a Nion UltraSTEM 200 and a Gatan Digiscan II.

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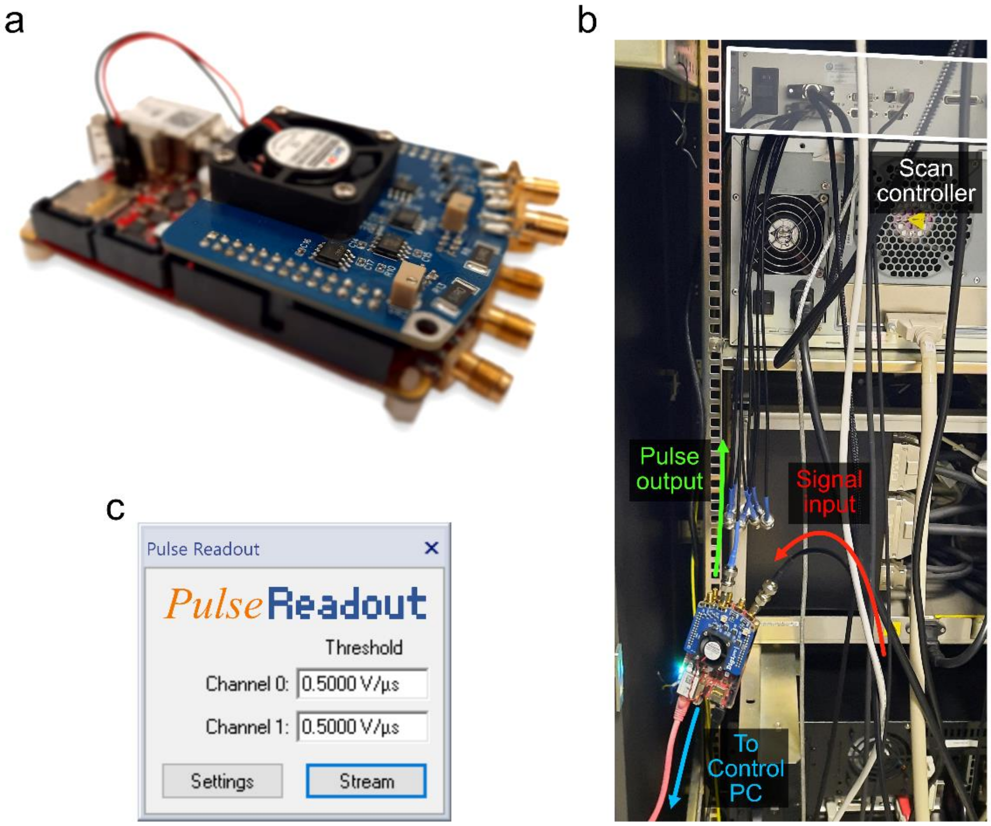

Channel 0: 0.5000 V/µs

Channel 1: 0.5000 V/µs

D

Figure 3. a The digital pulse readout device. **b** The hardware as connected to a point electronic scan controller on a Titan G2 rack. **c** Software interface integrated into Gatan DigitalMicrograph.

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[7] The authors would like to acknowledge the Centre for Research on Adaptive Nanostructures and Nanodevices (CRANN) and the Advanced Materials and BioEngineering Research (AMBER) Network for financial and infrastructural support for this work. L.J. is supported by SFI award number URF/RI/191637. J.J.P.P. and L.J. acknowledge SFI grant 19/FFP/6813, T.M. acknowledges the SFI-EPSRC CDT-ACM (grants 18/EPSRC-CDT-3581 and EP/S023259/1).

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