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Publication Date

2016-10-01

DOI

10.1109/nssmic.2016.8069681

Development of a Fast Framing Detector for Electron Microscopy

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***Abstract*–A high frame rate detector system is being developed to enable fast real-time data analysis of scanning diffraction experiments in scanning transmission electron microscopy (STEM). This is an end-to-end development that encompasses the data producing detector, data transportation, and real-time processing of data. The detector will consist of a central pixel sensor that is surrounded by annular silicon diodes. Both components of the detector system will synchronously capture data at almost 100 kHz frame rate, which produces an approximately 400 Gb/s data stream. Low-level preprocessing will be implemented in firmware before the data is streamed from the National Center for Electron Microscopy (NCEM) to the National Energy Research Scientific Computing Center (NERSC). Live data processing, before it lands on disk, will happen on the Cori supercomputer and aims to present scientists with prompt experimental feedback. This online analysis would provide rough information of the sample that can be utilized for sample alignment, sample monitoring and verification that the experiment is set up correctly. Only a compressed version of the relevant data is then selected for more in-depth processing.**

I. Introduction

ADVANCEMENTS in detector technology and data processing have enabled new scientific methods in electron microscopy. This specific high frame rate development aims to improve scanning diffraction experiments and will be installed on the Transmission Electron Aberration-corrected Microscope (TEAM) [1]-[2]. It will rapidly capture and analyze convergent beam electron diffraction (CBED) data [3]-[5] and the annular dark field (ADF) [6] signal. The former method investigates details about structure, composition, polarization, and three-dimensional defect crystallography; while the latter assesses the mass-thickness contrast of the sample.

The detector will consist of a central monolithic active-pixel sensor that is surrounded by annular silicon diodes. Both detector components will capture data synchronously with the scan coils at frame rates nearing 100 kHz. Data from the detector will be streamed over dedicated fiber-optic links to the National Energy Research Scientific Computing Center (NERSC), where the Cori [7] supercomputer will be utilized for real-time data processing.

Manuscript received November 28, 2016. This work was supported by the Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. Research was performed at the Molecular Foundry and the National Energy Research Scientific Computing Center, DOE Office of Science User Facilities.

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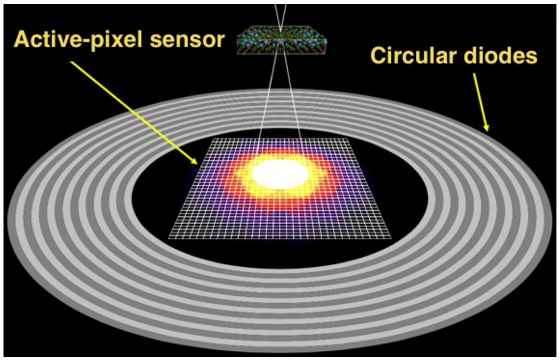

Fig. 1. The detector will consist of a central monolithic active-pixel sensor surrounded by annular silicon diodes to simultaneously capture convergent beam electron diffraction (CBED) data and the high-angle annular dark field (HAADF) signal.

II. Central Pixel Detector

One key advancement in transmission electron microscopy over the last 10 years has been the utilization of direct electron detectors. Semiconductor detectors can directly measure the ionization energy loss of individual electrons, and thus can reach image sensitivity at the single-electron level. CMOS Active Pixel Sensors have proven to be successful direct electron detectors. These developments are similar to those of modern digital cameras, however for electron microscopy applications radiation tolerant circuits must be implemented.

The detector detailed within is a new high-frame-rate addition to the family of active-pixel sensors [8] that have been developed for the TEAM project and commercialized as the Gatan K2 camera [9]. It contains a 576 x 576 array of 10 um pixels. Pixels are addressed and reset in a row-by-row, rolling shutter fashion. Selecting a row connects the source follower outputs of the pixels to a column-wise analog bus. Signal on these column-wise buses are further serialized by multiplexers that reside in the periphery of the chip before reaching the output pads. This serialization results in a tradeoff between frame rate and the number of output pads.

An almost 50-fold increase in frame rate, when compared to previous designs, is primarily being accomplished with a tenfold increase in the density of analog outputs. Current sensors in the TEAM family have 24 or even 64 pixel columns per analog-mux at the bottom of columns; this new version is almost fully column parallel with 3 pixel columns per output. Furthermore, the sensor will be read out from both the top and bottom halving the number pixel reads per column. Combining this more parallel readout architecture with a 80 MHz digitization rate results in the nearly 100 kHz frame rate. A custom preamp ASIC and a high speed analog to digital converter will be utilized to amplify and digitize the 384 parallel analog outputs of the sensor. With 12 bits of amplitude information per pixel this becomes an immense 370 Gb/s of data.

III. Digital Readout

Advancements in the ability to handle, transport and process big data has enabled new science by allowing detector systems to substantially increase both resolution and frame rate. Field Programmable Gate Array (FPGA) modules will receive and preprocess the flux of raw ADC data. To start, images will be constructed by reorganizing pixel data into the CPU preferred (x,y) coordinates. Other basic data calibrations and corrections, like dark noise subtraction, will also be applied directly in firmware. The option of placing more complex data processing algorithms, like single electron cluster finding, upstream in the firmware will be explored after experience with the real data is acquired.

IV. Data Transport And Parallel Processing

The FPGA modules will place the detector data on the network and stream it to compute nodes at NERSC for real-time data processing. A dedicated 400 Gb/s, 1 km, fiber-optic link connects the detector to NERSC compute nodes. A very parallelizable computation architecture is being developed to handle the immense data throughput. Processes launched on the Cori [4] supercomputer at NERSC will send image requests to a scheduler that resides in firmware on one of the FPGAs. Requests will be placed in a queue and processed in a first received basis. Having a backlog of requests reside in the queue will assure that the hardware is always ready for data and prevent the pileup of data in the hardware.

A multiple-buffer architecture, where a process requests a future chunk of data before processing the current chunk, will be implemented to guarantee data availability and readiness of the receivers. Each individual analysis process will have pre-allocated buffers for outstanding data requests to minimize the probability of dropping data at the receivers. Processes can then request future datasets before computing the current in-buffer datasets, so that the request-to-data-in-buffer delay happens in parallel with the processing of current data. This type of token-based scheduling automatically balances loads and allows for an optimal utilization of computational resources.

V. Prompt Experimental Feedback

Online processing of both the CBED and ADF will generate actionable feedback while the experiment is still in progress. This information will provide the scientist with real-time information on the sample, such as sample alignment, and a mechanism to select relevant data. Data compression will also occur within the online data processing pipeline to deliver more manageable datasets that can be saved for in-depth analysis. Initial experiments will focus on rapid computation of strain in crystals, imaging defects, dopants and other light elements in materials, and implementing phase contrast STEM methods such as MIDI [10] and ptychography.

VI. Conclusion

An interdisciplinary team of scientists and engineers from NCEM, NERSC and the Engineering Division of Lawrence Berkeley National Laboratory have joined together to co-design this detector system to collect, transport and analyze STEM data in real time. A new 100 kHz framing active-pixel sensor (576 x 576 pixels) and circular diodes are in development. These two detector systems will simultaneously capture a convergent beam electron diffraction pattern and the more highly scattered ADF signal. The data (370 Gb/s) from these detectors will be preprocessed in firmware and streamed over the network to NERSC. It will land in the memory of the Cori supercomputer for parallelized real-time data analysis. This not only avoids the high cost of saving huge data volumes at a high throughput, but more importantly provides scientists with prompt experimental feedback of data quality and experimental success. Furthermore, this enables the researcher to only save and further process a compressed version of relevant data.

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