Complete Compressed Sensing System For Scanning Probe Microscopy

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An approach to overcome barriers to practical Compressed Sensing (CS) implementation in serial scanning electron microscopes (SEM) or scanning transmission electron microscopes (STEM) is presented which integrates scan generator hardware specifically developed for CS, a novel and generalized CS sparse sampling strategy, and an ultra-fast reconstruction method, to form a complete CS system for 2D or 3D scanning probe microscopy. The system is capable of producing a wide variety of highly random sparse sampling scan patterns with any fractional degree of sparsity from 0-99.9% while not requiring fast beam blanking. Reconstructing a 2kx2k or 4kx4k image requires ~150-300ms. The ultra-fast reconstruction means it is possible to view a dynamic reduced raster reconstructed image based upon a fractional real-time dose. This CS platform provides a framework to explore a rich environment of use cases in CS electron microscopy that benefit from the combination of faster acquisition and reduced probe interaction.

CS in serial scanning instruments involves sampling a minority fraction (i.e., 20%) of the full pixel density while allowing a faithful reconstruction of the object. A faithful reconstruction requires a high degree of statistical randomness in the sparse sampling strategy. Executing a highly random, high speed, precise scan pattern has presented a barrier to implementing a practical CS Scan Generator (CSSG) for scanning probe microscopy. Our CSSG is a combination of hardware and novel CS sampling methods. The optimal solution was to employ a space-filling curve (SFC) as a "slow" carrier signal modulated by a "fast" randomized signal. In this manner, a programmatic highly randomized pattern may be invoked with any fractional degree of sparsity and with a high geometrical degree of freedom (DOF) in 2D or 3D. The DOF enabled by this method is a distinct advantage over line-hopping methods applied to CS electron microscopy[1]. Note, the method does not generally require any beam blanking along the scan path! The patent-pending method is represented schematically in Figure 1. 2D image reconstruction is performed via a proprietary ultra-fast algorithm, Adaptive Real-Time Inpainting (ARTI). Representative results are presented in Figure 2 and Figure 3. All images shown were acquired on a Zeiss EVO60 thermal emitter using a Hilbert-style SFC with 90% sparsity. The extremely good results are attributed to, in large part, local randomness enabled by these methods.

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[1] L. Kovarik, et al., "Implementing An Accurate And Rapid Sparse Sampling Approach For Low-Dose Atomic Resolution Stem Imaging", Appl. Phys. Lett. **109**, 164102 (2016); https://doi.org/10.1063/1.4965720

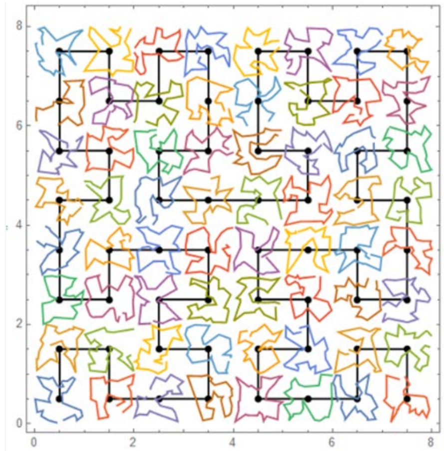

Fig. 1. Schematic of Sparse Sampling Using A Programmatically Randomized Signal Modulating A Carrier Signal.

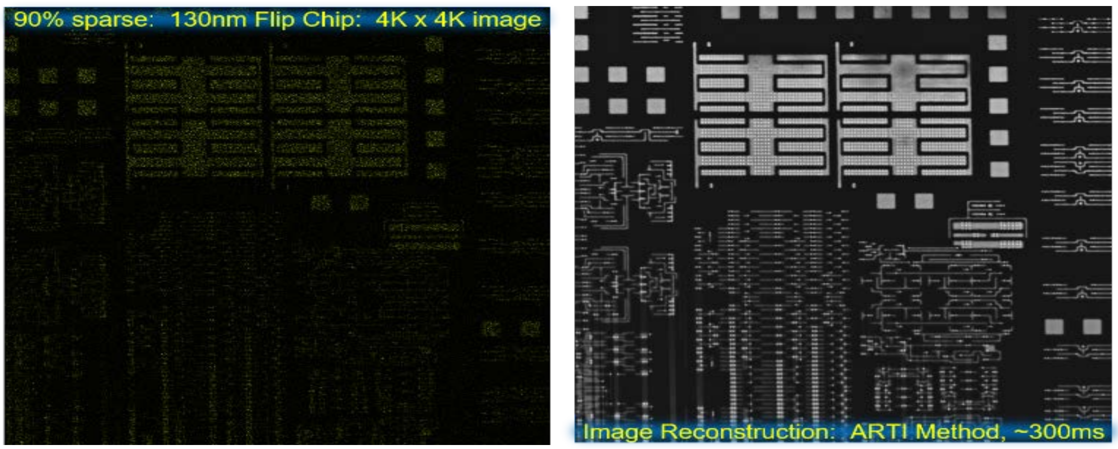

Fig. 2. Left panel: 90% sparse acquisition using a Hilbert-style space-filling curve obtained from a 130nm node flip-chip die. Sparse pixels highlighted in yellow. Right panel: ARTI image reconstruction obtained in ~300ms.

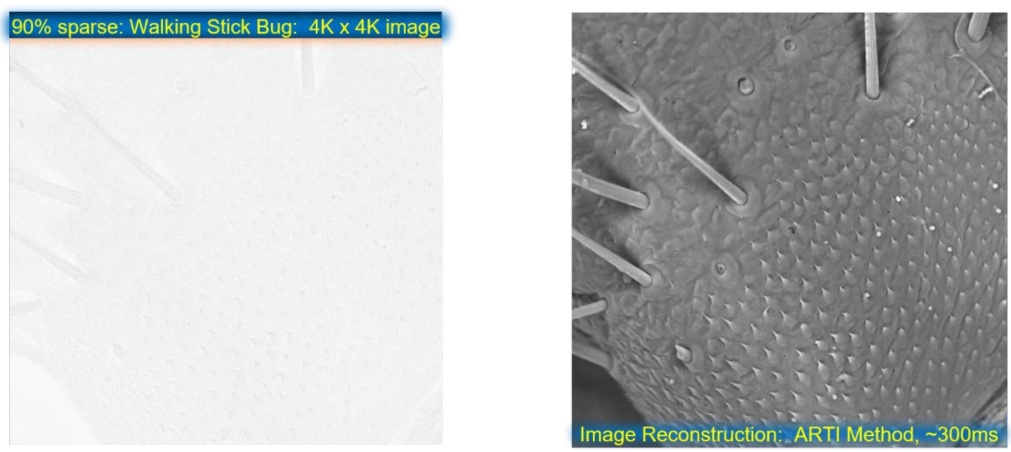

Fig. 3. Left panel: 90% sparse acquisition on 4Kx4K full pixel density image using a Hilbert-style SFC obtained from a section of leg from a walking stick bug. Sparse image contrast is inverted for visualization. Right panel: ARTI image reconstruction of the Left Panel image obtained in ~300ms.