Electron Tomography of Advanced Transistor Architectures

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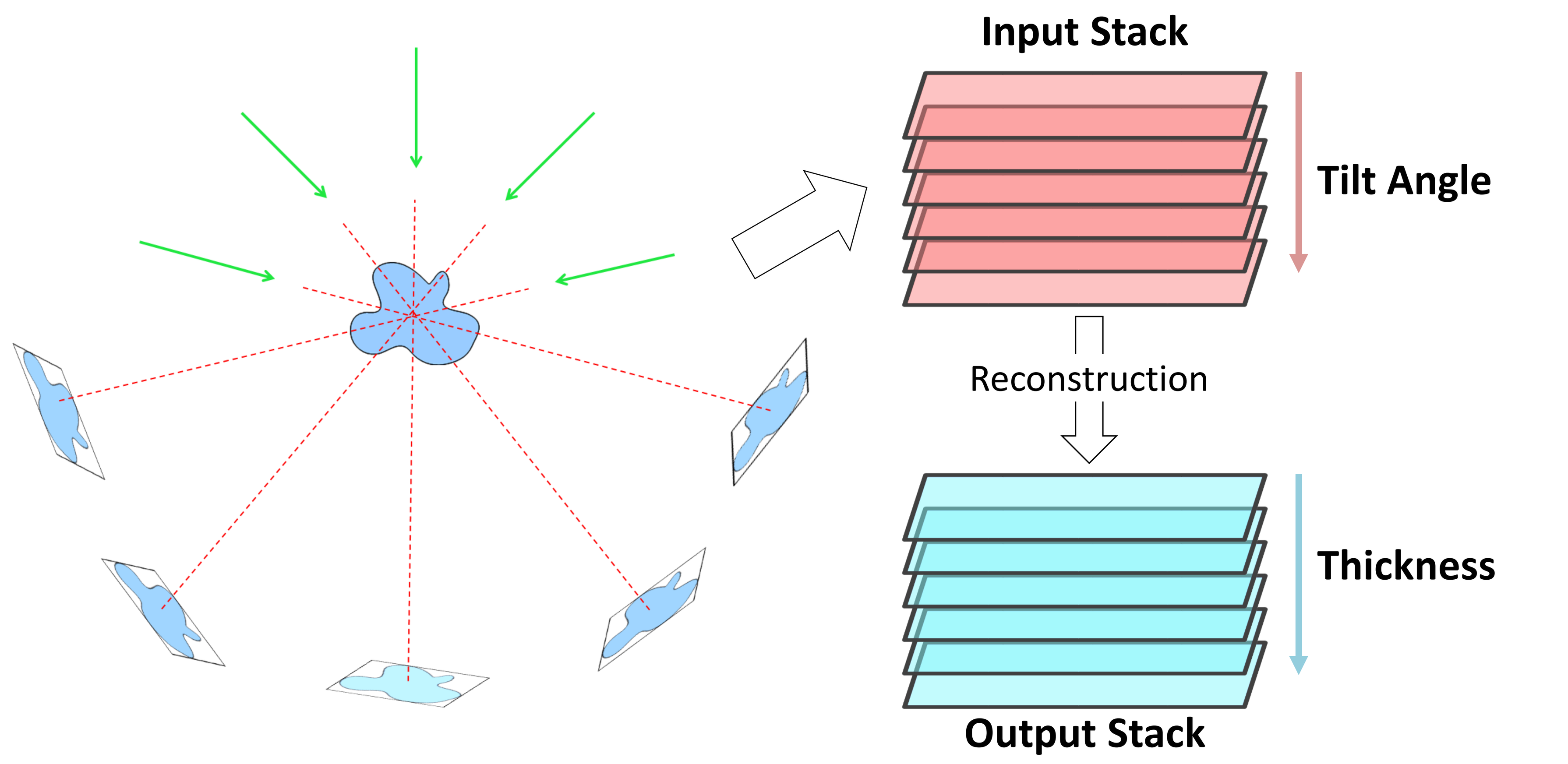
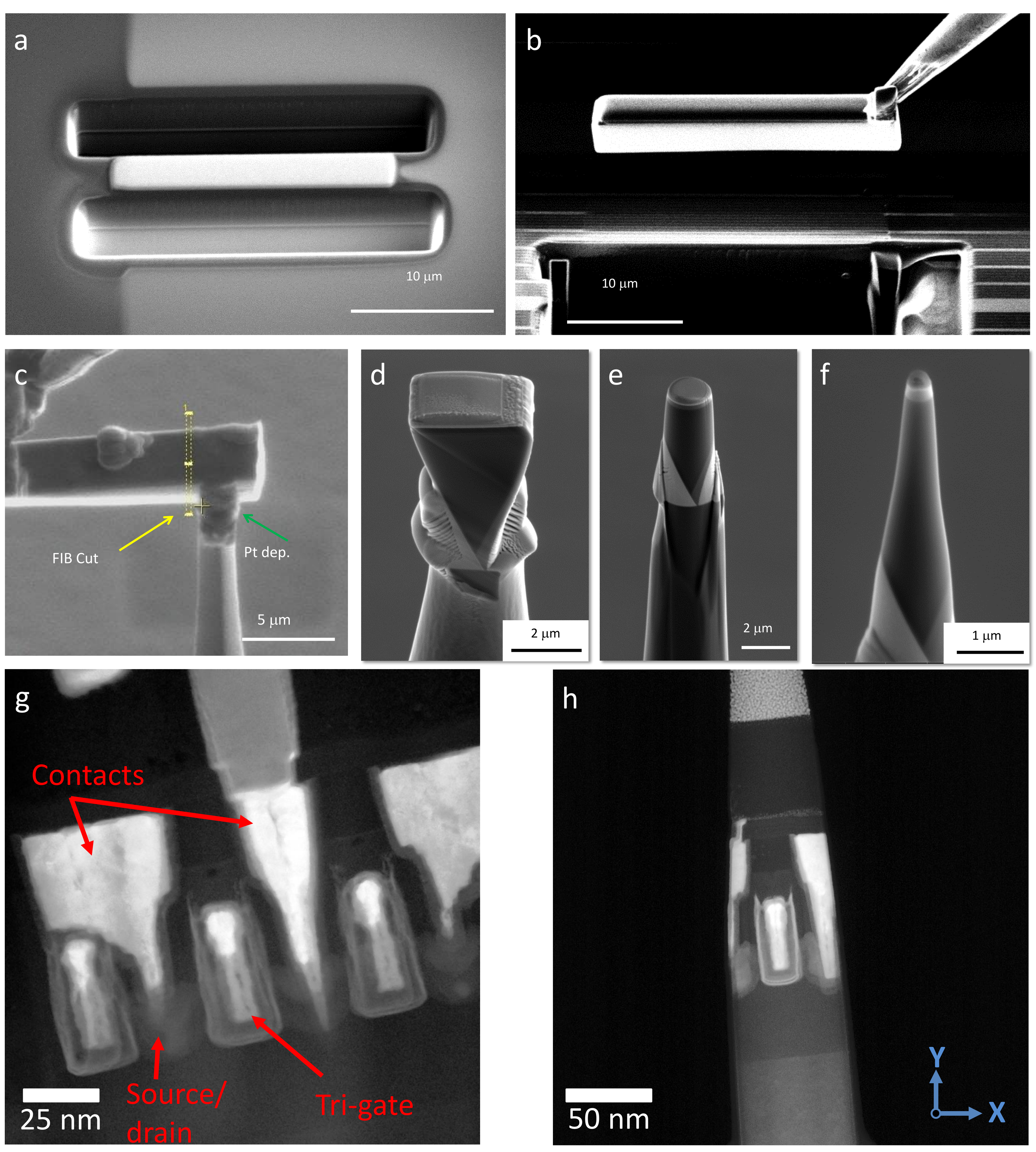
Motivation

- The relevant feature sizes in state of the art transistors continues to decrease, even as the complexity of the architectures employed increases
- Traditional characterization methods are proving insufficient for analyzing such devices
- Transmission electron microscopy is more than capable of resolving these features, however, the resulting images are inherently two-dimensional projections of the structure
- Robust methods for characterizing the 3-D nanoscale structure of these architectures will prove to be indispensable for further device development and process optimization
- Electron tomography is a well-developed tool for 3-D characterization; however, reproducible and quantifiable data is often difficult to achieve especially at high spatial resolution
- Here, we have used a combination of an advanced sample preparation approach and automated data processing to yield robust, reproducible models of nanoscale structures in a tri-gate type device architecture.



- Electron tomography is carried out by acquiring a series of images of a specimen over a range of tilt angles (α) with respect to the incident electron beam, as shown schematically on the left
- The stack of images (shown in red with dimensions X, Y, and α) is then used as input for reconstruction of the full volume. This results in an image stack with dimensions X, Y, and Z (shown in blue) where Z refers to the through-thickness direction of the volume.
- The quality of the reconstruction is determined by many factors, especially the signal-to-noise of the input data, the quality of image stack alignment, and the extent of the angular range that can be sampled
- In a traditional, slab-type specimen, the tilt range is limited by the increasing effective thickness of the specimen at high tilt of tilt and by the confined space in the microscope itself

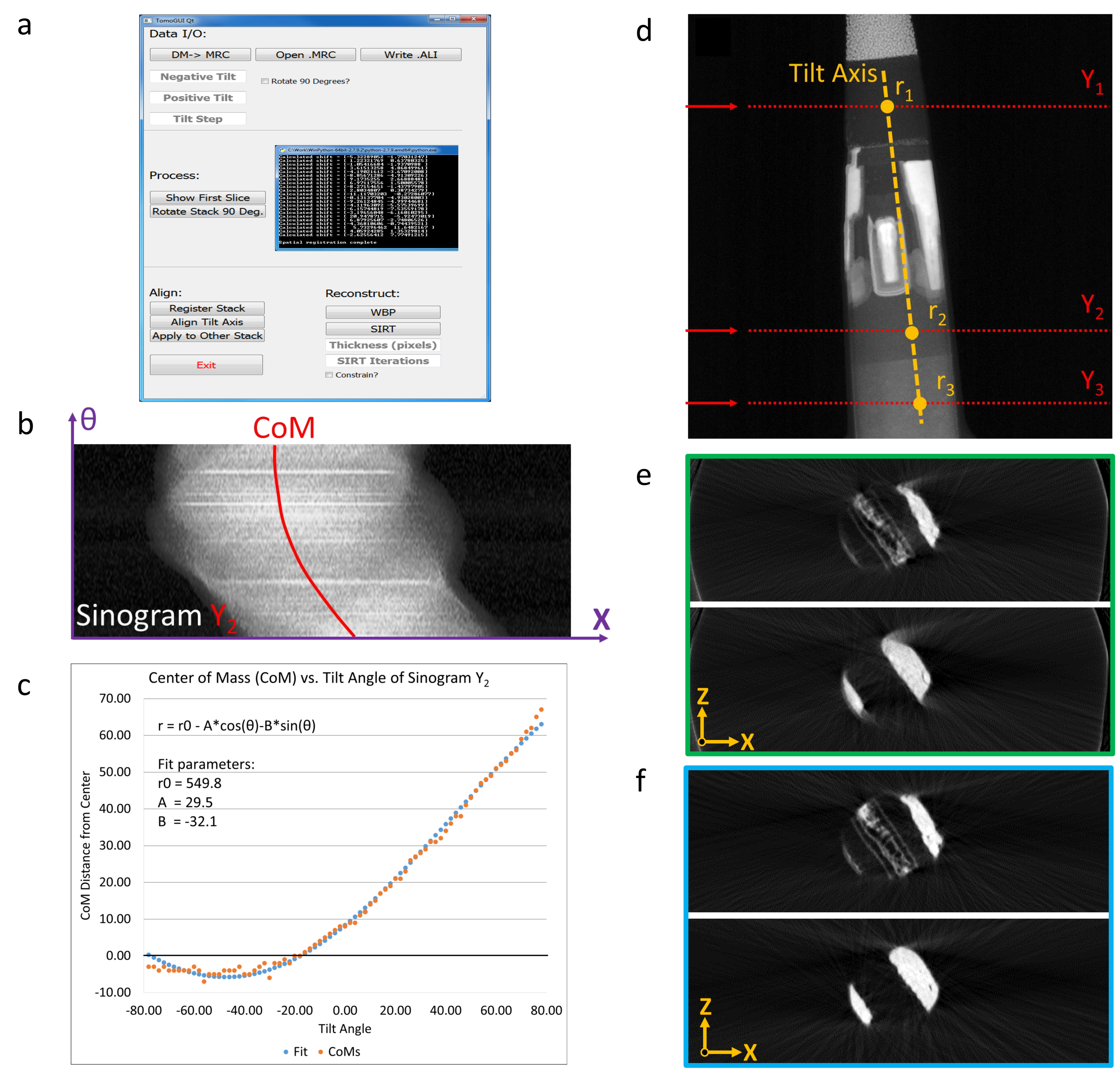
Specimen Preparation



- Needle-shaped specimens of individual transistor features were prepared for STEM tomography using in-situ lift-out in a dual-beam FIB
- This geometry is ideal as it can be tilted through the full angular range (0 to π)
  - This eliminates so-called 'missing wedge' effects and the specimen thickness remains constant throughout **[1]**
- In this case, a wedge was milled from a pre-identified location on the specimen (a), and lifted free from the bulk via a micromanipulator (b)
- The wedge is transported to a metal support post, where a small section of the total wedge was micro-welded by ion-beam deposited platinum, while the rest was cut away (c).
- The sample was then annularly milled using a high-energy Ga ion beam, producing a cylindrical, electron transparent volume (d-f)
- The tri-gate structure studied is shown in cross-section (g) and after cylindrical milling (h)

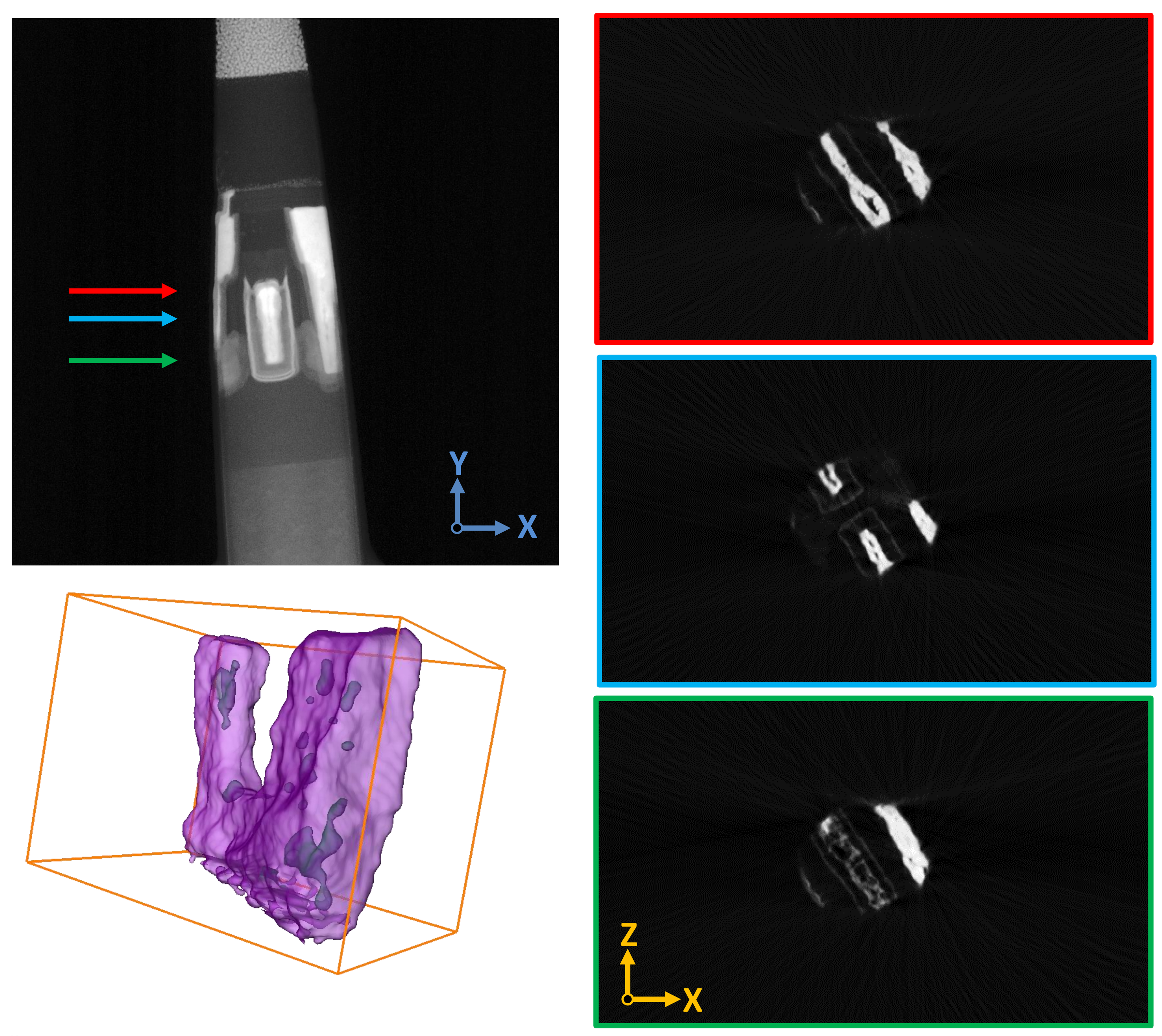
Data Alignment and Reconstruction

- Data processing was carried out using custom code written in Python 2.7 (a)
- Computation of the transforms to align the image stack collected from a cylindrical specimen is often quite difficult and requires a great deal of pre-processing
- We have employed phase correlation as implemented in the OpenCV Python library **[2,3]**
  - This approach requires no interaction on behalf of the analyst
  - Pre-processing is limited to the application of a Hanning Window to limit edge effects
- The crucial tilt axis alignment was done in automated fashion based on an approach first detailed by Wolf *et al.* **[4]**
  - The center of mass (CoM) of the cylinder is tracked as a function of tilt at three different locations along the specimen axis: Y_1, Y_2, and Y_3 (b)
  - The CoM's path is fit to a function describing the path of an ideal cylinder rotating about an arbitrary axis (c)
  - By calculating the distance from the true tilt axis at all three locations, the tilt axis displacement and rotation can be directly calculated (d)
  - This process is iterated until both the shift and rotation achieve sub-pixel precision
  - Reconstruction was carried out using Tomo3D **[5]** and slices extracted from data that was aligned using cross-correlation and manual tilt axis alignment (e) is compared to that done using our automated approach (f)



Evaluation of Reconstructed Data

- Slices extracted from three positions in the reconstructed tomogram after automated alignment
- Nanoscale features and their shapes are quantitatively assessed as artifacts have been eliminated
- Segmentation is also improved, producing a 3D rendering of the true tri-gate structure



References

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4. D. Wolf, Proc. of 15th Euro. Microsc. Cong., Manchester, UK, Sept. 16 – 21, 2012.
5. J. I Agulleiro and J. J. Fernandez, *J. Struc. Bio.*, 189, 582-583 (2011).