Comparison of Analyis Routines for EDS and EELS Spectrum Images of Electrical Contacts to Single-Walled Carbon Nanotubes

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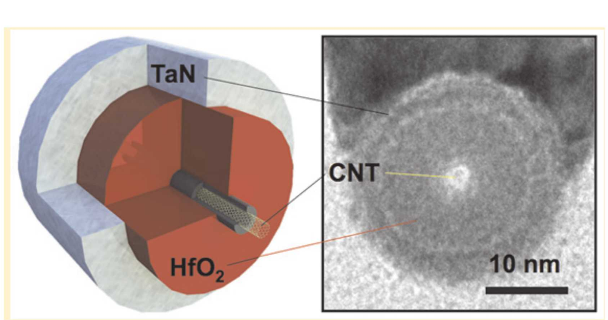
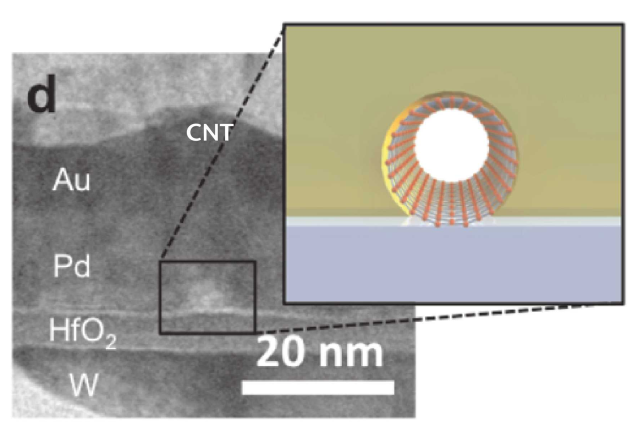
SAND2014-19895C

Motivation:

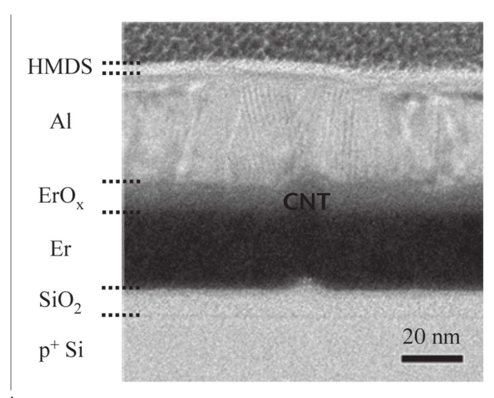
Carbon nanotubes (CNTs) are a promising material for the development of new types of field-effect transistors. They offer advantages over traditional CMOS FETs because of their potential for high device density, low power consumption, and ballistic carrier transport. One area of increased importance to electrical device performance is the metal contact/CNT interface. The CNT and metal must be in intimate contact so that charge carriers can be injected into the CNT with no barriers to transport. The chemistry and morphology of these CNT/meta contact interfaces has been the subject of many studies in the literature. Some of these are shown below. Here, we show how the combination of aberration-corrected TEM imaging and spectroscopy can give us insight into how the various device processing steps affect the checmistry and morphology of the interface. Because the typical dimensions of a semiconducting nanotube are approximately 1 nm in diameter, TEM is one of the only analytical tools with the appropriate spatial resolution to investigate this problem. We performed imaging and spectroscopy using an FEI probe-corrected G2 80-200 Titan with a SuperX large-angle SDD EDS detector and a Gatan Quantum 963 EELS spectrometer.



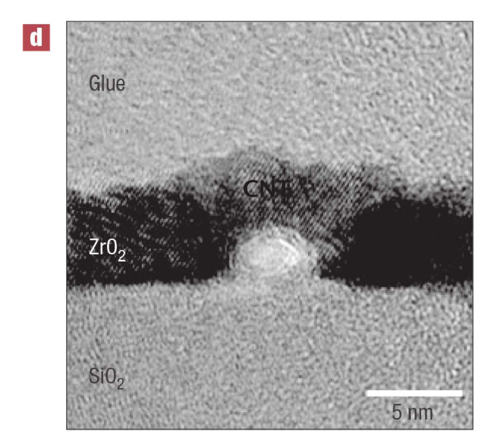
Franklin, A.D., et al., Carbon Nanotube Complementary Wrap-Gate Transistors. Nano Letters, 2013. 13(6): p. 2490-2495.



Franklin, A.D., et al., Sub-10 nm Carbon Nanotube Transistor. Nano Letters, 2012. 12(2): p. 758-762.

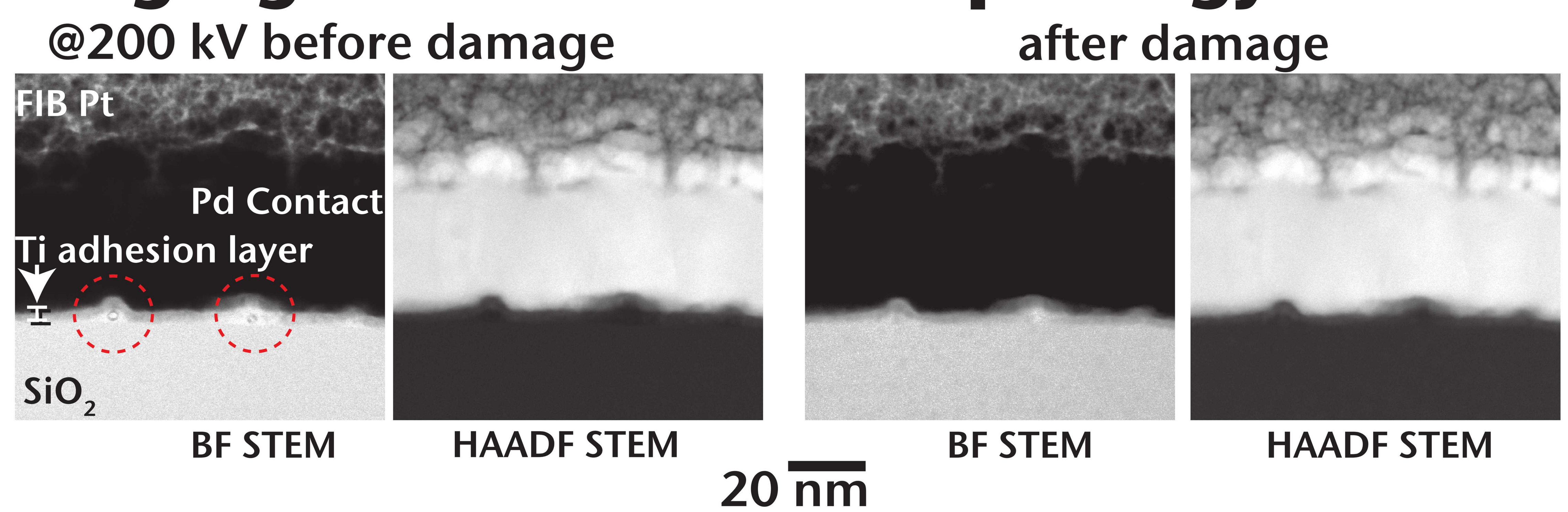


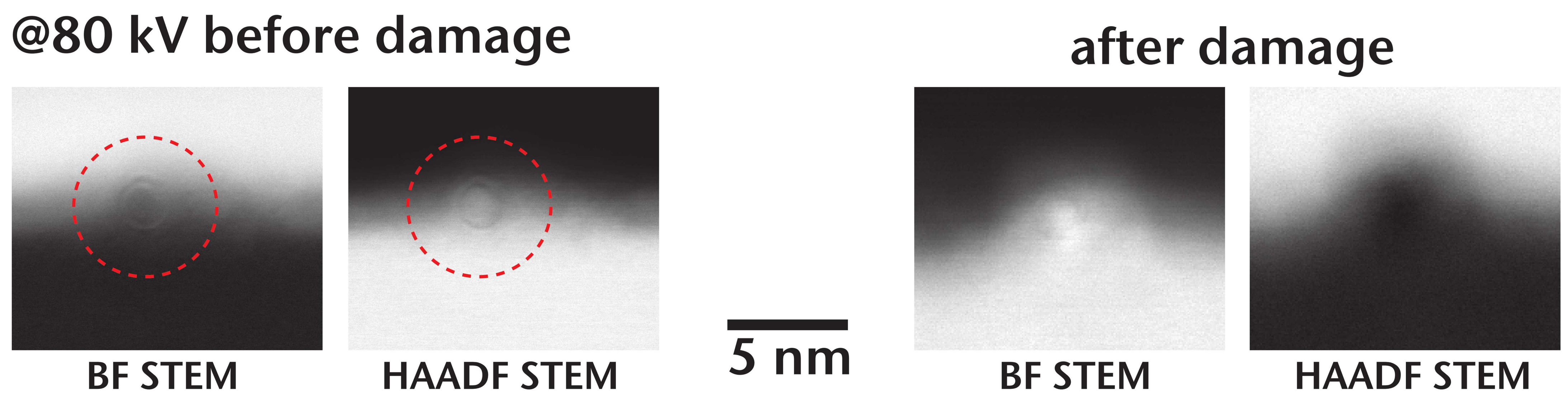
Shahrjerdi, D., et al., High-Performance Air-Stable n-Type Carbon Nanotube Transistors with Erbium Contacts. ACS Nano, 2013. 7(9): p. 8303-8308.



Javey, A., et al., High-kappa dielectrics for advanced carbon-nanotube transistors and logic gates. Nature Materials, 2002. 1(4): p. 241-246.

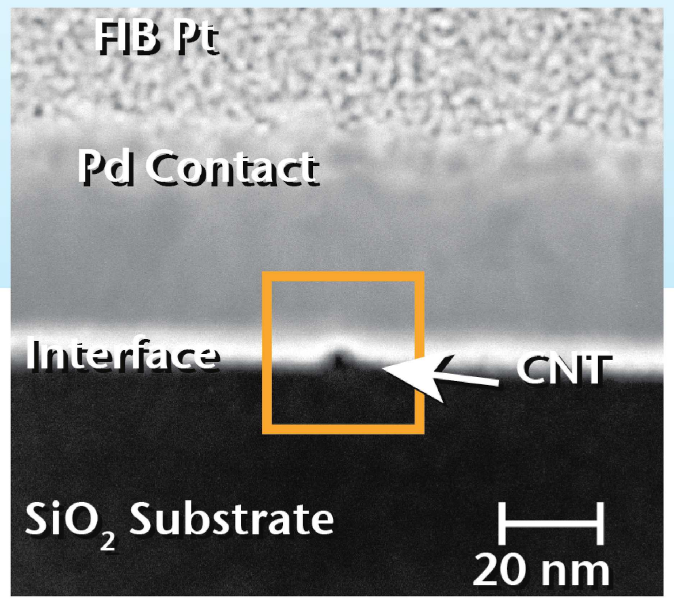
Imaging CNT Contact Morphology:

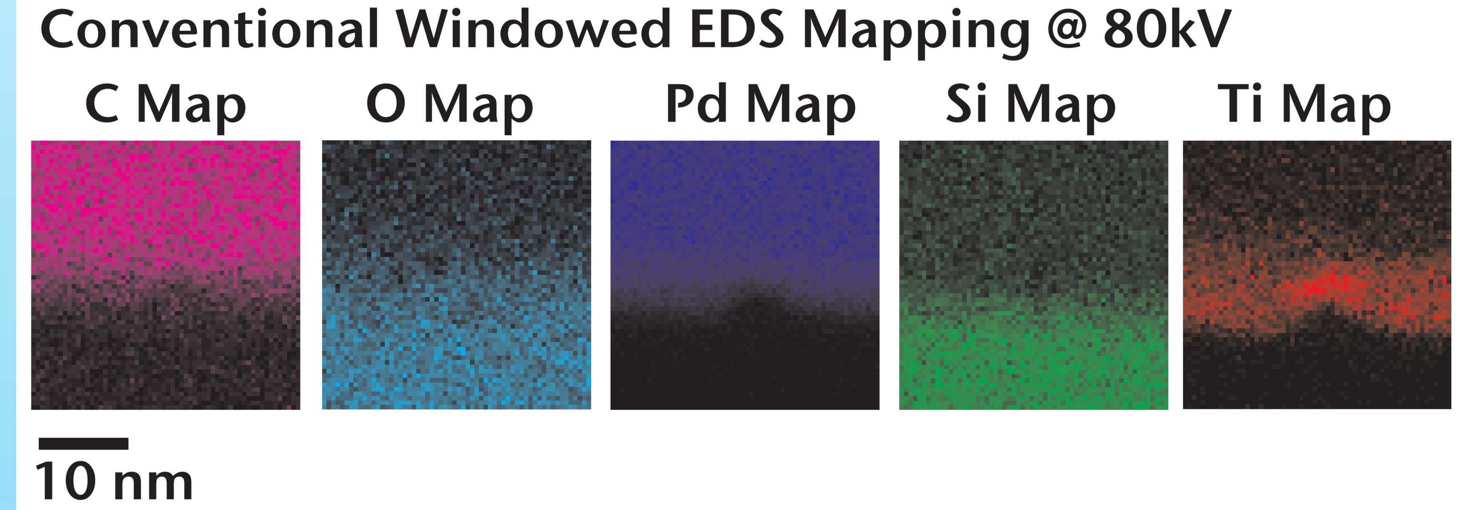


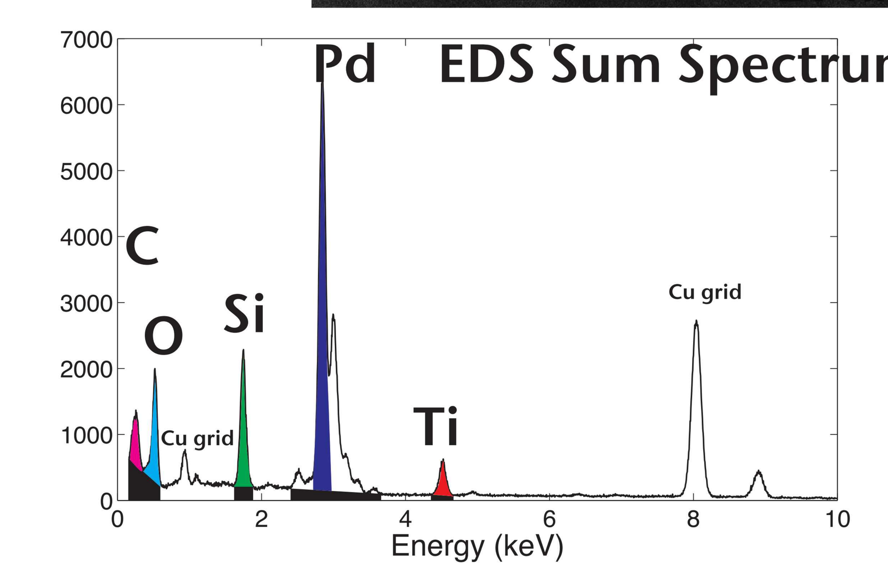


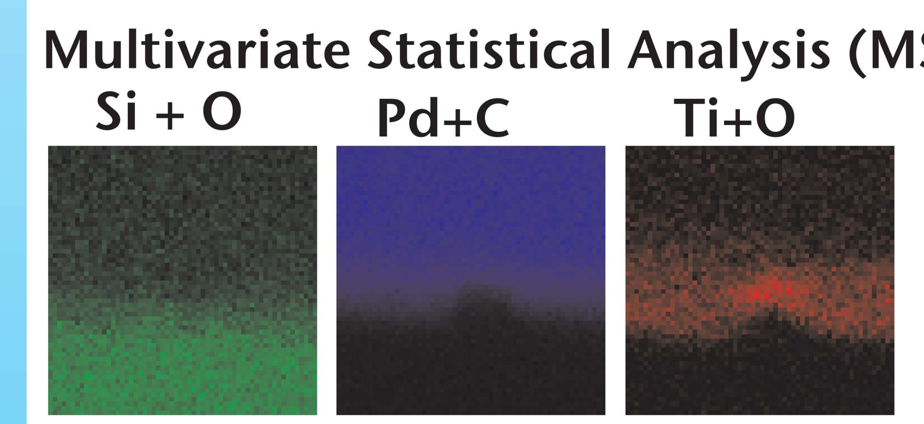
STEM imaging at both 80 kV and 200 kV showed that it was possible to image the CNT/contact interface in cross section. Beam damage, however, detroyed the morphology of the interface within minutes of imaging regardless of incident electron energy. For our processing conditions, the images show that the contact does not form the "omega" pattern as described in Franklin et al. (above). Instead, there is only direct contact with the Pd electrode on the top of the CNT, which reduces the contact area and has the potential to reduce the efficiency of charge carrier injection into the CNT.

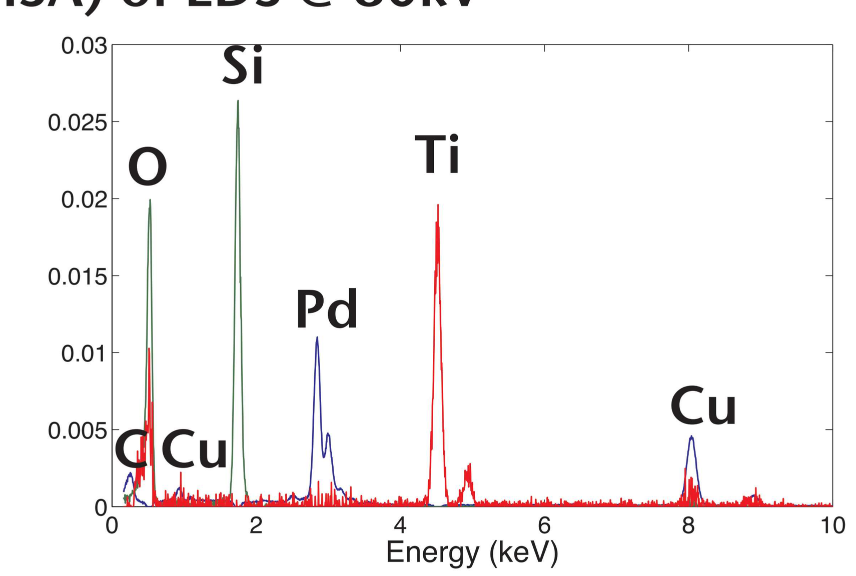
EDS and EELS Analysis:



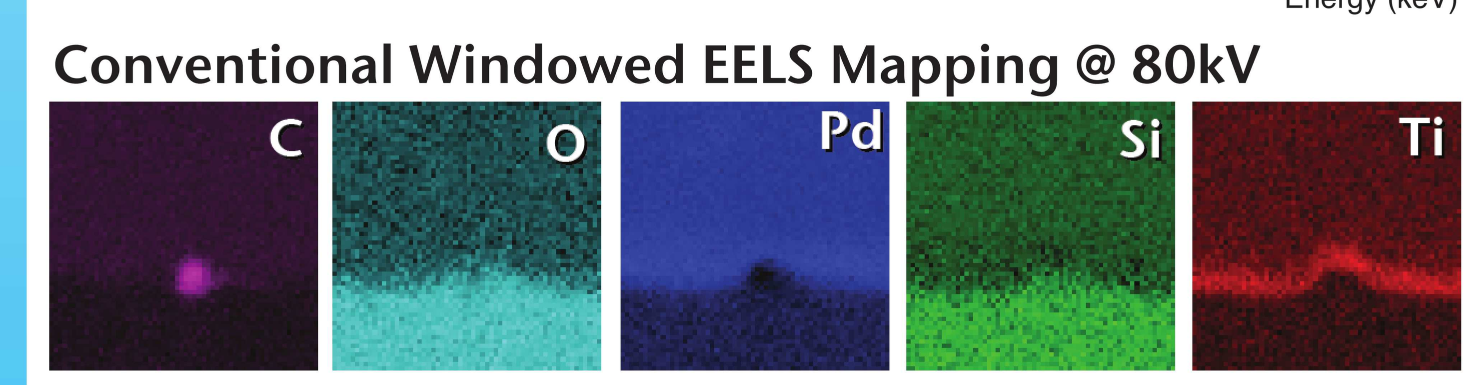


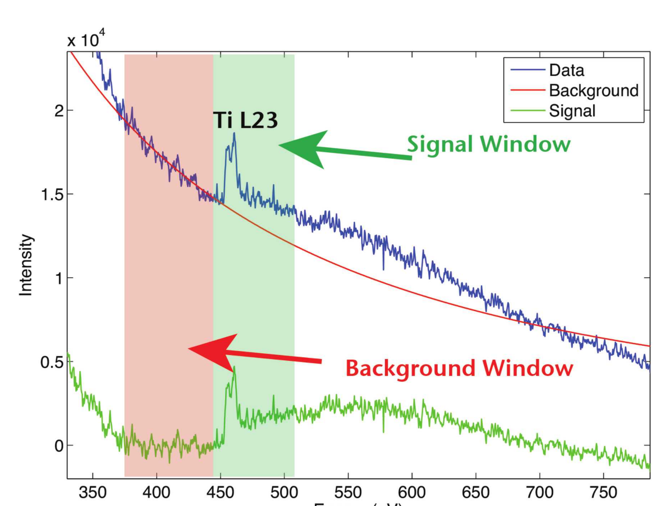




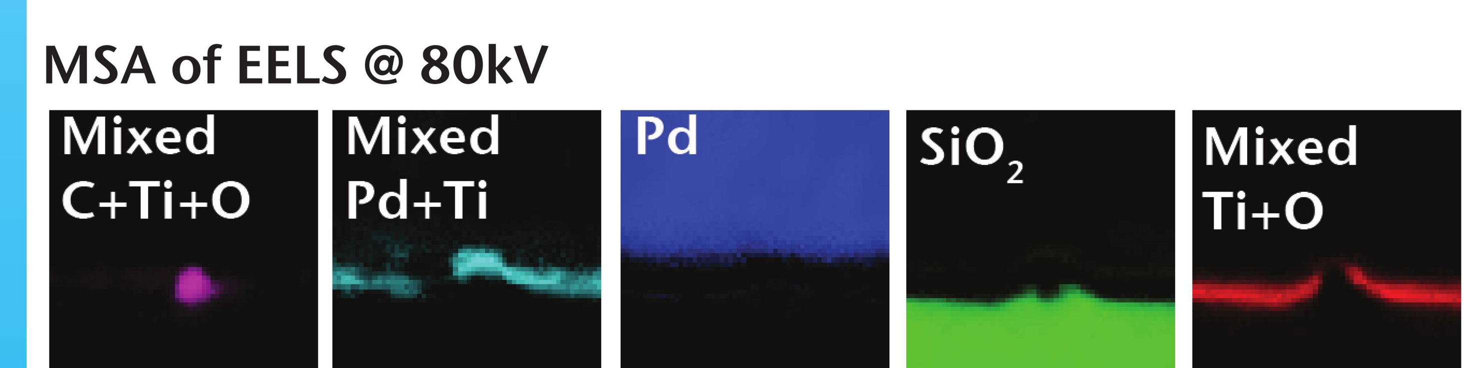


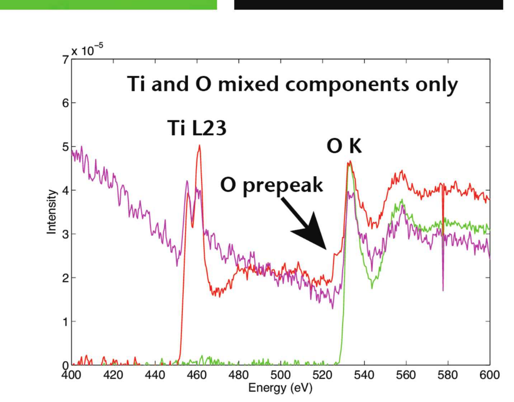
Spatial simplicity MCR-ALS was applied to the data with no a priori knowledge of the sample. The results show that there are three "pure components" containing SiO_2, Pd, and Ti. There is some mixing of C in the Pd, and O in the Ti component. This suggests that there could be a reaction layer at the interface.

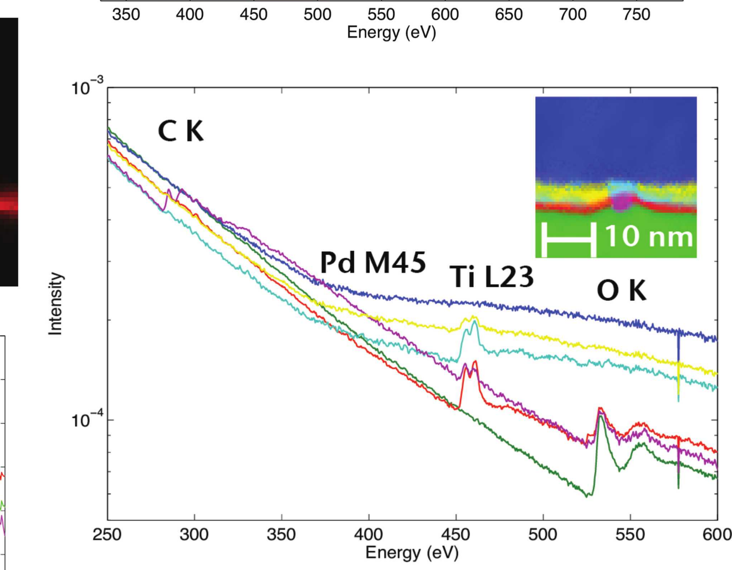




Example of window used for conventional Ti map.







Spatial simplicity MCR-ALS applied to EELS data. The oxygen pre-preak present in the mixed Ti and O components is indicative of a hybridized O2p-Ti3d vacant orbitals. (Kurata et al. *PRB* **47** 1993).

Conclusions:

The electron beam damage in these samples poses a problem becasue the CNT is damaged and no longer present by the time a spectrum image is acquired. However, even after the CNT is damaged, chemical analysis on the region near a CNT provides useful information about the processing steps used to fabricate CNT devices. In this case, MSA offers advantages over conventional mapping becasue for EDS, it simplifies the output into three "pure" components with no a priori knowledge instead of 5 elemental maps. It also shows elemental mixing similar to the EELS data. When MSA is applied to the EELS data, in addition to chemical mixing of elements at the interface indicative of reaction layers, it is also possible to see changes in bonding between Ti and O at the interface. This suggests that we must reduce the oxygen content present as a result of our solution processing steps because a dielectric layer such as TiO_2 at the interface could reduce charge carrier injection efficiency into the CNT. A detailed understanding of our processing steps would not be possible without the advanced nanoscale chemcial and morphological analysis possible with modern analytical electron microscopes.

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