

Investigation of Dielectric Breakdown on the Atomic Length-scale Using *In situ* STM-TEM

K. van Benthem, C.S. Bonifacio, A.M. Thron, S.M. Weil, T.B. Holland

* Department for Chemical Engineering and Materials Science, University of California, Davis, 1 Shields Ave., Davis CA 95616

The insulating properties of dielectrics are based on their low density of free charge carriers in the conduction band. Dielectric materials are insulating and are technologically relevant due to their polarization properties, which modify the complex dielectric function of the vacuum, e.g. to increase the ability to store charges in capacitors. Dielectric breakdown describes the loss of insulating properties. A fundamental understanding of dielectric breakdown mechanisms is critical for many technological applications, such as field-effect transistors [1], storage devices and even field-assisted sintering [2].

We have used *in situ* transmission electron microscopy to determine nucleation sites and atomic-scale processes responsible for dielectric breakdown in nanostructures. The evolution of defect structures under applied electrical fields was studied using a Nanofactory double-tilt STM-TEM specimen holder in a Jeol JEM 2100F/Cs aberration corrected STEM/TEM.

During one case study, the tip of the scanning tunneling microscope (STM) was used to apply positive bias to the gate electrode of a single field effect transistor device while measuring the induced gate current I_g across the gate dielectric. Figure 1a is a plot of I_g across the poly-Si/HfO₂/SiO_x/Si gate stack a function of time. During the experiment, the gate bias was increased from zero to +10V to stimulate dielectric breakdown. Figure 1b shows the device structure and morphology *before* and *after* breakdown occurred. In the presentation, we will discuss first results about changes of the atomic interface structure that lead to time-dependent dielectric breakdown at a constant positive bias.

In a second case study we investigate the fundamental atomic-scale processes of spark plasma sintering, during which materials transport for consolidation is stimulated by a (pulsed) electrical current [2]. Nickel particles with nominal diameters of 20 nm were brought into contact with each other using the *in situ* STM-TEM specimen holder. After contact between two particles was established, an increasing negative electrical bias was applied to the STM tip, which generates current flow from the tip across the contacting particles to the specimen grid. The thin passivating NiO layer on the particles' surface initially delayed current flow. Eventually, dielectric breakdown was observed from the recorded *I-V* curves as a rapidly increasing current. Simultaneously, enhanced materials transport lead to sintering of neighboring Ni nanoparticles, which was simultaneously recorded by TEM video capturing (See Figure 2).

- [1] R. Waser, *Nanoelectronics and Information Technology: Advanced Electronic Materials and Novel Devices*. 2nd Edition, Germany, 2005.
- [2] Z.A. Munir, U. Anselmi-Tamburini, M. Ohyanagi. *Journal of Materials Science* **41** (2006) 763-777
- [3] The authors acknowledge financial support through start-up funds from the University of California at Davis. Fruitful discussions with J.R. Groza and A.K. Mukherjee and technical assistance by Junhang Luo of Nanofactory are greatly appreciated.

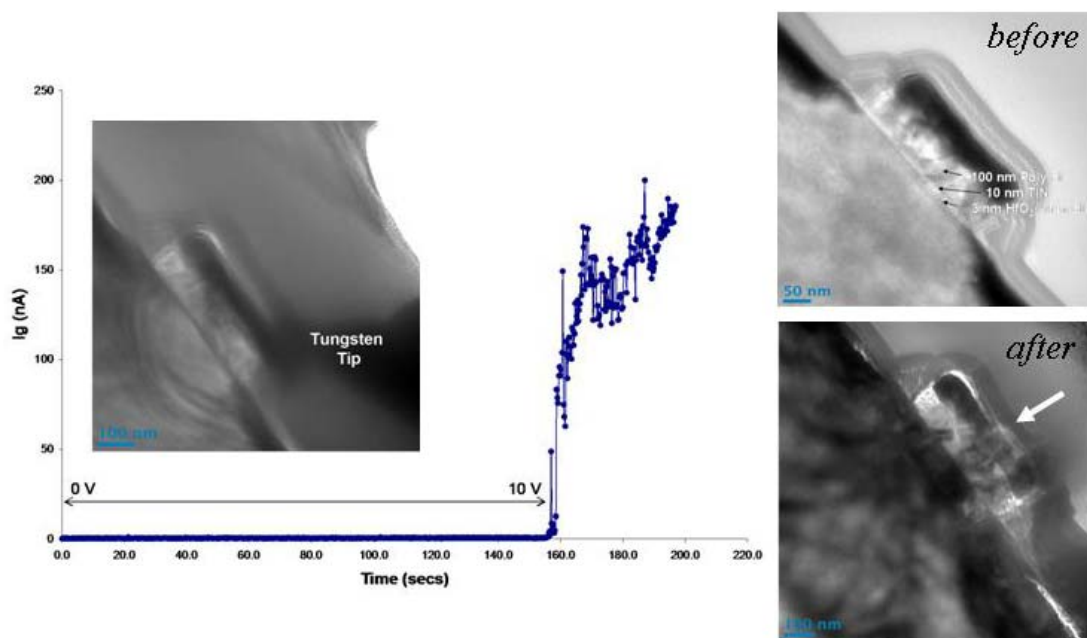


Figure 1. Evolution of the current across the gate dielectric. Rapidly increasing current observed at 10V indicates dielectric breakdown. Cross-sectional TEM micrographs of the field effect transistor are shown on the right *before* and *after* breakdown occurred.

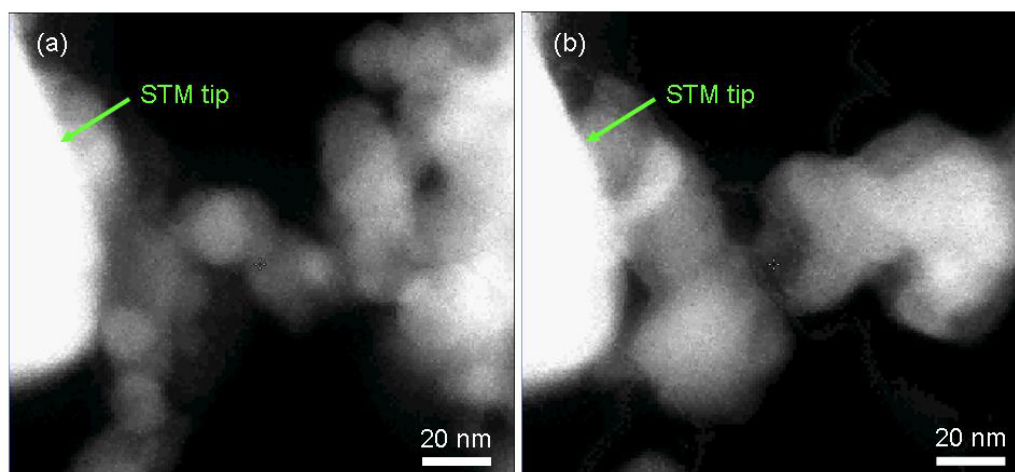


Figure 2. TEM micrograph of the STM tip that contacts to Ni nanoparticles (a) before and (b) after dielectric breakdown and successive sintering have occurred.