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Scanning TEM EBIC Imaging of Resistive Memory Switching Processes

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The function of a nanoelectronic device is determined by its electronic structure. While scanning transmission electron microscopy (STEM) is one of the premier techniques for determining the physical structure of a sample, it is almost blind to electronic structure. Electron beam-induced current (EBIC) imaging, on the other hand, produces images sensitive to the electronic state of a sample. Here we describe a case study of *in situ* STEM EBIC imaging: observing dynamic switching processes in resistive random access memory (RRAM) devices.

With prospects for smaller size, higher speed, less power, and cheaper cost, RRAM could replace the nonvolatile flash memory that is now common in USB drives, smart phones, and personal computers. In RRAM, metal electrodes sandwiching an insulating electrolyte form a digital memory element. The presence ('1') or absence ('0') of a conducting path through the insulator represents one bit of information.

Depending upon the chemistry and the mechanisms perceived to be underlying the formation and dissolution of this conducting path, RRAM is divided into several different categories. Two of these RRAM categories are conducting bridge memory (CBRAM) and valence change memory (VCM). In a previous study [1] we observed *in situ* the formation and dissolution of nanoscale copper filaments in CBRAM devices with STEM. Because the high-*Z* copper atoms scatter electrons effectively, the motion of Cu atoms is readily visualized with standard STEM annular dark field imaging. In VCM, however, the oxygen vacancies that are thought to form the conducting path [2] produce a subtle signal that has proven difficult to image with traditional STEM. STEM EBIC [3], however, can readily map switching-induced changes to the electronic structure of nanoscale Ti/HfO_2/Pt VCM elements.

VCM devices are fabricated in a slant-vertical geometry [1] on an electron-transparent membrane. This geometry (Fig. 1 top right) gives functional devices that are topologically similar to the vertically-stacked devices that would be used in a complete memory system: the materials constituting a memory element are put down in the usual order of bottom electrode, insulator, and top electrode. However, we displace the top electrode horizontally relative to the bottom electrode. This 'slant' gives good STEM imaging access to the switching region, and avoids introducing unrealistic surfaces or contamination to the device. Fabrication begins with a 15 nm Si_3N_4 membrane on which an 8 nm layer of HfO_2, deposited with atomic layer deposition (ALD), acts as a sticking layer for 30 nm Pt patterned electrodes. A second 8 nm-thick layer of HfO_2 is next, and followed by 30 nm Ti electrodes. The conformal layer of oxide between the two electrodes ensures that any conduction between the electrodes must pass through the HfO_2 – no interface or exposed surface connects the electrodes. Finally, a capping layer of 8 nm-thick ALD HfO_2 is deposited to further guard against oxidation and surface migration.

Figure 1 shows annular dark-field (ADF) STEM (top left) and STEM EBIC images (bottom row) of a Ti/HfO_2/Pt VCM device. While no striking changes appear in the traditional STEM images (not shown), the STEM EBIC images change dramatically as the bias between the electrodes is increased from 0 to

10 and 12 V. As the potential is increased a conducting path, connected to the Pt, grows between the electrodes. At 12 V the gap has decreased, and the electric field increased, to the point that electron-hole pair separation is starting the saturate the amplifier. As STEM EBIC imaging reveals the forming process for this VCM device, it can also show details about the SET and RESET processes that are invisible to standard TEM or STEM imaging modes.

References:

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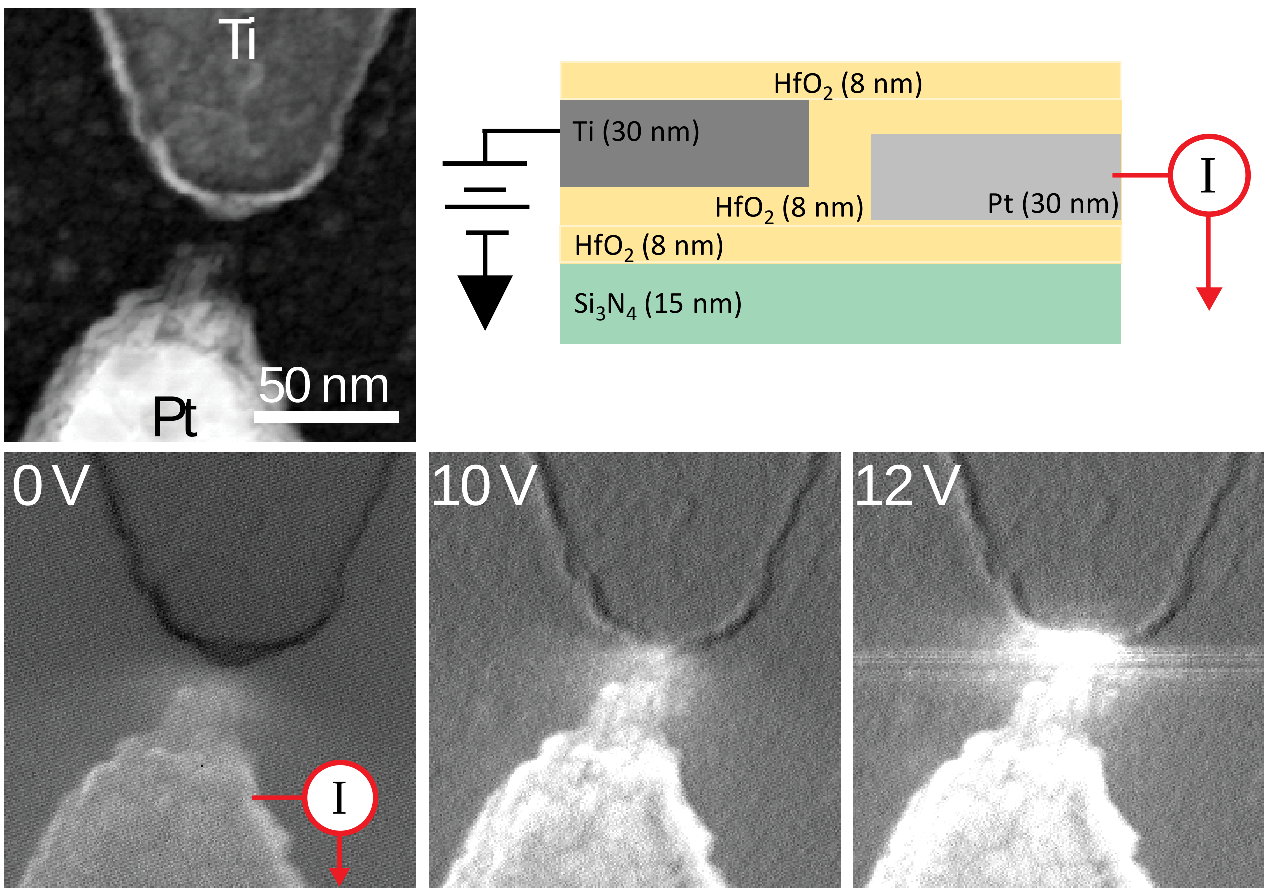

Figure 1: STEM EBIC of a VCM device under increasing bias. The VCM device consists of a Ti electrode, ALD HfO_2, a Pt electrode, and a capping layer of HfO_2. The standard, annular dark field (ADF) STEM image shows the device in its pristine (0 V) state, but in fact the ADF image shows no significant changes with applied bias (images not shown). In contrast the EBIC images acquired with 0, 10, and 12 V applied to the Ti electrode show clearly the development of a conducting path connecting the electrodes. The transimpedance amplifier (red current meter symbol in the schematic) is attached to the Pt electrode, which is thus at virtual ground.

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