Principles and Practice of Electron Beam Induced Current Microscopy of Resistive Nanodevices

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Resistive switching devices (ReRAM) represent a broad class of two-terminal continuously tunable resistors including memristors, phase change memory (PCM), valence change memory (VCM), and electrochemical metallization cells (ECM). Though these devices, especially PCM, are increasingly being commercialized by industry for use in next generation memories, they are also all actively studied for use as synaptic weights in next generation hardware-accelerated neuromorphic networks.

Due to the small length scales and complicated physics of these devices, often involving coupled electrical, thermal, mechanical, and chemical fields, new metrology is needed to understand their behavior. To that end, we investigate electron beam induced current (EBIC) microscopy to develop reliable and robust characterization of resistive switching devices. In our investigation, we observe surprising electronic effects, such as internal secondary electron emission, in addition to more conventional electron-hole pair separation, and we break these up into constituent currents based on their origin (Figure 1).

By doing both state and energy dependent probing of the device (Figure 2.), it's possible to observe variations in the relative intensities of these competing current contributions, and we observe a maximum in internal secondary electron emission at low incident beam energy when the device is in the on state. By doing Monte Carlo modeling of the device-beam interaction as a function of energy and combining this with physical arguments governing the origins of the various excited currents, we have developed a linear combination model which allows us to accurately replicate both the energy and device state dependence of the overall EBIC signal (Figure 3).

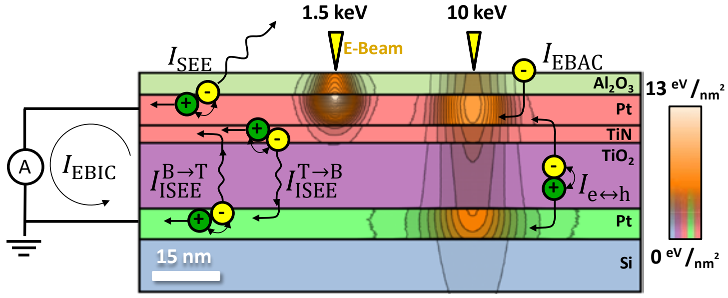

Figure 1. Monte Carlo simulated absorption in a multi-layer ReRAM device at both 1.5 keV incident beam and 10 keV incident beam. Absorption in different layers can result in the different depicted currents including the secondary electron current ($\boldsymbol{I_{SEE}}$), the electron beam absorbed current ($\boldsymbol{I_{EBAC}}$), the electron-hole pair current ($\boldsymbol{I_{e\leftrightarrow h}}$), and the internal secondary electron currents from top-to-bottom ($\boldsymbol{I_{ISEE}^{T\to B}}$) and bottom-to-top ($\boldsymbol{I_{ISEE}^{B\to T}}$). These all sum to create the measured electron beam induced current ($\boldsymbol{I_{EBIC}}$).

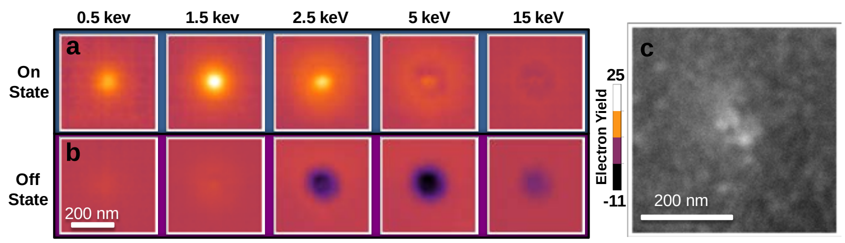

Figure 2. a) Electron beam induced current micrograph series showing contrast evolution with beam energy for the on-state and b) for the off-state. The on-state signal maximum implies the signal is due to absorption in the top electrode whereas the off-state signal minimum implies the signal is due to absorption in the TiO_2 layer. c) Scanning electron micrograph of the device after switching showing no tears in the electrode.

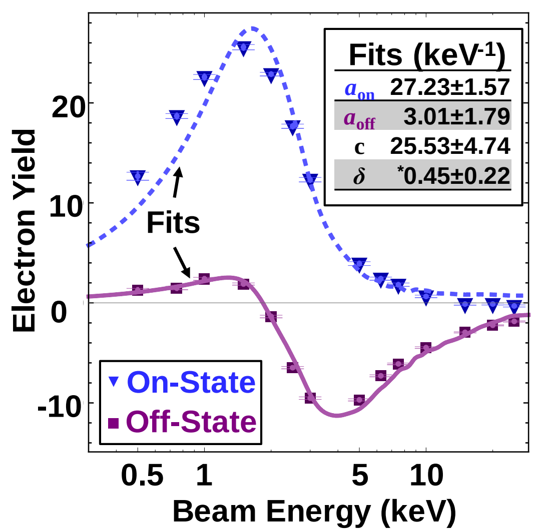

Figure 3. Measured electron yield as a function of energy. Error bars indicate two standard deviations of the mean within an 11 × 11 pixel box at the signal center for the on-state and off-state micrograph series in Figure 5. All quantities are measured with respect to the background. Fits are shown with least-squares 95 % confidence intervals with units of keV^{-1}(*note δ is dimensionless). Only the least-squares coefficient for the internal secondary electron emission (ISEE) signal, a, with associated variables a_{on} and a_{off} changes between the off-state and the on-state.