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Tentative Thesis Title:

Characterization of Nanoscale Conducting Filament in High-k Oxides by Scanning Tunneling Microscopy and Conductive Atomic Force Microscopy

Tentative Thesis Abstract

By virtue of its simple structure, high operating speed and scalability, the resistive memory or RRAM is deemed a promising alternative to the charge-based memory, which is now facing severe scaling challenges. Of particular interest is the HfO_2 RRAM due to its immediate compatibility with mainstream integrated-circuit technology. A major problem is, however, the relatively high switching current. Currents on the order of 10^{-3} A are typically observed in large-area cells (~10^{-8} cm^2). In a recent work, a substantial reduction of the switching current to ~10^{-5} A was achieved by scaling the cell area down to 100 nm^2.

Since one of the main strengths of RRAM is scalability, a further reduction of the switching current is deemed necessary in order to make ultra-high density memory application viable. At present, it is unclear to what extent could the switching current be reduced with cell area scaling. To address this question, resistance switching in HfO_2 is examined using a conductive atomic force microscope (C-AFM) and scanning tunneling microscope (STM) in this thesis. The excellent spatial resolution of C-AFM and STM enables the electrical properties of a thin dielectric to be probed over an extremely localized region. Through the C-AFM/STM technique, in this thesis, we examined resistance switching in a 4-nm thick HfO_2, within a region of ~2 nm in diameter and achieved an ultra-low current switching capability.

Furthermore, the unique abrupt reset behavior is observed in nanoscale RRAM with nanometer-level conducting filament (CF), on the contrary, the gradual current

reduction trend is typically observed during the reset process in relatively large area RRAM device. We addressed the origin of the gradual resistance reset behavior by studying, via STM/C-AFM, the reset characteristic of the nanoscale CFs and its relation with the macroscopic gradual electrical reset behavior in device level. The statistical result shows that the nanoscale CFs tend to exhibit abrupt resistance reset behavior with significant variations in the reset voltage and current. It is shown that this wide variation of reset voltage and current contributes to the gradual resistance reset behavior observed in large area RRAM device with multiple nanoscale CFs formed beneath the top electrode.

The memory device seldom works individually. The crossbar memory array is the most commonly used architecture. However, the fundamental problem of a crossbar memory array is the sneak-path current, which can severely compromise the integrity of data readout. To overcome the problem, a typical approach would be to connect a selection device, e.g. diode or transistor in series with each memory element, at the expense of a lower integration density and greater processing complexity. In this thesis, we show, via STM/C-AFM study, that the filamentary path in the HfOx dielectric could exhibit a highly asymmetrical conduction property when the forming hardness is appropriately controlled. The finding suggests possible exploitation for extremely compact cross-point bipolar resistive memory with built-in rectification.

With the further scaling of the RRAM/MOSFET devices, electrical-stress-induced breakdown of the scaled thin gate oxide is a serious reliability issue that has received widespread attention for many years. Studies have shown that gate-oxide breakdown

can be broadly classified as soft or hard. Ultra-thin gate oxides (< 5 nm) typically exhibit the former. As soft breakdown (SBD) typically does not lead to a total loss of transistor functionality, there has been much interest on the breakdown mechanism and its evolution towards eventual hard breakdown. With HfO_2 replacing SiO_2 as the gate oxide, recent attention was mostly centered on the reliability of the metal/HfO_2 gate stack. It has been found that SBD of HfO_2 can be electrically reversed with a greater ease as compared to SiO_2, prompting considerable interest on the recovery mechanism as well as the role of the metal electrode. In this thesis, we report that a nanoscale percolation path in SiO_2 and HfO_2 can be disrupted upon exposure to white light. The disruption is either complete or partial, depending on the resistance of the percolation path determined at the point of breakdown, i.e. the breakdown hardness. The electrical robustness of the light-restored oxide is tested and analyzed using statistical Weibull distributions. Unlike the classical photo-response behavior of narrow bandgap oxides and perovskites which is commonly manifested as an increase in electrical conduction due to the generation of excess charge carriers by the incident photons, the photo-response here comes in the form of a disruption of electrical conduction through the nanoscale conducting filament or percolation path formed during breakdown. When that occurs the insulating properties of the breakdown oxide region can be restored. The disruption in electrical conduction caused by white-light illumination is proposed to occur through photon-stimulated migration of interstitial oxygen ions nearby the vacancy-filled filament, resulting in the migrating oxygen ions recombining with the vacancies in the filament. This unique photo-responsive

behavior, which we termed as negative photoconductivity (NPC) of SBD HfO_2, ZrO_2 and SiO_2 points towards the possibility of gate oxide reliability rejuvenation as well as the incorporation of optical functions into mainstream CMOS-based integrated circuits, e.g., imaging sensors and photodetectors with built-in non-volatile memory capability. As a photodetector, the relation between the CF disruption speed and the light intensity has been investigated, as well as the wavelength influence. The infrared light is proved to be effective for CF disruption on our device, indicating a possible room temperature infrared detector. A systematic study is presented in this thesis regarding the influence factors to the photosensitivity/CF disruption speed, such as the stoichiometry of the oxide layer, sample temperature, and the electrode dependence.