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Highly uniform low-power resistive memory using nitrogen-doped tantalum pentoxide

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ABSTRACT

Highly uniform current distributions of high resistance state (HRS) and low resistance state (LRS), low 0.6 pJ switching energy, fast 30 ns switching speed, and good 10^6 cycling endurance are achieved in Ni/GeO_x/$Ta_2O_{5-y}N_y$/TaN resistive random access memory (RRAM) devices. Such good performance is attributed to nitrogen-related acceptor level in $Ta_2O_{5-y}N_y$ for better hopping conduction, which leads to forming-free resistive switching and low self-compliance switching currents.

The endurance degradation of Flash memory [1–3] at highly scaled sub-25 nm cell size is the fundamental physical limitation as listed in *International Technology Roadmap for Semiconductors* (*ITRS*) [1]. Therefore, new non-volatile memory (NVM) devices should be developed. Among various NVM devices, the resistive random access memory (RRAM) [4–15] has the simpler structure, faster switching speed, and better embedded memory integration beyond the Flash memory. However, the poor switching uniformity, high set/reset currents, large compliance currents with large size transistor, and low endurance are the difficult challenges for RRAM devices. To address these issues, we previously used the hopping conduction [16] to reach low switching current RRAMs [12–14]. The hopping conduction provides a large internal resistance to reach low self-compliance set/reset currents with unique negative temperature coefficient (TC), which is quite different from the large switching currents and the positive TC in conventional metal–oxide (MO) RRAM by metallic filament conduction [4]. Similar low switching power RRAM, using hopping conduction with negative TC, was also demonstrated by Samsung [15]. However, the switching current distribution needs to be improved to reach the production-level requirement of low tail bits.

In this paper, we report an ultra-low 0.6 pJ switching energy GeO/TaON RRAM with much tighter distribution and more stable endurance to 10^6 cycles. Such excellent performance is attributed to low self-compliance set/reset currents with the hopping conduction via nitrogen defects which is different to reported Pt/TaO_x/Pt RRAM [11] with a large-size transistor to drive high current compliance.

The RRAM devices were integrated into VLSI backend with a 200-nm SiO_2 on a Si substrate. Then 100 nm TaN was deposited by physical vapor deposition (PVD). After patterning the TaN electrode, the 36-nm-thick $Ta_2O_{5-y}N_y$ dielectric was deposited on TaN/SiO_2/Si followed by the optimized annealed condition of 400 °C for 15 min under oxygen ambient. The $Ta_2O_{5-y}N_y$ film remained amorphous phase after annealing which has been examined by X-ray diffraction (XRD). The control Ta_2O_5 layer was also deposited for performance comparison. After that, a 7.5-nm-thick GeO_x was deposited to form the stacked GeO_x/$Ta_2O_{5-y}N_y$ dielectric. Finally, a 50-nm-thick Ni was deposited and patterned as top electrode by a metal mask with an area of 11,300 μm^2. The fabricated devices were characterized by capacitance–voltage (*C*–*V*), current–voltage (*I*–*V*), switching speed, and endurance measurements using an Agilent 4284 LCR meter, 4156 semiconductor parameter analyzer, 81110 pulse generator and oscilloscope.

Fig. 1a shows the swept *I*–*V* curves of the Ni/GeO_x/$Ta_2O_{5-y}N_y$/TaN and control Ni/GeO_x/Ta_2O_5/TaN RRAM devices, and the swept

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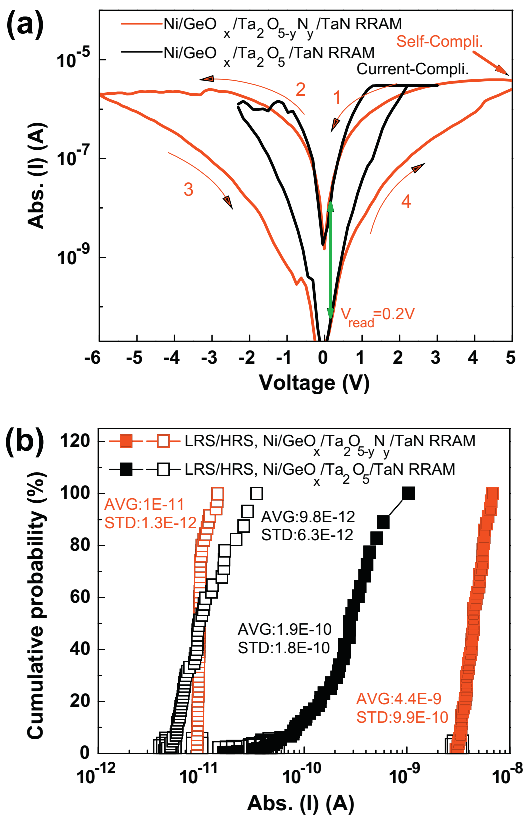

Fig. 1. (a) Swept *I–V* curves and (b) set/reset current distributions of Ni/GeO_x/$Ta_2O_{5-y}N_y$/TaN and control Ni/GeO_x/Ta_2O_5/TaN RRAM devices. The arrows indicate the bias sweeping directions.

directions were indicated by the arrows. The resistance changes from high resistance state (HRS) to low-resistance state (LRS) during set process, and changes from LRS to HRS during reset. The needed forming-free and self-compliance resistive switching characteristics are obtained in Ni/GeO_x/$Ta_2O_{5-y}N_y$/TaN RRAM device; however, the control Ni/GeO_x/Ta_2O_5/TaN device requires additional current-compliance to avoid breakdown during set/reset operations. The current-compliance will require a transistor to deliver and limit the set current, but the extra transistor consumes a larger area. The nitrogen-incorporated Ni/GeO_x/$Ta_2O_{5-y}N_y$/TaN RRAM device shows a resistance ratio >100 at 0.2 V read, a low set power of 19 μW (3.8 μA at 5 V) and reset power of 12 μW (−2 μA at −6 V). The low self-compliance currents during set/rest operation are related to the large internal resistance in nitrogen-doped RRAM device by hopping conduction [13]. To further investigate the nitrogen-doping effect, we have plotted the HRS/LRS current distributions in Fig. 1b. The control RRAM device, even with additional current-compliance, still exhibits wide LRS and HRS current distributions, which may be ascribed to random distribution of oxygen vacancies in Ta_2O_5 dielectric. In sharp contrast, highly uniform LRS and HRS currents and >100 resistance ratio are found in the nitrogen-doped RRAM device that is even better than published GeO/HfON RRAM [13]. The excellent switching uniformity is linked to the low power operation of forming-free resistive switching and low self-compliance set/reset currents, which have less stress to the dielectric of metal–insulator–metal (MIM) RRAM devices. This is significantly better than conventional RRAM using metallic filament conduction.

To explore such uniform switching currents, the current conduction mechanism was analyzed. Fig. 2a shows the measured and simulated *I–V* characteristics at HRS and LRS, respectively.

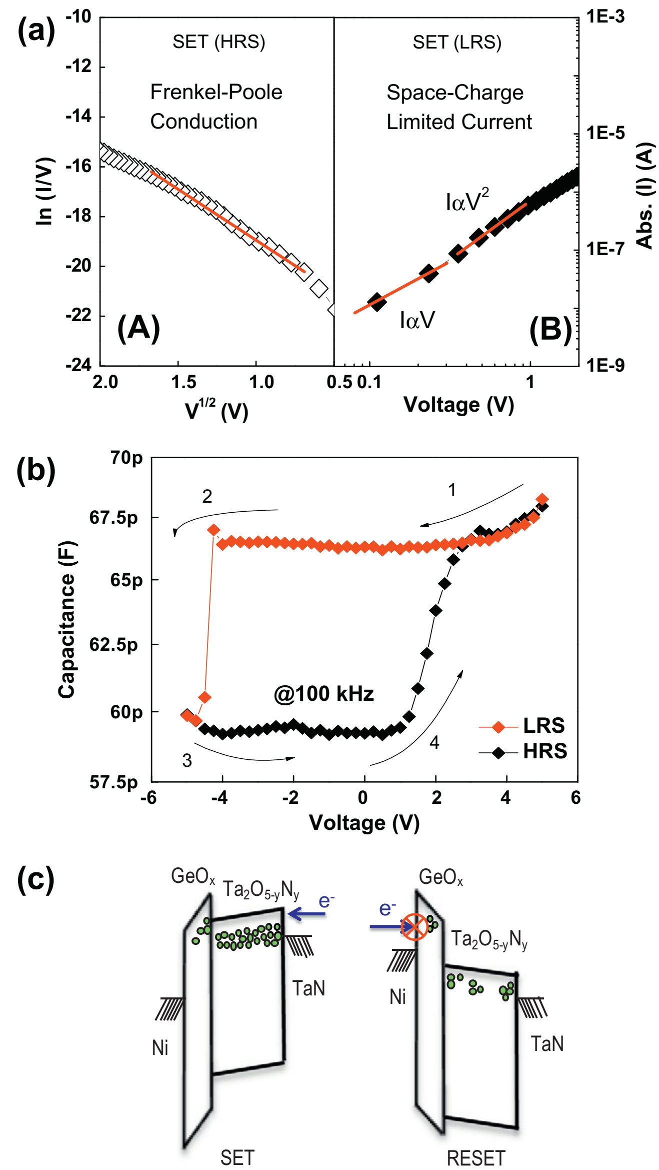

Fig. 2. (a) Measured and simulated HRS and LRS currents, (b) *C–V* curves at HRS and LRS and (c) the schematic energy band diagrams under set and reset conditions of Ni/GeO_x/$Ta_2O_{5-y}N_y$/TaN RRAM devices.

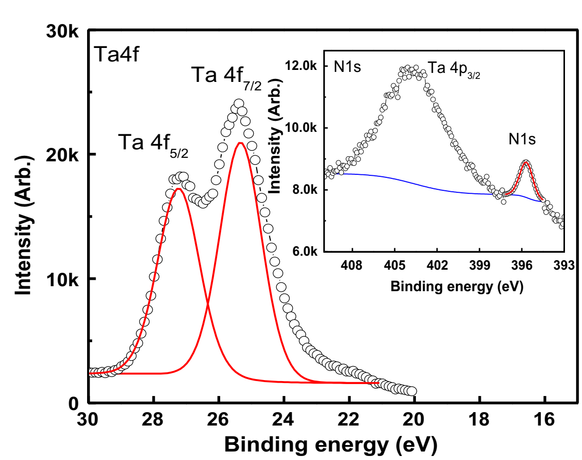

Fig. 3. The XPS spectra of Ta 4f and N 1s core level in $Ta_2O_{5-y}N_y$.