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Citation: Applied Physics Letters **102**, 133503 (2013); doi: 10.1063/1.4799655
View online: http://dx.doi.org/10.1063/1.4799655
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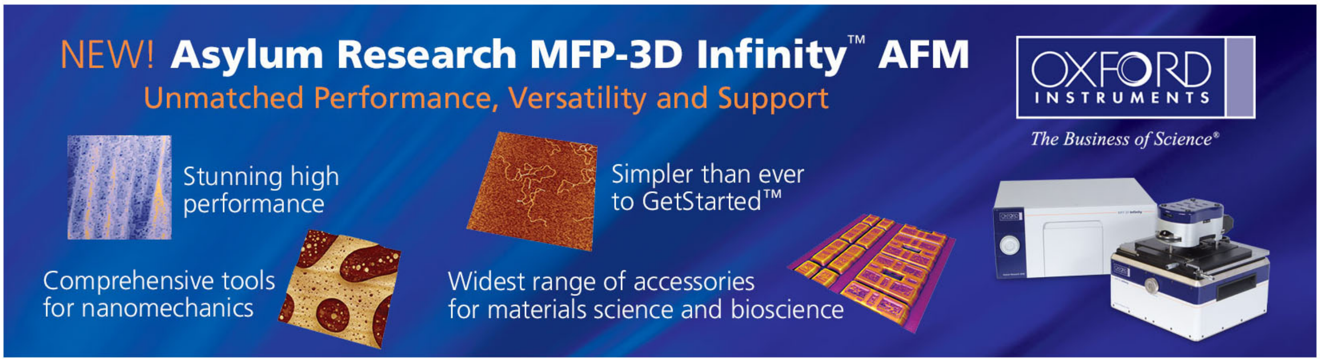

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APPLIED PHYSICS LETTERS **102**, 133503 (2013)

Hopping conduction distance dependent activation energy characteristics of Zn:SiO_2 resistance random access memory devices

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(Received 20 February 2013; accepted 21 March 2013; published online 2 April 2013)

In this study, the hopping conduction distance variation of Zn:SiO_2 resistance random access memory (RRAM) devices with different operating compliance currents was discussed and verified. To investigate and determine the hopping conduction distance dependent activation energy characteristics, the Arrhenius plot of low resistance state of Zn:SiO_2 RRAM devices was applied, from which we proposed carrier conduction model. With the increase of current compliance, more metal ions would accumulate to form precipitates with larger diameter, which in turn resulted in the shortening of hopping distance. Because of shorter hopping distance, activation energy for carrier hopping would decrease. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4799655]

Recently, the non-volatile random access memory devices were widely discussed and investigated for applications, including resistance random access memory (RRAM), ferroelectric random access memory (FeRAM), magnetic random access memory (MRAM), and phase change memory (PCM).[1–9] Among these memory devices, silicon oxide based RRAM devices attract vast attention owing to great compatibility in integrated circuit (IC) processes, non-destructive readout, low operation voltage, high operation speed, long retention time, and simple structure.[10–15]

Various materials have been reported having resistance switching properties.[16–24] And zinc is an extensively researched material in semiconductor device.[25–29] In this letter, the resistive switching mechanism of zinc-doped SiO_2 RRAM was thoroughly analyzed. In the experiment, we found that the low resistance state (LRS) of Zn:SiO_2 RRAM devices using different operating compliance currents had different hopping distances. Besides, the hopping conduction distance dependent activation energy was investigated by the Arrhenius plot, which also confirmed the hopping distance variation.

Metal-insulator-metal (MIM) structure for RRAM devices, which was fabricated over a polished p-Si wafer with nominal resistance ~1.0 Ω cm, was schematically shown in inset of Fig. 1. Native-oxide, contaminant particles, and metal ions on silicon wafer were removed during RCA™ clean process. In order to remove contaminants of metal target and obtain relative pure plasma during deposition time, pre-sputtering was maintained for 30 min under argon ambient. The Zn:SiO_2 thin film was later deposited on the TiN/Ti/SiO_2/Si substrate by co-sputtering with pure SiO_2 and zinc targets. The sputtering power was fixed with RF power 200 W and DC power 10 W for silicon dioxide and zinc targets, respectively. Additionally, the Pt top electrode with a thickness of 200 nm was deposited on Zn:SiO_2 film to form Pt/Zn:SiO_2/TiN sandwich structure by DC magnetron sputtering. The entire electrical measurements of devices

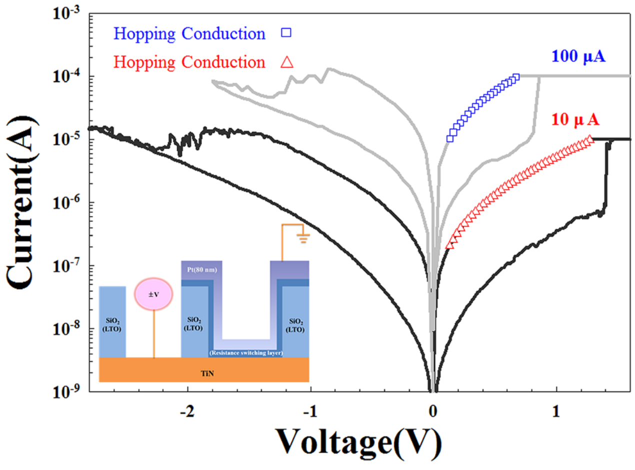

FIG. 1. I-V characteristics of Zn:SiO_2 RRAM devices with different operating compliance currents of 10 μA and 100 μA, respectively. The inset is the structure of device.

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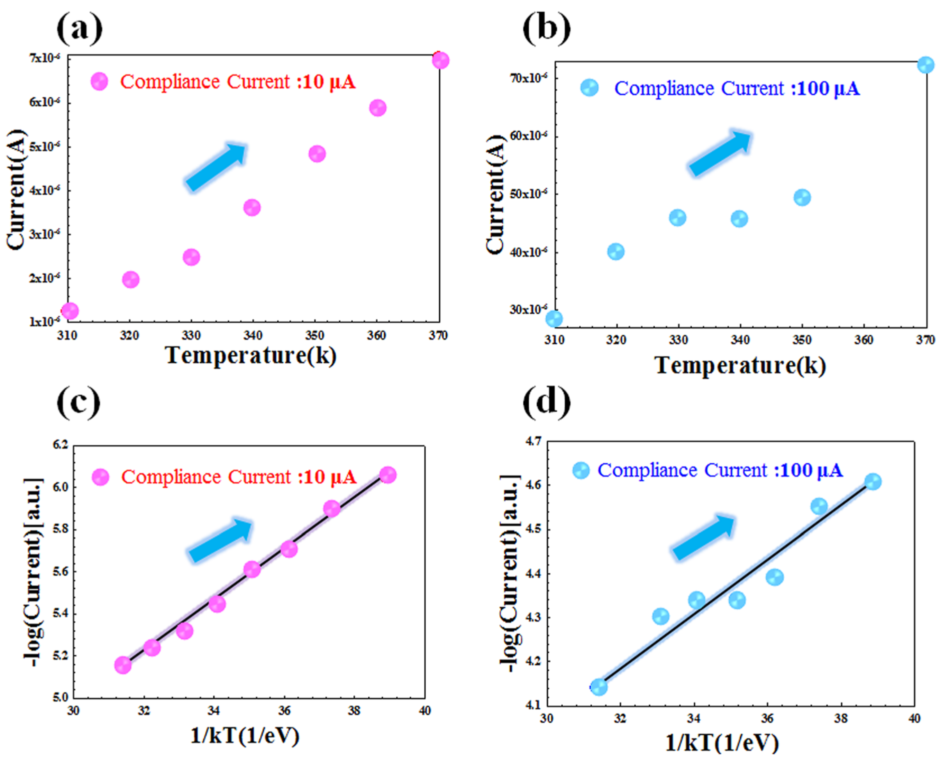

FIG. 2. (a) and (b) are the current temperature relationship for 10 μA and 100 μA current compliance, respectively. (c) and (d) are their corresponding hopping equation plots.

with the Pt electrode of 4 μm diameter were performed using Agilent B1500 semiconductor parameter analyzer.

Figure 1 shows the typical I-V curves of Zn:SiO$_2$ RRAM devices under different operating compliance currents of 10 μA and 100 μA, respectively. By conduction current fitting, both LRS with different operating compliance currents were dominated by hopping conduction mechanism. From comparison, we could find that the I-V window with higher current compliance was escalated by nearly two order magnitude.

To investigate the resistance switching behaviors in Zn:SiO$_2$ RRAM with different compliance currents, the relationship between LRS and temperature was measured as shown in Figs. 2(a) and 2(b). We could observe in both Figures 2(a) and 2(b) that current increased with the rising temperature, which was similar to semiconductor current-temperature property. According to the equation of hopping conduction, $J = qNa\upsilon_0 e^{-q\phi_T/kT} e^{qaV/2dkT}$, where N, a, ϕ_T, υ_0, and d are density of space charge, mean of hopping distance, barrier height of hopping, intrinsic vibration frequency, and film thickness, respectively, we can draw out the curve ϕ_T-aV/2d with a vertical axis of In(I) and a lateral axis of 1/kT (Figure 2(c) for 10 μA of compliance current, Fig. 2(d) for 100 μA). From Figs. 2(c) and 2(d), we could observe that experimental data matched with hooping conduction equation, which was also testified by our previous current fitting (Figure 1).

In order to further investigate the characteristics of hopping conduction with different current compliances, activation energy verses voltage were drew out in Figure 3. Arrhenius equation was applied to analyze the relationship between activation energy and voltage. The activation energy equation is $E_{A,exp} = -\frac{\partial \ \log I}{\partial(\frac{1}{kT})}$, where E$_a$ is active energy, k is the Boltzmann's constant, and T is the absolute temperature. The intercept of vertical axis represent their corresponding activation energy. And from Figure 3, we could obtain the activation energy of 10 μA and 100 μA compliance current operating situation, which were 0.1533 eV and 0.0682 eV, respectively. With the increase of current compliance, activation energy dropped from 0.1533 eV to 0.0682 eV.

Furthermore, hopping distance could be extracted from Arrhenius equation. As $E_{A,exp} = -\frac{\partial \log I}{\partial(\frac{1}{kT})} = E_C - E_F - qV_A\frac{\Delta z}{2u_a}$,

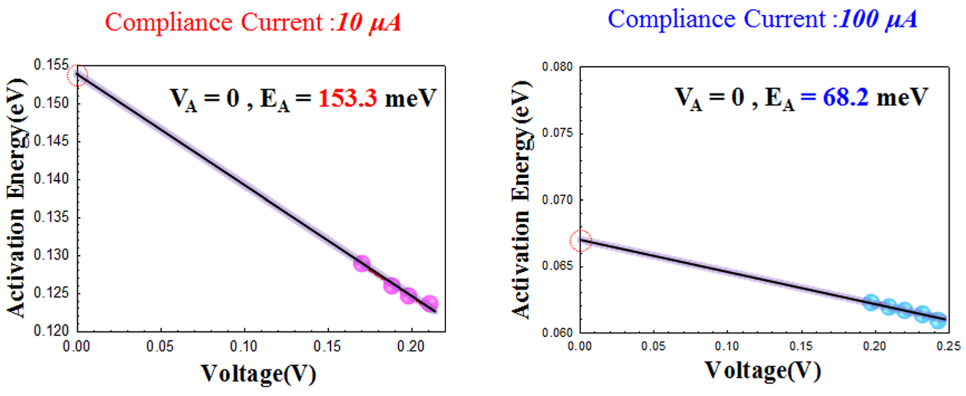

FIG. 3. The activation energy and voltage properties for 10 μA and 100 μA compliance current operating situation.

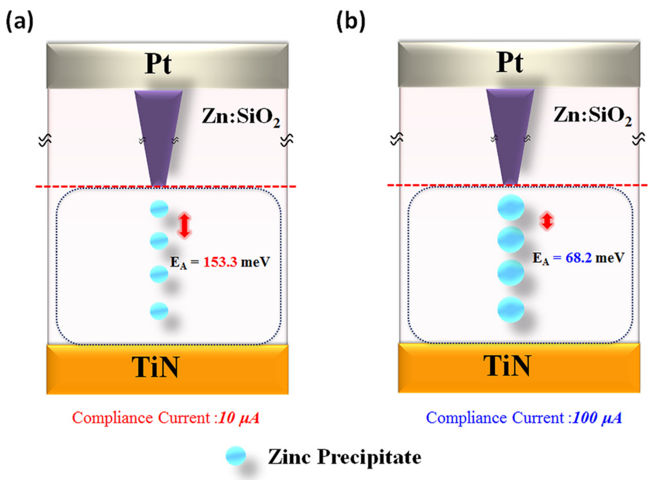

FIG. 4. Model of hopping distance variation which is induced by the diameter change of metal precipitates.

we could get $\frac{dE_A}{dV_A} = \frac{q\Delta z}{(2u_a)}$, where E_A is activation energy, V_A is applied voltage, Δz is average hopping distance, and u_a is the thickness of switching layer. According to our previous research,[24] the thickness of switching layer is about 5 nm, namely u_a equals to 5 nm. What's more $\frac{dE_A}{dV_A}$ can be obtained from Figure 3, it is the slope of fitting curve. By substituting $\frac{dE_A}{dV_A}$ and u_a into $\frac{dE_A}{dV_A} = \frac{q\Delta z}{(2u_a)}$, hopping distance can be obtained, which are 1.44 nm for 10 μA compliance operating situation 0.3 nm for 100 μA compliance operating situation, respectively.

Based on the analysis above, carrier conduction model was proposed, which was shown in Figure 4. As the intensity of current was the main reason for the soft break down of switching dielectric layer, the more intensive the conduction current, the easier the dielectric to break down, which in turn denser metal ions would accumulate to form conduction filament. With the increasing of current compliance, the diameter of metal precipitates would rise and it became easier for carrier hopping, from which shorter hopping distance was obtained. When the compliance current was smaller, there was less possibility for metal precipitate growing bigger.

In conclusion, bipolar resistance switching characteristics with different compliance currents of 10 μA and 100 μA of Zn:SiO$_2$ RRAM were thoroughly analyzed. By conduction current fitting, both LRS with different operating compliance currents were dominated by hopping conduction mechanism. With assistance of Arrhenius equation, we found that activation energy dropped from 0.1533 eV to 0.0682 eV when current compliance rose from 10 μA to 100 μA. Owing to the increase of current, it became easier for metal ions to form precipitates with larger diameter, which led to the decrease of hopping distance.

This work was performed at National Science Council Core Facilities Laboratory for Nano-Science and Nano-Technology in Kaohsiung-Pingtung area and supported by the National Science Council of the Republic of China under Contract Nos. NSC 101-2221-E-110-044-MY3 and NSC 101-2120-M-110-002.

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