Journal of Physics D: Applied Physics

Stabilizing the forming process in unipolar resistance switching using an improved compliance current limiter

To cite this article: S B Lee *et al* 2010 *J. Phys. D: Appl. Phys.* **43** 485103

View the article online for updates and enhancements.

You may also like

- Oxygen Reduction Reaction Activity for Surface-Magnetic-Anisotropy-Controlled Pt-Co/Pt(111) Bimetallic Surface
Tetsuro Nagao, Morimichi Kimura, Naoto Todoroki et al.

- Forming mechanism of the bipolar resistance switching in double-layer memristive nanodevices
S B Lee, H K Yoo, K Kim et al.

- Electric Potential Distribution at Interfaces in PEFC by First Principle Simulation
Juanjuan Zhou, Xiangyang Zhou and Hongtan Liu

The Electrochemical Society
Advancing solid state & electrochemical science & technology

243rd ECS Meeting with SOFC-XVIII

Boston, MA • May 28 – June 2, 2023

Abstract Submission Extended Deadline: December 16

Learn more and submit!

This content was downloaded from IP address 165.194.103.25 on 13/12/2022 at 01:54

J. Phys. D: Appl. Phys. **43** (2010) 485103 (4pp) doi:10.1088/0022-3727/43/48/485103

Stabilizing the forming process in unipolar resistance switching using an improved compliance current limiter

S B Lee[1], S H Chang[1], H K Yoo[1] and B S Kang[2]

[1] ReCFI, Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Republic of Korea
[2] Department of Applied Physics, Hanyang University, Ansan, Gyeonggi-do 426-791, Republic of Korea

E-mail: bosookang@hanyang.ac.kr

Received 17 July 2010, in final form 30 August 2010
Published 16 November 2010
Online at stacks.iop.org/JPhysD/43/485103

Abstract

The high reset current I_R in unipolar resistance switching is a major obstacle to practical applications in memory devices. In particular, the first I_R value after the forming process is so high that the capacitors sometimes do not exhibit reliable unipolar resistance switching. We find that the compliance current I_{comp} is a critical parameter for reducing I_R values in polycrystalline Pt/NiO_w/Pt, Pt/$SrTiO_x$/Pt, Ti/$SrTiO_x$/Pt, Pt/TiO_y/Pt and Pt/FeO_z/Pt capacitors, which show unipolar resistance switching. We therefore introduce an improved, simple and easy-to-use I_{comp} limiter that stabilizes the forming process by drastically decreasing the current overflow so as to precisely control the I_{comp} and subsequent I_R values.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Dielectric breakdown has been considered as an important and interesting problem in various phenomena in nature including lightening and earthquakes, and in the performance degradation of electronic devices [1]. From the early 1960s, through elaborate control of dielectric breakdown in nanoscale thin films, reversible resistance switching (RS) phenomena have been reported in numerous materials, including oxides, organics and electrolytes [2]. Unipolar RS shows reversible bistable resistance states that depend on the magnitude of the same-polarity bias voltage in thin film capacitors. It has attracted renewed interest due to its potential application in nonvolatile resistance random access memory (RRAM) devices [3–6]. However, to use unipolar RS as a commercial nonvolatile memory device, several technical issues need to be resolved.

The major challenge is reducing the high current required by the reset process to change from the low (LRS) to the high resistance state (HRS) [7–9]. The reset current I_R is usually so high that unipolar RRAM requires a very high density of oxide diodes switch elements to produce a reliable three-dimensional array structure [10]. Therefore, high I_R value is not merely a power consumption issue, but also a serious constraint on the feasibility of practical device operation.

A high I_R value is closely related to the dielectric breakdown-like failure in unipolar RS capacitors. Even if the capacitors are fabricated on the same wafer, they show a large I_R value distribution after the forming process, which is the first dielectric breakdown-like resistance change from the pristine state to the LRS. In the forming process, conducting channels originally have percolating connectivity inside the film [4, 6, 9]. The subsequent unipolar RS is widely accepted to occur due to the formation and rupture of these conducting channels inside the film [3–6]. After the forming process, some of the capacitors show an I_R value high enough to exceed the capacity of typical measuring equipment. The unipolar RS in those capacitors was therefore regarded as permanently failed, and that failure was attributed to poor sample quality without sufficient evidence. Therefore, to consistently achieve reliable unipolar RS, the forming process should be studied systematically to obtain consistent control of the process.

We observed that a current overflow during the forming process plays an important role in the subsequent I_R values and hence in the prevention of permanent breakdown after the

 © 2010 IOP Publishing Ltd Printed in the UK & the USA

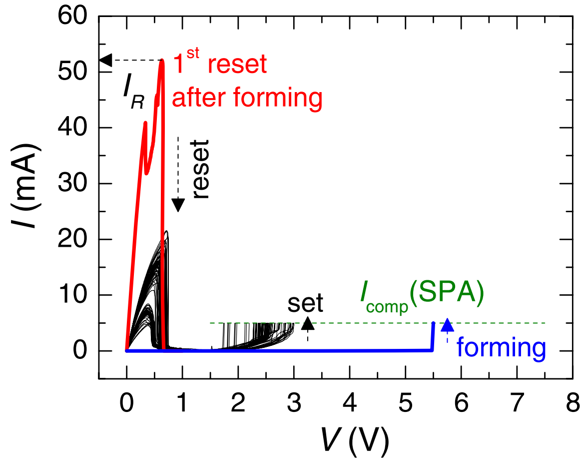

Figure 1. Current–voltage (I–V) curves in a Pt/NiO_w/Pt capacitor showing unipolar RS. We used a SPA as a compliance current (I_{comp}) limiter for both the forming and set processes. Even with $I_{comp} = 5$ mA during the forming process (blue line), the subsequent reset current I_R was around 50 mA (red line). Subsequently, I_R values fluctuated significantly between 5 and 20 mA despite the small I_{comp} value during the set processes.

forming process. In the following, we discuss our simple and easy-to-use method of overcoming current overflow.

2. Experiments

We fabricated polycrystalline Pt/NiO_w/Pt, Pt/$SrTiO_x$/Pt, Ti/$SrTiO_x$/Pt, Pt/TiO_y/Pt and Pt/FeO_z/Pt capacitors that showed unipolar RS. Details on the fabrication methods are well described elsewhere [9, 11, 12]. Current–voltage (I–V) characteristics were measured with a simple two-probe method using an Agilent 4155C semiconductor parameter analyzer (SPA). The bottom electrodes were grounded and the voltage was swept on the top electrodes for all the electrical measurements.

3. Results and discussion

Figure 1 shows the typical I–V curves for the Pt/NiO_w/Pt unipolar RS capacitors, which are highly insulating in the pristine state. When we applied a voltage of approximately 5–7 V, the current increased suddenly, electroforming the capacitors, as indicated by the blue line. Immediately after this forming process, the capacitor entered into a LRS. When the bias voltage increased above a reset voltage, the capacitor switched from the LRS to a HRS. As we further increased the bias voltage in the HRS, it reached a set voltage which was higher than the reset voltage, and the film returned to the LRS, which is called a set process. For both the forming and set processes, we used a compliance current I_{comp} to prevent permanent breakdown of the capacitors.

For the first reset process (red line) after the forming process, the I_R value is around 50 mA despite the small I_{comp} value of 5 mA. In this measurement, we used an I_{comp} limiter function provided by the SPA. Subsequently, even though the same I_{comp} value of 5 mA was used for the set processes, the I_R values fluctuated between 5 and 20 mA, smaller than the first I_R value but still larger than the I_{comp} value. After the forming process in some capacitors, the first I_R value was larger than 100 mA, after which we failed to accomplish the reset process within the available I_{comp}-range of the SPA ($\leqslant$100 mA). Many researchers have regarded those capacitors as undergoing a permanent breakdown. Therefore, the forming process and the subsequent reset process are important steps in obtaining reliable unipolar RS. In the same measurement system, we also observed the problematically high I_R value phenomenon after the forming process for many Pt/$SrTiO_x$/Pt, Ti/$SrTiO_x$/Pt, Pt/TiO_y/Pt and Pt/FeO_z/Pt capacitors.

Recently, after performing conductive atomic-force microscopy studies on polycrystalline TiO_y thin film surfaces, we have reported that conducting channels are locally formed during the forming and set processes [4]. At those moments, the total cross section of the conducting channels is determined by the I_{comp} values, so I_R values should be theoretically proportional to I_{comp} values [9]. However, as shown in figure 1, conventional I_{comp} limiters such as the SPA of figure 2(a) could not block an abrupt change in current exactly during the forming and set processes.

How can the I_{comp} values be precisely controlled to obtain the correct I_R values? Many reports have addressed the discrepancies between the I_{comp} values of the set processes and the I_R values that occur due to the parasitic capacitance between the unipolar RS capacitor and the I_{comp} limiter [8, 13]. Recently, Song *et al* pointed out that this problem was due to the dissipation of capacitive charges that accumulated in the unipolar RS capacitor itself [14]. These two effects can also work together to induce these discrepancies.

To solve the discrepancies between the I_{comp} and I_R values of the set processes, Kinoshita *et al* suggested that the cable connection between the capacitor and the I_{comp} limiter should be as short as possible [8]. They also fabricated unipolar RS capacitors and I_{comp} limiters on the same wafer. Although this latter technique is expected to be effective in solving the permanent breakdown problem after the forming process, it is too difficult to apply at a laboratory level. Therefore, we used a switching transistor (ST, 2N2369), connected externally as shown in figure 2(b), as the I_{comp} limiter. An ideal ST rising time would be 6 ns, which is much shorter than the reported switching times of 10–200 ns in the set processes [9, 15]. We kept the cable connection between the bottom electrode and the ST as short as possible.

As shown in figure 2(c), the first I_R value after the forming process in the Pt/NiO_w/Pt capacitor is drastically reduced by using the ST I_{comp} limiter. For I_{comp} = 0.2 mA, the SPA (red line) measured an I_R value of around 10 mA. The ST I_R value (blue line), however, is approximately 0.5 mA at $I_{comp} \approx 0.2$ mA. After using the ST I_{comp} limiter, all the capacitors successfully underwent reset processes after the forming process and showed reliable unipolar RS. During successive RS, the I_R values become stable at around 0.5 mA. A reduction in the first I_R values by using a ST I_{comp} limiter was also observed in the Pt/$SrTiO_x$/Pt, Ti/$SrTiO_x$/Pt, Pt/TiO_y/Pt and Pt/FeO_z/Pt capacitors.

To address the physical effect of the ST I_{comp} limiter, we monitored the current flow time evolution through the

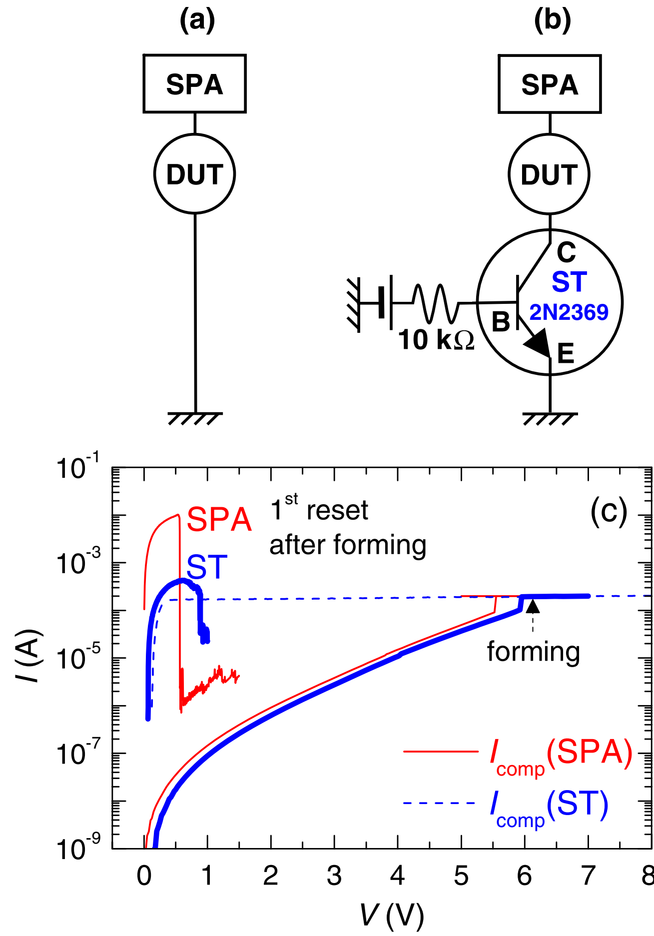

Figure 2. Schematic diagrams of the electrical measurement systems. We used (*a*) a SPA or (*b*) a ST as the I_{comp} limiter. (*c*) Comparison of I_R values after the forming process using SPA or ST I_{comp} limiters. The I_R value with the ST (blue line) was much smaller than for the SPA (red line), even if we use approximately the same 0.2 mA I_{comp} value.

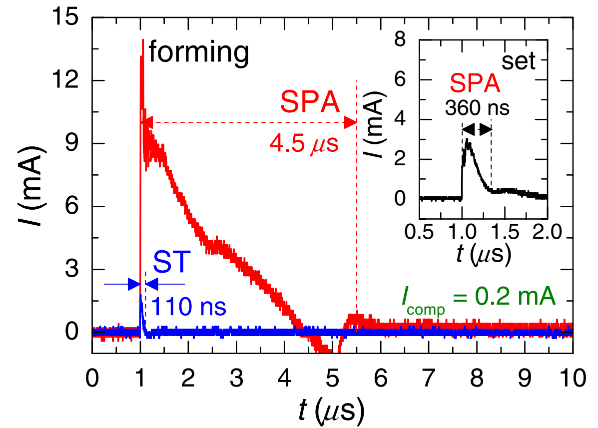

Figure 3. Time evolution of the current following the forming process. Even if we block the current using an I_{comp} limiter, the forming process exhibits a current overflow much larger than $I_{comp} = 0.2$ mA. However, the ST current overflow (blue line) decreases drastically compared with that of the SPA (red line). The inset shows the time evolution of the current for the set process with the SPA I_{comp} limiter. Even with the SPA I_{comp} limiter, the current overflow of the set process decreases more than that of the forming process.

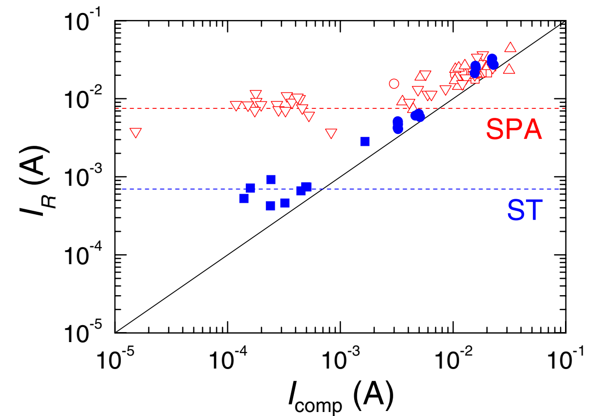

Figure 4. I_R values as a function of I_{comp} values for the set processes in unipolar RS. I_R values vary linearly with I_{comp} values only above approximately 7 mA for the SPA I_{comp} limiter (red open symbols). However, the ST I_R values (blue closed symbols) are saturated at a smaller value than that for the SPA by an order of magnitude.

Pt/NiO_w/Pt capacitor during the forming process. Using a YOKOGAWA DL1740 digital oscilloscope, we measured the voltage change across a serially connected 50 Ω load resistor on the unipolar RS capacitor to calculate the current flow.

Current overflow during the forming process decreases drastically by using a ST I_{comp} limiter instead of a SPA; see figure 3. The maximum ST current flow is around 1.5 mA at $I_{comp} \approx 0.2$ mA. The subsequent I_R value was approximately 0.5 mA, as mentioned in figure 2(*c*). In contrast, for the SPA, the current flow was above 14 mA for $I_{comp} = 0.2$ mA and the subsequent I_R value was around 10 mA. The overflow time for the ST (≈110 ns) is much smaller than that for the SPA (≈4.5 μs). The large differences in current overflow for the ST versus the SPA causes the remarkable difference in the subsequent I_R values; see figure 2(*c*).

Note that as shown in the inset of figure 3, even when we used the SPA I_{comp} limiter, the current overflow decreased drastically for the set process as compared with the forming process. As an example, in a set process with $I_{comp} = 0.2$ mA, the maximum current flow and time were around 3 mA and 360 ns, respectively. Therefore, the I_R values after the second reset process could become smaller than those of the first reset process; see figure 1. Understanding how the current overflows decrease at the set process is important. One possibility is that the HRS capacitive charges accumulated less than those in the pristine state. For the set processes, the reconnection of conducting channels occurs at the sub-nanometre local regions [4, 6]. The capacitive regions, which can accumulate capacitive charges, might be much smaller than those of the forming process [14]. Further studies should help in elucidating this decrease in current overflow for the set process.

As shown in figure 4, the reduction in I_R values in the Pt/NiO_w/Pt capacitors while using the ST I_{comp} limiter is also applicable to set processes. The relationship $I_R \propto I_{comp}$ holds for I_{comp} values down to approximately 0.7 mA for the ST (blue closed symbols), which is lower than that for the SPA (red open symbols) by an order of magnitude. However, below

$I_{comp} \approx 0.7$ mA, the ST I_R values are saturated due to the current overflow, which is beyond the blocking ability of the ST. This relationship was also observed in the Pt/SrTiO$_x$/Pt, Ti/SrTiO$_x$/Pt, Pt/TiO$_y$/Pt and Pt/FeO$_z$/Pt capacitors, although the I_R values were saturated at somewhat different values for different film materials.

4. Conclusions

We found that permanent breakdown after the forming process in unipolar RS was due to current overflow, which was attributed primarily to the imperfect control of the dielectric breakdown by the measurement system. We solved this problem by using a ST as an I_{comp} limiter for both the forming and set processes. This improved I_{comp} limiter could control the dielectric breakdown properly during the forming and set processes, resulting in a decrease in the minimum possible value of I_R by an order of magnitude compared with those when a conventional I_{comp} limiter was used. This improvement in the I_{comp}-limiting was attributable to the drastic decrease in current overflow in the forming and set processes. Our method is so simple and easy to use that it can be applied at the laboratory level.

Acknowledgments

The authors acknowledge both the valuable discussions with and the fabrication of samples by Dr M-J Lee and Dr C J Kim at the Samsung Advanced Institute of Technology. This research was supported by the National Research Foundation of Korea (NRF) grants funded by the Korean Ministry of Education, Science and Technology (MEST) (No 2009-0080567 and No 2010-0020416). BSK was supported by the Basic Science Research Programme through the NRF funded by the Korean MEST (Grant No 2010-0011608). SBL acknowledges the support from the Seoam Fellowship.

References

[1] O'Dwyer J J 1973 *The Theory of Electrical Conduction and Breakdown in Solid Dielectrics* (Oxford: Clarendon)
[2] Dearnaley G, Stoneham A M and Morgan D V 1970 *Rep. Prog. Phys.* **33** 1129
[3] Waser R, Dittmann R, Staikov G and Szot K 2009 *Adv. Mater.* **21** 2632
[4] Chae S C *et al* 2008 *Adv. Mater.* **20** 1154
[5] Chang S H, Lee J S, Chae S C, Lee S B, Liu C, Kahng B, Kim D-W and Noh T W 2009 *Phys. Rev. Lett.* **102** 026801
[6] Kwon D-H *et al* 2010 *Nature Nanotechnol.* **5** 148
[7] Ahn S-E *et al* 2008 *Adv. Mater.* **20** 924
[8] Kinoshita K, Tsunoda K, Sato Y, Noshiro H, Yagaki S, Aoki M and Sugiyama Y 2008 *Appl. Phys. Lett.* **93** 033506
[9] Lee S B, Kim A, Lee J S, Chang S H, Yoo H K, Noh T W, Kahng B, Lee M-J, Kim C J and Kang B S 2010 *Appl. Phys. Lett.* **97** 093505
[10] Kang B S, Ahn S-E, Lee M-J, Stefanovich G, Kim K H, Xianyu W X, Lee C B, Park Y, Baek I G and Park B H 2008 *Adv. Mater.* **20** 3066
[11] Seo S *et al* 2004 *Appl. Phys. Lett.* **85** 5655
[12] Lee S B, Chae S C, Chang S H, Liu C, Jung C U, Seo S and Kim D-W 2007 *J. Korean Phys. Soc.* **51** S96
[13] Wan H J, Zhou P, Ye L, Lin Y Y, Tang T A, Wu H M and Chi M H 2010 *IEEE Electron Device Lett.* **31** 246
[14] Song S J, Kim K M, Kim G H, Lee M H, Seok J Y, Jung R and Hwang C S 2010 *Appl. Phys. Lett.* **96** 112904
[15] Choi B J, Choi S, Kim K M, Shin Y C, Hwang C S, Hwang S-Y, Cho S-S, Park S and Hong S-K 2006 *Appl. Phys. Lett.* **89** 012906