Electrical breakdown in a $V_2O_3$ device at the insulator-to-metal transition

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Abstract – We have measured the electrical properties of a $V_2O_3$ thin film micro bridge at the insulator-metal transition (IMT). Discontinuous jumps to lower voltages in the current voltage characteristic (IV) followed by an approximately constant voltage progression for high currents indicate an electrical breakdown of the device. In addition, the IV curve shows hysteresis and a training effect, i.e., the subsequent IV loops are different from the first IV loop after thermal cycling. Low-temperature scanning electron microscopy (LTSEM) reveals that the electrical breakdown over the whole device is caused by the formation of electro-thermal domains (ETDs), i.e., the current and temperature redistribution in the device. On the contrary, at the nanoscale, the electrical breakdown causes the IMT of individual domains. In a numerical model we considered these domains as a network of resistors and we were able to reproduce the electro-thermal breakdown as well as the hysteresis and the training effect in the IVs.

Stoichiometric $V_2O_3$ is a strongly correlated material that undergoes a first-order insulator-to-metal phase transition (IMT) from an antiferromagnetic insulating to a paramagnetic metallic phase. Because the IMT causes a change in the resistivity of several orders of magnitude, novel devices based on the IMT and their applications are actively investigated [1], and it is in focus of current research whether there is a voltage-driven IMT in strongly correlated materials [2–8]. If this hypothesis holds, a micro bridge made of a strongly correlated material would experience a dielectric breakdown for high bias voltages. However, because of the large resistivity change, self-heating in such a device can be strong enough to cause an electro-thermal breakdown, i.e., a current and temperature redistribution [9,10]. In order to investigate the electrical breakdown of a $V_2O_3$ micro bridge, we used a very unique low-temperature scanning electron microscope (LTSEM) to image the metallic and insulating phases and developed a numerical model to simulate the electrical device properties. Here we show that the electrical breakdown over the whole device is due to the formation of electro-thermal domains (ETDs), and that the distribution in the IMT temperature as well as the hysteresis in the resistance vs. temperature function (RT) of domains at the nanoscale are significantly influencing the current-voltage characteristic (IV).

The $V_2O_3$ film was grown by rf-sputtering on an r-cut sapphire substrate at a temperature of approximately 750°C. XRD revealed that the polycrystalline film grows textured under these conditions. Optical contact lithography was used for patterning. A 200 µm wide $V_2O_3$ bridge was etched using reactive ion etching and gold electrodes were deposited on top, refer to fig. 1(a) for an SEM image of the device.

The same experimental setup was used for LTSEM imaging and IV characterization. The LTSEM is a conventional, state of the art SEM equipped with a LN$_2$-cryostat. The sample is mounted in vacuum on a cold plate and the
Fig. 1: (Color online) Electrical breakdown. (a) SEM image of the device. The area under investigation is indicated by a red rectangle. A 200 µm wide V$_2$O$_3$ stripe runs vertically indicated by two white dashed lines. The two gold electrodes at the top form a 10 µm wide gap. The current flows between those two electrodes vertically. (b) Temperature dependence of the device resistance (RT). (c)–(f) Current voltage characteristics (IVs) at two different base temperatures. The black arrows indicate the sweep direction. The overall progression of the electrical breakdown is indicated by red dashed arrows. Panels (c) and (e) are IVs of the pristine device after thermal cycling. Panels (d) and (f) are subsequent IVs to (c) and (e), respectively.

To ensure that the V$_2$O$_3$ film was completely in the insulating state, the device temperature was reduced to approximately 80 K and then heated to the intended base temperature before electrical measurements were started. In the following, we refer to this procedure as “thermal cycling”.

Figure 1(c) shows an IV of the pristine device (after thermal cycling) acquired at a base temperature $T_b = 145$ K. Starting at the origin of the graph, the IV shows an almost linear dependence with a slight upwards bent. At a current value of 0.6 mA there is a jump from 10 V to 7 V followed by several small jumps and a big jump to 3.8 V. The curve continues almost vertically with a positive slope and several sawtooth-like discontinuities of different sizes. The down-sweep curve is different from the up-sweep one, i.e., there is a hysteresis. Immediately after the first IV curve, without changing the base temperature, a second IV was acquired (see fig. 1(f)). Note, that the IV of the second sweep is very similar to the first one except that the maximum voltage is significantly reduced. When the device is thermally cycled, the old state (first sweep) is restored. Hence, there is a training effect.

The curve acquired in the first sweep at 155 K (see fig. 1(e)) is different from the one at 145 K. Starting at the origin, the IV is almost linear. After 1 mA and 3.5 V it progresses with a negative slope and saw tooth like discontinuities of different sizes. The down-sweep curve is rounded with some very small discontinuities and the hysteresis is much more pronounced than at 145 K. In the second IV (see fig. 1(f)) the down-sweep is similar to the down-sweep of the first IV, but the up-sweep curve is round and there are only a few small discontinuities. A comparison between the IV of the first and second sweep reveals that the training effect at 155 K leads to a qualitative change of the up-sweep curve. The consecutive IVs do not change significantly after the second sweep at both base temperatures. Moreover, we have observed that the details of the IV depend on the sweep velocity. If the current is swept faster, there are more and smaller jumps, but the overall shape of the IV stays the same.

At $T_b = 145$ K a big jump in the IV followed by a vertical progression indicates an electrical breakdown of the device. The diagonal progression with a negative slope and small jumps in the first IV at $T_b = 155$ K implies that the electrical breakdown now evolves via stable intermediate states. From the hysteresis in the IVs and the training effect, it can be inferred that there is a memory effect in the V$_2$O$_3$ device, i.e., the device properties depend on its history. Similar effects were reported in VO$_2$ devices [13]. The slight influence of the sweep velocity on the IV might be caused by a slowed-down relaxation of a small fraction of the film due to the spread in the IMT temperatures of individual domains [14].

The LTSEM images at a base temperature of 145 K, are discussed below (see fig. 2). In order to relate the images to the IV, the IV of the second sweep in fig. 1 is depicted and the bias points are marked with corresponding letters.
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Fig. 2: (Color online) LTSEM voltage images acquired at different bias currents at a base temperature of 145 K. (a) IV of fig. 1(d). The start points and the end points before and after imaging are indicated by red arrows. (f) Image of the entire device. (b)–(k) Images with a zoomed field of view (indicated by a yellow dashed rectangle in (f)).

Because we have discovered that the imaging process changes somewhat the resistance of the device, the bias points before and after imaging are indicated by red arrows in fig. 2(a).

In the images at bias points below the first big jump (see figs. 2(b)–(e)) a cluster of dots appears in an approximately 10 $\mu$m wide section of the device indicated by a dashed yellow rectangle in fig. 2(f). In the images at bias points above the first jump (see figs. 2(f)–(k)) a bright stripe appears whose width increases with increasing currents.

A series of LTSEM images acquired at a base temperature of 155 K are shown in fig. 3. If the current is increased, submicron-sized dots of different brightness appear. The majority of them are clustered in the same small section of the device, where at $T_b = 145$ K the electrical breakdown occurs. For increasing currents the density of these dots increases and they merge. When an imaging scan is repeated at the same current, the images look more or less the same but additional bright spots appear at different positions.

By estimating the conductance change caused by a local temperature distribution in the device, one can show that $\Delta V$ is proportional to the temperature derivative of the conductivity close to the electron probe $\frac{dg}{dT}$ (supplement section in [15]). Because $\frac{dg}{dT}$ in the insulating phase is several orders of magnitude smaller than in the metallic phase, a large response $\Delta V$ is predominately caused by the metallic domains. The bright submicron-sized spots, which saturate the signal in the LTSEM images, might be due to current redistribution.

In the LTSEM image series at $T_b = 145$ K (see fig. 2), a metallic filament appears (ETDs) like reported in VO$_2$ devices [9,10]. In the $T_b = 155$ K series no filament appears, but the device becomes gradually metallic in a small section of the device when the current is increased.

In order to investigate how the IMT of domains at the nanoscale are influencing the electrical breakdown,
we have developed a numerical model (similar to the one used in [16]), in which we represent domains with different IMT temperatures by a $20 \times 400$ resistor network (supplement section in [15]). We also included thermal coupling between the nearest neighbors of the resistor network and to the heat sink. For each domain the same hysteresis $\Delta T_c$ in the RT dependence was assumed, but for the IMT temperatures $T_c$ a Gaussian distribution was used (see fig. 4(a)). The hysteresis as well as the median and the standard deviation of this Gaussian distribution were obtained by optimizing the simulated RT curve with respect to the measured RT (see fig. 4(b)). Then these values ($\Delta T_c = 8$ K, $T_c = 163$ K and RMSD $\approx 3.16$ K) were used to simulate the IVs as well as the temperature, current and voltage distributions for the base temperatures $T_b = 145$ K (see figs. 4(c)–(e)) and $T_b = 155$ K (see figs. 4(f)–(h)).

The hysteresis and the training effect in the IVs could be reproduced. The simulation at $T_b = 145$ K shows the formation of ETDs (see the stripes with high temperature) like in the LTSEM images (see fig. 2). There are significant differences between the simulation and measurements at $T_b = 155$ K: The simulation clearly shows the formation of ETDs (filaments), while the IV progresses vertically (see figs. 4(f), (g)). In the LTSEM images no filament appears and the IV progresses diagonally (see fig. 3).

**Conclusion:** The hysteresis and the training effect in the IV are the results of the RT hysteresis as well as the distribution of IMT temperatures of nanoscaled domains in the polycrystalline thin film. It is plausible that the RT hysteresis originates from the structural bistability reported earlier [17–19] and the spread in the transition temperatures is most likely caused by differences in the strain in the polycrystalline film [14,20].

The LTSEM images revealed that the electrical breakdown occurs always at the same position in the device. This is possibly the result of a device inhomogeneity like a small variation in the oxygen stoichiometry of the V$_2$O$_3$ film.

At a base temperature of 145 K the overall IV and the ETDs (filaments) depicted in figs. 2(f)–(k) were reproduced in the simulation, clearly indicating an electro-thermal breakdown of the device.

On the contrary, at a base temperature of 155 K the electrical breakdown, with the small metallic domains clustered in a small section of the device and the diagonal progression of the IV (see figs. 1(e) and (f), and fig. 3), is very atypical for an electro-thermal breakdown. Generally, in a system, where the electro-thermal bistability is caused by a large decrease in the device resistance with increasing temperature, the ETD walls are parallel to the current direction, i.e. in the sample under investigation, ETDs always have the shape of a filament. After ETDs have nucleated, the IV progresses vertically, while the hot ETD increases in size [21,22] (supplement section in [15]).

For the electrical breakdown via stable intermediate states at a base temperature of 155 K, which is accompanied by a diagonal progression of the IV with negative slope, we provide three possible explanations. First, it is possible to stabilize an electro-thermal bistable device in intermediate states by using a load resistor, which forces the IV to progress along a diagonal load line during the electro-thermal breakdown [23]. The device under test has
a relatively high contact resistance of approximately 80 Ω. If one assumes that this contact resistance is nonohmic and has a tunneling characteristic, the sawtooth like discontinuities and the diagonal progression of the IV at 155 K can be explained. Second, an intrinsic shunting of small domains above a certain threshold voltage that could be caused by Landau-Zener tunneling [2–5] or other dielectric breakdown mechanisms which might have a similar effect. From the simulated voltage distribution (supplement section in [15]) a threshold voltage for a dielectric breakdown mechanisms which might have a similar effect. From the simulated voltage distribution (supplement section in [15]) a threshold voltage for a dielectric breakdown below 20 kV/cm can be inferred. This value would be very small for a dielectric breakdown. Third, in a theoretical model considering voltage-induced switching two different electrical breakdown mechanisms were predicted —bolt-like and percolative switching [24]. According to these results one might interpret the electrical breakdown at a base temperature of 145 K as bolt-like and at 155 K as percolative switching. In [24] thermal coupling within the thin film and to the heat sink was not considered. When we explicitly included voltage-induced switching in our model, which included thermal coupling, we were never able to observe percolative switching, but we always observed the formation of a filament accompanied by a vertical progression of the IV. Therefore, we consider the first explanation as the most likely scenario.

In this study we have demonstrated that a self-heating–driven change in the resistivity of V₂O₃ in combination with its structural bistability can lead to discontinuities, hysteresis, and training effects in the device current-voltage characteristic. These findings may also apply to devices probing the electrical properties of similar materials like Fe₃O₄ or VO₂.

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REFERENCES

[1] Yang Z., Ko C. and Ramanathan S., Annu. Rev. Mater. Res., 41 (2011) 337.
[2] Oka T., Arita R. and Aoki H., Phys. Rev. Lett., 91 (2003) 066406.
[3] Okamoto S., Phys. Rev. Lett., 101 (2008) 116807.
[4] Eckstein M., Oka T. and Werner P., Phys. Rev. Lett., 105 (2010) 146404.
[5] Heidrich-Meisner F., González I., Al-Hassanieh K. A., Feiguin A. E., Rozenberg M. J. and Dagotto E., Phys. Rev. B, 82 (2010) 205110.
[6] Liu M., Hwang H. Y., Tao H., Strikwerda A. C., Fan K., Keiser G. R., Sternbach A. J., West K. G., Krittivatanakul S., Lu J., Wolf S. A., Omenetto F. G., Zhang X., Nelson K. A. and Averitt R. D., Nature, 487 (2012) 345.
[7] Ruzmetov D., Gopalakrishnan G., Deng J., Narayananurthi V. and Ramanathan S., J. Appl. Phys., 106 (2009) 083702.
[8] Lee S., Fursina A., Mayov J. T., Yavuz C. T., Colvin V. L., Sumesh Sofin R. G., Shivets I. V. and Natelson D., Nat. Mater., 7 (2008) 130.
[9] Berglund C., IEEE Trans. Electron Devices, 16 (1969) 432.
[10] Duchene J., Terraillon M., Pailly P. and Adam G., Appl. Phys. Lett., 19 (1971) 115.
[11] Clej J. R. and Huebener R. P., J. Appl. Phys., 51 (1980) 2764.
[12] Gross R. and Koelle D., Rep. Prog. Phys., 57 (1994) 651.
[13] Kim J., Ko C., Frenzel A., Ramanathan S. and Hoffman J. E., Appl. Phys. Lett., 96 (2010) 213106.
[14] Grygiel C., Pautrat A., Prellier W. and Mercey B., EPL, 84 (2008) 47003.
[15] Guénon S., Scharinger S., Wang S., Ramrez J., Koelle D., Kleiner R. and Schuller I. K., arXiv:1210.6648 (2012).
[16] Sharoni A., Ramírez J. G. and Schuller I. K., Phys. Rev. Lett., 101 (2008) 026404.
[17] Bao W., Broholm C., Aeppli G., Carter S. A., Dai P., Rosenbaum T. F., Honig J. M., Metcalfe P. and Trevino S. F., Phys. Rev. B, 58 (1998) 12727.
[18] Tanaka A., J. Phys. Soc. Jpn., 71 (2002) 1091.
[19] Pfalzer P., Obermeier G., Klemm M., Horn S. and den Boer M.L., Phys. Rev. B, 73 (2006) 144106.
[20] Schuler H., Klemm S., Weissmann G., Renner C. and Horn S., Thin Solid Films, 299 (1997) 119.
[21] Volkov A. and Kogan M., Sov. Phys. Usp., 11 (1969) 881.
[22] Gurevich A. V. and Mints R. G., Rev. Mod. Phys., 59 (1987) 941.
[23] Fisher B., J. Phys. C, 8 (1975) 2072.
[24] Shekhatwata A., Papakokalou S., Zapperi S. and Sethna J. P., Phys. Rev. Lett., 107 (2011) 276401.
[25] Sanderson C., Technical Report NICTA Australia (October 2010).