Joule Heating Effects in Nanoscale Carbon–based Memory Devices

T. A. Bachmann[1*], A. M. Alexeev[1], W. W. Koelmans[2], F. Zipoli[2], A. K. Ott[3], C. Dou[3], A. C. Ferrari[3], V. K. Nagareddy[1], M. F. Craciun[1], V. P. Jonnalagadda[2], A. Curioni[2], A. Sebastian[2], *Senior Member, IEEE*, E. Eleftheriou[2], *Fellow, IEEE*, C. D. Wright[1], *Member, IEEE*

I. Introduction

One of the emerging candidates to bridge the gap between fast but volatile DRAM and non–volatile but slow storage devices is tetrahedral amorphous carbon (ta–C) based memory [1]–[3]. This offers a very good scalability, data retention and sub–5 ns switching [2], [3]. Amorphous carbon memory devices can be electrically and optically switched from a high resistance state (HRS) to a low resistance state (LRS) [4]. The electrical conduction in the LRS is thought to be through sp^2 clusters that form a conductive filament [4].

Joule heating is assumed to be a primary contributor to memory switching in ta–C [4]. Since the conductivity on the nanometer scale varies locally due to randomly distributed sp^3 and sp^2 sites [5], [6], large local differences in current densities and hence in Joule heating can be expected.

A key challenge for carbon–based memory is cycling endurance. Excessive Joule heating could lead to the formation of large spatially–extended conductive filaments that makes reversible switching back to the HRS difficult to achieve. The high temperatures and high current density could also degrade the electrodes as the devices are switched back and forth multiple times.

Here, we investigate Joule heating and temperature distributions within ta–C memory devices. This is essential to gain further insights into the switching mechanism and to address the key challenge of cycling endurance. We account for both field and temperature dependence of electrical conductivity in ta–C. We also consider the local distributions of sp^2 and sp^3 clusters. The simulations are validated with experimental data.

II. Memory Device and Model Implementation

The memory devices consist of Pt (W) bottom (top) electrodes, a SiO_2 layer with a cylindrical opening into which 5 nm ta–C is deposited by filtered cathodic vacuum arc. A load resistor is used to limit the current flowing through the device–under–test (DUT) during the SET (i.e. switching to LRS) process. The load resistors (3–14 kΩ) are fabricated in series next to the device with e–beam lithography. No load resistor is used for reverse switching (RESET). The read out of the current during the programming is done across a 50 Ω resistor using an oscilloscope. The device state is read out using a Source Measurement Unit (SMU). More fabrication details and information on the electrical equipment used for the switching studies can be found in [3]. A schematic of the DUT and the electrical circuit is shown in Fig. 1.

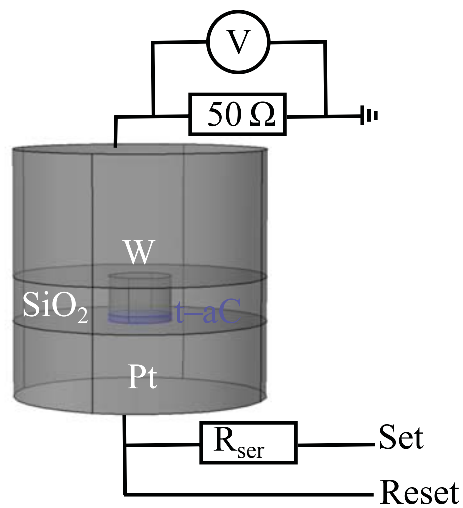

Fig. 1. SET (RESET) pulses are applied to the bottom electrode (Pt). A load resistor limits the current during the SET process.

To reflect local sp^2 variations within our model we use a beta–random distribution to assign locally different sp^2–rich cluster concentration. The threshold for sp^2–like conduction (within each simulation cell) is set above 90% in our simulation.

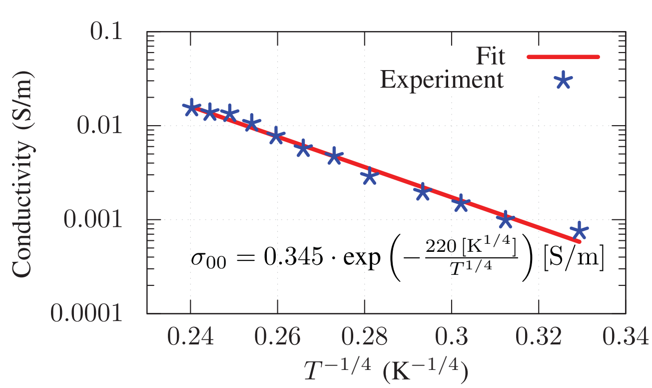

Fig. 2. Conductivity of a carbon memory device measured at low voltages from 85 K to 300 K.

[1]Centre for Graphene Science, CEMPS, University of Exeter, Exeter EX4 4QF, United Kingdom *tb352@exeter.ac.uk
[2]IBM Research – Zurich, Säumerstrasse 4, 8803, Rüschlikon, Switzerland
[3]Cambridge Graphene Centre, University of Cambridge, Cambridge, CB3 0FA, United Kingdom

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To separate the temperature dependence of the conductivity from the field dependency we measure the conductivity of pristine devices (HRS) at low voltages from 85 K to 300 K. This is plotted against $T^{-1/4}$ in Fig. 2. The conductivity can be fitted by a straight line over the whole temperature range which indicates that the electrical transport is mainly governed by hopping in localised states [7].

The field–dependent part of the conductivity is approximated using a hyperbolic sine function. In order to obtain the temperature distribution in the device when a voltage is applied we use a finite element solver (COMSOL®) to solve the coupled heat and Laplace equations. A 14 kΩ resistor is used to limit the current flow through the device.

To validate our simulation and to determine the field–dependent part of the conductivity we compare our results with the experimentally measured conductivity, for voltages high enough (~ 0.1 V) to see an exponential dependence of the conductivity, but for low (~ 1 V) enough currents to avoid Joule heating.

III. Results & Discussion

The simulated field–dependent conductivity curve is compared with experimental data in Fig. 3. The simulation describes the ohmic conductivity as well as the exponential dependence for high electric fields. To investigate the temperature distributions present during memory switching we apply typical switching voltages of 3.5 V [3].

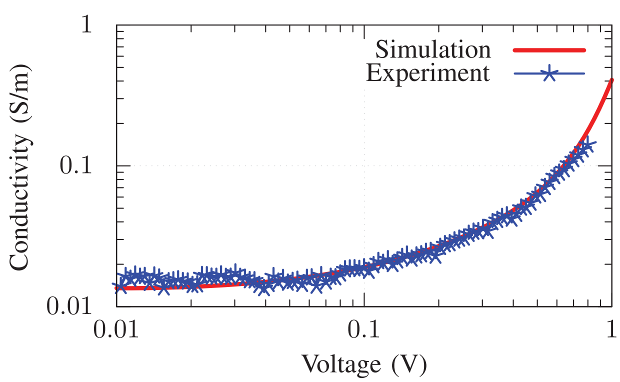

Fig. 3. Measured and simulated conductivity of a carbon memory device as a function of the applied voltage.

The resulting temperature profile within the device is shown in Fig. 4. The voltage across the device is 2.6 V, with 0.9 V dropped across the load resistor. The current flowing through the device is 80 µA.

The highest temperatures are obtained in the mid–plane of the ta–C layer at z = 2.5 nm; this is expected as the metal electrodes act as a heat sink [3]. The observed high temperatures of up to 1771 K are in agreement with molecular dynamic simulations [3]. The observed high temperatures are also in agreement with reports of local meltdown of electrode material without the presence of a current limiting load resistor [2].

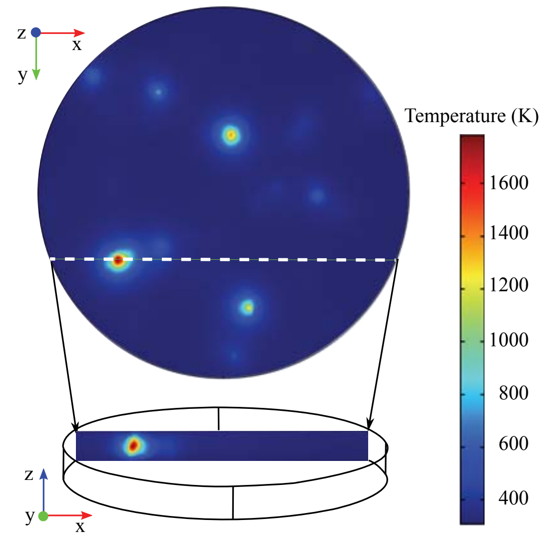

Fig. 4. The temperature distribution (top) in the mid–plane of the ta–C layer (z = 2.5 nm) and (bottom) in the cross–section indicated by the dotted line; applied voltage is 3.5 V.

IV. Conclusions

Joule heating plays a key role in the operation of carbon based memory devices.

We developed a model that describes the field and temperature dependence of electrical conductivity in ta–C based memory devices. This model was used to obtain the temperature distribution within these devices just prior to memory switching.

Despite low overall currents prior to memory switching, high electric fields between sp^2–like conductive clusters, along with the field and temperature dependent conductivity of the sp^3–bonded regions, can lead to very localised Joule heating which in turn creates a form of thermal runaway and locally very high temperatures.

This highlights the role of precise current control to improve the cycling endurance of these devices.

Acknowledgement

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References

[1] C. A. Santini *et. al.*, "Oxygenated amorphous carbon for resistive memory applications", Nature Communications, vol. 6, Oct. 2015.

[2] F. Kreupl *et. al.*, "Carbon-based resistive memory", 2008 IEEE International Electron Devices Meeting, pp. 1–4, Dec. 2008

[3] W. W. Koelmans *et. al.*, "Carbon–based resistive memories", in 2016 IEEE International Memory Workshop (IMW).

[4] A. Sebastian *et. al.*, "Resistance switching at the nanometre scale in amorphous carbon", New Journal of Physics, vol. 13, no. 1, p.013020, Jan. 2011.

[5] A. C. Ferrari *et. al.*, "Stress reduction and bond stability during thermal annealing of tetrahedral amorphous carbon", Journal of Applied Physics, vol. 85, no. 10, p. 7191, 1999.

[6] K. Takai *et. al.*, "Structure and electronic properties of a nongraphitic disordered carbon system and its heat-treatment effects", Physical Review B, vol. 67, no. 21, pp. 214202–11, Jun. 2003.

[7] C. Godet, "Analytical derivation of the effective temperature for field-dependent hopping conductivity", Philosophical Magazine Letters, vol. 83, no. 11, pp. 691–698, Nov. 2003.