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Mapping electric fields in real nanodevices by operando electron holography

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Background

The development of nanometer-scaled electronic devices with reduced dimensions, involving new materials or new architectures such as Magnetic Random Access Memories (MRAM), memristors or Phase Change Memories (PCM)1, requires a deeper understanding of their operating properties. While electrical and physical characterizations are widely used to monitor and evaluate both the device performance and the quality of the layer stack, there is a lack of knowledge on how the electromagnetic fields are precisely mediated along devices at the nanoscale level. Correlating electric fields mapped at the nanoscale across a chosen device with its structural properties and chemical composition would give new insights on the local electrical properties such as resistivity, polarisation, and charge traps.

Off-axis Electron Holography (EH) is an interferometric technique that allows quantitative mapping of electrical potentials inside and around the specimen, as well as the measurement of charge distributions2. However, operando EH has been rarely used, in particular on real devices3,4, because of key issues such as specimen preparation, surface damage layers, stray field and electron radiation.

We will present the methodology that we have been developing for mapping the electrical properties of nano-electronic devices extracted directly from production lines without using a probe-based approach. Taking the example of phase change memory cell, we will show how electron holography can be used to measure in situ the resistivity distribution within the active layer after changing its state.

Methods

Phase-change materials exhibit a huge change of electrical resistivity between the amorphous (high resistance) and crystalline phase (low resistance). The electrical resistivity encodes the state of the bit, denoted SET for the crystalline state (low resistance) and RESET for the amorphous state (high resistance). To read the device, the resistance is measured by biasing the top and bottom electrode connected to a thin metallic filament called the “heater”. To write, a high-amplitude current pulse is injected, whose exact form depends on whether the operation is to stabilize the crystalline phase (SET) or the amorphous state (RESET). Current passing through the heater and GST layer causes localised Joule heating; the associated rise in temperature in turn causes the phase change. To SET, a relatively long pulse allows gradual crystallisation of the amorphous state whilst for RESET, a short pulse induces rapid melt-quench of the crystalline to amorphous state.

In situ biasing TEM experiments necessitate a specific and complex sample preparation that minimizes preparation artifacts whilst ensuring the electrical functionality of the nanodevice itself. The specimen-device was extracted from production lines before being thinned by focused ion-beam (FIB) and contacted to a chip with predefined electrical contacts, similarly to our previous work on electrostatic fields.5 An important part of the preparation was to preserve the encapsulation layer of insulating material all around the heater and GST layer. Special care was also taken to avoid any electrical discharges which would destroy the device. Holograms were recorded during long exposure time using dynamical automation for compensating instabilities under bias, and while measuring the total current. Experimental phase images were then compared to additional numerical simulations using finite element modelling (FEM) including factors such as specimen geometry, stray fields and local resistivity.

Results
The GST layer within the device is initially crystalline (Initial state) and holograms were first recorded under a DC bias as if the memory was to be read. The layer was then switched to an amorphous state (Final state) by sending a sequence of pulses. Remarkably, the thin lamella survived the injection of peak currents of several hundreds of µA during the pulse. The overall resistance, measured under a biasing of 0.5 V during the holography experiments, changed radically between the initial and final states, increasing 5-fold after switching.
The corresponding phase images in initial and final states are presented in Figure b and e, respectively. We can clearly see the difference of the potential distribution between both states, with a dome-like shape in spanning the GST layer in the final state after amorphisation. The electrical information, in the form of isophase contours, has also been superimposed onto the conventional TEM images (Figure a and d) to help visualise the region involved. We can see, notably, that the phase contours seem to radiate outwards from the tip of the heater into the GST layer.

We obtained a very good agreement between experimental and simulated phase images using finite element modeling (Figure b and Figure e). This agreement gives access to the distribution of the electric potential within the device, and therefore to the local resistivity with the Ohm's law. From the reasonable assumption that the conductivity is radially symmetric around the heater tip and using the experimentally measured total current flowing through the device in situ, we determined the local map of the conductivity. A small seed of highly resistive material around the heater tip was revealed in the initial crystalline state and for the final state, the crystalline to amorphous transformation occurred at a certain radius, about 10 nm, from the heater tip.

Figure. Conventional bright-field TEM image, Initial state (a), Final state (d) with isophase contours (values on the right) extracted from experimental phase maps, Initial (b), Final (e). Simulated phase maps, Initial (c), Final (f). In dotted line the dome-like shape where the phase change occurs. Scale bars are 20 nm.

Conclusion
We developed a new methodology to map the local resistivity across the active area of an individual device in operation. This method, based on operando electron holography, has been applied on a PCM cell and directly highlights unexpected features. On switching the device by electrical pulses, we demonstrated that electrical resistance is inhomogeneous near the heater. This study shows the power of our methodology for studying the local electrical properties of active devices and can be applied in a general way.

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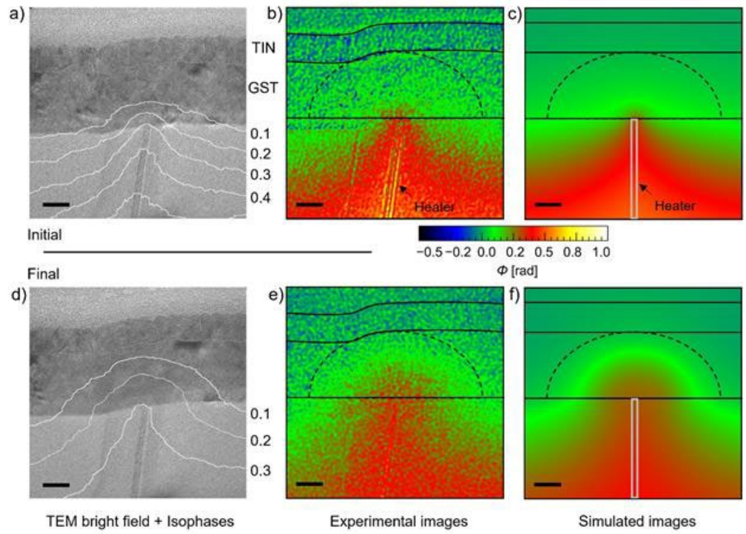
Graphic:



Keywords:

Phase change materials, in situ

Reference:

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