Researchers based at University College London, UK, are paving the way to a new kind of silicon oxide memory technology with outstanding capabilities.

**A fairly heated debate exists within the academic community over what is or isn’t a memristor, and there isn’t yet a consensus over whether resistive switching materials and RRAM devices are memristors.**

Nonlinear circuit theory pioneer Professor Leon Chua recently published a paper entitled ‘Resistance switching memories are memristors’, which sets out his position. However, one of the defining properties of a memristor is that it is passive, i.e. it cannot dissipate energy and does not generate voltages or currents.

Recent work by Rainer Waser, a leading expert on resistive switching, has demonstrated that there is a very small internal voltage generated in what are known as redox-based resistive switches; the group of devices that our silicon oxide (SiOx) switches belong to. This means that they are active devices, and cannot be described as memristors unless we change the definition to make it more flexible. Partly because of this, we now refer to our devices as resistive switches.

In 2010, the International Technology Roadmap for Semiconductors (ITRS) predicted that the evolution of memory technologies would begin to slow by 2013, when current architectures would reach their fundamental limits. An example of this is Flash, one of the most dominant memory technologies of the past few decades, whose memory cells have now been reduced to sizes around 10 nm. Were they to undergo further shrinkage, writing errors and difficulties with power dissipation would emerge. The industry is now looking to new leading-edge technologies to allow the continuation of growth at the rate to which consumers have become accustomed.

One of those technologies is resistive random-access memory (RRAM).

**NOVEL PROPOSITION**

RRAM has the potential to create more adaptable devices that could, in the long
Why have you chosen to focus your studies on resistive switches and memristive behaviour in silicon-rich oxides?

Firstly, any device based solely on silicon and SiOx has an immediate advantage over one using more exotic materials: ease of integration with existing silicon complementary metal-oxide-semiconductor (CMOS) microelectronics. Using a silicon-based resistive switching material allows us to exploit the considerable fabrication and processing experience that the CMOS industry has.

Secondly, semiconductor memory technology is rapidly reaching a bottleneck; increasing speed, lowering power dissipation and scaling to ever-smaller dimensions are each becoming increasingly difficult using conventional approaches. The semiconductor industry has a technology roadmap that predicts the need for new memory technologies three to five years from now.

On what is your hypothesis based that nanoinclusions nucleate preferentially at internal grain boundaries in nanostructured films?

We know from structural studies that we grow has a columnar structure with boundaries between neighbouring nanometre-diameter columns. They are not really grain boundaries because the oxide is amorphous rather than crystalline, but it is easy to picture them as something conceptually similar. We know from our scanning tunnelling microscopy results that the column boundaries are where we see the highest conductivity. We also know that it is a general principle in materials science that defects will tend to cluster around such features.

Could you elucidate how the different operational modes of RRAM devices allow dynamic adjustment of device properties, including nonlinearity and self-rectification?

RRAM devices can be switched in one of two different modes: unipolar or bipolar. The first means that the transition from high to low resistance (the set process) and the transition from low to high resistance (the reset process) both occur for the same polarity of applied voltage.

In the bipolar case, they occur in opposite polarities. In SiOx, we can choose which of these to use. This is unusual – most resistive switching materials are one or the other. In the unipolar case, we are able to gradually change the resistance of the conductive filaments depending on the strength of the applied field, and the time for which it has been applied. Consequently, we can change the linearity of the device, ie. how linear the current versus voltage graph is. This has important ramifications for device applications, as the higher the nonlinearity, the better we are able to distinguish between high and low resistance states in the case of crossbar array structures.

Are you able to provide some insight into your future research plans?

We are currently waiting for delivery of a set of RRAM memory arrays that are being fabricated in Sematech’s state-of-the-art CMOS facilities in the US. These will be a huge step forward as they will essentially be demonstrator RRAM chips allowing us to look at issues such as device yield, reproducibility and stability.

In parallel, we are investigating the underlying physics of the switching phenomenon in SiOx, modelling the formation of filaments, working on structural studies of filament formation and destruction, investigating different device geometries, looking at neuromorphic applications of RRAM, and investigating transparent RRAM and the photonic applications of these devices.

MEMRISTIC MECHANISMS

Two researchers making great strides in this field are Drs Tony Kenyon and Adnan Mehonic from University College London (UCL) in the UK. Kenyon’s work with silicon resistive switching has led to a number of national and international collaborations with French, Spanish, German and Singaporean scientists. As research in this area is inherently connected to industry, Kenyon’s close ties to semiconductor firms are highly beneficial to the commercialisation of their work. Together, the researchers are evaluating the market viability of these next-generation technologies.

Silicon-based resistive random-access memory technology has the potential to become the backbone for the next generation of computer memory

IF YOU CAN’T BEAT THEM...

Through extensive research, Kenyon and Mehonic have been able to utilise silicon in their development of RRAM. They found that silicon-rich silicon oxide (SiOx) could indeed exhibit resistive switching and thus be used in RRAM devices. Furthermore, silicon is an extremely abundant material that is hugely important for commercial applications. A counter example of this is the mobile phone industry’s use of indium tin oxide in smartphone touchscreens – indium is a rare element that is likely to soon be exhausted, which has already led to a desperate search for alternative materials. Both these factors highlight that the potential implications of silicon-based RRAM technologies are huge: an adaptable, low power, high speed next-
RESISTIVE SWITCHES (RRAM) AND MEMRISTIVE BEHAVIOUR IN SILICON-RICH SILICON OXIDES

OBJECTIVES
To overcome existing memory problems using silicon oxide resistive random-access memory; a faster, lower power and higher density alternative to such technologies as flash.

TEAM MEMBERS
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DR TONY KENYON completed a DPhil in Chemical Physics at the University of Sussex in 1992 before joining the Department of Electronic and Electrical Engineering of UCL, where he currently holds the position of Reader. He is also the Department’s Postgraduate Tutor, overseeing and coordinating PhD programmes; a Fellow of the Institute of Physics; Senior Member of the IEEE; a Member of the Institution of Engineering and Technology; and serves on the Board of Delegates of the European Materials Research Society.

DR ADNAN MEHONIC completed a degree in Electrical and Electronic Engineering at the University of Sarajevo, Bosnia, in 2009 and was awarded the best student in the generation prize by the University. He then undertook a Master’s in Nanotechnology at UCL, UK, in 2010, with a further award from Oxford Instruments for the best MSc project prize that year. He recently defended his PhD thesis, which was also conducted at UCL, under Kenyon’s tutelage.

arrays of rram devices of varying sizes on a silicon wafer

As a result of this research, a potential new memory technology has moved from a developing possibility, hindered by issues around implementation, to a feasible commercial silicon system. The semiconductor industry has been reliant on the increased downscaling of existing architectures for improved performance for many years, and as these technologies begin to reach their theoretical and practical limits it becomes ever more vital for academia to supply and develop further possibilities.

The links that Kenyon, Mehonic and colleagues are maintaining with semiconductor firms are crucial; there is a well-known struggle within academia to effectively exploit potential innovations by cultivating ties with industry. If the work carried out by these researchers continues to progress at the current rate, silicon-based RRAM technology has the potential to become the backbone for the next generation of computer memory.