Opening Remarks — Some Scientific Issues

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1. Introduction

It is a very great pleasure for those of us based in Cambridge to welcome E*PCOS to this city and this university. The field of phase-change media and optical storage is very active: strong technologies are established and significant advances are certainly in prospect. There are many connections between Cambridge and this field, but easily the most distinguished is that provided by Sir Nevill Mott (co-recipient of the 1977 Nobel prize for physics). Sir Nevill, based at the Cavendish Laboratory, was an associate of the father of our field, Stanford Ovshinsky, and in the late 1960s turned his attention to threshold switching in thin-film chalcogenide glass. This topic formed part of Sir Nevill's Nobel lecture "Electrons in Glass" (see below), and formed part of the body of work which led to what he was pleased to call "the first Nobel prize to be awarded wholly for work on amorphous materials" [1]. Although optical storage is still a technology making great progress, attention does turn increasingly to phase-change random-access memory (PC-RAM); in this context, threshold switching is a topic deserving renewed attention.

There are many technologies competing to provide an ideal, "universal", memory which would be non-volatile and would have short erase, write and access times, low power consumption, high areal density and good durability. Presentations at this and previous E*PCOS meetings show that, among the competitors, chalcogenide PC-RAM may not excel in any category but still has an excellent all-round performance. This presentation focuses on some of the fundamental issues raised by the development of PC-RAM, especially when it is pushed to the limits of short erase and write times and high areal density. The technologies considered include those based on memory cells addressed by lithographically patterned metallization (e.g. Ovonic Unified Memory, OUM) and those based on blanket films addressed by scanning probes (as in the IBM "millipede" [2]). There are many open questions, suggesting that the technological developments will provide a basis for much fundamental scientific work in the near future.

2. Some Issues

2.1. What is the nature of the phase change?

In optical storage, it is clear that the change in state of the chalcogenide thin film can be interpreted as a thermal effect: local heating due to a laser pulse can cause local melting followed by rapid quenching to form the amorphous phase, or can permit the amorphous phase to crystallize. In PC-RAM, when a change in state can be induced by the passage through the chalcogenide of an electric current, there are possibilities other than thermal. To introduce this topic, we can do no better than to cite Sir Nevill Mott's Nobel lecture [1]:

> "Now I would like to finish the scientific part of this lecture by mentioning …
> … the threshold switch invented by S. R. Ovshinsky[38]. This in its simplest form consists of a deposited film of a chalcogenide glass about one micron thick, with a molybdenum or carbon electrode on each side. Such a system switches into a highly conducting state as the potential across it is increased, switching off again when the current through it drops below a certain value (fig. 8).

The claims made for this device generated a considerable amount of controversy, it being suggested that a thermal instability was involved and that similar phenomena had been observed many years ago. I do not think this is so, and proposed[39] in 1969, soon after the phenomenon was brought to my notice, that the phenomenon is an example of double injection, holes coming in at one electrode and electrons at the other. This is still my opinion."

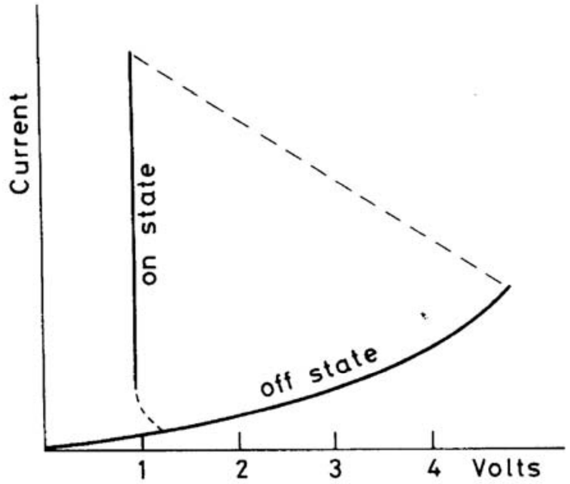

Fig. 8. Current voltage curve of a threshold switch, consisting of a thin chalcogenide film between two electrodes.

— from Sir Nevill Mott's Nobel lecture [1].

38. Ovshinsky, S. R., Phys. Rev. Lett., 21, 1450 (1968).
39. Mott, N. F., Contemporary Physics, 10, 125 (1969)]

The mechanism by which threshold switching occurs continues to be debated [3–7]. In addition to fully thermal and electronic models for the phenomenon, it is now recognised that both thermal and electronic effects may be involved [8]. It has also been noted that the switching may occur along narrow "filaments", rather than reflecting a uniform change [4]. It is somewhat alarming that the basic nature of threshold switching continues to be disputed, but it must be recognised that observed switching phenomena may present a variety of mechanisms, depending on such factors as film thickness [6]. In PC-RAM and similar devices, work remains to be done on the extent to which the non-volatile memory states based on the full amorphous-crystalline phase change can alternatively be based on changes within the amorphous phase related to electronic threshold switching.

2.2. How can the phase change be modelled?

Even if we restrict our attention to the full amorphous-crystalline phase change, there are significant questions about how to model the phase transformations. Clearly understanding and control of melting and crystallization are essential for the optimization of PC-RAM performance. Much work has been done on the kinetics of crystallization in the chalcogenide alloys used for optical data storage (e.g. [9]). This has been extended to work on PC-RAM cells [10]. It has been noted that classical analyses of transformation kinetics start to fail for transformations in volumes so small that they are finer than the scale of the grains in the crystallized structure [11]. A further complication is that the phase change may occur non-uniformly within a memory cell [12, 13].

2.3. What is the smallest possible phase-change mark?

There is no doubt that the superparamagnetic limit is a fast-approaching barrier to higher areal density in magnetic data-storage technologies, and that potentially high areal densities are one of the most attractive features of PC-RAM. Smaller marks would bring benefits not only in higher areal density, but also in reduced power consumption [14]. There are many aspects to the question on what sets the limit to miniaturization of marks in phase-change media. What are the finest memory-cell structures which can be fabricated? What are the finest cells which can be read without the reading disturbing the state of the cell [7]? In scanning-probe technologies, what is the smallest volume which can be transformed [15], addressed and read? And finally there is the very interesting question of what is the smallest transformed volume that would be stable [16]? This may be related to how fast the imposed phase changes can be: a more readily crystallized material is also one in which amorphous marks are less stable.

2.4. Design of PC-RAM memory cell

An individual PC-RAM memory cell cannot be based on the phase-change volume alone. Current designs have transistor and a resistor associated with each cell (e.g. [17]), but other designs have been shown to be viable [18]. The phase-change volume is normally contacted top and bottom, but the relatively large cross-section of such cells leads to high power consumption [19]. It is therefore of interest to try geometries in which the current is lateral rather than vertical [20, 21]. And work continues on optimizing the phase-change medium itself, for example exploiting nitrogen doping of GST to reduce the reset writing current [22]. Evolution of design and compositions will throw up new scientific issues, particularly in connection with endurance, analogous to the recurring reliability problems with continuing miniaturization of conventional microelectronic devices.

2.5. Endurance

Existing PC-RAM technology shows survival after 10^{13} cycles, a much greater endurance than is found for optical-storage media. This highlights how much reliability can be affected by device design, mode of operation and absolute length scales. The excellent endurance seen so far in relatively large memory cells will not necessarily be maintained as PC-RAM designs and materials evolve. In memory cells, electromigration and thermomigration effects have yet to be analysed. In other devices these can pose serious challenges. There are yet other reliability issues in scanning-probe technologies, associated with the stability of the film surface addressed by the probe.

3. Conclusion

As PC-RAM continues to evolve into a highly competitive technology, the conditions under which the phase change takes place will continue to become ever more extreme: smaller volume, higher fields, faster heating and cooling. These conditions are far removed from those usual in studies of amorphous-crystalline phase changes, suggesting that ever greater caution will need to be taken in applying classical analyses. This prospect of finding some new physics is exactly why scientists will find much of interest coming out of the advancing technology of phase-change chalcogenides, just as did Sir Nevill Mott.

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