315 CU

OVONIC PHASE CHANGE MEMORY MAKING POSSIBLE NEW OPTICAL AND ELECTRICAL DEVICES

Stanford R. Ovshinsky

Energy Conversion Devices, Inc.
1675 W. Maple Road, Troy, MI 48084, USA

Phone: (248) 280-1900, Fax: (248) 280-2697, Email: ovonic@aol.com

Thank you for the honor of inviting me to present a paper at this meeting on phase change memories, a subject which is so dear to my heart. It offers me the opportunity to thank you in the audience whom I look upon as colleagues and collaborators for the important and creative role that you have played in making my invention (1-3) into such an important information area. This has led to the building of the whole new field of optical phase change memory that is the basis for the much heralded rewriteable DVD industry. All of this would not have taken place without the vision, insight and entrepreneurial skills of the Japanese companies who depend upon your talented contributions.

I particularly would like to thank the engineers and scientists at Matsushita for the pioneering role that they have played. I wish that my great friend Dr. Hayakawa as well as Dr. Suemitsu were in the audience today. I am very happy that Dr. Ohta is continuing in this tradition. I thank all of you, our other licensees in this field, for your many contributions.

I have not come here, as we say, to teach birds how to sing. You have shown great skill in tuning the layer structures to optimize the thermal environment; have done very important work in increasing the quality of the shape of the recorded spot which has improved the reproducibility of the recording process and therefore the spot size and jitter; have continued the improvements in the servocontrols, the optics, and, of course, will be utilizing shorter wave length lasers as they become available, all of which increases the storage capacity.

In this talk I wish to show where the opportunities for major advances lie. I will therefore first discuss the materials science that will permit great increases of information density, speed and lifetime, for it is in the materials that the answers are to be found.

Phase change memories are based on thin-film alloys typically incorporating one or more elements from Column VI of the Periodic Table. These chalcogenide materials have been designed to exist in two or more distinct atomic structural states. An energy barrier separates the structural states thereby providing the temporal stability required by any memory device.

The energy necessary to allow the memory materials to change their atomic configuration can be supplied in various ways, including exposure to a laser beam or application of a current pulse. Laser exposure is used for recording, erasing, and rewriting in the case of the optical memory. If the laser energy applied exceeds a threshold value, the memory material will be excited to a state of high atomic mobility. It becomes possible for the chemical bonding to rapidly rearrange by slight movement of the individual atoms, especially in phase-congruent materials.

In lone-pair materials (alloys containing chalcogen atoms such as selenium, tellurium, or sulfur) the Group VI atoms use two of their p electrons to be divalently bonded, and the atomic rearrangement that takes place during the phase change process may occur by simply shifting the other two non-bonding or weakly bonding "lone-pair" p electrons to make new connections. The flexibility allowed by divalency and the utilization of excited lone pairs to affect both conformational and configurational changes in materials, as we have explained, are of critical importance in the phase change mechanism. This permits structural changes such as altering the shape of molecules due to the strong repulsive forces that lone pairs exert. Lone-pair electrons provide a spectrum of interactions which include non-bonding and various bonding configurations including the dative bond (4).

Tellurium-based materials can be made with fewer and weaker crosslinks and therefore be susceptible to rapid crystallization/amorphization.[1] Selenium-based materials with their stronger bonds, for example, to arsenic, can be made to resist crystallization/amorphization and reversible elastomeric and rheological changes can be designed in. What is important to note is that we are utilizing atomic engineering to provide a very large number of lone pairs that can be coupled to light or an electric field. The creation of a high density of electron-hole pairs either by electric field or photon absorption is the means by which one can provide an electronic mechanism rather than a thermal one. There is no doubt that the amount of laser light absorbed by the medium causes significant heating. However, one can minimize the thermal effects and emphasize the electronic through the materials science that we have described.

We have already shown through our work in Ovonic electrical memories that the performance of the chalcogenide alloy memory materials goes far beyond what has been accomplished in optical memories. For example, optical memories typically have a cycle life of about 10^6 and they use a record pulse width on the order of 50 or 60 nanoseconds. As we will show here, we have demonstrated that the similar phase change memory materials used in electrical memory devices have a lifetime of over 10^{13} cycles (where we discontinued testing)[2], and can be recorded with pulse widths of less than three nanoseconds. These performance parameters are at the limit of our present test equipment and do not reach the limits of the materials. We think these numbers prove that the cycle lifetime of these materials is essentially unlimited and that the theoretical expectations of the time for structural change to take place can be realized in the proper device configuration. This means that the optical memory lifetime is limited by the substrate material and not by the chalcogenide media. For example, while I am not suggesting it, I am sure that changing to a glass substrate would greatly increase the lifetime of the optical memory. Shifting the emphasis from the more energetic thermal mode to the faster, electronically-driven mode will be beneficial in every way.

Selection of an appropriate composition for the memory alloys and the creation of a high mobility state during laser exposure are the underlying principles in direct-overwrite phase change erasable optical recording media. The coming generations of optical memory disks will have a huge increase in information density by storing many different states of information in one spot, no matter how small the spot.

We have been able to make unique electrical memory devices that we call Ovonic Universal Memories (OUM). By utilizing similar materials and by optical means such as a laser,

---

[1] When phase change is not desired in these tellurium-based materials, one adds more and strongly bonded crosslinks, e.g., instead of germanium only as in the memory materials, one uses silicon, and instead of antimony, one uses arsenic. In this manner, electronic excitation does not lead to phase change but to an Ovonic threshold switch.

[2] We have every reason to believe that the cycle life is as good as any conventional semiconductor device.

we can make a new family of optical phase change memories that have either two states or are multilevel in their ability to be recorded, read, erased and rewritten.

Let us look at some of the electrical memory features first to get a better understanding of its operation and its possibilities. In Fig. 1 we show an OUM test device in which we have electrically programmed 16 different states. Fig. 2 shows a device with a cycle life of over 10^{13} and Fig. 3 shows programming down to 3 nanoseconds.

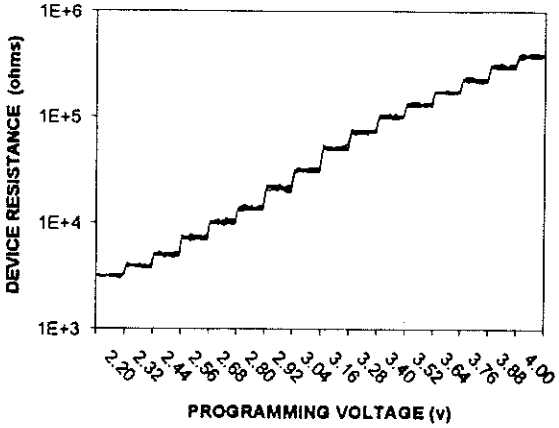

Fig. 1.Multiple-Bit Storage in One Memory Cell (Ten steps per voltage increment repeated ten times).

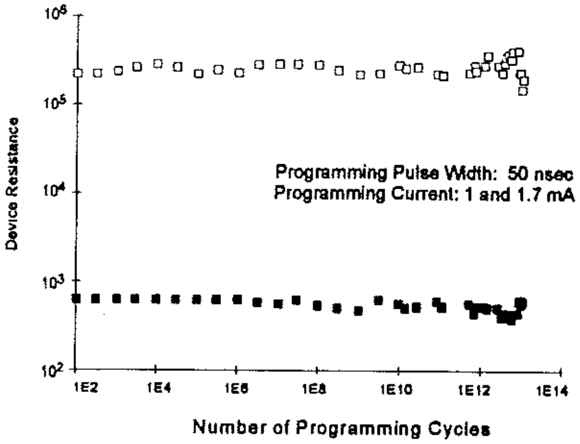

Fig. 2. Device resistance of a test cell subjected to alternating SET and RESET pulses as a function of number of pulses.

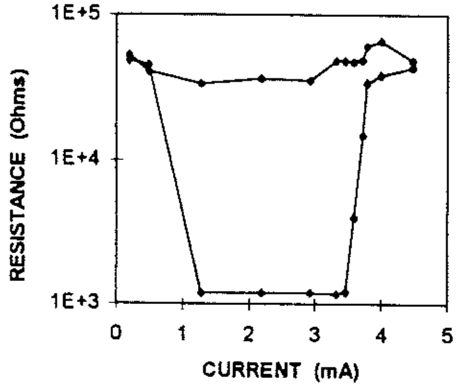

Fig. 3. Programmed resistance vs. current for very short programming pulses.

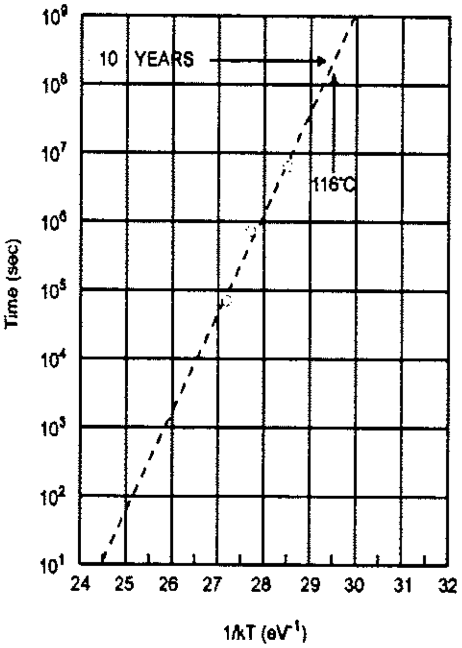

Fig. 4. Arrhenius Plot of the Crystallization Time of a Memory Alloy Film.

■Current Advantages

- non-volatile information storage (unique and proprietary)
- high speed --- nanosecond programming
- long cycle life > 10^{13}
- scaleable with improved lithography
- low voltage operation < 2 volts
- areal density > silicon devices
- simple structure --- two terminal device
- multi-state --- capable of storing multiple bits per cell
- compatible with conventional silicon processing

■Next Generations

- Adaptive memory/interconnect
- 3 - Dimensional -- multilayer
- Integrated logic (OTS and OUM) and memory (OMS)
- all thin-film computers
- Optical interface circuits and computation
- Artificial Intelligence

Fig. 5.

To investigate long term data retention in these memory devices, the thermal stability of programmed information has been investigated by measuring the crystallization time of the memory alloy materials as a function of temperature. These data are shown in Fig. 4 as an Arrhenius plot. Extrapolations indicate that a data storage time greater than ten years can be expected at a temperature of 116° C.

It is apparent from the data that advances in rapidly crystallizing phase-change memory materials and new thin-film device designs have permitted the development of a new type of high-performance, non-volatile semiconductor memory. The combination of rapid programming speed, extremely long cycle-life, simple fabrication process, small device footprint, and the ability to store multiple bits of data per memory cell demonstrated by these devices is unique among non-volatile memory technologies. (See Fig. 5). We call these devices universal because one single plane of our memory can replace DRAM, SRAM and FLASH memory. At the same time it can be used flexibly, for example, as a programmable and rewriteable imbedded memory. Fig. 6 compares our proprietary OUM multistate memory with Intel's multilevel FLASH memory which they announced as the "Holy Grail" which will have a "revolutionary" impact on the FLASH market.

Property	Intel Strataflash	Ovonic Multistate Memory
Density (bits)	2 bit (4 levels)	>4 bit (16 levels)
Write Cycles	10,000	$>10^{13}$ (no limitation)
Write Voltage	5V (with large 12V Charge pump)	<4V
Write Time	10 microseconds times n iterations	0.6 microseconds times n iterations
Erase Time	1 second per block	No erase required
Minimum Erasure Block	must erase 128 Kbytes Before writing	direct overwrite byte-by-byte
Read Access Time	~20 microseconds	~1.0 microseconds

Fig. 6. Comparison between Intel and Ovonic multistate memory

Utilizing the principles for optical memories that we have described for electrical memories will allow us to have multilevel (multistate) memories that can be read by measurements of the intermediate reflectivity levels. It has been shown that complicated analog signals can be successfully decoded into the digital data stream. The number of levels that can be stored will depend on the accuracy of attaining the intermediate reflectivity levels in the material and the accuracy of the drive system in reading the levels back. Proper electronic control mechanisms can assure this.

Electronic transformation of the materials will allow very accurate and predictable intermediate structural changes. Intermediate reflectivities will most likely be provided by continuous changes in the short and mid range atomic order, but other changes, like mixed partial volume fractions of amorphous and crystalline phases on a very small size scale, or crystal orientations, or even layering of the phases within the material, can be designed into the system.

Edge sharpness capabilities of phase change optical memory material are on an atomic scale. The limitation of achieving this resolution in the present devices and systems is governed by heating and heat transfer within the media. Of course, the transition from Pulse Position Modulation to Pulse Width Modulation is being made, but the capabilities of the materials are not being challenged in the current work. Rather, the limitation is the thermal structure. The transition to an electronically governed system from the current thermally governed system will open new regimes of recorded spot accuracy, and the concomitant increases in capacity and transfer rate.

It is interesting to note that there have been only two types of commercial electronic data recording processes prior to phase change. The first was the physical deformation of the surface started by Edison to make his wax drum recordings. These principles are still used in CD-ROM media. The second was magnetic recordings which, from their humble beginnings, have progressed to magneto-optic and magnetic hard drives. The third generation is phase change—the great adventure that we all have embarked on and, as I have tried to show, whose potential for advancement in materials, configuration and, in fact, low cost production technology is exciting.

To put all this in perspective, in this talk I have described ways that phase change optical memory storage can not only go down to smaller spot sizes by virtue of a photonic source which can include electron beams so that one can realistically speak of 100 angstrom spots if one desires, but of greater importance, one can have multi-sites so that there can be many states of information in one spot which can lead to many new kinds of devices including my favorite, the adaptive memory that can be used for much more real intelligence than present artificial intelligence attempts.

In any case, there is a world to win for all of us in the information field. Good luck.

Acknowledgements

It is with great appreciation that I thank David Strand and his Optical Memory Group who have been so important in this project; Wally Czubatyj, head of the Microelectronics Group in collaboration with Pat Klersy, Sergey Kostylev, and Boil Pashmakov for their important work on the electrical memory; Ben Chao and the ECD analytical laboratory; Steve Hudgens for his collaborative input; Iris Ovshinsky, the other half of our lone pair.

References

1. S. R. Ovshinsky, Storing and Retrieving Information, U.S. Patent # 3,530,441.

2. S. R. Ovshinsky, The Ovshinsky Switch, Proc. Fifth Ann. Natl. Conf. on Industrial Research, Chicago, Illinois, Sept. 1969.

3. S. R. Ovshinsky, Historique du Changement de Phase, Memoires Optiques & Systemes, No. 127, Sept. 1994.

4. Numerous papers in D. Adler, B. Schwartz, and M. Silver, eds, Disordered Materials, Science and Technology, Selected Papers by Stanford R. Ovshinsky, (Plenum Press, New York, 1991).