# Phase Change Electronic Memories: Towards Cognitive Computing

## 1. *Introduction*

Information and energy are the twin pillars of our global society. We view information to be encoded energy and amorphous and disordered materials the media for expressing new rich and deep physics so that one can atomically engineer many new synthetic materials. Most importantly, in these materials one can develop new electronic, chemical, and physical mechanisms that open an exciting area for expansion for the semiconducting and computer fields.

The basic difference between amorphous and disordered materials and crystalline materials is that disorder offers many new degrees of freedom for atomic design of materials while crystalline materials have the tyranny of the lattice to contend with. Crystalline silicon, the overwhelming choice for information devices, depends of course upon periodicity which cannot be disturbed except for the addition of parts per million acceptor or donor dopants which are fitted into its rigid tetrahedral structure.

## 2. *Phase Change Memories*

We have chosen instead the chalcogenides, group VI elements such as selenium and tellurium which are isomorphous with each other, as the basis of unique new materials and mechanisms so as to develop divalent polymeric chain structures. For example, we utilize two of tellurium's and/or selenium's bonding orbitals to provide structure leaving the lone pair (Kastner 1972) nonbonded or weakly bonded orbitals available to couple to an electric or optical field. Depending upon the elements used for cross-linking,

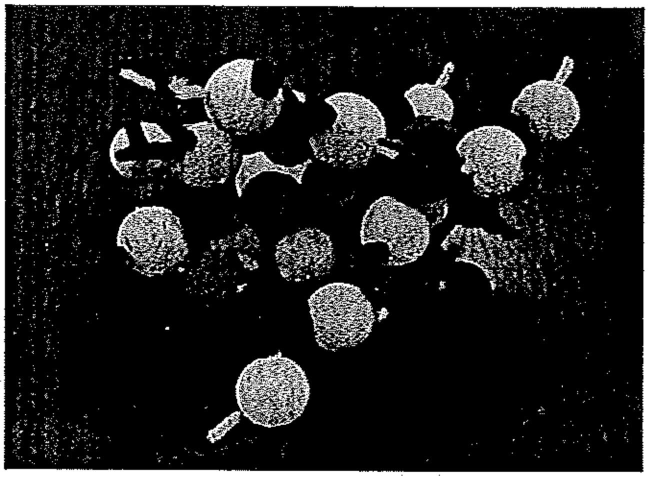
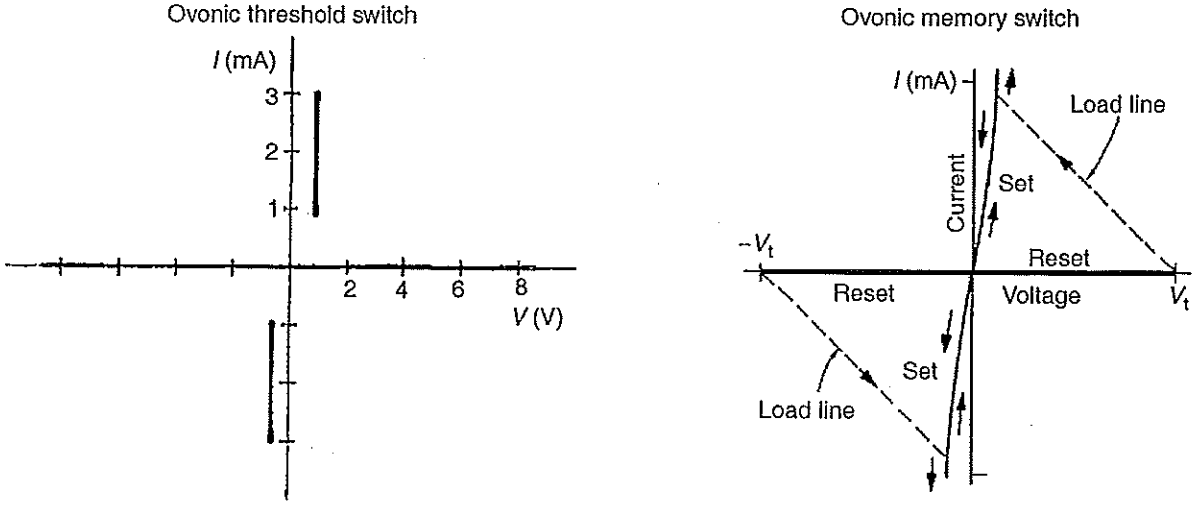


*Figure 2*
Three-dimensional model of the Ovonic threshold material. Yellow balls represent Te atoms and red sticks represent their lone-pairs. The dark balls are Ge, Si, and As. The coordination can vary from site to site, however, the model shows Ge and Si as 4-coordinated and As 3-coordinated.



Switching in chalcogenide materials based on lone-pair excitation:

- Threshold --- noncrystallizing --- OTS
- Memory --- phase change --- OMS

*Figure 1*
*I–V* characteristics.

either a noncrystallizing Ovonic threshold switch or a nonvolatile Ovonic phase change memory switch, both reversible binary devices (*I–V* curves shown in Fig. 1) (Ovshinsky 1968) are obtained. The amorphous phase of the Ovonic threshold switch has a high resistance in the "on" condition, it is in a highly conductive plasma state. In the Ovonic memory switch, the amorphous phase is also highly resistant. It becomes conducting when it switches to its microcrystalline phase. Figures 2 and 3 are atomic models of the Ovonic threshold switch and Ovonic memory switch (Ovshinsky and Sapru 1974).

The Ovonic threshold switch is amorphous and remains so throughout its operation. It has a shorter chain structure and many more strongly bonded cross-links than the Ovonic phase change memory, for example, arsenic, germanium, and silicon which assure the structural integrity of the material while at the same time leaving the nonbonded lone pairs available for excitation. The result is a switching device whose speed has never been measured; it is under

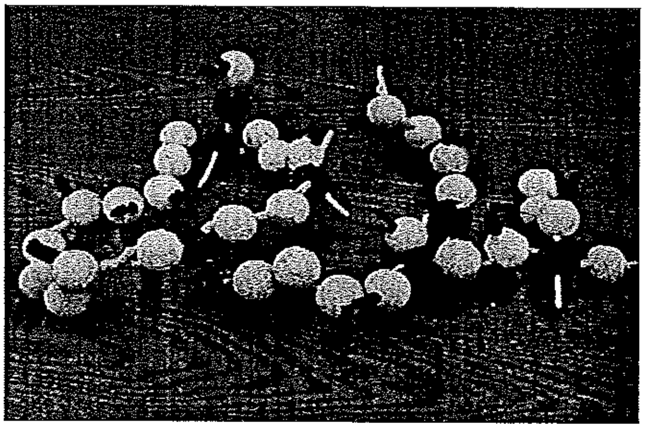


*Figure 3*
Three-dimensional model of the Ovonic memory material. Yellow balls represent Te atoms and dark sticks represent their lone pairs. Dark balls are Ge atoms. The purple ball is Sb. To fit particular device needs other elements can be added. Note: Polymeric chain structure and cross-linking.

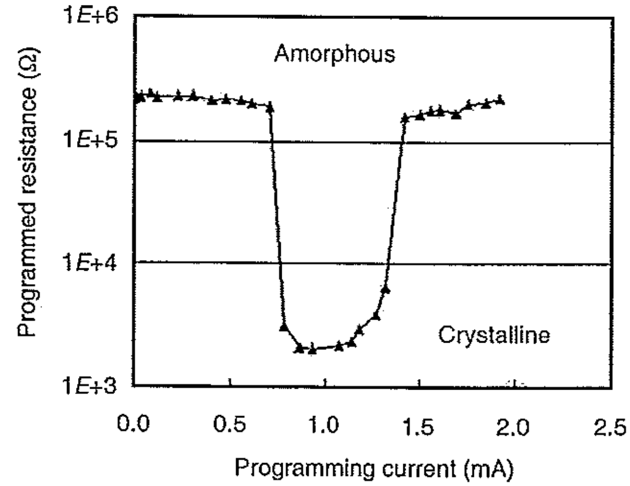
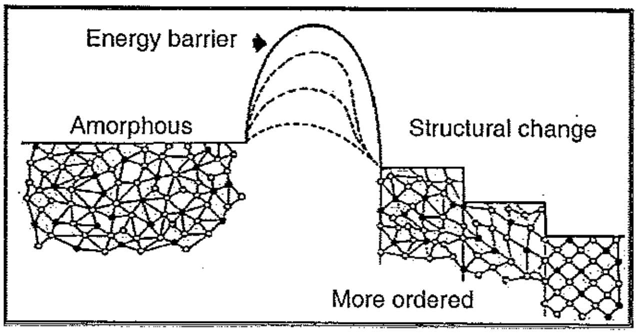


*Figure 5*
Resistance vs. current for an Ovonic phase change binary memory device.



Energy barrier can be reduced by any of the following–applied singly or in combination:

(i) Light
(ii) Heat
(iii) Electric field
(iv) Chemical catalyst
(v) Stress–tension pressure

Transformations in amorphous materials produce changes in:

(i) Resistance
(ii) Capacitance
(iii) Dielectric constant
(iv) Charge retention
(v) Index of refraction
(vi) Surface reflection
(vii) Light absorption, transmission and scattering
(viii) Differential wetting and sorption
(ix) Others, including magnetic susceptibility

*Figure 4*
Ovonic information storage/retrieval and display by structural transformation.

*Table 1*
A comparison of the features and operational characteristic of conventional silicon elements and arrays with those of the Ovonic cognitive element and computer.

| Conventional silicon computers | Ovonic cognitive computer multifunctionality in a single element |
|---|---|
| *Each element*<br>● Computes based on single bit (binary) manipulation<br>● Manipulates data sequentially, bit by bit | *Each element*<br>● Manipulates, processes, and stores information in a nonvolatile fashion<br>● Hardware and software are unified<br>● Low-voltage and low-current operation<br>● Performs arithmetic operations $(+, -, \times, \div)$ on multibit numbers $(0, 1, 2, 3 \ldots, n)$<br>● Performs modular arithmetic<br>● Executes multivalued logic<br>● Stores the result in a nonvolatile manner<br>● Simple, powerful encryption<br>● Acts as a neurosynaptic cell; that is, possesses intelligence capability<br>● Scales down to nanoscale dimensions; huge density<br>● Device speed is in the picosecond range<br>● Capable of massive parallelism<br>● Combines logic and memory in a single device<br>● Has attributes of proposed quantum computers without their limitations, such as analogs of quantum entanglement and coherence at practical conditions and environments |
| Arrays of computation and storage elements are combined in a conventional computer which:<br>● Requires separate storage and processor units or regions<br>● Has limited parallel processing capability<br>● Is limited to von Neumann operations | *An array of Ovonic cognitive elements working as a system*<br>● Easily factors large numbers<br>● Performs high-level mathematical functions (e.g., vector and array processing)<br>● Has high three-dimensional interconnectivity, huge density, giving rise to high speed, hyper-parallel processing (i.e., millions of interconnected processors)<br>● Has adaptive learning capability<br>● Interconnectivity is simply and inherently reconfigurable<br>● Can generate dynamic activity |
|  | *The Ovonic cognitive devices are*<br>● Mass produced in exceptionally dense, all thin film, uniquely interconnected arrays<br>● Mass manufactured as a thin film, flexible device using proven technologies<br>● Ovonic "transistor" unique high speed low cost three-terminal device. Nanostructure capable of carrying large amounts of current both in nonvolatile and volatile modes |

a picosecond and operates at room temperature and above. In nanostructure sizes, it carries current orders of magnitude higher than the best crystalline transistor. Its lifetime is that of any other semiconductor device.

The Ovonic phase change memory is nonvolatile and rapidly switches reversibly between the amorphous and crystalline phase in response to electronic, optical, or other forms of energy. It has a high signal to noise ratio between "off" and "on" and can have stable intermediate states (Fig. 4).

Figure 5 is the U-shaped $I$–$R$ curve for the Ovonic phase change binary memory. The mechanism for its reversible phase change is that tellurium is atomically designed to have longer chains, fewer and weaker cross–links, for example, instead of arsenic, antimony, instead of silicon, germanium; the lone pairs can be weakly bonded as well as nonbonded and they are the source of the excitation process.

The Ovonic memory switch is now called the Ovonic Universal Memory (OUM) since it is designed to replace Flash memories, DRAMs, and SRAMs, all with

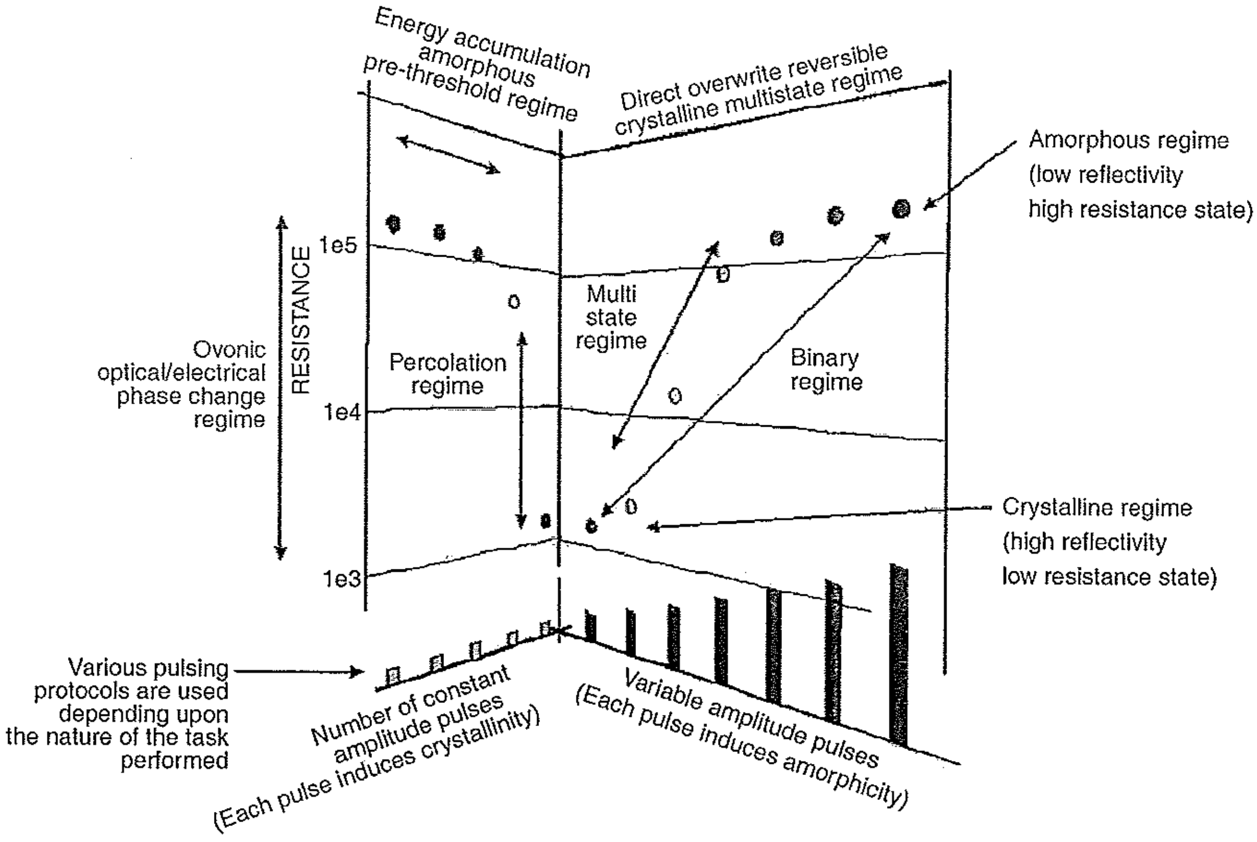


*Figure 6*
Operation of Ovonic cognitive device.

the same device (Ovshinsky 1999). Its optical twin is the basis for all CD- and DVD-rewritables, and has been in commercial production for many years through ECD's licensees (Ovshinsky 1994). The OUM is now being commercialized (Lowrey *et al.* 2003).

Conventional computers are based on the binary von Neumann sequential principle. Their ability to be used in a cognitive manner has been limited by their architecture. Transistors are not well suited for the highly parallel needs of a cognitive approach, and they are burdened by the complexities and number of weighting devices and circuits. What has been lacking is inherent plasticity, which is the sine qua non of biological neurons and their synapses as well as the ability to make billions of neurons with large numbers of synapses.

## 3. *Cognitive Properties*

By utilizing the left side of the U-shaped *I–R* characteristic of the OUM (Fig. 5) as well as the multistate properties of the right side, we can achieve cognitive properties which constitute a paradigm shift wherein a single device can have plasticity and a high degree of multi-functionality and behaves both as a neuron and as synapses. The advantages to this approach are not only of scientific value, but have transformative implications to the computer and semiconducting industry. Table 1 lists not only the multi-functionality of the device but also how this relates to the conventional von Neumann approach utilized in present day computers.

The small size of the devices (they are scalable both in thickness and diameter and operate even more advantageously the smaller they are – well under 100 Å), their plasticity, speed, nonvolatility, and low power usage, combined with the huge parallelism possible, all make for revolutionary change for computers and other information processing. Ohta, using a laser, has shown transformations in the femtosecond range (Ohta *et al.* 2001).

For many years, the chalcogenide devices have been hybridized with conventional silicon technology (Adler *et al.* 1991). Thus in the first generation of the Ovonic cognitive computer, the cognitive devices can be integrated with silicon technology en route to all thin-film architecture. Also of importance is that the same functions can be achieved optically and therefore optical or optoelectronic computers can be part

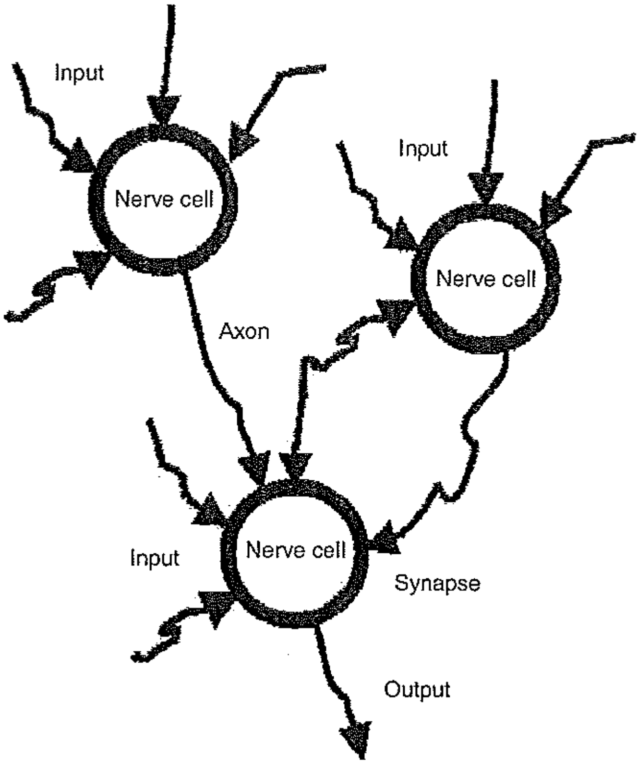


*Figure 7*
Neurosynaptic cell. Ovonic single and multiple cells have the analogous properties as neurons and synapses. The neuron fires when the threshold is reached by summing up the synaptic inputs.

of the evolutionary development of the Ovonic cognitive computer (Ovshinsky and Pashmakov 2004).

These multi-function capabilities are demonstrable, their mechanism understood (Ovshinsky 2003, Ovshinsky and Pashmakov 2004), and the technology proven over many years since it is the same as in the Ovonic commercial optical phase change memory.

The mechanism for the cognitive learning, information processing, and adaptability are summarized in Fig. 6. The synaptic activity occurs in the amorphous state where pulses of energy which can be generated from various sources nucleate an amorphous nano-spot in a nondetectible but coherent manner, that is, the effect of each succeeding pulse is dependent upon those of previous ones. The synaptic information accumulates in the form of extremely small, nonforensically detectable structural changes in the amorphous highly resistive state. When a percolation threshold is reached, a phase change to the crystalline conducting state occurs, allowing passage of the information to other neurons. The operation of the Ovonic cognitive neurosynaptic device is analogous to that of nerve cells (Fig. 7). Nerve cells, of course, rely upon chemical changes as well.

Plasticity occurs in the amorphous phase through the accumulation of energy while encoding information in a coherent manner through structural changes. For example, if one uses it to do mathematics, one can finish an operation many years later since the encoded information is nonvolatile. This is very important for encryption. Information in the neurosynaptic regime, unlike most of its biological counterparts, can be

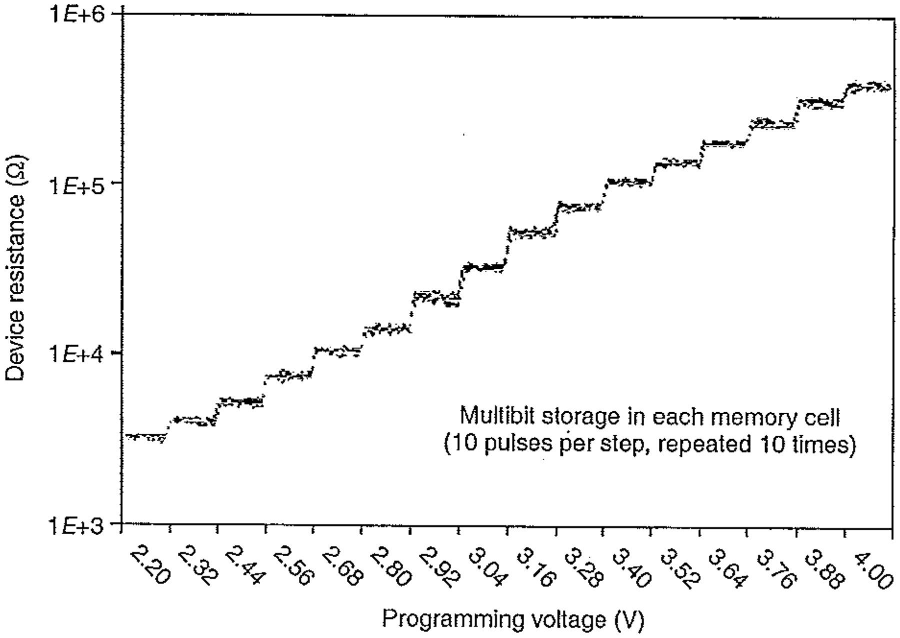


*Figure 8*
Ovonic electrical multi-state data storage.

erased and rewritten, that is, the conducting state can be on the right-hand side of the cognitive U, and it can either return to the amorphous state or can be used in a multibit manner such as shown in Fig. 8 since it has analog properties to either contain new information or follow learning protocol.

It is remarkable that a single nanostructure thin film device apparently featureless in its amorphous and synaptic phase can achieve what we have described here. It is extremely robust and operates at room temperature and above.

Intelligence in biological systems depends upon the plasticity, number of neurons, and the number of synapses and their interconnections; the same is true of the Ovonic cognitive computer. The Ovonic neurosynaptic devices can be cloned to be in the billions as they are in their commercial binary mode in the Ovonic phase change memories, both optical and electrical. While binary operation is trivial for these devices, by going beyond the binary mode into the cognitive regime, a new paradigm of computation and adaptive learning is achieved.

*See also*: Magneto-optic Recording: Overwrite and Associated Problems; Total Film Stack, Layer Configuration, Optical and Magneto-optic Data Storage: Channels and Coding, Optical Recording: Error Correction, Phase Change Memories: Optical Disk.

## *Bibliography*

Adler D, Schwartz B B, Silver M (eds.) 1991 *Disordered Materials*: Science and Technology – Selected Papers by *Stanford R. Ovshinsky*, 2nd edn. Institute for Amorphous Studies Series. Plenum, New York

Kastner M 1972 Bonding bands, lone-pair bands, and impurity states in chalcogenide semiconductors. *Phys. Rev. Lett.* **28**, 355–7

Lowrey T, Hudgens S, Czubatyj W, Dennison C, Kostylev S, Wicker G 2003 Characteristics of OUM phase change materials and devices for high density nonvolatile commodity and embedded memory applications. *Mat. Res. Soc. Symp. Proc.* **803**, 101–12

Ohta T, Yamada N, Yamamoto H, Mitsuyu T, Kozaki T, Qui J, Hirao K 2001 Progress of the phase-change optical disk memory. *Mat. Res. Soc. Symp. Proc.* **674**, V1.1.1

Ovshinsky S R 1968 Reversible electrical switching phenomena in disordered structures. *Phys. Rev. Lett.* **21**, 1450–3

Ovshinsky S R, 1994 Historique du changement de phase (phase change optical memory history). *Memoires Optiques & Systemes*, No. 127, 65–7

Ovshinsky S R 1999 Amorphous and disordered materials—the basis of new industries. *Mat. Res. Soc. Symp. Proc.* **554**, 339–412

Ovshinsky S R 2003 Optical cognitive information processing—a new field. Keynote presentation at Intl. Symposium on Optical Memory '03, Nara, Japan. *Jpn. J. Appl. Phys.* **43** (7B), 4695–9

Ovshinsky S R, Pashmakov B 2004 Innovation providing new multiple functions in phase-change materials to achieve cognitive computing. *Mat. Res. Soc. Symp. Proc.* **803**, 49–60

Ovshinsky S R, Sapru K 1974 Three dimensional model of structure and electronic properties of chalcogenide glasses. *Proc. 5th Intl. Amorphous and Liquid Semiconductors Conf.*, Garmisch-Partenkirchen, Germany, pp. 447–452

Cohen M H, Fritzsche H, Ovshinsky S R 1969 Simple band model for amorphous semiconducting alloys. *Phys. Rev. Lett.* **22**, 1065–8

Ovshinsky S R, Fritzsche H 1973 Amorphous semiconductors for switching, memory, and imaging applications. *IEEE Trans. on Electron Devices* **ED-20**, 91–105

Ovshinsky S R, Ovshinsky I 1970 Analog models for information storage and transmission in physiological systems. *Mat. Res. Bull.* **5**, 681–90

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