The Ovonic Cognitive Computer - A New Paradigm

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Abstract

Paul Davies, a well-known theoretical physicist recently stated that “the essence of life is information.”(1) I will describe how the essence of information is plasticity, that information is encoded energy requiring what neurophysiologists call plasticity. Plasticity is the ability of neurons through their synapses to have memory, learn, adapt and evolve in response to their environment. I will show that Ovonic memories, both optical and electrical, have rich and deep new physics that make them cognitive devices and therefore open up a huge new field of chalcogenide-based intelligent computers, intelligence that works in a similar manner to the brain.

Keywords: chalcogenide materials, neurosynaptic computing, optical computing, phase change memories, threshold switching

Discussion

The Ovonic optical and electrical phase change memories are well known to this audience. A typical device is composed of tellurium, germanium and antimony and when exposed to optical or electrical energy, usually in the form of pulses, it changes state from crystalline to amorphous or amorphous to crystalline. It is fast, reversible, nonvolatile, and does not require large amounts of input energy. The amorphous state is a high resistivity state; the crystalline state is conducting. The Ovonic optical phase change device also has changes in terms of being able to absorb light in the amorphous state and have the crystalline state reflecting. In a rewritable optical disk, the energy absorbed by the chalcogenide layer is the same both when it is amorphous and when it is crystalline. The optical stack provides this to optimize direct overwrite. When the reflectivity of the stack is lower, the excess energy is absorbed in the aluminum layer below.

This simple description is not sufficient to explain why it also can demonstrate plasticity, the key factor of neuronal and synaptic activity of the brain. Plasticity is the ability of a biological material or its nonbiological analog to be able to adapt or change in response to incoming energy signals. The resulting changes are structural in nature very much like electrical or optical signals can make for conformal and configurational alterations in the amorphous phase of the Ovonic Phase Change Memory.

Information is encoded energy reflecting adaptation and learning as well as switching and memory. This paper will describe how the simple phase change binary memory can also show such plasticity and emulate brain function. Indeed, a single device can have many multifunctions, opening up an entirely new field of nonbiological, cognitive computing.

Figure 1 illustrates neurons (nerve cells) receiving inputs in the form of coherent energy pulses through dendrites (shown in a simplified manner) which, when the input energy is summed up to reach a threshold, cause the neurons to fire and transmit the information through nerve fibers (axons) to other nerve cells.

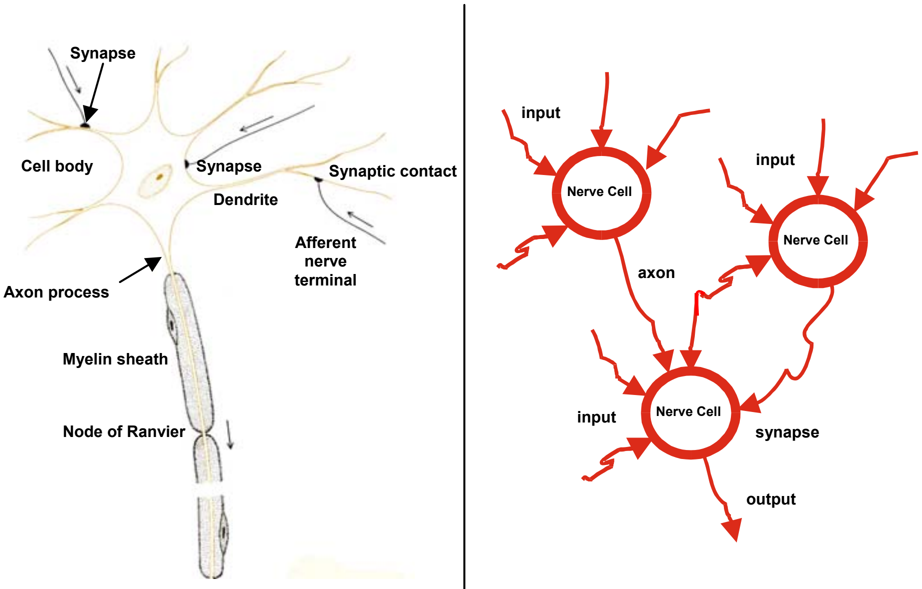

Figure 1a. Diagram of a biological nerve cell showing synapses and synaptic contacts (2)

Figure 1b. A simplified schematic of the communication of information between neurons

Figure 1

Ovonic Cognitive Devices have analogous functions to the neurons and their synapses, However, the neurosynaptic system of the brain is, of course, made of organic material. How can an inorganic analog have such plasticity and intelligent, that is learning, activity?

I will describe the functions which make the Ovonic Phase Change Memory capable of being a cognitive computer and will then discuss how the Ovonic phase change memory material can perform such neurosynaptic functions.

The Ovonic Cognitive Computer is a technology that makes it possible to fulfill the long-awaited goal of achieving intelligent computing, a new paradigm. While a single Ovonic Cognitive device (or in some cases, two devices) of subnanometer size is able to have many multiple functions such as the demonstration of addition, subtraction, multiplication and division, along with the standard binary activity of any computer, it also can do nonbinary processing, modular arithmetic and encryption as well as factoring. It has the plasticity of a biological neurosynaptic cell and is based on a densely interconnected network of proprietary Ovonic Cognitive Devices where even a single device has such computing qualities.(3-5) We have also been able to emulate optically the Ovonic cognitive functions showing that electrical and optical ovonic cognitive computing are possible.(6)

A single device realistically simulates the neurosynaptic behavior of biological neurons. Like biological neurons, the device is capable of synaptic function such as receiving and weighting multiple inputs that result in threshold activation, an operational mode in which it accumulates input energy signals without responding until the total accumulated energy reaches a threshold level. Once the threshold is reached, the device undergoes an abrupt transformation from a high resistance state to a low resistance state in a process that mimics the firing of a biological neuron.

Such an individual Ovonic device can be readily interconnected to many other such devices in highly dense two-dimensional arrays or in three-dimensional, vertically integrated networks. The threshold level of individual Ovonic devices can be controlled by various means. A remarkable multi-terminal thin-film device - the Ovonic Quantum Control Device (Figure 2) - which can replace transistors as well as adding new functionalities, offers new degrees of freedom to the design of computer architecture. The plasticity of the Ovonic neurosynaptic arrays opens up possibilities of unifying software and hardware.

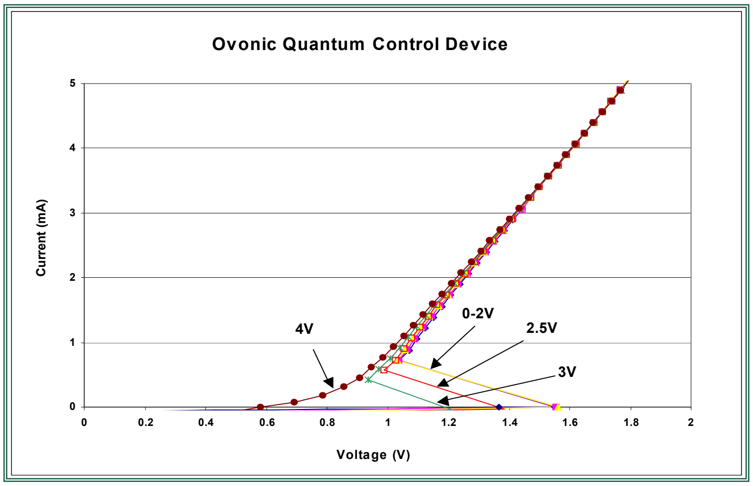

Figure 2 - IV Curves of Multi-Terminal OQCD

From its beginning the conventional computer was based on the principles of VonNeumann. The Ovonic Cognitive Computer, however, need not be binary or sequential as required by VonNeumann and, therefore, opens up many new important possibilities.

The combination of small device size, speed, intrinsic neurosynaptic device functionality and dense device parallelism and interconnectivity in three dimensions offered by the Ovonic devices provides the Ovonic Cognitive Computer with a functionality and highly parallel mode of operation that follows the neurophysiological activity of the biological brain.

Inherently, individual Ovonic devices within a network are adaptive and can also be configured to function as weighting devices that can be used to control the interconnection strength between Ovonic devices configured to function neurosynaptically. Since the interconnection strength is adjustable, networks formed from Ovonic devices display learning and adaptive properties analogous to those of biological neurosynaptic networks.

The Ovonic device, singly (or in a network), is able to both process and store information in a reconfigurational nonvolatile manner and, as a result, such unique multifunctionality obviates the customary need to separate memory and logic functions in computers. Of great interest is that these devices also can operate in a manner analogous to the much-talked about quantum computer. They have several important advantages in that they, of course, operate at room temperature and higher, are robust, and they are demonstrable now. In other words, they are real world devices that can be used for various functions, for example, encryption.

To summarize, we can uniquely demonstrate addition, subtraction, multiplication, division, factoring, non-binary processing, modular arithmetic and encryption with Ovonic devices as well as neurosynaptic activity (3, 6) which, unlike present artificial intelligence, meets the criteria of true cognitive activity. The active chalcogenide material of the Ovonic devices and the Ovonic Cognitive Computer can be deposited in a low-cost, thin film fashion in a continuous manufacturing process. They can also be integrated and imbedded, that is hybridized with conventional silicon circuitry. Very importantly, they are scalable. A single device can operate at extremely small dimensions, for example under 100 angstroms. At the same time, its characteristics improve the smaller the dimension. Therefore, as photolithography goes to smaller sizes it is advantageous to our device operation.

Of great interest to this group, we have been able to duplicate these same basic functions of the Ovonic Phase Change Memory not only electrically but optically through the use of lasers. (See Figures 3 and 4.)

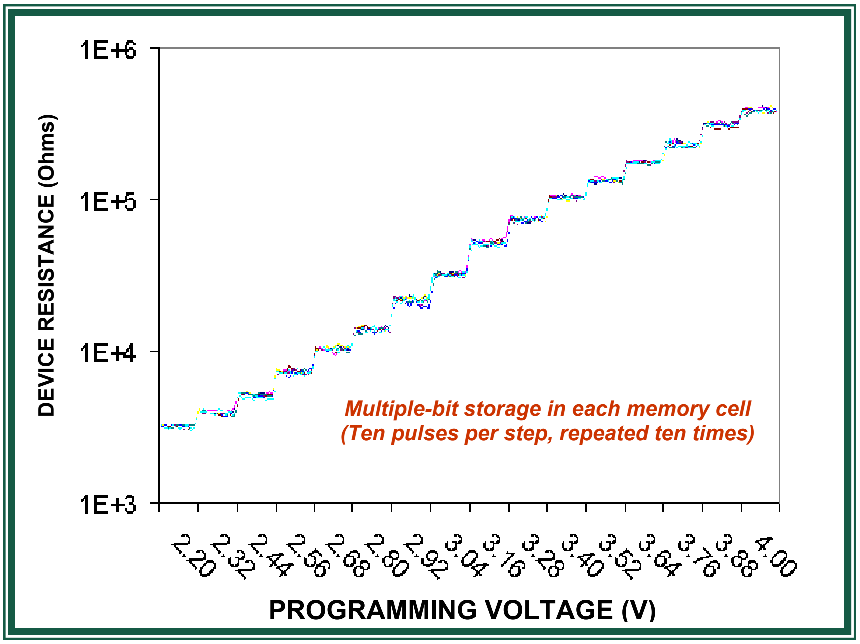

Figure 3 - Ovonic Electrical Multi-State Data Storage

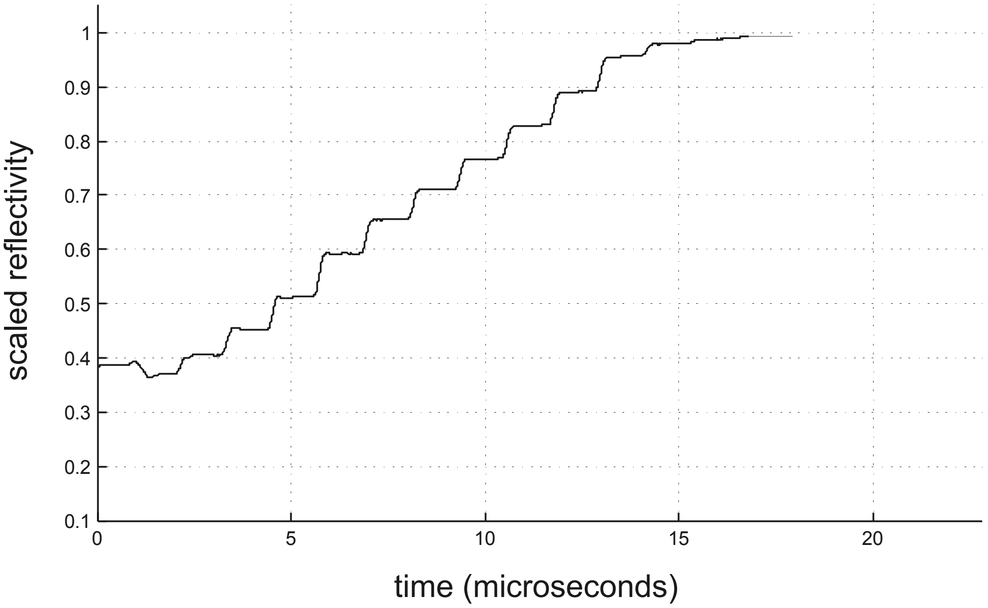

Figure 4 - Ovonic Optical Multi-State Data Storage

Most importantly, we can duplicate optically the neurosynaptic Ovonic Cognitive Computer Device. Figure 5 shows that with pre-threshold pulses <u>in the amorphous state</u>, we can induce structural changes too small to be seen using the ultimate read technique. These pulses accumulate information which is revealed and transferred at the threshold. This is analogous to the synaptic activity taking place on the left side of the U as will be described in Figure 7.

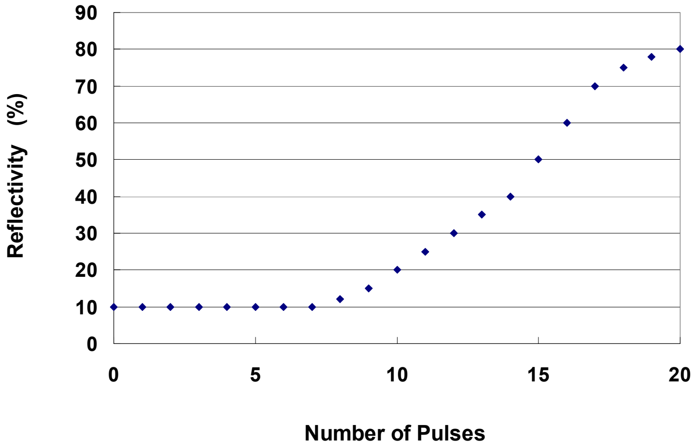

Figure 5 - The Optical Ovonic Cognitive Effect

We will now describe the principles of atomic engineering which lead to the choice of elements which permit these unusual electronic and structural changes.

The divalency of tellurium, the length of its chains and particularly its free lone pairs, which are available for electronic or optical excitation, provide the flexibility of the material which is the requirement for plasticity. Germanium and antimony crosslink the tellurium chains and the material plasticity is controlled by the number and strength of crosslinks and their relatively weak bonding. This in brief is the mechanism providing reversible phase change without disturbing the plasticity. As one uses stronger and more crosslinks to tellurium such as germanium, silicon, and arsenic, the material becomes stiffer and much less flexible and the tellurium chains are much shorter.

The strongly crosslinked materials are the basis of the Ovonic Threshold Switch in which an electric field can couple to the lone pairs of tellurium and the many and strong crosslinks prevent crystallization so that the material always remains amorphous. The switching is volatile, its speed is so fast that it has never been measured and its conducting state is a highly dense solid state plasma which can carry orders of magnitude more current than a crystalline transistor and, of course, is faster and smaller. It is the basis of our 3-terminal device shown in Figure 2.

It is the ability of excited lone pairs in the Ovonic Phase Change Memory to cause conformal and configurational structural changes that is the basis for the change of phase that occurs in response to the coupling of the electrical or optical field to those lone pairs. In other words, the structure cannot withstand excitation of the large number of lone pairs and a phase change occurs. Recall that multielemental amorphous and disordered materials provide new degrees of freedom for atomic design.

Figure 6 shows the R-I curve that makes for the reversible binary state of the standard Ovonic Phase Change Memory.

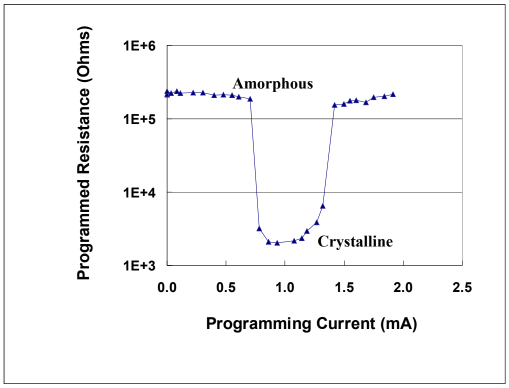

Figure 6 - Resistance vs. Current for an Ovonic Phase Change Binary Memory Device

Let us now compare the electrical and optical characteristics of the Ovonic Phase Change Memory with the newly described Ovonic Cognitive Computer device.

As can be seen in Figure 7, the amorphous plasticity phase is where the synaptic activity occurs by accumulating multiple energy inputs to provide a percolation path of submicrocrystalline regions which when reaching threshold, fires the switch to change from the amorphous to the crystalline phase.

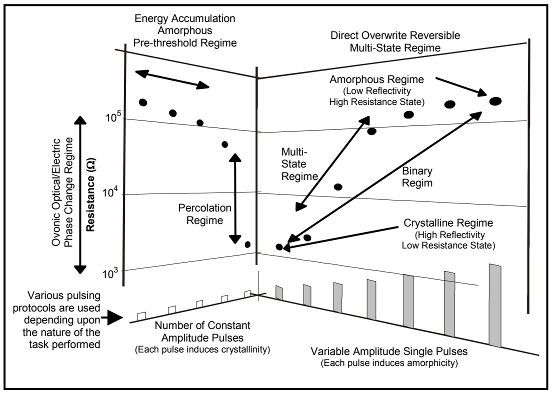

Figure 7 - Operation of Ovonic Cognitive Device

The difference between Figures 6 and 7 is that Figure 6 is binary and can have multistates on the right side of the U while in Figure 7, the left side of the U is where the synaptic and neuronal action take place in the amorphous phase. The pulses induce growth of nanocrystals to form the percolation path.

It is remarkable that a single nanostructure can have such multifunctionality and yet retain the reversible amorphous to crystalline transition including the multistates of the right side of the U. The structural changes that provide the synaptic intelligence are too subtle to be detected by forensic means, making it an exceptional encryption device.

Conclusion

The cognitive devices that I have described here are the beginning of a new paradigm of intelligent devices and computers. The information field is one of the most important pillars of our global economy. Conventional computers are powerful but dumb. Let us consider making all-thin-film computers powerful and intelligent. I hope that our symposium, the European Symposium on Phase Change and Ovonic Science(E*PCOS 04), can be stimulated by what I have described here since as we have shown, optical and electrical switching, memory and computing will become unified in the future and we can be the enablers and leaders of such basic and important new industries.(7-8)

Acknowledgements

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