Japanese Journal of Applied Physics
Vol. 43, No. 7B, 2004, pp. 4695–4699

Optical Cognitive Information Processing — A New Field

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(Received November 28, 2003; revised March 16, 2004; accepted April 28, 2004; published July 29, 2004)

I will discuss unique electronic and structural mechanisms of Ovonic optical phase-change devices making possible orders of magnitude increase of density of memory and introducing multiple information functions in a single nanostructure spot. [DOI: 10.1143/JJAP.43.4695]

KEYWORDS: optical computing, phase change material, chalcogenide, neural computing

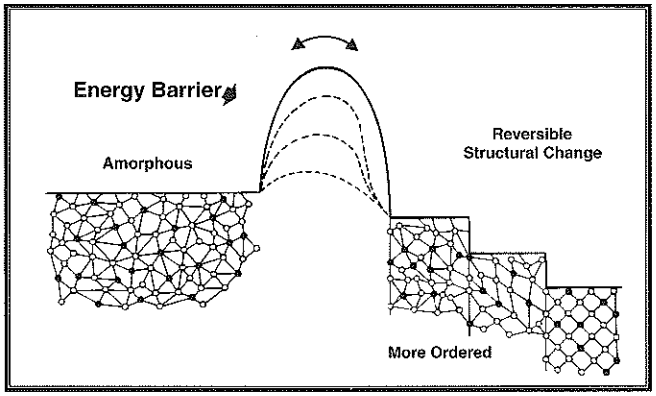
1. Introduction

I have always considered a keynote talk – especially on our Ovonic optical phase change memory – not to be a summary of work completed, but to point to the future by introducing new concepts which can stimulate new work so that the field that we love can grow to its full potential.

In the past, I have also presented data in a very specific manner to show that my vision is not a utopian one, but a road map with basic principles and foundations in place so that there is little question that the end result desired can be achieved. A detailed presentation of our previous work can be found in earlier publications[1–4] and two books of my collective papers.[5,6]

The commercial work in phase change memory has been devoted to binary activity, for the binary paradigm is how one stores optical memory, no matter what its mechanism is, magnetic or phase change. The strategy is always to make the spots/marks smaller and the density much higher. Hence, the blue laser.

Of course, there is always ongoing work on how to use the gradation of amorphous to crystalline with its various changes of local and intermediate range order as a means to achieve readable multistates. This has been accomplished both electrically and optically.



Energy barrier can be reduced by any of the following–applied singly or in combination:
- Light
- Heat
- Electric field
- Chemical catalyst
- Stress-tension pressure

Transformations in amorphous materials produce changes in:
- Resistance
- Capacitance
- Dielectric constant
- Charge retention
- Index of refraction
- Surface reflection
- Light absorption, transmission and scattering
- Differential wetting and sorption
- Others, including Magnetic Susceptibility

Fig. 1. Mechanism for information storage/retrieval and display by structural transformation.

2. Electrical and Optical Memory

Figure 1 shows my original concept of multistate for Ovonic phase change memory. Figure 2 shows the performance we have attained in Ovonic electrical phase change memory devices optimized for multistate storage.

The work to utilize this concept by David Strand successfully showed that such graded/multi-states could be achieved optically[7] (Fig. 3). The multi-state optical function is analogous to the electrical multi-state function in that each of these functions are achieved by delivering energy to the device in a direct overwrite fashion that first amorphizes the memory location and then by design of the pulse profile leaves the location in the desired final state of partial crystallinity. The barrier to its commercialization has not been that it doesn't work, but that today's lasers change power output as their temperature changes, and these fluctuations limit the accuracy that any given reflectivity level can be reproduced. It is the standardized optical storage products that have been the commercial successes, and industry giants will have to lead introduction of multi-level products with their increase storage capability.

Figure 4 shows the "U", which is the resistance versus current ($R(I)$) curve of an Ovonic binary memory device. The devices can be made for both binary and multistate (see Fig. 2) storage. The ability to attain intermediate states comes from the fact that the materials can exist in configurations that range from completely amorphous to completely crystalline, including a continuum of structures having partial amorphous and partial crystalline nature. The device resistance when in the intermediate states is determined by both the volume fraction in each structure and also the configuration of the regions in the two structures within the volume of the entire device. It is by control of these that we can optimize a device for binary or multistate performance.

In summary, on the left side of the "U" is the synaptic activity in the amorphous phase which is not accessible to be read until the percolation path is reached, whereas on the right side the changes can be continuously measured and available for interrogation. The right side is multi-state. The left side can have many states and they carry coherent information without being accessible. Accessibility is only available through the crystalline. The left side is cumulative while the right side is direct overwrite. All the work that I have been discussing for detectible multiple phases has been accomplished on the right hand side of this "U". But

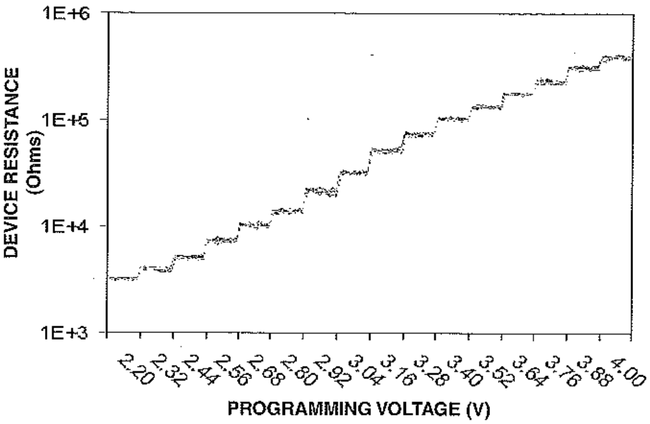


Fig. 2. Multistate electrical phase change memory. The stepwise appearance of the data in the graph arises from the testing sequence. We programmed the device a total of 1600 times, or 100 times at each applied voltage. We first applied ten programming pulses at one voltage, measuring the resulting resistance each time. We plotted these resistance values over a short distance on the horizontal axis for clarity in the presentation. We then increased the voltage to next level and programmed ten more times. After we completed programming at all 16 levels, we repeated this entire process nine more times. In this way one can see the reproducibility of the device resistance following these two programming sequences. Showing the data as steps allows visual confirmation of the clear separation between the states. The device is capable of truly continuous intermediate resistance levels. The number of states shown is arbitrary to demonstrate the principle. The number of states chosen in a particular device is determined by the specifics of its application.

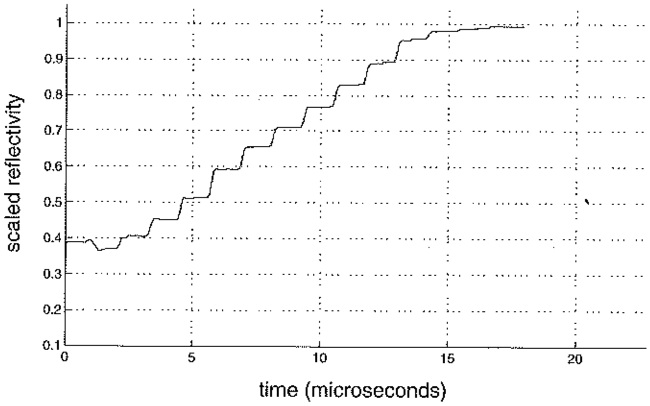


Fig. 3. Optical multistate phase change data storage.

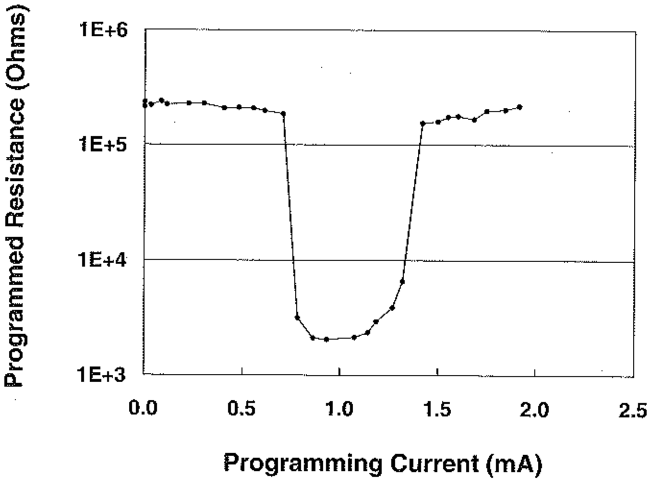


Fig. 4. Resistance as a function of current for an Ovonic phase change memory device (also referred to as the U in the text).

remember that I have always said that a single spot of our "simple" tellurium-germanium-antimony material and its siblings, even in the nanostructure range, has new, rich and deep physics. The left side of Fig. 5 emphasizes the unique cognitive function.

3. Percolation Behavior

The U of an Ovonic memory device consists of two distinct regions: On the left-hand side, starting from the amorphous (reset) state, is the so-called 'pre-threshold' or 'energy-accumulation' regime. This is the region of crystal growth. If we send constant amplitude pulses in this region, we will cause crystallites to grow one step at a time with each pulse – that's why we call it energy-accumulating regime.

After sending a number of pulses, which number is determined by their amplitude and width, we reach the percolation threshold, which marks the point at which a conducting crystalline path is being formed for the first time in the amorphous material.

At the percolation threshold, the conduction of the device drops in a fast non-linear fashion, typically by about two orders of magnitude. Because of the cumulative incorporation of the pulse energy, existence of a threshold and non-linear transition from one resistance state to the other, the device in this region operates as a solid-state analogue of the biological neuron.

This region of the U can also be used to perform arithmetic operations, store multiple bits in one device, encode information that is not forensically detectable, factor large numbers, etc. We encompass all this multi-functionality with the term 'cognitive regime', emphasizing the possibility to use such devices for building truly intelligent computers.

4. Direct Overwrite Regime

The right-hand side of the $R(I)$ curve includes the so-called 'multi-state' or 'direct overwrite, reversible' regime. Direct overwrite is the ability to go from any arbitrary recorded state to any other arbitrary recorded state without having to go through any sort of refresh state or action. This eliminates the need for an erase step, for example, and thereby increases the data transfer speed dramatically. Flash memories can be recorded in microseconds, but need on the order of a second for erasure and pumps to provide higher voltages. Flash memories also have a lifetime of no longer than 10^6 cycles, and most flash devices are not even capable of that many cycles. Optical disks can be both erased and written in 50 nanoseconds, although latency adds milliseconds to the process.

In the direct overwrite regime of the U, sending an electrical pulse to the device always puts it in a distinct resistance state uniquely determined by the amplitude of that pulse. One can go forwards and backwards in terms of pulse amplitude and always return to the same point on the curve. This regime can be utilized either as a binary, non-volatile memory (which Intel and ST are developing now as flash-memory replacement) or to store multiple bits in a single device.

5. Cognitive Functionality

At the Fall 2003 Materials Research Society (MRS) meeting in Boston,[8,9] I gave a complete description of how

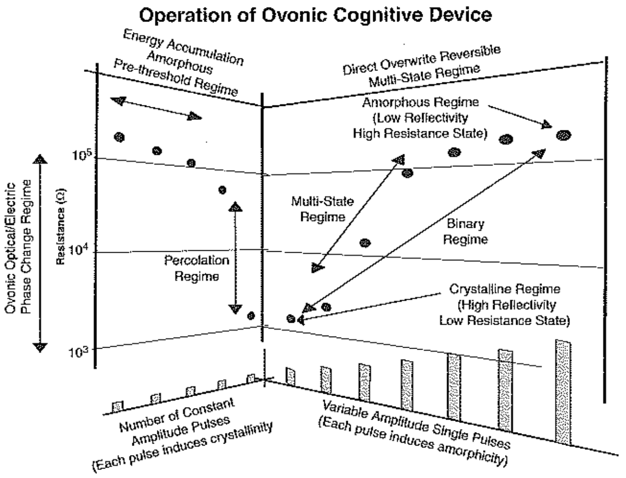


Fig. 5. Operation of an Ovonic Cognitive Device.

electronically we can use the mechanism on the left side of the U to provide a remarkable number of cognitive information states rather than binary ones in a single spot (or you would call it "mark"); a unique new behavior that I call the cognitive regime. As can be seen from Fig. 5, this regime can perform mathematical and cognitive functions. Our conventional binary regime is an amorphous to crystalline transformation and requires no pre-synaptic activity. The pre-threshold states can change the binary paradigm into an entirely new non-Von Neumann activity that is reflected in our Figs. 4 and 5.

The left side of the U is the basis of a fundamental change in computing that while it can easily do conventional Von Neumann binary operations, it is also possible in a single spot to do higher mathematical and cognitive computing. That is, the objective of building intelligence, such as learning capability and adaptability, into the computer is possible. In fact, the activity represented by the left side of the U very much resembles the neurosynaptic activity of the brain. Keep in mind that the left and right side describe memory in a single spot and cooperatively work together to perform tasks heretofore not possible in semiconductors. An amazing situation for a single device.

Sufficient here for my optical talk is to start by saying that optical computers will come; but hybrid computers, that is, optical and electronic together, will be the most likely next step. The mechanisms that I discuss here, which can be accessed optically or electronically, can be the basis for launching such an approach.

Of course, one can start by using the binary amorphous to crystalline transformation (or vice versa) and the most exciting aspect of doing so is that it can be accomplished without interfering with the non-binary mechanisms that we discuss here. Both binary and non-binary activity are permitted within a single spot.

The defining difference between binary and non-binary activity is that non-binary activity takes place in the amorphous phase through pre-threshold activity; think of the activity as being like a nerve cell surrounded by dendrites making synaptic connections. The synaptic activity carries the information. The energy of the summation of inputs then reaches the threshold and fires the neuron. This is the way the brain works and this is analogous to the non-binary activity associated with the left side of the U seen in Fig. 5, except that our synapses are pulses of energy carrying information. In this way we can emulate the behavior of the brain and build an analogous device. Our design starts with the neuron itself and builds into networks. We are currently building devices having three and more terminals. Since our devices are built in thin film form we can add layers of our devices not possible with silicon devices which require lattice matching not yet achieved. In one example implementation we can create a pattern of parallel lines, followed by a layer of Ovonic material, followed by another layer of lines orthogonal to the lower layer. The ability to program the Ovonic material at the cross points of these lines allows for the weighting required in successful neural implementations. Since we are building an analog and not a biological replacement we can achieve our design goals without having to attain the level of three-dimensionality present in the brain.

The brain operates on several biological levels of fundamental information processing. The evolution of the nervous system starts with reflex actions which are considered in neurophysiology to be hard-wired, fixed-action behavioral patterns. These always occur in a fixed manner when they are triggered and carry with them responsive actions to incoming information; that is, animals are genetically programmed to carry on certain activities such as an automatic response to stimuli to avoid danger. Such nerve cells (neurons) are specifically activated in a specific manner. Their functions do not change.

In higher vertebrates there is also adaptive behavior, which is the ability to change behaviors as a result of experience. This adaptive behavior is the result of plasticity of various nerve cells and their interacting networks that results in learning. The learning procedures require repetition so that changes occur in the nerve cells to repeated inputs which modify nerve cells through synaptic activity in response to incoming information from other nerve cells. In this way a task can be learned by strengthening the signal and encoding it into memory by, for example, having the synaptic connections change the nerve cell in such a manner that the execution of a task can be put into a memory. This repetition is called weighing in neurological terms and results in the nerve cells and the networks they are involved in to incorporate memory. This is why memory is a general property of neural nets and a basis for adaptive behavior. Learned activity is stored in memory cells. Our device incorporates the plasticity needed for learning in the same device that encodes as memory. The extent of intelligence is due to the number of cells and number of interconnections. In summary, nerve cells that have plasticity change their structure with each learning incoming "pulse" which at a certain threshold level uses these very minute changes of structure to encode it as memory.[10,11]

We make devices that duplicate this action by having incoming information make minute changes in our neural device. These minute changes are almost exactly analogous to the nerve cell. When enough pulses are accumulated the information is completed, it is encoded in our device, and, like a nerve cell, our device fires and by a dramatic change in resistance connects itself to other devices undergoing the same activity. Being non-biological gives us advantages because each pulse is not based on timing, but is coherently involved with the next pulse in space rather than time. A mathematical operation can be started in our devices and, for example, 40 years can pass by and then the same formula can be completed. In humans the formula is likely forgotten years before! Arithmetic operations in brains are similarly done in single neurons.[12,13]

In other words, the coherence of the information is a result of a series of pulses summing up to a threshold. These thresholds can be changed and we have degrees of freedom not found in the brain because that memory is reversible. This is important in that we do not require excessive numbers of synapses and the devices can be reused for other tasks. The easiest way to understand what this paper is about is that with a much smaller number of neurons and synapses we can achieve cognitive function and amazingly achieve it even in a single cell. Adaptiveness and memory become synonymous.

Inputs can be optical, electrical, or others, and outputs can be directed to various types of human interfaces. Early applications include pattern recognition and will progress to more sophisticated functions. Our device can be used to factor large numbers and therefore be applied in coding/decoding. The synaptic pulses can be optical or electrical. They operate in the amorphous state where the information is very secure and cannot be forensically investigated. Therefore, they are perfect for encryption.

6. Duality of Energy and Information

Recall also that the reason that Iris and I called our company Energy Conversion Devices is that we have used as our fundamental concept that energy and information are opposite sides of the same coin, that information is encoded energy and that pulses of energy correspond to the storage of energy/information.

I have always said that the Ovonic phase change memory and the ovonic threshold switch have new rich and deep physics. When one sees the amorphous-crystalline transition or intermediate stages that can be detected optically or electronically, one sees that the transitions that are achieved can have many different kinds of inputs and many different kinds of outputs. Paraphrasing Marshall McLuhan, the media is in fact the message.

However, if one examines the mechanism shown in Fig. 5 from another viewpoint, the richness of physics that it contains shows that there can be new phenomena that can open up the field of phase change memory, transforming it into something entirely new with exciting potential.

This makes possible the ability to expand beyond the usual memory applications and at the same time to consider new unique operations such as cognitive computing and, in fact, aspects of quantum computing; the latter a desired but far distant goal.

Figure 6 shows that it is possible to have a "silent space"; that is, the storage of energy/information by optical means very much like the storage of energy shown in Fig. 4 by electrical pulses. It also shows the possibility that optical pulses, just like electrical pulses, can encode and entangle information in the amorphous phase. This is what we mean when we say that one can have a quantum computer analog that is realistic and operates at room temperature and above (the activity in the amorphous cognitive phase acts very much like having non-accessible, but real portions of a wavefunction, in which at a certain point the wavefunction collapses and the data emerges). The information stored in the amorphous phase can then be read out or combined with the multistate activities of the crystalline phase; that is, combined with either the binary crystalline phase or the multistate activities of that phase.

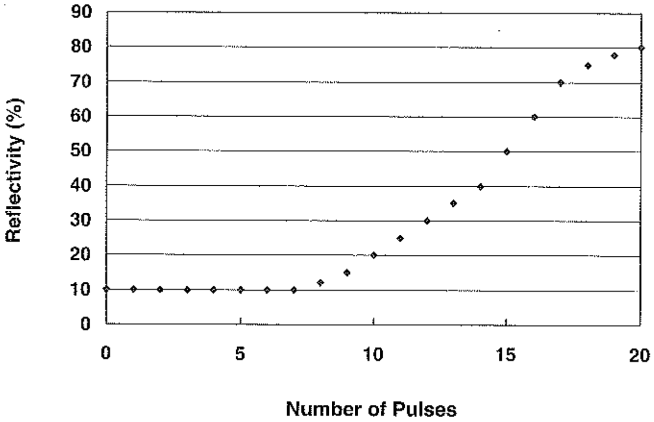


Fig. 6. Optical cognitive behavior of an Ovonic phase change material.

7. Multifunctional Operation

The device that I am describing can perform in one spot a unique multiplicity of tasks. Yet that spot can be as small or smaller than a hundred angstroms. In fact, it so scales that as one makes it thinner and smaller, all parameters show increased performance. Obviously, we cannot go smaller than the overall limits imposed by the wavelengths of light that are available to us optically. Therefore, the possibility of getting more information into one mark optically or electrically would be of great value. The unique mechanism that permits us to use the amorphous state as a means of storing information is a great advance; however, we are still in the early stages in the development of the optical mode of operation, while we have been demonstrating the electronic version for some time. We are pleased to say that we have received many complimentary validations of our cognitive computer work in the electronic area. It is the electronic area that will be the first to be commercialized. The reason for thinking in new ways optically is that the optical field of data storage needs new innovative approaches beyond making the mark size smaller and smaller. We are all familiar with the above noted wavelength limitations.

The mechanisms in Figs. 5 and 6 are a means of outwitting such limitations by having one spot/mark with the capability of storing not only a one or a zero, but having multi-capabilities that can also mathematically represent a greater number of events in that one mark. Both of these mechanisms enable the cognitive function of the device, and therefore we can design devices that work with electrical pulses, optical pulses, and combinations of these energy deliveries. For example, humans have their sensory inputs from their eyes that activate nerve cells and their synapses and the cerebral cortex that responds to direct electrical stimulation, which means that one can perform their functions from the use of optical or electrical input.

The capacity and versatility of an optical phase change memory is thus increased, opening up new important fields of applications.

It is my wish to stimulate the field by introducing new concepts into the optical phase change arena, for new scientific insights and mechanisms make this field very exciting.

What I am suggesting is not only an increase in storage, but the use of the same devices (that is, the same material in its thin film form), which are so widely used and that you are so accustomed to, to offer opportunities for not only nonvolatile reversible storage of information, but, in addition, for using these ideas that I have expressed and the data that I show to explore the expansion of the optical memory field so that optical activity can be used for logic, learning, etc. with a natural link to our ongoing work in the Ovonic cognitive computer.

In other words, marrying optical and electronic together to create new industries that offer unique, low cost multifunctionality in a mark that you already use for optical phase change storage.

In summary, I am proposing that for optical applications and for the marriage of optics and electronics we understand that we have a commonality. Our optical or electronic pulses are inputs of shaped energy that contain information. We have made devices that have transparent cover layers that enable us to address the memory cells by both electrical and optical pulses.

In our binary mode, we only need to use a single pulse, but the use of multi-sub-threshold pulses in the cognitive regime offers new possibilities for energy storage and information formation and therefore gives us greater freedom to investigate new applications for the field of phase change memory.

For example, the summation of pre-threshold pulses of energy, either electrical or laser, can result in the ability to factor numbers/information and perform other mathematical functions as well as being able to have neurosynaptic, that is, adaptive, learning capabilities. After all, human optical information is closely related to the pulse firing of cells and their response to various frequencies of light.

I have not mentioned that an advantage that we have in using our nonvolatile memories that the brain does not have is that the brain depends greatly on the timing of its prethreshold firing for its information.[14,15] While that can be a degree of freedom for us to utilize in our excitation activities, we do not require it for the mechanism described. It is just another degree of design freedom.

8. Other Members of the Ovonic Device Family

I am pleased to report that the Ovonic Unified Memory that makes it possible to have one device that has the potential to perform Flash memory, DRAM and SRAM functions is coming along very well under the Ovonyx joint venture which includes Tyler Lowrey, formerly technical head of Micron and Intel. Intel and STM have reported important progress and contributions. It is very encouraging to see that Intel and STM as well as additional powerhouse organizations such as Samsung, the Data Storage Institute and CEA-LETI are showing great interest in our field.

I also announced important new electrical devices such as an Ovonic multi-terminal device at the MRS meeting in Boston in December, 2003. I think that you can see that the amorphous and disordered field, with its unique switching and phase change activities, is living up to its potential and has many new possibilities.

Our colleague, Dr. Takeo Ohta, who has made through the years so many important contributions to the Ovonic optical phase change memory, reported on some of the OUM work at PCOS 2003. I would like to thank him deeply for presenting my paper and at the same time tell you how much I missed being able to be with you at that meeting.

There is much more to be said and much more to be done. This is a beginning and not an end. You are all my colleagues and collaborators and I feel privileged to unveil this new possibility to you. It has been an honor to have been invited here. Thank you.

My sincere and warmest best wishes and good luck to all of you.

Acknowledgements

I wish to express my deep appreciation and thanks to Boil Pashmakov, who is the co-inventor with me of the Ovonic Cognitive Computer. I would also like to thank the information team of Wally Czubatyj, David Strand, Takeo Ohta, Genie Mytilineou, Kevin Bray and the technical staff who have been involved in the preparation of our materials. David Strand has been the leader of our optical work and his important contributions are distributed throughout all of our semiconductor activities. I wish to thank Genie Mytilineou for her contributions and help as well as Kevin Bray who has been so valuable in our activities. As always, Iris is my inspiration and loving collaborator.

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