Chapter 1

A new information paradigm - the Ovonic Cognitive Computer

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We discuss our work on our optoelectronic devices and describe a basic new scientific and technological approach for information and computing use. The Ovonic chalcogenide materials exhibit the ability to not only accomplish conventional binary computing but are capable of nonbinary generation of information, storage and encryption, higher mathematics and neurosynaptic activity. Uniquely all of these functions can be accomplished in a single nano-sized device. These robust devices are not only nonvolatile but include devices such as the multiterminal Ovonic Threshold Switch and Ovonic Memory devices. The above functions have been demonstrated and we will describe the mechanisms.

Introduction

We discuss the unique optoelectronic properties of our Ovonic devices, past, present and in process. We conclude with a description of the mechanism of the Ovonic Cognitive Computer which can also operate optoelectronically.

The Ovonic Cognitive Computer is a remarkable new paradigm in computation since it is not based upon the serial, binary Von Neumann paradigm. It can perform many tasks that are not accessible to a conventional computer.

It is a unique non-biological neurosynaptic device and system that utilizes the plasticity that we atomically design into our chalcogenide material. The nanostructure devices which are analogs of neurons, dendrites and synapses gather multiple informational signals and interact with other devices resulting in a highly dense interactive and parallel matrix.

The devices have threshold activity, switching and memory that are analogous activity to that found in biological intelligence. Such informational / intelligent multifunctionality in a single nanostructure device is the source of a new paradigm.

Plasticity is the basic defining characteristic of biological intelligence and our Ovonic Cognitive Computer with its optoelectronic characteristics functions in this manner.

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The past

The Ovonic memory has always been an optoelectronic device. We demonstrated very early [1] that the same memory material which we utilized in our electrical memory, e.g., germanium, tellurium and antimony, functions optically in the same reversible phase change manner – from the amorphous to the crystalline state or vice versa. The mechanism is the same.

The name of our company, Energy Conversion Devices, that Iris and I founded in January 1960, reflects our premise that energy and information are opposite sides of the same coin and that information is encoded energy. In this paper we will show the proof again of that concept.

Indeed that very early basic concept has been repeatedly shown. See Fig. 1 [1]. The chemical energy barrier between amorphous and crystalline is overcome by various external energy inputs. The outputs are high signal to noise changes in many physical, chemical and electronic properties.

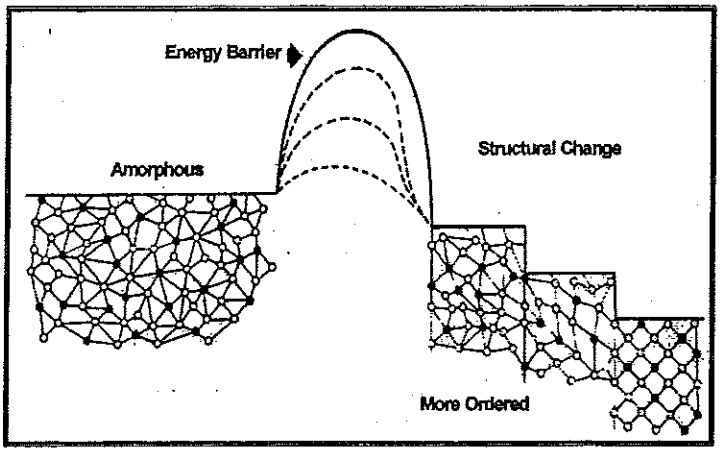

Fig. 1. The chemical energy barriers between amorphous and more order phases.

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

We will show later that the learning and memory (cognitive) processes of the optical and electronic versions of the Ovonic Cognitive Computer are fundamentally the same.

We have certain advantages over biological intelligence since not only are our devices nonvolatile and can have gray scale and multistate functionality, but also have very fast transition times as compared to neurons. Our computer can perform higher mathematical operations and the final calculations, if one desires, can be finished at a later time – for example, forty years later.

Optically, in the early days, I utilized electron beam and flash lamps to interact with our material; when lasers were introduced, they were very big and had very limited life. However, I utilized them as I described my optical approach to phase change in 1969:

"It is obvious that the drum that we have just described for our printer is a mass storage medium. Using the optical changes which occur simultaneously with the changes of electrical resistance when the material is switched, we have the basis for an optical mass memory. Densely packed data dots less than 2 microns in diameter are written with a finely focused laser beam and can be read out optically, such as by sensing the change in transmissivity or reflectivity as scattering that occurs in the material when it is switched. The data can be erased at will and new data written in the same location. In other words, the memory film is a beam addressable, beam alterable mass memory medium" [2].

I will finish the past by saying that when we began our work, amorphicity and disorder in materials were considered failure mechanisms by all but us and our dedicated colleagues, collaborators and some of our early supporters, heroes of the golden age of science exemplified by I. I. Rabi, Linus Pauling, John Bardeen, Bob Wilson and Kenichi Fukui.

Our own golden age was made up of our early collaborators--Hellmut Fritzsche, David Adler, Morrel Cohen, Artie Bienenstock, Heinz Henisch, Marc Kastner, and Neville Mott. Radu Grigorovici has a special place in our hearts.

Of course, we are very proud of the new generation of our talented, committed colleagues who are building the future with us. Internationally many more people are working in amorphous and disordered materials. It is a pleasure to note that Romania under Mihai Popescu is reassuming a leadership position.

Our work continues with the common theme that there is a mechanism for information encoding, retrieval and display based upon reversible structural transformations.

The Ovonic Threshold Switch, a nonvolatile, non-structural change device with under picosecond switching speeds which carries several orders of magnitude more current than the transistor, is recognized as is our Ovonic Memory as fundamentally new types of semiconductors [3, 4] and are now gaining much attention.

The connection between the Ovonic Memories and the Ovonic Threshold Switch is that they both follow my principles of atomically engineered amorphous and disordered materials that depend upon chalcogenide lone pairs that couple to either electric field or light.

We will not go into the atomic engineering principles of polymeric crosslinking and bonding which I developed which bring out the various

mechanisms and are the basis of the devices that we make. That has been well covered. See for example [1,5].

The universality of mechanism which has been associated with our inorganic materials also has applications in photography. We developed organo-tellurium (TeBAC) compounds that have the quality of being useful in making photographic film. These compounds can be made such that they undergo photochemical reduction, separating the tellurium atoms from the organo-metallic moiety. The tellurium forms microscopic needle-like particles, invisible to the naked eye [6].

When these compounds are formed into polymeric matrices and exposed to actinic radiation, the submicroscopic particulates can be thermally induced to agglomerate into larger crystals, although small enough for very high resolution image formation. Image-wise exposure and thermal processing of the latent images result in high resolution, full gray scale images. This instant, non-chemical processing, high resolution film is the only non-silver film that has amplification.

My interest in neurophysiology dates back to the 1940s and culminated in 1955 with my formal entrance into neuroanatomy and neurophysiology, working at Wayne University with Morin and Gardner on my ideas about the nerve impulse [7].

Realizing that the nerve cell had little relationship to the crystalline work with transistors, I proposed to work on disordered and amorphous materials and surfaces so that I could make a true nonbiological analog of a nerve cell. At Wayne Medical School, we worked on the mechanisms and interactions between the cerebral cortex and cerebellum [8,9].

This was the thread that Iris and I worked on. That theme was elaborated in a Mott Festschrift so that we could interest others in the amorphous field in the implications of Ovonic Phase Change devices with various energy inputs to biological system [10]. This favorite topic of ours will be readdressed when we describe the Ovonic Cognitive Computer.

Now to the present:

Having established that background, it is well known that Ovonic optical phase change is in wide use for such products as CD-RWs and rewritable DVDs. There are many companies all over the world who are utilizing our work in the optical field.

We are quite pleased that, in fact, the main scientific organization in this field, E*PCOS, last year changed its name from European Symposium on Phase Change Optical Storage to European Symposium on Phase Change and Ovonic Science. The Japanese scientists in this field are major participants.

Beyond the application of Ovonic Phase Change materials to optical and electrical data storage, and Ovonic threshold switching, other applications abound and these days the field is enjoying great growth. It is important to remember that in the past we have shown that not only visible light but the rest of the spectrum down to the electron beam can induce phase change. Scaling down of the phase

change spot size started with less than 100 angstroms from the electron beam in the early 1960s.

Solid state lasers became a preferable light source for our optical phase change discs, making for an all solid state system which became a burgeoning international field. The reduction in spot size for the phase change memory has accelerated with the introduction of the solid state blue laser. This has permitted us to make use of our scaling capability so that now information density is increased to 23GB and our spot size is approximately 0.16 microns.

Ohta, an important contributor to our field, following my urging that we extend phase change to much higher speeds, achieved femtosecond results [11]. We shall still advance.

In process:

We invent the materials, the products and the production technology that have opened up our field to new vistas. For example,

Frequency selective surfaces

Ovonic Phase Change materials can be used as the basis for fabricating frequency selective surfaces. These devices have patterned surfaces, comprised of conducting or diffractive elements. Each element can have a segment of Phase Change material in it, such that by switching the phase change material between the amorphous and crystalline phases, the impedance is changed, and the configuration of the surface is modified. In this way the surface changes its response to incoming radiation. Another important application in this field is that of having a non-moving part reconfigurable antenna.

All optical switching using phase change materials

Ovonic tellurium-based chalcogenide reversible phase-change materials developed in the early 1960s [1, 3, 4] undergo large changes in their optical and electrical properties as they transform from the amorphous to the crystalline states as a result of fundamental differences in the bonding chemistry of each state. We exploit the large differences in the complex dielectric function [ε_1, ε_2] of Ovonic Phase Change materials for the purpose of switching light signals at or near the 1550 nm wavelength. There are several features of Ovonic phase change materials that are attractive for this purpose, including: (a) a strong natural bi-stability; (b) high index and extinction contrast between the two states; (c) high switching speed; (d) a non-mechanical actuation; and (e) proven reliability. We are developing two types of devices: a broad-band provisioning or routing switch, and a narrow-band demultiplexing switch. Although the two formats are quite different, both are

guided by a unified principle based on Ovonic Phase Change materials properties, and together, they bracket a rich range of integrated platforms.

An important performance aspect is the bi-stable or latching nature of the switching elements. Once the material changes between amorphous and crystalline states by absorption of suitable energy, the states will persist after removal of that energy. Furthermore, the switching speed is quite fast. Amorphization occurs in sub-nanosecond time and crystallization ranges from 10 to 60 ns, which is about five orders of magnitude faster than switching speed achievable with MEMS micro-mirrors. Moreover, the absence of moving parts also removes issues of robustness. Reliability is also a key feature of this technology. ECD has demonstrated switching above 10^{13} cycles for phase change devices.

One device we are developing is a stationary mirror that can steer a beam of light by controlling the optical phase of reflection at each point of the mirror. Our first application is broad-band switching where we alter the direction of optical light beams using phase angle controlled stationary elements in a subwavelength (no diffraction) mirror array. The underlying concept is similar to that of a phased array antenna [12].

In our device we rely on properties of Ovonic Phase Change materials within multi-layered optical stacks to locally control the complex Fresnel reflectance coefficient. The angle between the real and imaginary parts of this complex quantity is by definition the phase angle upon reflection from this optical stack.

By controlling the physical state of the Ovonic Phase Change layer, we locally alter the complex reflectivity, and in this manner establish a latching phase-taper. In principle, we can have light normally incident onto the device and reflected at arbitrary angles. Using one material, the range in phase angle is about 128°, with a moderately high reflectance ($R > 64$ %) for both the amorphous and crystalline structures. The reflectances in the amorphous and crystalline states are essentially identical, thus making the reflection of the device dependent only on the phase angle. Higher values of reflection and phase angle can be achieved. The angular deflection of a light beam for the device depends on both the phase angle and the array's lateral physical dimension so that for a phase angle difference of 128° we can achieve nearly 20° of angular control.

The required variation in crystal fraction across the device can be accomplished by systematically varying the amorphous/crystalline volume fractions using a laser wavelength shorter than that of the light we are steering. The volume fraction of amorphous content can be controlled by suitable selection of power and duration of the laser pulses [13]. We are able to establish the volume fraction distribution on a size scale that is far smaller than the reading wavelength. The light will simply see a smooth taper in the optical phase angle.

Another switching device we are developing is a channel drop filter constructed from a photonic crystal, where the Ovonic Phase Change material will control the resonance state of the switching cavity. This is complementary to the

broadband provisioning application of the mirror device, in that it performs highly frequency-dependent switching, in the form of tunable or on/off resonators.

Narrow-band channel drop resonant filters are usually conceived as passive devices [14], but the addition of a switching function is extremely desirable, in that it can supplant expensive and power-hungry routers downstream from the filter array. In a photonic bandgap (PBG) setting, channel drop filters not only provide the highly touted advantages of subwavelength size and extremely narrow wavelength response [15], but can be designed in a form that uses the switching properties of Ovonic Phase Change materials to important advantage.

Each resonator becomes switchable by changing the phase between a lossy crystalline phase and a relatively non-lossy amorphous phase. The phase change is performed optically or electrically.

The Ovonic Cognitive Computer

It is impossible to give here more than the highlights and describe the basic mechanism of this fundamentally new transformative computer. It is a new paradigm for the generation, storing and transmission of information and the first non-biological means of achieving cognition [16].

It has important implications as well to the semiconducting industry which has already begun using our Ovonic Universal Memory that has the ability with a single device to replace flash memory, DRAM and SRAM.

Fig. 2 shows a comparison of the features and operational characteristics of conventional silicon elements and arrays with those of the Ovonic Cognitive Element and Computer.

Note three important points. One that an Ovonic Cognitive Computer device is both a memory and a logic element in one device; two that memory can be distributed and not a separate function; three that we utilize not only the Ovonic Threshold Switch but that we have unique three-terminal devices that can replace transistors and carry several orders more current and yet are in the picosecond range in speed. Our devices are inherently scalable, e.g. they can be scaled down to the tens of angstroms range.

We show in Fig. 3 the response of our Ovonic Cognitive device as a function of electrical energy (lower axis) applied to the cognitive device in the form of current pulses. The amorphous regime, which in the past has been considered silent regarding information, is where the pre-threshold pulses act. The pre-threshold states are the equivalent of the coherent and entangled states of the quantum computer. In contrast to quantum computers, they are non-volatile; new pulses needed to complete a computation or encryption can be added much later (e.g. over forty years later). The devices are also radiation hard.

Conventional Silicon Computers	Ovonic Cognitive Computer Multifunctionality in a Single Element
Each Element: •Computes based on single bit (binary) manipulation • Manipulates data sequentially, bit by bit	Each Element: • Manipulates, processes and stores information in a non-volatile fashion • Hardware and software are unified • Low voltage and low current operation • Performs arithmetic operations (+,-,x,÷) on multi-bit numbers (0,1,2,3…n) • Performs modular arithmetic • Executes multi-valued logic • Stores the result in a non-volatile manner • Simple, powerful encryption • Acts as a neurosynaptic cell; i.e. possesses intelligence capability • Scales down to nanoscale dimensions; huge density • Device speed is in the picosecond range • Capable of massive parallelism • Combines logic and memory in a single device • 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: •Requires separate storage and processor units or regions • Has limited parallel processing capability • Is limited to Von Neumann operations	An Array of Ovonic Cognitive Elements working as a System: • Easily factors large numbers • Performs high level mathematical functions (e.g. vector and array processing) • Has high 3-dimensional interconnectivity, huge density, giving rise to high speed, hyper-parallel processing (i.e. millions of interconnected processors) • Has adaptive learning capability • Interconnectivity is simply and inherently reconfigurable • Can generate dynamic activity
	The Ovonic Cognitive Devices are: • Mass produced in exceptionally dense, all thin film, uniquely interconnected arrays • Mass manufactured as a thin film, flexible device using proven technologies • Ovonic "transistor" unique high speed low cost 3-terminal device. Nanostructure capable of carrying large amounts of current both in nonvolatile and volatile modes

Fig. 2. Ovonic Cognitive Computer. Comparison with conventional silicon computers.

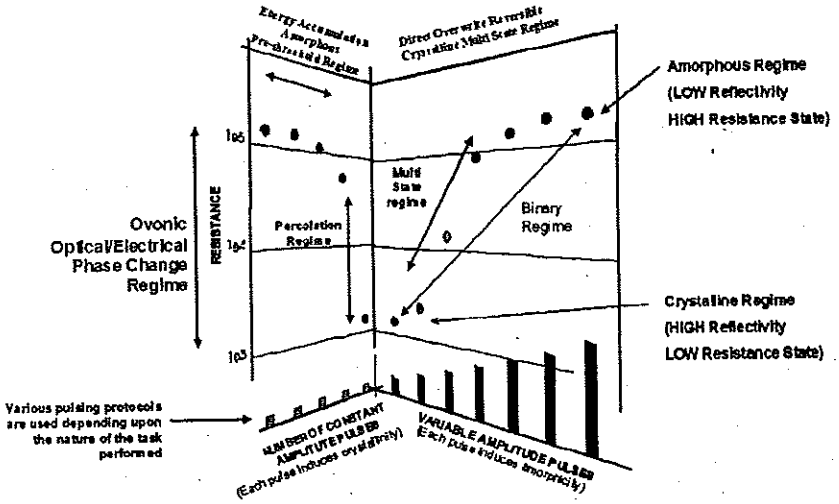

Fig. 3. Resistance characteristics of an Ovonic Cognitive Device. The cognitive amorphous pre-threshold synaptic regime (left side) culminates in a percolative transition to crystalline material, the equivalent of neurosynaptic switching. The resistance change accompanying the transition to the crystalline regime can provide readout and transferring of a completed signal to other devices. The leftmost and rightmost data points of Fig. 3 (the high resistance endpoints) both correspond to material that is substantially amorphous and the material becomes increasingly crystalline toward the center of the figure, with the lowest resistance states having the greatest crystallinity. The right side is the multistate crystalline cognitive regime (CCR). One should look upon the left side as being either standalone when the crystalline sums up the synaptic information or united with the activities of the right side.

The response of the material to the current pulses can be described via the two general response regimes depicted in the folded presentation format shown in Fig. 3. The fold coincides with a minimum in the resistance and demarcates a low constant amplitude pulse regime to the left from a higher current variable amplitude pulse regime to the right. The higher current range shows the multistate activity of our Ovonic electrical memory [1, 5].

Operation in the variable amplitude regime (VAR) requires a minimum current pulse amplitude and this minimum amplitude pulse produces the lowest resistance (highest crystallinity) state in the VAR regime. The amorphous-crystalline transition utilizes a reversible phase-change mechanism.

Our Ovonic cognitive devices make use of new mechanisms in the deceptively simple single, amorphous, nano-dimensional spot in the low current operational regime shown to the left of the fold in Fig. 3. As current pulses are applied in the cognitive regime, minute nanocrystalline regions form, the volume fraction of such crystalline phases increasing with each current pulse. Crystallization can occur through nucleation/growth upon the application of a

current pulse. The nanocrystallites generated by a sequence of pulses form a coherent sequence of states.

The nanocrystallites are distributed randomly throughout the chalcogenide material. As they grow, a percolation path results, a continuous, high-conductivity pathway across the material between the contacts. Once percolation has occurred, the material exits the amorphous cognitive regime and enters the right side, the CCR regime, if desired. Otherwise, the material can be reset to an amorphous state [17].

Accumulated energy, rather than current pulse amplitude, is a more fundamental representation of the modification of the Ovonic chalcogenide material in the cognitive regime. The increment of crystallization that occurs upon application of a current pulse is dictated by the energy deposited by the pulse into the material. This is an essential feature of the cognitive functionality of our new device because the structural state (defined by its crystalline volume fraction) of the material at any point in the cognitive regime is a manifestation of the total accumulated energy applied to the material. The crystallites represent stored energy that has encoded meaning. This stored energy represents what we mean when we say information is encoded energy.

The accumulative nature of the cognitive regime also provides a close analogy to the neurosynaptic functionality essential to cognitive behavior in biological organisms [8-10]. In the cognitive regime, each application of energy to our adaptable polymeric material induces a partial crystallization of the material to an extent characteristic of the applied energy. Upon removal of the energy source, the material remains in the partially crystallized state until exposed to energy once again. Since the pulse energies in the cognitive regime are sufficiently low to prevent reversion of crystallized regions back to the amorphous phase, the crystallization process is stable until one desires to erase it or make it reversible as in the Ovonic memory. The structural state is thus a record of the energy accumulated by the material.

Fig. 4 shows how nerve cells and synapses operate biologically. The incoming information comes through the synapse and when summed in energy to a threshold condition, the nerve cell fires and sends the information to other cells.

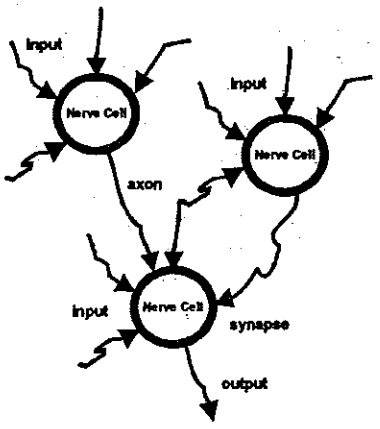

Fig. 4. Nerve cells and synapses.

Just as one does not design an airplane to flap its wings, so does a nonbiological analog of a nerve cell not need to have the same configuration, for example, the threshold in firing is incredibly analogous to the nerve cell action; the synapses are replaced from being actual points on the interface of a cell with the incoming signal coming from dendrites by nanostructure changes in the amorphous state which act as synapses - they are indeed very similar in function to synapses.

It is important to note that synaptic information is realized through coherent activity. We simulate that activity by evolving information through incoming energy pulses. The intelligence in the pulses is encoded energy where one pulse by itself has no meaning but the various pulses coherently sum up to a complete bit of information.

Unlike a proposed quantum computer many years away, our approach operates at room temperature and above, is stable, nonvolatile, impossible to decipher and there is no decoherency problem, the crucial difficulty of quantum computing. Our information can only be made decoherent by outside probing to determine the encoded information which destroys the information by so doing.

There is a great deal more to be said. However, it would require a book, not a chapter. I will close by showing in Fig. 5 that the same synaptic and firing effects on the left side of the U are achievable by optical means by replacing electrical energy with optical energy. In other words, we have shown the equivalence of mechanism in both the optical and electrical operation of the Ovonic Cognitive Computer. Fig. 3 shows the multistate optical characteristics, which permit many detectable states in the same nanostructure spot just as in Fig. 7, which occurs on the right hand side of the U and has been switched electrically. These figures show the equivalence of the multistate memory storage when using optical or electrical energy inputs.

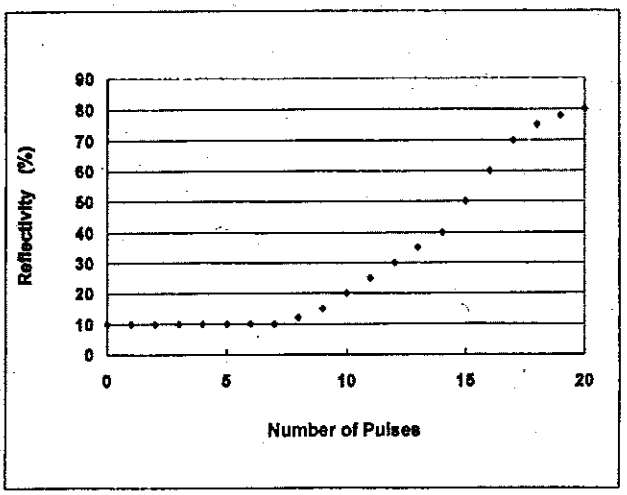

Fig. 5. Optical Ovonic Cognitive Effect. The figure shows the behavior of the reflectivity in response to 20 optical pulses of the same duration and amplitude. The first seven pulses produce no change in reflectivity, but obviously affect the material so that it starts to show reflectivity change on the eighth pulse. The region where no reflectivity change occurs is the cognitive effect.

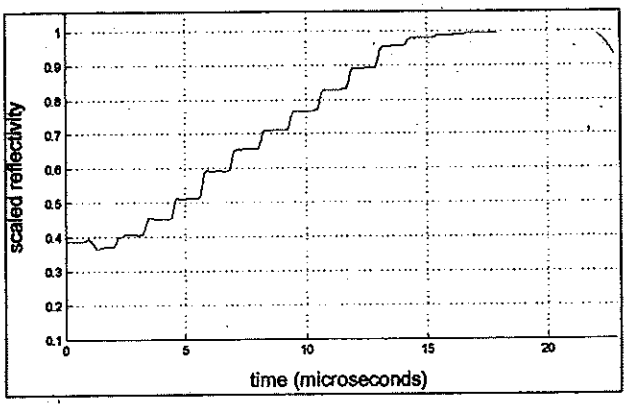

Fig. 6. Ovonic Optical Multi-State Data Storage. The figure shows the reflectivity achieved after application of pulses of differing energy (constant power, different duration). The process is direct overwrite, in that any state can be achieved by application of the same pulse, independent of the starting state of the material.

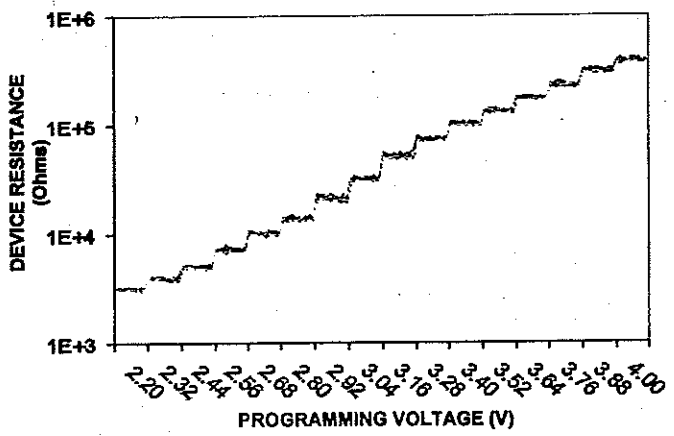

Fig. 7. Ovonic Electrical Multi-State Data Storage. The stepwise appearance of the data in the graph arises from the testing sequence. We programmed the device a total of 1600 times, or 100 times at each applied voltage. We first applied ten programming pulses at one voltage, measuring the resulting 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.

In summary, hybridization of optical and electronic cognitive devices and computers will be the most realistic way of introducing optical computers. The future will be not only hybridization including crystalline substrates which we have achieved with our Ovonic Threshold Switch and memories, but one where the entire circuits will be on thin film flexible substrates such as we have achieved with our eleven layer Ovonic semiconducting photovoltaic triple junction amorphous silicon alloy and amorphous silicon and germanium alloy where some layers are under a hundred angstroms and the substrate is thin film plastic with the entire thickness of the active material being less than a half micron. Obviously the Ovonic triple junction solar cell is an optoelectronic device.

This proprietary triple junction continuous web production machine (Fig. 8) is capable of making 9 miles and 6 tons of thin film photovoltaics in a single run.

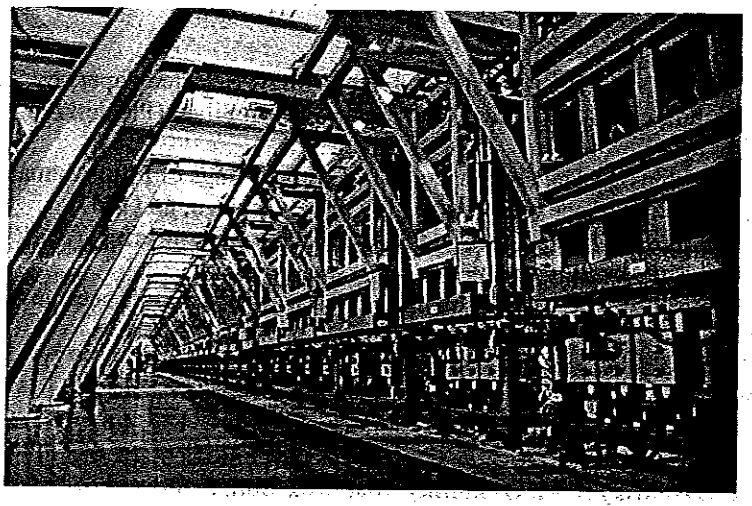

Fig. 8. The 30 MW annual capacity photovoltaic manufacturing machine using ECD Ovonics proprietary continuous roll - to - roll solar cell deposition process.

Such machines can be adapted to many other industrial usages. For example, ECD is currently involved in developing a roll-to-roll manufacturing line for Organic Light- Emitting Diodes (OLED devices). Such an approach will be applicable to display and other optoelectronic OLED applications. We are also involved in developing surface treatments and manufacturing methods to adapt flexible stainless steel substrates for OLED and other display applications.

In this paper we have sought to show the rich and deep physics that has been achieved in amorphous and disordered materials. We have clearly shown that energy and information are opposite sides of the same coin and the coin is our atomically engineered amorphous and disordered material.

Acknowledgements

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