

**Amorphous and Disordered  
Materials – The Basis of  
New Industries**

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## AMORPHOUS AND DISORDERED MATERIALS – THE BASIS OF NEW INDUSTRIES

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### ABSTRACT

As in the past, materials will shape the new century. Dramatic changes are taking place in the fields of energy and information based on new synthetic materials. In energy, the generation of electricity by amorphous silicon alloy thin film photovoltaics; the storage of electricity in nickel metal hydride batteries which are the batteries of choice for electric and hybrid vehicles. In the information field, phase change memories based on a reversible amorphous to crystalline transformation are widely used as optical memories and are the choice for the new rewritable CDs and DVDs. The scientific and technological bases for these three fields that have become the enabling technologies are amorphous and disordered materials. We will discuss how disordered, multielemental, multiphase materials can throw new light upon metallic conductivity in both bulk and thin film materials. We will demonstrate new types of amorphous devices that have the ability to learn and adapt, making possible new concepts for computers.

### INTRODUCTION

The great advances in civilization have been based on materials – the Stone Age, the Bronze Age, the Iron Age. The interaction between materials and the industries that have transformed society was the driving force for the Industrial Revolution. The twin pillars of our society today are energy and information. In a deep sense they are opposite sides of the same coin. They both must be generated, stored and transmitted. Information is structured energy that contains intelligence.

I will show how a new scientific approach to materials based upon disorder and local order can enable the development of new pollution free technology which will answer society's urgent needs to reduce its dependence upon uranium and fossil fuels, particularly oil; the latter is a causative factor not only in climate change but a root cause of war. Science and technology which can change the world's dependence on it can create new huge industries so necessary for economic growth. \$30 trillion in 30 years for new electricity alone [1]. Furthermore, over 2 billion people in developing countries are without electricity. Electricity is the fundamental requirement of modern life and the common link between energy as an undifferentiated source of power and energy which can be encoded, switched and stored as information.

Devices made of amorphous and disordered materials have become the enabling technology for generating electricity through thin film photovoltaics which can be cost competitive to fossil fuels, for storage of electricity in batteries for electric and hybrid vehicles, ushering in a new, much needed transportation revolution, and high density switching and storage media based on phase change optical and electrical memories, so needed for our information society. Computers which have adaptability, can learn from experience and provide neuronal and synaptic type intelligence, are being made possible by devices described here.

How is it possible that multi-elemental disorder can be the basis for such "revolutionary" possibilities [2] when it is well-known that the great success of the 20<sup>th</sup> century, the transistor is based upon the periodicity of materials with particular emphasis on one element, silicon? Indeed, with the great success of the transistor based upon the crystal structure of germanium and silicon, we entered the historical era where achieving crystalline perfection over a very large distance became the sine qua non of materials science.

From a materials point of view, the physics that made the transistor possible was based upon the ability to utilize periodicity mathematically which permitted parts per million

perturbations of the crystalline lattice by substitutional doping. But right from the beginning, the plague of their disordered surfaces prevented for a decade the fulfillment of the field effect transistor. The disorder of the surface states swamped out the transistor action. Emphasizing again Pauli's statement "God created the solids, the devil their surfaces" [3]. The irony was that the solution that made not only the field effect transistor possible but also the integrated circuit which became the basis for the information age was the utilization of amorphous silicon oxide for photolithography and for the gate oxide.

When I introduced the idea that there was a new world of interesting physics and chemistry in minimizing and removing the constraints of periodicity [4,5], one can understand the resulting consternation of the solid state physicists who had received their Ph.Ds by accepting the dogma of periodicity as being the basis of condensed matter and of the theoretical physicists to whom the control of many elements was as incomprehensible as the conundrum of many-body theory. The change from periodicity to local order permitted atomic engineering of materials in a synthetic manner by opening up new degrees of design freedom. Literally many scores of new materials could be developed and new physical phenomena could be displayed, new products made and new process dependent production technology invented.

Disorder is the common theme in the minimization and lifting of lattice constraints, (what I call the tyranny of the crystalline lattice) which permits the placing of elements in three-dimensional space where they interact in ways that were not previously available. This allowed the use of multi-elements and complex materials including metals where positional, translational and compositional disorder removed the restrictions so that new local order environments [6,7] could be generated which controlled the physical, electronic and chemical properties of the material. Just as the control of conductivity through doping was the Rosetta Stone of understanding and utilizing the transistor, the unusual bonding, orbital configurations and interactions affecting carriers, including ions, are the controlling factors in disordered materials [8-11].

The tools that I utilize for generating these configurations are hydrogen, fluorine, f- and particularly d-orbitals, and nonbonding lone-pair orbitals of the chalcogens. The latter, like the d-orbitals, can be distinguished from their cohesive bonding electrons, freeing them for varied interactions. Even in a sea there are channels and currents affected by topology and climate; in a metallic sea of electrons, we can design paths, control flow and make hospitable environments for incoming ions/protons. Since we are designing new local environments, we also utilize rapid quench technology to make for non-equilibrium configurations and offer a new degree of freedom for the production of unusual local order. Of course, rapid quench and non-equilibrium are associated with vacuum deposition, sputtering and plasma generated materials, in brief, such materials are process dependent.

The understanding of these basic premises became a design tool which we applied universally across the periodic table to build new types of semiconductors, dielectrics and metals. We showed that we can control the density of states in a band/mobility gap affecting conductivity in several ways including chemical modification and the generation of chemically reactive sites [12,13] so as to design, for example, complex, disordered, metallic electrodes of our nickel metal hydride batteries. What we mean by complex is not just that there are many elements, but that we build into a material a chemical, electronic and topological system which performs in the same material various functions such as catalysis, hydrogen diffusion paths, varying density of electrons, acceptor sites for hydrogen, etc. Such a material system in a battery must provide high energy density, power, long life and robustness [14-17].

To put into perspective the principles of disorder, what is required is a metaphor. It is helpful to continue the analogy of the sea. In ancient times, the earliest explorers stayed as close to the shore as possible; there were many things to discover that way – new people, animals,

physical environment, things could be strange but understandable. However, to explore the great unknown ocean, they were filled with anxiety for out there was the end of the world and where the dragons lay. Navigational skills were needed to avoid dangerous shoals, utilize favorable currents, etc.

As I pointed out in the 1970s [18-19], amorphous tetrahedral materials to be useful would have to be as close to the four-fold coordination of their crystalline cousins as possible, otherwise, the huge density of states of dangling bonds would prohibit their use. Hydrogen and fluorine were able to act as organizers to assure sufficient four-fold coordination resulting in a low density of states so that the materials could be electronically useful, a necessity for successful photovoltaic products [20,21]. Hydrogen not only capped dangling bonds, but was also valuable as a bridging element providing the connectivity between the silicon atoms and under the proper circumstances assuring enough four-fold coordination. I chose fluorine since it is the superhalogen and provides a much stronger bond and, most importantly, expands the undercoordinated bonds of silicon and germanium so that they can have their full tetrahedral structure. Fluorine also provides useful functions in the plasma and on the surface in the growth of the film. It does its job so well not only in intermediate order but as a preferred element to make microcrystalline tetrahedral materials [22] as well as thin-film diamond-like carbon [23]. It also played a role in making superior superconducting films [24].

The most exciting physics lay in the unexplored ocean that I have been working in since 1955 with our only nautical chart the periodic table and physical intuition our compass. Even though disordered materials could not be easily categorized mathematically, one can constructively design nonequilibrium, nonstoichiometric graded and mixed phase materials to discover new phenomena [8].

In order to follow the exploration process, we will intermingle the relevant scientific and technological approaches with the materials, products, and technologies made possible by utilizing the freedom permitted by disorder to design and atomically engineer local environments.

## **ENERGY GENERATION –PHOTOVOLTAICS**

In photovoltaics, we started our exploration relatively close to the silicon shoreline but had to push further out because contrary to conventional thinking, elemental amorphous silicon had no possible electronic use and therefore required the alloying described above so as to eliminate dangling bonds and yet to retain its four-fold coordination. I felt that it also required new technology befitting its thin film form. Rather than choosing heavy glass as a substrate, we used flexible, thin stainless steel as well as other flexible materials such as kapton.

A historical perspective is needed to show the interaction of science, technology and product. Starting in the late 1970s, we invented the materials, the products and designed and built six generations of production machines utilizing our multi-junction, continuous web technology, the most recent, our 5 MW machine shown in Fig 1. These machines, designed and built at Energy Conversion Devices (ECD), manufacture much needed, simple products using our advanced science and technology and, most importantly, this continuous web approach has shown that it is possible in larger machines to make solar energy cost competitive to conventional fuels. This, of course, would set off an enormous positive change in the use and economics of energy. The plasma physics involved in such a machine makes it possible to discard the power consuming crystal growing methods of crystalline semiconductors and the billion dollar costs now involved in building crystal wafer plants. In crystalline materials, the investment and throughput are linearly coupled, in our amorphous thin film technology, a 4 times increase of capital investment (in the millions of dollars) would yield a 20 times increase in throughput.



Fig. 1

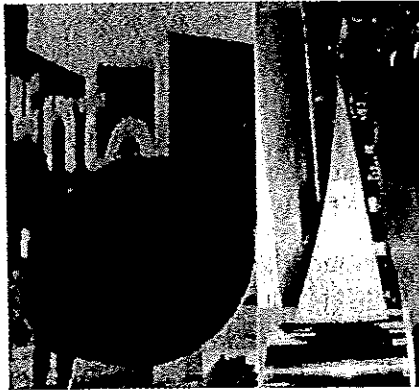


Fig. 2

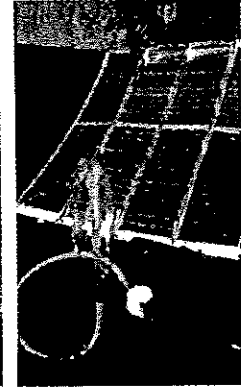


Fig. 3

Fig. 2 shows a 3 inch crystalline wafer (at bottom, center), the state of the art of semiconductors at the time, and what Gordon Moore and Bob Noyes, founders of Intel, utilized as opening humor for their talks, a huge cardboard "wafer", representing what they felt would be the electronic requirements of the 90s. On the right, made in our second generation continuous web machine in 1982 for our joint venture with Sharp Corporation, is the first half mile long, over a foot wide roll of a sophisticated multi-junction thin film semiconductor solar cell continuously deposited on thin, flexible stainless steel. This revolutionary new process was the answer to the fantasy of the cardboard wafer. Obviously the roll could be made much wider and longer. I have called our photovoltaic roll an infinite "crystal".

In order to show the extreme light weight, high energy density potential of our approach, we deposited our films on kapton and demonstrated in 1984 the highest energy density per weight of any kind of solar cell. This is shown in Fig.3 in a water pumping application at that time. These days the same approach is beginning to be utilized for telecommunication, space and satellite applications by Guha, Yang and colleagues[25]. The power density in thin film stainless steel and especially kapton which can store almost 3000 watts per kilogram is so exceptional as to become the solar cell of choice for telecommunication. Just last month, in November 1998, an amorphous silicon solar array was installed on the MIR space station. It was fabricated in Troy, Michigan by United Solar Systems Corp (United Solar), (ECD's joint venture with Canon), and assembled in Russia by Sovlux, ECD's Russian joint venture with Kvant, the developer of the original photovoltaics on MIR, and the Russian Ministry of Atomic Energy.

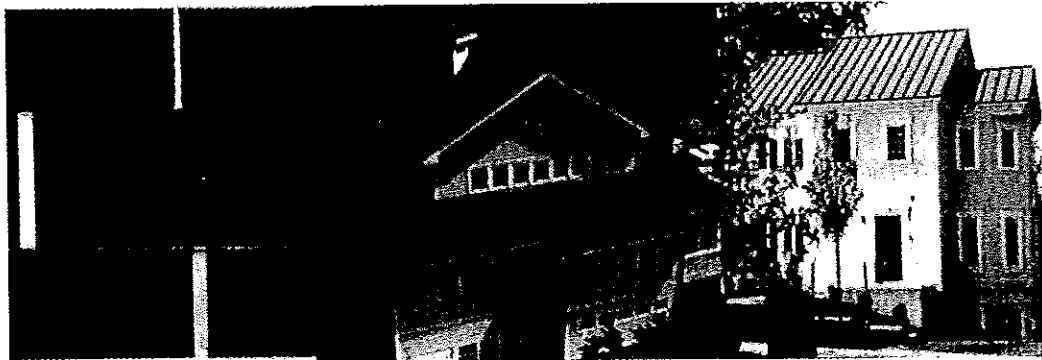


Fig. 4

Fig. 5

Fig. 6

Fig. 4 shows shingles made in 1980 [26] providing a new paradigm for energy generation. Paradigm shifting takes time. Figs 5 and 6 are current installations of the shingles and a standing seam roof. These products are gaining widespread approval. Fig 7 shows former Secretary of Energy Pena displaying our solar shingles in 1998.



Fig. 7

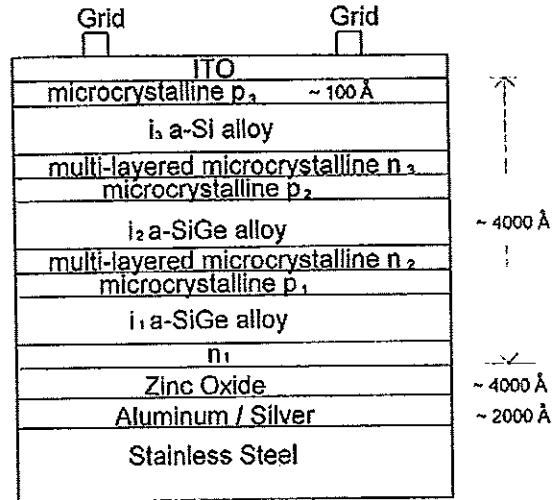


Fig. 8

Fig 8 is a schematic of our triple-junction solar cell showing its multi-layered configuration wherein light can be absorbed in sub-cells with different bandgaps so as to utilize as much of the sun's spectrum as possible. The blue, green and red light is absorbed in layered thin films of amorphous silicon and germanium alloys containing hydrogen/fluorine. ECD and United Solar have all the world's records for efficiency, culminating in the latest world record of 10.5% stable efficiency on a one square foot module and 13% stable efficiency on a .25 square cm cell [27].

Amorphicity is crucial for several reasons. Unlike crystalline tetrahedral materials in which quantum mechanical selection rules make for indirect bandgaps and require layers of 50 to 100 microns in order to absorb the light energy, amorphous materials act as direct band gap materials and therefore the entire triple layer system is less than 1 micron in total thickness. It is important to note that in crystalline materials of different bandgaps, lattice mismatch is a serious problem and therefore such multi-layered structures could not be made in a production manner. In this case, we can see that amorphicity and the physics make possible continuous web production. Amorphous photovoltaics illustrate that when one removes the lattice constraints, atomic engineering can be merged with machine engineering to provide a new, much needed approach to energy generation.

There has been much ongoing work in photovoltaics at ECD since 1977 [28], advancing the science and technology of materials, production processes and new products. At the MRS 1998 Spring Meeting, my collaborators, Guha, Yang and coworkers at United Solar, who have made very significant contributions to our work, gave an excellent review of our recent commercialization progress [29]. The ECD-United Solar team, which also includes Masat Izu, Prem Nath, Steve Hudgens, Joe Doehler, Scott

Jones and Herb Ovshinsky among others (the latter the head of ECD's Machine Division which has designed and built our continuous web processors) has through the years made important contributions to our field and has been working on products, production and plasma technology that increase throughput.

From a materials science point of view, we note several points of importance. While amorphous tetrahedral materials are close to the crystalline shoreline in their need for low density of states and substitutional doping, being direct bandgap materials, one can make large area, thin film multi-junction devices by the decomposition of plasmas in a continuous manner. Accomplishing this, we were able to basically alter the way materials could be laid down in a continuous manner, showing the tight coupling in amorphous materials between basic science and advanced technology.

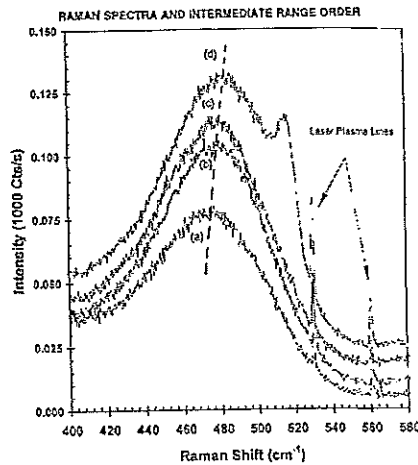


Fig. 9

Illustrating the scientific and technological richness of amorphous materials is the ability to develop intermediate range order in an amorphous matrix as we do in the intrinsic silicon alloy layer of our photovoltaic product [11,30]. (Fig. 9) It is of great interest that quasi one-dimensional ordering is accomplished without introducing grain boundaries that would interfere with electron and hole conductivity. This intermediate state is the signature of the best material. We have shown that fluorine is a great facilitator of intermediate order [31-34] and leads to crystallization. The intermediate order has important implications for the future. It is possible that the carriers have increased mobility due to the intermediate structures and could affect the important parameter of hole mobility in these materials. Microcrystalline materials can also have unique properties that bridge the gap between crystalline and disordered solids. We have incorporated them in our continuous web process by utilizing fluorine [11,21] to make under 120 angstrom micro-crystalline silicon p-layers. When one considers that this is accomplished in a continuous web, very high yield production process, it can be appreciated that atomic engineering and manufacturing are a reality.

#### ENERGY STORAGE – NICKEL METAL HYDRIDE BATTERIES

Nickel metal hydride batteries are in a real sense misnamed, for while nickel, by virtue of its filled d-orbital, plays an important catalytic role, there are usually seven or eight other elements that make up the alloy used in the negative electrode; certainly hydrogen is the key component. It is the smallest and simplest atom in the universe (which, by the way, in terms of

actual matter is composed of over 90% hydrogen). Therefore, to attain the highest energy storage density not only for batteries but for hydrogen as a fuel is a matter of designing the highest density of reversible hydrogen sites. This can be accomplished by our principles of disorder and local order [11,14-17,35]. From 1960 on, we have demonstrated that hydrogen is not just a future source of energy but a here and now solution that, together with solar energy, offers the ultimate answer to society's need for clean, virtually inexhaustible energy.

Energy technology should be regarded as a system. We have described energy generation. Equally as important is energy storage. Now we must go much further from shore in order to discuss the basis for the materials used for energy storage and later for information which is structured energy and must also be stored.

In the energy storage area, we cannot discern the shoreline, we are in the ocean of many-body theory which has never been adequately understood. I have had a long interest and worked for many years with d-orbital materials [36]. A recent publication sums up present day advanced thinking regarding d-electrons: "d-electron-based systems, in particular, present the combined intrigue of a range of dramatic phenomena, including superconductivity and itinerant ferromagnetism, and the tendency toward inscrutability associated with the fact that key electronic states are often intermediate between the ideals of localization and itineracy which provide the starting points for most theory" [37]. By making multi-elemental, multi-phase d-orbital materials for hydrogen storage in a completely reproducible manner, it is clear that we have been able to understand how to take the mystery out of them and utilize these orbitals in new and unique ways.

We are literally at sea when we discuss metals for they are always described as being composed of a sea of electrons. Why does the sea not swamp out the background provided by local atomic environments? Paradoxically, this is because when we use many, for example, ten, different atoms, particularly those with directional d-orbitals, to make up a material such as the negative electrode in our nickel metal hydride battery, we provide through the disordered state regions of lower electronic density which have a larger probability to overlap with negative hydrogen ions in interstitial sites. To simplify, one can say that it is the s-electrons that provide the sea, the d-electrons sculpt out the channels and receptors. Obviously there is some hybridization possible in many of these materials.

It is in the multielemental f- and particularly the d-orbital material that we introduce a means of delocalizing electrons and still have them represent their parentage. This is where internal topology begins to play an important role in metallic conduction for, as noted, we need channels in the sea of electrons just as we take into account sea level/Fermi level. The different types of atoms provide the interatomic spacings for the hydrogen ions to operate in and the varying electronic density is the steering means for the ions to reach the preferred sites of low electron density. Disordered materials are therefore necessary to provide the spectrum of binding sites. In summary, large interatomic spacing and low energy density make for the optimal binding/storage of negative hydrogen ions. The electron environment surrounding the hydrogen provides the degree of negativity and coulombic repulsion is the steering means. The binding energy provided by the local environment is of such a nature as to assure reversibility so important for the rechargeable battery. While we list characteristics of individual atoms in Fig.10, it is how they act and interact in the alloy that makes for the mechanism that we have described above.

The acceptance of nickel metal hydride batteries has been very rapid. All significant manufacturers of nickel metal hydride batteries are under agreement with ECD and our Ovonic Battery Company (OBC) and over 600 million consumer batteries were sold last year with a 30% per year predicted growth rate. These high production volumes have made for a very low cost battery.



The problems of pollution, climate change and our strategic dependence on oil have provided a global impetus for the use of electric and hybrid electric vehicles [38,39]. The automotive industry has made our nickel metal hydride battery the battery of choice for these vehicles. GM, Toyota, Honda, Hyundai, Ford and Chrysler all have chosen nickel metal hydride batteries. We have a joint venture with GM, GM Ovonic, which manufactures and sells electric vehicle and hybrid electric vehicle batteries to all companies.

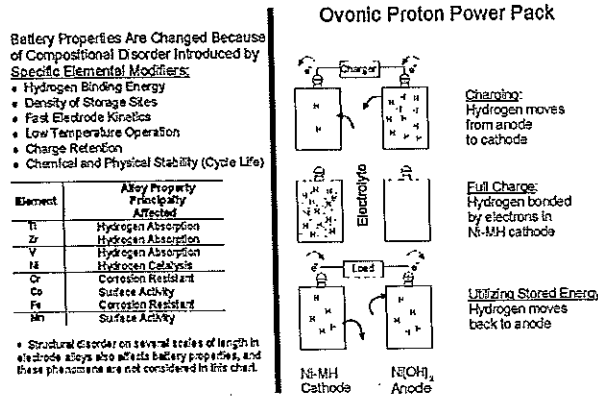


Fig.10

Fig. 11



Fig. 12

Fig. 11 shows a very simplified schematic of the nickel metal hydride battery. The battery is based on hydrogen transfer in which hydrogen is shuttled back and forth between the nickel hydroxide and metal hydride without soluble intermediates or complex phase changes. Fig. 12 shows an ingot of our materials as well as our green battery.

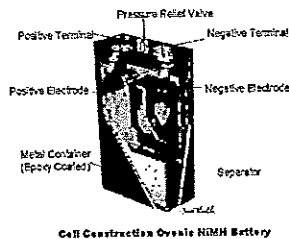


Fig. 13

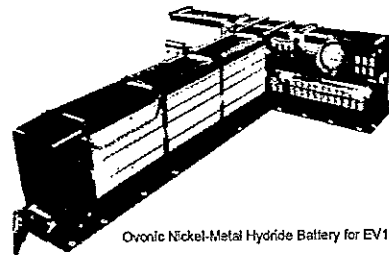


Fig. 14

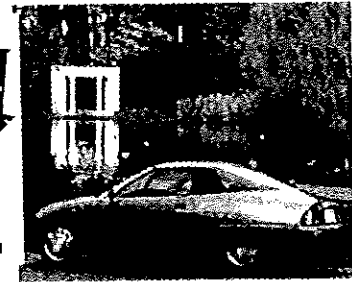


Fig. 15

Fig.13 is a cutaway drawing of our NiMH automotive battery illustrating its simplicity. Fig. 14 is a GM EV1 battery pack; Fig. 15 is a photo of the EV1 car whose range is between 160 and over 200 miles, its acceleration is 0 to 60 mph in less than 8 seconds, less than 15 minutes for an over 60% recharge, very robust, environmentally benign, lifetime of the car battery.

Fig. 16 shows James Worden, cofounder of Solectria, having driven his 4 passenger Solectria Sunrise from Boston to New York on the equivalent BTU energy of less than 1 gallon of gas and he had 15% energy remaining [40]. Fig. 17 gives world record ranges of EVs using

Ovonic NiMH batteries, and Fig. 18 shows the capability of nickel metal hydride to be continuously improved by atomic engineering of the materials.

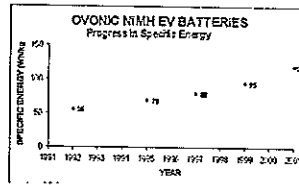
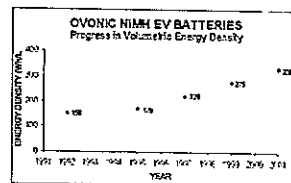


Fig. 16

**World Record Ranges of Electric Vehicles Using Ovonic NiMH Batteries**

Boston to New York One charge (15% unused)	217 miles
Ground-Up Tour de Sol 1996 (Solectria Sunrise)	375 miles
GM Impact (EV1)	245 miles
Conversion EV T. de Sol 1996 (Solectria Force)	214 miles
1997	249 miles
1998	241 miles
Pikes Peak Hill Climb (30% unused) GM S10	14,100 ft
Ovonic Prototype Scooter near hurricane conditions:	69 miles
normal weather conditions:	93 miles

Fig. 17



Progress in Gravimetric and Volumetric Energy Density

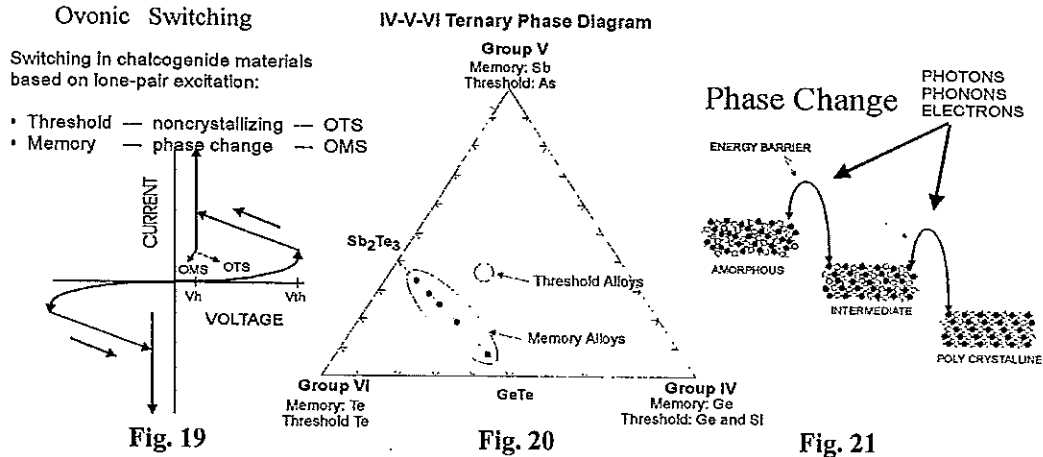
Fig. 18

A gasoline powered GM Geo Metro was tested against the same make and model car rebuilt by Solectria to be an electric vehicle with our Ovonic batteries. In New York City driving, the gasoline car provided an equivalent range of 120 miles compared to the 220 mile equivalent range of the electric vehicle with our batteries [41]. It is quite clear that scientific and technological issues are not what is holding back electric vehicles. Hybrid electric vehicles with our batteries will offer at least 80 miles per gallon in the charge sustaining mode and over 100 miles per gallon in the charge depletion mode.

## INFORMATION

Disordered materials depend upon optional bonding configurations of atoms generating various kinds of new orbital relations. While boron and carbon are helpful in this regard, the elements of choice as I have shown for NiMH batteries are f- and d-orbitals. For the information side of our work, we prefer the chalcogenides characterized by Kastner as lone pair materials [42]. We utilize lone pair p-orbitals since they are not only nonbonding but have a spectrum of lone pair interactions that include various new bonding configurations [43-46]. In some respects, they have similarity to the directional d-orbitals, in other respects, they are different, for example, the empty or filled d-orbitals are very localized and do not reach out as far as the lone pair p-orbitals of the chalcogens, where two of the p-orbitals are deep in energy and serve as strong structural bonds responsible for the cohesiveness of the material. The many lone pair interactions are spread in energy throughout the mobility gap. Their similarity to d-orbitals is that neither the lone pairs nor the d-orbitals play a strong role in cohesive bonding but both are available for interesting electronic, optical and chemical interactions. However, their dissimilarity is that the lone pairs being the outer electrons (they are as far out as any valence electrons), can remain free or form weak or strong bonds, covalent or coordinate, depending on the environment. They are as far out as any valence electrons. The d-orbitals, on the other hand, form a narrow but designable band of high density states at the Fermi level and they too can act as receptors in the coordinate bond configuration. A more profound difference is that the divalency of the lone pair chalcogens allows a flexibility of structure which can be controlled by crosslinking so that we can make either an electronic Ovonic threshold switch (OTS) in which the excitation process does not affect bonding (see Fig. 19) or an Ovonic memory switch (OMS)

[4] in which the electronic processes initiate structural, that is, reversible phase change. We will concentrate here on the OMS which is now universally utilized in its optical phase change form (see Figs. 20 and 21) [47].



Phase change rewritable memories have become the basis for the rapidly growing DVD rewritable market which holds so much promise for the future since it is replacing VCRs and CD-ROMs.

The energy necessary for an Ovonic optical memory material to change its atomic configuration is provided by a laser beam which couples to the non-bonding lone pairs so that the electronic energy exceeds a threshold value, causing a high atomic mobility state to occur and a change from the amorphous to the crystalline phase to take place. The same laser, but at different power, is used for recording, erasing and rewriting since the amorphous material can become crystalline again by rapid rearrangement through slight movements of atoms. The different structural phases of the material have different optical constants, so information is stored in the form of regions with different reflectivity. It is particularly favorable to use a phase congruent material for these applications and as we will show, the cycle life for phase change memories is exceptionally long. Electrical phase change memories have gone over  $10^{13}$  cycles when testing was stopped [48,49].

Since Ovonic phase change optical memories are having great commercial success and the markets are growing rapidly, we are now entering the semiconductor memory market with devices using these materials. Conventional semiconductor memories are the basic building blocks of the information age. The data shown in Fig. 22 clearly show that conventional memories can be replaced by Ovonic semiconductor memories since a single plane of our memory can replace DRAM, SRAM and Flash. To indicate the great advantages that our multi-state memory offers in this highly competitive industry, we show a comparison with Intel's multi-level flash memory which was announced as "the Holy Grail" and which they said would have a "revolutionary" impact on the Flash market. (Figs. 23 and 24).

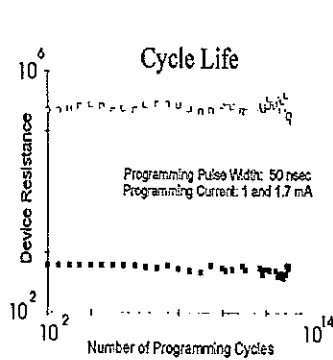


Fig. 22

### Multilevel Memory Comparison

Property	Intel Stratiflash	Oxonic Multistate Memory
Density (bits)	2 bit (4 levels)	> 4 bit (16 levels)
Write Cycles	10,000	> 10 <sup>11</sup> (no limitation)
Write Voltage	5V (with large 12V charge pump)	< 4V
Write Time	10 microseconds (erase & reprogram)	0.6 microseconds (erase & reprogram)
Erase Time	1 second per block	No erase required
Minimum Erasure Block	most erase 128 Kbytes (erase within)	direct overwrite (byte-by-byte)
Read Access Time	~20 microseconds	1.0 microsecond (estimated)

Fig. 23

### Multi-State Data Storage

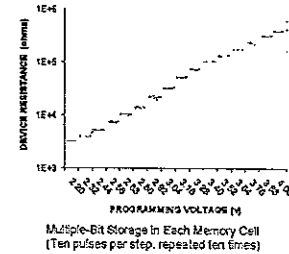


Fig. 24

It can be appreciated that the multi-state memory is also a learning device since it adapts its electrical conductivity to the amount of information it receives. In other words, it displays what neurophysiologists refer to as plasticity as the basis for intelligence. We have also developed another version of this thin-film memory which is truly neuronal and synaptic in that it accumulates a number of sub-threshold pulses before it changes state. This device takes advantage of the fact that a small portion of the active volume of the memory will change phase upon application of every sub-threshold energy pulse. After a specified amount of energy has been deposited, a percolation path is established among the crystallized regions, and a large change in electrical resistance results. The device is reset into its virgin state in the same manner as our other semiconductor memory. This accumulation mode memory device will have important near-term applications in secure, tamper-proof information storage in smart cards and other devices.

What I have in mind for the future is an all thin-film intelligent computer. We have designed all thin-film circuits which can have logic, memory, and adaptive or intelligent memory integrated into a circuit. We have already proven that these devices can be made in three-dimensional and multi-layered circuits, can receive information from various sources, integrate it, remember it and learn from it. This is the basis of a truly cognitive machine, not artificial intelligence as we now know it, nor just a large number of parallel circuits, but a huge density of switching points, receiving and integrating information, in other words, many neurons of different thresholds and frequencies, receiving huge amounts of synaptic information, responding to it and utilizing it [50]. This is what I have wanted to build since 1955; this is what we can build now. I feel that this kind of computer is the computer of the next millenium. Combined with amorphous sensors and displays which we introduced many years ago and which have found widespread use, such a computer could perform tasks which are now beyond the ken of present "dumb" computers. All the various parts have been shown to work and they are all based on amorphous and disordered materials.

## CONCLUSION

I believe that I have shown that science and technology can be utilized to build new industries that are responsive to societal problems and needs, providing jobs, educational opportunities and the chance to express the creative urge that has driven humankind since time immemorial. Fig. 25 shows a young woman climbing a mountain barefooted with her future on her back, our photovoltaics, and her future in front of her, her child, bringing our photovoltaics to a village that does not have electricity. There can be no civilization without energy and without knowledge (information). We take this picture as inspiration to continue our work.



Fig. 25

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