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ANALOG MODELS FOR INFORMATION STORAGE AND TRANSMISSION IN PHYSIOLOGICAL SYSTEMS

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ABSTRACT

Various disordered systems can be reversibly changed from a nonconducting to a conducting state in response to a signal, and indefinitely kept in either state if chemical bond changes are allowed. We have shown that such changes can encode information in a manner which resembles the informational systems observed in nerve-cell conduction. They may also have a bearing upon the mechanism of memory systems that operate in organisms.

In this paper we wish to examine in a qualitative way the problem of encoding information in atomic structures with, effectively, a high signal-to-noise ratio. How can such information be retained as memory and in what forms can it be detected and used? These are great unsolved problems of biology and their solution would also be of real value in electronic technology.

We propose certain hypotheses based upon our work and these suggest at least some plausible answers to the above questions. It is our starting point that there are physical processes which are common to inorganic materials and organisms. This does not imply the crude and misleading analogy to computers that has plagued the neurophysiological field almost since the computer's inception. On the contrary, it is our hope to provide from our knowledge of model systems a physical base for the storage and exchange of information which is directly relevant to real biological structures.

Schroedinger (1) has postulated that "order comes from order". This means, for instance, that a specific item of genetic information must be retained by a structure of considerable rigidity and stability; the original function is lost as the structure is altered. Solid state physicists can appreciate this point by reference to an illustration from their own field: impurities or structural defects in periodic systems alter their properties and thereby, in a sense, the "information content" of such systems. The kind of change considered by Schroedinger was somewhat different, namely that associated with the transition from one relatively stable molecular configuration to another. Information of the type contained in reflex action will not be considered here. It can be compared to the wired-in instructions of a computer. In biology, it has its corresponding counterpart in the function of DNA.

It is our belief that in the field of memory which is not genetically controlled but relies upon information-imprinting events, one is dealing with a form of disorder to order phenomenon, the two phases having the ability to coexist within a prescribed temperature range. The ordered regions extend probably to only tens of angstroms. The structural changes have electrical, optical and mechanical consequences which can serve for read-out purposes. Of course, our analog models are inorganic while the nervous system is organic, but similar kinds of mechanisms should be present and the working areas should have similar dimensions. This means that we limit ourselves here to models which can have the same density of information storage as the central nervous system (CNS). Accordingly, realistic neuronal models should not have areas larger than a few square microns, nor thicknesses greater than hundreds of angstroms. Our models (see below) have such dimensions. This is of great importance when one starts treating the traffic problems of an informational system; quantity is all too quickly reflected in quality.

We know from comparative neurophysiology that nerve cells in a dog's brain number 3 billion, in a chimpanzee 5.5 billion and in a man 10 billion. The multitude of interconnections associated with each cell creates complexities and choices for various types of switching events. Subthreshold activity, we believe, determines the point in time of switch activation and whether it is excitatory or inhibitory. For example, a cell can be altered by chemical and electrical events taking place in the synaptic region. The traffic flow problems of the CNS are essentially problems of the timing of switching events (2) and the introduction into the circuit of switches with specific threshold values offers a further facility, namely that of keying the selection of useful information. However, we will here concern ourselves primarily with the aspect of intelligence handling which involves memory. In physical terms we think of this as the ability of a matrix material to have impressed upon it (by some energy source) a chemical or structural order which reflects the input information and which, under proper conditions, can give up that information without substantial distortion.

We have attempted since 1957 to elucidate, by experimental model building (3-7), disorder to order mechanisms which would switch from a high impedance to a low impedance state. Several types of switching action are necessary for informational control. The first is a monostable switch wherein a change of resistance is effected through a control signal. At the termination of such a sustaining energy, the device will switch off. The only type of memory action in which this switch can participate is a volatile one.

The second and third types of switches, both based on nonvolatility and bistability are required for true memory purposes. One can be reversibly altered between the nonconducting and the conducting state. The other changes its resistance in a varying manner in response to energy events from the outside. The latter is an analog memory.

Little is known about the memory mechanism in organisms. As regards nerve impulses, we know that the nerve fiber is surrounded by a semipermeable membrane charged positively on the outside and negatively on the inside. Nerve cell action is initiated at the surface of the cell which is a region for the reception and integration of various physical stimuli. When the stimulus reaches the surface of the fiber, its permeability to certain ions increases, which can be considered as a reduction in electrical resistance.

Crystalline models do not fit into this picture because cell surfaces are by definition disordered and ionic movements are not compatible with PN junctions. We felt that various disordered materials could be utilized for models. We picked tantalum with an anodically grown amorphous oxide film, some hundreds of angstroms thick. It had to be a stable film that would not chemically react with a surrounding electrolyte that was to serve as a reservoir for selected ions. The intention was to direct these ions into at least portions of the amorphous film. The electrolyte was considered to be the equivalent of the synaptic gap, a chemically inactive electrode (Au or Pt) controlled the ion transport to and from the oxide film by the application of a voltage between it and the tantalum substrate (Fig. 1). Of course, neither the electrolyte nor the film were chosen for their resemblance to physiological material as such, but only as a means of studying possible mechanisms. The electrolyte was hydrochloric acid (20%) which was then saturated with zinc chloride to provide the metal ions. Upon the application of a small signal, typically 2 Volts (inert electrode positive) and with a small amount of current flowing there would be a drastic change in resistance. The tantalum oxide whose resistivity was ordinarily 10^{14} ohm-cm was changed to a conductor. This change persisted as long as the signal remained applied. Without the metallic ions

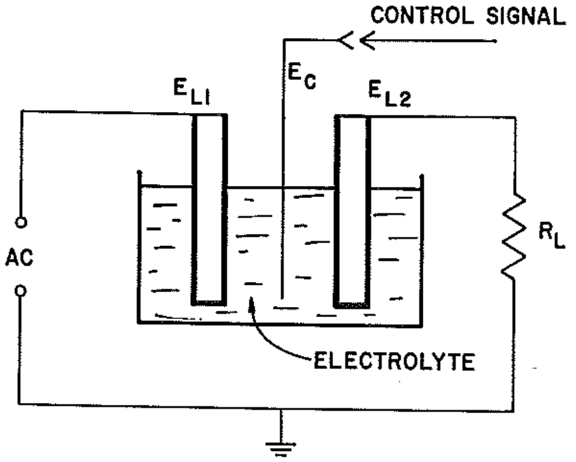


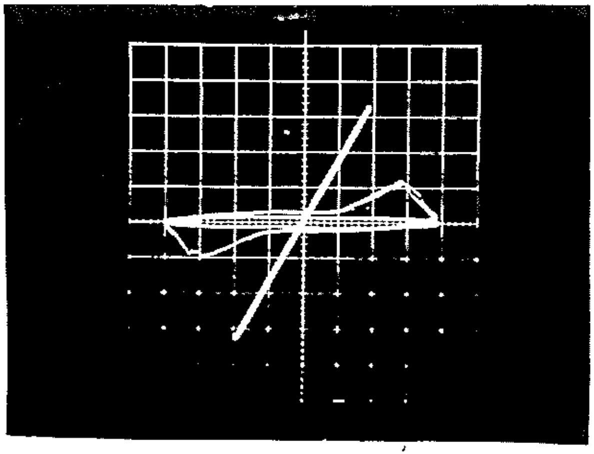
FIG. 1

Schematic diagram of amorphous dielectric film switch and modulator. The load resistor R_L and the amorphous film on the anodized tantalum electrodes E_{L1} and E_{L2} submersed in electrolyte form the load circuit. Current flows through the load circuit if a positive signal is applied to the control electrode E_C. Gain and memory are observed when metallic ions influence the blocking properties of the amorphous dielectric films which are shown for AC operation back to back.

the control process was lost. Therefore, the interaction of the metallic ion with the amorphous film was responsible for the functioning of an active switching device.

Apart from being a source of ions the electrolyte served merely as a conductor and can be considered simply as an extension of the inert electrode. This was proved by potential probing. Oxidation and reduction processes were present as well as double-layer effects, but were shown not to be primarily responsible for the amplification and switching action. The device could also be used as a field effect modulator since the flow of current could be controlled in response to variable changes in the control circuit.

The above described device, the "Ovitron", met the criteria of nerve cell and synaptic action in that an amorphous film displayed a change of resistance concomitant with an increase of permeability to ions in response to a stimulus. It also indicated how some memory effects could be achieved. They were obtained when the electrolyte was made more neutral and essentially became a metal electrode such as zinc. A transient pulse of one polarity turned the device on and a pulse of opposite polarity turned it off. Figure 2 shows the voltage-current characteristics on AC of such a device.



Horizontal 5V/div.
Vertical 50mA/div.
3 Stages of Memory Action
On-Transient-Off
(Superimposed)

FIG. 2

Memory action of amorphous oxide film
(Two devices back to back)

[Simmons and Verderber (8) later reported on their observation of some similar effects.] We welcomed repeated reversibility of the switching effect as a demonstration of the fact that dielectric breakdown was not a contributing factor for in our earlier bipolar memory experiments with amorphous materials, reversibility was difficult to control since memory action and dielectric breakdown seemed often associated (9). Ovitron switching and modulation of electrical resistance by a metal-dielectric amorphous film-metal structure indicated that storage of information was polar in nature even though the conduction process was electronic. It was felt that the information was being stored by ionic distortion of local chemical bonds.

Pursuing our study of both unistable and bistable switches, we began in January of 1960 to investigate other types of amorphous materials. Semiconductor aspects were emphasized in order to assure electronic breakdown possibilities. It was also felt that memory action could be achieved by inducing phase changes, locking in the information in structure. This has since been proved to be true for a large range of materials. The most appropriate materials for our purposes turned out to be chalcogenides. Reversible changes of resistance which can be indefinitely maintained without external energy consumption have been amply demonstrated in devices which have come to be known as Ovonic Memory Switches (10-16). Changes of resistance are associated with the disordered or high resistance state being transformed into a more ordered or crystalline conductive state. We originally chose tellurium and selenium because they were the most similar (by virtue of their chain structure) to the basic informational configuration which was just then changing the outlook of the biological world: the helix. This is illustrative of the fact that a synthesis of seemingly unrelated fields is often the basis for new scientific advances.

We have previously described (17-20) how electronic and structural changes are responsive to temperature, electric fields, and light in these materials. Here we will discuss a memory which utilizes some of our earlier concepts of ion interaction, with chalcogenide glasses being the materials altered. For instance, a long chain polymeric material such as selenium is deposited on a conducting substrate (Fig. 3). Another contact is deposited

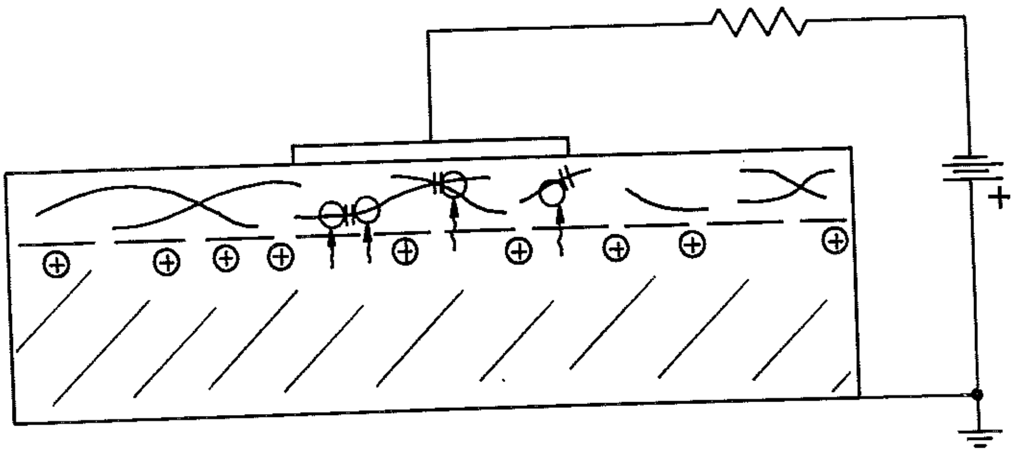


FIG. 3

Ion initiated semiconductor switch and modulator. Schematic view of structural changes caused by field induced ion migration.

on top of the selenium film and completes the structure in its simplest form. One of the contacts is a source of alkali ions. When an electric field is applied ions move into the selenium chains, thereby causing crystallization as the final result, possibly through the intermediate process of chain shortening. Before crystallization, changes can occur which alter the resistivity of the material in a less drastic manner. To disorder the material again a pulse of opposite polarity is used. This also helps to restore the amorphous phase by transient heat dissipation.

Where structural changes are desired for memories one has various processes available, either singly or together: 1. Thermal - When amorphous materials which have not been sufficiently cross-linked to prevent atomic diffusion are heated above a critical temperature (the glass transition temperature), crystallization takes place. 2. Chemical - Various elements which may be internally present in small amounts or made available by diffusion from outside can quasi-catalytically cause the crystallization process to take place with less input of thermal energy. 3. Electric - It is known (10,21,22) that at least some materials crystallize in the presence of an electric field at much lower temperatures than ordinarily expected. Thus, tantalum oxide crystallizes at approximately 100°C in the presence of a strong electric field, as compared with its normal crystallization temperature of 650°C. Moreover, any other process that weakens chemical bonds favors crystallization effects, for example, light, shock waves, etc. Structural changes in response to all of the above can create images opening up new fields of application.

Structural changes often have other clear-cut effects besides changes of conductivity which can be readily detected by external means ranging from differential thermal analysis to electron microscopy. When a material goes from the amorphous to the crystalline condition, there are changes of band gap, optical absorption and reflectivity (19), volume, permeability to ions, surface charge and adhesive properties (23). Some similar changes can indeed be seen in connection with nerve action (24,25). To account for the electronic behavior of amorphous covalent alloys, an unconventional band theory has been proposed (26) which may also have implications for biological systems. Band gaps of the type associated with crystalline structures have no obvious applicability, and attempts to utilize conventional semiconductor approaches to these problems are not, therefore, likely to succeed. We have seen switching in layered structures indicating that anisotropic effects may be a link between crystalline and amorphous semiconductor theory.

Structure dependent conducting mechanisms associated with disordered systems will teach us much about amorphous semiconductors and we feel will be a bridge to the molecular biochemist in the search for unifying concepts of information control.

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We admire the scientific insight of Professor Sir Nevill Mott who still is the youngest of all of us.

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