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Reprinted from Materials Research Society
Symposium Proceedings Volume 803,
Advanced Data Storage Materials and
Characterization Techniques,
SYMPOSIUM GG, Joachim W. Ahner,
Jeremy Levy, SYMPOSIUM HH,
Lambertus Hesselink, Andrei Mijiritskii, Editors

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Mat. Res. Soc. Symp. Proc. Vol. 803 © 2004 Materials Research Society HH1.1

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ABSTRACT

This paper describes a basic new scientific and technological approach for information and computing use. It is based on Ovonic cognitive devices that utilize an atomically engineered Ovonic chalcogenide material as the active medium. We demonstrate how such a device possesses many unique functions including an intrinsic neurosynaptic functionality that permits the processing of information in a manner analogous to that of biological neurons and synapses. Our Ovonic cognitive devices can not only accomplish conventional binary computing, but are capable of non-binary generation of information, storage, encryption, higher mathematics, modular arithmetic and factoring. Uniquely, almost all of these functions can be accomplished in a single nanosized device. These devices and systems are robust at room temperature (and above). They are non-volatile and also can include other volatile devices such as the Ovonic Threshold Switch and Ovonic multi-terminal threshold and memory devices that can replace transistors.

INTRODUCTION

The global computer industry is based upon silicon in a binary mode where information is processed sequentially. The transistor is fabricated from crystalline silicon where periodicity is fundamental and where doping in the ppm and above range of donor and acceptor atoms such as P and B is required.

Computers are characterized by two fundamental attributes. First, operation is based on binary logic. The storage and manipulation of data occurs through conversions to binary strings and transformations of binary strings. Second, today's computers operate sequentially in a manner first described by John Von Neumann. Completion of a computational function is inherently a step by step process. Computer programs are simply line by line instructions that outline a sequence of steps to be implemented. They are executed in a one by one fashion in which the results of preceding steps are typically forwarded to later steps.

Despite their tremendous successes, certain computations, functions and tasks remain largely unamenable to solution or implementation by conventional silicon computers. Such computers become increasingly inefficient as the complexity of computation increases. Computational problems whose time of computation scales exponentially with the input size (number of bits) become intractable with conventional computers. Examples of such problems include the factoring of large numbers and searching or sorting large databases.

Quantum computing has recently been proposed as a solution for overcoming these limitations of conventional computers. Proposed quantum computers seek to exploit the quantum mechanical principle of wavefunction superposition to achieve more than binary state computing through the massive parallelism inherent in entangled, yet coherent states. These states are not accessible for detection and utilization except upon wavefunction collapse. Quantum algorithms such as Shor's factoring algorithm [1] and Grover's searching algorithm [2] demonstrate the benefits potentially available from such computation. However, the systems involved are operable mostly at very low temperatures with states stable only for very brief periods of time.

The statistical nature of the quantum activity requires very complex error correction. Decoherence is a fundamental problem, and device states are volatile with short lifetimes. Therefore quantum computing is a topic of scientific interest, but it will be far in the future before it can become a viable industry [3]. Laboratory quantum computer experiments at exceedingly low temperatures received worldwide attention by showing that it is possible to factor the number 15. With our approach, we can factor 15 trivially and stably at room temperature with none of the above problems. Our approach is demonstrable now, not only for factoring, but also for the many functions described below.

We have taken the position since the 1950's that information is physical; it is encoded energy. Our computer principles are therefore based upon generating and storing units of energy so that they can be added, subtracted, multiplied and divided to provide simple arithmetic and to be utilizable for higher mathematics, while having the inherent plasticity needed for neurosynaptic operation, all in a stable, non-volatile manner.

Our devices are able to emulate the biological functions of memory, switching, learning, adaptability, higher mathematics etc. occurring in the brain, see e.g. refs. 4, 5. The materials of choice through which we achieve our unique mechanisms replicating these functions, are inorganic and polymeric. The devices can operate as neurons, synapses and dendrites, all in a single nanostructure. The devices are able to generate, store, and transform information within a single multifunctional entity in the nanostructure range, assuring high density and high speed. These devices and their systems, while not being quantum computers in any sense, are still able to emulate in a much improved and practical manner some of the quantum computing operations that have been proposed.

The devices must be cost effective, manufacturable and near term. To accomplish this, we utilize thin film structures in the nanoscale at room temperature and above, with both non-volatile as well as volatile operation. We construct multi-terminal devices which achieve the equivalent function of the transistor with far faster speed, increased current capacity and smaller size. One example is a device of nanometer size made of Ovonic threshold material [6] showing a normal threshold voltage of less than 2V with a third electrode that modulates the threshold voltage, while at the same time reducing the holding current to essentially zero, keeping the conducting state intact. When the third electrode is turned off, the original threshold voltage appears [7]. This behavior clearly demonstrates the electronic nature of Ovonic switching by establishing that the conducting filament is a plasma as orginally proposed [8]. The lifetimes of the threshold and memory devices have been proven to be the same as that of other semiconductor devices.

The basis of our work in chalcogenide based materials (e.g. $Ge_{22}Sb_{22}Te_{56}$) is well known [8-11]. Ge, Sb and Te have been the archetypical elements for the Ovonic memory material from its beginnings [8,12-15] to which other elements can be added. Ovonic optical phase-change materials are utilized throughout the world in devices such as rewritable DVD's. Our Ovonic electrical phase-change memories are the basis of our joint venture Ovonyx with Tyler Lowrey, Intel and others [16]. Ovonyx has several licensees, including STMicroelectronics, and the work is progressing very well [17]. Both the Ovonic optical and electrical memory are currently binary in nature, and the latter are intended as replacements for flash, DRAM and SRAM.

Current implementations of artificial intelligence utilize conventional transistor technology. We have many more degrees of freedom in material and device design that, while non-biological, permit achievement of higher level functionality of intelligence. We describe here the principles permitting this higher level functionality. We show that we are able to use our proven materials, production techniques and devices to achieve functions that cannot be achieved in any other known manner.

From a socioeconomic viewpoint, our economics are far more favorable than those of conventional computing. The capital costs of equipment can be lowered by adapting our eighth generation, continuous-web, multijunction nanostructure layer machines. These fabrication facilities can produce complex multilayer materials such as our Ovonic triple junctions by miles and tons with very high yield. The materials can have as many as eleven layers in an overall thickness of less than 0.5 μm with individual layer thicknesses of 80 - 100Å [18,19]. The cost of our machines is in the millions instead of the billions of dollars required for silicon wafers, including the cost of complex photolithography for the latter, however.

The first step along the path to full realization of the potential of cognitive computing may well be the implementation of a hybrid technology. Arrays of our devices can be compatibly fabricated upon a silicon chip engineered to contain all necessary drivers and other auxiliary circuits if desired.

A NEW COMPUTING PARADIGM

The familiar consumer computer and semiconductor industries are now cyclical, approaching important fundamental limits of the science, technology and costs. A new tranformative approach is needed. We offer one that operates in the nano-range with new physical mechanisms on various thin film substrates, assuring mechanical flexibility. We have already described the transformative potential of our technology for a new information age [20].

Figure 1 presents a comparative summary of the features of the current silicon paradigm and those of our approach. We emphasize that the functions described in Figure 1 have been and are being demonstrated on the benchtop. Since the field of application is so large, building integrated systems is required now as the first task on our critical path to commercialization. It is important to recognize that the device can be used to perform in the binary or in higher modes as required for particular tasks, emulating various functions within the brain. More explicitly, our proprietary devices can also perform as non-binary processors capable of manipulating and storing data in high level arithmetic bases (e.g. decimal, hexadecimal, base 8) which provide for additional operational capabilities via multi-valued logic. The Ovonic Cognitive Computer also has remarkable encryption possibilities and has the plasticity to show adaptive learning and cognitive functions, hence the name.

We can make full use of the unique functionality of individual devices to increase dramatically the functionality at the array level. The device principles make possible the variable interconnection strengths among cognitive devices needed to emulate the biological plasticity and complexity needed for adaptive and learning capabilities. Each cognitive device can further be connected to a very large number of devices in an array, with three-dimensional interconnectivity made possible with large fan in and fan out of the connections. **As a result, a**

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

Figure 1. A comparison of the features and operational characteristic of conventional silicon elements and arrays with those of the Ovonic Cognitive Element and Computer.

highly dense, interactive, and massively parallel architecture is achievable. This makes possible the use of dynamical states of activity for computation, as in human brains, instead of the sequential switching from static state to state in conventional computers.

HOW DOES THE OVONIC COGNITIVE DEVICE WORK?

There are two kinds of Ovonic materials, the Ovonic threshold switch material (OTS) and the Ovonic memory switch (OMS) or phase-change material. The OTS material has a strongly crosslinked polymeric structure and strong interbond interactions which ensure its structural stability during the electronic transitions associated with switching. The OMS, on the other hand, has a different polymeric structure which is designed to have fewer, weaker crosslinks and strong interactions between lone pairs, all of which facilitates reversible structural transitions between the amorphous and crystalline states.

The active material in our cognitive device is our Ovonic, solid-state, chalcogenide phase-change material, the same material that is used in commercial applications. Those applications, however, are binary in nature. In them, the devices utilize only the reversible phase-change from amorphous (high resistance, low reflectivity state) to crystalline (low resistance, high reflectivity state) in current commercial applications. In contrast, we show here the deep and rich new physics that be utilized in single or multiple elements, especially in the amorphous state.

The basic operation of the active material is illustrated by the data presented in Figure 2, showing the resistance characteristics of a representative Ovonic chalcogenide material, $Ge_{22}Sb_{22}Te_{56}$. This is the material used in the binary mode by our optical phase-change licensees and in the electrical Ovonic memory device now called the Ovonic Unified Memory (OUM) currently so successfully pursued by Tyler Lowrey, a towering figure in the memory field, and his talented group at Ovonyx.

We show in Figure 2 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.

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 Figure 2. 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 [10,11]. 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 new 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 Figure 2. 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 microcrystallites generated by a sequence of pulses form a temporally

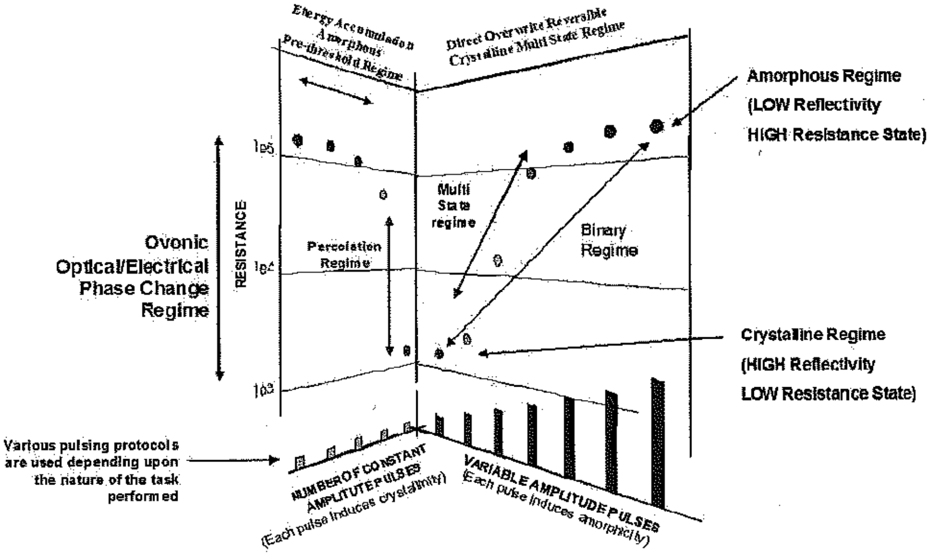

Figure 2. Resistance characteristics of an Ovonic Cognitive Device. The cognitive amorphous pre-threshold synaptic regime (left side) culminates in a percolative transition to crystalline material, the equivalent of neurosynaptic switching. The resistance change accompanying the transition to the crystalline regime can provide readout and transferring of a completed signal to other devices. The leftmost and rightmost data points of Figure 2 (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.

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 [12].

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 [21-23]. 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. Continued application of energy to the structural state induces additional crystallization and further accumulation of energy until sufficient energy has been applied to reach the percolation transition. The energy required to induce percolation is a threshold for a transition from a high resistance state to a low resistance state. In optical applications, we replace resistance with reflectivity. We have proposed that an Ovonic hybrid optical-electrical memory will precede the emergence of the all-optical memory [20].

The ability of our cognitive device to undergo an abrupt change in a readily detectable manner after accumulating its threshold energy provides for neurosynaptic functionality [21-23]. A biological neuron receives energetic inputs at its dendritic synaptic terminals and accumulates them until it reaches a threshold and fires. Before firing, a neuron "acts" as if uncognizant of the signals it has accumulated, and yet it fires when the net signal reaches the threshold value. Our cognitive device exhibits analogous accumulation and threshold activated firing capabilities. The accumulation response is a series of pre-percolation structural states with altered local order having similar resistances and crystalline volume fractions, increasing in proportion to the accumulated energy. Since the resistances of the pre-percolation states are similar, these states are functionally equivalent and analogous to the pre-threshold states of a biological neuron. The abrupt reduction in resistance that occurs at the percolation transition is analogous to the firing event of a biological neuron. This apparently silent zone is the basis of our encryption and other functions.

The firing pulse, which represents crystallization (or in quantum analogy terms, collapse of the wavefunction) gives meaning to the pre-threshold events which could not be interrogated individually. These events are correlated in such a way as to provide functionality analogous to that derivable from quantum entanglement, while representing a significant number, symbol, or information value, etc. The firing pulse in effect reveals the meaning of information stored in forensically inaccessible pre-percolation states. Upon firing, that which was inaccessible becomes tangible and can be read out and interacted with other devices and functions. What was once inaccessible in the "silent" processes of information gathering and storage in a pre-percolation state becomes detectable and manipulable by other devices.

Keep in mind that we are thus far speaking of a *single* cognitive device in the *nanosize range* that can perform a wide variety of mathematical operations, neurosynaptic functions etc. Such activity is unique and exemplifies the deep and rich physics of our nanostructured amorphous material.

APPLICATIONS OF THE OVONIC COGNITIVE DEVICE

We offer a fundamental new approach to computing that enables Ovonic cognitive devices and networks to provide new strategies for doing not only conventional computing but, even more importantly, a whole new approach to informational and computational applications. It also opens up a new phase in the use of non-silicon material for semiconductors. Several illustrative examples of the dramatic increase in multifunctionality are discussed below.

Non-Binary Storage

Non-binary data storage is a unique aspect of the Ovonic cognitive device. In non-binary data storage, a single Ovonic cognitive device can be programmed to store any one of three or more numerical values. Each distinct numerical value corresponds to a distinct structural state in the cognitive regime. Programming or storage of a particular numerical value occurs by providing energy to the Ovonic cognitive device in an amount sufficient to transform the device to the structural state corresponding to the information or value (e.g. letter, number, symbol). In a typical application, the programming energy is provided to the Ovonic cognitive device in its reset state (the initial state (amorphous endpoint) in the cognitive regime) and becomes characteristic of the numerical value being stored. Distinct numerical values are assigned to each of a series of selected structural states in the cognitive regime. Since each structural state has a unique programming energy, a numerical value is encoded through the programming energy and retained by the material through its structural state in a non-volatile manner.

The assignment of numerical values to specific selected structural states can occur in many ways. From an operational point of view, it is most convenient to assign increasing (or decreasing) consecutive integer values to the structural states in order of increasing accumulated energy relative to the initial, reset state of the cognitive regime. In its simplest operation, it is desirable to separate consecutive integer values by equal intervals of accumulated energy so that repeated application of a particular pre-threshold energy pulse increases the stored value by one. This pulsing is done in the amorphous state. The energy relative to the reset state required to store an integer is proportional to the integer. This is advantageous because it renders the cognitive device inherently additive. The reproducibility of the values is assured because the materials always respond in the same way, making for a very stable computer.

Transformations of the Ovonic cognitive device from a structural state assigned to one integer to a structural state assigned to a different integer is a basic operation of the Ovonic cognitive device in mathematical computations. These transformations correspond to incrementing the device from one state to another through the application of energy, typically in the form of one or more electrical current (or optical) pulses of the same energy. Pulse energy can be varied through the pulse amplitude, pulse duration and even the shape of the pulse. In practical operation, non-binary storage and incrementing are most conveniently accomplished with pulses having a common amplitude and variable duration so that energy is proportional to pulse duration and different structural states separated equally in energy are separated by equal pulse durations. New degrees of freedom of electronic and material design can also be utilized.

An inherent feature of our cognitive device is the ability to operate it according to many different non-binary storage protocols. Figure 2 presents an example of a five state protocol in which the threshold energy separating the reset and set states is divided into five intervals so that five incrementing pulses are required to transform the material from its reset state to its set state.

The energy threshold can be divided into a desired number of intervals to provide arbitrary multistate storage in which an arbitrary number of pulses is used to transform the material from its reset state to its set state. Storage protocols based on three states, four states, etc. can be realized by dividing the threshold energy into three intervals, four intervals etc. Devices that operate using a large number of states are readily realized and operate reproducibly over a large number of reset-set-reset cycles. Our cognitive device can easily be reconfigured from one non-binary storage protocol to another. A device utilizing a three state protocol in one computation, for example, can be reconfigured to operate in a seven state protocol in another computation.

Encryption

The reconfigurable storage capability of our cognitive device provides a unique and remarkably effective mechanism for encrypting information. The encryption capabilities of our cognitive device originate from the non-uniqueness of the relation between the structural state of the active material and the information stored in the device. Reconfigurability precludes a unique one-to-one correspondence between the structural state and the stored information. The information content of a particular structural state in the cognitive regime depends on the number of states included in the non-binary storage protocol of the device. Different information can be encoded in the same structural state. In the absence of knowledge about the number of storage states and the energy increments separating energy states, knowledge of the structural state of the cognitive device provides no insight about the information value (alphanumeric, symbolic or otherwise) assigned to the structural state.

Another level of security provided by our cognitive device involves the difficulties in inferring the structural state of the device. Except for the set state, the structural states in the cognitive regime of our device are pre-percolation states that consist of a random, non-contiguous distribution of nanocrystallites within an amorphous matrix. The pre-percolation crystallites can be nanoscale particles that are below the size resolution of common analytical techniques. Furthermore, efforts to identify the structural state necessarily require exposing the device to energy in the form of electron beams, photons etc. Any manipulations or probes of the device that alter its structural state have the effect of deleting the stored information because a change in structural state corresponds to changing the information content of the device. Even if one were able to deduce the structural state, one would still be faced with the impossible task of decoding the information content of the state since a particular structural state is determined by the accumulated energy and this accumulated energy can be provided in a variety of different ways through variations in the pulse amplitude, pulse duration, and number and shape of pulses. Each of the different ways of transforming the material to a particular structural state corresponds to a different way of encoding information. The information content of our cognitive device cannot be determined merely through knowledge of the structural state.

Non-Binary Arithmetic

The multistate, non-binary storage capability of our cognitive device provides a natural basis for calculations in non-binary arithmetic systems. Whereas conventional computers are limited to binary computations, our cognitive devices can operate in a non-binary fashion and permit computations in base 3, base 4, etc., where the arithmetic base of operation corresponds to the number of states included in the multistate, non-binary protocol. Decimal (base 10) operation, for example, is a particularly intuitive mode of operation and may be accomplished using a ten state protocol in which ten current pulses are used to traverse the energy threshold of a cognitive device. The important factor is that we can go to any base up to the resolution of our ability to distinguish distinct states in the cognitive regime. We can even use base 60, the sexagesimal base of the ancient Sumerians, which persists to this day in angular and temporal measurements.

Addition

Because of its intrinsic accumulative functionality, our device is naturally suited to addition. Since each pulse applied to the device signifies the operation of incrementing by one, the structural state of our device provides a record of the cumulative number of increments applied to the device since its last reset. Addition of two numbers is accomplished by storing one of the addends in the device and subsequently applying pulses to the device in a number equal to the other addend.

Division

Division exploits the accumulative nature and reconfigurability of our cognitive device. In division, the divisor is used to define the arithmetic base of computation for a cognitive device and a number of pulses equal to the dividend is applied to the device with a requirement that the device be reset each time it sets until all of the pulses have been applied. The quotient of the division is equal to the number of times the device sets while applying the pulses corresponding to the dividend and the remainder corresponds to the final state of the device.

Modular Arithmetic

Implementation of modular arithmetic with our cognitive device is similar to the method of division described above. Determination of the modulo X equivalent of the number Z is accomplished by applying Z pulses to a cognitive device whose cognitive operational range is partitioned into X intervals, resetting the device each time it sets and reading the final state of the device to obtain the result. The modulo 7 equivalent of 17, for example, can be obtained by applying 17 incrementing pulses to a cognitive device requiring 7 incrementing pulses to progress from its reset state to its set state. Application of the 17 incrementing pulses causes the device to set twice and leaves the device in a state removed from the reset state by 3 incrementing pulses. Hence, 17(mod 7) = 3.

Factoring in Parallel

Our cognitive device offers a new approach to factoring that is efficient and amenable to parallel operation. During factoring, a number of pulses equal to the input number is applied to each of several devices configured to divide by a different prime number and each device is reset every time it sets. After all pulses have been applied, each device is in a state that corresponds to the modular equivalent of the input number in the modulus of a different prime number. Since any factor of the input number necessarily has a modular equivalent of zero, the prime numbers that are factors of the input number are those associated with cognitive devices that are in their set state after applying pulses in a number equal to the input number. This method can also factor information that is not numerical; for example, intelligent database searching and associative memory.

SUMMARY

We have described and demonstrated a unique new computational/information device that possesses the neurosynaptic functionality necessary to achieve cognitive computing. The cognitive device shows threshold activated firing, possesses a threshold energy that is variable, records experiential history, combines memory and processing in a single device, and responds to stimuli of many types. The cognitive devices can be connected into densely interconnected, highly parallel networks that exhibit plasticity and learning capabilities. The neurosynaptic properties of individual devices and the connection strengths between devices in a network are adjustable and permit reconfiguration and adaptation of a network as it confronts new situations. A single device can do both logic and memory.

In addition to providing a new concept in computing, our cognitive devices make possible the redefining of the manufacturing of computers. The atomically engineered chalcogenide materials used in our cognitive devices and networks can be deposited uniformly as thin films on a variety of substrate materials, including silicon, using methods such as sputtering, physical vapor deposition, and chemical vapor deposition. These processes are inexpensive and adaptable to large scale manufacturing. Post-deposition processing and patterning can be achieved using existing techniques that are well-known in silicon technology and can be incorporated into our continuous-web technology.

The era of truly cognitive computing in which machines utilize higher order reasoning capabilities to process, interpret and respond to information is now upon us. Our continuing efforts will focus on interconnecting devices, scale up of cognitive networks from the few to the many, optimizing learning protocols and answering emerging needs by developing task-specific devices that display adaptability within a bounded range of input conditions with first implementation via a hybrid technology. Space prohibits the description of our multiterminal junction devices that have the potential to replace the transistor, providing great performance advantages [6,7].

ACKNOWLEDGEMENTS

We thank the information team of Wally Czubatyj, my longtime collaborator in information; David Strand, for his leadership of our optical phase-change memory activities; Genie Mytilineou, for her contributions and continuous help; Kevin Bray, for his invaluable work on the preparation of the paper; and the technical staff of our Information Group. We are grateful to Morrel Cohen, a long-time collaborator, for his helpful comments. As always, SRO pays homage to his inspiration and loving collaborator, Iris.

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