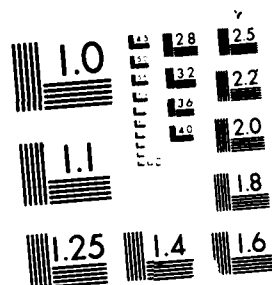


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ROYAL SIGNALS & RADAR
ESTABLISHMENT

BIOLOGICAL MATERIALS FOR INTEGRATED CIRCUITS

Authors: J D Benjamin, A L Meers

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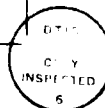
AUTHORS: J D Benjamin, A L Mears

DATE: May 1986

SUMMARY

The use of biological materials as active components in electronic systems is examined. It is concluded that signal processing is not possible unless their inherently slow switching speed is compensated for by a massive increase in number of elements, which could only be achieved in a cost effective manner if the systems were self organising. However, as components in sensors they are certainly viable and may also be of use for data storage at very high densities. They may also be of use in the fabrication of conventional integrated circuits through exploitation of their capability to self-organise through highly selective biochemical reactions.

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RSRE MEMORANDUM 3965

BIOLOGICAL MATERIALS FOR INTEGRATED CIRCUITS

J D Benjamin, A L Mears

The most complex signal processing system in the world today is the human brain. Its ability to recognise patterns far outstrips that of the fastest computers. In view of this, it is worth considering whether future circuits will be made from biological materials. In this note we seek to identify the factors which determine the potential performance of solid state and biological systems and thus to see when each should be used.

The key advantage of the brain over microelectronics lies in the fact that the brain contains of the order of a billion times as many elements (see table 1). This is achieved in part because the size of features in the brain goes down to about $0.3 \mu\text{m}^*$ as compared with $1.2 \mu\text{m}$ for present day integrated circuits^(2,3), leading to roughly twenty times the number of elements per unit volume. A more important reason is that the brain is a three-dimensional structure with an economical system of interconnection, whereas the modern integrated circuit is confined to a two micron thick layer in the surface of a chip, much of which is taken up by interconnect. The chief drawback of the brain is its low speed which renders it poor at "number crunching" operations. The "gate delay" in the brain is about a million times longer than in integrated circuits, leading to the "clock speed" of the system being about a hundred thousand times slower. *The brain ceases to function outside a very narrow temperature range.*

The viability of integrated circuits made of biological materials depends on how far these advantages and disadvantages carry over into the context of a man made device. The key difference between an artificial device and the brain is that the brain has been built up by a process of self-replication, whereas for the foreseeable future man-made structures will have to be made by layer processing techniques. In both semiconductors and biological systems, layers can be deposited which are only a few angstroms thick, so very fine features can be defined normal to a surface. In the plane of the surface lithography and pattern transfer techniques have to be used. The resolution, pattern complexity and defect densities which can be achieved using these techniques depend very little on the materials being patterned and will therefore be much the same for both semiconductors and biological materials. Likewise, the complexity of the processing will be similar in both cases. The dimensions achieved in modern mass production are of the order of a micron, through experimental structures as little as 10 nm across have been produced.

Finer and more complex structures might be achieved using self-organisation based on the interaction of biological molecules or phase segregation in solid state systems. In both cases this is very hypothetical and we see no reason why a useful result should be substantially easier to achieve in this way in biological than in semiconductor systems.

- * In making this comparison we consider a "feature" to be a body of material which changes its electrical potential as a single unit. This is not to say that there are not finer structures eg the individual "pump" and "channel" protein molecules in the brain which are only 6 nm across ⁽¹⁾, but the switching behaviour of a neuron depends on the concerted operation of a large number of such elements.

Assuming that similar feature sizes and complexities are achieved for both biologically based and semiconductor based systems, we now compare their performance. An upper limit on the speed of operation of a device arises from the speed with which carriers diffuse. The mobility of electrons is typically a factor of a thousand lower in organic conductors than in semiconductors. If transport is by protons, their mobility is a million times less than that of electrons in a semiconductor, and if larger species have to move the response is further slowed (see table 2). The serial speed of operation of organically based systems is therefore much slower than those of semiconductor devices, but this leaves open the possibility of achieving throughput in a biological structure by massive parallelism, as is done in the brain.

In highly parallel structures the speed of operation is constrained not by the mobility of the carriers but by the need to get rid of the heat. The amount of heat which a system can dissipate depends on how good thermal contact is between it and its surroundings, and on how large a temperature difference between the device and its surroundings can be accepted. Conventional semiconductor devices may run at temperatures of up to 100°C above their surroundings. Normally the heat dissipation is limited by the package to a couple of watts, though special packages have been designed which take full advantage of the high thermal conductivity of silicon and allow power densities of 1 kW cm⁻² to be dissipated (7). Devices based on biological materials are at a disadvantage here on three counts. Firstly they dissipate more energy in changing state. The switching energy of a neuron is estimated at 200 times that of a modern CMOS gate (see Appendix 1, Table 1); this arises because semiconductor devices store energy capacitively whereas biological systems store energy chemically (see Appendix 2). Secondly, the thermal conductivity of biological materials is two orders of magnitude poorer than that of silicon, so the maximum power density which can be dissipated for a given temperature rise is less. Finally, the maximum temperature which biological materials can withstand is typically an order of magnitude closer to that of their surroundings than for semiconductor devices. Taking these factors together, the maximum number of operations which can be performed per unit volume per unit time is roughly five orders of magnitude poorer for biological systems. They further suffer from the drawbacks that they operate through chemical changes which tend not to be perfectly reversible and also that they generally require a well defined environment in which to function. In view of these considerations the use of biological systems for signal processing does not appear viable. The only qualification to this is that if self organising and self replicating systems could be made, they might be sufficiently cheap and complex that this would compensate for the limitations identified above.

There are however three areas in which they do have a role. The first is in the sensing of organic species, where sensing and preamplification may be carried out using biological systems, and some have indeed been demonstrated. The second is the use of biochemical reactions to deposit layers selectively onto specific areas of conventional integrated circuits as part of their structure. The third is the storage of data, where the much greater energy density in an electrochemical system compared with that in an electrostatic system allows far higher storage densities. For example, a bit of information might be recorded using an energy of 1 eV which can be stored in a single chemical bond, allowing data storage densities of $\sim 10^{27}$ bits m⁻³ or 10¹⁸ mbits m⁻², whereas capacitive elements could only store 10²⁴ bits m⁻³ or 4 x 10¹⁶ bits m⁻².

A further application of biological materials may be in the fabrication of conventional integrated circuits when their ability to bind selectively onto specific types of surfaces may be of value in the fabrication of self aligned structures. Applications could include masking layers, dielectrics, tunnel barriers and resists.

To summarise, electronic systems made with biological elements will never run very fast or achieve a high processing density per unit volume, so they are unlikely to be of use in man made signal processing systems. The only consideration which might change this is if self-organising or self-replicating systems were devised. Biological materials may however be of use for data storage, for sensing and in fabricating conventional devices.

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APPENDIX 1 ESTIMATES OF THE SWITCHING ENERGY OF A NEURON

Three separate estimates are given:

1) By estimating the electrostatic energy associated with the neuron switching:

Assuming that: Area of neuron surface = $4 \times 10^{-8} \text{ m}^2$
 Thickness of cell wall = $7 \times 10^{-9} \text{ m}$
 Dielectric constant of cell wall = 20
 Maximum switching voltage = 90mV
 Efficiency of the chemical processes which drive the electrical processes = 10% *

Electrostatic energy = $\epsilon \epsilon_0 A V^2 / (2 \times \text{thickness}) = 4.1 \times 10^{-12} \text{ J}$,
 so energy dissipated per operation = $4 \times 10^{-11} \text{ J}$

2) Based on the static power dissipation of the brain:

Assuming that:
 The "resting" power dissipation in the brain is 20W.
 The level of activity in the brain when "resting" is small compared with that during strenuous mental activity.
 The power dissipation in a neuron is proportional to the flow of ions across the membrane.
 There are 10^{11} neurons in the brain.

It is known that a pulse going along a neuron takes roughly 1ms to pass, and that during that time the permeability of the cell wall to sodium is increased by a factor of 200⁽¹⁰⁾. Thus the power dissipation when the brain is resting is the same as the additional amount of power which would be required to perform 5×10^{11} operations per second.

Thus the power per operation =

$$\frac{\text{the resting power dissipation of the brain}}{\text{number of neurons} \times \text{pulse time} \times \text{ratio of power}}$$

$$= \frac{20}{10^{11} \times 200 \times 10^{-3}} = 4 \times 10^{-11} \text{ J}$$

3) Based on the total power dissipation in the brain when thinking:

Assuming that: During strenuous mental effort the power dissipation in brain is increased by 10W.
 The "background" power dissipation in the neurons and glial cells is independent of what the brain is doing.
 When thinking hard 2.5% of the neurons are working flat out and the rest are idle.
 There are 10^{11} neurons in the brain.
 Switching speed of neurons = 100Hz.

Neuron operations per second = active neurons x clock speed = $2 \times 10^{11} \text{ s}^{-1}$
 so power per operation = $5 \times 10^{-11} \text{ J}$

These calculations agree remarkably well, but I am very uncertain about several of the underlying assumptions, especially those marked with with an * so this may well be fortuitous. In particular, if instead of the third calculation, I considered an epileptic fit, and assumed that the neurons then work flat out and dissipate a total of 20W, the calculated power per operation is decreased by an order of magnitude.

APPENDIX 2

In semiconductor devices, energy is stored electrostatically. A MOS capacitor is typically an oxide dielectric 40 nm thick with an electric field of 10^8 V m^{-1} in it, leading to an energy density of $1.7 \times 10^5 \text{ Jm}^{-3}$ or $7 \times 10^{-3} \text{ Jm}^{-2}$. As the thickness of the gate oxide is reduced, the energy density per unit area will decrease proportionately. It will probably be possible eventually to reduce the oxide thickness and thus the energy density per unit area by a factor of five. In biological devices a chemical change is needed. If a bond is made with an energy of 1 eV in a molecule occupying 10^{-27} m^3 , the energy density is $1.6 \times 10^8 \text{ Jm}^{-3}$ which is a factor of a thousand greater than that in a MOS capacitor. If the single monolayer is used with a total thickness of 2 nm, the energy density per unit area is $\sim 0.3 \text{ Jm}^{-2}$ ie 40 times higher than for a present day semiconductor device.

TABLE 1 COMPARISON OF THE BRAIN WITH MICROELECTRONIC CIRCUITS

	BRAIN	MICROELECTRONICS (1985)
Number of elements	10^{14} synapses (7)	10^5 gates
"Clock speed"	≤ 100 Hz	10 MHz
Gate delay	1 mS	1 nS
Gate operation s^{-1}	10^{16}	10^{12}
Volume of active material	1300 cm^3	10^{-4} cm^3
Volume/element	$2 \times 10^{-10} \text{ cm}^3$	10^{-9} cm^3
Minimum feature size	$\sim 0.3 \mu\text{m}$ for a macroscopic feature (8); 6 nm for a protein molecule, eg an ion channel which constitutes a basic "switch"	$1.2 \mu\text{m}$
Gate operations $s^{-1} \text{ cm}^{-3}$	5×10^{12}	10^{16}
Power delay product	$\sim 4 \times 10^{-11} \text{ J}$ (Appendix 1)	$2 \times 10^{-13} \text{ J}$
Optimum for	Pattern recognition	Number crunching
Interfaces well to	Human body	Machines
Operating temperature range	$33\text{--}41^\circ\text{C}$	-55°C to 125°C

TABLE 2 COMPARISON OF BIOLOGICAL MATERIALS WITH SILICON

	BIOLOGICAL MATERIAL	SILICON
Mobility of carrier/ $\text{m}^2 \text{V}^{-1} \text{s}^{-1}$	3.63×10^{-7} (proton in water (5)) 10^{-5} (electron in phthalocyanine (9))	~ 0.1
Electrical conductivity/ $\Omega^{-1} \text{cm}^{-1}$	5×10^{-3} (Polyacetylene (4))	10^{-3} (heavily doped silicon) 10^{-5} (aluminium tracks)
Thermal conductivity / $\text{W K}^{-1} \text{m}^{-1}$	~ 1	~ 150
Maximum operating temperature/ $^{\circ}\text{C}$	~ 50	> 125
Diffusion coefficient of carrier/ $\text{cm}^2 \text{s}^{-1}$	9.3×10^{-5} (proton in water) 1.9×10^{-5} (nitrate in water) $4.5 \times 10^{-4} \times \text{mol wt}^{-0.6}$ (PMMA in chloroform) (6)	25.7

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