Protein Based Memory Storage

ABSTRACT

While magnetic and semi-conductor based information storage devices have been in use since the middle 1950's, today's computers and volumes of information require increasingly more efficient and faster methods of storing data. While the speed of integrated circuit random access memory (RAM) has increased steadily over the past ten to fifteen years, the limits of these systems are rapidly approaching

. In response to the rapidly changing face of computing and demand for physically smaller, greater capacity, bandwidth, a number of alternative methods to integrated circuit information storage have surfaced recently. Among the most promising of the new alternatives are photopolymer-based devices, holographic optical memory storage devices, and protein-based optical memory storage using rhodopsin , photosynthetic reaction centers, cytochrome c, photosystems I and II, phycobiliproteins, and phytochrome.

This paper focuses mainly on protein-based optical memory storage using the photosensitive

protein bacteriorhodopsin with the two-photon method of exciting the

molecules, but briefly describes

what is involved in the other two. Bacteriorhodopsin is a light-harvesting protein from bacteria that live in salt marshes that has shown some promise as feasible optical data storage. The current work is to hybridize this biological molecule with the solid state components of a typical computer. Along with that this paper is explaining some currently existing projects.

“Internal revolution and External Evolution in Memory Research

Protein Based Memory Storage

Introduction:

From the time of homosafien, man has tried to record important events and techniques for everyday life. At first, it was sufficient to paint on

the family cave wall how one hunted. Then came the people who invented spoken languages and the need arose to record what one was saying without hearing it firsthand. Therefore, year’s later, more early scholars invented writing to convey what was being said. Pictures gave way to letters which represented spoken sounds. Eventually clay tablets gave way to parchment, which gave way to paper. Paper was, and still is, the main way people convey information. However, in the mid twentieth century computers began to come into general use . . .

Evolution of Memories:

Computers have gone through their own evolution in storage media. In the forties, fifties, and sixties, everyone who took a computer course used punched cards to give the computer information and store data. In 1956, researchers at IBM developed the first disk storage system. This was called RAMAC (Random Access Method of Accounting and Control)

Since the days of punch cards, computer manufacturers have strived to squeeze more data into smaller spaces. That mission has produced both competing and complementary data storage technology including electronic circuits, magnetic media like hard disks and tape, and optical media such as compact disks.

Today, companies constantly push the limits of these technologies to improve their speed, reliability, and throughput -- all while reducing cost. The fastest and most expensive storage technology today is based on electronic storage in a circuit such as a solid state "disk drive" or flash RAM. This technology is getting faster and is able to store more information thanks to improved circuit manufacturing techniques that shrink the sizes of the chip features. Plans are underway for putting up to a gigabyte of data onto a single chip.

Magnetic storage technologies used for most computer hard disks are the most common and provide the best value for fast access to a large storage space. At the low end, disk drives cost as little as 25 cents per megabyte and provide access

time to data in ten milliseconds. Drives can be ganged to improve reliability or throughput in a Redundant Array of Inexpensive Disks (RAID). Magnetic tape is somewhat slower than disk, but it is significantly cheaper per megabyte. At the high end, manufacturers are starting to ship tapes

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that hold 40 gigabytes of data. These can be arrayed together into a Redundant Array of Inexpensive Tapes

(RAIT), if the throughput needs to be increased beyond the capability of one drive.

For randomly accessible removable storage, manufacturers are beginning to ship low-cost cartridges that combine the speed and random access of a hard drive with the low cost of tape. These drives can store from 100 megabytes to more than one gigabyte per cartridge.

Standard compact disks are also gaining a reputation as an incredibly cheap way of delivering data to desktops. They are the cheapest distribution medium around when purchased in large quantities ($1 per 650 megabyte disk). This explains why so much software is sold on CD-ROM today. With desktop CD-

ROM recorders, individuals are able to publish their own CD-ROMs.

With existing methods fast approaching their limits, it is no wonder that a number of new storage technologies are developing. Currently, researches are looking at protein-based memory to compete with the speed of electronic memory, the reliability of magnetic hard-disks, and the capacities of optical/magnetic storage. We contend that three-dimensional optical memory devices made from bacteriorhodopsin utilizing the two photon read and write-method is such a technology with which the future of memory lies.

Current Vs Latest:

The demands made upon computers and computing devices are increasing each year. Processor speeds are increasing at an extremely fast clip. However, the RAM used in most computers is the same type of memory used several years ago. The limits of making RAM more dense are being reached. Surprisingly, these limits may be economical rather than physical. A decrease by a factor of two in size will increase the cost of manufacturing of semiconductor pieces by a factor of 5.

All Dimms are 12cm by 3cm by 1cm or about 36 cubic centimeters. Whereas a 5 cubic centimeter block of bacteriorhodopsin studded polymer could theoretically store 512 gigabytes of information. When this comparison is made, the advantage becomes quite clear. Also, these bacteriorhodopsin modules could also theoretically run 1000 times faster.

In response to the demand for faster, more compact, and more affordable memory storage devices, several viable alternatives have appeared in recent years. Among the most promising approaches include memory storage using holography, polymer-based memory, and our focus, protein-based memory. Protein-Based Memory:

There have been many methods and proteins researched for use in computer applications in recent years. However, among the most promising approaches, and the focus of this paper, is 3-Dimensional Optical RAM storage using the light sensitive protein bacteriorhodopsin.

Bacteriorhodopsin is a protein found in the purple membranes of several species of bacteria, most notably Halo bacterium halobium. This particular bacteria lives in salt marshes. Salt marshes have very high salinity and temperatures can reach 140

degrees Fahrenheit. Unlike most proteins, Bacteriorhodopsin does not break down at these high temperatures.

Early research in the field of protein-based memories yielded some serious problems with using proteins for practical computer applications. Among the most serious of the problems was the instability and unreliable nature of proteins, which are subject to thermal and photochemical degradation, making room- temperature or higher-temperature use impossible. Largely through trial and error, and thanks in part to nature's own natural selection process, scientists stumbled upon Bacteriorhodopsin, a light-harvesting protein that has certain properties which make it a prime candidate for computer applications. While Bacteriorhodopsin can be used in any number of schemes to store memory, we will focus our attention on the use of Bacteriorhodopsin in 3-Dimensional Optical Memories.

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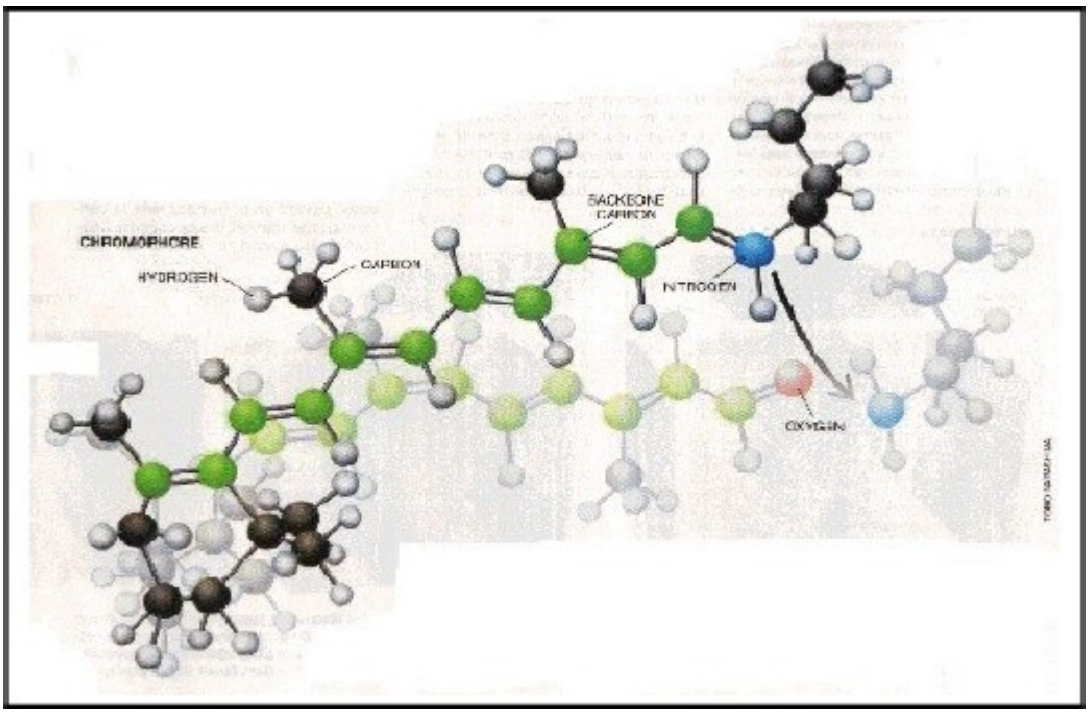
BACTERIORHODOPSIN PHOTOCYCLE

Bacteriorhodopsin is a photochemically active protein found in the purple membrane of the bacteria Halobacterium salinarium, which was known as Halobacterium halobium. The polypeptide chain is made of seven closely spaced alpha-helical segments

looped across the lipid bilayer. The interhelical space contains the all-trans-retinal chromophore which is linked to lys-216 on helix G as a protonated Schiff base.



Photochemically active means that it reacts to light. It has a photochemical reaction cycle, or photocycle. This cycle basically transports protons from inside the cell to outside the cell in the bacteria Halobacterium halobium. The native photocycle has several spectroscopically unique steps, bR --> K <--> L <--> M1 --> M2 <--> N <-->O, which occur in a roughly linear order. The bR state is the protein in its native state and each intermediate is represented by a letter of the alphabet. However, the important, main photochemical event in this cycle is a trans to cis photoisomerization around the thirteenth Carbon atom to the fourteenth carbon double bond in the chromophore.

This is the chromophore

At around the temperature of 80 K, the native protein undergoes this photocycle and switches between a green absorbing state and a red absorbing state. At approximately room temperature, the protein switches between a green absorbing state and a blue absorbing state. In both the ground (green) and excited (red or blue) states, the chromophore displays several metastable configurations. The main event follows these steps:

1.

A change in the shape of the conformational potential energy surface

resulting from electron excitation

2.

A conformational change

3.

A non-radiative decay to the ground state

The single critical step in the proton pumping ability of the protein is the transfer of the Schiff base proton do D85, and piece of the protein, in the L --> M reaction. Absorption of light leads to rapid photoisomerization in the excited state because the barrier to conformation al change in that state is negative. In a

manner of thinking, the conformational motion of the excited state acts to gate the conformational motion of the ground state.

In the L state, the Schiff base exhibits strong H-bonding with close water molecules and distorts the chromophore near the Schiff base. The two necessary coordinators for these water molecules are the anionic Asp85 and Asp212. That coincides with the Trp182 interacting with the retinal skeleton by the 9-methyl group. These events bring about the deprotonation of the Schiff base.

Also in the L intermediate state, the backbone has good local structural flexibility. This is evidenced by the many different change in the peptide C to O double bond stretching vibrational frequencies. Some of these frequency variations correlate to the O to H single bond stretching vibrational frequencies. This indicates that the structural changes can come from changing interaction with water molecules. A network of H-bonding including bonds between water and peptides, exists between two pieces of the protein, Asp85 and Asp96. This network exhibits changes most often in the bR to L transformation, which would be the first step in writing to a block of bacteriorhodopsin memory.

In the K intermediate, an H-bonding change of the peptide C to O double bond of a valine residue, called Val49, occurs. This stays on in the L intermediate, but is gone in the M intermediate. This is affected by a mutation in the protein.

Water appears to affect the C to O double bond affects the protein at specific regions. Some, which exhibit O to H single bond stretching frequencies, interact with the C to O double bond of the Val49 piece.

The relative stability of some of the intermediate states determines their usefulness in computing applications. The initial state of the native protein, often designated bR, is quite stable. Some of the intermediates are stable at about 80K and some are stable at room temperature, lending themselves to different types of RAM.

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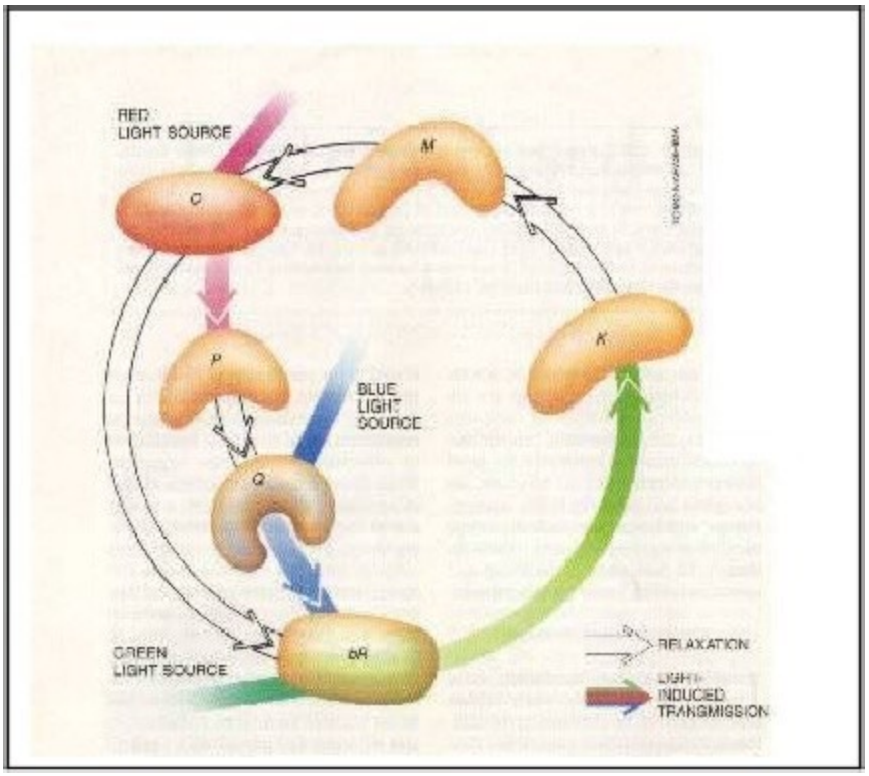
For computers, the two or three most stable states of the protein would be used to record
data in binary form. This is the proposed photocycle for computing needs



An interesting intermediate in the photocycle is theO intermediate. TheO intermediate is an all-trans structure like the native protein state. The native state is a light-adapted state. TheO state is the red absorbing state.
The M state, or unprotonated Schiff base, does not accumulate in the photocycle. This is strange since this protein transports protons. This could mean two things. The first is that the M state cannot be observed because the kinetics is set against its build-up. The other is that the Schiff base does not deprotonate and the transport is based on a completely different mechanism than the wild type protein. The two kinetic reasons for this lack of M are that the rate of decay of M is faster than the rate of formation or that the L <--> M and M <--> N equilibrium are tilted away from the M state
3-Dimensional Optical Memories:

Three-dimensional optical memory storage offers significant promise for the development of a new generation of ultra-high density RAMs. One of the keys to this process lies in the ability of the protein to occupy different three-dimensional shapes and form cubic matrices in a polymer gel, allowing for truly three-dimensional memory storage. The other major component in the process lies in the use of a two-

photon laser process to read and write data. As discussed earlier, storage capacity in two-dimensional

optical memories is limited to approximately 1/lambda2 (lambda = wavelength of light), which comes out to approximately 108 bits per square centimeter. Three-dimensional memories, however, can store data at approximately 1/lambda3, which yields densities of 1011 to 1013 bits per cubic centimeter. The memory storage scheme which we will focus on, proposed by Robert Birge inComp u ter (Nov. 1992), is designed to store up to 18 gigabytes within a data storage system with dimensions of 1.6 cm * 1.6 cm * 2 cm. Bear in mind, this memory capacity is well below the

theoretical maximum limit of 512 gigabytes for the the same volume (5-cm3).

Data Writing Technique:

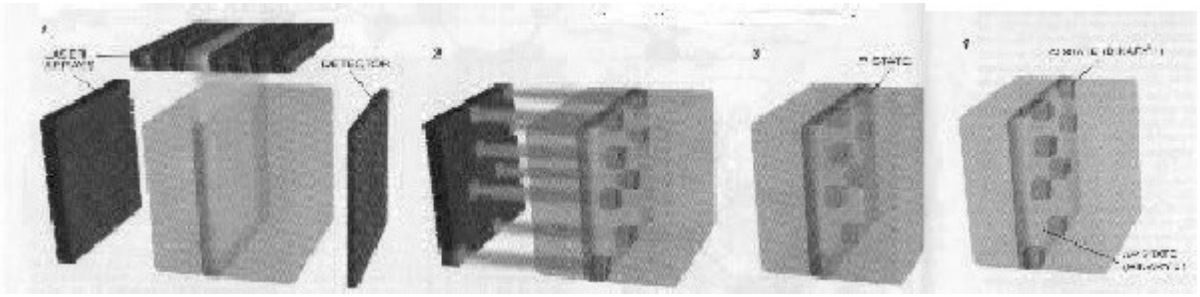
Bacteriorhodopsin, after being initially exposed to light (in our case a laser beam), will change to between photo isomers during the main photochemical event when it absorbs energy from a second laser beam. This process is known as sequential one-photon architecture, or two-photon absorption. While early efforts to make use of this property were carried out at cryogenic temperatures (liquid nitrogen temperatures), modern research has made use of the different states of bacteriorhodopsin to carry out these operations at room-temperature.

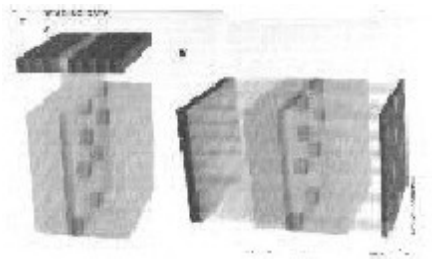
The process breaks down like this: Upon initially being struck with light (a laser beam), the bacteriorhodopsin alters its structure from the bR native state to a form we will call theO state. After a second pulse of light, theO state then changes to aP form, which quickly reverts to a very stableQ state,

which is stable for long periods of time (even up to several years).

The data writing technique proposed by Dr. Birge involves the use of a three-dimensional data storage system. In this case, a cube of bacteriorhodopsin in a polymer gel is surrounded by two arrays of laser beams placed at 90 degree angles from each other. One array of lasers, all set to green (called "paging" beams), activates the photo cycle of the protein in any selected square plane, or page, within the cube. After a few milliseconds, the number of intermediateO stages of bacteriorhodopsin reaches near maximum. Now the other set, or array, of lasers - this time of red beams - is fired.

The write process





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The second array is programmed to strike only the region of the activated square where the data

bits are to be written, switching molecules there to theP structure. TheP intermediate then quickly relaxes to the highly stableQ state. We then assign the initially-excited state, theO state, to a binary value of 0, and theP andQ states are assigned a binary value of 1. This process is now analogous to the binary switching system which is used in existing semiconductor and magnetic memories. However, because the laser array can activate molecules in various places throughout the selected page or plane, multiple data locations (known as "addresses") can be written simultaneously - or in other words, in parallel.

Data Reading Technique:

The system for reading stored memory, either during processing or extraction of a result relies on the selective absorption of red light by theO intermediate state of bacteriorhodopsin. To read multiple bits of data in parallel, we start just as we do in the writing process. First, the green paging beam is fired at the square of protein to be read. After two milliseconds (enough time for the maximum amount ofO intermediates to appear), the entire red laser array is turned on at a very low intensity of red light. The molecules that are in the binary state 1 (P orQ intermediate states) do not absorb the red light, or change their states, as they have already been excited by the intense red light during the data writing stage.

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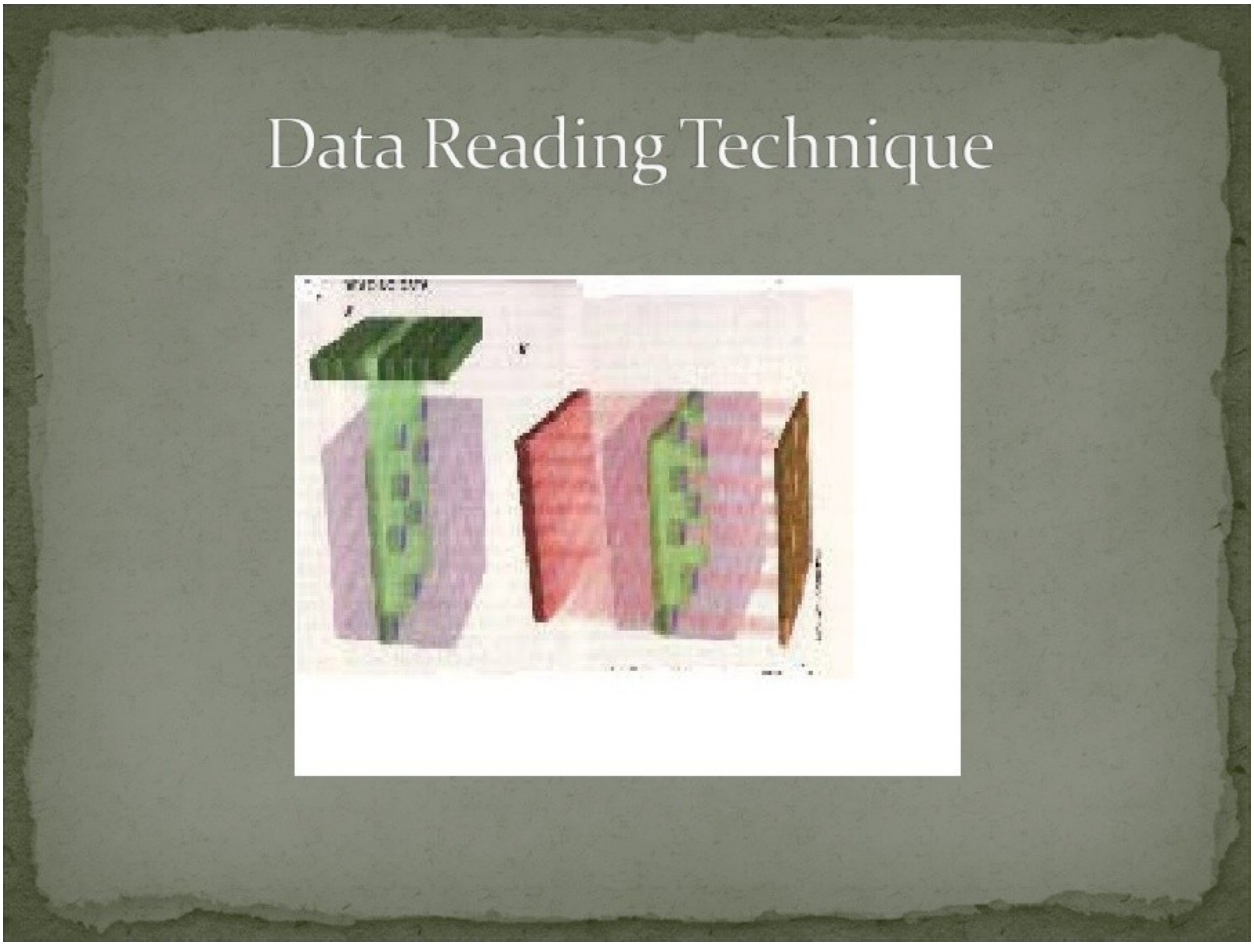
The read process



However, the molecules which started out in the binary state 0 (theO intermediate state), do absorb the low-intensity red beams. A detector then images (reads) the light passing through the

cube of memory and records the location of theO andP orQ structures; or in terms of binary code, the detector reads 0's and 1's. The process is complete in approximately 10 milliseconds, a rate of 10 megabytes per second for each page of memory.

Advantages:

Clearly, there are many advantages to protein-based memory, among the most significant being cost, size, and memory density. However, there are still several barriers standing in the way of mass-produced protein-based memories. For three-dimensional memory to work, all of the molecules need to be reached without altering any other molecules. This is done with a process called two-photon interaction.

Single Vs Two Photons:

First, let's consider why we even need to use two photons. Let's try to do this with a single photon. A chunk of bacteriorhodopsin-laden polymer would be the memory in this example. The source of light in this example would be a laser of appropriate

wavelength to excite the bacteriorhodopsin from the bR to the M or Q state. As a person was using this computer, the RAM would begin to be used up. The surface of the chunk of polymer with our favorite protein would slowly get used up. Eventually, the need to use the memory storage capacity inside the chunk of polymer would arise.

No big deal, you're thinking. Just shine the laser on the molecules inside. the chunk. Okay. Let's try it. Zap!! we've encoded on the in sided of the chunk. Now, it's time to read the entire RAM for some computations you need to do for chemistry class. The computer starts reading the RAM and all of a sudden it can't go any further because the memory has been corrupted. This corruption was due to the use of a single photon to change the state of the bacteriorhodopsin. A two photon method would reduce this type of corruption. The two photons would each have only part of the energy needed to change the state of the bacteriorhodopsin. Therefore

they would pass through the polymer until they coincided at a point and changed a molecule of bacteriorhodopsin. The single photon method would not be a good choice for a three- dimensional memory. A single photon would excite all of the molecules that are in its path. If the surface of the chunk of polymer was used to store something for the computer, that information would be corrupted by the photon as the computer attempted to write to some of the molecules in the inside of the polymer. The photon would also excite all of the molecules in its path through the polymer chunk.

Projects:

Bacteriorhodopsin Optical Memory

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Purple membrane from Halo bacterium, Halobium.

•

Bi-stable red/green switch

•

In protein coat at 77K, 107-108 cycles

•

10,000 molecules/bit

•

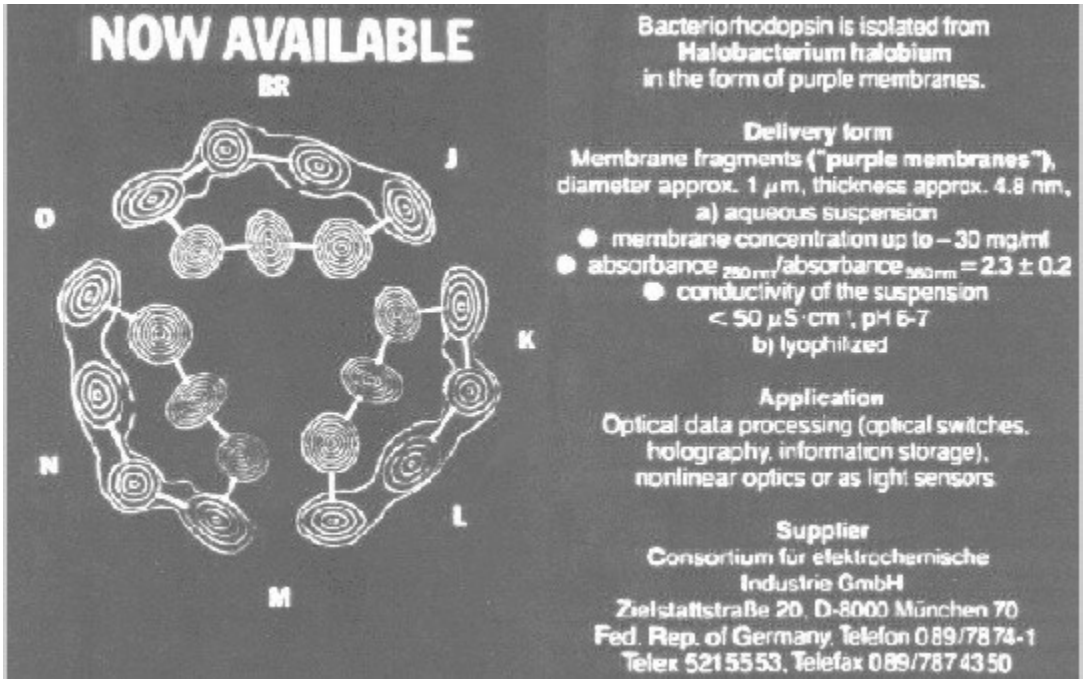
Switching time, 500 femto seconds

•

Monolayer fabricated by self-assembly ,Speed currently limited by laser addressing

As an example of current work, consider the molecular optical memory research underway by Prof. Robert Birge and his group at Syracuse University. Using the purple membrane from the bacterium Halo bacterium Halobium, they've made a working optical bi stable switch, fabricated in a monolayer by self- assembly, that reliably stores data with 10,000 molecules per bit. The molecule switches in 500 femto seconds--that's 1/2000 of a nanosecond, and the actual speed of the memory is

currently limited by how fast you can steer a laser beam to the correct spot on the memory.

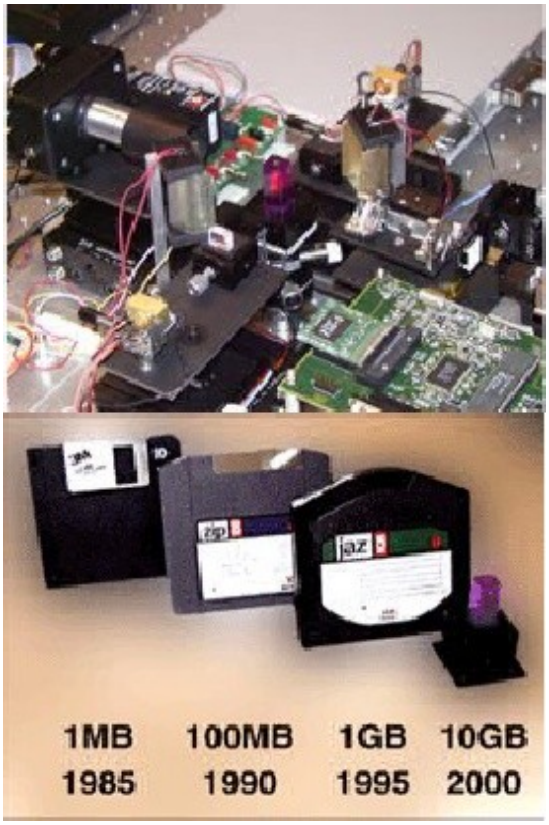


Lest you think this is some far out distant future research topic, here's an ad from a couple weeks ago by a company in West Germany offering bacteriorhodopsin for sale, listing under applications, ``Optical data

processing, optical switches, holography, information processing, nonlinear optics, and light sensors.''

New

Protein based storage...is an experimental means of storing data. Using proteins that respond to light from bacteria found in salt water, a small cube can store large amounts of data. By using lasers the protein can be changed depending on various wave lengths, allowing them to store and recall data. As a result protein can be used to store enormous amounts of data using lasers to read and write binary code. With this new found technology scientists are now developing a larger more efficient storage media.



The students from Fowler High School, Syracuse New York, have created this presentation with help from the Living School Book of Syracuse University and the W. M. Keck Center for Molecular Electronics to show the possibilities of protein memory.

Conclusion:

This paper focuses mainly on protein-based optical memory storage using the photosensitive protein

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