# Future Memory Storage Technology: Protein-Based Memory Devices May Facilitate Surpassing Moore's Law

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**Storage media based on biomolecules may provide a commercially viable alternative to current magnetic and optical storage systems. Our research is aimed at developing the storage media systems based on newly designed thermostable bacteriorhodopsin (bR) mutants and exploring limits of high-density optical recording using far-field and near-field approach.**

***Index Terms*—Bacteriorhodopsin (bR), optical recording, scanning near-field optical microscopy (SNOM), storage media.**

## I. Introduction

STORAGE technology based on silicon- and inorganic-based materials are reaching their logical limits. Increase in areal density of storage devices based on silicon and inorganic materials is becomingly increasingly difficult [1]. Our research is focused on using genetically engineered light-activated proteins in the design of storage devices.

Bacteriorhodopsin (bR) is produced by *Halobacterium Salinarum* as monolayer crystalline chips of submicron dimensions, Purple membrane patches (see Fig. 1) occur in a form that gives its rigidity and makes it feasible for incorporation in a physical storage device. Seven transmembrane alpha-helices constitute the basic structural motif of bR (Fig. 2), which belong to the G-coupled protein receptor (GCPR) family. When bR absorbs light it undergoes series of structural changes accompanied by alteration in absorption spectrum (i.e., color) and refractive index of the protein. We are exploiting nonlinear optical properties of bR in the design of memory storage devices.

When a bR molecule situated in a membrane absorbs light it undergoes series of protonation changes accompanied by alteration in the absorption spectrum (i.e., color), as shown in Fig. 2, as well as changes in the refractive index of the protein. During this process, a positive charge is transferred from the inner to the outer side of the cell, which is the basis for the subsequent energy storage mechanism in the bacterium. After receiving a green laser pulse, bR molecule drives from the ground state bR state into $K$ state and that relaxes into $O$. If the molecule receives a red light pulse upon arrival to $O$ it will be converted into $P$ state that can slowly decay into $Q$ but will not relax into intial bR state. States $P/Q$ and bR have extended life time and, therefore, can be used as logical "0" and "1" for long-term data storage.

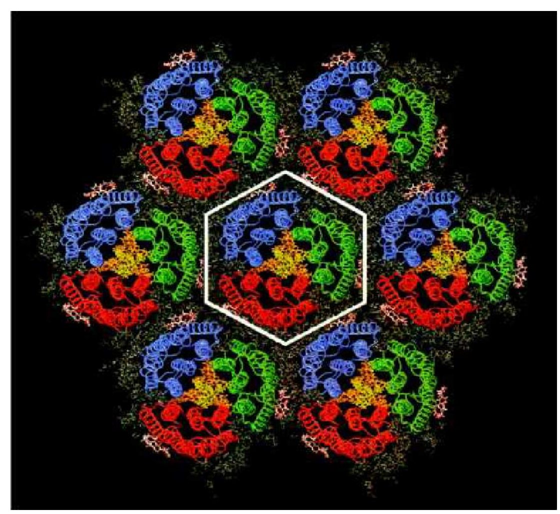

Fig. 1. Purple membrane.

Genetic engineering techniques may be used to stabilize these two natural states of the bR molecule such that it is possible to switch between them using light of different wavelength but spontaneous switching is essentially nonexistent. The unprecedented thermal stability of the genetically engineered bR recently achieved by Renugopalakrishnan *et al.* [2], [3] makes the protein-based devices the commercially viable future data storage systems with areal densities reaching well beyond 1 Tb/in$^2$ mark. Their naturally evolved properties, along with their genetically engineered variants, make them superior to any magnetic material used in storage devices. Moreover, bR film can be used in a three-dimensional (3-D) volumetric

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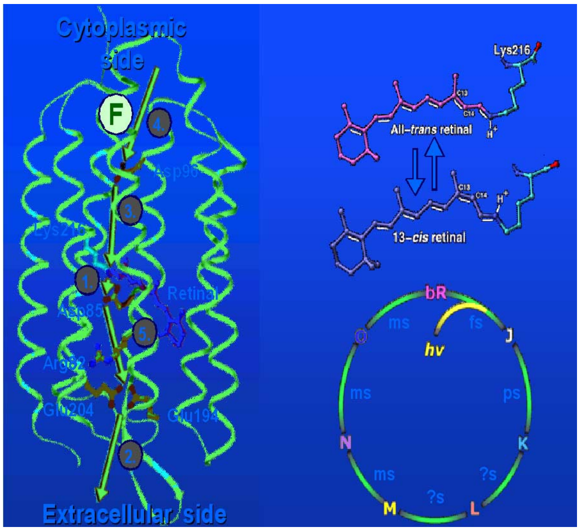


Fig. 2. Structure of bR and photochemical cycle of bR.

memory as discussed by Birge *et al.* [4] and Hampp [5]. For example, the following is true.

- bR molecules are less than 3 nm in diameter, potentially leading to storage capacity well beyond 1 Tb/in$^2$.
- bR media have demonstrated shelf life of ten years at the room temperature.
- bR media have unprecedented recyclability and durability including resistance to microbial degradation.
- bR media can be rewritten more than $10^9$ times.
- bR media has demonstrated time response in picosecond range versus nanoseconds for best magnetic disk currently available making it superior in terms of data transfer rate as well. Excellent physical and optical properties make new stable bR mutant a real alternative to magnetic recording media that would become inefficient at recording densities above approximately 250 Gb/in$^2$ due to superparamagnetic limit. However, before the protein-based data storage can be finally implemented, suitable methods for immobilizing bR mutants on platforms [6] and adequate mechanisms for writing and reading back information from this type of media should be investigated.

## II. Methodology

The major aim of our research is to explore the ultimate density limits of bR memory based on newly synthesized thermostable mutants and explore limits of high-density reading and writing of this media reaching ultimately the level of single molecule. Scanning near-field optical microscopy (SNOM) and laser diodes with nanofabricated aperture and several variants of atomic force microscopy (AFM) were applied to explore a range of novel high-resolution techniques to record and read information from the bR medium including state-of-the-art far-field techniques. We envisage several main routes for developing bR thin-film storage devices including incorporating bR molecules into a polymer matrix and development of lipid membranes suitable for self-assembly of bR. Within the project framework, we will address a number of issues essential for future development of practical storage device based on bR mutants [7], [8] including immobilization of bR on suitable surfaces, formation of very thin films, characterization of bR media, and achieving ultimate resolution in far-field and near-field optical techniques.

## III. Thin-Film Technology

The preparation of recording media is a key element in bR technology assuring stability and sensitivity of the recording media. We are working on several methods for immobilization of bR. In the initial applications, we strongly believe entrapment of bR in thin films will be the most practical method. Molecule immobilization can prevent diffusion of bit-encoded bR molecules from the encoding site which is crucial for long-term viability of the memory.

## IV. SNOM-Based Reading and Writing

SNOM microscopy is based on a tapered optical fiber scanning in close proximity to the surface of bR film. In this way, light pulses of different wavelength can be selectively delivered to a small group of molecules (spot size down to 50–30 nm). Modular structure of Aurora-3 (Digital Instruments, Santa Barbara, CA) allows to use simultaneously up to four light sources [red to blue lasers and ultraviolet (UV) lamp] to deliver photons through a fiber to the sample in the near-field regime. Besides nanoscale accuracy in positioning, multimode AFM provides a unique feature of maintaining the basic scanning probe microscopy (SPM) functionality to scan an image in a wide range of temperature (from room temperature to $\sim$500 K) of the substrate. This feature will be used to study thermal stability of the recording media under test.

## V. Apertureless Scanning Microsopy

We are exploring resolution limits of apertureless SNOM based on localized plasmon resonance between metallized tip and gold surface using ultrasharp tips (20 nm and below). Further increase in the resolution may be achieved using bright nanometer-sized light sources such as quantum dots attached to the tip [9]. In comparison to traditional fluorophores, quantum dots offer large cross section, high quantum efficiency, very long bleaching time, and tunable emission wavelength and, therefore, they can be used to form a stable bright nanometer-sized light source. Reading can be achieved within the same approach using large refractive index changes in bR mutants as local plasmon resonance is extremely sensitive to refractive index.

We propose to use geometry where bR layer is deposited onto a thin gold film ($\sim$50-nm thick). The sample is illuminated from below using high numerical aperture microscope objective in total internal reflection mode (TIRF). AFM with a metallized tip is scanning the film from top; the light scattered by the tip from the evanescent film is detected through the same lens. This technique can be used both for writing (when the sample is pulsed by external light source of appropriate wavelength, higher local field under the tip will ensure that writing will happen under the tip only) and for reading as plasmon resonance is extremely sensitive to local refractive index.

## VI. Development of High-Throughput Light Delivery System

High-intensity light sources on nanometer scale will be essential for commercial application of high-density protein memory. The most promising implementation of such nanometer light source could be metal-coated diode lasers directly placed at the air bearing surface. The source is a semiconducting diode with a 30-nm-long slit aperture in a 70-nm-thick layer of Al sputter deposited on the emitting edge. The modeling indicates that the transverse electric (TE), compared to the transverse magnetic (TM) mode, is substantially more evanescent.

The previous type modeling led to the idea of using a diode laser with a metal-coated emitting edge. The thickness of the metal is sufficiently thick to block the light propagation in a regular mode. In this case, apertureless light propagation is implemented: Focused ion beam (FIB) is used to make a truly nanoscale (subwavelength) aperture in the coated metal film. It appears that in this case the intensity of the light in the near-field regime (in the vicinity of the emitting edge) strongly depends on the shape of the aperture relative to the polarization (TE or TM) of the wave. It has been predicted that the geometrical effects could result in a substantially increased throughput (at least 1000 times greater) compared to the conventional case of the light conductance via fiber. This "focusing" effect may become a way to focus the light at a spot size smaller than the limit of the conventional state-of-the-art SNOM ($\sim$ 30 nm) without otherwise great loses in signal-to-noise ratio (SNR). The simulations performed by the team indicate that due to the focusing effect of the "aperturless" transducer, at least 1000 times larger amount of energy can be delivered to the same nanospot. In summary, to quantify the key advantage of the aperturless transducer, the FEM simulations indicate that the amount of power delivered into a 30-nm nanospot will be in microwatt range versus the nanowatt range in the conventional case with a fiber probe. FIB-based nanofabrication will be used to fabricate the previously described "apertureless" transducers to record onto protein thin films.

## VII. Summary

The unprecedented thermal stability of the genetically engineered bR recently achieved by Renugopalakrishnan *et al.* [2], [3] makes the protein-based devices a commercially viable future data storage system with areal densities reaching beyond 1 Tb/in$^2$ mark.

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