Chapter 2
Bionic (Nano) Membranes

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Abstract The goal of this chapter is to offer a concise and clear picture of the most important artificial nanomembrane-related procedures and technologies, including those for fabrication and functionalization, and to present the main properties and potential applications, stressing recent results in the field contributed by the authors. Nanomembranes are probably the most ubiquitous building block in biology and at the same time one of the most primordial ones. Every living cell, from bacteria to the cells in human bodies, has nanomembranes acting as interfaces between the cytoplasm and its surroundings. All metabolic processes proceed through nanomembranes and involve their active participation. Functionally, the man-made nanomembrane strives to mimic this most basic biological unit. The existence of the life itself is a proof that such a fundamental task can be performed. When designing artificial nanomembranes, the whole wealth of structures and processes already enabling and supporting life is at our disposal to recreate, tailor, fine-tune, and utilize them. In some cases, the obstacles are formidable, but then the potential rewards are stunning.

There is an additional advantage in bionic approach to nanomembranes: we do not have to use only the limited toolbox of materials and processes found in nature. Instead we are free to experiment with enhancements not readily met in natural structures – for instance, we may utilize nanoparticles of isotopes emitting ionizing radiation, even at lethal doses. We can introduce additional structures to our bionic nanomembranes, each carrying its own functionality, for instance nanoparticles or layers with plasmonic properties (e.g., to be used in sensing applications), target-specific binding agents (to improve selectivity) and carbon-nanotube support (to enhance mechanical strength). In this way, we are able to create meta-nanomembranes with properties exceeding the known ones (Jakšić and

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Matovic, Materials 3:165–200, 2010). In this chapter, we present some small steps toward that goal.

2.1 Artificial Nanomembranes

Artificial nanomembranes are a very recent concept in micro and nanotechnologies [1, 2]. They may be defined as free-standing (self-supported) planar structures ranging 5–100 nm in thickness. A thickness of 5 nm corresponds to 15–20 atomic layers of silicon, which approaches the fundamental limits. Because of their unique structure, man-made nanomembranes with areas of several cm^2 and giant aspect ratios exceeding 1,000,000 are sufficiently robust to withstand laboratory handling without any special equipment and with only a modest degree of precaution [1,3,4]. Artificial nanomembranes simultaneously belong to two worlds: to that of the nanoelectromechanical systems (NEMS) because of their thickness and to that of the microelectromechanical systems (MEMS) owing to their area. They represent an artificial counterpart of the living cell membranes that divide the cytoplasm of the living cell from its environment and at the same time provide communication and enable their active interaction [3].

The most basic classification of man-made nanomembranes is inorganic and organic (macromolecular) ones. Early inorganic nanomembranes were in the form of homogenous (Cr, Pt) metallic films. Their areas were limited to about 1 μm^2 at a 6-nm thickness. These simple structures led to the next generation – the metal-composite nanomembranes. It is well known that composites can be tailored to have superior mechanical and thermal properties when compared with pure materials [5].

In a novel manufacturing process developed at Vienna University of Technology, metallic nanomembranes are modified by incorporating oxide and nitride nanoparticles within a metallic matrix [3]. The process is based on the standard MEMS technologies and does not require excessively expensive equipment and approaches. This technology combines reactive ion sputtering with simultaneous ion implantation into the substrate [3]. In this manner, nanoparticles are generated in situ during the deposition process itself. The result is a considerable enhancement of the mechanical properties enabling the fabrication of nanomembranes with areas 10^7-fold larger than previously possible (Fig. 2.1).

The second class includes organic (macromolecular) nanomembranes. This class is considerably greater than the inorganic structures, as there exists a plethora of organic molecules from which such nanomembranes may be assembled (see Fig. 2.3). There is also a wider choice of manufacturing processes available for organic nanomembranes compared with the inorganic ones.

During the 1930s, the Langmuir-Blodgett (LB) process was invented [6, 7]. LB nanomembranes are highly ordered. Being double-layered, they resemble biological membranes. Therefore, they were the first bionic membranes ever produced. Unfortunately, LB nanomembranes are very unstable and until now have found only niche applications [8].

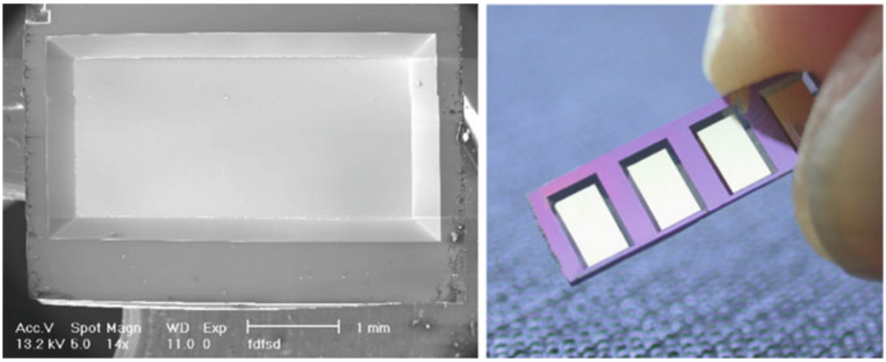

Fig. 2.1 *Left*. SEM image of a metal-composite nanomembrane with lateral dimensions of $1.5 \times 3.5\,\text{mm}^2$. Full thickness of the nanomembrane is only 7 nm. *Right* A photo illustrating the mechanical robustness of the metal-composite nanomembranes: the dimensions are identical to those in the image on the *left*. Current research in TU Wien – ISAS

More recent production methods include spin coating or thermal deposition of macromolecules based on thiol or silane compounds onto a substrate. However, unlike the LB process, these methods do not allow the molecular order in the films to be controlled; therefore, those films are hardly appropriate for bionic structures [9].

Finally, there is a relatively recently introduced method for film self-assembly that makes use of the alternating adsorption of oppositely charged macromolecules (polymers, nanoparticles, and proteins) – the layer-by-layer (LbL) technique [10]. The assembly of alternating layers of oppositely charged long-chained molecules is a simple process, which closely mimics the natural self-organization in living cells. It provides the means to form 5–500 nm thick films with monolayers of various substances growing in a preset sequence on any substrate. These nanomembranes have lower molecular order than LB films, but they have the advantage of high strength and easy preparation [11].

The properties of inorganic and organic nanomembranes are fundamentally different, the only common trait being miniscule thickness and large aspect ratio. Inorganic nanomembranes are mechanically robust and stable in harsh environments, but largely lack functionalization possibilities. However, polymer nanomembranes provide a variety of functional advantages over inorganic nanomembranes because they can have a wide range of source materials, tunable surface, and structure functionalities.

The practical utilization of nanomembranes is still in its infancy; however, some application fields seem rather promising. Some examples include new generations of photonic and chemical sensors, fluid separation, and energy conversion. The function of most of them resembles the biological cell nanomembranes. The essential step toward wider applications of artificial nanomembranes is the combination of inorganic and organic materials into a single structure. This may be done by applying laminated inorganic and organic layers and by incorporating various functional groups.

2.2 Biological Nanomembranes

Biological nanomembranes consist of lipid bilayers incorporating proteins and carbohydrates and typically have a very complex internal structure. The biological nanomembranes are highly functionally ordered, not simply geometrically ordered, Fig. 2.2. Science still has a way to go toward full understanding of the structure and function of the cell membranes, even in the simplest cases. However, the phenomenological reactions of a cell membrane to stimuli are better known: the membrane actively alters its permeability to respond to the specific molecule concentrations inside or outside the cell. It can transport molecules symmetrically or asymmetrically, passively by diffusion or actively by various "pumps". The key to this complex behavior is the membrane functionalization, which appeared at the very beginning of life itself.

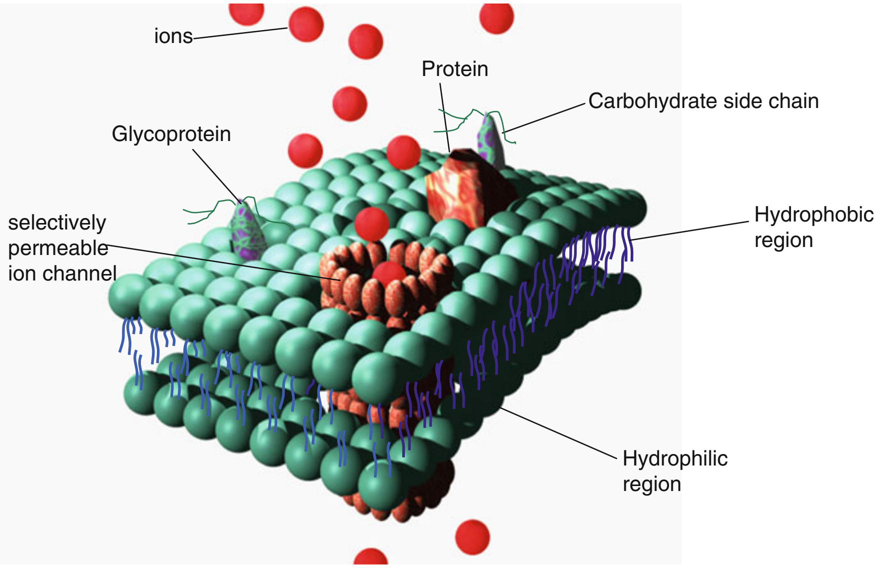

Fig. 2.2 Simplified representation of a lipid bilayer biological nanomembrane

2.3 Functionalization of Artificial Nanomembranes Toward Bionic Structures at ISAS: TU Wien

Bionic or biomimetic science may be defined as the study of biological systems as models for design and engineering of materials and systems. The model for the artificial nanomembranes, at least regarding their form and dimensions, are obviously the biological cell membranes. There is one fundamentally different trait of the artificial nanomembranes at their current state of development – their striking lack of complex functionalities. This is in stark contrast with the biological structures where such functionalities are not only common but also at the core of their function. This may appear like a very serious drawback of the man-made structures. However, one has to bear in mind that the research field of the artificial nanomembranes was conceived very recently, and the main body of literature being published within the last several years. Imparting complex biomimetic properties to nanomembranes is even more recent and is literally at its onset. Witnessing the present accelerating progress toward more complex functional structures, rapid advances may well be expected in the near future. The current research at the ISAS of nanomembranes with bionically enhanced functionality is directed exactly toward this goal [33]. Currently, it is proceeding along two main and seemingly disparate lines, fuel cell-based energy harvesting and detection of long wavelength infrared (IR) radiation.

2.3.1 Nanomembrane-Based Bionic Structures for Energy Harvesting

Stable and continuous energy supply is one of the very foundations of a peaceful and prosperous society. Considered from the thermodynamical point of view, the forms of energy currently used can be basically classified into two main groups: the low quality thermal energy, and the high quality energy like electricity or mechanical work.

Low quality energy (i.e., heat) is still mostly produced by burning accumulated fossil fuels. Other alternatives for obtaining thermal energy in large quantities and at high temperatures still fail from various causes. For instance, solar energy is highly dispersed (max. $2\,\mathrm{kW/m^2}$, rapidly declining at higher latitudes). Also, it is very difficult and technologically challenging to obtain high amounts of such energy in industrial plants and to further deliver it. Other energy sources such as biomass are helpful, but have many drawbacks and definitely do not suffice for the increasing energy demands of the modern society.

The situation with the production of electric power is even more complex. Nowadays the basic principles in power production remain unchanged when compared with those at the beginning of the industrial era. An energy carrier, typically fossil fuel, is used to generate heat, which is further transferred to a fluid.

In the next stage, the energy of the heated fluid is converted first to mechanical work and then to electricity in the plant's generators. The overall efficiency of this process is fundamentally limited by the Carnot cycle to 30–50%. Generally, the conversion of heat into the mechanical work is a low efficiency process. Unused heat is released into the environment, causing heat pollution, together with the emission of carbon dioxide and other harmful pollutants. Even a nuclear power plant deviates little from this scheme, indeed emitting no carbon dioxide, but churlishly leaving the problem of radioactive waste to the next generations.

Another process to convert chemical energy bound in fuel molecules to electricity is the electrochemical conversion. Its advantage is that, being an isothermal process, it is free of the Carnot cycle limitation. Examples of man-made electrochemical generators are batteries and fuel cells (FC). Although they share many similarities, FC substantially differ from batteries. They do not internally contain fuel and continue to convert chemical energy into electric energy (and some heat) as long as fuel and oxidant are supplied from external sources.

The operation principle of a proton exchange membrane (PEM) fuel cell is shown in Fig. 2.3. The central part of PEM FCs is a thin membrane, nonconductive but highly permeable to hydrogen ions (protons). On the anode side, the fuel, in this case hydrogen gas (H_2), is dissociated to protons and electrons by means of nanodispersed platinum catalyst. Electrons are collected on the anode side and made to flow into an external circuit, generating electricity. Simultaneously, protons migrate through the membrane toward the cathode. On the cathode side, the protons and electrons recombine with oxygen from the atmosphere, again with the assistance of the platinum catalyst. The basic reaction chain is given below:

$$H_2 \rightarrow 2H^+ + 2e^- \; (E_r = 0\,V)$$

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \; (E_r = 1.23\,V)$$

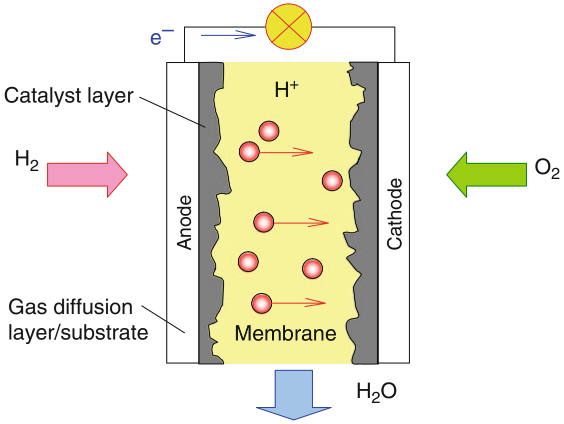

Fig. 2.3 Schematic of electrochemical reactions in proton exchange membrane fuel cell (PEM FC). Among many types of fuel cells existing today, the PEM FCs have the highest specific energy density and work at a temperature of about 100 °C

The final process of hydrogen oxidation is water. The FC are essentially zero emission generators. The practical efficiency of the conversion process is still around 40%, although the theoretical limit is close to 90% [12].

The PEM or proton exchange barrier is the critical part of a PEM fuel cell. The basic function of the membrane is to enable proton transport, while being simultaneously impermeable for electrons and gases. Typically, membranes for the PEM, FC are made up of perfluorocarbon-sulfonic acid (PSA) ionomer. The best-known material of this class is Nafion (Trademark of DuPont). Nafion has a unique interpenetrating structure of hydrophobic perfluorocarbon regions (providing thermal and chemical resistance, mechanical strength, and gas diffusional resistance) combined with hydrophilic regions of water clusters surrounding charged sulfonic acid groups (which allow selective proton transport), Fig. 2.4. For these reasons, Nafion, although already introduced in the mid-1960s, is still considered the benchmark against which most of the new materials are compared [13, 14].

However, Nafion and Nafion-like membranes suffer from several deficiencies that limit the efficiency of FCs to about 50% of the theoretical limit, but also make the production of FCs complex and expensive.

Ideally, a linear path between the two electrodes would provide the most efficient proton transport. However, the proton transport in Nafion polymer follows a random path, because of spatially disordered pores and the pore-geometry characterized by broad size distributions. The next and fundamental deficiency of Nafion materials is the prevalent mechanism of proton transport through the polymer nanochannels via the “vehicle” mechanism. At the molecular level, proton transport may follow two principal mechanisms:

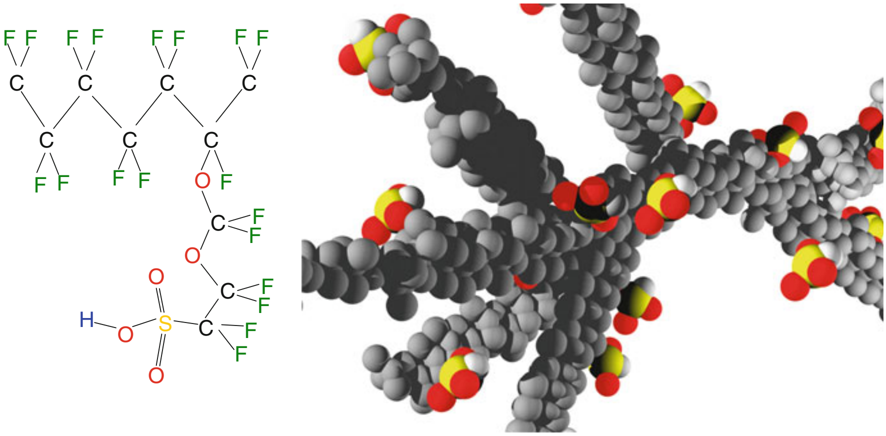

Fig. 2.4 Chemical and physical structure of Nafion. *Grey spheres* represent the hydrophobic backbone structure (Teflon) and *red* are the hydrophilic sulfonated clusters connected by an oxygen ion to the backbone chain

(a) "Vehicle" mechanism, i.e., diffusion of protons bound to carriers like $H^+(H_2O)_n$ ions, which travel along a nanochannel under electro-osmotic drag force, from the anode to the cathode side. Therefore, the vehicle proton transport is unavoidably associated with water molecule transport, resulting in water flow through the membrane [15].

(b) Proton hopping mechanism (Grotthuss transport). In some confined geometries, water molecules are aligned along a chain (called the "water wire"). If an excess proton is brought to the chain, it forms a protonic "defect." This defect moves by diffusion along the hydrogen bond chain of water molecules by alternately forming covalent bond with a molecule, which then releases another proton by splitting its covalent bond. Thus, the proton "hops" from one water molecule to the next along a quasi one-dimensional water wire [16]. The same effect may also occur in other liquids with hydrogen bonds. The water molecules within the water wire are immobile and transport of protons involves only temporary modification of covalent bonds within the water molecule during proton hopping [17,18]. Instead of H^+ $(H_2O)_n$ molecules, which exist in Nafion channels, water wires almost entirely conduct H^+ ions, i.e., protons. Hence, in the Grotthuss transport, there is no net water flow within the channel, Fig. 2.5. The path in this case is much closer to a straight line.

Now we can correlate the proton transport of artificial membranes such as Nafion with the biological nanomembranes. The flow of protons through a biological cell membrane is as fundamental to the cell metabolism as the flow of water, being coupled to the energy cycle that fuels the cell metabolism. It is advantageous for a cell to have separate transport of water (to maintain the internal pressure) and protons (necessary for cell energetics). The water balance within a cell is maintained

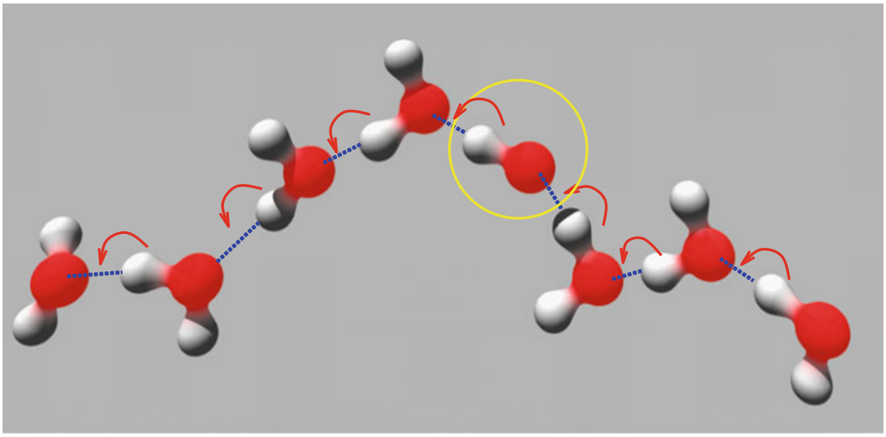

Fig. 2.5 Proton hopping mechanism confined to a one-dimensional water wire, the dominant proton transport mechanism in biological and bionic structures

by aquaporin water channels (Nobel Price in Chemistry 2003; [19]). Aquaporins are proteins with a hole along their middle with somewhat paradoxical behavior: they allow the flow of water molecules but are impermeable to protons that are much smaller than water molecules. In contrast, proton nanochannels are highly selective to protons (i.e., hydrogen ions) but are impermeable to water molecules. Any significant imbalance in proton or water concentration immediately causes cell dysfunction or death. Because of that both classes of channels are actively gated by the cell control mechanisms enabling control of proton concentration and internal osmotic pressure inside the cytoplasm within narrow margins. These molecular assemblies were definitely the first proton transport structures designed by nature and can be found in all organisms. A comprehensive analysis of proton channels is given by [20].

Ungated proton channel structures also exist in the natural world, although are less common. The most extensively studied one is gramicidin A (gA). gA is a small, double helix shaped molecule with hydrophilic body and hydrophobic ends (Fig. 2.6, left).

Each of the helices contains a water-filled channel, a natural water wire. Gramicidin channels have astonishingly high proton conductivity, reaching $2 \times 10^9\ \mathrm{H}^+/\mathrm{s}$ and thus surpassing any other known ion channel. The primary role of gA in natural environment is the self-defense weapon of *Bacillus brevis*. gA can disable the alien cell ability to maintain proton concentration in the cytoplasm, causing death of the invader cell.

As an organic molecule gA is relatively stable against weak acids and at moderately elevated temperatures. Further gA can be readily incorporated into artificial phospholipid bilayer membranes. These properties of gA already attracted attention of the industry with respect to proton conductive structures (Hewlett

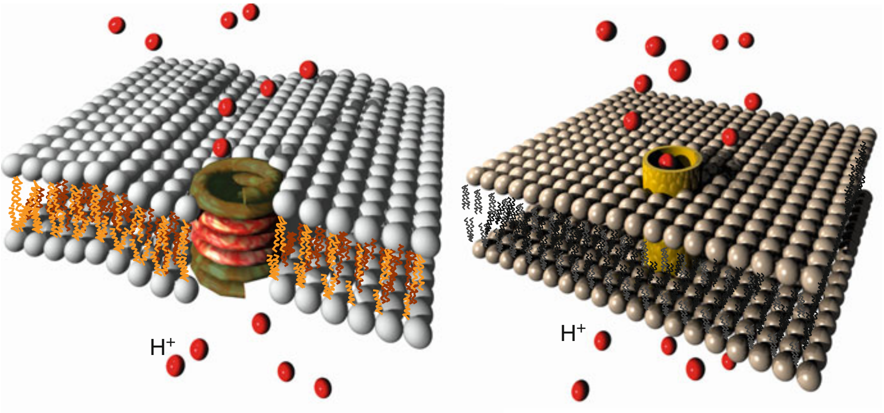

Fig. 2.6 (*Left*) gA helix molecule embedded in the biological phospholipids bilayer membrane. (*Right*) Bionic proton conductive structure. The artificial lipid-bilayer includes an array of proton conductive nanochannels, for example gA [21]

Packard) (Jackson and Jeon 2004). However, the stability and durability of the gA protein molecule is still insufficient for direct application in FCs at temperatures around 100 °C for prolonged periods of time. An idea is therefore to use alternative mechanisms to build artificial ion channels (Fig. 2.6, right).

Water-filled carbon nanotubes (CNTs) appear also as the candidate for a new generation of proton conductive structures. In this case, CNTs play the role of the ion channel within the living cell. CNTs are mechanically robust, chemically and thermally exceptionally stable, and have an integrated nanochannel. CNTs normally have hydrophobic walls, which can be made hydrophilic and their channel filled with a one-dimensional water wire theoretically resembling a gA structure [22], Fig. 2.7. A similar structure utilizing calixarene molecules with well-defined channels was also proposed [23].

The general direction in the further development of proton conductive membranes from the stochastic structure of Nafion-like materials toward highly efficient bionic nanomembranes seems to be marked out. However, the technological difficulties on the way toward practical realizations are tremendous. Many groups around

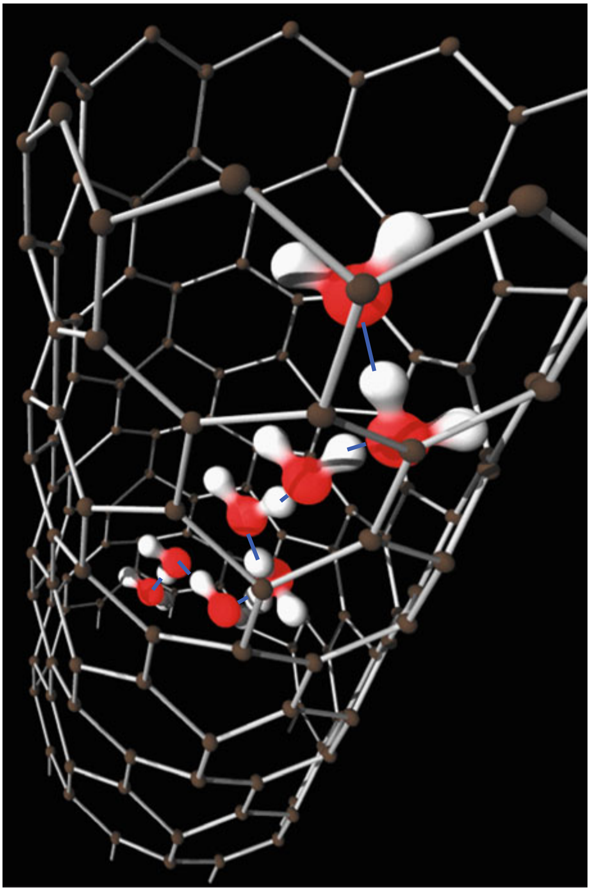

Fig. 2.7 CNT filled with water to form proton conductive water wire. The proton conductive mechanism is Grotthuss transport

the world are engaged in development of bionic proton conductive membranes. The TU WIEN, ISAS joined that circle through an EU FP7 project MultiPlat, "Biomimetic Ultrathin Structures as a Multipurpose Platform for Nanotechnology-Based Products." As the project is at a relatively early stage, not all details are currently available for publication.

2.3.2 Nanomembranes as Bionic Detectors of Electromagnetic Radiation

In the course of evolution, starting practically from the very emergence of life, most living organisms developed sensitivity to some wavelength range of electromagnetic radiation. Organisms like plants are able to perceive the direction of the electromagnetic radiation in the range 0.4–0.7 μm, since it ensures the energy necessary for their development (heliotropism).

In the case of organisms able for active movements (animals), the receivers of electromagnetic radiation evolved over time into their sense of vision. The information obtained through it helps the animals to orient, communicate, find food, and to escape from enemies.

Anthropocentrically, man called his electromagnetic sense the sense of vision, and the narrow electromagnetic range from 0.37 to 0.75 μm to which his/her sense is sensitive became the "visible light." However, some animals developed senses for other electromagnetic ranges, which cannot be registered by man's unaided eye. The wavelengths of maximum sensitivity of these senses suit the specific needs of these species, i.e., enable them to obtain the maximum of the information important for their survival. For instance, the common bee (*Apis mellifera*) sees radiation from yellow light to UV-A range (300 nm). Clouds are transparent at a wavelength of 365 nm, which ensures a safe solar navigation to bees and at the same time facilitates them to find food, since flowers with ultraviolet reflecting pigments clearly stand out against the background of green leaves. For humans, these flowers are simply white.

Other species developed senses for the IR range. IR radiation carries a significant portion of the information about our environment. Actually, more than 50% of the solar radiation (blackbody at 6,000 K) belongs to the IR range. A body heated to a temperature of 1,000 K (red heat) emits only 0.0002% of its energy in the visible range, while even 50% of the energy (and thus information) belongs to a wavelength range above 4.2 μm. Our environment at a temperature of 300 K emits solely in the IR. It is not surprising that the past few decades have seen a tremendous interest and also an unsurpassed growth in the technology of IR detection.

Two intensively studied species that developed specialized sensory organs for IR radiation are the insect *Melanophila acuminata* (jewel beetle) and the snakes from *Crotalidae* and *Boidae* families (Fig. 2.8a).

Jewel beetles, which lay their eggs into burned pinewood in recently burned forests, have organs sensitive to IR radiation, with a maximum sensitivity at

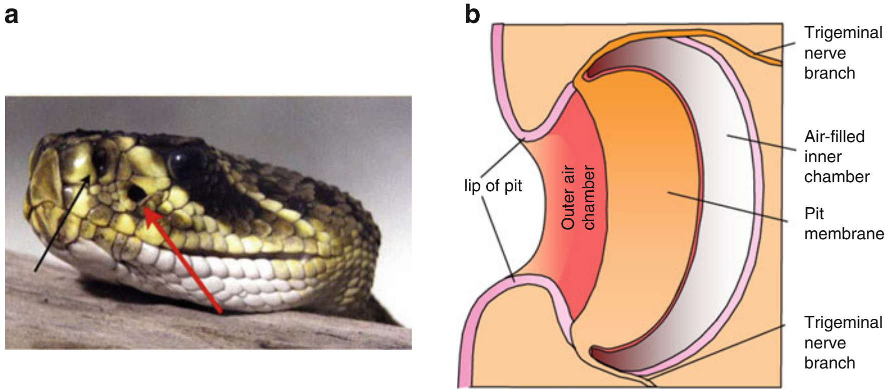

Fig. 2.8 (**a**) Rattlesnake, genus *Crotalus*. The *arrow* on the *right* points to the pit organ, the one on the *left* (*black*) shows the nostril (*Source*: Wikimedia Commons, under GNU Free Documentation License); (**b**) Cross-section of the pit organ where a membrane at the bottom of the pit serving as thermal infrared detector (denoted as Pit membrane) is clearly visible

2.8–3.5 μm, corresponding to the signature of a forest fire [24]. The IR systems of the snakes belonging to the subfamily *Crotalidae* and to the family *Boidae* are especially complex. IR organs are located in the head of the snake as a linear array of tiny apertures (pit organs) [25], Fig. 2.8a). Pits actually represent a pinhole optic system (Camera obscura) as no organic materials are transparent to 10 μm IR radiation (Fig. 2.8b). This wavelength corresponds to the maximum of the Planck blackbody radiation spectrum at a temperature close to 40 °C, which is the radiation of warm-blooded animals representing the basic pray of these snakes [26, 27].

It is accepted in biophysics that IR sensing in snakes is a thermal process [27]. IR photons are absorbed in the membrane via molecular resonant frequencies inherent to the chemical structure of the tissue. In essence, this energy transfer from the IR photons causes the molecules within the system to “vibrate” on the molecular level [28].

Prior to the development of the bionic nanomembrane-based IR sensors, one would do well to review the state of artificial IR detectors. Basically, IR detectors fall into two categories: photon and thermal detectors. The photon detectors of long wavelength IR radiation are made from semiconductor materials, and contemporary detectors must be cooled to achieve high sensitivity. Because of their requirements for cryogenic cooling, the photonic IR detectors tend to be expensive, complex, bulky, and difficult to maintain [29].

Man-made thermal detectors are based on the excitation of phonons or electrons in a solid by incident IR photons. This occurs through a cascade of different physical processes, and thus the incident IR energy is converted into random motion of lattice ions, i.e., into heat. This process is similar to those in biological sensors.

The sensitivity of modern thermal detectors approaches that of the semiconductor ones, and at the same time there is no need for cryogenic cooling. However, the response time of thermal detectors (including biological sensors) is radically inferior compared with that of the photon detectors. Thermal detectors respond relatively slowly (of the order of 10^{-3} s) compared with the photon detectors (of the order of 10^{-8} s).

A thermal detector response may be essentially characterized by two figures of merit: its specific detectivity D^* and response time τ as:

$$D* = \sqrt{\frac{A}{4k\varepsilon T^2 G}},$$

$$\tau = \frac{c}{G},$$

where A is the detector area, G is its thermal conductivity toward the ambient, ε is the detector emissivity, T is the detector temperature, and c is the thermal mass of the detector. To reach a high specific detectivity, the thermal conductivity of an IR detector should be the lowest possible to prevent leakage of heat. The sensitive IR organ in *Python molurus bivittatus* is therefore a freestanding membrane surrounded by air, thus minimizing thermal losses. Low thermal capacity is essential for a high response speed of a detector. The python sensitive membrane is only 15-μm thick, including blood vessels and thermosensitive nerve ends. Further, nerves in the membrane are very sensitive to small temperature variations. It is interesting that the sensitivity of the thermal receptors in the python's IR organ is not higher than that of the corresponding receptors in the human skin. However, our thermal receptors are located relatively deep under the skin surface. This naturally designed IR detector is relative sensitive and comparably fast for a thermal detector.

Bionic IR detectors attract increasing R&D interest nowadays [28, 30, 31]. However, there is an important difference in the development of bionic IR detectors compared with the development of the previously elaborated bionic proton-conductive structures. The performance of the artificial proton conductive structures still lags behind their natural counterparts, while the performance of the contemporary man-made IR detectors exceeds the natural ones. The principal rationale for this situation is that our detector technology exploits a wider range of materials than are available in biological structures. Some of these materials are highly toxic (Mercury Cadmium Telluride, MCT for example), others require excessively high or cryogenic temperatures during production processes, high pressure, etc. We conclude that the application of bionic principles, not materials themselves, still can result in vastly improved performance of IR detectors.

Bionic nanomembranes are a logical further step in developing thermal IR detectors. They can be manufactured to be highly sensitive to small temperature variations. At the same time, their thermal mass is generally very close to or just about equal to the fundamental limits. For example, graphene, a monatomic planar structure of carbon atoms arranged in a benzene ring network, is still sufficiently robust to be incorporated in a structure similar to the snake pinhole-based IR sensing organ. It is hard to imagine a structure with a lower thermal mass.

TU Wien actively works on bionic IR detectors within an FWF (Austrian Science Fund) project. Currently, the thickness of the nanomembranes used in the

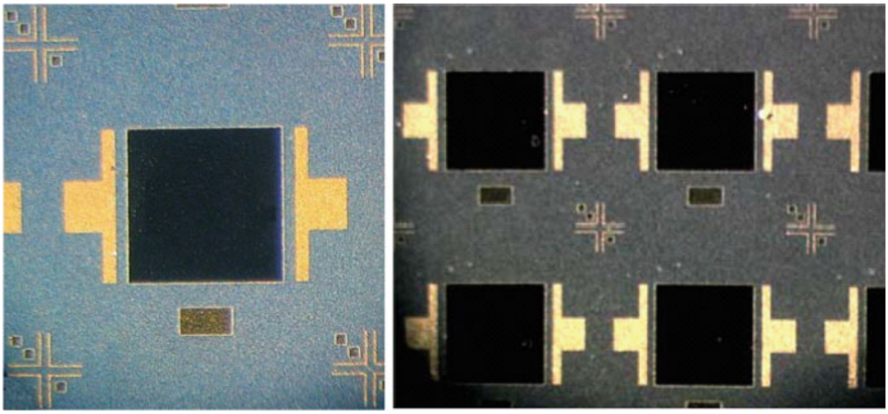

Fig. 2.9 Microphotograph of the experimental bionics IR detector based on nanomembrane. Current research at TU Wien – ISAS within a FWF Project

experimental detector is 6–7 nm and will be reduced even more in the future. The time constant of this thermal detector should be in the nanoseconds range, compared with milliseconds of the contemporary thermal devices (Fig. 2.9).

2.4 Conclusion

In this chapter, we have reviewed the most important procedures, technologies, and structures related to bionic nanomembranes as the artificial counterparts to the biological lipid bilayer membranes. We stressed our related contributions and presented our current works. Among these, we dedicated special attention to two particular biomimetic applications of the artificial nanomembranes: the proton-exchange membranes for the novel generation of FC and the nanomembrane-based thermal detectors mimicking the function of snake pit organs for IR vision.

When designing an artificial nanomembrane, one does not have to use the severely limited toolbox of nature. The available materials, structures, and processes can be far extended both into the inorganic and organic world. We may use various procedures and conditions usually not encountered with the living tissue, including high temperatures, aggressive media, radiation, etc. The much higher degree of design freedom and possibilities to include properties not found in natural materials already helped our research related to thermal detectors, resulting in performance exceeding that found in the living beings.

The research of artificial nanomembranes has the following three main goals:

- To build artificial nanomembranes using an extended toolbox
- To ensure membrane functionalization; for instance, to enable artificial transmembrane passageways (various engineered nanopores and artificial ion

channels), to implement structural reinforcements and many other additional functionalities
- To find ways for the most widespread application of the new building blocks in different practical applications and to optimize them

Different fields of application include nanoelectrochemistry and nanocatalysis, life science/biomedicine, optical engineering, photonics, and plasmonics, the use in various sensors (Jiang et al. 2004) including mechanical, thermal, chemical, biological ones, etc. Of large importance are protection (increasing mechanical stabilization and durability, avoiding tribological problems) and separation (nanofiltering, selective ion transfer) [32]. The bionic properties of nanomembranes enable us to rethink and reinvent some classical applications of ultrathin structures, this time by imparting them quasi-living features. Examples include transmembrane transport in proton-exchange FC, enhancement of various photochemical processes including energy conversion and hydrogen generation, artificial photosynthesis, to mention just a few. Bionic nanomembranes have a potential to improve environmental protection, to bring breakthroughs in life science, to enable the production of clean energy, and to contribute in numerous other ways to an enrichment of the overall quality of life.

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