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Membranes as Self-Assembling Coating of Solid State Device Components: Integration of Submicron Electrical Circuitry with Biological Systems

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1. Introduction

A prominent aim in the emerging field of bionanotechnology is to develop bioelectronic systems that combine the electrical properties of solid state materials with the specific recognition and catalytic properties of biomaterials such as proteins and DNA. The nanometer dimension of individual biomolecules may seem unfavourable from an engineering perspective, but since these molecules have evolved to form supermolecular functional structures by self-assembly, mechanical manipulation on the nanoscale is not required. The biochemically relevant size range is 1 nm to 1 μm, so that bioelectronic devices could be of a similar or even smaller size than is presently achievable lithographically, while offering a wealth of additional functionality [1,2].

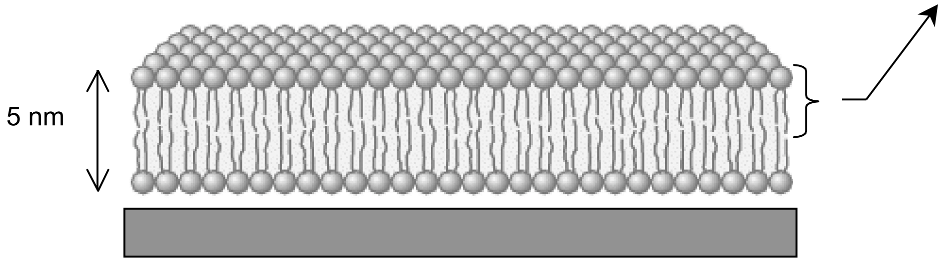
2. Membranes as insulating coating

Bioelectronic devices are required to contain water because biomolecules can only function in an electrolytic aqueous solution. To enable electrical (nano)circuitry, it is thus essential that the electronic components of the device are insulated from the biological solution. But this electrical insulation should also be flexible, enabling a coupling between biochemical recognition events and electrical input or output signals. Cell membranes, which selectively isolate the inside of cells from the outside, fulfill a similar requirement in living organims, and simplified versions of cell membranes could therefore be suitable as an insulating coating in biodevices.

The building blocks of cell membranes are lipid molecules which are composed of a hydrophilic headgroup and two hydrophobic chains (Figure 1). Upon exposure to water, these commercially available lipids self-assemble into a flat bilayer which curves to close in on itself, forming an enclosing shell or membrane. Although lipid bilayers are traditionally studied as such three-dimensional liposomes, glass-supported two-dimensional bilayers have long been used for microscopy studies. The techniques to produce flat bilayers on glass-like hydrophilic surfaces are now being adapted for nanotechnological relevant, generally more hydrophobic, substrates [3,4].

3. Supported bilayers

Supported bilayers have recently been formed on solid state materials such as silicon oxide, graphite and gold [5,6]. These bilayers have a thickness of 4-5 nm, a capacitance of ~0.5 μF/cm^2 and a resistance of ≥10 MΩ·cm^2 [7], and thus constitute an ultrathin coating which electrically insulates the metallic substrate from the electrolyte aqueous solution. Because lipid bilayer membranes are a component of living organisms, biomolecules do not aggregate on their surface [8], while specific molecular recognition events can be communicated to the solid state substrate by incorporating selective ion channel proteins in the bilayer.



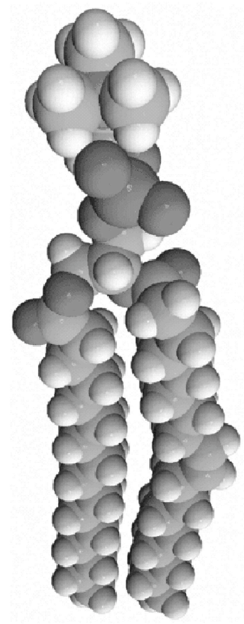


Fig. 1 Schematic representation of a flat lipid bilayer on a solid support (left). The individual lipids are depicted as a roughly spherical hydrophilic headgroup with two flexible hydrophobic chains. A typical lipid structure is also displayed with its individual atoms (right).

4. Carbon nanotube-based electrical circuitry

Our research interests concern carbon nanotubes, cylinders of graphene sheets with a diameter of 1-200 nm and a length of 1-100 μm. Their small size, significant strength, and high thermal and electrical conductivity make them ideal electrical components for nanodevices. Carbon nanotubes could be used as connecting nanowires that enable communication between different functional units within a bioelectronic device, or as biosensors in which molecular recognition events are transmitted by ion channel receptor proteins [9,10]. However, both these applications require electrical insulation of the carbon nanotubes from the aqueous solution.

5. Results

We have optimized a surface treatment which transforms the graphene surface of multiwalled carbon nanotubes into a suitable substrate for fusion of liposomes composed of commercially available synthetic phosphatidylcholine lipids. We show with atomic force and fluorescence microscopy that fusion of the (fluorescently labeled) liposomes results in the formation of continuous lipid bilayers that completely cover the carbon nanotubes. This efficient wrapping of the carbon nanotubes with artificial cell membranes electrically insulates the tubes from the biocompatible aqueous solution, which can be verified with electrical measurements. Significantly, under specific fusion conditions, the lipid coating also induces edge-on-edge contact of the carbon nanotubes, thus providing a starting point for the formation of electrically conductive nanocircuits.

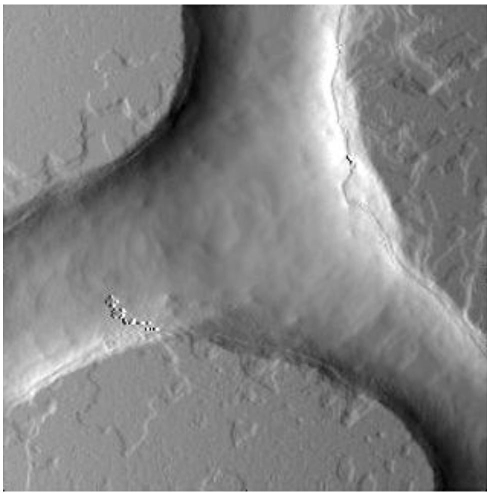


Fig. 2 Atomic force microscopy image (5x5 μm) of a three-way junction of multiwalled carbon nanotobes that is completely coated with lipid bilayers.

6. Conclusions

We have demonstrated for the first time that carbon nanotubes can be coated with self-assembling lipid bilayers without any additional components. Moreover, under specific preparation conditions the lipids enable carbon nanotube contacts and patterns. These results are promising for the development of nanoelectronic biodevices.

Acknowledgements

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