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MATHEMATICAL MODELING OF BIO-HYBRID DEVICES: TOWARDS POLYMERIC ARTIFICIAL RETINA

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In the latest years the research activity in the field of retinal prosthetics has been intense and several different approaches have been investigated, involving both traditional and unconventional methods. The development of a polymeric artificial retina belongs to this latter branch and recent promising results [1, 2] suggest that this could represent a viable alternative to the mainstream silicon-based approaches. Among the specific advantages of organic materials, we mention their increased biocompatibility and the fact that power supply is not a structural limitation of the technology. Nevertheless, such hybrid interfaces are still not extensively investigated and many fundamental aspects are currently under debate. In this respect, a mathematical description of the involved phenomena can provide a crucial support in the interpretation of the experimental measurements and in the comprehension of the device working principles.
The considered prototype consists of a few nanometers thick substrate of P3HT, a conjugated polymer commonly used in photovoltaic applications, deposited on a transparent and flexible contact. This layer, which represents the photosensitive part of the device, is immersed in an electrolytic solution reproducing a biological environment, and some cells (HEK, neurons) or even a piece of animal retina are grown onto it. When the device is illuminated, a depolarization of the cellular membrane occurs and, if the biological substrate has spiking ability, elicitation of active potentials is observed. The origin of such behavior might be ascribed to several phenomena but it is still not clear which is the predominant one. An established concept is that upon illumination free charges are generated in the polymer, determining the flow of capacitive currents in the junction region between cell and substrate and hence a change in the local electric potential. Moreover, light absorption also determines heat production, and consequently the temperature of the solution close to the cellular membrane is increased, modifying the properties of this latter, like resting potential, capacitance and conductivity. These effects are both suitable candidates for explaining the observed membrane depolarization and most probably a combination of them might occur.

In order to better understand the role of the polymer substrate in the device, a simplified configuration with no biological elements is tested using several experimental techniques, such as transient photovoltage and photocurrent measurements. Then the system is modeled using a set of approaches with different degree of refinement in order to reproduce the experimental results and to validate the hypotheses on the device operation principles.
The basic approach consists of a lumped parameter model in which the device is represented by an equivalent electric circuit whose elements reproduce the behavior of each device part. Constitutive laws of the parameters are derived by a proper reduction of a Drift-Diffusion (DD) model that adapts to the present context the formulation developed in [3, 4, 5] in the framework of organic photovoltaics. A fitting procedure is then performed in order to calibrate the parameter values by comparison between lumped model predictions and measure trends observed by consistently changing the experimental conditions, such as device thickness and light intensity. To refine the lumped parameter description, the DD model is also implemented and numerical simulations are performed to validate our hypotheses on the aspects of the device operation principles which cannot be accounted for by the lumped model such as the spatial distribution of charge dissociation mechanisms. Finally, to include also the effect of temperature changes on the device upon illumination, a thermal diffusion model is developed and coupled with the known dependency on temperature of ion channel conductivities, membrane capacitance and equilibrium potential in order to understand the dynamics of membrane voltages obtained under patch clamp conditions.
Results of the computations conducted so far show good agreement with measured device behavior in fast illumination regimes. Future work will be devoted to considering in more detail phenomena occurring in the case of prolonged illumination of the device, such as oxygen photodoping and irreversible degradation of the polymer. Moreover we plan to couple the electric and thermal effects in a unified model to identify the configurations in which either phenomenon is predominant in determining the device operation.

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