

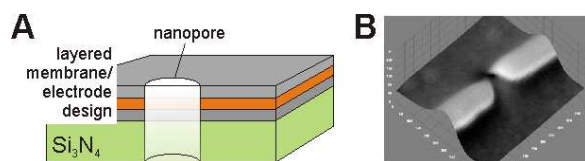
## Solid-State Nanopore Sensors with Integrated Electrodes

T. Albrecht\*, A. Bahrami, S. Di Lecce, F. Dogan, J.B. Edel, T. Gibb, A. Ivanov, A. Rutkowska, J. Skalkowska

Imperial College London  
Department of Chemistry, Exhibition Road, London SW7  
2AZ, UK  
t.albrecht@imperial.ac.uk

Solid-state nanopores are versatile sensing platforms with potential applications in medicine and biochemistry.<sup>1, 2</sup> Conventional nanopore sensors consists of a thin, free-standing dielectric membrane, which separates a liquid cell into two reservoirs with one electrode in each compartment. A nanometer-scale pore ("nanopore") in the membrane constitutes the only connection between the two reservoirs that allows ion, liquid and analyte transport. Upon application of an external electric field, charged biomolecules in solution may be driven through the pore, depending on their charge, the magnitude of the electric field, and the properties of the pore.<sup>3, 4</sup> Each translocation event modulates the ion current through the system, providing information on molecular size, composition and intermolecular interactions of the analyte. The conceptual simplicity does, however, come at a price. For example, there are limited capabilities to sense the identity of the analyte directly (specificity) or to control the translocation process. Moreover, the translocation of DNA and other long biopolymers is a rather complicated process driven by electrophoretic and/or electroosmotic forces. Polymer dynamics are particularly important, the radius of gyration and the pore dimensions are similar.

Integrating of electrode structures into or close to the nanopore offers interesting perspectives towards resolving at least some of these difficulties. An electrode embedded into the nanopore membrane can function as electrostatic gate, fig. 1A, thus affecting both ion and biopolymer transport in a controlled way.<sup>[5,6]</sup> Devices with two embedded electrodes acting as functional tunneling junction have been suggested as next-generation DNA, RNA or even peptide sequencing platforms, fig. 1B.<sup>[7,8]</sup> Here, the sensing principle is rooted in the different tunneling conductance of, say the DNA bases in the strand (molecular specificity), in combination with the strong localization of the tunneling effect (enhanced spatial resolution).



**Fig. 1:** Solid-state nanopore sensor with integrated electrodes. A: Gating nanopore with a metallic film embedded in the membrane. B: Tunneling junction aligned with a nanopore on a silicon nitride membrane (SEM image, tilted deposition).<sup>[8]</sup>

Beyond sensing, local electrode structures also enhance the fabrication and design capabilities of nanopore devices. For example, bipotentiostatic control of both the transmembrane bias and the potential of a membrane electrode allow for the fabrication of very small, metallic nanopores with real-time ion current feedback.<sup>[9]</sup> In this case, the nanopore is shrunk by metal electrodeposition, while at the same time the ion current through the pore is

monitored until a desired conductance value is reached.

The process is then stopped by switching the potential of the membrane electrode to a redox-inactive region. Pt and Au have proven to be well suited for this purpose, withstanding the strong local electric fields at the nanopore. On the other hand, aluminum films, which have interesting prospects zero-mode waveguide materials, were found to be less stable at high transmembrane voltages.<sup>[3, 10]</sup>

Understanding the current distribution in the nanopore sensor cell is fundamental to all of these applications, since the current determines the potential drop and hence the local electric field at the nanopore. For the first time, we have recently addressed this question in a three-electrode setup under bipotentiostatic control, see. fig. 1A, both experimentally and theoretically.<sup>[6,11]</sup> Interestingly, depending on the charge transport properties of the membrane electrode, in terms of the charge transfer resistance  $R_{ct}$ , we found different regimes of operation for the nanopore sensor. When  $R_{ct}$  is very large, the nanopore is electrostatically gated and does not affect the steady-state current distribution in the cell. In the opposite limit, when  $R_{ct}$  is small, the effect of the membrane electrode is large and may become a significant current source in the system. This may lead to significant (apparent) rectification in the pore current, which is however purely "Faradaic", and not rooted in the local charge distribution in the pore, its geometry or hydrodynamic effects (electroosmosis).

[1] C. Dekker, "Solid-state nanopores", *Nature Nanotechnol.* 2007, 2, (4), 209-215; [2] B.M. Venkatesan, R. Bashir, "Nanopore sensors for nucleic acid analysis", *Nature Nanotechnol.* 2011, 6, (10), 615-624; [3] M. Ayub *et al.*, "Nanopore/electrode structures for single-molecule biosensing", *Electrochimica Acta* 2010, 55, (27), 8237-8243; [4] R.M.M. Smeets *et al.*, "Salt dependence of ion transport and DNA translocation through solid-state nanopores", *Nano Letters* 2006, 6, (1), 89-95; [5] D. Stein, M. Kruihof, C. Dekker, "Surface-charge-governed ion transport in nanofluidic channels", *Physical Review Letters* 2004, 93, 035901; [6] T. Albrecht, "How to understand current flow in nanopore/electrode structures", *ACS Nano* 2011, 5, 6714-6725; [7] T. Albrecht, "Electrochemical tunneling sensors and their potential applications", *Nature Comm.* 2012, 3, art. no. 829; [8] A. Ivanov *et al.*, "A DNA tunneling detector embedded in a nanopore", *Nano Lett.*, 2011, 11, 279-285; [9] M. Ayub *et al.*, "Precise electrochemical fabrication of sub-20 nm solid-state nanopores for single-molecule biosensing", *J. Phys.: Cond. Mat.* 2010, 22, art. no. 454128; [10] G.A.T. Chansin *et al.*, "Single Molecule Spectroscopy Using Nanoporous Membranes", *Nano Letters*, 2007, 7, 2901-2906; [11] A. Rutkowska, J.B. Edel, T. Albrecht, "Mapping the ion current distribution in nanopore/electrode devices" (submitted)