Modeling of Charge Transport in Ion Bipolar Junction Transistors

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Introduction: A special class of ionic transistors, the ion bipolar junction transistors (IBJTs), is especially attractive for applications within biotechnology and life science, since these transistors are functional at physiological conditions and have been employed to modulate the delivery of neurotransmitter to neuronal cells. Detailed understanding of the device physics of these transistors was lacking which hampers further development of components and circuits. In this manuscript we, for the first time, report on the modeling of IBJTs with the Poisson's-Nernst-Planck equations and the finite element method.

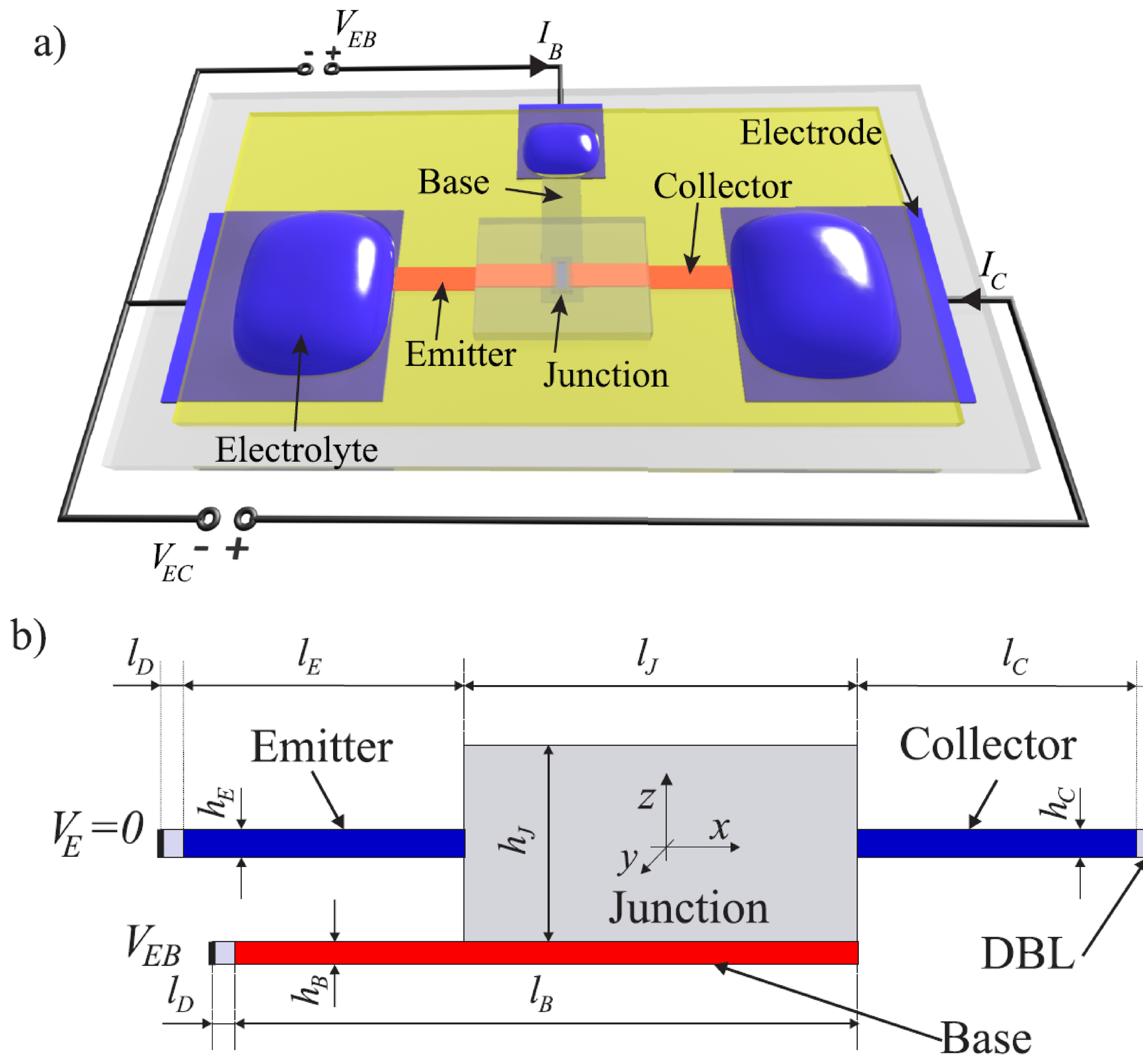


Figure 1. (a) Schematic representationof the IBJT. (b) The corresponding 2D geometry used in the computer simulation.

This *npn*-IBJT comprises a collector (C), an emitter (E), a base (E) and a neutral junction, (Figure 1a. The emitter and collector are anion-selective membrane channels while the base is a cation-selective membrane channel. Each channel is connected to a reservoir filled with NaCl solution. The reservoirs include conducting PEDOT:PSS polymer electrodes which are used to convert electric signals into ionic ones.

Computational Methods: Our model describes the ion bipolar junction transistor which was developed and experimentally studied by Tybrandt et al. [1]

The Nernst-Planck equation is employed to model the ion transport in the IBJT

$$\vec{j_i} = -D_i(\mathbf{r})\left[\vec{\nabla} c_i + z_i f c_i \vec{\nabla} V\right]$$

The flux densities are obtained by solving the steady-state equation

$$\vec{\nabla}\vec{j_i} = 0$$

together with Poisson's equation

$$-\varepsilon\varepsilon_0 \triangle V = F\left(c_+ - c_- + c_{fixed}(\mathbf{r})\right)$$

The boundary conditions for eqs 2, 3 are as follows. The concentration for each species is c_0=0.1 M at each border of the diffusion boundary layers. The potential V_{EB} is applied on the left end of the base DBL, V_{EC} is applied on the right end of the collector DBL and V_E =0 is applied on the left end of the emitter DBL. The potential gradients and normal fluxes vanish at all other boundaries.

The parameters used in the model are estimated from material properties and no fitting to device characteristics is performed.

References:

Klas Tybrandt *et. al.*, Toward Complementary Ionic Circuits: The npn Ion Bipolar Junction Transistor, *J. Am. Chem. Soc.* **133**, 10141-10145 (2011)

Results:

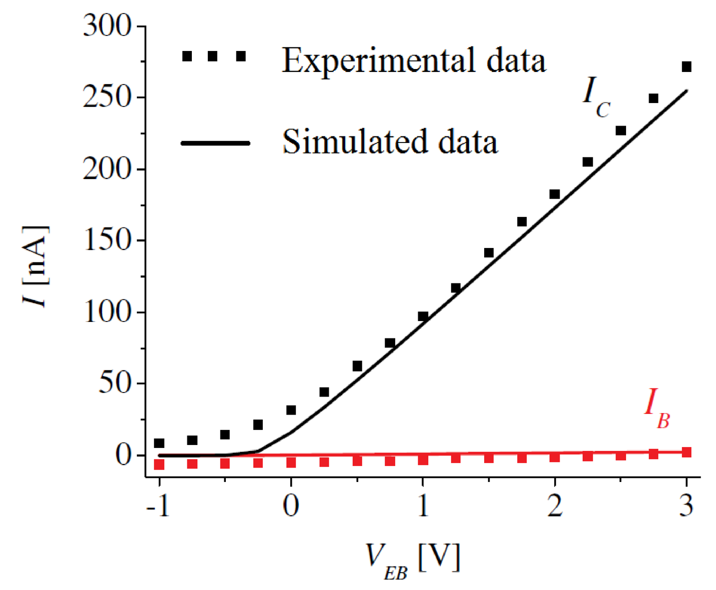


Figure 2. The transfer curves (I-V_{EB} dependence) for V_{EC}=10 V. I_C depends linearly on emitter-base voltage in the active mode while I_B remains low.

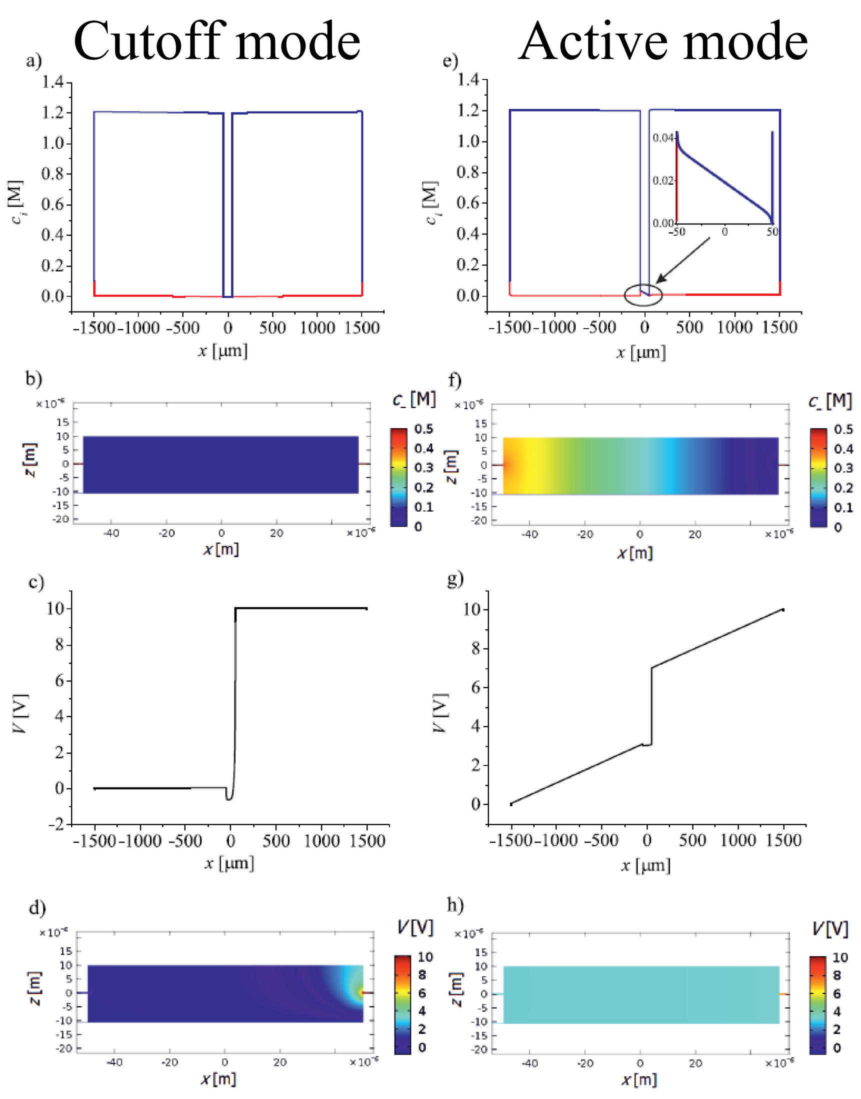
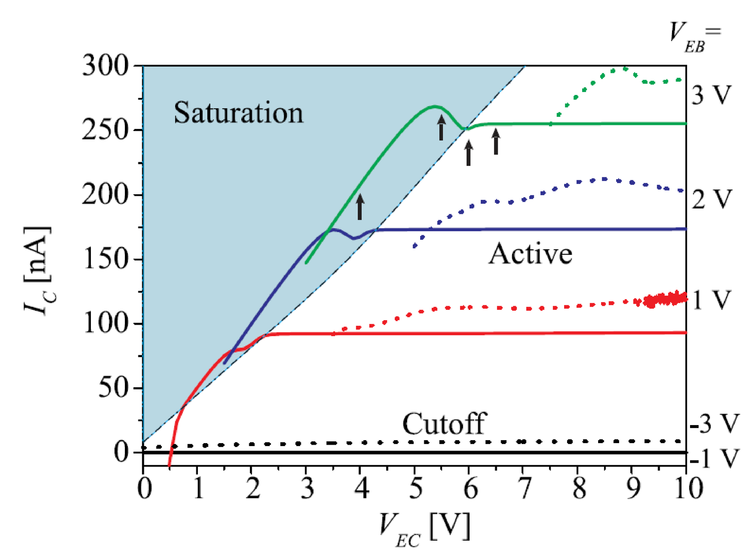


Figure 3. The concentration and potential profile in steady state for (a-d) cutoff mode V_{EB}= -1 V and (e-h) active mode V_{EB}= 3 V for V_{EC}=10 V.

In active mode, anions are injected into the junction from the emitter and diffuse over the junction to the collector where they are extracted. Cations, however, are trapped and are not transported through the junction. The current through the system causes ohmic potential losses in the emitter and collector.

The low I_C in cutoff mode is a consequence of that there are very few mobile ions within the junction. The whole potential drop occurs at the collector-junction interface while the potential is flat in highly conductive regions (emitter and collector).

Figure 4. The output characteristics of the *npn*-IBJT from numerical simulation (line) and experimental data (dot)[1]. The graph shows active, cutoff and saturation modes of the operation. The concentration and potential profiles of the points indicated by arrows are given in **Figure 5**.



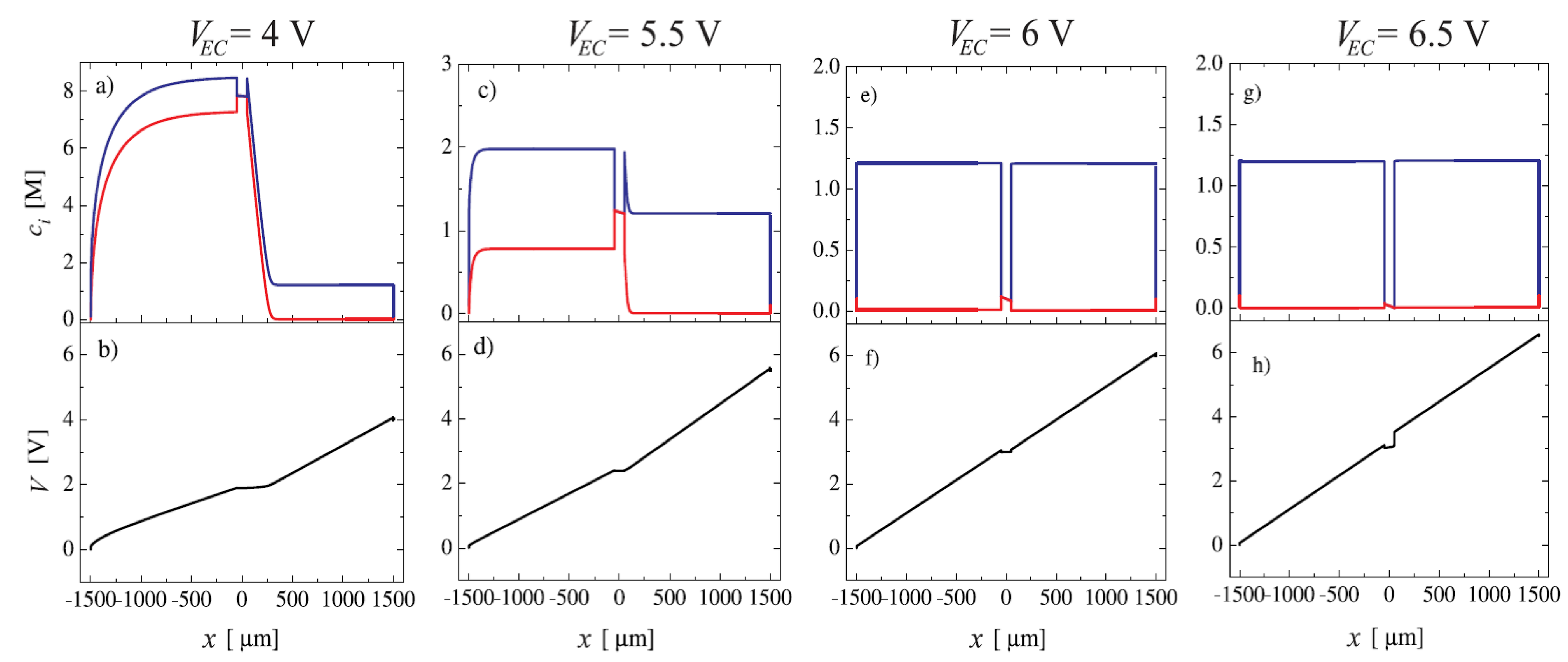


Figure 5. The transition from saturation (V_{EC}= 5.5) to active mode (V_{EC}= 6.5) for V_{EB}= 3 V. When the operation goes towards active mode (V_{EC}= 5.5 -> V_{EC}=6.5 V) the base current decreases gradually. This reduces the leakage of coions and the salt concentration within the junction goes down. In saturation mode there is no significant potential drop at the junction-collector interface. The transition from saturation to active mode occurs when the concentration at the junction-collector interface becomes close to zero.