Quantum transport and correlated switching – beating the Landauer limit

Avik Ghosh

University of Virginia, 351 McCormick Rd, Charlottesville, USA

It is generally believed that the biggest challenge to the continued scaling of semiconductor electronics is the high cost of binary switching. In the quest for the ultimate switch, there has been a happy emergence of sophisticated 'first principles' computational models on how electrons flow at the atomic scale. Much of nanoscale quantum transport can now be reduced to two limiting cases – for weakly correlated systems, the Landauer-Keldysh Non-Equilibrium Green's Function (NEGF) formalism describes the self-consistent time evolution of the one-electron states through a combination of interference and scattering pathways. The challenge here is to capture the relevant non-equilibrium many-body diagrams with a proper self-energy matrix that must be nonlocal in time. The opposite, strongly correlated regime requires a multi-electron master equation that describes the time evolution of the nonequilibrium occupancies (more generally, the density matrix) in their many-body Fock space. The challenge here, beyond the sheer numerical grunt work, is to capture the broadening of the one-electron transitions by the ensemble of non-interacting contact states.

Simulation plays a critical role in deconstructing the intricate physics above, as well as guiding material and device design. On the material front, we can use 'first principles' theory to scan through entire classes of materials in order to identify promising behavior, such as high magnetic polarization. On the device front, we now understand what digital switches may need to look like in order to operate at very low power, namely, employ alternate state variables beyond uncorrelated charges. The energy dissipated in today's devices is governed by the number of redundant charges set by interconnect 'drivability', and the switching energy per unit charge set by the Shannon-Landauer thermal limit of kTln2. Accordingly, one way to circumvent these limitations is to design 'correlated switches' - embodied in nano-magnetic logic and metal insulator transitions, where many spins or charges lock up through internal exchange-correlation fields and cut down the overall energy cost. An alternate class is 'subthermal switches' where each degree of freedom operates near a phase transition point below the classical 'Boltzmann-Landauer' kTln2 limit. One example is a nano-mechanical relay with a Van der Waals pull-in force that shuts off the current abruptly. A more topical example is chiral electron tunneling across graphene PN junctions, where we can engineer a gate tunable transport gap using geometry alone, thereby preserving the mobility while achieving a high ON-OFF ratio and a steep subthermal switching below the Landauer limit.