The Wigner-function approach to electron transport in semiconductor nanostructures

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The need for a fully quantum theory of electron transport in semiconductor nanostructures will first be discussed.
Then the Wigner function (WF) will be introduced with its formal definition, its physical meaning, and its main properties.
The dynamical equation for the WF will be derived and used to show that in many situations the WF behaves as a classical distribution function, thus explaining why the semiclassical Boltzmann equation gives good results even when its limits of validity seem to be exceeded.
The dynamical equation of the WF will be extended to the case of electrons interacting with phonons, showing the usefulness of such approach to the intermediate case between coherent dynamics and self-averaging transport.
An integral form of the dynamical equation will be presented particularly useful for the formulation of boundary conditions and for numerical solutions by means of a "particle simulation" method. In this approach Wigner paths in the Wigner phase space are introduced analogous to the particle trajectories in a semiclassical approach. They are formed by "free flights" separated by "scattering processes". Quantum theory of transport is thus seen as similar to the transport of an ensemble of classical particles with the addition of phase information. It contains all quantum features such as tunneling, resonances, collisional broadening, and intracollisional field effects. Monte Carlo codes can then be developed in analogy with the well known semiclassical algorithms.

An extension of the WF that depends upon momentum p and frequency ω as independent variables will be discussed, based on the two-time, single-particle, $G^<$ Green function.

Numerical applications to some prototypical quantum semiconductor structures will be presented.