Quantum Shuttle in Phase Space

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PACS numbers: 05.60.Gg, 73.23.Hk,85.85.+j

We present a quantum theory of the shuttle instability in electronic transport through a nanostructure with a mechanical degree of freedom. A phase space formulation in terms of the Wigner function allows us to identify a cross-over from the tunnelling to the shuttling regime, thus extending the previously found classical results to the quantum domain. Further, a new dynamical regime is discovered, where the shuttling is driven exclusively by the quantum noise.

Advances in microfabrication technology are pushing today's microelectromechanical systems (MEMS) towards the nanometer regime, and the emerging new technology of nanoelectromechanical systems (NEMS) is expected to play an important role in the future. The ubiquitous quantum mechanical effects affecting the performance of these devices present many theoretical challenges, only few of which have so far been addressed in the literature. The purpose of this communication is to present a fully quantum theory for an electromechanical instability in a generic NEMS device, the single-electron shuttle first studied by Gorelik et al.

This device consists of a movable single-electron transistor (SET) and exhibits an electromechanical instability from the standard tunnelling regime to a new regime in which the SET oscillates and carries an integer number of electrons per a cycle (shuttle regime). Since the original suggestion, there has been increasing interest in the shuttle phenomenon: e.g. by incorporating the shot noise due to the electron transfer, gate effects, the coherence effects in the electronic subsystem and strong dissipation of the oscillator energy . Only very recently the quantum mechanical treatment of the oscillations in various modifications of the shuttle setup has been considered.

The classical theory of shuttle transport has been used to describe the experiments on C_{60} single-electron transistor, where the oscillations of the center of mass of the molecule were found to be important. However, also explanations based on incoherent phonon assisted tunnelling theory which do not take into account the correlation between the coherent oscillator motion and the electron transfer seem to yield reasonable predictions for the I–V curves.

Therefore, a fully coherent quantum mechanical treatment of the oscillator which does take into account possible correlations and which would, in principle, allow to join the two approaches into a unified framework is a most desirable theoretical task. In this study we present an attempt for such a treatment for a simplest model supporting the shuttling transition in the classical regime. A complementary study to ours already exists which uses a similar model, albeit without any mechanical damping. However, the quasiclassical approximation used in that work does not give access to the purely quantum phenomena discussed here.

We demonstrate that the characteristic strong correlation between the oscillator motion and the electron transfer persists even in the quantum regime. The noise generated by various sources (shot and thermal, both having quantum components) is found to be very important for the phenomenon. Not only does it smear the classical transition found in into a crossover with a considerably shifted position in parameter space compared to the classical "mean field" study but the quantum component of the shot noise also generates the shuttle instability even in the classically stable region with zero electric field.

For further details see cond-mat/0301441 v1.

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