ELECTRONIC NOISE IN NANOSTRUCTURES

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One of the main drivers of the current interest in nanoscience is the potential for designing electronic devices that consume less power, operate at higher speed, and can be arranged in arrays even more dense than current ones. The ultimate goal is to develop *molecular electronics*, in which individual molecules function as electronic devices (e.g., switches) coupled to metallic wires (or atomic-resolution metallic tips) that act as electrodes or electronic gates. Other schemes envision using a variety of nanoscale structures, including semiconducting quantum dots or wires and others that exploit the extraordinary properties of graphene, for electronic devices and systems.

Key to realizing those schemes is a previous knowledge of the electronic transport mechanisms involved, including ballistic transport, hopping or tunneling. If the experience in mesoscopic physics is any guide, that knowledge cannot be fully derived from the electrical conductance alone. In the last few years, the inherent fluctuations (*noise*) of the current have received increasing attention, on the realization that when a system is out of equilibrium these fluctuations, especially those that arise from the discrete nature of the charge itself (*shot noise*), can convey information complementary to that provided by conductance. In addition, because of its intrinsic character, shot noise sets limits to the ultimate performance of an electronic device.

Here we review recent experimental studies of shot noise in two-dimensional (2D) semiconductor heterostructures, in which at least one of their dimensions is at the nanoscale. The control and perfection with which these nanostructures are nowadays prepared (by epitaxial growth on a crystalline substrate), together with the extensive knowledge (both theoretical and experimental) accumulated in the last thirty years, makes them ideal to correlate shot noise with electron-transport mechanisms. The obtained results can serve as a “catalog” or “library” to identify those mechanisms in other, not so well characterized nanostructures. For instance, we have shown that in semiconductor nanostructures that exhibit negative differential conductance (NDC) the amount of shot noise is determined by whether or not electrons are accumulated in confined regions. It will be possible to use this general conclusion (and others summarized below) in future studies aimed at elucidating the electronic transport in a wide spectrum of nanostructures.

1. Shot Noise in the Hopping Regime of 2D Systems[1]

In spite of the regained interest in hopping conduction, an electron-transport mechanism associated with the metal-insulator transition observed in Si MOSFETs and other 2D systems, until recently little was known about the shot noise properties in the hopping regime.

Our study on a 2D hole system confined in a SiGe quantum well has showed that in the hopping regime shot noise is suppressed relative to its "classical" value $2eI$ by an amount that depends on the length of the sample and its gate-controlled carrier density. We have found that the suppression factor, F, is about 1/2 for a 2μm long sample, and of 1/5 for a 5μm sample[1], which we have explained in terms of the characteristic length (≅1μm in our case) of the inherent non-homogeneity of hopping transport, obtained from percolation theory.

We have done subsequent measurements in a 2D electron gas in a Si-doped GaAs structure whose carrier density and localization length, ξ, were controlled by a gate voltage[1]. We have confirmed that F is inversely proportional to the sample length, L, and that it changes as the conductivity changes with gate voltage. We have discovered that the proportionality factor, L_0^*, between F and L^{-1} can be identified with the length L_0 given by percolation theory only when $\xi/L_0^* << 1$. On the other hand, when $\xi \approx L_0^*$, we have found that L_0^* is much smaller than L_0 obtained from the percolation model of hopping, thus signaling a reconstruction of the hopping paths[1].

2. Shot Noise in Semiconductor Superlattice Tunnel Diodes[2]

One of the major questions about shot noise in NDC devices is its universality, that is, whether or not the noise properties of all NDC systems are similar regardless of the mechanism that causes their multi-stability. We have addressed this question by studying the shot noise of two GaAs-GaAlAs devices with NDC of very different physical origin: a superlattice tunnel diode and a double-barrier resonant tunneling diode[2]. In the former, the NDC is caused by an energy gap in the collector electrode, while in the latter diode the NDC results from momentum conservation and is accompanied by charge accumulation in the well between the two potential barriers.

Our results have shown that in NDC devices in which transport proceeds via tunneling and and there is no charge accumulation, the electronic motion is uncorrelated and the noise is Poissonian. On the other hand, when the transport is such that charge is accumulated, charging effects correlate electron motion, either negatively or positively, and shot noise deviates from the $2eI$ Poissonian value[2]. These results contradict a previous calculation that predicted that shot-noise would be enhanced over $2eI$ in any device with NDC, regardless of the mechanism that caused it.

3. Shot Noise of Triple-barrier Resonant-tunneling Diodes[3]

As a first step toward the goal of measuring the shot noise of strongly coupled quantum wells, we studied the noise of thick triple-barrier resonant-tunneling diodes in both the positive- and negative-differential-conductance regions, and compared it with that of a double-barrier diode[3]. The diodes were prepared using lattice-matched $In_{0.53}Ga_{0.47}As$-$In_{0.48}A_{0.52}As$ epitaxial layers grown by metal-organic chemical-vapor deposition on InP substrates.

We found that in triple-barrier diodes the shot noise was reduced over $2eI$ whenever the differential conductance was positive, and enhanced when the differential conductance was negative[3]. This behavior is qualitatively similar to that found in double-barrier diodes, but it differs from it in important details. First, the noise reduction was considerably greater than predicted by a semiclassical model, and, second, the enhancement did not always correlate with the strength of the NDC, in contrast with what is found experimentally in double-barrier diodes.

4. Shot Noise of Strongly Coupled Quantum Wells[4]

Very recently, we have measured the shot noise of three GaAs-GaAlAs nanostructures, each consisting of two quantum wells separated by a central barrier of thickness d. We have found that in nanostructures in which d is small enough (≤ 2.0 nm) as to allow for coherent coupling of the wells' electronic wavefunctions, the characteristic noise reduction of the positive-conductance region (see above) is less pronounced that in structures in which that coupling is negligible ($d = 6.0$ nm). This result, which qualitatively can be explained in terms of an "effective" disappearance of the central barrier in case of coherent coupling, casts some shadow on calculations that predict a larger suppression of noise when tunneling is coherent than when it is sequential.

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