Slow and Fast Electron Channels in a Coherent Quantum Dot Mixer

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1. Introduction

Transport of electrons through coupled quantum dot nano-systems can be strongly regulated because electrons possess both charge and spin, e.g., Coulomb blockade [1] and spin blockade [2] are familiar mechanisms that lead to strong suppression of current. Here we describe and demonstrate another mechanism in quantum dots, which can potentially be realized in different ways, that leads to strong modulation of the current not related to charge or spin. The mechanism is coherent mixing (interference) and it can lead not only to pronounced current suppression but also marked current enhancement in the vicinity of a specific value of an external control parameter. The current suppression (enhancement) corresponds to the slow-down (speed-up) of electron tunneling through resonant channels. This slow-down (speed-up) effect represents an electronic analogue of slow (fast) light in quantum optics recently observed in solids [3,4,5].

2. Concept

As it is easier to visualize, we first outline the concept with the aid of Fig. 1. Suppose between emitter and collector electrodes, there is an up-stream probe dot (P) and a down-stream system (S=S₁, S₂, S₃, S₄, …) of two, three, four, … distinct dots (D). Although it is not a fundamental restriction, we will assume here for simplicity that all dots have just one gate-controllable single-particle energy level and the total number of electrons in P and S together at any one time is zero or one. Within S, inter-dot couplings, ideally independently controllable, are parameterized by C-numbers. With appropriate biasing and gate voltage control, presuming the coupling between P and S is weak, single-electron resonant tunneling currents (rc₁, …) can flow through channels P-D₁, …, D₄. In general, the current flow through each of these channels depends critically on the nature of the coherent mixing between the dot levels in system S. Furthermore, the characteristic electron tunneling time can be significantly lengthened or shortened when the channel current is respectively suppressed or enhanced due to the coherent mixing.

3. Experiment

Quantum dot structures with lateral coupling could be a vehicle for realizing the device conceptualized in Fig. 1, however, while for instance few-electron triple dots have been recently realized [6,7], the mixing effects of interest here have not yet been reported.

Instead, we employ a weakly coupled vertical double dot structure. As illustrated in Fig. 2, the upstream-dot still plays the role of P, however, the single down-stream dot replaces S, and two, three, four, … intra-dot mixed single-particle states (a, b, c, d, …) are the surrogate for the inter-dot coupled states. Explained elsewhere [8,9], the intra-dot level mixing is a positive byproduct of natural anharmonicity and anisotrophy in real dot confining potentials. An out-of-dot plane magnetic (B-) field (applied parallel to the tunneling current I) acts as the external control providing tunability via the single-particle energy level dispersion inherent to the Fock-Darwin-like spectrum for the near elliptical parabolic in-plane confinement of the dots.

Figure 3 shows data for one specific realization of down-stream dot system S₃ with two resonant channels. The left panel shows the single-electron resonant tunneling...
current, extracted from two anti-crossing branches, as a function of B-field. Well to the left and right of the B-field where the branches are minimally separated in energy (ΔB=0 T), both resonant channels (rc1, rc2) carry approximately equal current (≈1 pA). At ΔB=0 T, the current in one channel essentially doubles while the current in the other channel practically vanishes. Note that in the absence of mixing between rc1 and rc2 the current through each channel would remain close to 1 pA more or less independent of the B-field. The right panel shows the tunneling time (τ=e/I) converted from the resonant current. Tunneling times extended to several hundred ns for the slow channel and reduced to ~70 ns for the fast channel are evident near ΔB=0 T. Even accounting for uncertainty in extracting small resonant currents of ~50 fA or less (corresponding to τ exceeding ~3.2 µs), electrons can be slowed-down by a factor of at least 10 in the slow channel.

Systems S3 and S4 depicted in Fig. 1 can also be realized respectively with three and four intra-dot mixed states in the down-stream dot of the vertical double dot structure. Figure 4 shows examples of a slow channel for both systems. As in Fig. 3, a slow-down of the tunneling electrons by a factor ~10 is observed when one of the branch currents is dramatically suppressed by coherent mixing. Interestingly, the underlying physics at play for the slow channel in S3 [9] is identical to that relevant to dark-state formation by three-level coherent population trapping recently demonstrated optically for self-assembled dots [10]. We will discuss in detail the conditions for observing the slow and fast channels and present other relevant data concerning the spectral properties of the current resonances.

4. Conclusions

We described a means to create slow and fast electron channels by coherent mixing with vertical double dot structures that could potentially be applied to more complex multi-dot structures. In analogy with slow and fast light in quantum and atom optics we observed both extended and shortened tunneling times in the µs and tens of ns range. Slow-down factors of ~10 were seen in systems of two, three, and four mixed states.

References