Photon-Assisted Transport Through a Double Quantum Dot With a Time-dependent Interdot Barrier

Ph. Brune, C. Bruder, and H. Schoeller

Institut für Theoretische Festkörperphysik, Universität Karlsruhe, D-76128 Karlsruhe, Germany

Abstract

We study transport through two ultrasmall quantum dots with discrete energy levels to which a time-dependent field is applied (e.g., microwaves). The AC field causes photon-assisted tunneling and also transitions between discrete energy levels of the dot. Using the Floquet-matrix technique we propose an electron pump consisting of two serially coupled single-level quantum dots with a time-dependent interdot barrier. We compare our results to recent experiments by Fujisawa and Tarucha.

Many aspects of the Coulomb blockade are now well understood. Recently, a new issue has come up, viz., time-dependent transport through small quantum dots. High-frequency AC voltages can be applied to mesoscopic structures (e.g., in the form of microwaves). They lead to photon-assisted tunneling, i.e., electrons can overcome the Coulomb blockade by absorbing photons from the external field. This has become a very active area recently both experimentally[1–6] and theoretically[7–13].

In this work, we will study transport through two ultrasmall quantum dots with discrete energy levels to which a time-dependent field is applied. The electron interaction in the dots is taken into account by the Coulomb blockade model. The dots are weakly coupled to source and drain reservoirs by tunnel junctions. Time-dependent gate voltages lead to photon-assisted tunneling. We propose an electron pump consisting of two serially coupled single-level quantum dots strongly coupled by time-dependent fields. Transport through a double dot with a time-dependent interdot barrier has been measured recently by Fujisawa and Tarucha[5].

Our system consists of two interacting quantum dots in a time-dependent periodic field coupled to two reservoirs by tunnel junctions, see Fig. 1. We will use the time-dependent Hamiltonian $H(t) = H_{res} + H_{dot}(t) + H_{tun}$[9]. Here $H_{res}(t) = \sum_{k,\alpha,\sigma} \epsilon_{k\alpha\sigma}\, c^{\dagger}_{k\alpha\sigma} c_{k\alpha\sigma}$ describes noninteracting electrons in the reservoirs $\{\alpha\} = \{L, R\}$, $c^{\dagger}_{k\alpha\sigma}/c_{k\alpha\sigma}$ are the creation/annihilation operators of an electron with momentum k and spin σ in the reservoir α. The dot Hamiltonian is given by

$$H_{dot}(t) = \sum_{\alpha,\sigma} \epsilon_{\alpha\sigma}(t)\, d^{\dagger}_{\alpha\sigma} d_{\alpha\sigma} + \sum_{\sigma} w(t)\, d^{\dagger}_{L\sigma} d_{R\sigma} + h.c. + H_{ch}(N_{dot}) \, , \tag{1}$$

where $d^{\dagger}_{\alpha\sigma}/d_{\alpha\sigma}$ create/annihilate electrons with spin σ in dot α. The energy of the level in dot α is given by $\epsilon_{\alpha\sigma}(t) = \epsilon^{0}_{\alpha\sigma} + \Delta_D \cos(\omega t)$, where the time dependence is taken into account by a periodic shift of the level. The coupling strength of the field to the dot is given by Δ_D. The time-dependent transition matrix element $w(t) = \Delta_0 + \Delta \cos(\omega t)$ describes transitions between the dots, i.e., transitions that do not change the total number of electrons in the dots. The Coulomb interaction between electrons in the dot is taken into account by the Coulomb-blockade model $H_{ch}(N_{dot}) = E_C N^2_{dot}$. Here, $N_{dot} = N_L + N_R = \sum_{\alpha=L/R,\sigma} d^{\dagger}_{\alpha\sigma} d_{\alpha\sigma}$ is the particle number in the dots, $E_C = 2e^2/3C$ is the charging energy with $C = C_L + C_R + 2C_g$. The capacitance C_M between the dots is chosen to be $C_M = C/2$ and we set $C_L = C_R$. Note that we have included the time-dependent parts $[2E_C n_0^{L/R}(t) + E_C n_0^{R/L}(t)]N_{L/R}$ of the original $H^{orig}_{ch}(N_{dot}, t) = E_C N^2_{dot} + [2E_C n^L_0(t) + E_C n^R_0(t)]N_L + [2E_C n^R_0(t) + E_C n^L_0(t)]N_R$ in the energies $\epsilon_{\alpha\sigma}(t)$. The $e n^{\alpha}_0(t) = C_\alpha V_\alpha(t) + C_g V_{g\,\alpha}(t)$ are related to the polarization charges produced by the voltages of the left and right reservoirs $\mu_{L/R}$ as well as the time-dependent gate voltages $eV_{g\,\alpha}(t) = V_{g\,\alpha} + \Delta_{g\,\alpha} \cos(\omega t)$ applied to the left and right dot by the capacitance C_g. The tunneling part is given by $H_{tun} = \sum_{k,\alpha,\sigma} T_{k\alpha}\, c^{\dagger}_{k\alpha\sigma} d_{\alpha\sigma} + h.c.$, where $T_{k\alpha}$ denotes the tunneling matrix element.

We now generalize the work of Stafford and Wingreen[11] to the case where the height of the tunneling barrier also depends on time. The time-dependent Schrödinger equation is solved by the Floquet-matrix approach[14]. It is now possible to transform the tunneling Hamiltonian and calculate the current by the master equation technique[9,13]. The resulting dependence of the pumped current on the frequency and the amplitude of the applied microwaves is plotted in Fig. 2. Here and in the rest of the paper we used $E_C = 75, , , _L = , _R = ,$ is the tunneling rate. In Fig. 2 we set $\epsilon_L^0 = -10, , \epsilon_R^0 = 10, , \mu_L = \mu_R = 0, \ T = 5, .$

In Fig. 3 we show a comparison of our results with a recent experiment[5].

In conclusion, we have calculated the photon-assisted transport through a double quantum dot with a time-dependent interdot barrier. We have proposed a new electron pump and found qualitative agreement with recent experimental results by Fujisawa and Tarucha.

REFERENCES

[1] L. P. Kouwenhoven *et al.*, Phys. Rev. B **50**, 2019 (1994).

[2] L. P. Kouwenhoven *et al.*, Phys. Rev. Lett. **73**, 3443 (1994).

[3] R. H. Blick *et al.*, Appl. Phys. Lett. **67**, 3924 (1995); R. H. Blick *et al.*, Surf. Science **361** 595 (1996).

[4] K. Fujii *et al.*, Physica B **227**, 98 (1996).

[5] T. Fujisawa and S. Tarucha, Superlattices and Microstructures **21**, 247 (1996); Jpn. J. Appl. Phys. **36**, xxxx (1997).

[6] T. H. Oosterkamp *et al.*, Phys. Rev. Lett. **78**, 1536 (1997).

[7] M. Büttiker, A. Prêtre, and H. Thomas, Phys. Rev. Lett. **70**, 4114 (1993).

[8] N. S. Wingreen, A.-P. Jauho, and Y. Meir, Phys. Rev. B **48**, 8487 (1993); A.-P. Jauho, N. S. Wingreen, and Y. Meir, Phys. Rev. B **50**, 5528 (1994).

[9] C. Bruder and H. Schoeller, Phys. Rev. Lett. **72**, 1076 (1994); C. Bruder and H. Schoeller, in *Quantum Dynamics of Submicron Structures*, edited by H. A. Cerdeira, B. Kramer, and G. Schön, NATO ASI Ser. E, Vol. 291 (Kluwer, Dordrecht, 1995), p. 383.

[10] T. H. Stoof and Y. V. Nazarov, Phys. Rev. B **53**, 1050 (1996).

[11] C. A. Stafford and N. S. Wingreen, Phys. Rev. Lett. **76**, 1916 (1996).

[12] Y. Isawa, A. Okamoto, and T. Hatano, preprint.

[13] Ph. Brune, C. Bruder, and H. Schoeller, Phys. Rev. B (Aug. 15, 1997).

[14] J. H. Shirley, Phys. Rev. **138**, B979 (1965).

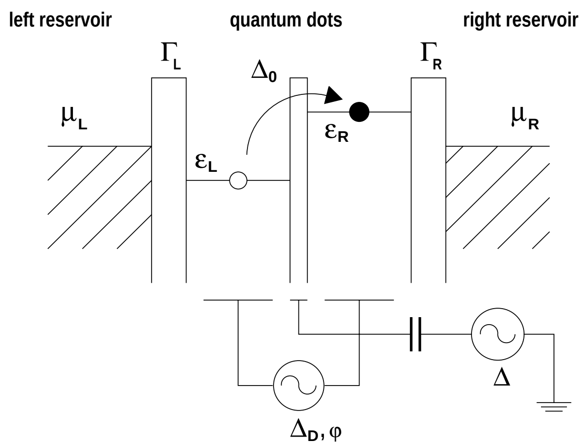

FIG. 1. Energy landscape of two serially coupled quantum dots connected by a weak time-dependent barrier (periodicity ω).

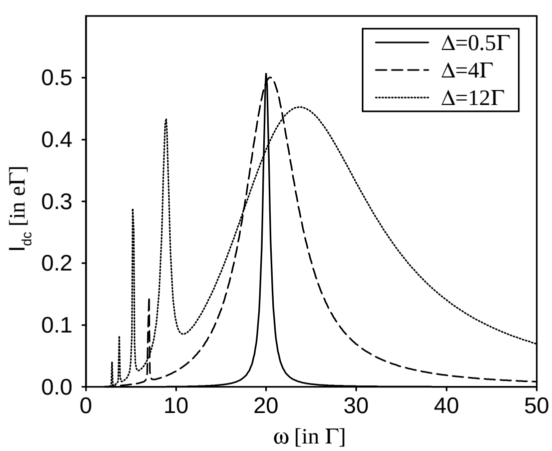

FIG. 2. Current response of a double quantum-dot electron pump versus frequency ω for a time-dependent barrier separating the dots. $\Delta_0 = 0, \;\; \Delta_D = 0$.

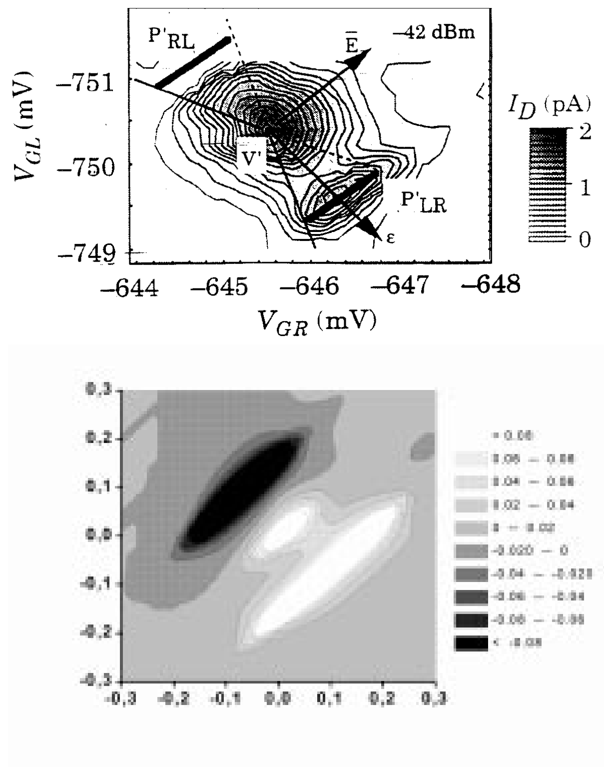

FIG. 3. Experimental results of Fujisawa and Tarucha[5] showing the current through a double quantum dot with a time-dependent interdot barrier (upper figure) as a function of the gates voltages applied to the left and right dot. Comparison to our results (lower figure) shows qualitative agreement. In the lower figure, the gate voltages are given in units of e/C_g, the current in units of e, . $\omega = 25$, , $\Delta_0 = 2$, , $\Delta = 3$, , $\Delta_D = 0$, $\mu_L = 2.5$, , $\mu_R = -2.5$, , $T = 3$, .