Zero-bias anomaly in cotunneling transport through quantum-dot spin valves

Ireneusz Weymann,[1] Józef Barnaś,[1,2] Jürgen König,[3] Jan Martinek,[4,5,2] and Gerd Schön[4]
[1]*Department of Physics, Adam Mickiewicz University, 61-614 Poznań, Poland*
[2]*Institute of Molecular Physics, Polish Academy of Sciences, 60-179 Poznań, Poland*
[3]*Institut für Theoretische Physik III, Ruhr-Universität Bochum, 44780 Bochum, Germany*
[4]*Institut für Theoretische Festkörperphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*
[5]*Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*
(Received 27 April 2005; published 2 September 2005)

We predict a zero-bias anomaly in the differential conductance through a quantum dot coupled to two ferromagnetic leads with antiparallel magnetization. The anomaly differs in origin and properties from other anomalies in transport through quantum dots, such as the Kondo effect. It occurs in Coulomb-blockade valleys with an unpaired dot electron. It is a consequence of the interplay of single- and double-barrier cotunneling processes and their effect on the spin accumulation in the dot. The anomaly becomes significantly modified when a magnetic field is applied.

DOI: 10.1103/PhysRevB.72.113301 PACS number(s): 73.63.Kv, 72.25.Mk, 85.75.−d, 73.23.Hk

INTRODUCTION

The combination of Coulomb interaction effects, which frequently are strong in nanostructures, and spin-dependent transport in systems coupled to ferromagnetic leads opens a new field of research with qualitatively new transport properties.[1,2] Spin-dependent transport through nonmagnetic grains may be influenced by the presence of spin accumulation,[3] leading to a different transmission for parallel and antiparallel orientation of the leads' magnetization, which results in a finite tunnel magnetoresistance.[4] In the limit of weak dot-lead coupling, and when a dot level is in resonance with the Fermi level of the leads (linear response regime), transport is dominated by sequential tunneling. Away from resonance, sequential tunneling is exponentially suppressed, and transport is due to higher-order tunneling.[5,6] In the Coulomb-blockade valley with an unpaired electron occupying the dot, Kondo-assisted tunneling[7] gives rise to a pronounced zero-bias anomaly in the differential conductance at temperatures below the Kondo temperature, T_K. Above T_K, transport is dominated by (second-order) cotunneling, with regular zero-bias behavior for nonmagnetic leads.

In this paper, we study cotunneling transport through a single-level and singly occupied quantum dot attached to ferromagnetic leads. When source and drain electrodes are magnetized antiparallel to each other, we find a pronounced zero-bias anomaly that is completely unrelated to Kondo correlations. It is rather a consequence of the interplay of spin accumulation and spin relaxation due to spin-flip cotunneling. A finite spin accumulation on the quantum dot partially suppresses transport. Spin-flip cotunneling provides a channel of spin relaxation and, hence, reduces the spin accumulation. As we show below, single-barrier spin-flip cotunneling (in the absence of a magnetic field) plays a role in linear response, $|eV| \ll k_B T$, but is negligible in the opposite limit. This gives rise to a zero-bias anomaly in the differential conductance. The prediction of this zero-bias anomaly as well as the study of its properties is the central issue of this paper.

MODEL AND METHOD

We consider a quantum dot with a single level at energy ε coupled to ferromagnetic leads with either parallel or antiparallel magnetization directions. The model Hamiltonian is $H=H_L+H_R+H_D+H_T$. The terms $H_r=\Sigma_{q\sigma}\varepsilon_{rq\sigma}c^{\dagger}_{rq\sigma}c_{rq\sigma}$ for $r=L,R$ represent noninteracting electrons in the left and right lead, where $\varepsilon_{rq\sigma}$ denotes the energy of an electron with wave number q and spin σ in lead r. The dot is modeled by $H_D=\Sigma_\sigma(\varepsilon\pm\Delta/2)d^{\dagger}_\sigma d_\sigma+Ud^{\dagger}_\uparrow d_\uparrow d^{\dagger}_\downarrow d_\downarrow$, where Δ is the Zeeman energy due to an external magnetic field, U is the charging energy, and the $+$ $(-)$ sign corresponds to $\sigma=\uparrow(\downarrow)$. Tunneling between the dot and leads is described by $H_T=\Sigma_{rq\sigma}(t_r c^{\dagger}_{rq\sigma}d_\sigma+t^*_r d^{\dagger}_\sigma c_{rq\sigma})$. Ferromagnetism of the leads is included via spin-dependent densities of states, $\rho^\uparrow_r\neq\rho^\downarrow_r$. The degree of spin polarization in the leads is characterized by the factor $p_r=(\rho^+_r-\rho^-_r)/(\rho^+_r+\rho^-_r)$, where $\rho^+_r(\rho^-_r)$ is the density of states for spin-majority (spin-minority) electrons. The tunnel-coupling strength is characterized by $\Gamma^\sigma_r=2\pi|t_r|^2\rho^\sigma_r$. Finally, we define $\Gamma_r\equiv(\Gamma^\uparrow_r+\Gamma^\downarrow_r)/2$, $\Gamma^\sigma\equiv\Gamma^\sigma_L+\Gamma^\sigma_R$, and $\Gamma\equiv\Gamma_L+\Gamma_R$, and assume $\Gamma_L=\Gamma_R\equiv\Gamma/2$.

We consider the Coulomb-blockade valley in which the dot is singly occupied with either spin. The probabilities for occupation with spin σ are P_σ. We determine the rate $\gamma^{\sigma\Rightarrow\sigma'}_{rr'}$ for a cotunneling process, in which one electron leaves the dot to reservoir r' and one electron enters from r with the initial and final dot state being σ and σ', respectively, in second-order perturbation theory. For $\sigma=\sigma'$, i.e., when the dot spin is not changed, and $\Delta=0$, the corresponding rate is[8]

$$\gamma^{\sigma\Rightarrow\sigma}_{rr'}=\frac{1}{2\pi\hbar}\,\mathrm{Re}\int d\omega[1-f(\omega-\mu_r)]f(\omega-\mu_{r'})\times\left[\frac{\Gamma^\sigma_r\Gamma^\sigma_{r'}}{(\omega-\varepsilon+i0^+)^2}+\frac{\Gamma^{\bar\sigma}_r\Gamma^{\bar\sigma}_{r'}}{(\omega-\varepsilon-U+i0^+)^2}\right],\quad(1)$$

while we get

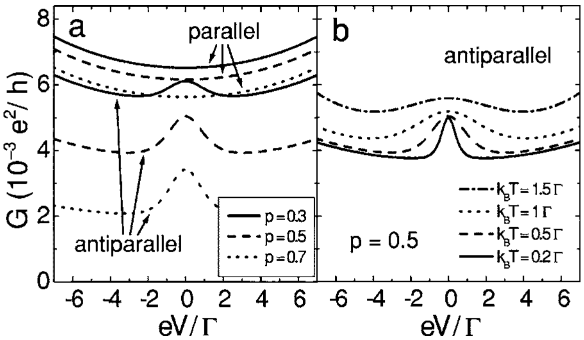

FIG. 1. (a) Differential conductance in the parallel and antiparallel configurations as a function of bias voltage for different values of spin polarization p at $\varepsilon=-U/2$, $U=30\Gamma$, $k_BT=0.5\Gamma$, and (b) for different temperatures and $p=0.5$.

$$\gamma_{rr'}^{\sigma\Rightarrow\bar{\sigma}}=\frac{\Gamma_r^{\sigma}\Gamma_{r'}^{\bar{\sigma}}}{2\pi\hbar}\,\mathrm{Re}\int d\omega[1-f(\omega-\mu_r)]f(\omega-\mu_{r'})\times\left[\frac{1}{\omega-\varepsilon+i0^+}+\frac{1}{\varepsilon+U-\omega+i0^+}\right]^2, \quad (2)$$

for the cotunneling process in which the dot spin is flipped ($\bar{\sigma}$ is the opposite spin of σ). Here, $f(\omega-\mu_r)$ is the Fermi function of reservoir r with electro-chemical potential μ_r.

The probabilities P_σ are obtained from the stationary rate equation $0=\Sigma_{rr'}[P_\uparrow\gamma_{rr'}^{\uparrow\Rightarrow\downarrow}-P_\downarrow\gamma_{rr'}^{\downarrow\Rightarrow\uparrow}]$ together with the normalization condition $P_\uparrow+P_\downarrow=1$. The current I is, then, given by

$$I=e\sum_{\sigma\sigma'}P_\sigma[\gamma_{LR}^{\sigma\Rightarrow\sigma'}-\gamma_{RL}^{\sigma\Rightarrow\sigma'}]. \quad (3)$$

RESULTS IN THE ABSENCE OF MAGNETIC FIELD

We consider symmetrically polarized leads, $p_L=p_R\equiv p$ and, first, ignore a Zeeman splitting, $\Delta=0$. The differential conductance $G=\partial I/\partial V\equiv(e^2/h)g$ as a function of the bias voltage is shown in Fig. 1(a). For leads magnetized in parallel, we find the typical parabolic behavior of the cotunneling conductance with increasing bias voltage. This is distinctively different for the antiparallel configuration, for which a zero-bias anomaly appears. The bias-voltage dependence of the conductance for different temperatures is shown in Fig. 1(b), where the width of the peak grows with T. It is possible to get some insight into the basic properties of this behavior using analytical results obtained in a limit in which the formulas simplify considerably while all the main physics of the zero-bias anomaly remains included. Deep inside the Coulomb-blockade regime, we can neglect corrections in the ratios A/B with $A=|eV|,k_BT$ and $B=|\varepsilon|,\varepsilon+U$. We find

$$g^P=\frac{\Gamma^2}{2}\left[\frac{1}{\varepsilon^2}+\frac{1}{(\varepsilon+U)^2}+\frac{1-p^2}{|\varepsilon|(\varepsilon+U)}\right], \quad (4)$$

for the parallel configuration, independent of $|eV|/k_BT$. For the antiparallel configuration, we get

$$g_{\max}^{\mathrm{AP}}=\frac{\Gamma^2}{2}(1-p^2)\left[\frac{1}{\varepsilon^2}+\frac{1}{(\varepsilon+U)^2}+\frac{1}{|\varepsilon|(\varepsilon+U)}\right], \quad (5)$$

in linear response, $|eV|\ll k_BT$, and

$$g_{\min}^{\mathrm{AP}}=\frac{\Gamma^2}{2}\frac{1-p^2}{1+p^2}\left[\frac{1}{\varepsilon^2}+\frac{1}{(\varepsilon+U)^2}+\frac{1-p^2}{|\varepsilon|(\varepsilon+U)}\right], \quad (6)$$

for $|eV|\gg k_BT$. We see that $g^P>g^{\mathrm{AP}}$, i.e., the system displays a tunnel magnetoresistance. But, furthermore, we find a zero-bias peak, since $g_{\max}^{\mathrm{AP}}>g_{\min}^{\mathrm{AP}}$, whose relative strength, characterized by $x\equiv(g_{\max}^{\mathrm{AP}}-g_{\min}^{\mathrm{AP}})/g_{\min}^{\mathrm{AP}}$, increases from $x=p^2$ at the edges ($|\varepsilon|\ll\varepsilon+U$ or $|\varepsilon|\gg\varepsilon+U$) to $x=4p^2/(3-p^2)$ in the middle ($\varepsilon=-U/2$) of the Coulomb-blockade valley.

The zero-bias anomaly, present (for $\Delta=0$) only in the antiparallel configuration, has the following properties:

(i) The crossover from $g_{\max}^{\mathrm{AP}}$ to $g_{\min}^{\mathrm{AP}}$ is around $|eV|\approx k_BT\sqrt{8/(1+p^2)}$, i.e., the width of the zero-bias anomaly scales linearly with k_BT and depends only weakly on p.

(ii) The *relative* peak height x increases monotonically with p and when moving from the edges towards the middle of the Coulomb-blockade valley.

(iii) The *absolute* peak height $g_{\max}^{\mathrm{AP}}-g_{\min}^{\mathrm{AP}}$ depends nonmonotonically on p, since it vanishes for $p=0$ and $p=1$.

(iv) At low temperature both $g_{\max}^{\mathrm{AP}}$ and $g_{\min}^{\mathrm{AP}}$ increase with temperature, $g_{\max,\min}^{\mathrm{AP}}(T)/g_{\max,\min}^{\mathrm{AP}}(0)=1+(T/B)^2+\mathcal{O}(T^4)$ with the same constant B, such that x is nearly independent of temperature.

Processes responsible for the zero-bias anomaly in the cotunneling regime are of second order, while these leading to the Kondo effect are higher than second order. The zero-bias anomaly of the cotunneling current is therefore distinctively different from that associated with the Kondo effect. The latter occurs at low temperature, $T\lesssim T_K$, shows up in the parallel configuration as well,[9,10] grows logarithmically with decreasing temperature, and reaches perfect transmission, $g=1$. Its width at low temperature saturates at k_BT_K, and it has a different magnetic-field dependence.

We close with the remark that the exchange field due to the presence of ferromagnetic leads discussed in Refs. 9 and 11 does not affect transport in the case considered here. Spin precession does not appear since the leads are magnetized collinearly.

MECHANISM OF THE ZERO-BIAS ANOMALY

To understand the mechanism of the zero-bias anomaly, we distinguish between four different types of cotunneling processes. In each of them two tunneling events are involved, either through the same or through the two opposite tunnel barriers. Accordingly, we refer to them as single-barrier [Fig. 2(a)] and double-barrier cotunneling [Fig. 2(b)]. Furthermore, the two electrons involved may carry the same or opposite spin, i.e., both single-barrier and double-barrier events come as either spin-flip or non-spin-flip cotunneling. In calculation we have taken into account all possible cotunneling processes. Here, however, we discuss just the ones responsible for the anomaly. Double-barrier cotunneling contributes directly to the current, while single-barrier cotunnel-

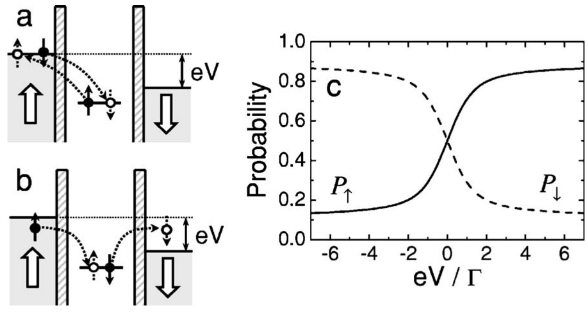

FIG. 2. Single-barrier (a) and double-barrier (b) cotunneling processes, and the occupation probabilities for spin-up and spin-down electrons in the antiparallel configuration (c). The parameters are $k_BT=0.5\Gamma$, $U=30\Gamma$, $\varepsilon=-U/2$, and $p=0.5$.

ing preserves the total charge. Nevertheless, spin-flip single-barrier cotunneling can influence the total current indirectly, by changing of the magnetic state of the dot. In the antiparallel configuration, the dot hosts a nonequilibrium spin accumulation, $m=(P_\uparrow-P_\downarrow)/2$. A different occupation of up- and down-spin levels in the dot, $P_\uparrow \neq P_\downarrow$, appears (even for $\Delta=0$) when the spin-flip cotunneling rates that change the dot from $\uparrow$ to $\downarrow$ and $\downarrow$ to $\uparrow$ are different from each other. In equilibrium, $V=0$, both rates are trivially the same and, hence, $P_\uparrow=P_\downarrow$. The situation is different at finite bias voltage and antiparallel magnetized electrodes. Now, only the two spin-flip processes that transfer an electron from the left to the right lead determine the magnetic state of the dot. The one shown in Fig. 2(b) changes the dot spin from $\downarrow$ to $\uparrow$. Since only majority spins of the electrodes are involved, the corresponding rate is larger than that of the other process that changes the dot spin $\uparrow$ to $\downarrow$ by using minority spins only. This results in a nonequilibrium spin accumulation $m>0(P_\uparrow>P_\downarrow)$, that increases with V [Fig. 2(c)]. The initial state for the dominant spin-flip cotunneling process that contributes to the current, Fig. 2(b), is $\downarrow$. Thus, the reduced probability $P_\downarrow$ decreases transport. This is the mechanism by which spin accumulation gives rise to the tunnel magnetoresistance effect, $g^P>g^{\mathrm{AP}}$.

Any spin-flip process that reduces the spin accumulation will enhance the conductance. Such a process is provided by single-barrier spin-flip cotunneling. The corresponding rate scales with k_BT, while that of double-barrier cotunneling is proportional to $\max\{|eV|,k_BT\}$. This explains the zero-bias anomaly: For $|eV|\lesssim k_BT$, single-barrier processes play a significant role, and, therefore, the current increases relatively fast with applied bias, which yields $g^{\mathrm{AP}}_{\mathrm{max}}$. For $|eV|\gg k_BT$, on the other hand, the relative role of single-barrier spin-flip processes is negligible as compared to double-barrier cotunneling, and the conductance is reduced to $g^{\mathrm{AP}}_{\mathrm{min}}$. It is, thus, the interplay of spin-dependent single- and double-barrier cotunneling processes that gives rise to the zero-bias anomaly in the differential conductance. This zero-bias anomaly is distinctively different from experimentally observed peaks in the differential conductance for nonmagnetic systems[6] which occur at the onset of sequential tunneling.

Finally, we remark that no zero-bias anomaly occurs in the Coulomb-blockade valleys with an even number (0 for $\varepsilon>0$ and 2 for $\varepsilon+U<0$), as in this case the total dot spin is zero, and spin accumulation is absent.

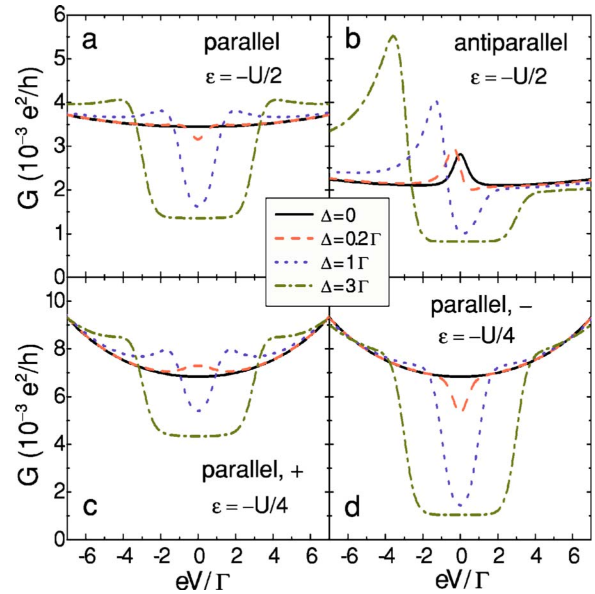

FIG. 3. (Color online) Differential conductance in presence of a Zeeman splitting with $p=0.5$, $k_BT=0.2\Gamma$, and $U=40\Gamma$ for the symmetric (a),(b) and asymmetric (c),(d) Anderson model with parallel (a),(c),(d) and antiparallel (b) relative magnetization of the leads. In (c), the Zeeman splitting favors a dot polarization parallel, in (d) antiparallel to the leads.

RESULTS IN THE PRESENCE OF MAGNETIC FIELD

In the presence of an external magnetic field, the dot levels are split by a Zeeman energy Δ. We restrict ourselves to the case of an external field that is collinear with the leads' magnetization directions. When the Zeeman splitting Δ is larger than both temperature and bias voltage, $|\Delta|\gg\max\{k_BT,|eV|\}$, only the lower spin level is occupied, i.e., the dot is fully polarized. In this case, spin-flip cotunneling is completely suppressed, which leads to a reduction of the conductance. With the same approximations as we used for $\Delta=0$, we obtain

$$g^{P,\pm}_{\mathrm{field}}=\frac{\Gamma^2}{4}\left[\frac{(1\pm p)^2}{(\varepsilon-|\Delta|/2)^2}+\frac{(1\mp p)^2}{(\varepsilon+U+|\Delta|/2)^2}\right], \tag{7}$$

for the parallel configuration. Here, $\pm$ corresponds to the cases when the Zeeman splitting favors a dot polarization that is parallel or antiparallel to the leads, respectively. We remark that for $\varepsilon=-U/2$ the conductance is symmetric under reversal of the magnetic field, in contrast to $\varepsilon\neq-U/2$, where the field reversal results in a different conductance [Figs. 3(c) and 3(d)], similar to the spin-readout scheme proposed in Ref. 12. For antiparallel magnetized leads, we find

$$g^{\mathrm{AP}}_{\mathrm{field}}=\frac{\Gamma^2}{4}(1-p^2)\left[\frac{1}{(\varepsilon-|\Delta|/2)^2}+\frac{1}{(\varepsilon+U+|\Delta|/2)^2}\right]. \tag{8}$$

The above expressions approximate the plateaus shown in Fig. 3. When the bias voltage is increased such that $|eV|\sim|\Delta|\gg k_BT$, spin-flip processes are again possible, and the dot is no longer fully polarized. For antiparallel magnetization of the leads and fixed orientation of the external field, the conductance is asymmetric under reversal of bias voltage; see Fig. 3(b). The reason is that single-barrier spin-flip cotunneling favors the dot state with the lower energy, which is, depending on the direction of the voltage drop, either the right or the wrong initial state for the dominant double-barrier cotunneling contribution to the current. The magnetic-field dependence of the peak height reflects the fact that single-barrier spin-flip cotunneling increases linearly with Δ.

In the parallel configuration, a plateau evolves for $\max\{k_BT,|eV|\} \ll |\Delta|$, again due to suppression of the spin-flip contributions to the current. In addition, we find that a zero-bias anomaly evolves even for parallel leads, when the Zeeman splitting favors a dot polarization in the same direction, Fig. 3(c). As the dominant transport channel is non-spin-flip cotunneling with majority spins, and for $|eV| \ll |\Delta| \lesssim k_BT$, thermal occupation of the dot's magnetic states favors occupation with a majority spin, transport is enhanced as compared to $\Delta = 0$.

SUMMARY

We predict a zero-bias anomaly in cotunneling transport through quantum dots attached to ferromagnetic leads that are magnetized antiparallel to each other. This zero-bias anomaly originates from the interplay of single-barrier and double-barrier spin-flip cotunneling processes. From an experimental point of view, the anomaly may be observed in quantum dots and/or molecules attached to ferromagnetic leads, which include an odd number of electrons. Such structures already have been realized experimentally.[3,6,10]

ACKNOWLEDGMENTS

We thank M. Braun, S. Maekawa, Yu.V. Nazarov, D. Ralph, and Y. Utsumi for helpful discussions. The work was supported by the projects PBZ/KBN/044/P03/2001 and 2 P03B 116 25, "Spintronics" RT Network of the EC RTN2-2001-00440, EC G5MA-CT-2002-04049, the DFG through SFB 491, GRK 726, and under CFN.

[1] K. Ono, H. Shimada, and Y. Ootuka, J. Phys. Soc. Jpn. **66**, 1261 (1997).

[2] J. Barnaś and A. Fert, Phys. Rev. Lett. **80**, 1058 (1998); S. Takahashi and S. Maekawa, *ibid.* **80**, 1758 (1998).

[3] Y. Chye, M. E. White, E. Johnston-Halperin, B. D. Gerardot, D. D. Awschalom, and P. M. Petroff, Phys. Rev. B **66**, 201301(R) (2002); M. M. Deshmukh and D. C. Ralph, Phys. Rev. Lett. **89**, 266803 (2002).

[4] B. R. Bułka, Phys. Rev. B **62**, 1186 (2000); W. Rudziński and J. Barnaś, *ibid.* **64**, 085318 (2001).

[5] D. V. Averin and A. A. Odintsov, Phys. Lett. A **140**, 251 (1989); D. V. Averin and Yu. V. Nazarov, Phys. Rev. Lett. **65**, 2446 (1990); K. Kang and B. I. Min, Phys. Rev. B **55**, 15412 (1997).

[6] S. De Franceschi, S. Sasaki, J. M. Elzerman, W. G. van der Wiel, S. Tarucha, and L. P. Kouwenhoven, Phys. Rev. Lett. **86**, 878 (2001); A. Kogan, S. Amasha, D. Goldhaber-Gordon, G. Granger, M. A. Kastner, and Hadas Shtrikman, Phys. Rev. Lett. **93**, 166602 (2004); D. M. Zumbühl, C. M. Marcus, M. P. Hanson, and A. C. Gossard, *ibid.* **93**, 256801 (2004); M. Ciorga, M. Pioro-Ladriere, P. Zawadzki, J. Lapointe, Z. Wasilewski, and A. S. Sachrajda, Phys. Rev. B **70**, 235306 (2004);

[7] L. I. Glazman and M. E. Raikh, JETP Lett. **47**, 452 (1988); T. K. Ng and P. A. Lee, Phys. Rev. Lett. **61**, 1768 (1988); Y. Meir, N. S. Wingreen, and P. A. Lee, *ibid.* **70**, 2601 (1993).

[8] The regularization $+i0^+$ in the resolvents is added here by hand; however, it can be derived within the complete perturbation theory [H. Schoeller and G. Schön, Phys. Rev. B **50**, 18436 (1994); J. König, J. Schmid, H. Schoeller, and G. Schön, *ibid.* **54**, 16820 (1996)].

[9] J. Martinek, Y. Utsumi, H. Imamura, J. Barnaś, S. Maekawa, J. König, and G. Schön, Phys. Rev. Lett. **91**, 127203 (2003); J. Martinek, M. Sindel, L. Borda, J. Barnaś, J. König, G. Schön, and J. von Delft, *ibid.* **91**, 247202 (2003); M. S. Choi, D. Sanchez, and R. Lopez, *ibid.* **92**, 056601 (2004).

[10] A. N. Pasupathy, R. C. Bialczak, J. Martinek, J. E. Grose, L. A. K. Donev, P. L. McEuen, and D. C. Ralph, Science **306**, 86 (2004).

[11] J. König and J. Martinek, Phys. Rev. Lett. **90**, 166602 (2003); M. Braun, J. König, and J. Martinek, Phys. Rev. B **70**, 195345 (2004).

[12] P. Recher, E. V. Sukhorukov, and D. Loss, Phys. Rev. Lett. **85**, 1962 (2000); V. N. Golovach and D. Loss, Phys. Rev. B **69**, 245327 (2004).