Fano-Kondo Spin Filter

A. C. Seridonio\textsuperscript{1,2}, F. M. Souza*\textsuperscript{1,3}, J. Del Nero\textsuperscript{4,5} and I. A. Shelykh\textsuperscript{1,6}

\textsuperscript{1}International Center for Condensed Matter Physics, Universidade de Brasília, 04513, Brasília, DF, Brazil
\textsuperscript{2}Instituto de Física, Universidade Federal Fluminense, 24230-346, Niterói, RJ, Brazil
\textsuperscript{3}Instituto de Física, Universidade Federal de Uberlândia, 38400-902, Uberlândia, MG, Brazil
\textsuperscript{4}Departamento de Física, Universidade Federal do Pará, 66075-110, Belém, PA, Brazil
\textsuperscript{5}Instituto de Física, Universidade Federal do Rio de Janeiro, 21941-972, Rio de Janeiro, RJ, Brazil
\textsuperscript{6}Science Department, University of Iceland, Dunhaga 3, IS-107, Reykjavík, Iceland

Abstract

We study spin-dependent conductance in a system composed of a ferromagnetic (FM) Scanning Tunneling Microscope (STM) tip coupled to a metallic host surface with an adatom. The Kondo resonance is taken into account via the Doniach-Sunjic spectral function. For short lateral tip-adatom distances and due to the interplay between Kondo physics, quantum interfering effects and the ferromagnetism of the tip, a spin-splitting of the Fano-Kondo line shape arises in the conductance. A strong enhancement of the Fano-Kondo profile for the majority spin component of the FM tip is observed. When the tip is placed on the adatom, this gives a conductance 100\% polarized for a particular range of bias voltage. The system thus can be used as a powerful generator of spin polarized currents.

1. Introduction

One of the most fascinating phenomena due to strong correlated electrons is the Kondo effect [1]. Observed originally in the context of magnetic impurities diluted in bulk alloys, the Kondo physics results in the enhancement of the material resistance for temperatures $T$ below the characteristic Kondo temperature $T_K$. In the 90’s, with the development of miniaturization techniques, systems of quantum dots (QDs) coupled to a left and to a right electron reservoir (e.g. metallic electrodes) became quite feasible [2]. In this new context of QDs attached to electrodes, the Kondo effect results in a wealth of novel features [3,4]. Probably, the appearance in the dot density of states of a narrow peak (width given by $k_B T_K$) at the Fermi level of the reservoirs is one of the most remarkable features. This peak gives rise to an enhancement of the conductance, thus significantly improving the charge transport in the system. In particular, in the presence of an external bias voltage applied in a left and a right electrode (non-equilibrium regime), two Kondo peaks appear pinned at the Fermi levels of the leads [5,6]. When the electrodes are ferromagnetic (FM), additional spin-dependent effects emerge. For instance, due to a large local exchange field on the QD, the Kondo resonance splits into two peaks, where the energy separation can be tuned via the magnetization alignment of the electrodes, their polarizations and a possible external magnetic field [7,8,9,10,11]. Nowadays, systems of a single QD coupled to leads are routinely developed in the laboratories and the observation of the Kondo resonance is frequent, including the measurement of the Kondo peak splitting [12,13].

An alternative system is composed of a metallic host surface with an adatom (adsorbed atom) and a FM tip [14,15]. Contrastingly to the well studied lead-QD-lead geometry, the present system (tip-adatom-host) presents a more wealth physics in the sense that quantum interference between distinct tunneling paths emerges. The two possible interfering ways are the direct tunneling tip-host and the indirect one, tip-adatom-host. In particular, below $T_K$ the Kondo resonance at the adatom spectral function provides the tunneling channel through the adatom. The quantum interference mechanism results in an asymmetric line shape of the Kondo resonance, that instead of looks like a Lorentzian
it becomes similar to a characteristic Fano resonance. This Fano-Kondo resonance has been widely measured in experiments with nonmagnetic tips and also discussed in theoretical works.

The development of FM tips makes the system tip-adatom-host a potential candidate to future implementation of spintronic devices. Recently, Patton et al. studied theoretically the effects of the tip ferromagnetism on the conductance in the Kondo regime. It was found a splitting of the Fano line shape of the conductance. Additionally, for FM tips it was investigated the effects of the lateral tip-adatom separation on the conductance in the full range of the Fano parameter, i.e., the rate between the tip-adatom and the tip-host coupling strengths.

In the present work we calculate the spin-resolved conductance for the system FM tip-adatom-host in the linear regime of tunneling. The Kondo resonant peak is modeled via the Doniach-Sunjic spectral function. We predict a powerful generation of spin polarized currents even for tips with a tiny magnetization.

The current can be full up or down polarized, depending on the external bias. This effect comes from the spin splitting of the Fano-Kondo resonance, that strongly suppresses one spin component of the conductance in a particular bias range. The effects of the lateral tip-adatom distance of this spin-polarizer device are also investigated.

2. Theoretical Model

We start from the model Hamiltonian

\[ H = H_{SIAM} + H_{tip} + H_T, \]

where the terms represent the host metal with the magnetic impurity (\( H_{SIAM} \)), the FM tip (\( H_{tip} \)) and the coupling between them (\( H_T \)). For the description of a magnetic impurity coupled to a host metal, we use the Single Impurity Anderson Model (SIAM)

\[ H_{SIAM} = \sum_{\vec{p}\sigma} \epsilon_{\vec{p}} a_{\vec{p}\sigma}^d a_{\vec{p}\sigma} + \epsilon_0 \sum_{\sigma} c_{0\sigma}^d c_{0\sigma} + U n_{0\uparrow} n_{0\downarrow} + v \sum_{\sigma} \left( f_{0\sigma}^d c_{0\sigma} + H.C. \right), \]

where \( a_{\vec{p}\sigma} \) is the destruction operator for a conduction electron with momentum \( \vec{p} \) and spin \( \sigma \), \( c_{0\sigma} \) is the destruction operator for an electron localized at the adatom site. The parameters \( \epsilon_0 \) and \( U \) are the energy of the adatom level and the Coulomb repulsion between two electrons with opposite spins at the adatom, respectively.

For temperatures \( T \ll T_K \), this magnetic moment becomes screened by the host conduction electrons, due to the antiferromagnetic correlations and the Kondo peak with half-width \( k_B T_K \) and centered at the Fermi energy, appears in the adatom spectral density.

where \( a_{\vec{p}\sigma} \) is the destruction operator for a conduction electron with momentum \( \vec{p} \) and spin \( \sigma \), \( c_{0\sigma} \) is the destruction operator for an electron localized at the adatom site. The parameters \( \epsilon_0 \) and \( U \) are the energy of the adatom level and the Coulomb repulsion between two electrons with opposite spins at the adatom, respectively.

For a sake of simplicity, we consider the case of a conduction band with a flat density of states \( \rho_0 \) and half-width denoted by \( D \). In order to describe the hybridization of this band with the adatom, we introduce a normalized fermionic operator \( f_{0\sigma} \) as follows

\[ f_{0\sigma} = \frac{1}{\sqrt{N}} \sum_{\vec{p}} a_{\vec{p}\sigma}, \]

where \( N \) denotes the total number of the conduction states.

As we are focusing on the Kondo regime, we consider only the range of system parameters favoring the formation of a localized magnetic moment at the adatom, namely \( \epsilon_0 < \epsilon_F, \epsilon_0 + V > \epsilon_F \) and \( \Gamma \ll |\epsilon_0|, \epsilon_0 + V \). For temperatures \( T \ll T_K \), this magnetic moment becomes screened by the host conduction electrons, due to the antiferromagnetic correlations and the Kondo peak with half-width \( k_B T_K \) and centered at the Fermi energy, appears in the adatom spectral density. Here we use the same
estimate for the Kondo temperature as in \[29\],
\[
k_B T_K = \sqrt{\frac{\Gamma U}{2}} \exp[\pi \varepsilon_0 (\varepsilon_0 + U)/2\Gamma U].
\] (4)

In this work the electron-electron interactions inside the FM tip are neglected and thus
\[
\mathcal{H}_{\text{tip}} = \sum_{k\sigma} (\varepsilon^T_k + eV) b_{k\sigma}^\dagger b_{k\sigma},
\] (5)

where \(b_{k\sigma}\) is the destruction operator for a tip conduction electron and \(V\) is the tip bias voltage. As we consider the case of a ferromagnetic tip, the corresponding density of states becomes spin-dependent and is described by
\[
\rho_{\text{tip}}^\sigma = \rho_0 (1 + \sigma p),
\] (6)

with \(\sigma = \pm 1\) denoting the spin orientations, \(p\) being the tip magnetization.

The tunneling Hamiltonian couples the tip with the host metal and the adatom, i.e.,
\[
\mathcal{H}_T = \sum_{k\sigma} b_{k\sigma}^\dagger \left( t \sum_{\vec{f}} \phi_{\vec{R}}(\vec{R}) a_{\vec{f}\sigma} + t_0 R \cos \sigma \right) + \text{H.C.}
\] (7)

where the terms \(t\) and \(t_{0R} = t_0 \exp(-k_F R)\) correspond to the tip-host and tip-adatom hopping terms, respectively. Following \[23\], we introduce the exponential decay of \(t_{0R}\) with increasing of the tip-adatom lateral distance \(R\). The amplitude of the tip-host metal tunneling depends on the value of the conduction band wave function \(\phi_{\vec{R}}(\vec{R})\) calculated at the tip position.

3. The Conductance Formula

The derivation of the conductance formula treats the tunneling Hamiltonian \[7\] as a linear perturbation \[22\]. As we consider \(eV \ll D\) and \(T \ll T_K\) in the Kondo regime, we can safely evaluate the conductance formula at \(T = 0\), which results in
\[
G(eV, T \ll T_K, R) = \sum_{\sigma} G_0 \left[ \frac{\rho_{\text{tip}}^\sigma}{\rho_0} \right] \left[ \frac{\rho_{0R}^\sigma}{\rho_0} \right],
\] (8)

where
\[
G_0 = (2\pi \rho_0)^2 \left( \frac{e^2}{h} \right)
\] (9)
is the background conductance and
\[
\rho_{0R}^\sigma(eV) = \rho_0 \left\{ 1 - \left( \frac{F_{k_F R}}{\rho_0} \right)^2 + \frac{\tilde{\rho}_{0R}^\sigma(eV)}{\rho_0} \right\}
\] (10)
is the host metal density of states in the presence of the Kondo adatom with the tip. The function
\[
F_{k_F R} = \sum_k \phi_{\vec{R}}(\vec{R}) \delta(\varepsilon_k - \varepsilon_F) = \rho_0 J_0 (k_F R)
\] (11)

with \(J_0\) being the zeroth-order Bessel function, accounts for the spatial dependence of the conductance on the lateral tip-adatom distance \(R\). The density in the spectral representation over the eigenstates of the Hamiltonian \[2\] given by expression
\[
\tilde{\rho}_{0R}^\sigma(eV) = \sum_m |m| \left( \frac{F_{k_F R}}{\rho_0} \right) f_{0\sigma}
\]
\[+ \pi \rho_0 v q R \cos \sigma |\Omega|^2 \times \delta(E_m - E_\Omega - eV),\]

(12)

accounts for the quantum interference between the tunneling paths \(t_{0R}\) and \(t\), characterized by the Fano factor \[23\]
\[
q_R = (\pi \rho_0 v)^{-1} \left( \frac{t_{0R}}{t} \right) = q_{R=0} \exp(-k_F R).
\] (13)

The cases \((q_R \gg 1)\) and \((q_R \ll 1)\) correspond to the domination of tip-adatom and tip-host metal tunneling, respectively, while the limit \((q_R \approx 1)\) corresponds to the case where these two processes are of comparable intensity. After some algebra (see Ref. \[15\] for relevant details), we can write Eq.\(10\) as
\[
\rho_{0R}^\sigma(eV) = \rho_0 \left\{ 1 + \left( \frac{F_{k_F R}}{\rho_0} \right)^2 - (\tilde{q}_R)^2 \right\} \times \pi \Gamma \rho_{\text{ad}}^\sigma(eV)
\]
\[+ 2\Gamma \left( \frac{F_{k_F R}}{\rho_0} \right) \tilde{q}_R \tilde{R} \left\{ G_{\text{ad}}^\sigma(eV) \right\},\]

(14)

where
\[
\tilde{q}_R = q_R + \left( \frac{F_{k_F R}}{\rho_0} \right) q
\] (15)
is the effective Fano factor,

\[ q = \frac{\sum_{k} 1}{\pi \rho_0} = \frac{1}{\pi} \ln \left( \frac{eV + D}{eV - D} \right) \]  

(16)

is the Fano factor for the SIAM in the absence of the tip and is the adatom spectral density determined by the interacting adatom Green function \( G_{ad}^{Ret}(eV) \), written in terms of the Doniach-Sunjic formula \( G_{ad}^{Ret}(eV) = \frac{i}{\Gamma} \left[ (eV + \sigma \delta) + i\Gamma \right] \) and the phase shift \( \delta_{eV}^\sigma \) of the conduction states, respectively.

The Kondo peak splitting \( \delta \) originates from the ferromagnetic exchange interaction between the tip and the magnetic adatom, resulting in the lifting of the spin degeneracy for the adatom level \( \epsilon_0 \). Following the “poor man’s” scaling method, this splitting can be estimated as

\[ \delta = \epsilon_{0\uparrow} - \epsilon_{0\downarrow} \]

\[ = \frac{\gamma_{\text{tip}}}{\pi} p \ln(D/U) \]

\[ = \left[ \frac{\gamma_{\text{tip}}}{\pi} \ln(D/U) \right] p \exp(-2k_FR) \]  

(18)

where

\[ \gamma_{\text{tip}}^\sigma = \pi \rho_{\text{tip}} \left| t_{0\text{R}} \right|^2 \]

\[ = \gamma_{\text{tip}} (1 + \sigma p) \exp(-2k_FR) . \]  

(19)

In the regime \( eV \ll D \) one can neglect the contribution of Eq. (16) in Eq. (17), thus we prefer to express the spin-resolved conductance as

\[ G^\sigma / G_{\text{max}} = \left[ \rho_{\text{tip}}^\sigma / \rho_0 \right] \left[ \rho^\sigma(eV) / \rho_0 \right] \],  

(20)

where

\[ G_{\text{max}} = (1 + q_R^2) G_0 \]  

(21)

and

\[ \rho^\sigma(eV) = \rho_{0R}^\sigma(eV) / (1 + q_R^2) , \]  

(22)

which is a function bounded by two in units of \( G_{\text{max}} \). Using the expressions

\[ \tan \delta_{eV}^\sigma = -\frac{\Im \left( \sum \{ G_{ad}^{Ret}(eV) \} \right)}{\Re \left( \sum \{ G_{ad}^{Ret}(eV) \} \right)} \]

(23)

and particularizing for \( R = 0 \), Eq. (20) reduces to the simple form

\[ G^\sigma / G_{\text{max}} = (1 + \sigma p) \cos^2(\delta_{eV}^\sigma - \delta_{qR=0}) . \]  

(24)

Finally, the spin polarization of the tunneling current is determined as

\[ \wp = \frac{G^\uparrow - G^\downarrow}{G^\uparrow + G^\downarrow} \]  

(25)

4. Results

For quantitative analysis of the conductance we choose a following set of system parameters: \( q_{R=0} = 1, \epsilon_0 = -0.9eV, \gamma_{\text{tip}} = 0.02eV, U = 2.9eV, D = 5.5eV, T_K = 50K \) and \( k_F = 0.189^{-1} \). The Kondo temperature was estimated using Eq. (11).

Figure (2) shows the Spin Polarization \( \wp \) as a function of the bias voltage for differing tip magnetization parameter \( p \). The case \( p = 0 \) gives no spin
polarization as it is indeed expected for a nonmagnetic lead. When \( p \neq 0 \), \( \varphi \) reveals two remarkable features: (i) it attains a maximum plateau \((\varphi = +1)\) around \( eV = 0 \), and (ii) it shows a narrow dip at some specific negative bias voltage, yielding to \( \varphi = -1 \). Increasing \( p \), it is possible to enlarge the plateau in which \( \varphi = +1 \), and the dip \((\varphi = -1)\) moves toward negative biases. Particularly, for \( p = 1 \) (full polarized tip) the spin polarization loses its structure, assuming a constant value \( \varphi = 1 \). Note however, that even for small tip polarizations (e.g., \( p = 0.2 \)), it is still possible to find \( \varphi = \pm 1 \), around \( eV = 0 \). So this system operates as a powerful current polarizer, even for tips with weak magnetization (small \( p \)).

For relatively high voltages, the Spin Polarization reaches a constant value equal to the tip magnetization parameter \( p \). This system, thus, provides the means to choose the spin polarization from \(-1\) to \(+1\), by simple tuning a tip’s voltage \( V \). A variety of systems capable to tune the current polarization such as spin-filters \[30,31,32,33\] and the spin-diodes \[34\] have emerged in the context of spintronics. Some of them were recently realized experimentally \[35\]. It is also possible to control dynamically the current polarization by using time dependent bias voltages \[36,37\]. However, to the best of our knowledge, the system we consider here is first to use the interplay between Kondo effect and quantum interference to control and amplify a current polarization.

Figure 3 shows separately the Spin-Resolved Conductances, \( G^\uparrow \) and \( G^\downarrow \). For \( p = 0 \) we find \( G^\uparrow = G^\downarrow \), with Kondo resonance having asymmetric Fano line shape coming from the interference between the two possible tunnelings paths. Similar Fano-Kondo profile has been observed in systems with normal metal tips \[17,18,19,20,21\]. With increasing of \( p \), the conductances demonstrates a spin-splitting with \( G^\uparrow \) moving to the left and \( G^\downarrow \) to the right, thus generating a window of completely spin polarized transport \((G^\uparrow \approx 0)\). This window corresponds to \( \varphi = 1 \) plateau in Fig. 2. Additionally, the \( \varphi = -1 \) dip in Fig. 2 comes from the minimum of \( G^\uparrow \) in the negative voltage range in Fig. 3. While \( G^\uparrow \) increases in amplitude, \( G^\downarrow \) is suppressed. This happens because \( G^\uparrow \) is weighted by the tip density of states, which is proportional to \((1 \pm p)\) (see Eq.\[24\]). In the limiting case \( p = 1 \) only \( G^\uparrow \) remains.

Finally, in figure 4 we show the effects of the lateral tip-adatom separation on the Spin Polarization \( \varphi \). As \( R \) increases, the minimal and maximal

![Figure 3: Spin-Resolved Conductances at \( R = 0 \) (Eq.\[24\]) as a function of the bias voltage \( eV \) in units of the Kondo half-width \( \Gamma_K \) for \( q_{R=0} = 1 \). For a normal tip \((p = 0)\) the spin resolved conductances, \( G^\uparrow \) and \( G^\downarrow \), are degenerate and present the typical Fano-Kondo line shape. For ferromagnetic tip \((p \neq 0)\) the Fano-Kondo profile is spin-split, thus resulting in a region in which \( G^\uparrow \approx 0 \) while \( G^\downarrow \) is maximum. In this region the conductance spin-polarization \( \varphi \) develops a plateau with \( \varphi = 1 \) (full polarized transport). Parameters as in Fig. 2.](image)

![Figure 4: (a) Spin polarization \( p \) against bias voltage \( eV \) in units of the Kondo half-width \( \Gamma_K \) for fixed tip magnetization \( p = 0.4 \), \( q_{R=0} = 1 \) and differing tip-adatom lateral displacements \( R \). When \( R \) increases the spin polarization structure (maximum plateau and dip) is washed out and the overall curve tends to a background polarization \( p \). In panels (b)-(d) we present the evolution of the spin resolved conductances, \( G^\uparrow \) and \( G^\downarrow \), with the distance. Increasing \( R \) the splitting of \( G^\uparrow \) and \( G^\downarrow \) is quenched and the asymmetric Fano resonances (for each spin) evolve toward a more symmetric profile. In the inset we sketch the tip displaced from the adatom for \( R = 1 \) and \( 2 \) A. A voltage \( V \) is applied on the tip. Others parameters as in Fig. 2.](image)
values of $\varphi$ are reduced, and the whole curve approaches a flat line corresponding to a magnetization of the tip $p$. This behavior of $\varphi$ can be understood from right panels (b)-(d), where spin-resolved conductances $G^\sigma$ are shown. Increasing $R$, the Fano-Kondo resonances for both $G^\uparrow$ and $G^\downarrow$ tend to a more symmetric antiresonance and the spin-splitting is quenched. It is valid to note that similar evolution of the Fano-Kondo line shape with $R$ was experimentally reported in Ref. [17] for an unpolarized tip. The overall evolution picture in this experiment consisted of a Fano like resonance for $R \approx 0$, a more symmetric antiresonance for intermediate $R$ and an approximately flat profile (background) for large enough $R$. This general picture is also seen for each $G^\sigma$ in the present spin-dependent case. However, due to the ferromagnetism of the tip, $G^\uparrow$ remains above $G^\downarrow$ which makes the spin-polarization $\varphi$ approach the background polarization $p$.

5. Conclusions

We have calculated Spin-Resolved Conductances for a system with a ferromagnetic tip coupled to an adatom on a nonmagnetic metallic surface (host). The conductance line shape is characterized by a Fano resonance, which differs for each spin component. In particular, we find a bias range in which $G^\downarrow \approx 0$ while $G^\uparrow$ is maximum, due to the Fano interference between tunneling paths. This contrasting features for $G^\uparrow$ and $G^\downarrow$ develops a plateau in the Spin Polarization $\varphi$ in which the current can be full polarized ($\varphi = +1$). By increasing the tip magnetization parameter $p$, it is possible to enlarge this plateau, thus covering a more broaden bias window. A full down polarized current ($\varphi = -1$) can also be achieved by simple tuning the bias voltage. This system thus operates as a powerful source of polarized current, with its polarization being dependent on the biases.

6. Acknowledgments

This work was supported by the Brazilian agencies IBEM, CAPES, FAPESP and FAPERJ.

References

[1] A. C. Hewson, The Kondo Problem to Heavy Fermions, Cambridge University Press, Cambridge (1993).
[2] U. Meirav, M. A. Kastner, S. J. Wind, Phys. Rev. Lett. 65 (1990) 771.
[3] D. G.-Gordon, H. Shtrikman, D. Mahalu, D. A.-Magder, U. Meirav, M. A. Kastner, Nature 391 (1998) 156.
[4] S. M. Cronenwett, T. H. Oosterkamp, L. P. Kouwenhoven, Science 281 (1988) 1549.
[5] F. Simmel, R. H. Blick, J. P. Kotthaus, W. Wegscheider, M. Bichler, Phys. Rev. Lett. 83 (1999) 804.
[6] M. Krawiec and K. I. Wysokiński, Phys. Rev. B 66 (2002) 165408.
[7] J. Martinek, Y. Utsumi, H. Imamura, J. Barnaś, S. Maekawa, J. König, G. Schönh, Phys. Rev. Lett. 91 (2003) 127203.
[8] J. Martinek, M. Sindel, L. Borda, J. Barnaś, J. König, G. Schönh, J. von Delft, Phys. Rev. Lett. 91 (2004) 247202.
[9] M.-S. Choi, D. Sánchez, R. López, Phys. Rev. Lett. 92 (2004) 056601.
[10] Y. Utsumi, J. Martinek, G. Schönh, H. Imamura, S. Maekawa, Phys. Rev. B 71 (2005) 245116.
[11] R. Świrkowicz, M. Wilczyński, M. Wawrzyniak, J. Barnaś, Phys. Rev. B 73 (2006) 195312.
[12] A. N. Pasupathy, R. C. Bialczak, J. Martinek, J. E. Grose, L. A. K. Donev, P. L. McEuen, D. C. Ralph, Science 306 (2004) 86.
[13] K. Hamaya, M. Kitabatake, K. Shibata, M. Jung, M. Kawamura, K. Hirakawa, T. Machida, T. Taniyama, Appl. Phys. Lett. 91 (2007) 232105.
[14] K. R. Patton, S. Kettemann, A. Zhuravlev, A. Lichtenstein, Phys. Rev. B 76 (2007) 100408(R).
[15] A. C. Seridonio, F. M. Souza, I. A. Shelykh, J. Phys.: Condens. Matter 21 (2009) 95003.
[16] U. Fano Phys. Rev. 124 (1961) 1866.
[17] V. Madhavan, W. Chen, T. Jamneala, M. F. Crommie, N. S. Wingreen, Science 280 (1998) 567.
[18] N. Knorr, M. Alexander Schneider, Lars Diekhöner, Peter Wahl and Klaus Kern, Phys. Rev. Lett. 88 (2002) 096804.
[19] K. Nagaoka, T. Jamneala, M. Grobis, M. F. Crommie, Phys. Rev. Lett. 88 (2002) 077205.
[20] P. Wahl, L. Diekhöner, G. Wittich, L. Vitali, M.A. Schneide, K. Kern, Phys. Rev. Lett. 95 (2005) 166601.
[21] Y.-S. Fu, S.-H. Ji, X. Chen, X.-C. Ma, R. Wu, C.-C. Wang, W.-H. Duan, X.-H. Qiu, B. Sun, P. Zhang, J.-F. Jia, Q.-K. Xue, Phys. Rev. Lett. 99, (2007) 256601.
[22] A. Schiller, S. Hershfield, Phys. Rev. B 61 (2000) 9036.
[23] M. Plihal, J. W. Gadzuk, Phys. Rev. B 63 (2001) 089404.
[24] O. Újságyi, J. Kroha, L. Szunyogh, A. Zawadowski, Phys. Rev. Lett. 85 (2000) 2557.
[25] S. Heinze, M. Bode, A. Kubetzka, O. Pietzsch, X. Nie, S. Blügel, R. Wiesendanger, Science 288 (2000) 1805.
[26] I. Zutic, J. Fabian, S. Das Sarma, Rev. Mod. Phys. 76 (2004) 323.
[27] The Doniach-Sunjic formula was recently used to fit experimental Kondo resonances, revealing a quite good agreement. See [28].
[28] P. W. Anderson, Phys. Rev. 124 (1961) 41.
[29] T. A. Costi, A.C. Hewson and V. Zlatić, J. Phys.: Condens. Matter 6 (1994) 2519.
[30] J. C. Egues, Phys. Rev. Lett. 80 (1998) 4578.
[31] M. Popp, D. Frustaglia, K. Richter, Nanotechnology 14 (2003) 347.
[32] A.A. Kiselev, K.W. Kim, J. Appl. Phys. 94 (2003) 4001.
[33] I.A. Shelykh, N.G. Galkin, N.T. Bagraev, Phys. Rev. B 72 (2005) 235316.
[34] F. M. Souza, J. C. Egues, A. P. Jauho, Phys. Rev. B 75 (2007) 165303.
[35] C. A. Merchant, N. Marković, Phys. Rev. Lett. 100 (2008) 156601.
[36] F. M. Souza, Phys. Rev. B 76 (2007) 205315.
[37] F. M. Souza, J. A. Gomez, Phys. Stat. Sol. b 246 (2009) 431.