Tunnel magnetoresistance of a supramolecular spin valve

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Abstract – We theoretically study the transport properties of a supramolecular spin valve, consisting of a carbon nanotube with two attached magnetic molecules, weakly coupled to metallic contacts. The emphasis is put on analyzing the change of the system’s transport properties with the application of an external magnetic field, which aligns the spins of the molecules. It is shown that magnetoresistive properties of the considered molecular junction, which are associated with changing the state of the molecules from the superparamagnetic to the ferromagnetic one, strongly depend on the applied bias voltage and the position of the nanotube’s orbital levels, which can be tuned by a gate voltage. A strong dependence on the transport regime is also found in the case of the spin polarization of the current flowing through the system. The mechanisms leading to those effects are explained by invoking appropriate molecular states responsible for transport. The analysis is done with the aid of the real-time diagrammatic technique up to the second order of expansion with respect to tunneling processes.

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Introduction. – Over the past decades the transport properties of nano-scale devices based on magnetic molecules have been intensively studied [1–18]. Due to the bistability of magnetic molecules [19,20], such systems have a great potential for applications in the information storing and processing technologies [21–24]. Moreover, when attached to ferromagnetic contacts, magnetic molecules can exhibit a large spin-valve effect when the magnetic configuration of the device varies from the parallel to the antiparallel alignment of leads’ magnetic moments [25,26]. Quite interestingly, recently, a spin-valve–like behavior has also been found in the case of nonmagnetic junctions involving single molecular magnets [27,28]. In particular, Urdampilleta et al. examined transport through a supramolecular spin-valve — a tunnel junction with an embedded carbon nanotube to which molecular magnets were attached. By aligning the spins of magnetic molecules with an external magnetic field, a change in the conductance of the system was observed. Such tuning of the current flowing through the system without the necessity to use ferromagnetic contacts provides a perspective way of the current control through the spin degrees of freedom, which is important for molecular spintronics [29–31].

Motivated by this experimental achievement, in this paper we theoretically investigate the transport properties of a tunnel junction involving a single-wall carbon nanotube with two attached magnetic molecules in the presence of external magnetic field. Our considerations are carried out by assuming a weak tunnel coupling between the nanotube and external reservoirs, such that the current is mainly driven by sequential tunneling processes. However, we also examine the role of cotunneling processes, which determine the magnetoresistive properties of the considered device in the low-bias-voltage regime. By determining the currents flowing through the system in the absence and presence of external magnetic field, we analyze the behavior of the tunnel magnetoresistance of the device. Our work quantifies thus the change of spin-resolved transport properties when the state of the molecules switches from the superparamagnetic to the ferromagnetic one. Depending on the occupation of the carbon nanotube and the applied bias voltage, we find transport regimes of both large positive magnetoresistive response and transport regions where this response becomes negative. The calculations are performed by using the real-time diagrammatic technique in the first and second order of expansion with respect to tunneling processes [32–34].

Model and Hamiltonian. – The considered molecular system embedded between two nonmagnetic electrodes is schematically shown in fig. 1. It consists of two magnetic
molecules of spin $S_r$ and magnetic anisotropy $D_r$, with $r = L$ (left) and $r = R$ (right) molecule. The molecules are exchange-coupled to the single-wall carbon nanotube with strength given by $J_r$. It is assumed that the coupling of the molecules to the nanotube results in the formation of orbital levels in the nanotube in their vicinity, through which transport takes place [27, 28]. Thus, the total Hamiltonian of the system can be written as

$$H = H_{\text{leads}} + H_{\text{mol}} + H_B + H_{\text{tun}}. \quad (1)$$

The first part of $H$ describes the noninteracting electrons in the external electrodes and takes the form

$$H_{\text{leads}} = \sum_{r\sigma} \varepsilon_r c_r^\dagger \sigma c_{r\sigma}, \quad (2)$$

with $c_{r\sigma}$ being the operator for creation (annihilation) of a spin-$\sigma$ electron with momentum $k$ and the energy $\varepsilon_r$ in the $r$-th lead. The second term of the total Hamiltonian characterizes the nanotube-magnetic molecule subsystem and can be expressed as [3, 5, 26, 35]

$$H_{\text{mol}} = \sum_r \varepsilon_r n_r + E_C(n - n_0)^2 + t \sum \langle d_{L\sigma}^r d_{R\sigma} + \text{h.c.} \rangle - \sum (J_z S_z + D_z S_{z}^2). \quad (3)$$

The particle number operator for an electron of spin $\sigma$ occupying the nanotube’s orbital level $r$ is given by $n_{r\sigma} = d_{r\sigma}^\dagger d_{r\sigma}$, and $n_r = n_{r\uparrow} + n_{r\downarrow}$, $n = n_L + n_R$. The charge of a neutral nanotube is denoted by $n_0$. $E_C$ is the charging energy of the nanotube and $t$ denotes the hopping between the two orbital levels. The exchange coupling between molecule $r$ and the nearby orbital level is denoted by $J_z$, with $S_z$ and $s_z$ denoting the operators for the spin of the molecule and the spin of the electron on the orbital level, respectively. The magnetic anisotropy associated with the $r$-th molecule is represented by $D_r$, where $S_z$ is the $z$-th component of $S_r$. The third part of $H$ describes the external magnetic field $B_z$ (in units of $g\mu_B \equiv 1$) applied to the molecular system

$$H_B = B_z S^{\text{tot}}_z, \quad (4)$$

where $S^{\text{tot}}_z = \sum_r (S_r + s_r)$. Finally, the last term of the total Hamiltonian describes the electron tunneling processes and can be written as

$$H_{\text{tun}} = \sum_{r\sigma} v_r c_{r\sigma}^\dagger d_{r\sigma} + d_{r\sigma}^\dagger c_{r\sigma}, \quad (5)$$

with $v_r$ denoting the respective tunnel matrix elements. The coupling between the $r$-th electrode and the $r$-th orbital level of the nanotube can be defined as $\Gamma_r = 2\pi \rho_r v_r^2$, with $\rho_r$ denoting the density of states of the $r$-th lead at the Fermi level. In our analysis, we take into account the symmetric case assuming $\Gamma_r \equiv \Gamma$. Moreover, we also assume that the two molecules are identical, i.e., $S_r \equiv S$, $D_r \equiv D$ and $J_r \equiv J$.

**Method.** – In order to calculate the current flowing through the considered molecular device, we use the real-time diagrammatic technique [32–34] including the first- and second-order terms of expansion with respect to the tunnel coupling $\Gamma$. In calculations, one first needs to determine the corresponding diagrams that contribute to the elements $W_{\chi\chi'}$ of the self-energy matrix $W$ in a given order of expansion, i.e., $W = W^{(1)} + W^{(2)}$. Here, $|\chi\rangle$ denotes the eigenstate of $H_{\text{mol}}$, $H_{\text{mol}}|\chi\rangle = \varepsilon_\chi |\chi\rangle$, and $\varepsilon_\chi$ is the corresponding eigenenergy. In the first-order of expansion the off-diagonal elements of $W^{(1)}$ are given by

$$W^{(1)}_{\chi\chi'} = 2\pi \sum_{\sigma\sigma'} \rho_r \left\{ f_r (\varepsilon_\chi - \varepsilon_{\chi'}) [|\chi\rangle \langle \chi'| |d_{\sigma}\rangle |\chi\rangle^2]' + [1 - f_r (\varepsilon_\chi - \varepsilon_{\chi'})] [|\chi\rangle \langle \chi'| |d_{\sigma}\rangle |\chi\rangle^2] \right\},$$

where $f_r (\varepsilon) = 1/[e^{(\varepsilon - \mu_r)/T} + 1]$ is the Fermi-Dirac distribution function with the electrochemical potential of the $r$-th lead denoted as $\mu_r$ and $T$ standing for temperature ($k_B \equiv 1$). The diagonal elements of $W^{(1)}$ are equal to $W^{(1)}_{\chi\chi} = -\sum_{\gamma\gamma'} W^{(1)}_{\chi\chi'}$. The formulas for the second-order self-energies ($W^{(2)}$) are much more cumbersome since they involve summations over many virtual states of the molecule [36], therefore, we will not present them here. The self-energy matrices allow for the calculation of the corresponding probabilities of occupation of states $|\chi\rangle$ which can be done using the following equations [34]:

$$W^{(1)} P^{(0)} = 0 \quad \text{and} \quad W^{(2)} P^{(0)} + W^{(1)} P^{(1)} = 0, \quad (6)$$

where the vector of probabilities in a given order is normalized such that $\text{Tr} \{ P^{(0)} \} = 1$ and $\text{Tr} \{ P^{(1)} \} = 0$. Then, the current in the first ($I^{(1)}$) and second order ($I^{(2)}$) of expansion can be found from [34]

$$I^{(1)} = \frac{\epsilon}{2\hbar} \text{Tr} \{ W^{(1)} P^{(0)} \}, \quad (7)$$

$$I^{(2)} = \frac{\epsilon}{2\hbar} \text{Tr} \{ W^{(2)} P^{(0)} + W^{(1)} P^{(1)} \}, \quad (8)$$

respectively. Here, the self-energy matrices $W^{(1)}$ and $W^{(2)}$ are similar to $W^{(1)}$ and $W^{(2)}$ except for the fact
that they take into account the number of electrons transferred through the system. The total current is then simply given by $I = I^{(1)} + I^{(2)}$.

In the following, we study the transport properties in the full parameter space, i.e., in the full range of bias and gate voltages. However, because the calculation of the second-order contribution to the current in the full parameter space is a numerically demanding task, we will discuss the role of the second-order processes only in the low-bias-voltage regime, where such processes play the most important role in transport [37]. For larger voltages, sequential processes give a dominant contribution to the conductance and therefore the transport properties of the system can be reliably described including only first-order processes. Therefore, we first discuss the transport behavior in the full parameter space considering sequential processes and only later on we extend the discussion to the case of cotunneling in the linear response regime.

**Results and discussion.** – Our calculations are performed for the following parameters of the system. Each magnetic molecule is characterized by spin $S = 1$ and the uniaxial magnetic anisotropy $D/E_C = 0.2$. The exchange coupling between the corresponding molecule and orbital level in the nanotube is assumed to be of antiferromagnetic type [27,28], and we take $J/E_C = -0.4$. The hopping between the orbital levels of the nanotube is assumed to be $t/E_C = 0.2$, while the position of the orbital levels is characterized by the energy $\varepsilon$ with the assumption $\varepsilon_L = \varepsilon_R \equiv \varepsilon$. The coupling to external leads is taken as $\Gamma/E_C = 0.02$ and the calculations are performed at the temperature $T/E_C = 0.08$. Finally, we use the charging energy as the energy unit $E_C \equiv 1$.

The differential conductance. – Let us start the discussion with the analysis of the behavior of the differential conductance. Figure 2 presents $G$ plotted as a function of the bias voltage $V$ and the position of the nanotube’s energy levels $\varepsilon$ in the case of (a) $B_z = 0$ and (b) $B_z/E_C = 0.2$. The bottom panels show the bias dependence of $G$ calculated for (c) $\varepsilon/E_C = -3.6$ and (d) $\varepsilon/E_C = -1.1$. The parameters are: $S = 1$, $D/E_C = 0.2$, $J/E_C = -0.4$, $\Gamma/E_C = 0.02$, $t/E_C = 0.2$, $T/E_C = 0.08$, and $E_C \equiv 1$.

![Fig. 2: The differential conductance $G$ as a function of the bias voltage $V$ and the energy of nanotube's orbital levels $\varepsilon$ in the case of (a) $B_z = 0$ and (b) $B_z/E_C = 0.2$. The bottom panels show the bias dependence of $G$ calculated for (c) $\varepsilon/E_C = -3.6$ and (d) $\varepsilon/E_C = -1.1$. The parameters are: $S = 1$, $D/E_C = 0.2$, $J/E_C = -0.4$, $\Gamma/E_C = 0.02$, $t/E_C = 0.2$, $T/E_C = 0.08$, and $E_C \equiv 1$.](image)

To exemplify the supramolecular spin valve effect, in figs. 2(c) and (d) we present the bias voltage dependence of the differential conductance for two different values of $\varepsilon$, as indicated. When $B_z = 0$, the molecules are in a superparamagnetic state and their spins become aligned only when an external magnetic field is applied to the system. Thus, by manipulating the spins of the molecules, it is possible to change the current flowing through the whole device. However, the behavior of the system is not as simple as one could expect, i.e., depending on $\varepsilon$ and $V$, one can find both regimes of the current suppression or its enhancement with the application of magnetic field. Such behavior can be seen in figs. 2(c) and (d).

The tunnel magnetoresistance. To quantify the change of the system’s transport properties in the presence and absence of external magnetic field, we introduce the tunnel magnetoresistance (TMR), defined as

$$TMR = \frac{I(B_z = 0) - I(B_z)}{I(B_z)}, \quad (9)$$
the presence of magnetic field $B$ where parameters are the same as in fig. 2.

where $I(B_z)$ is the current flowing through the system in the presence of magnetic field $B_z$.

The bias voltage and level position dependence of the TMR for a few values of magnetic field is presented in fig. 3. First of all, one can note that the TMR is very low in the high-bias-voltage regime. In this case many molecular states of the system are relevant for transport and sequential tunneling dominates the current. Consequently, the difference between the currents flowing in the case in which $B_z = 0$ and $B_z \neq 0$ is very small, which results in $\text{TMR} \approx 0$, see fig. 3. The situation becomes however completely different when only a few molecular states contribute to the current, which happens in the low-bias-voltage regime. We note that in this transport regime the current can flow due to thermally activated sequential tunneling processes, which in the case of $\Gamma \ll T$ are relevant, as well as cotunneling processes. In fig. 3 we show the results due to the first-order processes, while the role of cotunneling will be analyzed further on.

Generally, one can see that for low-bias voltages the TMR strongly depends on the charge state of the nanotube. More specifically, in the two-electron Coulomb diamond (around $\varepsilon = 0$, see fig. 3), the TMR is negative, while in the case in which the nanotube is either fully occupied or empty ($|\varepsilon/E_C| \gtrsim 3.5$), the TMR is positive. On the other hand, in the Coulomb blockade regimes with odd number of electrons on the nanotube, the TMR can be both negative and positive, depending on $\varepsilon$, see fig. 3 for $1 \lesssim |\varepsilon/E_C| \lesssim 3.5$. To understand this behavior, one needs to consider the corresponding molecular states relevant for transport in each region. When the nanotube is either empty or fully occupied, the presence of attached magnetic molecules is not that important for low-bias voltages. Because with increasing value of magnetic field, the number of states relevant for thermally activated transport decreases due to the Zeeman splitting, $I(B_z) < I(B_z = 0)$, and consequently $\text{TMR} > 0$.

This is however opposite to the case in which the nanotube is occupied by two electrons, where one finds $I(B_z) > I(B_z = 0)$, yielding $\text{TMR} < 0$. The reason for this behavior is associated with the fact that in the presence of magnetic field the spins of the molecules become aligned, such that the molecule-nanotube system is mainly occupied by a two-electron state with $S^z_{\text{tot}} = -2S$ being a linear combination of local states with one electron on each level and zero and two electrons on different levels. This increases transport compared to the case of no magnetic field, where the occupation probability is distributed between several two-electron states.

When the nanotube is occupied by an odd number of electrons at low voltages the system is in the state with $S^z_{\text{tot}} = -2S + 1/2$. In this case it is relevant whether the excitation energies to charge states with an empty (fully occupied) nanotube and states with two electrons on the nanotube are more favorable. In the former case the current becomes suppressed in finite $B_z$, whereas in the latter case the current gets enhanced with the application of magnetic field, see fig. 3. It is also interesting to note that the above-described behavior becomes enhanced with increasing $B_z$, resulting in larger $|\text{TMR}|$, cf. fig. 3.

**Current spin polarization.** Let us now analyze how the spin polarization of the flowing current changes with increasing external magnetic field. The spin polarization is defined as

\[
\text{Pol} = \frac{I_{\uparrow}(B_z) - I_{\downarrow}(B_z)}{I_{\uparrow}(B_z) + I_{\downarrow}(B_z)},
\]

where $I_{\sigma}(B_z)$ is the current flowing in the spin-channel $\sigma$ at magnetic field $B_z$. The spin polarization as a function of the bias voltage $V$ and the nanotube’s level position $\varepsilon$ for different values of $B_z$ is shown in fig. 4. First of all, one can note that the dependence is symmetric with respect to the particle-hole symmetry point of the model, i.e., $\varepsilon = 0$, with $\text{Pol}(\varepsilon < 0) = -\text{Pol}(\varepsilon > 0)$. Moreover, as in the case of TMR discussed above one observes a gradual increase of $|\text{TMR}|$ with boosting $B_z$, now this is not the case. More specifically, $|\text{Pol}|$ increases when $B_z$ grows from $B_z/E_C = 0.05$ to $B_z/E_C = 0.1$, however, then it slightly drops when magnetic field is raised further to $B_z/E_C = 0.2$, see fig. 4.

A general observation is that out of the Coulomb blockade regime, $\text{Pol} < 0$ (Pol > 0) for $\varepsilon > 0$ ($\varepsilon < 0$). On the other hand, the largest magnitude of the spin polarization is found in the low bias voltage regime when the nanotube
Fig. 4: The dependence of the current spin polarization (Pol) on bias voltage $V$ and the nanotube’s orbital level position $\varepsilon$ for a few different values of the external magnetic field, as indicated. The parameters are the same as in fig. 2.

is either empty or fully occupied. One then finds $\text{Pol} > 0$ ($\text{Pol} < 0$) for $\varepsilon/E_C \gtrless 3.5$ ($\varepsilon/E_C \lesssim -3.5$), which is simply associated with the fact that for $\varepsilon/E_C \gtrless 3.5$ ($\varepsilon/E_C \lesssim 3.5$) the excitations to positive (negative) spin states are more favorable.

Effects of cotunneling. Finally, in this section we discuss the role of cotunneling processes on the tunnel magnetoresistance and spin polarization of the flowing current. Figure 5 shows the total (sequential plus cotunneling) TMR as well as the total spin polarization as a function of the nanotube’s level position $\varepsilon$ calculated in the linear response regime. For comparison, we also show the results obtained by considering only the first-order tunneling processes. One can easily see the differences between both results, which are most revealed in the case of an empty or a fully occupied nanotube, $|\varepsilon/E_C| \gtrsim 3.5$, where elastic non-spin-flip cotunneling processes are most important for the current. There, one finds a strong suppression of the tunnel magnetoresistance, such that $\text{TMR} \approx 0$, which is completely opposite to the sequential tunneling result, see the left column of fig. 5. Because in this transport regime elastic cotunneling processes, in which the spin of tunneling electrons is conserved, drive the current, the difference between the currents $I(B_z = 0)$ and $I(B_z)$ decreases as one moves deeper and deeper into the empty or fully occupied nanotube regime, cf. figs. 5(a)–(c). A similar observation also applies to the behavior of the current spin polarization, which becomes generally suppressed compared to that predicted by considering only sequential tunneling processes, see the right column of fig. 5. On the other hand, as far as other transport regimes with different nanotube occupations are concerned, it can be concluded from fig. 5 that sequential tunneling processes give a qualitatively reliable insight into the transport behavior of the system. In these transport regimes the cotunneling processes rather weakly modify the observed behavior.

Summary. We have analyzed the magnetoresistive properties of a supramolecular spin valve consisting of a nanotube with two attached magnetic molecules embedded in a tunnel junction. The considerations were performed by using the real-time diagrammatic technique in the first and second order of expansion with respect to the tunnel coupling. We have shown that the tunnel magnetoresistance of such device, associated with a change of the magnetic molecules’ state from the superparamagnetic to the ferromagnetic one, can take both positive and negative values, depending on the transport regime. Our work demonstrates thus that it is possible to tune the TMR by either the bias or gate voltage. This offers an interesting route for the control of the magnetoresistive transport properties without the need to use ferromagnetic contacts.

In addition, we have also studied the spin polarization of
the tunneling current and shown that it strongly depends on the transport regime, which allows for tuning both the magnitude and the sign of the spin polarization.

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REFERENCES

[1] GATTESCHI D. and SESSOLI R., *Angew. Chem., Int. Ed.*, 42 (2003) 268.
[2] ROMIEKE C., WEGEWIJS M. R., HOFSTETTER W. and SCHOELLER H., *Phys. Rev. Lett.*, 96 (2006) 196601.
[3] TIMM C. and ELSTE F., *Phys. Rev. B*, 73 (2006) 235304.
[4] JO M.-H., *Nano Lett.*, 6 (2006) 2014.
[5] ELSTE F. and TIMM C., *Phys. Rev. B*, 75 (2007) 195341.
[6] MISORYN M. and BARNÁS J., *EPL*, 78 (2007) 27003.
[7] TAKAHASHI S., VAN TOL J., BEEDLE C. C., HENDRICKSON D. N., BRUNEL L.-C. and SHERWIN M. S., *Phys. Rev. Lett.*, 102 (2009) 087603.
[8] MISORYN M. and BARNÁS J., *Phys. Status Solidi B*, 246 (2009) 695.
[9] PARKES J. J., CHAMPAGNE T. A., SHUM W. W., PASUPATHY A. N., NEUSCAMMAN E., FLORESTORRES S., CORNAGLIA P. S., ALIGIA A. A., BALSEIRO C. A., CHAN G. K.-L., ABRUŠA H. D. and RALPH D. C., *Science*, 328 (2010) 1370.
[10] ELSTE F. and TIMM C., *Phys. Rev. B*, 81 (2010) 024421.
[11] ANDERGASSEN S., MEDEN V., SCHOELLER H., SPLITTSSTOESSER J. and WEGEWIJS M. R., *Nanotechnology*, 21 (2010) 272001.
[12] XIE H., WANG Q., CHANG B., JIAO H. and LIANG J.-Q., *J. Appl. Phys.*, 111 (2012) 063707.
[13] MISORYN M. and BARNÁS J., *Phys. Rev. Lett.*, 111 (2013) 046603.
[14] MISORYN M., BURZURÍ E., GAUDENZI R., PARK K., LEINSE M., WEGEWIJS M. R., PAASKE J., CORNIA A. and VAN DER ZANT H. S. J., *Phys. Rev. B*, 91 (2015) 035442.
[15] PŁOMIŃSKA A. and WEYMANN I., *Phys. Rev. B*, 92 (2015) 205419.
[16] URDAMPILLETA M., KLAYSKAYA S., RUBEN M. and WERNSDORFER W., *ACS Nano*, 9 (2015) 4458.
[17] PŁOMIŃSKA A., MISORYN M. and WEYMANN I., *Phys. Rev. B*, 95 (2017) 155446.
[18] PŁOMIŃSKA A., WEYMANN I. and MISORYN M., *Phys. Rev. B*, 97 (2018) 035415.
[19] GATTESCHI D., SESSOLI R. and VILLAIN J., *Molecular Nanomagnets* (Oxford University Press, New York) 2006.
[20] BARTOLOMÉ J., LUIS F. and FERNÁNDEZ J. F., *Molecular Magnets* (Springer, Berlin, Heidelberg) 2013.
[21] LOSS D. and DI VINCENZO D. P., *Phys. Rev. A*, 57 (1998) 120.
[22] ARDÁN A., RIVAL O., MORTON J. J. L., BLUNDELL S. J., TYWYSHIK A. M., TIMCO G. A. and WINPENNY R. E. P., *Phys. Rev. Lett.*, 98 (2007) 057201.
[23] MANNINI M., PINEIDER F., SAINCTAVIT P., DANIELI C., OTERO E., SCIANCIALEPORE C., TALARICO A. M., ARRIO M.-A., CORNIA A., GATTESCHI D. and SESSOLI R., *Nat. Mater.*, 8 (2009) 194.
[24] FRANKLAND P. W. and JОСSELYN S. А., *Nature*, 493 (2013) 312.
[25] BARNÁS J. and WEYMANN I., *J. Phys.: Condens. Matter*, 20 (2008) 423202.
[26] MISORYN M., WEYMANN I. and BARNÁS J., *Phys. Rev. B*, 79 (2009) 224420.
[27] URDAMPILLETA M., KLAYSKAYA S., CLEUZIOU J.-P., RUBEN M. and WERNSDORFER W., *Nat. Mater.*, 10 (2011) 562.
[28] URDAMPILLETA M., NGUYEN N.-V., CLEUZIOU J.-P., KLAYSKAYA S., RUBEN M. and WERNSDORFER W., *Int. J. Mol. Sci.*, 12 (2011) 6056.
[29] ROCHA A. R., GARCÍA-SUÁREZ V. M., BAILEY S. W., LABBECK C. J., FERRER J. and SANVITO S., *Nat. Mater.*, 4 (2005) 335.
[30] BOGANI L. and WERNSDORFER W., *Nat. Mater.*, 7 (2008) 179.
[31] AYCHALOM D. D., Basset L. C., DZURAK A. S., HU E. L. and PETTA J. R., *Science*, 339 (2013) 1174.
[32] SCHOELLER H. and SCHÖN G., *Phys. Rev. B*, 50 (1994) 18436.
[33] KÖNIG J., SCHMID J., SCHOELLER H. and SCHÖN G., *Phys. Rev. B*, 54 (1996) 16820.
[34] THIELMANN A., HEITTLER M. H., KÖNIG J. and SCHÖN G., *Phys. Rev. Lett.*, 95 (2005) 146806.
[35] OREG Y., BYCZUK K. and HALPERIN B. I., *Phys. Rev. Lett.*, 85 (2000) 365.
[36] WEYMANN I., *Phys. Rev. B*, 78 (2008) 045310.
[37] GRABERT HERMANN and DEVORET MICHEL, *Single Charge Tunneling - Coulomb Blockade Phenomena in Nanostructures* (Springer) 1992, 978-1-4757-2168-3, 10.1007/978-1-4757-2166-9.