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Asymmetric tunable tunneling magnetoresistance in single-electron transistors

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Abstract

We show that the tunneling magnetoresistance (TMR) of a ferromagnetic single-electron transistor in the sequential tunneling regime shows asymmetric Coulomb blockade oscillations as a function of gate voltage if the individual junction-TMRs differ. The relative amplitude of these oscillations grows significantly if the bias voltage is increased, becoming as large as 30% when the bias voltage is comparable to the charging energy of the single-electron transistor. This might be useful for potential applications requiring a *tunable* TMR. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Inspired by successful experimental work on spin-dependent tunneling [1,2], there has recently been a growing interest in spin-dependent transport through ferromagnetic single-electron transistors (SETs) [3–12]. In such a device a mesoscopic metallic island, made from a ferromagnetic material such as Fe, Co or Ni, is coupled via two-tunnel junctions ($i = \mathrm{l}, \mathrm{r}$ for left, right) to two ferromagnetic leads, and capacitively to a gate (Fig. 1). Interesting novel effects can then arise from the combination of features specific to SETs, such as Coulomb blockade phenomena, and features specific to spin-dependent tunneling, such as a tunneling magnetoresistance (TMR).

By TMR we here mean a dependence of the resistance of the SET on the relative orientations of the magnetizations of the leads and the island. This dependence arises since the tunnel resistances of tunnel junctions sandwiched between ferromagnets are spin-dependent. Following Ref. [3], we always take the magnetizations of the leads to be parallel to each other, but allow the magnetization of the grain to be either parallel or antiparallel (denoted by a 'magnetization index' $\alpha = \mathrm{p}$ or a, respectively) relative to those of the leads. (Both configurations can be obtained experimentally by turning on a magnetic field H, since the magnetizations of the leads and of the grain do not reverse at the same field.) Then the TMR

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FIGURES

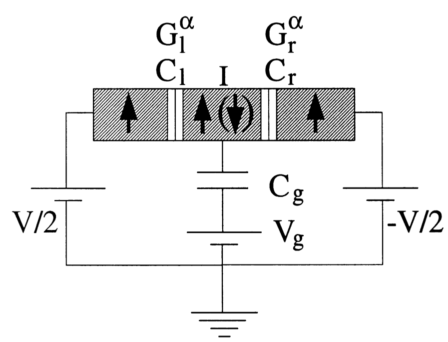


Fig. 1. A ferromagnetic (F/F/F) single-electron transistor with bias voltage V (applied symmetrically) and gate voltage V_g. The magnetization directions of the leads and the grain are denoted by arrows. The two arrow directions for the island correspond to parallel or antiparallel alignment ($\alpha = \mathrm{p}$ or a) of the island relative to the leads.

of the SET is defined by

$$\mathrm{TMR} = \frac{R_a - R_p}{R_p} = \frac{G_p}{G_a} - 1 = \frac{I_p}{I_a} - 1\,, \tag{1}$$

where $R_\alpha = V/I_\alpha$ and $G_\alpha = I_\alpha/V$ are its α-dependent resistance and conductance, respectively, I_α being the current and V the bias voltage.

Now, both I_p and I_a, and hence also the TMR, are sensitive to charging effects when the temperature T and bias voltage V are sufficiently small, i.e. if T and eV are of the same order or smaller than the charging energy $E_C = e^2/2(C_l + C_r + C_g)$ of the SET, which represents the energy cost for changing the number of electrons on the island by one. For example, then G_α shows Coulomb blockade oscillations [13] as a function of the gate voltage V_g at fixed V, with peaks at the so-called resonance points, where island states whose electron number differs by one are degenerate. Takahashi and Maekawa (TM) [4] studied the effect of these oscillations on the TMR for a ferromagnetic SET with two identical junctions in the linear-response regime ($V \simeq 0$). They found that the TMR increased significantly (by a factor of 2) if the SET is tuned from a regime where sequential tunneling dominates to one where cotunneling dominates; the latter requires that $T \ll E_C$, that the junction conductances be not too small relative to e^2/h, and that V_g is not near any resonance point. Consequently, they found large *TMR-oscillations* with V_g, with TMR minima located at the resonance points (where sequential tunneling dominates).

These oscillations imply, very interestingly, that a TMR can be realized that is *tunable* as a function of V_g. From the point of view of potential applications, however, the cotunneling regimes considered by TM have the drawback that the currents I_α are very small, implying unfavorable signal-to-noise ratios. It would conceivably be useful if such oscillations could also be achieved in regimes in which *sequential tunneling still dominates over cotunneling*. In this note we point out that this can be achieved very easily in an *asymmetric* SET in which the two tunnel junctions have different junction TMRs. Moreover, we find that the relative oscillations in the TMR with V_g *become significantly stronger with increasing* V, while their shape develops a striking asymmetry; a particularly favorable case arises at a rather large bias voltage of order $eV \simeq E_C$, with $T \ll E_C$, for which TMR oscillations between roughly 0.2 and 0.3 can be achieved, implying relative changes as large as 30%.

2. Description of a ferromagnetic SET

Each of the two tunnel junctions ($i = \mathrm{l,r}$) can be characterized by the TMR that it would show if it were considered on its own, namely

$$\mathrm{TMR}_i = \frac{G_i^p - G_i^a}{G_i^a}. \tag{2}$$

Here G_i^p (or G_i^a) is the conductance through junction i if the magnetizations of the two ferromagnets that sandwich it, say F_i and F'_i, are oriented parallel (or antiparallel) to each other. Adopting Julliere's picture for spin-dependent tunneling [1,2,14] and its elaboration by MacDonald et al. [15], G_i^α can be written in the phenomenological form

$$G_i^p = G_i^0(1 + \tilde{P}_i\tilde{P}'_i) \quad G_i^a = G_i^0(1 - \tilde{P}_i\tilde{P}'_i)\,. \tag{3}$$

Here G_i^0, the junction's spin-averaged conductance, depends on the geometry and electronic structure of the insulating barrier, and $\tilde{P}_i$ and $\tilde{P}'_i$ are phenomenological parameters characterizing F_i and F'_i: they describe the spin polarization near the Fermi surface, suitably weighted by the tunneling probabilities for electrons originating from different (s, p or d) bands [15,16], and can be determined directly from tunneling experiments between ferromagnets and superconductors — typical $\tilde{P}$ values are 0.40, 0.35 and 0.23 for Fe, Co and Ni, respectively [1,2,17,18].

Let $P_\alpha(N)$ denote the probability to find N excess electrons on the island (relative to the charge-neutral case) if the ferromagnetic SET has magnetization index α. We shall assume that the spin-relaxation rate is sufficiently fast that spin-accumulation effects [4,8–11] can be neglected. Then the probabilities $P_\alpha(N)$ can be determined [3,4] by numerically solving the stationary master equation

$$0 = \sum_{s=\pm} \sum_{i=\mathrm{l,r}} [P_\alpha(N-s1)\Gamma^s_{i,\alpha}(N-s1) - P_\alpha(N)\Gamma^s_{i,\alpha}(N)]\,.$$

Here, the sequential tunneling rates for tunneling through junction i onto ($\Gamma^+_{i,\alpha}(N)$) or off ($\Gamma^-_{i,\alpha}(N)$) an island containing N excess electrons may be found by first-order perturbation theory using Fermi's golden rule. This yields, for the symmetrically biased SET shown in Fig 1,

$$\Gamma^s_{i,\alpha}(N) = \frac{G^\alpha_i}{e^2}\frac{\delta E^s_{\mathrm{ch},i}(N)}{\exp(\delta E^s_{\mathrm{ch},i}(N)/k_\mathrm{B}T) - 1}, \tag{4}$$

$$\delta E^s_{\mathrm{ch},i}(N) = s\,eV_i + 2sE_C(N - N_G - N_H + s/2), \tag{5}$$

$$N_G = (C_\mathrm{r} - C_\mathrm{l})V/2e + C_\mathrm{g}V_\mathrm{g}/e, \tag{6}$$

where $V_\mathrm{l} = -V_\mathrm{r} = V/2$. These formulae differ in two respects from the standard ones for an SET made from normal metals [13]: (i) Eq. (4) contains the factor G^α_i instead of the usual G^0_i, reflecting the spin-dependence of tunneling between ferromagnets. (ii) Eq. (5) contains an extra term N_H, which is linear in $\mu_\mathrm{B}H/E_C$ and describes the effect on the charging energy of an external magnetic field H, due to the Zeeman splitting which it induces between the majority and minority bands [6,7]. Since N_H is usually still $\ll 1$ at the coercive field of the SET (the magnetic field needed to switch the magnetization of the island between $\alpha = \mathrm{a}$ and p, typically of order $H_{\mathrm{coer.}} \simeq 0.01\mathrm{T}$ [8]), we neglect it below. For the sake of completeness, its general form is given in an appendix.

The DC current through the SET due to sequential tunneling (neglecting cotunneling) is given by

$$I_\alpha = -e\sum_N P_\alpha(N)[\Gamma^+_{\mathrm{l},\alpha}(N) - \Gamma^-_{\mathrm{l},\alpha}(N)]\,. \tag{7}$$

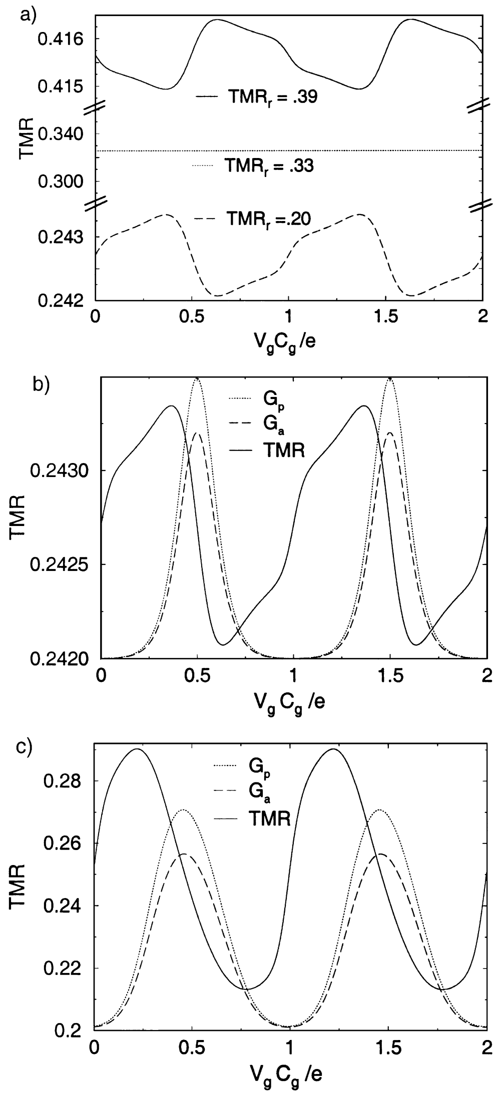
3. Results

Using the above formulae, we have calculated the TMR of the SET as a function of gate voltage V_g for various values of the transport voltage V, and various values of the junction parameters TMR_i, with a view to determining under what conditions the TMR-oscillations with V_g would be most pronounced. Our results are summarized in Figs. 2(a)–(c).

The first important point to note, illustrated in Fig. 2(a), is that the TMR shows charging effects (i.e. depends on V_g), only if the junctions are *not identical*, with $\mathrm{TMR_l} \neq \mathrm{TMR_r}$. The reason is not difficult to understand: if instead $\mathrm{TMR_l} = \mathrm{TMR_r} \equiv \overline{\mathrm{TMR}}$, Eqs. (4) and (2) would imply that $\Gamma^s_{i,\mathrm{p}} = (\overline{\mathrm{TMR}} + 1)\Gamma^s_{i,\mathrm{a}}$, i.e. that the proportionality factor between these rates is independent of $i = \mathrm{l,r}$ and $s = \pm$. This immediately implies that the master equations for $P_\mathrm{p}(N)$ and $P_\mathrm{a}(N)$ differ only by a factor $(\overline{\mathrm{TMR}} + 1)$ that can be factored out completely from under all sums in the master equation, so that these quantities in fact are equal, $P_\mathrm{p}(N) = P_\mathrm{a}(N)$. Thus, the only α-dependence in Eq. (7) for the currents I_α resides in the factors G^α_i occurring in $\Gamma^i_{i,\alpha}$, implying that $I_\mathrm{p} = (\overline{\mathrm{TMR}} + 1)I_\mathrm{a}$. It follows that even when both I_p and I_a individually show strong charging effects, these cancel out in the TMR ratio of Eq. (1), so that $\mathrm{TMR} = \overline{\mathrm{TMR}}$. The first example that the TMR can show charging effects if $\mathrm{TMR_l} \neq \mathrm{TMR_r}$ was found (without explanation) in Ref. [2], where TMR-oscillations as a function of V at fixed V_g were found.

Next, we note that the Coulomb oscillations of the TMR with V_g that occur if $\mathrm{TMR_l} \neq \mathrm{TMR_r}$

have a rather unusual asymmetric form. To understand this, recall a fact well-known [13] for standard (non-ferromagnetic) SETs: if the bias voltage V is nonzero and the two junction conductances are unequal, $G_l^0 \neq G_r^0$, the shape of the Coulomb-oscillations of the conductance with V_g becomes asymmetric with respect to the resonance points. Since $\mathrm{TMR}_l \neq \mathrm{TMR}_r$ implies that $G_l^\alpha \neq G_r^\alpha$ for at least one of $\alpha = \mathrm{p}$ or a (in general both), it follows immediately that the Coulomb-oscillations of at least one of G_p or G_a (in general both) will likewise be asymmetric; this is illustrated by the dotted and dashed curves in Figs. 2(b) and (c). Though this asymmetry in G_α is not very strong, it is very sensitively reflected in the ratio G_p/G_a occurring in the TMR of Eq. (1).



Thirdly, a comparison of Figs. 2(b) and (c) also illustrates our most important result: *the relative amplitude of the TMR oscillations with V_g increases significantly as the bias voltage V is increased;* in fact, for the parameters chosen in Fig. 2(c), where for $eV \simeq E_C$ the TMR fluctuates between 0.22 and 0.29, the relative amplitude of the oscillations reaches roughly 30%. The reason is that as V is increased between 0 to beyond E_C, the magnitudes of both G_p and G_a increase significantly, *but in unequal ways* [due to the factor G_i^α in Eq (4)]; this causes the TMR oscillations with V_g to become more pronounced too as eV is increased, because, by construction, the TMR reflects differences between G_p and G_a. The maximum strength of these TMR oscillations is reached when the bias voltage is comparable to the energy scale responsible for the charging effects, namely $eV \simeq E_C$. If $eV \gg E_C$, however, all charging effects are washed out, including the TMR oscillations with V_g.

4. Summary

We explained that the TMR of a ferromagnetic SET in the sequential tunneling regime can show

Fig. 2. Coulomb oscillations of the TMR as functions of gate voltage for a Co/Fe/Ni SET, symmetrically biased, at temperature $T = 0.1E_C$, with $C_l = C_r = 100C_g$, $E_C = 1$ meV, $G_l^0/G_r^0 = 2$, and $G_r^0 = 0.05e^2/h$. (a) Illustrates the dependence of the TMR on junction asymmetry, for $\mathrm{TMR}_l = 0.33$ and three different values for TMR_r, with bias voltage $V = 0.01E_C/e$. A comparison of (b) and (c) illustrates that with increasing V, the conductances G_p (dotted lines) and G_a (dashed lines) become increasingly asymmetric relative to the resonance points ($V_gC_g/e \simeq$ half-integer), and that the amplitude of the TMR oscillations (solid lines) increases significantly. The parameters are as in (a), except that $\mathrm{TMR}_r = 0.20$ throughout, and $V = 0.01E_C/e$ in (b) and $V = E_C/e$ in (c). The vertical scale in (b) and (c) refers only to the TMR; G_p and G_a have been plotted in arbitrary units, since only their ratio matters for the TMR (the maximum values of G_p in (b) and (c) correspond to currents of $I_p = 6.7$ and 690 pA, respectively, the minimum values are very close to zero). The TMR slope is large near the points of most complete Coulomb blockade ($V_gC_g/e \simeq$ integer), since near these G_p and G_a approach zero with different slopes.

charging effects only if the junction TMRs differ, $TMR_l \neq TMR_r$. In this case, we showed that TMR shows asymmetric oscillations with gate voltage, and that the relative amplitude of the oscillations of the TMR with V_g can be tuned by changing the bias voltage, with TMR values as large as 30% being possible at $eV \simeq E_C$. These results might be useful in applications that require a tunable TMR.

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Appendix A. Appendix

The influence of an external magnetic field H on a ferromagnetic SET was first described by Shimada and Coworkers [6,7]. Due to the Zeeman effect, a magnetic field rigidly shifts the majority band downward in energy and the minority band upward in energy, so that the number of electrons in the majority band increases slightly and in the minority band decreases slightly. Since for ferromagnets the densities of states near the Fermi energy of the majority and minority bands differ considerably, this can cause a net change in the electrochemical potential of the island.

This effect was discussed and analyzed at length in Ref. [7]. Here we wish to point out that the analysis of Ref. [7] can be summarized and included in a very simple manner into the standard description of the SET, by writing the charging energy as

$$E_{ch}(N) = E_C(N - N_G - N_H)^2, \tag{A.1}$$

where the new magnetic-field-induced term N_H is given by

$$N_H = \frac{\mu_B H}{4E_C}\left(o_I g_I P_I - \sum_{i=l,r,g} \frac{o_i g_i P_i C_i}{C_l + C_r + C_g}\right). \tag{A.2}$$

Here the subscript $i = l, r, g, I$ labels the various components of the ferromagnetic SET: $i = l, r$ denotes the leads connected to the voltage source, $i = g$ the gate electrode, and $i = I$ the island. The o_i are the orientations of the magnetizations of these components with respect to the external field: $o_i = 1$ means parallel, $o_i = -1$ antiparallel, and $o_i = 0$ means that the component is non-magnetic. g_i denotes the electronic g-factors and P_i denotes the spin polarizations near the Fermi surface (they differ from the $\tilde{P}_i$ occurring in Eqs. (3), since here not the tunneling but the shift in the electrochemical potential is considered, thus no weighting factors due to different tunneling probabilities are needed).

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