Journal of Applied Physics

RESEARCH ARTICLE | JULY 15 1998

Resonant tunneling spin valve: A novel magnetoelectronics device

P. Bruno; J. Wunderlich

Check for updates

J. Appl. Phys. 84, 978–982 (1998)
https://doi.org/10.1063/1.368163

View Online
Export Citation

Articles You May Be Interested In

Fluctuations in nanoscale magnetoelectronics devices

J. Appl. Phys. (November 2012)

Three-terminal gated magnetoelectronic device

Appl. Phys. Lett. (April 2002)

Ferromagnetic metal/semiconductor hybrid structures for magnetoelectronics

J. Appl. Phys. (April 1999)

23 November 2026 15:11:42



AIP Publishing

Resonant tunneling spin valve: A novel magnetoelectronics device

P. Bruno[a)]
Institut d'Électronique Fondamentale, CNRS URA 22, Bâtiment 220, Université Paris-Sud, F-91405 Orsay, France

J. Wunderlich[b)]
Institut d'Électronique Fondamentale, CNRS URA 22, Bâtiment 220, Université Paris-Sud, F-91405 Orsay, France

(Received 18 November 1997; accepted for publication 25 March 1998)

The concept of a novel magnetoelectronics device, the *resonant tunneling spin valve*, which combines the spin-valve tunneling junction and the double barrier resonant tunneling diode, is proposed. Model calculations are performed in order to investigate the spin-valve effect in this structure. © *1998 American Institute of Physics.* [S0021-8979(98)02213-0]

I. INTRODUCTION

During its brilliant half-century-long success story, electronics has almost completely ignored the spin of the electron. This matter of state is currently changing, with the emergence of a novel field, *magnetoelectronics*, merging together electronics and magnetism.[1] Among the various topics in magnetoelectronics, spin-dependent electronic transport in heterostructures combining ferromagnetic and semiconducting or insulating materials is currently attracting a strong interest.[2–7] Of particular interest is the spin valve tunneling junction,[3] which basically consists of two ferromagnetic electrodes separated by a tunneling barrier; in this device, the current flowing through the junction depends on the angle between the magnetizations of the ferromagnets, due to the spin valve effect.[8–10] In this case, the emitter serves as a spin polarizer, and the collector as a spin analyzer. In another type of experiment, spin-polarized electrons are produced by using photoexcitation with circularly polarized light.[2,4,6,7]

In the present article, we propose the concept of *resonant tunneling spin valve*, which combines the spin-valve tunneling junction[3,8–10] and the double-barrier resonant-tunneling diode,[11,12] and we present some model calculations of the electronic structure and transport properties of a resonant tunneling spin valve.

The resonant tunneling spin valve consists in a resonant tunneling double barrier diode sandwiched between two ferromagnetic electrodes. The idea is to achieve a large spin-valve effect for the voltage corresponding to resonant tunneling though the double barrier. This can be done if the band structures of the emitter and collector have a large spin asymmetry for the energy corresponding to the resonant state in the well.

In the standard single-barrier spin valve, most of the current is due to electrons in the vicinity of the Fermi level, so that the magnitude of the spin-valve effect is essentially determined by the spin asymmetry of the band structure in the emitter and collector *at the Fermi level*. In contrast to this, in the double-barrier spin-valve ballistic electrons with energies corresponding to the resonant state in the well are injected into the collector; in other words, the resonant tunneling double barrier acts as an energy filter for transmitted electrons. By introducing an undoped spacer between the double barrier, one can vary the kinetic energy of the collected electrons, and tune it in order to maximize the spin sensitivity of electron collection, and hence the spin-valve effect.

The article is organized as follows. In Sec. II, we discuss the materials and the structure that would be suitable for building a resonant tunneling spin valve. The modelization of the chosen structure and the theoretical method of calculation are presented in Sec. III. Then the results are discussed in Sec. IV. Finally, Sec. V is devoted to concluding remarks and outlook.

II. DISCUSSION OF THE STRUCTURE

Whether the fabrication of such a device is within the reach of present day technology remains to be clarified. Very likely, III-V compound heterostructures such as $GaAs/Ga_{1-x}Al_xAs$ are best candidates for building the double barrier. However, in the present case, the double barrier has to be sandwiched between metallic ferromagnets; thus it has to be grown on top of a metal. This can be a serious problem, because the growth of III-V compounds on metals is not as well mastered as on semiconductors. Nevertheless, it has been shown recently that GaAs can be grown on δ MnGa.[13]

Note δ MnGa is a ferromagnet having a bct structure, a Curie temperature above room temperature, and a strong magnetic anisotropy, the c axis being the easy magnetization direction;[13–15] it can be grown epitaxially on GaAs (001).[14,15] The density of states of δ MnGa is very similar to the one of τ MnAl:[16] it has a rather weak spin asymmetry at the Fermi level, but a strong one at an energy of about 1 eV above the Fermi level. As observed by Prins *et al.*, due to the weak spin asymmetry of electronic structure at the Fermi level, the spin-valve effect in a single-barrier tunneling junction with a MnAl collector is very weak; we suggest that a

[a)]Present address: Max-Planck-Institut für Mikrostrukturphysik, Weinberg 2, D-06120 Halle, Germany.
[b)]Also at: Institut für Angewandte Physik, Universität Regensburg, D-93040 Regensburg, Germany.

23 November 2026 15:11:42

 © 1998 American Institute of Physics

much higher spin-valve effect could be obtained with a double-barrier tunneling structure, by tuning the energy of the transmitted electrons at an energy of about 1 eV above the Fermi level.

Let us consider now the emitter. The electrons participating to current transport are those located within a few tenths of eV below the Fermi level. Thus, in order to have a strong spin asymmetry of injected current, one needs a material having a large spin asymmetry of density of states at and near the Fermi level. An obvious candidate is transition-metal strong ferromagnet such as cobalt. Indeed, cobalt has a very strong spin asymmetry of density of states near the Fermi level, and it can be grown epitaxially (in the bcc form) on GaAs (001). Due to the large perpendicular anisotropy and coercivity of the MnGa, the orientation of the cobalt magnetization can be switched from parallel (P) to antiparallel (AP) to the one of the MnGa, by applying a field larger than the coercivity of the cobalt, but smaller than that of the MnGa.

Thus, the structure we shall consider consists of the following stacking sequence; (i) GaAs substrate, (ii) MnGa (collector), (iii) a heavily n-doped (10^{18} cm^{-3}) GaAs layer (30 nm), (iv) an undoped GaAs spacer (35 nm), (v) an undoped $Ga_{0.67}Al_{0.33}As$ barrier (3 nm), (vi) an undoped GaAs layer (3 nm), (vii) an undoped $Ga_{0.67}Al_{0.33}As$ barrier (3 nm), (viii) an undoped GaAs spacer (5 nm), (ix) a heavily n-doped (10^{18} cm^{-3}) GaAs layer (30 nm), (x) a Co layer (emitter).

For purposes of comparison, we shall also consider a standard resonant tunneling double barrier diode, consisting of the same structure, with the MnGa and Co replaced by heavily n-doped (10^{18} cm^{-3}) GaAs.

The rather thick (35 nm) undoped GaAs spacer layer on the collector side has been chosen in order to achieve resonant tunneling for an applied voltage of about 0.7 V.

III. MODEL AND THEORETICAL METHOD

In order to compute the electronic structure and the current in the device, one needs to use a model that is able to model both semiconductors and ferromagnetic metals. The semiconductors are commonly described by using a quasifree-electron effective mass model. However, ferromagnetic metals, having narrow $3d$ bands, cannot be described reliably by a free-electronlike model. Rather they can be described by using a tight-binding model.

Thus, we have chosen to use a simple cubic tight-binding model. For the semiconductors, the tight-binding Hamiltonian is obtained by discretizing the effective mass Hamiltonian; the hopping parameter and the on-site energy are adjusted in order to reproduce the effective mass and the energy of the bottom of the conduction band, respectively.

For the ferromagnets, one uses a two-band simple cubic tight-binding model, with one s band and one d per spin. The reason for using only one d band instead of five is the following: most of the current transmitted through the semiconductor double barrier originates from the center $\bar{\Gamma}$ of the two-dimensional Brillouin zone, where the barrier height is the smallest; at $\bar{\Gamma}$ the only d band which has a symmetry compatible with the states in the semiconductor, and hence can be transmitted and contribute to the current, is the $d_{3z^2-r^2}$ band; thus, we consider only this one.

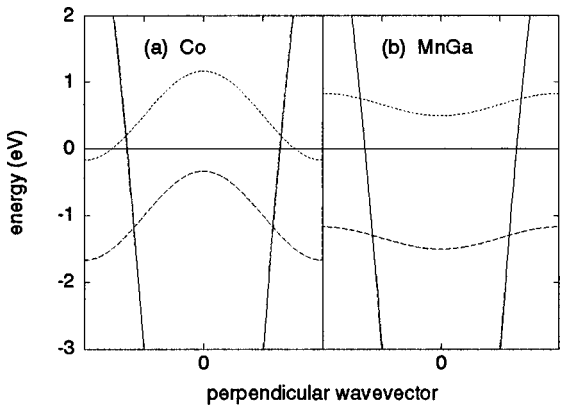


FIG. 1. Tight-binding model band structures, at the center $\bar{\Gamma}$ of the two-dimensional Brillouin zone; (a) Co, (b) MnGa. Solid line: s bands; long-dashed line: majority d band; short-dashed line: minority d band. The zero of energies is taken at the Fermi level.

The on-site energies and hopping parameters for the ferromagnets for the s and d bands have been selected in order to mimic the density of states in MnGa and Co. Clearly, such a rough modelization of the electronic structure is intended only to give an estimate of the order of magnitude of the spin-valve effect in the proposed structure; it is not claimed that the present model is able to provide an accurate description of the ferromagnetic electrodes. In all the following of the article, the terms ''MnGa'' and ''Co'' will refer to this oversimplified model, not to the real materials. The model band structure of the various materials is shown on Fig. 1.

Once the tight-binding Hamiltonian has been obtained, the electronics structure is calculated by using the transfer matrix method. The band bending due to charge transfer is calculated self-consistently in the Hartree approximation by solving simultaneously the Schrödinger and Poisson equations. For nonzero applied voltage, the transport is assumed to be perfectly ballistic, i.e., inelastic processes are completely neglected. The current flowing through the structure is calculated from the Landauer–Büttiker formula[17] using the transmission coefficients obtained from the transfer matrix.

IV. RESULTS AND DISCUSSION

A. Nonmagnetic resonant tunneling double barrier diode

We first present the results obtained for the nonmagnetic resonant tunneling double barrier diode. The current density versus applied voltage is shown in Fig. 2. The conduction band profiles and the charge densities at $U=0$ V, $U=0.62$ V (resonance), and $U=1.0$ V are shown in Fig. 3.

The dipole barriers due to charge transfer at the boundaries between doped and undoped regions are clearly seen in Fig. 3. At resonance [Fig. 3(b)], the electron accumulation on the resonant level in the well is clearly seen; this contributes to push the potential towards higher energies, so that resonance takes place at higher voltage in a self-consistent calculation than in a non-self-consistent one, as can be seen from Fig. 2. Another point to be noted is that the wide un-

23 November 2026 15:11:42

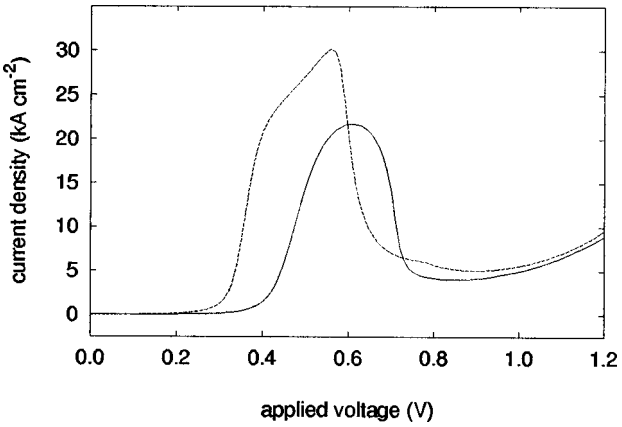


FIG. 2. Current density vs applied voltage at $T=4$ K, for the nonmagnetic double barrier diode. Solid line: self-consistent calculation; dashed line: non-self-consistent calculation.

doped spacer on the collector side sets the resonance at a rather large voltage, and injects electrons with a large kinetic energy into the collector.

B. Resonant tunneling spin valve

The calculated current density versus applied voltage for the resonant tunneling spin valve in P and AP configurations as shown in Fig. 4. Several points can be observed. First, in contrast to the case of the nonmagnetic resonant tunneling barrier, for which a rather smooth curve with a broad maximum at resonance is obtained, the curves for the resonant tunneling spin valve exhibit a very strong structure with numerous narrow maxima. This is due to the fact that the potential steps at the ferromagnet/semiconductor interfaces are very large; thus these produce large reflection of incoming electrons. It follows that the whole stack of semiconductors plays the role of a confinement layer, with transmission resonances. These resonances produce the sharp peaks in the curves of current density versus applied voltage.

Superimposed with the above-mentioned sharp peaks, the resonance due to the resonant tunneling through the double barrier is clearly seen, both in the P and AP configurations. As expected from our qualitative discussion of the resonant tunneling spin valve, the current density at the resonance is larger in the P configuration than in the AP one. The *spin-valve efficiency* may be defined as the difference between the P and AP current densities, normalized to the sum of P and AP current densities.[18] The spin-valve efficiency of the resonant tunneling spin valve versus applied voltage is shown in Fig. 5.

On can clearly see from Fig. 5 that the spin-valve efficiency is nonzero only in the voltage range where ballistic tunneling between the Co minority d band and the MnGa minority d band can take place. By switching from the P to the AP configuration, the tunneling channel between the Co minority d band and the MnGa minority d band becomes closed, so that the current is thereby reduced. For applied voltages between 0.5 and 0.8 V, the magnitude of the spin-valve efficiency ranges between 10% and 20%. In the linear response regime, the spin-valve efficiency is zero, in agreement with the observation of Prins *et al.* for a related structure.[4] This illustrates the improvement brought by the present structure, which allows one to optimize the spin-valve efficiency by selecting the energy of the injected electrons.

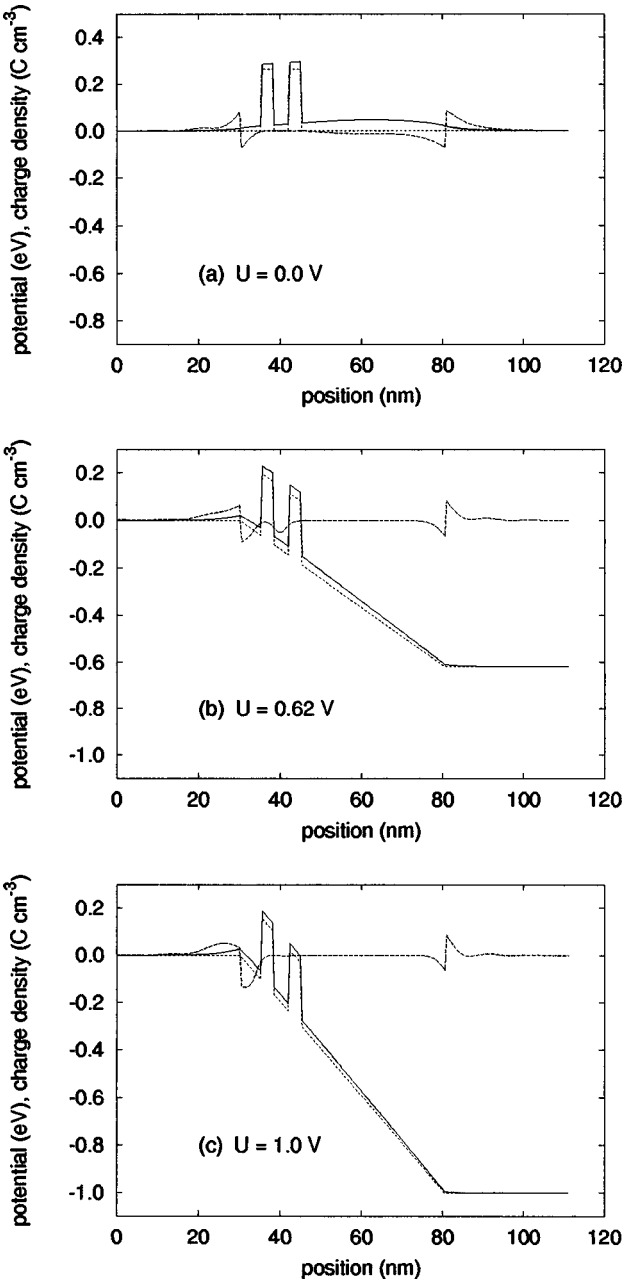


FIG. 3. Profile of the conduction band minimum and charge density for the nonmagnetic double barrier diode; solid line: self-consistent potential; short-dashed line: non-self-consistent potential; long-dashed line: charge density; (a) $U=0.0$ V, (b) $U=0.62$ V (resonance), (c) $U=1.0$ V.

The results obtained here illustrate also a very important point which is frequently overlooked. It is frequently stated that the tunneling current is determined by the density of states in the emitter and collector, for the tunneling energy. Although this statement is not really incorrect, it must be used with care in cases where different kinds of states are available. In the present case, both s and d are present at the tunneling energy and contribute to the tunneling current. The

23 November 2026 15:11:42

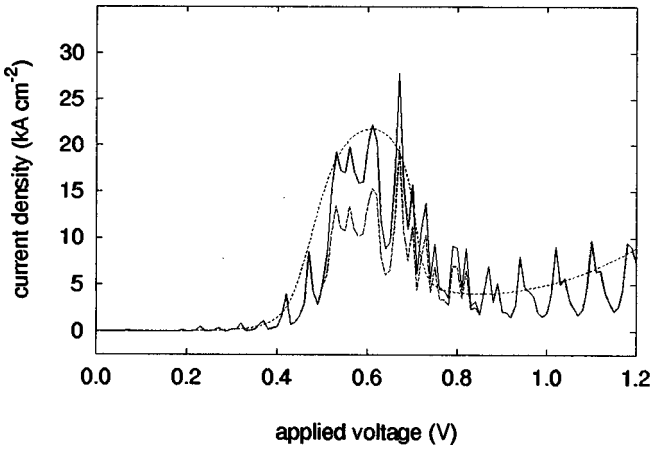


FIG. 4. Current density vs applied voltage at $T=4$ K, for the resonant tunneling spin-valve diode. Solid line: parallel configuration; long-dashed line: antiparallel configuration. The result for the nonmagnetic double barrier diode is also shown for comparison (short-dashed line).

density of *d* states is considerably larger than the density of *s* states. One should not conclude naively from this, however, that the tunneling current due to *d* is considerably larger than the one due to *s* states. Actually, the *d* states are much more localized than the *s* states, which compensates the effect their larger density of states. As a consequence, *s* and *d* states contribute approximately equally to the tunneling current.

V. CONCLUSIONS AND OUTLOOK

The results of calculations presented above suggest that the novel magnetoelectronics device proposed in the present article, the resonant tunneling spin-valve diode, exhibits interesting properties. However a number of questions need to be addressed before the properties of the resonant tunneling spin-valve diode can be assessed reliably.

First, the calculations presented here rely on rather drastic approximations. In particular, the effect of the inelastic scattering and of the spin flip scattering events (due to spin-orbit effect or to magnetic impurities) need to be considered. Qualitatively, inelastic scattering will result in a loss of energy of the electrons during their path between the emitter and the collector; as a consequence, the launching of ballistic electrons will be less efficient than in the simple model considered here. Also, any scattering mechanism resulting in a loss of the spin polarization of the injected electrons will contribute to reduce the spin-valve effect. In particular, one should consider the D'yakonov-Perel' [19] mechanism in the GaAs, and the effect of magnetic impurities in the vicinity of the ferromagnet/semiconductor interfaces. A further problem to consider is the possibility of growing an appropriate structure. As we have already discussed above, although the fabrication of a resonant tunneling spin-valve diode seems beyond the possibility of present technology, very recent progress in the growth of MnGa on GaAs[14,15] and of the regrowth of GaAs on MnGa[13] opens very promising outlooks and suggests that this could become possible in near future.

However, there is a variant of the resonant tunneling spin-valve diode which could be investigated more easily, in order to test the resonant tunneling spin-valve effect. It consists in pumping spin-polarized electrons from the valence band of GaAs, by using circularly polarized light of suitable wavelength. Thus, the ferromagnetic emitter is no longer needed. Then it is no longer necessary to perform the epitaxial growth of GaAs onto a ferromagnetic metal, which is probably the most difficult step in the fabrication. The structure of the sample would then be as follows; (i) a GaAs substrate, (ii) the GaAlAs-GaAs-GaAlAs double barrier, (iii) an undoped GaAs spacer layer (in order to launch hot electrons), (iv) a MnGa layer (collector). Spin-polarized electrons (with their polarization axis along the normal to the layers) are pumped in the GaAs substrate by shining circularly polarized light through the whole structure. This proposed experiment is a variant of the experiment performed by Prins *et al.*,[4] with a *single* tunneling barrier. This experiment seems to be feasible with the presently available fabrication and measurement techniques.

We hope that the present article will contribute to stimulate further experimental and theoretical work in this field.

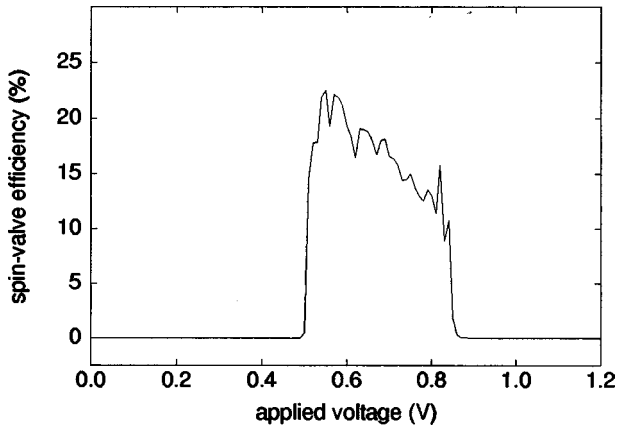


FIG. 5. Spin-valve efficiency vs applied voltage at $T=4$ K, for the resonant tunneling spin-valve diode.

ACKNOWLEDGMENTS

We wish to thank T. Valet for discussions. One of the authors (J.W.) acknowledges financial support from the Laboratoire Central de Recherches of Thomson-CSF.

[1] For an overview, see the special issue of Physics Today on ''Magnetoelectronics,'' edited by G. A. Prinz and K. B. Hathaway, April 1995, pp. 24–63.
[2] Y. Lassailly, H.-J. Drouhin, A. J. van der Sluijs, G. Lampel, and C. Marlière, Phys. Rev. B **50**, 13 054 (1994); H.-J. Drouhin, A. J. van der Sluijs, Y. Lassailly, and G. Lampel, J. Appl. Phys. **79**, 4734 (1996).
[3] J. S. Moodera, L. R. Kinder, T. M. Wong, and R. Meservey, Phys. Rev. Lett. **74**, 3273 (1995).
[4] M. W. J. Prins, H. van Kampen, H. van Leuken, R. A. de Groot, W. van Roy, and J. de Boeck, J. Phys.: Condens. Matter **7**, 9447 (1995).
[5] D. J. Monsma, J. C. Lodder, Th. J. A. Popma, and B. Diény, Phys. Rev. Lett. **74**, 5260 (1995).
[6] J. C. Gröbli, D. Guarisco, S. Frank, and F. Meier, Phys. Rev. B **51**, 2945 (1995).
[7] A. Filipe, H. J. Drouhin, G. Lampel, Y. Lassailly, J. Nagle, J. Peretti, V. I. Safarov, and A. Schuhl, Phys. Rev. Lett. **80**, 2425 (1998).
[8] M. Julière, Phys. Lett. A **54**, 225 (1975).
[9] S. Maekawa and U. Gäfvert, IEEE Trans. Magn. **18**, 707 (1982).
[10] J. C. Slonczewski, Phys. Rev. B **39**, 6995 (1989).

23 November 2026 15:11:42

[11] R. Tsu and L. Esaki, Appl. Phys. Lett. **22**, 562 (1973).
[12] L. L. Chang, L. Esaki, and R. Tsu, Appl. Phys. Lett. **24**, 593 (1974).
[13] W. Van Roy, H. Akinaga, S. Miyinashi, K. Tanaka, and L. H. Kuo, Appl. Phys. Lett. **69**, 711 (1996).
[14] K. M. Krishnan, Appl. Phys. Lett. **61**, 2365 (1992).
[15] M. Tanaka, J. P. Harbison, J. De Boeck, T. Sands, B. Philips, T. L. Cheeks, and V. G. Keramidas, Appl. Phys. Lett. **62**, 1565 (1993).
[16] A. Sakuma, J. Phys. Soc. Jpn. **63**, 9447 (194).
[17] M. Büttiker, Phys. Rev. Lett. **57**, 1761 (1986).
[18] Note that the definition we use here for the spin-valve efficiency differs from the one used by some other authors who take the difference of the resistances for A and AP configurations, normalized by the resistance of the P configuration. Our definition yields smaller numbers (typically by a factor of 2); it has the advantage that the spin-valve efficiency is strictly bounded between -1 and $+1$.
[19] M. I. D'yakonov and V. I. Perel', Sov. Phys. Solid State **13**, 3023 (1972).

23 November 2026 15:11:42