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Electrical spin injection in metallic mesoscopic spin valves

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Chapter 1

Introduction

The electron was discovered in 1897 by J.J. Thomson as an elementary particle embodying a finite amount of charge. The charge property makes a (moving) electron in free space interact with electromagnetic fields via the Coulomb and Lorentz forces and enables metals and semiconductors to carry an electrical current. The observation of the Zeeman effect in 1896 and fine structure anomalies in the line spectra of atoms led to the suggestion in 1925 by Uhlenbeck and Goudsmit [1, 2] that the electron also has a 'spin', an intrinsic angular momentum ($\mathbf{S}$), and directly coupled to it a magnetic moment. The electron spin provides another degree of freedom for the electron to interact with a magnetic field. The most direct experimental proof of the existence and quantized nature of the electron spin ($S_z = \pm\hbar/2$) was obtained by Stern and Gerlach in 1922 [3], being consistent with the earlier line spectra observations and predictions from Dirac's relativistic wave equation formulated in 1928 [4, 5]. The quantization of the spin of a free electron imposes that, whenever it is measured, it can have only two possible values: *spin-up* and *spin-down*.

1.1 Spintronics

Probably the first observation showing that the spin can affect electron transport dates back to 1857 when the anisotropic magnetoresistance (AMR) effect was reported [6], showing that the resistance of a metallic ferromagnet depends on the angle between the magnetization and current direction [7]. This thesis is the result of the ongoing effort to study spin dependent electron transport phenomena and to understand the underlying physical mechanisms from which they result. The justification for this research is both curiosity driven as well as a vision that explicit use of the spin degree of freedom of the electron could result in spin-based electronic applications of new and improved functionality, for example in the area of quantum computation or information (storage) technology [8–11]. This field of research has been labelled with the term "spintronics" and has seen a rapid growth over the past few years.

Since the discovery of the AMR effect, the most well known examples of spin dependent electron transport phenomena are the superconducting tunnelling experiments[12–14], the giant magnetoresistance (GMR) effect in metallic multilayers [15–19] and tunnelling magnetoresistance (TMR) of magnetic tunnel junctions [20–22]. This work lead to the idea of electrical spin injection as a method to create non-equilibrium spin populations in nonmagnetic metals as was proposed in 1976 by Aronov and Pikus [23, 24]. Electrical spin injection was experimentally realized by Johnson and Silsbee in 1985 when they demonstrated spin accumulation and precession in a single crystal aluminium bar up to temperatures of 77 K [25–27]. The work described in this thesis focuses on the electrical injection of spins, the transport and manipulation of the spin information and the detection of the resulting spin polarization in nonmagnetic diffusive metals in the linear response regime. Planar spin valve devices are used to study and determine the spin relaxation length, which is the fundamental length scale involved with spin dependent electron transport in the diffusive regime.

Recent years have also seen a number of other potential interesting spintronic devices. The injection of hot electrons $\approx 1\ eV$ above the Fermi energy E_F in Co/Cu multilayers have shown a significant spin filtering effect, enabling transistor functionality and ballistic electron magnetic microscopy [28–30]. Another interesting development is the ability of spin polarized currents to initiate a (local) magnetization reversal in thin ferromagnetic wires and Co/Cu multi-layer pillars [31–36]. For a recent and more complete overview on the field of spintronics, including the developments of the semiconductor spintronics area, the reader is referred to Refs. [8, 10, 37].

1.2 This thesis

In the early stages of this PhD project research efforts were directed towards spin accumulation and spin polarized Andreev reflection in ferromagnetic metal-superconductor (F/S) systems [38]. However, drawing conclusions from these initial experiments proved to be difficult. At the same time experimental efforts in Groningen, undertaken by Andrei Filip [39], had failed to realize the electrical injection of spins from a ferromagnetic metal into a 2-dimensional semiconductor via transparent contacts.

Therefore the focus shifted towards the realization of electrical spin injection in nonmagnetic diffusive metals and an effort was made to reproduce results reported in 1993 by Johnson [40–42]. These efforts have resulted in a clear and unambiguous experimental demonstration of spin injection in metallic systems at room temperature and are presented in the successive chapters of this thesis.

In *chapter 2* the basic model for spin transport in the diffusive transport regime is given, involving the electrical injection of spin currents into non-magnetic metals, the transfer and manipulation (precession) of the spin information, and the electrical detection the resulting spin polarization. This model is applied to our multi-terminal device geometry. A multi-terminal resistor model of spin injection and detection is presented in order to elucidate the principles behind the reduction of the polarization of the spin current at a transparent F/N interface, also referred to as "conductivity mismatch" [43].

Chapter 3 describes the sample fabrication processes to make the spin injection devices and discusses the used sample geometries and measurement techniques.

Chapter 4 describes the behavior of magnetization reversal in ferromagnetic strips. Control of the magnetization direction of a ferromagnetic strip is an important prerequisite to be able to perform spin injection experiments. It is shown that by measuring the AMR resistance of submicron ferromagnetic strips the magnetization reversal can be monitored under application of an external magnetic field. The magnitude of the switching field is found to depend on the width of the submicron strips.

In *chapter 5* the spin injection and spin accumulation measurements are presented for ferromagnetic metal-nonmagnetic metal-ferromagnetic metal (F/N/F) spin valves with transparent contacts. Clear spin accumulation signals are obtained in a 'non-local' measurement geometry, whereas these signals can be completely overwhelmed by spurious magnetoresistance effects in a 'conventional' measurement geometry. Permalloy $Ni_{80}Fe_{20}$ (Py), cobalt (Co) and nickel (Ni) are used as ferromagnetic injector and detector electrodes, whereas copper (Cu) and aluminum (Al) are used as nonmagnetic metal. The obtained results (spin relaxation lengths and spin polarization) are analyzed using the model for spin transport in the diffusive regime and are compared to theoretical calculations and results obtained from GMR, CESR, anti-weak localization and superconducting tunneling experiments.

Chapter 6 reports on spin injection experiments from a ferromagnetic metal into a nonmagnetic metal strip via a tunnel barrier contact. The injection via a tunnel barrier leads to an increased polarization of the current in the nonmagnetic metal and hence an increased spin accumulation signal. It is shown that the spin direction can be controlled by inducing a coherent spin precession due to an applied perpendicular magnetic field. By inducing an average precession angle of 180 degrees, the sign of the spin signal can be reversed.

In *chapter 7*, the last chapter, it is shown that the spin reversal associated with Andreev reflection generates an excess spin density close to the F/S interface, which leads to a spin contact resistance.

References

[1] G. Uhlenbeck and S. Goudsmit, Naturwissenschaften **Heft 47**, 264 (1925).

[2] G. Uhlenbeck and S. Goudsmit, Nature **117**, 264 (1926).

[3] M. Karplus and R. N. Porter, *Atoms and Molecules* (The Benjamin/Cummings Publishing Company, 1970), ISBN 0-8053-5218-X.

[4] P. A. M. Dirac, *The Principles of Quantum Mechanics* (Oxford U. P., 1958).

[5] H. C. Ohanian, Am. J. Phys. **54**, 500 (1986).

[6] W. Thomsom, Proc. R. Soc. **8**, 546 (1857).

[7] T. G. S. M. Rijks, R. Coehoorn, M. M. de Jong, and W. J. M. de Jonge, Phys. Rev. B **51**, 283 (1995).

[8] D. D. Awschalom, D. Loss, and N. Samarth, *Semiconductor Spintronics and Quantum Computation* (Springer Verlag, Berlin, 2002).

[9] G. A. Prinz, Science **282**, 1660 (1998).

[10] S. A. Wolf, D. D. Awschalom, R. A. Buhrmann, J. M. Daughton, S. von Molnár, M. L. Roukes, A. Y. Chtchelkanova, and D. M. Treger, Science **294**, 1488 (2001).

[11] I. *Ž*utić, Journal of Superconductivity **15**, 5 (2002).

[12] R. Meservey, P. M. Tedrow, and P. Fulde, Phys. Rev. Lett. **25**, 1270 (1970).

[13] R. Meservey and P. M. Tedrow, Physics Reports **238**, 173 (1994).

[14] P. Fulde, Adv. Phys. **22**, 667 (1973).

[15] M. N. Baibich, J. M. Broto, A. Fert, F. N. V. Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J. Chazelas, Phys. Rev. Lett. **61**, 2472 (1988).

[16] G. Binash, P. Gr*ü*nberg, F. Saurenbach, and W. Zinn, Phys. Rev. B **39**, 4828 (1989).

[17] M. A. M. Gijs and G. E. W. Bauer, Advances in Physics **46**, 285 (1997).

[18] J.-P. Ansermet, J. Phys.:Condens. Matter **10**, 6027 (1998).

[19] J. Bass and W. P. Pratt Jr., J. Mag. Magn. Mater. **200**, 274 (1999).

[20] M. Julliere, Physics Letters **54A**, 225 (1975).

[21] J. S. Moodera, L. R. Kinder, T. M. Wong, and R. Meservey, Phys. Rev. Lett. **74**, 3273 (1995).

[22] P. LeClair, Ph.D. thesis, Eindhoven University of Technology (2002), ISBN 90-386-1989-8.

[23] A. G. Aronov and G. E. Pikus, Fiz. Tech. Poluprovdn. **10**, 1177 (1976).

[24] E. I. Rashba, Journal of Superconductivity **15**, 13 (2002).

[25] M. Johnson and R. H. Silsbee, Phys. Rev. Lett. **55**, 1790 (1985).

[26] M. Johnson and R. H. Silsbee, Phys. Rev. B **37**, 5312 (1988).

[27] M. Johnson and R. H. Silsbee, Phys. Rev. B **37**, 5326 (1988).

[28] D. J. Monsma, J. C. Lodder, T. J. A. Popma, and D. Dieny, Phys. Rev. Lett. **74**, 5260 (1995).

[29] D. J. Monsma, R. Vlutters, and J. C. Lodder, Science **281**, 407 (1998).

[30] W. H. Rippard and R. A. Buhrmann, Phys. Rev. Lett. **84**, 971 (2000).

[31] J. C. Slonczewski, J. Mag. Magn. Mater. **159**, L1 (1996).

[32] J. Z. Sun, Phys. Rev. B. **62**, 570 (2000).

[33] J. E. Wegrowe, D. Kelly, Y. Jaccard, P. Guittienne, and J.-P. Ansermet, Europhys. Lett. **45**, 626 (1999).

[34] E. B. Myers, D. C. Ralph, J. A. Katine, R. N. Louie, and R. Buhrmann, Science **285**, 867 (1999).

[35] J. A. Katine, F. J. Albert, R. A. Buhrman, E. B. Myers, and D. C. Ralph, Phys. Rev. Lett. **84**, 3149 (2000).

[36] J. Grollier, V. Cros, A. Hamzic, J. M. George, H. Jaffrès, A. Fert, G. Faini, J. B. Youssef, and H. Legall, Appl. Phys. Lett. **78**, 3663 (2001).

[37] R. Coehoorn, *Lecture notes 'New magnetoelectronic materials and devices'* (unpublished, 1999), 3 parts.

[38] F. J. Jedema, B. J. van Wees, B. H. Hoving, A. T. Filip, and T. M. Klapwijk, Phys. Rev. B **60**, 16549 (1999).

[39] A. T. Filip, Ph.D. thesis, University of Groningen (2002).

[40] M. Johnson, Phys. Rev. Lett. **70**, 2142 (1993).

[41] M. Johnson, Science **260**, 320 (1993).

[42] M. Johnson, J. Appl. Phys. **75**, 6714 (1994).

[43] G. Schmidt, D. Ferrand, L. W. Molenkamp, A. T. Filip, and B. J. van Wees, Phys. Rev. B **62**, R4790 (2000).