Journal of Magnetism and Magnetic Materials 356 (2014) 52–67

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Spin rotation after a spin-independent scattering. Spin properties of an electron gas in a solid

V. Zayets

Spintronic Research Center, National Institute of Advanced Industrial Science and Technology (AIST), Umezono 1-1-1, Tsukuba, Ibaraki, Japan

ARTICLE INFO

Article history:
Received 6 August 2013
Available online 28 December 2013

Keywords:
Spintronics
Ferromagnetism
Paramagnetism
Spin transfer torque

ABSTRACT

It is shown that spin direction of an electron may not be conserved after a spin-independent scattering. The spin rotations occur due to a quantum-mechanical fact that when a quantum state is occupied by two electrons of opposite spins, the total spin of the state is zero and the spin direction of each electron cannot be determined. It is shown that it is possible to divide all conduction electrons into two group distinguished by their time-reversal symmetry. In the first group the electron spins are all directed in one direction. In the second group there are electrons of all spin directions. The number of electrons in each group is conserved after a spin-independent scattering. This makes it convenient to use these groups for the description of the magnetic properties of conduction electrons. The energy distribution of spins, the Pauli paramagnetism and the spin distribution in the ferromagnetic metals are described within the presented model. The effects of spin torque and spin-torque current are described. The origin of spin-transfer torque is explained within the presented model.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

Spintronics is a new type of electronics that exploits the spin degree of freedom of an electron in addition to its charge. There are many expectations that in the near future, spintronics devices will be competitive with modern Si electronics devices. It is expected that spintronics devices will be faster, compacter and more energy-saving.

In the last decade there have been significant advances in the field of spintronics. New effects, new functions and new devices have been explored. Spin polarized current was efficiently injected from a ferromagnetic metal into a non-magnetic metal and a semiconductor [1–5], the method of electrical detection of spin current was developed [6,7], the Spin Hall effect [8] and the inverse Spin Hall effect [9] were experimentally measured, the operation of a spin transistor [10] and tunnel spin transistor [11–13] were experimentally demonstrated and the tunnel junction with magneto-resistance over 100% was developed [14,15].

However, it is still difficult for spintronics devices to compete with modern Si devices. Optimization of spintronics devices is important in order to achieve the performance required for commercialization. The modeling of spin transport and the understanding of spin properties of conduction electrons in metals and semiconductors are a key for such optimization.

The classical model used for the description of the magnetic properties of conduction electrons in metals is the model of spin-up/spin-down bands (the Pauli model for non-magnetic metals, the Zener model, the Stoner model and the s–d model for ferromagnetic metals) [16,20]. In this model it is assumed that all conduction electrons in a solid occupy two bands, which are named spin-up and spin-down bands. The electrons of only one spin direction occupy each band. Based on the fact that the probability of a spin-flip scattering is low, it was assumed that the electrons are spending a long time in each band and the exchange of electrons between the bands is rare. Using this key assumption the classical model describes the transport and magnetic properties of conduction electrons independently for each spin band. It includes only a weak interaction between the electrons of the spin-up and spin-down bands. For example, in the classical Pauli's description of paramagnetism in non-magnetic metals [16], it is assumed that electrons in one band have spin parallel and electrons in another band have spin anti-parallel to the direction of the magnetic field. Without a magnetic field there are equal number of electrons in each band and the total magnetic moment of the electron gas is zero. In a magnetic field the electrons with spin parallel to the magnetic field (spin-up) have lower energy compared to the case with no magnetic field, and electrons with spin anti parallel to the magnetic field have higher energy. In equilibrium the Fermi energy is the same for both bands. This means that in a magnetic field some electrons had spin-flipped from the spin-down band to the spin-up band and so the number of electrons in the spin-up band became larger than in

E-mail address: v.zayets@aist.go.jp
URL: http://staff.aist.go.jp/v.zayets/

0304-8853/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jmmm.2013.12.046

the spin-down band. Because of this difference, the magnetic moment of the electron gas became non-zero.

Since the probability of a spin-flip scattering is low, it has been assumed that the spin-flip from one spin band to another takes a relatively long time. This makes it possible to define the separate Fermi energies for the spin-up and spin-down bands in the classical model. The energy distribution in each spin band is described by the Fermi–Dirac distribution with different Fermi energies. The Fermi energies of the spin-up and spin-down bands relax into a single Fermi energy within a certain time, which is called the spin relaxation time.

In Section 2 it will be shown that even in the case of a spin-independent scattering the spin direction of a conduction electron is not conserved and its spin may rotate. This feature is due to the quantum nature of an electron. The scatterings, after which spin direction is not conserved, are rather frequent. If at some moment in time the electrons only have two opposite directions of spin, within a very short time (~10–100 ps) the spin-independent scatterings will mix up all electrons and there will be electrons with all possible spin directions. This fact questions the validity of the classical model of spin-up/spin-down bands.

In Section 3 it will be shown that it is possible to divide all conduction electrons into two groups, which are defined as the time-inverse symmetrical (TIS) assembly and the time-inverse asymmetrical (TIA) assembly. In the TIS assembly the spin can have any possible direction with equal probability. In the TIA assembly all electron spins are in one direction. The TIA assembly describes the electrons of a spin accumulation. Even though the exchange of electrons between assemblies is frequent, the spin-independent scatterings do not change the number of electrons in each assembly.

In Section 4, the energy distribution of electrons in the TIA and TIS assemblies is described. Since in the classical model of spin-up/spin-down bands only a weak interaction between electrons of different spin bands is assumed, the model allows the energy distribution of the total number of electrons to be different from the Fermi–Dirac distribution. It only requires that the energy distribution of the electrons in each band follows the Fermi–Dirac distribution. The proposed model gives a different energy distribution than the classical model. Since spin-independent scatterings intermix all electrons, including the electrons of different assemblies, the distribution of the total number of electrons should be described by a single Fermi–Dirac distribution even in the case of a spin accumulation. Using this fact and the properties of spin-scatterings, the energy distribution of electrons in each assembly is described in Section 4.

The presented model of TIA and TIS assemblies describes the magnetic properties of an electron gas in terms of conversion of electrons between the assemblies. For example, in equilibrium all conduction electrons of a non-magnetic metal are in the TIS assembly. When there is a spin accumulation in the metal, it means that there are some electrons in the TIA assembly. The relaxation of the spin accumulation corresponds to a conversion of electrons from the TIA assembly into the TIS assembly.

In Section 5, it is shown that in the presence of the magnetic field the electrons of the TIS assembly are converted into the TIA assembly. Therefore, a magnetic field causes a spin accumulation in an electron gas. The number of electrons of the spin accumulation is determined by the condition, that the conversion rate of electrons from the TIS assembly into the TIA assembly induced by the magnetic field should be balanced by the reverse conversion due to spin relaxation. The magnetization of the TIA assembly is non-zero, therefore the applied magnetic field induces magnetization in the electron gas. This effect is called the Pauli paramagnetism of an electron gas and it is described in Section 6.

In Section 7 the spin properties of an electron gas in a ferromagnetic metal are described. In equilibrium the conduction electrons in a ferromagnetic metal are in both TIA and TIS assemblies. This means that in equilibrium there is a spin accumulation in an electron gas in a ferromagnetic metal. The number of electrons in each assembly is determined by the condition that the conversion rate of electrons from the TIS into the TIA assembly, induced by the exchange interaction between local d-electrons and the delocalized conduction s-electrons, is balanced by the reverse conversion due to the spin relaxation.

In a metal one TIS and one TIA assembly can coexist for a relatively long time, while two TIA assemblies will quickly combine. It is possible that at some moment in time in a metal there are two or more TIA assemblies of different spin directions. However, within a short time (~10–100 ps) the assemblies combine into one TIA assembly and some electrons are converted into the TIS assembly. The temporal evolution of the interaction of two TIA assemblies is described in Section 8. Also, this section describes the torque acting on spin-polarized conduction electrons, when the electrons of another spin direction are injected into the material. This torque is defined as the spin-torque.

Section 9 describes an electron current flowing between regions of different spin directions of spin accumulation. This current is defined as the spin-torque current. In contrast to the conventional spin current, which is related to the diffusion of the spin accumulation, the spin-torque current is related to the diffusion of the spin direction. The spin-torque current tries to align the spin direction of a spin accumulation, so that it would be the same over the entire sample.

In Section 10 the physical origin of the spin-transfer torque is described. The spin transfer torque is the torque acting on the magnetization of a ferromagnetic electrode of a magnetic tunnel junction (MTJ), when an electrical current flows through the MTJ. It was shown that the spin-transfer torque occurs because a spin-torque current flows between the electrodes of the MTJ. Because of the spin-torque, the spin direction of the delocalized conduction s-electrons rotates out from the spin direction of the local d-electrons. The exchange interaction between the s- and d-electrons forces their spin to be aligned. This force causes a torque on the d-electrons, which is the spin-transfer torque.

2. Spin rotation after a spin independent scattering

By spin-independent scattering we define a scattering, which does not depend on the electron spin. That means there is no spin operator in the Hamiltonian describing the scattering event. In the following we will show that even in this case the electron spin may not be conserved during scattering because of the quantum nature of an electron.

At first, we describe an example of spin rotation, which an electron may experience in a metal after two consecutive elastic spin-independent scatterings. The spin properties of an electron gas in a metal depend on its density of states near its Fermi energy. Each state is distinguished by a direction of its wavevector k in the Brillion zone, its energy E and its spacial symmetry. Due to the Pauli excursion principle, each state can be occupied maximum by two electrons of opposite spin. We define a state as a "full", "empty" or "spin" state, as the state is filled by no electrons or one electron or two electrons of opposite spin, respectively (see Fig. 1(a)). The spin of "full" and "empty" states is zero and the spin of a "spin" state is 1/2. The energy distribution of electrons in the metal is the Fermi–Dirac distribution. The states of higher energy (at least 5 kT above the Fermi energy), are not occupied by electrons and almost all of them are "empty" states with no spin (see Fig. 1(b)). Almost all states of lower energy (at least 5 kT below the Fermi energy) are occupied by two electrons and almost all of them are the "full" states with no spin. A state, energy of which is near the Fermi energy, may be filled by one electron and have spin 1/2. Also, there is a probability that

Download English Version:

https://daneshyari.com/en/article/1799894

Download Persian Version:

https://daneshyari.com/article/1799894

Daneshyari.com