Physica B 515 (2017) 43–50

Contents lists available at ScienceDirect

Physica B

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

An alternative to the spin-coupled interface resistance for describing heat generation

Xiao-Xue Zhang, Yao-Hui Zhu*, Pei-Song He, Bao-He Li

Physics Department, Beijing Technology and Business University, Beijing 100048, China

ARTICLE INFO

Keywords:
Spin valve
Heat generation
Spin accumulation
Joule heating
Spin-coupled interface resistance

ABSTRACT

The spin-coupled interface (SI) resistance plays a crucial role in the interpretation of the giant magnetoresistance with current perpendicular to the plane. Recently, a theoretical work showed that its Joule heat also equals the total spin-dependent heat generation in a conceptual spin valve. Here we reexamine this conclusion in a practical spin valve with a finite nonmagnetic spacer layer and spin-selective interfaces. It turns out that this conclusion does not hold except for some special segments. The SI resistance has a more serious limitation: it may be negative in certain situation. In-depth analysis shows that its "Joule heating" should be interpreted actually as the extra energy supplied only in the ferromagnetic layers and at the interfaces. This extra energy is stored in the chemical-potential splitting due to spin accumulation and only part of it converts into heat locally. The rest flows to other layers, especially the nonmagnetic layer, in which the inflowing energy compensates exactly for the spin-dependent heat generation. In essence, this kind of energy transport makes the SI resistance unsuitable for a simple description of the heat generation, and thus we propose a new effective resistance as an alternative to it.

1. Introduction

Heat generation is a serious issue even for spintronic devices. [1–3] For example, large current is usually required for the operation of a spin-transfer-torque magnetic random-access memory. [4] The reduction of the working current and the associated heating is still a challenging problem. Moreover, heating in spintronic devices leads to temperature gradient, which may inversely have remarkable influence on the spin transport via the spin-dependent Seebeck effect [5].

Recent theoretical investigations have shown that there is still energy dissipation even if a pure spin current is present. [6–10] Meanwhile, experimental studies have also demonstrated various spin-dependent heating effects. [11–18] In spintronic devices, the spin-dependent processes produce extra heat in comparison to the conventional electronic devices. [6] Using a macroscopic approach, Ref. [6] also showed that the extra heat is equal to the Joule heat of the spin-coupled interface (SI) resistance in a conceptual spin valve. The SI resistance plays a crucial role in the interpretation of the giant magnetoresistance with current perpendicular to the plane (CPP). [19–21] However, Ref. [6] neglected the nonmagnetic (NM) spacer layer and the interface resistance of the spin valve. This raises doubt on the validity of their result in a practical spin valve with a finite NM layer. The following qualitative analysis shows the limitation of the SI resistance when it is used to describe heat generation. The SI resistance is zero in the NM layer owing to the absence of extra field. [21,22] However, the NM layer has extra heat generation due to spin transport. Thus the "Joule heat" of the SI resistance is unequal to the spin-dependent heat generation in the NM layer.

Motivated by the preliminary analysis above, we propose an alternative to the SI resistance in this work. First we examine whether the spin-dependent heat generation is equal to the "Joule heat" of the SI resistance in an arbitrary segment of a practical spin valve, which includes a finite NM layer and spin-selective interfaces. As we will prove later, they are not equal except for some special segments. The SI resistance has a more serious limitation: it may even be negative in some cases. Then we reveal the real meaning of the "Joule heat" of the SI resistance and analyze the reasons for its limitations. Finally, we propose a new effective resistance based on the spin-dependent heat generation as the alternative to the SI resistance.

This paper is organized as follows. In Section 2, we derive the basic equations for the spin-dependent heat generation and energy transport. We also show the limitation of the SI resistance. In Section 3, the basic equations are applied to a spin valve. We discuss the real meaning of the SI resistance and propose the effective resistance as an alternative. Our main results are summarized in Section 4.

* Corresponding author.
E-mail address: yaohuizhu@gmail.com (Y.-H. Zhu).

http://dx.doi.org/10.1016/j.physb.2017.04.004
Received 17 January 2017; Received in revised form 20 March 2017; Accepted 4 April 2017
Available online 06 April 2017

2. Basic equations

2.1. Separating the spin-dependent heat from the normal heat

We are concerned with the heat generation in a CPP spin valve driven only by a constant current of density J flowing in the positive z-direction. [21] In the stationary state, the heat generation rate can be calculated using a macroscopic equation like Eq. (6) in Ref. [6]

$$\sigma_{\text{heat}} = \frac{J_+}{e}\frac{\partial\bar{\mu}_+}{\partial z} + \frac{J_-}{e}\frac{\partial\bar{\mu}_-}{\partial z} + \frac{4(\Delta\mu)^2}{e^2}G_{\text{mix}} \tag{1}$$

where we use σ_{heat} to denote the heat-generation rate following Ref. [23]. This kind of equation can be derived by using the Boltzmann equation [6] as well as nonequilibrium thermodynamics [23] in the linear regime. In Eq. (1), J_+ (J_-) and $\bar{\mu}_+(\bar{\mu}_-)$ are the current density and the electrochemical potential in the spin-up (down) channel, respectively (see Appendix A). The electron-number current is given by $-J_\pm/e$, where $-e$ is the charge of an electron. Moreover, $\Delta\mu = (\bar{\mu}_+ - \bar{\mu}_-)/2$ describes the spin accumulation, and G_{mix} defined by Eq. (5) of Ref. [6] stands for the associated spin-flip rate. The first two terms of Eq. (1) can be interpreted as the rate of decrease in the (electrochemical) potential-energy current or the heat generation, in each spin channel. [24] The last term means the heat generation due to the spin-flip scattering [6].

Eq. (1) can be rewritten in a more convenient form. The heat-generation rates of the two spin channels are unequal in ferromagnetic (FM) layers and at spin-selective interfaces. If the two spin channels cannot exchange heat effectively with each other or other heat reservoir, they may have different temperatures. [25] However, this is beyond the scope of the present work and we will neglect this effect by assuming that the two spin channels can exchange heat effectively (the thermalized regime [25]). Then it is more meaningful to write Eq. (1) in terms of the total current $J = J_+ + J_-$ and the spin current $J_{\text{spin}} = J_+ - J_-$ like Eq. (12c) of Ref. [6]

$$\sigma_{\text{heat}} = \frac{J}{e}\frac{\partial\bar{\mu}}{\partial z} + \frac{J_{\text{spin}}}{e}\frac{\partial\Delta\mu}{\partial z} + \frac{\partial J_{\text{spin}}}{\partial z}\frac{\Delta\mu}{e} \tag{2}$$

where $\bar{\mu} = (\bar{\mu}_+ + \bar{\mu}_-)/2$ is the average electrochemical potential. One can further rewrite Eq. (2) as

$$\sigma_{\text{heat}} = JF + \frac{1}{e}\frac{\partial}{\partial z}(J_{\text{spin}}\Delta\mu) \tag{3}$$

by defining the effective field [21]

$$F = \frac{1}{e}\frac{\partial\bar{\mu}}{\partial z} \tag{4}$$

The heat generation due to interface resistance is only caused by the spin-conserving scattering since the spin-flip scattering is neglected (Appendix B). Then it can be calculated by simply summing the two spin channels [6]

$$\Sigma^{\text{C}}_{\text{heat}} = \frac{J_+(z_{\text{C}})}{e}\delta\bar{\mu}_+ + \frac{J_-(z_{\text{C}})}{e}\delta\bar{\mu}_- \tag{5}$$

where $\delta\bar{\mu}_\pm = \bar{\mu}_\pm(z_{\text{C}}^+) - \bar{\mu}_\pm(z_{\text{C}}^-)$ is the change in electrochemical potential across the (infinitesimally thin) interface at z_{C} for spin " ± ". One can also rewrite Eq. (5) in a more convenient form

$$\Sigma^{\text{C}}_{\text{heat}} = \frac{J}{e}[\bar{\mu}(z_{\text{C}}^+) - \bar{\mu}(z_{\text{C}}^-)] + \frac{J_{\text{spin}}(z_{\text{C}})}{e}[\Delta\mu(z_{\text{C}}^+) - \Delta\mu(z_{\text{C}}^-)] \tag{6}$$

where we have used Eq. (B.4).

Up to now, we have outlined some results of Ref. [6] as a basis for our study. Since we are mainly interested in the spin-dependent heat generation, we need to separate it from the normal Joule heat in Eqs. (3) and (6). The normal Joule heat exists no matter whether spin accumulation is present or not, whereas the spin-dependent heat depends on the spin accumulation and the spin current.

In NM layers, the field F is just the unperturbed constant field $E_0^{\text{N}} = \rho_{\text{N}}^* J$ according to Appendix A or Ref. [21]. Then the normal Joule heat is just the first term of σ_{heat} in Eq. (3)

$$\sigma_{\text{heat}}^{\text{norm,N}} = J^2\rho_{\text{N}}^* \tag{7}$$

The second term of σ_{heat} is the spin-dependent heat generation

$$\sigma_{\text{heat}}^{\text{spin,N}} = \frac{1}{e}\frac{\partial}{\partial z}(J_{\text{spin}}\Delta\mu) \tag{8}$$

which relies on both the spin accumulation and the spin current.

In FM layers, by summing the " ± " versions of Eq. (A.2), we can write the field F as

$$F = E_0^{\text{F}} \pm \frac{\beta}{e}\frac{\partial\Delta\mu}{\partial z} \tag{9}$$

where the sign "+" ("-") corresponds to the "up" ("down") magnetization. The bulk spin asymmetry coefficient β is defined in Appendix A. Note that $\Delta\mu$ also depends on the magnetization direction. In Eq. (9), the field F of the FM layer has been divided into the constant term $E_0^{\text{F}} = (1-\beta^2)\rho_{\text{F}}^* J$ and the exponential term, which depends on the gradient of spin accumulation. Thus the first term of σ_{heat} in Eq. (3) is not entirely the normal Joule heat and needs to be rewritten. To this end, we subtract the " ± " versions of Eq. (A.2), and write J_{spin} as

$$J_{\text{spin}} = J_{\text{spin}}^{\text{bulk}} + J_{\text{spin}}^{\text{exp}} \tag{10}$$

where the bulk and exponential terms are defined as

$$J_{\text{spin}}^{\text{bulk}} = \mp\beta J \tag{11}$$

$$J_{\text{spin}}^{\text{exp}} = \frac{1}{e\rho_{\text{F}}^*}\frac{\partial\Delta\mu}{\partial z} \tag{12}$$

The sign "-" ("+") corresponds to the "up" ("down") magnetization. Substituting Eqs. (9) and (10) into Eq. (3), we find

$$\sigma_{\text{heat}}^{\text{F}} = \sigma_{\text{heat}}^{\text{norm,F}} + \sigma_{\text{heat}}^{\text{spin,F}} \tag{13}$$

where we have divided the heat generation into

$$\sigma_{\text{heat}}^{\text{norm,F}} = JE_0^{\text{F}} = J^2(1-\beta^2)\rho_{\text{F}}^* \tag{14}$$

$$\sigma_{\text{heat}}^{\text{spin,F}} = \frac{1}{e}\frac{\partial}{\partial z}(J_{\text{spin}}^{\text{exp}}\Delta\mu) \tag{15}$$

We can identify $\sigma_{\text{heat}}^{\text{norm,F}}$ and $\sigma_{\text{heat}}^{\text{spin,F}}$ as the normal Joule heat and the spin-dependent heat, respectively. [6] In fact, Eq. (13) has the same form in the NM layer, where β is zero and J_{spin} has only exponential terms, $J_{\text{spin}} = J_{\text{spin}}^{\text{exp}}$ (Appendix A). This allows us to combine the equations for the FM and NM layers into one common equation

$$\sigma_{\text{heat}} = JE_0 + \frac{1}{e}\frac{\partial}{\partial z}(J_{\text{spin}}^{\text{exp}}\Delta\mu) \tag{16}$$

which yields the same value as Eq. (3) but has more transparent physical interpretation.

At interfaces, the sum of the " ± " versions of Eq. (B.2) yields

$$\bar{\mu}(z_{\text{C}}^+) - \bar{\mu}(z_{\text{C}}^-) = e(1-\gamma^2)r_{\text{b}}^* J \pm e\gamma r_{\text{b}}^* J_{\text{spin}}^{\text{sa}}(z_{\text{C}}) \tag{17}$$

where $J_{\text{spin}}^{\text{sa}}(z_{\text{C}})$ is defined by

$$J_{\text{spin}}(z_{\text{C}}) = \mp\gamma J + J_{\text{spin}}^{\text{sa}}(z_{\text{C}}) \tag{18}$$

The upper (lower) signs of " ± " and "∓" in Eqs. (17) and (18) correspond to the configuration where the spin-up channel is the minority (majority) one. The first term of $J_{\text{spin}}(z_{\text{C}})$ in Eq. (18), $\mp\gamma J$, stands for the normal spin current without spin accumulation, whereas $J_{\text{spin}}^{\text{sa}}(z_{\text{C}})$ means the spin current resulting from the change of spin accumulation across the interface (Appendix B). Therefore, the first term of $\Sigma_{\text{heat}}^{\text{C}}$ in Eq. (6) is not entirely the normal Joule heat and also needs to be rewritten. To this end, we subtract the " ± " versions of Eq. (B.2) and get