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The critical role of the barrier thickness in spin filter tunneling

Casey W. Miller

Department of Physics, Center for Integrated Functional Materials, University of South Florida, 4202 East Fowler Avenue, Tampa, FL 33620, USA

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ABSTRACT

Spin filter tunneling is considered in the low bias limit as functions of the temperature dependent barrier parameters. We demonstrate the generation of spin polarized tunneling currents in relation to the magnetic order parameter, and discuss how an interfacially suppressed order parameter leads to a temperature dependent tunneling current asymmetry. Analyzing the full parameter space reveals that the often overlooked barrier thickness plays a critical role in spin filter tunneling. With all else fixed, thicker barriers yield higher spin polarization, and allow a given polarization to be achieved at higher temperatures. This insight may open the door for new materials to serve as spin filter barriers.

Spin filter tunneling is one route to producing highly spin polarized currents, which are critical for the advancement of present and future spintronics applications [1]. This phenomenon relies on a tunnel barrier material whose conduction band is spin split, which leads to different tunneling probabilities for spin-up and spin-down electrons. As it is only the barrier that dictates the net tunneling spin polarization, the most unique attribute of spin filter tunneling is its ability to generate spin polarized currents using entirely non-magnetic electrodes, metallic or semiconducting. In fact, the first demonstrations of spin filter tunneling involved tunneling from normal metals through magnetic barriers into superconductors [2], where the tunneling spin polarization was quantified using the Meservey and Tedrow technique [3,4]. Although it has been twenty years since this pioneering work, only a handful of materials have been conclusively implemented as spin filter barriers. These include EuS [2], EuSe [5], EuO [6], $BiMnO_3$ [7], $La_{0.1}Bi_{0.9}MnO_3$ [8], $NiFe_2O_4$ [9], and $CoFe_2O_4$ [10].

Regardless of the specific material, most arguments regarding the utility of spin filter tunneling appeal to the general notion that distinct barrier heights for each spin species are both necessary and sufficient for the generation of a highly polarized tunnel current, even for very small height differences. While any height difference will lead to some spin polarization, the specific requirements to achieve a desired level of polarization have not been thoroughly quantified in the literature. Furthermore, the role of the barrier thickness is neglected more often than not. This article aims to illuminate the functionality of spin filter tunneling from the perspective of the three fundamental barrier parameters: height, width, and exchange splitting. We survey the entire parameter space, and model the influence of the temperature dependent magnetic ordering of the barrier on measurable quantities. We find that the temperature at which a given degree of spin polarization is achieved increases toward the ordering temperature with barrier thickness. Additionally, we find that the symmetry of the tunneling current can completely invert at low temperatures if the order parameter of the barrier differs at the two barrier-electrode interfaces (e.g., by local strains, disorder, or stoichiometry gradients). Finally, we demonstrate that the tunneling spin polarization is enhanced for thicker barriers, with all else constant. This is particularly notable in that it suggests the possible application as spin filter barriers of magnetic insulators whose magnetic properties may be suppressed in the traditionally used thicknesses range for tunneling (10−20 Å).

There are two fundamental parallel conduction channels in spin filter junctions, one for each spin. In the simplest case, the net current density is the average of the spin-up and spin-down current densities: $j_{net} = (j_\uparrow + j_\downarrow)/2$. Spin-up and spin-down electrons see different barrier heights below the ordering temperature of the magnetic insulator. The spin channel with the lower barrier height has a larger transmission coefficient, which implies that the current entering the collector electrode is spin polarized. This polarization is typically expressed as $P = (j_\uparrow - j_\downarrow)/(j_\uparrow + j_\downarrow)$, where the spin-dependent current densities are calculated using spin and temperature dependent barrier heights. We calculate the tunneling current density for each spin channel using an expansion of the model of Brinkman et al. [11] as

$$j = G_o\left(V + \frac{s\sqrt{2m/q}\Delta\phi}{24\hbar(\bar{\phi})^{3/2}}V^2 + \frac{s^2 mq}{12\hbar^2\bar{\phi}}V^3\right), \quad (1)$$

where the leading term is the tunneling conductance at zero bias

$$G_o = \left(\frac{q}{\hbar}\right)^2\left(\frac{2mq\bar{\phi}(0V)}{s^2}\right)^{1/2}\exp\left(-\frac{2s}{\hbar}\sqrt{2mq\bar{\phi}(0V)}\right).$$

E-mail address: cmilleratphysics@gmail.com

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Here, s (in m) is the barrier thickness; $\bar{\phi}$ (in V) is the position, bias, and temperature dependent average barrier height; $\Delta\phi$ is the interfacial barrier height difference at zero bias (in V); q (in Coulombs) is the elementary charge; and m (in kg) is the electron mass. This expansion is only valid for biases small relative to the barrier height; we previously determined "small" to mean biases less than roughly one third of the barrier height [12]. Above this, higher order terms take over as the system tends toward the Fowler–Nordheim tunneling regime. Assuming that the exchange splitting is proportional to the magnetization allows us to define the spin dependent barrier heights above and below the magnetic ordering temperature, T_c:

$$T \leqslant T_c : \begin{cases} \phi_\uparrow = \phi_o - \Delta E_{ex}\sqrt{1 - T/T_c}, \\ \phi_\downarrow = \phi_o + \Delta E_{ex}\sqrt{1 - T/T_c}, \end{cases}$$
$$T > T_c : \phi_\uparrow = \phi_\downarrow = \phi_o. \tag{2}$$

This temperature dependence is shown in the inset of Fig. 1. It would be straightforward to modify these temperature dependences for a specific material system (particularly with magnetization vs temperature data). We chose the present representation to capture the general temperature dependence near the critical temperature for local moments. Putting this all together, Fig. 1 shows that we find that the zero-bias resistance-area product ($\mathrm{RA} = 1/G_o$) drops dramatically as the temperature falls below T_c, which is a direct consequence of the spin-up barrier height reducing with decreasing temperature, as per Eq. (2). Further, the polarization increases with decreasing temperature, which results from the exchange splitting continuously approaching its zero temperature value.

In addition to the basic temperature dependence, there are some temperature dependent nuances that can be readily measured. The magnetic order parameter can be suppressed at interfaces for a variety of reasons (structure, composition, etc.). One example was recently reported for EuO, where non-magnetic Eu_2O_3 was found to be preferentially localized at the interface with some metallic electrodes [13]. A temperature dependent barrier asymmetry may result from this situation, where the order parameter of the magnetic material depends on the distance from the magnetically suppressed interface. In an extreme case, quenching at both interfaces may completely suppress the exchange splitting throughout the typically very thin barrier, leading to no detectable polarization of the tunneling current. In another case, only one interface may have the order parameter suppressed. This can easily be detected via the temperature dependent asymmetry of the differential conductance's bias dependence. A barrier with equal heights would have a symmetric $G(V)$ above T_c. Below T_c the barrier profile attains an asymmetry because only the magnetically active interfacial barrier height is temperature and spin dependent, with $\phi_\uparrow$ ultimately falling below ϕ_o. In fact, one can imagine a case where the asymmetry of the differential conductance actually inverts as the temperature is reduced: above T_c if the magnetically dead interfacial barrier height ϕ_{oL} is less than that of the active interface ϕ_{oR} by an amount less than the exchange energy (i.e., $\phi_{oL} < \phi_{oR} < \phi_{oL} + \Delta E_{ex}$), then the barrier asymmetry will be inverted below T_c when the spin-up barrier height $\phi_{R\uparrow}$ falls below ϕ_{oL}. This situation is illustrated in Fig. 2.

Fig. 3 summarizes the roles played by the barrier height, width, and spin splitting in establishing a spin polarized tunneling current as the barrier becomes magnetically ordered. For a given spin splitting and barrier thickness, the polarization is maximized with the smallest barrier height (Fig. 3(a)). For a given barrier height and thickness, the polarization is maximized with the largest spin splitting (Fig. 3(b)). These two results are obvious because the polarization is maximized when the net tunneling current is dominated by spin-up electrons, which is achieved with the smallest spin-up barrier height for the largest spin-down height. Something not quite as obvious, which has not been addressed thus far in the literature, is the role of the barrier thickness. According to Fig. 3(c), thicker barriers not only lead to increased spin-polarization for a given barrier height and exchange splitting, but also make it possible to achieve a high spin polarization at temperatures closer to T_c. To understand this more completely, consider the polarization in terms of the exponent that governs the tunneling current density for each spin species

$$P \propto \frac{e^{-s\sqrt{\phi_\uparrow}} - e^{-s\sqrt{\phi_\downarrow}}}{e^{-s\sqrt{\phi_\uparrow}} + e^{-s\sqrt{\phi_\downarrow}}} = \frac{e^{s(\sqrt{\phi_\downarrow} - \sqrt{\phi_\uparrow})} - 1}{e^{s(\sqrt{\phi_\downarrow} - \sqrt{\phi_\uparrow})} + 1}. \tag{3}$$

This is the maximum achievable spin polarization for a given set of barrier parameters. Fig. 4 shows the spin polarization as a function of the barrier height exponent for three different thicknesses (calculated fully as above). From this it is apparent

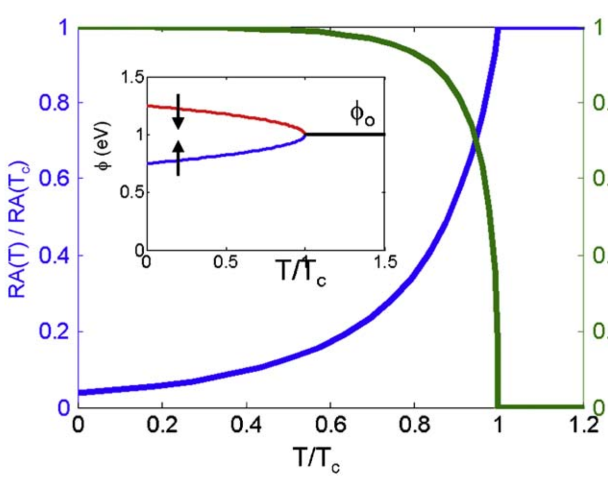

Fig. 1. (Color online) The normalized resistance-area product (blue) decreases as the spin-polarization of tunneling electrons (green) increases as temperature is reduced below T_c. (Inset) Spin-dependent barrier heights according to Eq. (2). The parameters used were $\phi_o = 1\,\mathrm{eV}$, $2\Delta E_{ex} = 0.5\,\mathrm{eV}$, and $s = 30\,\text{Å}$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

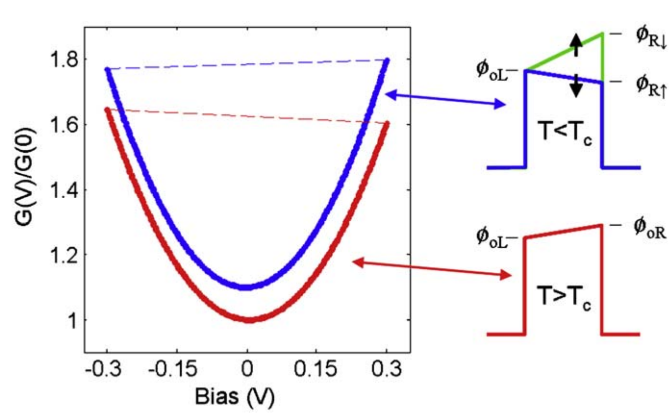

Fig. 2. (Color online) The differential conductance of a spin filter junction with the magnetic order parameter suppressed at one interface can show a temperature dependent asymmetry. The sign change of the slope of the dashed lines connecting $G(-0.3\,\mathrm{V})$–$G(0.3\,\mathrm{V})$ for $T > T_c$ (red) and $T < T_c$ (blue) emphasizes the barrier shape inversion. The barrier structures above and below T_c are indicated to the right, using $\phi_{oL} = 1\,\mathrm{eV}$, $\phi_{oR} = 1.13\,\mathrm{eV}$, $2\Delta E_{ex} = 0.5\,\mathrm{eV}$, and $s = 15\,\text{Å}$. The blue curve has been shifted up 0.1 units for clarity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

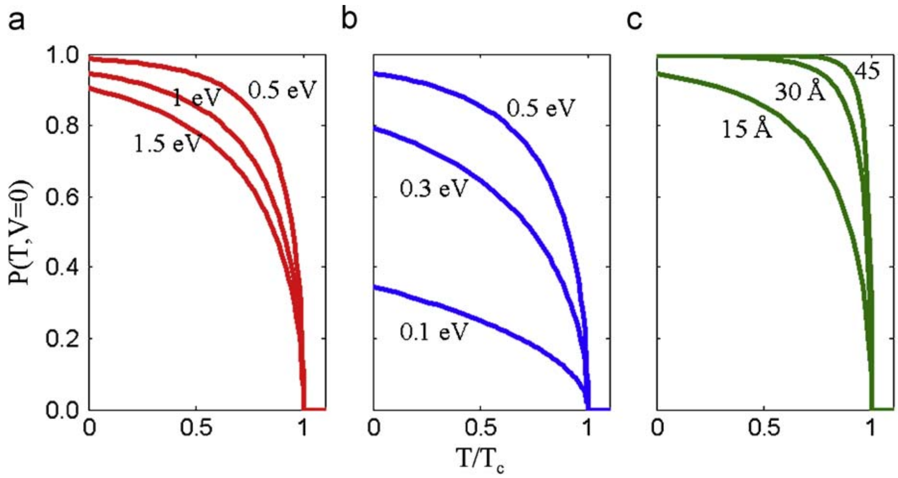

Fig. 3. (Color online) Dependence of the zero-bias spin-polarization on temperature and barrier parameters: (a) ϕ_o as noted for $2\Delta E_{ex} = 0.5\,\mathrm{eV}$, and $s = 15\,\text{Å}$; (b) $2\Delta E_{ex}$ as noted for $\phi_o = 1.0\,\mathrm{eV}$, and $s = 15\,\text{Å}$; and (c) s as noted for $\phi_o = 1.0\,\mathrm{eV}$, and $2\Delta E_{ex} = 0.5\,\mathrm{eV}$.

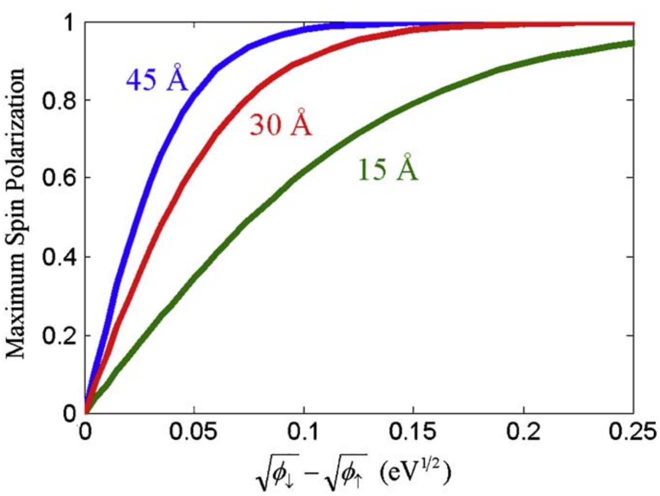

Fig. 4. (Color online) Dependence of the maximum spin polarization on the exponent in Eq. (3). The curves are for barrier thicknesses noted; $\sqrt{\phi_\downarrow} - \sqrt{\phi_\uparrow} = 0.25\,\mathrm{eV}^{1/2}$ corresponds to $\phi_o = 1\,\mathrm{V}$ and $2\Delta E_{ex} = 0.5\,\mathrm{eV}$.

that the largest polarization is achieved for both large differences in barrier heights and large thickness.

The functionality achievable through thickness is potentially critical to know for the future search for and design of spin filter barrier devices for several reasons. First, this is contrary to one traditional goal in junction design, namely making the barrier as thin as possible. Second, it is arguably easier to tune the polarization via thickness than the barrier height and exchange splitting, since these are ideally intrinsic properties of the barrier material. Third, thicker layers are often better, sometimes required, for establishing magnetism in thin films; this revelation may expand the number of materials with the potential for acting as spin filter barriers. Ultimately, for applications, tuning the tunneling spin polarization via barrier thickness must be balanced against the total tunneling resistance of the device. Consequently, the junction area may need to be larger than otherwise desired in order to keep the absolute resistance of the junction practical. Further, the barrier thickness must not be so thick that multiple-step tunneling takes place.

In summary, we have reported how the spin filter tunnel barrier parameters (height, width, and spin splitting) impact the polarization level of the tunneling current. We demonstrated the expected temperature dependence of the differential tunneling resistance and polarization throughout the magnetic phase transition. Surveying the entire barrier parameter space allows us to conclude that the barrier thickness plays a critical role in spin filtering. Increasing the barrier thickness with all else constant, and assuming single step tunneling, increases the maximum achievable spin polarization level, and allows a given spin polarization to be reached at higher temperatures. This revelation should open the door for new spin filter barrier materials whose magnetic properties are suppressed in the $10-20\,\text{Å}$ regime typically used for tunnel barriers, while also allowing higher temperature operation; the cost of increased tunneling resistance will need to be considered for practical applications.

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