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Hot-electron transport through $Ni_{80}Fe_{20}$ in a spin-valve transistor

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Hot-electron transport in $Ni_{80}Fe_{20}$ thin films was studied using a spin-valve transistor. By varying the NiFe thickness from 10 to 100 Å we obtain an attenuation length of 43 Å for majority-spin hot electrons at 0.9 eV above the Fermi level. Based on such relatively long bulk attentuation lengths, one would expect a current transfer ratio that is much larger than the measured value. We propose that the discrepancy can be accounted for by considering interfacial scattering. Increasing the growth quality should thus provide a means to improve the current transfer ratio. *© 2001 American Institute of Physics.* [DOI: 10.1063/1.1357853]

I. INTRODUCTION

The transport of hot electrons with an excess energy of ≈ 1 eV above the Fermi level in ferromagnetic metals is relatively unexplored, but has become of practical importance with the invention of the spin-valve transistor.[1–3] The spin-dependent hot-electron transport in Co was measured with ballistic electron emission microscopy (BEEM) by Rippard and Buhrman,[4] showing a majority- and minority-spin attenuation length of 23 and 8 Å, respectively. This measured attenuation length λ is the result of scattering with impurities, defects, phonons, magnons, and other electrons. All these scattering events have their corresponding change of energy and momentum and their characteristic lifetime τ. Furthermore, it depends on the experimental configuration if a scattered hot electron can still contribute to the measured current. The attenuation length is thus the effective length scale with which this measured current decreases with increasing layer thickness. We have determined the attenuation length in $Ni_{80}Fe_{20}$ using a spin-valve transistor in which hot electrons are injected and collected by a Schottky diode.

II. THEORY

The spin-valve transistor has an emitter/base/collector structure in which the emitter and collector are made of silicon and the base contains a metallic spin valve. At both sides of the spin valve, Schottky barriers are formed in the silicon. Electrons are emitted over the emitter barrier into the metal, which results in electrons with an excess energy of ≈ 0.9 eV above the Fermi level. Almost all of their momentum is perpendicular to the silicon–metal interface, due to the huge acceleration between the Schottky barrier maximum and the silicon–metal interface. These electrons have to travel through the base where they can scatter. Finally, only electrons that have enough energy and the right momentum can pass over the collector barrier ($\Phi_b \approx 0.8$ eV) and contribute to the collector current. So the collector current (I_C) is only a fraction of the emitter current (I_E) and this depends on the transfer ratios α_e, α_b, and α_c of the respective emitter, base, and collector

$$I_C = [\alpha_e \times \alpha_b \times \alpha_c] I_E + I_{\mathrm{leak}}. \tag{1}$$

Furthermore, parasitic leakage current (I_{leak}) also contributes to the collector current and should be smaller than the transmitted hot-electron current.

The emitter and collector transfer ratio α_e and α_c are due to scattering with optical phonons in the silicon region between the maximum of the Schottky barrier and the metal–silicon interface. Furthermore, electrons can backscatter from the collector due to quantum mechanical reflections. The combined emitter and collector transfer has been calculated[5,6] and experimentally[7] verified by Sze *et al.* in metal base transistors, which have the same structure but with a single metal layer in the base. They found that $\alpha_e \times \alpha_c \approx 0.4$ in the case of Si–Si metal base transistors.

The transfer ratio of the base α_b is related to the scattering events in the base. Inelastic scattering, for example by electron–electron interaction, will generally lower the hot-electron energy below the collector barrier, thereby preventing collection [see Fig. 1(a)]. Elastic scattering, as on impurities and defects results in a change of momentum without loss of energy. So an electron can scatter elastically several times, and only if the electron momentum is within the acceptance cone[8,9] can it contribute to the collector current [see Fig. 1(b)]. In the case of quasielastic scattering, like on phonons and magnons, both energy and momentum are important.

In the case that the injected distribution is highly forward focussed in the bulk, both elastic and inelastic scattering contribute to the attenuation. But when the electron momentum distribution in the metal layers has become isotropic, additional elastic scattering has little effect, and inelastic scattering will mainly contribute to the attenuation length. So experimental details determine how the attenuation length is related to elastic and inelastic scattering lengths. The combination of these bulk scattering events result in an exponential decay of the collector current with base thickness. This can be described in the case of a multilayer by a product over the different layers (i) with thickness t_i and attenuation length λ_i:

$$\alpha_b = \prod_i e^{-t_i/\lambda_i}. \tag{2}$$

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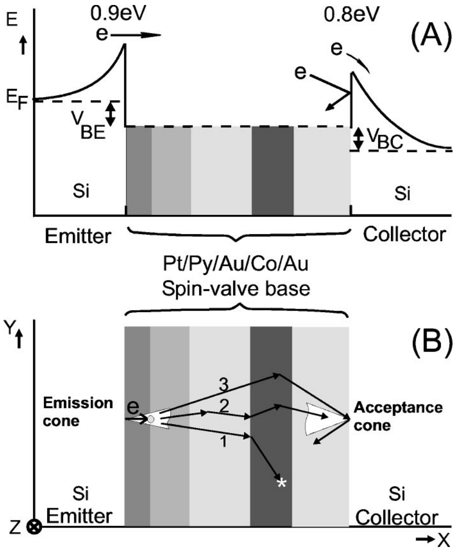

FIG. 1. The schematic energy diagram (a) and real-space momentum picture (b) of the SVT. In the energy diagram, the emitter ($\Phi_b = 0.9$ eV) and collector ($\Phi_b = 0.8$ eV) Schottky barriers are shown. In the momentum picture, three possible electron trajectories in the base are drawn: an electron can scatter inelastically (1) or can scatter several times elastically after which it can arrive within (2) or outside (3) the acceptance cone.

Note, that in ferromagnetic materials the attenuation length is spin dependent.

III. EXPERIMENTS AND DISCUSSION

The spin-valve transistor is made by bonding two moderately doped *n*-type silicon (100) wafers together, because this is the only way to obtain single crystalline silicon on both the emitter and collector side. Prior to the bonding, a cleaning procedure with HNO_3 to remove organic contaminants, tetramethylammonium hydroxide to remove all silicon particles, and a final HF dip to remove oxides is performed. After this cleaning the wafers are mounted on a bonding robot which can be triggered in vacuum. The layers of the spin valve (Pt 30 Å /NiFe *x* Å/Au 45 Å/Co 30 Å) is deposited on the emitter wafer. Next, a 20 Å Au layer is deposited on both the emitter and collector, while bringing them into contact.[10] After these steps, the emitter wafer is thinned down to several microns and patterned to form the emitters by photolithography and wet etching. Next, the base region is defined by lithography and ion-beam etching. Finally, the device can be contacted and measured.[11]

The collector current was measured in a series of spin-valve transistors with a NiFe thickness ranging from 10 to 100 Å. All devices were cooled down to 100 K and an emitter current of 2 mA was applied. Furthermore, the transistors are placed in an in-plane magnetic field of 250 Oe to assure a parallel alignment of the spin valve. In Fig. 2 we show the collector current versus NiFe layer thickness. We find that the collector current decays exponentially with increasing NiFe layer thickness, as expected from Eq. (2). The fit gives an attenuation length of 43 ± 3 Å. This is the attenuation length for majority-spin electrons, so for electrons with their spin aligned to the NiFe magnetization. The minority-spin attenuation length is generally known to be much smaller[4] and so the contribution of the minority-spin electrons to the collector current in the parallel state of the spin valve is negligible.

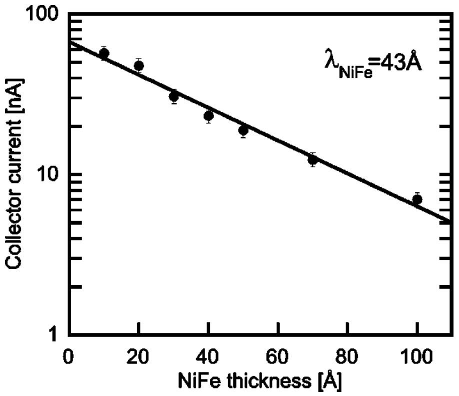

FIG. 2. The collector current in the parallel state for seven different spin-valve transistors with their NiFe layer thickness ranging from 10 to 100 Å. $I_E = 2$ mA and $T = 100$ K.

Furthermore, the collector current for the NiFe 20 Å device is only 48 nA at an emitter current of 2 mA, giving a current transfer ratio ($\equiv I_C/I_E$) of 2.4×10^{-5}. This low transfer ratio cannot be explained by attenuation in the bulk only. Taking the worst-case attenuation lengths (i.e., the shortest) we calculate the expected transfer ratio. The Pt buffer layer can be silicided and for these type of layers an attenuation length of ≈40 Å was reported.[12] The attenuation length in Au is known to be much longer than our layer thickness, so the influence of bulk scattering in the Au is small. Published BEEM data[13,14] range from 130 to 265 Å so in our worst-case analysis an attenuation length of 130 Å is taken for Au. For Co we use the majority-spin attenuation length of 23 Å reported by Rippard and Buhrman.[4] Finally, by including α_e and α_c and noting that only majority-spin electrons will contribute, we calculate a total current transfer ratio of 8.4×10^{-3}. This is about 350 times too high compared to our measured current transfer ratio. This discrepancy in current transfer comes from other scattering sources located at the interfaces between the layers. For example, the formation of a disordered or amorphous silicide at the silicon/metal interface might result in very strong elastic scattering. Another source of scattering might be the metal/metal interfaces of the spin valve and the bond interface where there can be a lot of elastic scattering due to dislocations, stress, and lack of epitaxy. We have modeled the electron transport in a spin-valve transistor with the Boltzmann equation, which describes the elastic and inelastic bulk scattering as well as the elastic interface scattering related to the above mentioned imperfections. With this method, similar current transfer ratios comparable to the experiment were obtained.[15] Further improvements of the layer growth, resulting in less bulk and interface scattering, should increase the current transfer ratio remarkably based on the found discrepancy. This higher collector current will increase the signal to noise ratio and make the spin-valve transistor more sensitive.

IV. CONCLUSIONS

We have determined an attenuation length of 43 Å for hot majority-spin electrons in NiFe. The hot electrons have an energy of $\approx 0.9\,\mathrm{eV}$ and are emitted and collected by Schottky diodes. Based on this attenuation length and values found in literature, the current transfer in the spin-valve transistor cannot simply be explained by bulk scattering. Scattering at the interfaces might be the reason of the low observed collector current. Increasing this collector current is essential for applications and can be obtained by a better layer growth.

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