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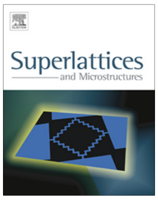

Spin-torque critical current of graphene-based lateral spin valves

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In this paper the spin transfer torque (STT) induced magnetization dynamics of graphene-based lateral spin valve (LSV) structures is investigated theoretically by using the Landau–Lifshitz–Gilbert–Slonczewski (LLGS) equation. Effect of parameters of the LSV, contact types between the ferromagnet and graphene on the STT critical current of magnetization switching in the free layer of the LSV are studied. The polarized current which is transformed from the injector to the detector (free layer) is calculated by the analytical expressions. The results show that, from the viewpoint of application as magnetic switch, tunnel contact can effectively reduce the spin torque critical current compared to the case of transparent contact. In addition, the spin-torque critical current can also be reduced by imposing a weak magnetic field, or reducing the spacing between the injector and detector. Another important feature found from the results is that, the magnetization reversal between the parallel and anti-parallel states is asymmetric, which is in agreement with the reports in literatures.

1. Introduction

As the demand for device miniaturization, multi-functional and low energy consumption is becoming higher and higher, the requirement for development of new functional devices becomes more and more urgent. Spintronic devices provide a new direction to breakthrough the bottleneck of traditional electronics and a revolution chance in electronic technology in the post-Moore era [1].

Traditional magnetic random storage needs to use magnetic field to drive magnetization switching, resulting a relatively large storage volume and energy consumption. The idea of full current driving of magnetization reversal under the condition without external magnetic field began in 1996, the discovery of the spin transfer torque (STT) effect [2,3]. STT is an important discovery in the field of spintronics in the end of last century.

STT can be used to achieve current-induced magnetization switching. In addition to flip and precession of spin, polarized current can also result in the magnetization oscillation and even chaotic behavior. This kind of device which can take advantage of the spin-torque and generate magnetization oscillation is called spin-torque nano-oscillator (STNO). In many well-studied non-linear oscillators driven by external forces, only a small fraction of them can achieve technical applications. The STNO has adjustable gigahertz frequency range, which is very suitable to be applied in the magnetic memory devices and radio communications [4].

Many kinds of all current device models based on STT have been proposed. In addition to the above mentioned STNO, another example is the STT-MRAM (magnetic random access memory).

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To realize the current-induced magnetization switching, the first step is to produce a strong enough spin current. At present there are two kinds of methods for generating spin current with strong enough intensity. The first one is to inject charge current into a ferromagnet to get a polarized spin current. However, the spin injection efficiency is generally lower by this method due to the resistance mismatch problem. The Datta and Das (DD) spin transistor [5] put forward in 1990 have not been successful till now, the main reason is because that the spin injection efficiency is too low. The second one is to use the spin Hall effect (SHE) of nonmagnetic materials [6]. One can expect that this new method can overcome the disadvantages of using magnets.

DD transistor is a kind of non-local device. From the measurement point of view, the non-local device is more convenient. The famous magnetic multilayer structure by which the giant magnetoresistance (GMR) effect was found is mainly composed of three layers of films, namely, ferromagnetic/nonmagnetic metal/ferromagnetic. This kind of structure is commonly known as spin valve (SV) structure. The early SV is a kind of vertical structure, called vertical spin valve (VSV). VSVs do not favor for large-scale integrating with other devices, in addition, VSV belongs to the local spin valve, unable to separate charge current and spin current. In recent years VSVs are generalized to lateral spin valves (LSVs). Compared with VSVs, LSVs' application seems more widely. First, the LSV is a kind of non-local SV, by which the charge current and spin current can be separated easily and pure spin current can be produced. Second, in the field of spintronics, the spin diffusion length (SDL) of nonmagnetic material and the spin polarizability at the ferromagnetic/nonmagnetic interface are two important physical quantities. These two quantities can be determined accurately only in terms of LSVs. Third, the LSV is a necessary device for observing the SHE effects. Fourth, LSV is the basic unit for realizing the all-spin logic gate.

In addition to spin injection efficiency, the magnitude decay of the spin current must also be considered in the process of transport for LSV devices. To measure the length scale over which spin current flows, the quantity of SDL is used. In general, materials showing the lowest spin–orbit interaction (SOI) have longer SDLs. Among the many materials with longer SDLs, graphene seems to be the most important one. Graphene is the generally acknowledged star of the current material, it has attracted the attention of many people in the areas of condensed matter physics and material science for its unique energy of linear dispersion relation, high mobility, high heat conductivity and excellent mechanical properties. In recent years, many authors put forward the use of graphene as a possibility to improve the performance of the SV channel materials. As to whether it is feasible to is uncertain.

There are many reports [7,8] on the studies of LSVs. For the dynamics of the SV, the micromagnetics, especially Landau–Lifshitz–Gilbert (LLG) equation has played a significant role [9,10].

In the description of the macroscopic magnetic dynamics, the effects of the spin-polarized current on the local magnetization reduces to the spin-torque, and leads to a generalized LLG equation. By solving this equation, the dynamics of spin waves, magnetic solitons and magnetic domain wall movements can be studied. This generalized LLG equation was first proposed by Slonczewski in 1996, so, it is also known as Landau–Lifshitz–Gilbert–Slonczewski (LLGS) equation [10].

Although the research on SVs has made a lot of progresses, there are a lot of problems. For example, to be applied to the memory device, the control of the magnetization flip of the free layer of the SV is very important. Full use of the spin-torque current technology does not require the use of the device due to the magnetic field and simplifies the equipment. But at present, the critical current density to achieve the magnetization reversal is too big, and this problem is still not completely resolved.

The current-driven magnetization switching in nanoscale ring-shaped magnetic tunnel junctions (MTJs) was studied by Wei et al. [11] with the help of a detailed micromagnetic analysis. Theoretical analysis and micromagnetic simulations show that the dominant mechanism for the observed current-driven switching is the spin-torque rather than the current-induced circular Oersted field. However, the combined effect of them helps to reduce the required critical flip current [11].

As reported in literatures, the critical current is proportional to the intensity of the out-of-plane demagnetizing field [12,13]. Therefore, the reducing of the demagnetizing field becomes a viable means of reducing the critical current. It was suggested that by using the materials with perpendicular anisotropy, the demagnetization field could be reduced effectively [12,13]. Our previous work shows that the demagnetization field could also be reduced by introducing an out-of-plane stress anisotropy field [14].

Alternative way to reduce the spin critical current is to use appropriate channel material. In recent years, many authors put forward the use of graphene as a possibility to improve the performance of the SV channel materials [15–17].

In this paper, we will focus our attention on the spin torque critical current of graphene LSVs. As far as we know, although there has been a lot of reports on the research of graphene LSVs, the calculations regarding their spin-torque critical currents are reported less to date.

2. Formalism and basic equations

In Fig. 1 we show a schematic cross section of a graphene LSV device in the non-local measurement geometry. The left ferromagnet (FM) is the injector, also called fixed layer, and the right FM is the detector (free layer). The current injects from the left FM, and after the polarization through this FM, it is transported to the detector by a nonmagnetic channel, here, the single layer graphene (SLG). This polarized current drives the magnetization of the free layer reversal.

The contact between FM and graphene can be transparent or tunnel. Studies show that the tunnel contact can effectively improve the injection efficiency [16–18]. In order to form a tunnel contact, a thin film of oxide, such as MgO [16,17], or Al_2O_3 [18], is inserted between the FM and graphene.