Study of voltage-controlled magnetic anisotropy (VCMA) in a FeB thin film and a FeB/W multilayer by the Anomalous Hall effect

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Abstract

The VCMA effect in a FeB thin film and a FeB/W multilayer was measured by four independent methods. All measurements show the same tendency. The coercive field, Hall angle, Δ and anisotropic field linearly decrease when the gate voltage increases. A possible origin of the VCMA effect in a FeB film is discussed. The VCMA effect was enhanced in an optimized FeB/W multilayer.

1. Introduction

The VCMA is a recently-found effect, which may be used in MRAM [1] and all-metal transistor [2] applications as a magnetization-switching mechanism.

The VCMA effect has been studied in a magnetic tunnel junction (MTJ). The linear dependence of the coercive field of the free layer on the applied voltage was obtained [3]. However, a thin MgO (~ 1.3 nm) was used and there was a substantial spin-transfer torque (STT) in the free layer, which may cause a systematical error in these measurements.

Another method to measure the VCMA effect is the use a MTJ, in which the electrodes magnetized perpendicularly each other [4]. From the magneto-resistance (MR) the angle between magnetization can be evaluated at a different applied voltage and the strength of the voltage-controlled perpendicular magnetic anisotropy (PMA) can be estimated. A thicker MgO was used. As result, the influence of the STT is neglectable for these measurements.

The VCMA measurements using the Anomalous Hall effect (AHE) is free from the influence of the STT and the magnetic field from the reference layer, because a thick gate oxide and non-magnetic gate electrode are used [5].

We have studied the VCMA effect in a FeB thin film and a FeB/W multilayer by the AHE. Four independent measurements show the same tendency, the same polarity and the same symmetry of the VCMA effect. Based on these measurements the possible origin of the VCMA effect is discussed.

2. Experiment

The samples were grown on a Si/SiO2 substrate. The FeB ferromagnetic layer of thickness range between 0.9 to 1.2 nm was grown on a 2-nm-thick Ta adhesion layer. A thick MgO layer of 7 nm is used as the gate oxide A thick MgO layer is used to suppressed the tunneling current. In the optimized sample the FeB layer is replaced to

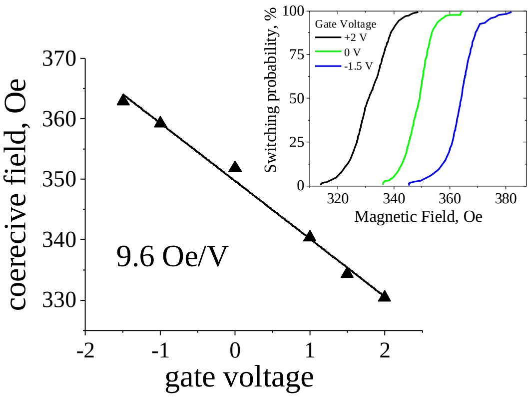

Fig.1 Coercive field vs gate voltage in the FeB/W multilayer. Inset shows switching probability from magnetization-up to magnetization-down direction as function of magnetic field

FeB(0.8)/W(1.5 nm)/FeB(0.8 nm) multilayer. A nanowire of different width between 100 and 3000 nm with a Hall probe was fabricated.

Using the AHE we have measured the gate-voltage dependence of the coercive field, Hall angle, Δ and anisotropic field. All measurements show similar dependency: the linear increase with decrease of the gate voltage. Each measurements reveals different features of the VCMA effect.

Since the magnetization switching is a thermo-activated process, a substantial number of measurements and statistical analysis are required in order to obtain the coercive field with a required high precision. In order to shorten the measurement time, we have develop an optimized measurement method of the coercive field, which consists of two sets of the measurements. In the first measurement, the magnetic pulses of gradually-increased amplitude was applied and the

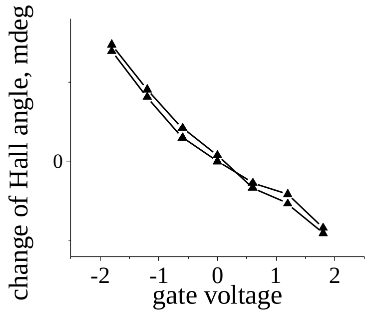

Fig.2 The change of the Hall angle under a different gate voltage in FeB film

magnetization switching field was measured. In the second measurements, the magnetic pulses of constant amplitude was applied and the magnetization switching time was measured. Combining data of these two measurements, the required measurement precision can be reached faster.

Figure 1 shows measured coercive field as function of the gate voltage. All measurement points lie on near perfect line. The change of the coercive field is substantial. The inset of Fig.1 shows the magnetization switching probability at different gate voltages. The curves practically do not overlap.

All measured samples show the gate-voltage dependence of the coercive field was linear with a negative slope. In case of a FeB film, the slope was between 2 and 3.5 Oe/V. In case of the optimized FeB/W multilayer, the slope was between 8 and 11 Oe/V. We did not find a clear dependence of the slope on the width or length of the nanowire and the value of the coercive field. The slope was slightly different for the different devices fabricated on the same wafer.

Figure 2 shows the change of the Hall angle in the FeB (1 nm) film as function of the gate voltage. The Hall angle is proportional to the magnetization of the ferromagnetic metal and the spin polarization of the conduction electrons [6]. From Fig.2 it can be suggested the magnetization of the FeB increases under a negative gate voltage and it decreases under a negative gate voltage at least in the region close to the gate oxide.

Figure 3 shows the dependence of the anisotropic field on the gate voltage. The anisotropic field is the in-plane magnetic field, at which initially-perpendicular magnetization turns completely into the in-plane direction. The inset of Fig.3 shows the in-plane component of the magnetization as function of in-plane magnetic field. The slope is substantially different at a different gate voltage. The anisotropic field increases at a negative gate voltage and it decreases at a positive gate voltage. The dependence is linear. The slope is 0.1 kG/V. The PMA energy can be calculated from the anisotropic field [4]. Corresponded change of the PMA is 50 fJ/V m, which well agrees with the measurements of a similar MTJ sample [4].

Figure 4 shows the dependence of the switching time on the magnitude of the external perpendicular magnetic field. The switching time becomes longer at a negative gate voltage and shorter at a positive gate voltage. The switching time is calculated by the Neel-Brown model [7]. Extrapolating lines of Fig.4 to zero magnetic field gives the retention time. The effective magnetization can be calculated from the slope [7]. As can seen from Fig.4, the retention time and Δ substantially depend on the gate voltage. In contrast, the slope is nearly the same. It means that the effective magnetization does not change significantly at a different gate voltage. The effective magnetization describes the average bulk magnetization during the magnetization reversal. It is not very sensitive to a small change of magnetization in a small region. In contrast, the data of Fig.2 are sensitive to such a small change of the magnetization [6].

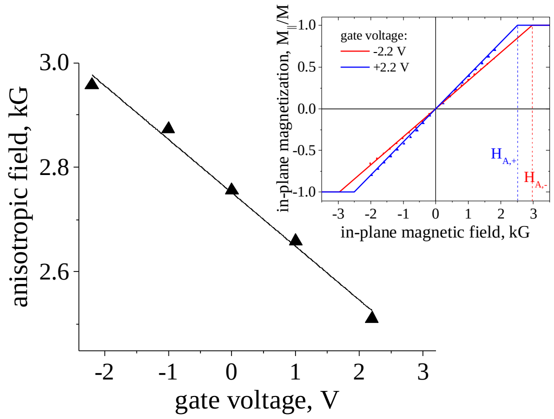

Fig.1 Fig. 3 Anisotropic field of gate voltage in FeB film. Inset shows in-plane magnetization as function of in-plane magnetic field

4. Conclusions

The coercive field, Hall angle, Δ and anisotropic field of a FeB and FeB/W thin film linearly decrease when the gate voltage increases. The polarity and symmetry of all measurement data imply that the change of Fermi level in the vicinity of the MgO gate [5] and the corresponded changes of the magnetization and the PMA may be a major contributor of the VCMA effect.

The VCMA effect is found to be substantially larger in the FeB/W multilayer comparing to a FeB thin film.

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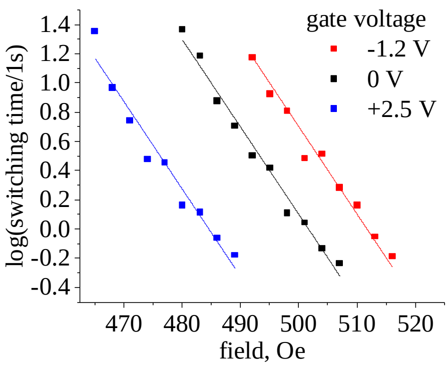

Fig.4 Magnetization switching time in FeB/W multilayer as function of external magnetic perpendicular magnetic field.