Study on Correlation between TMR and Exchange Bias in MTJs for STT-MRAM Applications

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To evaluate the thermal robustness of spin-transfer torque magnetoresistive random-access memory (STT-MRAM), we measured the temperature dependence of magnetization in an in-plane IrMn/CoFeB/MgO/CoFeB heterostructure as it cooled from 300 K to 10 K. Over this range, the exchange bias field at the IrMn/CoFeB interface increased significantly, from 239 Oe to 439 Oe, while the coercivities of the pinned and free CoFeB layers rose from 20 Oe to 179 Oe and from 20 Oe to 99 Oe, respectively. From the strong temperature dependence of exchange bias, we estimate the Néel temperature of IrMn and confirme that exchange bias is a critical parameter governing the thermal stability of magnetic tunnel junctions (MTJs). This quantitative evaluation provides key design guidelines for developing thermally reliable exchange-biased MTJs in future STT-MRAM applications.

***Index Terms*—Thermal robustness, exchange bias, Néel temperature, magnetic tunnel junction (MTJ)**

I. Introduction

Thermal stability is a key determinant of speed, retention, and endurance in both volatile and non-volatile memory technologies. [1]-[3] As electronic systems increasingly operate under extreme environmental conditions, particularly in automotive applications, ensuring device-level robustness has become essential. [3]-[4] Spin-transfer torque magnetoresistive random-access memories (STT-MRAMs), a leading candidate for next-generation memory, has attracted significant attention due to its non-volatility, high speed, and low power consumption, and exhibits thermal reliability that meets automotive memory standards across the −40 °C to +150 °C range. [4]-[5] However, how thermal robustness affects the operation of STT-MRAM, particularly in terms of both intrinsic and extrinsic factors, remains insufficiently understood. The fundamental unit of STT-MRAM is the magnetic tunnel junction (MTJ), whose thermal robustness directly affects magnetization switching and spin-dependent transport phenomena, including tunneling magnetoresistance (TMR) and exchange bias. [6] Therefore, evaluating the thermal stability of MTJs at the device level is necessary for understanding and controlling temperature-induced degradation in these transport properties.

In this study, we investigated the temperature dependence of TMR in a NiFe/IrMn/CoFeB/MgO/CoFeB MTJ structure. The TMR measured at each temperature was analyzed by comparing the contributions of spin-independent tunneling, direct elastic tunneling, and magnon-assisted inelastic excitations. The temperature dependence of the exchange bias field was also used to estimate the Néel temperature at the device level. In addition, size-dependent simulations using MuMax3 were conducted to examine the influence of extrinsic factors, and the variation in magnetization with respect to junction size was observed under various temperature conditions. This study proposes an analytical approach to explain how thermal stability affects the operation of STT-MRAM by simultaneously considering both intrinsic and extrinsic factors.

II. Experimental Procedures and Results

The heterostructure investigated in this study consisted of $Ni_{81}Fe_{19}$ (1 nm) / $Ir_{25}Mn_{75}$ (15 nm) / $Co_{32}Fe_{48}B_{20}$ (5 nm) / MgO (1.5 nm) / $Co_{32}Fe_{48}B_{20}$ (2 nm), capped with a ruthenium layer, as illustrated in Figure 1(a). All films were deposited at room temperature by magnetron sputtering onto Si/SiO_x (200 nm) substrates under a base pressure below 3.0×10^{-8} Torr. During deposition, an in-plane magnetic field of 15 mT was applied to induce uniaxial magnetic anisotropy in the CoFeB layers. The metal layers were deposited using DC sputtering at 30 W with a working pressure of 3 mTorr, while the MgO barrier was deposited via RF sputtering at 75 W and 10 mTorr. To enhance the exchange bias at the IrMn/CoFeB interface, a thin NiFe underlayer was inserted beneath the IrMn layer. Following film deposition, bottom electrodes with a dumbbell-shaped geometry (10 µm width) were defined by photolithography and Ar^+ ion milling. The MgO barrier and top electrode were subsequently etched, and a 70 nm-thick SiO_x isolation layer was deposited in situ to electrically separate the top and bottom electrodes. MTJ pillars with a diameter of 5 µm were then patterned. Finally, a Cr (5 nm)/Au (100 nm) bilayer was deposited, and the top electrodes were completed by a standard lift-off process. The devices were annealed in vacuum at 350 °C for 40 minutes under a magnetic field of 100 mT to establish exchange coupling at the IrMn/CoFeB interface. This field strength is sufficient to fully saturate the magnetization of the CoFeB layer. The tunneling resistance was measured at room temperature using a four-point probe configuration with a constant bias current of 10 nA, while sweeping the in-plane magnetic field in Figure 1(b). We also confirm that the TMR of the MTJ strongly depends on the temperature above 300K from 50.12% to 37.06%.

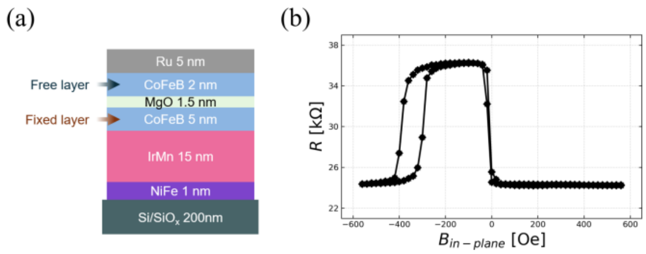

Fig. 1. (a) Cross-sectional schematic of the Ru-capped MTJ stack: 200 nm Si/SiO$_x$ substrate / 1 nm NiFe / 15 nm IrMn / 5 nm CoFeB / 1.5 nm MgO / 2 nm CoFeB / 5 nm Ru. (b) TMR curve measured at room temperature using a four-point probe with a 10 nA bias current as a function of in-plane magnetic field.

The temperature dependence of magnetization behavior in the NiFe/IrMn/CoFeB/MgO/CoFeB heterostructure was examined by measuring in-plane hysteresis loops using the vibrating sample magnetometer (VSM) module of an magnetic property measurement system (MPMS) at temperatures from 300 K to 10 K in 50 K intervals, as shown in Figure 2. From the power-law with a critical exponent (β) model [7], we could get the Néel temperature (T_N) of the IrMn, 434 K in the MTJ.

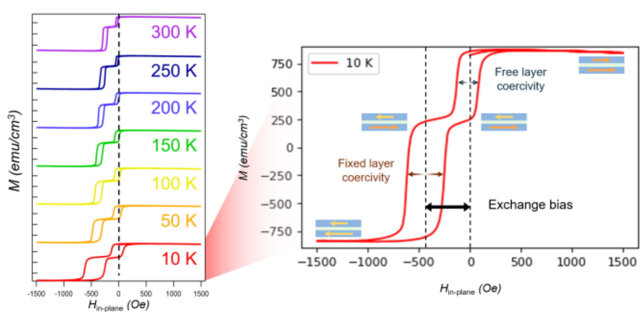

Fig. 2. VSM hysteresis loops of the IrMn/CoFeB/MgO/CoFeB heterostructure measured along the easy axis from 300 K to 10 K in 50 K intervals. The red curve represents the loop measured at 10 K, showing the coercivity fields of the free and fixed layers. The black dashed line indicates the center of the free and fixed layer loop. The black arrow denotes the exchange bias field.

From the two-measured parameters, we finally find the linear correlation between TMR and exchange bias of TMJs.

III. Conclusion

In this study, we experimentally investigated the temperature-dependent magnetic properties of an exchange-biased IrMn/CoFeB/MgO/CoFeB heterostructure. As the temperature decreased from 300 K to 10 K, the exchange bias field increased significantly, accompanied by enhanced coercivity in both the fixed and free layers, with a larger increase observed in the fixed layer. Based on these results, the Néel temperature of IrMn and thermal stability factors were quantitatively evaluated. These findings provide a useful framework for assessing the thermal reliability of lateral MTJ devices intended for memory applications in extreme environments. Future work will focus on analyzing the temperature dependence of the exchange bias field and tunneling resistance in individual MTJ cells to deepen the understanding of intrinsic and extrinsic thermal effects on STT-MRAM operation.

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