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Detection of pinholes in magnetic tunnel junctions by magnetic coupling

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Pinholes in tunnel barriers are detrimental to the performance of magnetic tunnel junctions (MTJs) since they create direct magnetic exchange coupling between the free and pinned magnetic films and may act as current short circuits. A simple and straightforward technique which enables observation of pinholes and distinguishes pinhole coupling from orange-peel coupling would aid greatly in optimizing the performance of MTJs. However, the existing methods for this determination are quite complex and destructive and do not work on complete structures. We have developed a simpler, nondestructive method that works on full MTJ structures which is able to identify whether an observed coupling arises primarily from magnetic exchange coupling through pinholes or from orange-peel coupling. The method is based on the shift in the free layer hysteresis loop at low temperatures. It is well known that the shift in the pinned layer loop at low temperatures is due to the sharp increase of the IrMn pinning strength. If pinholes exist, the free layer loop will also exhibit a shift due to direct exchange coupling. If there are no pinholes, no shift will be observed since orange-peel coupling is magnetostatic and cobalt has essentially no increase in magnetization below 300 K. In this way, a quick diagnosis can be made of whether or not pinholes exist in the MTJ.
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INTRODUCTION

Magnetic tunnel junctions (MTJs) are envisioned to have important applications in the development of spintronic devices, including magnetic random access memory and magnetic read head sensors for hard-disk drives, due to their high tunneling magnetoresistance (TMR) at room temperature. To realize these applications, junction resistances must be small since the read and write speed is determined by the *RC* constant in the system.[1,2] This requirement dictates the thickness of the oxide barrier. However, the accompanying reduction in oxide barrier thickness generally makes the samples more susceptible to pinholes. Pinholes are detrimental to MTJs because they couple the two magnetic layers ferromagnetically, making it difficult to achieve the antiparallel magnetization state, thereby limiting the TMR. Pinholes may also reduce the TMR by acting as current short circuits for the junctions.

There are currently no simple, nondestructive methods to observe pinholes existing in a full MTJ structure. Atomic force microscopy with a conducting tip[3] and electrodeposition of copper[4,5] may be used to image pinholes, but these techniques cannot be used to study pinholes in a completed MTJ structure. Transmission electron microscopy (TEM) may provide some insights into pinholes; however, it is unlikely that the cross section of the sample will cut across a pinhole unless the pinholes are very densely spaced.

Previously, we devised a method using hysteresis loops on giant magnetoresistive (GMR) spin valves to distinguish the regime of spacer-layer thickness in which pinhole coupling dominates from the one in which orange-peel coupling dominates.[6] These structures used a synthetic antiferromagnet Co/Ru/Co and the natural antiferromagnet $Ir_{20}Mn_{80}$. Unfortunately, their magnetic structure was relatively complicated. In this paper, we have simplified this technique by employing only the natural antiferromagnet $Ir_{20}Mn_{80}$ without the synthetic antiferromagnet and we have extended its application beyond GMR to detecting pinholes in MTJs.

EXPERIMENTAL METHODS

The thin films were deposited on thermally oxidized silicon wafers by dc magnetron sputtering in an ultrahigh vacuum chamber with a base pressure of 3×10^{-8} Pa (2×10^{-10} Torr). The metal films were deposited at room temperature in 0.3 Pa (2 mTorr) argon. The oxide barrier layer was made by first depositing a thin Al metal and then oxidizing it in an oxygen plasma [0.6 Pa (4 mTorr) argon 0.3 Pa (2 mTorr) oxygen] for 2.5 min. The magnetic hysteresis loop measurements were carried out with a superconducting quantum interference (SQUID) magnetometer (MPMS, Quantum Design, USA).

RESULTS AND DISCUSSION

The sample structure illustrated in Fig. 1 was used to investigate the magnetic coupling between two ferromagnetic layers. The bottom Co layer below the Al_2O_3 barrier is magnetically pinned by the natural antiferromagnet $Ir_{20}Mn_{80}$. The top Co layer is free to switch if the Al_2O_3 barrier is thick enough to prevent magnetic coupling. This sample, containing only three magnetic layers, is typical of the MTJs we

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FIG. 1. Sample structure: substrate \ 2.5 Ta\20 Ru\10 IrMn\4 Co*X* Al:oxidized\5 Co\5 Ta\7 Ru (*X*=1 for sample A; *X*=0.8 for sample B) (units in nm).

fabricate for our other TMR experiments and has a much simpler magnetic structure than the previous work, which involved nine magnetic layers (cf. Fig. 1 in Ref. 6).

Two samples were made: (a) sample A has a 1 nm Al layer oxidized to form the Al_2O_3 barrier and (b) sample B has a 0.8 nm Al layer oxidized to form the Al_2O_3 barrier. Their resistance-area products (*RA*) and TMRs were measured by current-in-plane-tunneling instrument (Capres, Denmark) without annealing. For sample A, its *RA* is 13 kΩ μm^2 and TMR is 13%; for sample B, its *RA* is 40 Ω μm^2 and TMR is 1%. The *RA* and TMR of sample A are typical for its oxide barrier thickness whereas the *RA* of sample B is excessively small due to the existence of pinholes. The existence of pinholes caused the significant reduction in the TMR of sample B. Therefore, sample A is a good MTJ sample without pinholes and sample B is a bad MTJ sample with pinholes. They are suitable for demonstrating the technique.

Figure 2 shows the shifts of the centers of the pinned layer loops and the free layer loops of samples A and B as a function of temperature from the SQUID hysteresis measurements (after correction for flux trapped in the superconductor). The shifts were measured relative to the centers of the pinned layer loops and the free layer loops at 300 K. The centers of the pinned layer loops of both samples shifted as the temperature decreased because the pinning strength of the antiferromagnetic IrMn is larger at low temperature. However, the centers of the free layer loops of samples A and B showed different behaviors with temperature. For sample A without pinholes [Fig. 2(a)], the center of the free layer loop did not shift but remained more or less at the same location. For sample B with pinholes [Fig. 2(b)], the center of the free layer loop shifted as the temperature decreased with a similar trend to that of the pinned layer loop center. Since orange-peel coupling is magnetostatic and Co has essentially no increase in magnetization below 300 K, they cannot cause the shift of the free layer loop. However, if the free layer is magnetically coupled through the pinholes with the pinned layer, then as the pinned layer loop shifted with temperature, the direct magnetic exchange coupling would force the free layer loop to shift as well. In short, the shift of the free layer loop at low temperature is an indication of the existence of pinholes. Such phenomenon can be leveraged for pinhole detection.

CONCLUSION

We have demonstrated that the temperature dependence of the magnetic coupling between the pinned layer and the free layer provides a simple, nondestructive means to detect pinholes in the oxide barrier of a MTJ. Previously this technique was illustrated with a GMR spin valve structure with synthetic antiferromagnet and natural antiferromagnet. In this paper, we improved the technique and made it much simpler by using only a natural antiferromagnet. In the hysteresis loop measurements, the response of the free layer in the MTJ sample with pinholes exhibited a shift at low temperature, whereas the response of the free layer in the MTJ sample without pinholes did not. The shift of the free layer loop is the manifestation of the direct magnetic exchange coupling between the pinned layer and the free layer through

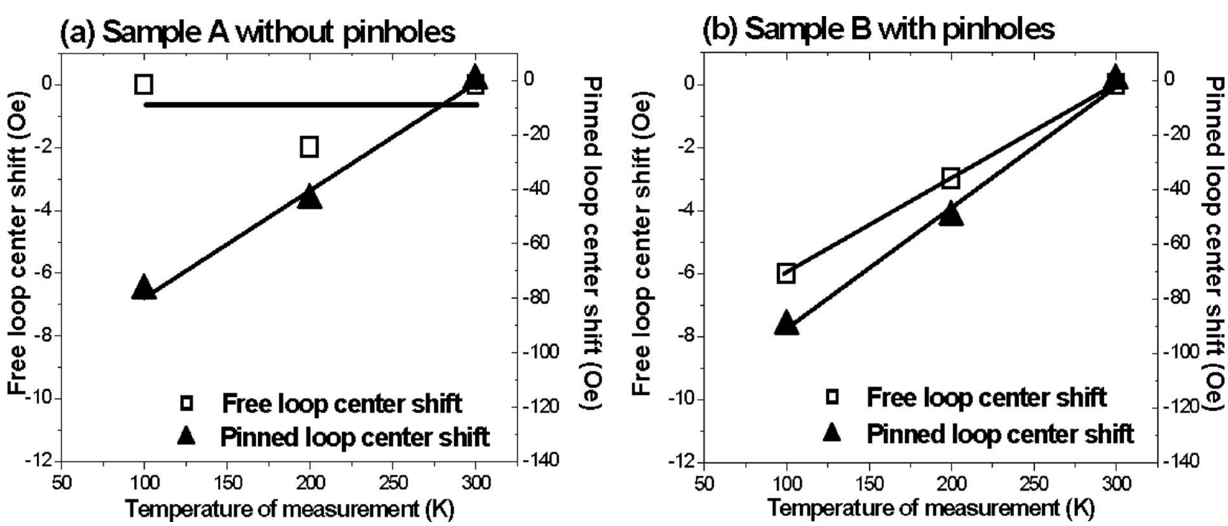

FIG. 2. Results of SQUID hysteresis loops on (a) sample A without pinholes and (b) sample B with pinholes.

the pinholes. As such, we demonstrated that the technique is applicable for detecting pinholes in the oxide barrier of a MTJ.

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