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Observation of Spin-Transfer Switching In Deep Submicron-Sized and Low-Resistance Magnetic Tunnel Junctions

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The spin-transfer effect has been studied in magnetic tunnel junctions (PtMn/CoFe/Ru/CoFeAl_{2}O_{3}/CoFe/NiFe) with dimensions down to 0.1x0.2 μm² and resistance-area product RA in the range of 0.5-10 Ωμm² (ΔR/R=1-20%). Current-induced magnetization switching is observed with a critical current density of about 8x10⁶ A/cm². The attribution of the switching to the spin-transfer effect is supported by a current-induced ΔR/R value identical to the one obtained from the R versus H measurements. Furthermore, the critical switching current density has clear dependence on the applied magnetic field, consistent with what has been observed previously in the case of spin-transfer induced switching in metallic multilayer systems.

Magnetization switching induced by spin-polarized current has stimulated considerable interest in recent years due to its rich fundamental physics and potential for new magnetoelectronic applications. Low switching current density and high read signal are required for the application of the spin-transfer switching to non-volatile magnetic random access memory (MRAM). Most of the work to date, however, has focused on magnetic metallic multilayers, which require large currents applied in the current-perpendicular-to-plane direction but yield small resistance (R) and nominal magnetoresistance (ΔR/R). On the other hand, magnetic tunnel junctions (MTJ) have both high R and ΔR/R, resulting in high signal output. In order to utilize MTJs in spin transfer based MRAM, however, requires an understanding of the limits of both the spin transfer effect and the electron transport properties of tunnel barriers used in MTJs.

We report the observation of the spin-transfer effect in low-resistance MTJs ( RA=0.5-10 Ωμm²) with dimensions down to 0.1x 0.2 μm². These deep submicron-sized MTJs minimize the Oersted (vortex) field contribution due to large vertical current through the MTJ pillars. MTJ films Ta20/NiFeCr35/PtMn140/CoFe20/Ru8/CoFeCr35/PtMn140/CoFe22/Al_{2}O_{3}/CoFe/Al_{2}O_{3}/NiFe/Al_{2}O_{3}/NiFe20/Ta50 (in A) were deposited in a magnetron sputtering cluster system and annealed at 250-270 °C for 10 hours. A thin tunneling barrier was formed by two-step natural oxidation of the pre-deposited Al layer in a pure oxygen atmosphere. The MTJ films were subsequently patterned into deep submicron ellipse-shaped pillars using DUV photolithography combined with resist trimming and ion milling. The pillar dimensions and microstructures have been characterized by high-resolution transmission electron microscope (TEM). The cross sectional TEM micrograph of an MTJ sample (0.12 x 0.23 μm² ellipse), taken along the long axis, shows a continuous well-defined alumina barrier layer (see Fig. 1). The edges of the nano-pillar are also well defined, smooth and steep. The lateral dimension is closed to 0.22 μm, considering the small overlayer of insulating material Al_{2}O_{3} at the edge of the nanopillar.

Fig. 1: Cross-sectional TEM micrograph of a sample with RA = 1.6 Ωμm². The cross-section is taken along the long axis of the 0.12 x 0.23 μm² ellipse shaped nanopillar.

The resistance/magnetoresistance versus magnetic field and current were measured by a quasi-static tester with pulsed current capability. Breakdown voltages for the samples in the RA range studied here are found to be between 0.3-0.8 V, allowing a current flow of density up to 6x10^7 A/cm² without dielectric breakdown of the thin junction barriers. The representative plots of resistance R (in the parallel state) versus the voltage bias, as shown in Fig. 2, exhibit two different types of behavior depending on RA value of the MTJ samples. For the low RA samples (0.2–1.6 Ωμm²), R increases with increasing voltage bias [see Fig. 2 (a)]. This R increase with voltage bias is similar to that characteristic of bottom spin-valve samples with similar structures except for the barrier layer, as shown in the insert of Fig. 2 (a) for comparison. For the higher RA samples (>1.6 Ωμm²), an inverse parabola similar to that seen previously in typical MTJs is observed [see Fig. 2 (b)], suggesting that most of the current passes though the barrier by tunneling. The difference in the R versus voltage bias curves between the low RA and higher RA samples may be the result of incomplete oxidation of the barriers in

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the low RA samples, where the current passing across the barrier is mainly leakage current through the pinholes. For the low RA samples (<1.6 Ωm²), the resistance becomes higher for higher voltage bias because of increasing electron-phonon and electron-magnon scatterings.

The resistance versus field scans are shown for two samples in Fig. 3 (a) and (c) having different RA, along with the corresponding resistance versus current scans in Fig. 3 (b) and (d). Positive field here is applied along the direction of the pinned sublayer in the synthetic antiferromagnet adjacent to the Al₂O₃ barrier layer. Positive direction of the pinned sublayer in the synthetic antiferromagnet adjacent to the Al₂O₃ barrier layer. Positive current I here denotes electron flow from the free to the pinned layer (current flow from the pinned to the free layer).

Two samples with RA of 1.6 and 2.6 Ωm² showed ∆R/R= 3% and 5% (measured at low bias I=0.25 mA), respectively. In both samples, a ferromagnetic coupling offset field H_{off} which arises from the orange-peel (Néel) coupling, can be seen. The R versus I scans were performed at zero effective magnetic bias with an applied field H_{a} opposite and equal to the offset field H_{off}. The R versus I curves show sharp resistance transitions between parallel and anti-parallel magnetization alignments, exhibiting ∆R/R values identical to those obtained from R versus H_{a} measurements. The average switching current density as calculated from (Ic⁺ - Ic⁻)/2A, where A is the junction area, Ic⁺ and Ic⁻ denotes the critical currents at which R jumps from low (parallel magnetizations) to high (antiparallel) and from high (antiparallel) to low (parallel), respectively, is around 8 x10⁶ A/cm², comparable to those obtained from spin valves with same free layer structure. It should be pointed out that the current switching thresholds depend on the applied field, as shown in Fig. 4 for a MTJ sample with RA=2.6 Ωm². Because the torque due to the spin current must overcome the increasing torque due to the increased applied field, Ic⁺ becomes more negative with a more negative H_{a} (more negative H_{a} favors more antiparallel magnetization alignments). The lack of Ic⁻ data at less negative H_{a} values is due to the limitation in the amount of current (-1.5-1.5 mA) that can be safely applied to MTJ sample during the R versus I scan without risking a dielectric breakdown of the junction barrier. Similar field dependence of the switching currents Ic has been observed in a number of MTJ samples. The insert in Fig. 4 shows Ic versus H_{a} for a simple bottom spin valve with the same free layer structure for comparison. A kink is observed in the insert on the Ic⁻ versus H_{a} curve when H_{a} approach the value that forces the free layer into alignment with the pinned layer in the absence of a current.

The clear field dependence of the critical switching current here is in contrast to the lack of field dependence of the current-induced switching observed in MTJs in earlier experiments due to the formation/annihilation of conduction channels by displacement of atoms or charges from the two electrodes into the thin insulating layer region (hot spots). In these earlier experiments, the switching current was observed to be independent of applied field up to kOe range, well beyond the coercive field of the free layer. And the ∆R/R observed during the current scans also varied over a wide range from below 50% up to 200% of the ∆R/R obtained from the R versus H_{a} scan. On the contrary, here we observe basically identical values of ∆R/R under both current and field scans, consistent with spin transfer experiments in Co/Cu/Co trilayers. Furthermore, the critical switching current density in our MTJ samples is found to increase, while ∆R/R remains unchanged.
generalization of these models in situations far from derived in the limit of weak non-equilibrium. A proper mechanical from electronic transport calculations, either quantum models proposed so far to obtain the spin transfer torque localized on the Fermi surface. Essentially all the theoretical encompassing theoretical framework. Transport in MTJ at finite bias involves a significant range of electronic state energies both above and below the Fermi level, as opposed to the situation in metallic systems where the transport is localized on the Fermi surface. Essentially all the theoretical models proposed so far to obtain the spin transfer torque from electronic transport calculations, either quantum mechanical or semi-classical in nature, have been derived in the limit of weak non-equilibrium. A proper generalization of these models in situations far from equilibrium is called for by the newly demonstrated spin-transfer effect in MTJ at finite current bias.

In conclusion, the spin-transfer effect has been observed in bottom synthetic MTJs with dimensions down to 0.1x 0.2 μm² and RA in the range of 0.5-10 Ωμm² (ΔR/R=1-20%). Spin transfer current induced switching was observed, as evidenced by R vs. H measurements compared with the current-induced ΔR/R, along with the field dependence of the current driven switching. A qualitative difference in the electron transport behavior was observed in RA above and below 1.6 Ωμm², however, spin transfer driven switching has been observed over a wide range of RA leading to the possibility of spin transfer based MRAM.

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Fig. 4: Switching current versus external applied magnetic field H₂ for a MTJ with RA= 2.6 Ωμm². The inert shows Ic versus H₂ for a simple bottom spin valve with the same free layer.

decreasing current pulse width (from 3000 ms to 3ms). We found that Ic decreases linearly with the logarithm of the pulse duration, a functional dependence which was previously observed in spin valve pillars, and is expected for thermally activated switching.

In addition to spin transfer switching, the R versus I curves shows distinct R versus voltage bias characteristics with a parabolic curve for RA<1.6 Ωμm² and an inverse parabolic curve for RA >1.6 Ωμm². It is interesting to note that the observed Ic values are similar for all the samples across the whole range of RA studied here (0.5-10 Ωμm²), even though a qualitative change in the electron transport process across the barrier layer is strongly indicated by the observed change in the curvature of the R versus voltage bias curves (see Fig.2). For the sample with RA=1.6 Ωμm² shown in Fig.3b, the relatively flat curvature of the R versus I curve could be the result of the presence of both transport modes (electron tunneling across the barrier and leakage current through pinholes in the barrier layer).

We want to point out that the present experimental results open a new domain for the spin-transfer physics, and create new challenges in regard to providing an all encompassing theoretical framework. Transport in MTJ at finite bias involves a significant range of electronic state energies both above and below the Fermi level, as opposed to the situation in metallic systems where the transport is localized on the Fermi surface. Essentially all the theoretical models proposed so far to obtain the spin transfer torque from electronic transport calculations, either quantum mechanical or semi-classical in nature, have been derived in the limit of weak non-equilibrium. A proper generalization of these models in situations far from

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