Bias Voltage Dependence of Tunneling Magnetoresistance and Annealing Effect in Spin Dependent Tunnel Junctions

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Junctions with Al₂O₃ and AlN barriers were fabricated through contact shadow masks (2.5×10⁻⁶ mm²-product) and by a self-aligned lithography process (9×2μm²-product). The Al₂O₃ barrier was formed by plasma oxidation. The AlN barrier was prepared by dc reactive magnetron sputtering.

Room temperature tunneling magnetoresistance (TMR) is 1.6% for the AlN junctions and up to 24% for the Al₂O₃ junctions. The TMR for all junctions decreases with increase of applied bias voltage and drops to half its initial value at a bias voltage between 116 mV and 437 mV. The weakest bias voltage dependence occurs for junctions with higher barrier heights, and thinner barrier thickness. Annealing at 100–200 °C leads to a 20% increase of TMR and a 40% decrease of junction resistance for the 9×2μm² junctions, leading to a maximum TMR of 27%. Both TMR and junction resistance were increased for the AlN junction due to annealing.

Keywords: tunnel junction, magnetoresistance, Al₂O₃, AlN, spin polarization, thin film, annealing

1. Introduction

Spin dependent tunnel junctions have attracted much attention since the discovery of large room temperature (RT) tunneling magnetoresistance (TMR)³, raising scientific and technological issues. The insulating barrier plays an important role in the spin dependent tunnel junction. Large room temperature TMR was only observed for junctions with Al₂O₃ barrier prepared by deposition of a thin Al film and followed by natural or plasma oxidation. The unusual bias dependence of TMR is one of the most interesting subjects in magnetic tunnel junctions. The TMR is strongly reduced when the applied bias is of the order of a few hundred millivolts. The mechanism behind the bias dependence of TMR is still not clear. The thermal stability of tunnel junctions is a key factor for application of junctions as magnetic devices. In this paper, the bias dependence of TMR for a variety of junctions with different barriers and areas are compared, and the annealing effect on tunnel junctions is studied.

2. Experimental Method

In this study, three types of junction structures were used, Type-I: buffer/FM/Al₂O₃ (or AlN)/FM2, Type-II: pinned bottom electrode, buffer/MnRh(or TbCo)/FM/Al₂O₃/FM, Type-III: pinned top electrode, buffer/FM/Al₂O₃/FM/MnRh(or TbCo). Here the buffer is an 80Å thick Ta layer or Ta(80Å)/Cu(40Å)/Ta(80Å) multilayers, and FM is 30–120Å thick NiFe or CoFe layer. The exchange layer, MnRh or TbCo, is 150–180 Å thick. Both bottom and top electrodes were deposited by magnetron sputtering in a Nordiko 2000 system with a base pressure of 5×10⁻⁶ Torr. An aligning field of 20 Oe was applied to induce a parallel easy axis in each electrode. The Al₂O₃ barrier was formed in a different setup, by depositing a thin Al layer (10–20Å, DC magnetron sputtering, 3mTorr, 0.25W/cm²) followed by a 1.5 to 2.5 minutes plasma oxidation (P₀₂=5mTorr, 4–8 mW RF/cm²). The AlN barrier (15–40Å) was prepared at room temperature by reactive dc magnetron sputtering in Ar-50%N₂ atmosphere from an Al target. For the 0.25 mm²-size junctions, both electrodes were deposited using contact shadow masks. For the 2mm²-size junctions, the full junction structure was deposited on a blank glass substrate, and a self-aligned lithography process is subsequently used to achieve junction areas down to a few μm². In this case, bottom electrode dimensions are 250×20 μm², and the easy axis is along the long dimension. The annealing was carried out in a vacuum furnace (10⁻⁶ Torr) for 1 hour at temperatures between RT and 300°C, followed by furnace cooling to room temperature in a field of 350 Oe applied along the easy axis of the electrodes.

3. Results and discussion

Figure 1 shows room temperature magnetoresistance (MR) curves for the three types of junctions. For all 0.25 mm²-size junctions, the junction resistance (R₀) is higher than 400 Ω, which is high enough to avoid the geometrically enhanced MR effect ³. The junctions show TMR in a range of 1.6% to 24%. The AlN junctions show quite low TMR signal, which may be due to defects and non-uniformity of AlN layer. A slight excess of Al in the film is a well-known feature of AlN insulator, independent of the technique used for the deposition⁶. The presence of metal particles in the tunnel barrier can adversely affect the spin polarization by causing spin flip scattering, decreasing the TMR signal². The Al₂O₃ junctions processed by lithography show higher TMR signal in comparison with junctions made by contact shadow masks. In junctions made by
shadow masks, it was found by magnetic force microscopy (MFM) on the top electrode, that there is a canting of the magnetization directions near the edges of the shadow mask, leading to reduction in TMR (no perfect antiparallel alignment between the magnetization of both electrodes).

Figure 2 (a) shows the bias voltage dependence of the TMR for different junctions. The TMR is constant or just decreases slightly at very low bias voltages, and then decreases rapidly with increasing bias voltage. The explanation for this bias dependence is still not clear. Several theoretical models were proposed for the bias dependence of TMR[29]. For comparison, the normalized bias voltage dependence of TMR for these junctions is shown in Fig. 2 (b). The voltage where the TMR drops to half its initial value is defined as $V_h$. It can be seen that the $V_h$ lies between 116 and 437 mV. The 9.2μm²-size Al₂O₃ junction shows the slowest decrease in TMR with increase of the bias voltage, giving in turn the maximum $V_h$ (437mV). While the 0.25mm²-size as-deposited AlN junction shows the fastest decrease in TMR, giving the minimum $V_h$ (116mV). In order to understand the differences of bias voltage dependence of TMR for these junctions, the I-V curves were fitted using the Simmons model[30], the effective barrier heights ($\Phi_{eff}$) and effective barrier thicknesses ($t_{eff}$) were obtained and plotted as a function of $V_h$ in Fig.3. $\Phi_{eff}$ increases from 0.6 to 2.6 eV, and $t_{eff}$ decreases from 27 to 13Å, with increasing of voltage $V_h$. This implies that the bias dependence of TMR is related to the effective barrier height and barrier thickness, and a weak bias dependence can be obtained by increasing the barrier height and decreasing the barrier thickness.

Figure 4 shows the annealing temperature dependence

\[ \text{Fig. 2 Bias voltage dependence of TMR (a) and normalized TMR (b) for junctions of (s) Ta/Cu/Ta/ Ni₇Fe₂₆₀/CoFe₃₄₆/Al₂O₃/CoFe₃₄₆/MnRh₁₈₈/Ta₂₅₈, (s) Ta/ Ni₇Fe₂₆₀/CoFe₃₄₆/Al₂O₃/CoFe₃₄₆/TbCo₁₈₈/Ta₂₅₈, (s) Ta/ Ni₇Fe₂₆₀/MnRh₁₈₈/Ni₇Fe₂₆₀/CoFe₃₄₆/Al₂O₃/CoFe₃₄₆/Ta₂₅₈, (s) Ta/Ni₇Fe₂₆₀/Al₂O₃/CoFe₃₄₆/Al₂O₃, (s) as-deposited and (s) annealed Ta/Ni₇Fe₂₆₀/AlN/Co₁₀₂₅.} \]

\[ \text{Fig. 3 Effective barrier height } \Phi_{eff} (a) \text{ and barrier thickness } t_{eff} (b) \text{ as a function of voltage } V_h \text{ for samples shown in Fig.2.} \]
Fig. 4: Annealing temperature dependence of TMR (a) and $R_J$ (b) for junctions of (●) Ta/Cu/TaNiFe$_{50}$/CoFe$_{20}$/Al$_2$O$_3$/CoFe$_{20}$/MnRh$_{30}$/Ta$_{20}$A, (●) Ta/NiFe$_{50}$/CoFe$_{20}$/Al$_2$O$_3$/TbCo$_{20}$/Ta$_{20}$A, (●) TaNiFe$_{50}$/MnRh$_{30}$/NiFe$_{50}$/CoFe$_{20}$/Al$_2$O$_3$/CoFe$_{20}$/, and (●) TaNiFe$_{50}$/AlN/Co$_{20}$/A.

of TMR and junction resistance, $R_J$, for different junctions. For the 0.25mm$^2$-size Type-I AlN junction, both TMR and $R_J$ increase after annealing at 200 °C. This is probably due to improvement of the AlN barrier quality.

For Type-II and Type-III junctions with a size of 0.25 mm$^2$, the TMR is stable up to 200 °C. The resistance changes slightly up to 150 °C and then decreases rapidly at high annealing temperature. For the 0.25 mm$^2$-size junctions, the Al$_2$O$_3$ barrier was prepared using high power (8 mW/cm$^2$) and long duration (2.5 min.) plasma oxidation, in order to avoid geometrically enhanced MR effect. The deposited Al layer (20 Å) was completely oxidized, as supported by the fitted effective barrier thickness (19.5 Å), giving rise to a relatively stable TMR and junction resistance in the low annealing temperature range. At high annealing temperatures, the junction resistance decreases rapidly due to interfusion. The junction structure probably becomes short-circuited. The higher than 20% TMR signal of the 0.25mm$^2$ Type-II junctions after annealing at 260 °C is due to the geometrically enhanced MR effect because the junction resistance becomes lower than 100Ω and comparable to the electrode resistance (20–30 Ω) in the junction area$^{19}$.

For Type-III junctions with a size of 9×2μm$^2$, the TMR increases and junction resistance decreases with increasing annealing temperature up to 200 °C. For the μm$^2$-size junctions, the Al$_2$O$_3$ barrier was always formed using a lower power (6 mW/cm$^2$) and shorter duration (≤2 min.) plasma oxidation than that for the 0.25mm$^2$-size junctions, in order to decrease junction resistance. This may result in a certain amount of pure Al left in the barrier of the μm$^2$-size junctions. In this case, the fitted effective barrier thickness (13 Å) is smaller than the as-deposited Al thickness (18 Å). The unoxidized Al on the surface of the bottom ferromagnetic electrode can significantly influence the behavior of magnetic tunnel junctions. At the FM/Al interface, the FM layer can induce spin polarization in the Al layer, which is lower than the spin polarization of FM materials$^{10}$. So the increase of TMR and the reduction of $R_J$ for the 9×2μm$^2$-size junction may result from further diffusion of oxygen into the unoxidized Al layer in the barrier due to annealing.

4. Conclusions

Spin dependent tunnel junctions with AlN and Al$_2$O$_3$ barriers were fabricated. The TMR is between 1.6% and 24% at RT for junctions with different sizes and barriers. The TMR decreases with increase of bias voltage for all junctions. The 9×2μm$^2$-size junction shows the weakest bias voltage dependence of TMR as well as the largest barrier height and smallest barrier thickness. Annealing results in an increase of TMR and a decrease of $R_J$ for the 9×2μm$^2$-size Al$_2$O$_3$ junctions, while it increases both TMR and $R_J$ for the AlN barrier junctions.

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References