Degradation of magnetic tunnel junctions with thin AlO$_x$ barrier

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Abstract

The degradation of magnetic tunnel junctions (MTJs) with AlO$_x$ barrier was experimentally investigated. Constant voltage stress (CVS) measurement was carried out to monitor the time evolution of the conductance and tunneling magnetoresistance (TMR) of MTJs. The gradual increase of the stress-induced leakage current (SILC) was observed prior to the breakdown, following a power law function of stress time with an exponent of about 0.2–0.4, which is similar to the case of the ultrathin gate oxide films in MOSFETs. The measured TMR for SILC suggests that the spin-dependent current component would be involved in the early stage of degradation, while spin-independent conduction becomes dominant before the breakdown resulting in a decrease of TMR.

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1. Introduction

Magnetic tunnel junctions (MTJs) have been attracting a lot of attentions since a large tunnel magnetoresistance (TMR) was found even at room temperature [1,2]. One of the most promising applications of MTJ is magnetoresistive random access memory (MRAM) [3], which is considered as a candidate for next-generation memory because of its desirable properties: nonvolatility, high reliability, high access speed, etc. MTJ consists of two ferromagnetic electrodes and a thin insulating layer. Because the thickness of the insulting films is very thin (1.0–2.0 nm), their degradation and breakdown phenomena are serious concerns for the long-term reliability of MRAMs. Although the degradation of such thin AlO$_x$ films has been studied by many groups [4–11], its mechanism has not been clarified yet.

In this study, we measured the time evolution of the conductance and TMR under constant voltage stress (CVS) in order to investigate the degradation of ultra thin AlO$_x$ films in MTJs. We focused in particular on the stress-induced leakage current (SILC) observed prior to the breakdown, which has been extensively studied to explore the degradation of ultrathin gate oxide films in metal oxide semiconductor field effect transistors (MOSFETs) [15].

2. Experimental

The MTJ cells with a sandwich structure of CoFeB/AlO$_x$/CoFeB were investigated in this study. The layers of the MTJ stack were formed by sputter-deposition techniques [3]. Two types of oval shaped MTJs with dimensions of 0.7 × 0.4 μm$^2$ (type A) and 0.6 × 0.2 μm$^2$ (type B) were used. The thickness of AlO$_x$ layer was estimated to be ~0.93 nm by fitting the measured tunneling current to Simmons’ equation [12] assuming tunneling effective mass of 0.4$m_0$ [13], where $m_0$ is the free electron mass. The variation of the estimated AlO$_x$ thickness in the samples used is within ±3%, and we believe that this fluctuation does not essentially affect the degradation properties observed in this study.

The measurement procedure is shown in Fig. 1. All the measurements were done with an Agilent 4156B semiconductor parameter analyzer. To degrade the insulting layer we applied the negative stress bias to the top electrode of MTJ whose magnetization state was set to be parallel. The
I applied to MTJ, and range of voltage sweep for monitoring the parallel and anti-parallel states, respectively, limited to 0.5 V, which is much smaller than means a procedure to flip the magnetization state of the top electrode in the MTJ.

degradation was accelerated by applying a stress bias of \( V_{\text{stress}} = 1.65 \text{ V} \), which is higher than the value usually used in the realistic MRAM operations (\(<1 \text{ V}\)). The time evolution of the current through the MTJ during the CVS was monitored until the breakdown occurred. The stress measurement was interrupted periodically to investigate the change of the MTJ characteristics under low bias conditions; \( I-V \) curves were measured for the MTJ both in the parallel and the anti-parallel states, and then bias-dependent TMR was evaluated as

\[
\text{TMR}(V,t) = \frac{I_P(V,t) - I_{AP}(V,t)}{I_{AP}(V,t)},
\]

where \( I_P \) and \( I_{AP} \) are the current through MTJ in the parallel and anti-parallel states, respectively, \( V \) the voltage applied to MTJ, and \( t \) the stress application time. The range of voltage sweep for monitoring the \( I-V \) curves was limited to 0.5 V, which is much smaller than \( V_{\text{stress}} \) and hence additional damage to the insulating layer could be avoided.

3. Results and discussion

Fig. 2 shows a typical example of the time evolution of the current during CVS. In the initial stage of the stress, the current through the MTJ increased gradually, which means that the MTJ became leaky due to the stress voltage application. Then the abrupt increase of the current was finally observed at stress time of \( t = 4850 \text{ s} \) indicating the destructive breakdown of the insulating layer.

Fig. 3 shows the measured \( I-V \) characteristics and the voltage dependence of TMR for the same sample as Fig. 2. The data monitored at \( t = 0 \text{ s} \) (fresh sample) and \( t = 4000 \text{ s} \) (degraded sample just before the breakdown) are plotted. Both \( I_P \) and \( I_{AP} \) increase similarly after CVS, which indicates that the excess leakage current induced by the stress is spin-independent. In addition, TMR degradation is observed to be regardless of the bias voltage. If the current increase in the parallel state (\( \Delta I_P \)) and that in the anti-parallel state (\( \Delta I_{AP} \)) are equal (\( \Delta I_P = \Delta I_{AP} = \Delta I \)), the TMR always decreases as

\[
\text{TMR}(V,t) = \frac{(I_P(V,0) + \Delta I(V,t)) - (I_{AP}(V,0) + \Delta I(V,t))}{I_{AP}(V,0) + \Delta I(V,t)} < \text{TMR}(V,0).
\]

(2)

Fig. 4 shows the voltage dependence of the SILC measured at several stress times for the same sample as used in Fig. 2. Note that, in the early stage of the stress, the \( \Delta I_P \) is slightly larger than \( \Delta I_{AP} \). However, after applying the long-time stress, they become comparable as discussed in Fig. 3. To further confirm this observation, we carried out the same stress experiment using other samples. Fig. 5
compares the time evolution of TMR and SILC measured at \( V = 0.1 \) V for three samples of type-A MTJ. Due to the stochastic nature of the degradation in thin insulating films, the results varied from sample to sample. However, qualitatively same properties are found, e.g., \( \Delta I_P \) and \( \Delta I_{AP} \) increase with \( t \) following a power law function \( (\propto t^m) \). The exponents \( m \) estimated by the fitting procedure are ranging from 0.25 to 0.34 for \( I_P \) and 0.31 to 0.37 for \( I_{AP} \). A similar observation has also been reported for SILC in the thin gate oxide films used in MOSFETs [15], which is often explained by the reaction–diffusion theory, e.g., the power law with \( m = 1/4 \) is driven by the desorption of \( \text{H}^0 \) from Si–H bonds during the stress (the value of \( m \) is dependent on the diffusion species) [16]. This similarity would also provide some information about the degradation process in \( \text{AlO}_x \) film in MTJs. Further investigations on the power law behavior are necessary. In Fig. 5 it is also found that \( \Delta I_P \) is larger than \( \Delta I_{AP} \) in the early stage of the stress, while they are comparable in the last stage. The same trend was also observed in the different type samples as shown in Fig. 6. In Fig. 7 we evaluated the TMR for the SILC defined as

\[
TMR_{\text{leak}}(V,t) = \frac{\Delta I_P(V,t) - \Delta I_{AP}(V,t)}{\Delta I_{AP}(V,t)}.
\]

Although the data fluctuate greatly, \( TMR_{\text{leak}} \) tend to decrease with stress time, and finally they converge to around zero indicating spin-independent current conduction.

It has been previously reported that the excess leakage current component through the post-breakdown MTJ is independent of magnetic polarization of the electrodes, and thus its current conduction channel is considered to be unable to support the spin-polarized current [10]. On the other hand, the gradual decrease of TMR with stress time has been observed in MTJs with very large junction area of 200 \( \mu \)m\(^2\) [11]. In this case the excess leakage is also reported to be spin-independent, and attributed to be due to the creation of conduction channels at the process-induced extrinsic defects such as pin holes and side-wall damages. The existence probability of these weak spots is higher in the larger area samples. In this study, however, much smaller MTJs have been used, and hence we believe that the observed degradation process is an intrinsic phenomenon. Our experimental results suggest that in the early stage of the degradation process the spin-dependent stress-induced leakage current could be observed, unlike with the previous observations for post-breakdown currents [10] and the leakage through extrinsic weak spots [11]. Then, however, the spin-independent component increases with stress time probably due to, e.g., the trap creation [14], which would be a precursor for the final destructive breakdown. Further investigations are necessary to clarify
the conduction mechanism responsible for the SILC depending on or independent of the spin polarization. We believe that the in-depth investigation into the spin dependence of the SILC using MTJ before breakdown would provide helpful information about the degradation process in insulating thin films and might offer some hints for predicting the MTJ lifetime as in the case of Si-MOSFETs [15].

4. Conclusion

The degradation of MTJs with AlOₓ barrier has been experimentally investigated using CVS method. The gradual increase of SILC with stress time has been observed prior to the breakdown, and its time dependence was found to follow a power law function with an exponent of about 0.2–0.4, similar to the case of the thin gate oxide films in MOSFETs. We have also evaluated the TMR of SILC. In the early stage of CVS, the spin-dependent current component would be involved in the SILC, while spin-independent current becomes dominant in the final stage before the breakdown reducing TMR.

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