Tunneling criteria for magnetic-insulator-magnetic structures

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The bias and temperature dependent resistance and magnetoresistance of magnetic tunnel junctions with and without intentional shorts through the insulating barrier were studied. Based on the experimental results, a set of quality criteria was formulated that enables the identification of barrier shorts. While the temperature and bias dependencies of the junction resistance and of the fitted barrier parameters are very sensitive to the presence of such shorts, the same dependencies of the magnetoresistance are surprisingly insensitive. Finally, junctions with a shorted barrier exhibit a dramatic increase in noise level and junction instability. [DOI: 10.1063/1.1413716]

Interest in magnetic tunnel junctions (MTJ) remains strong as their high magnetoresistance[1,2] (MR) allows for sensor, magnetic random access memory,[3] and read-head[4] applications.[5] To reduce the MTJ response time one tries to decrease the junction resistance-area product (RA) by using thinner and thinner insulating barriers—a trend that naturally raises concerns about the possible presence of direct metal–metal contacts through barrier pinholes. On the other hand, recent findings of up to 300% ballistic MR in magnetic nanocontacts[6] suggest that pinholes might *enhance* the device performance by simultaneously contributing to its high MR and low RA. To optimize device performance one hence needs to know whether conduction is dominated by tunneling or not.

Recent advances in microscopic techniques for the study of barrier quality include "hot spot" detection using STM and conductive AFM[7] and ballistic electron microscopy.[8] It should however be noted that typical RA values of about 10^3–10^5 $\Omega\,\mu\mathrm{m}^2$ for tunnel junctions and 10^{-3} $\Omega\,\mu\mathrm{m}^2$ for contacts imply that an ångström-sized contact can dominate the transport properties of a micron-sized junction, obviously putting very high demands on microscope resolution. Pinhole decoration using electrodeposition may relax this resolution requirement.[9] A faster, more convenient, and noninvasive approach would be a set of criteria that one applied to the transport properties of the final integrated device, much in the same way as the so-called "Rowell" criteria[10] are used for superconducting tunneling. Of the original Rowell criteria, only a few remain when none of the electrodes are superconducting (i) exponential thickness dependence of the resistivity (R), (ii) quasiparabolic $dI/dV-V$ curves, and (iii) insulator-like temperature (T) dependence of R. However, (i) and (ii) have recently been shown to be unreliable[11] and only $R(T)$ remains a good indicator of the barrier quality.[11,12] It would hence be of great value if a larger set of reliable criteria could be formulated.

In this work we study the T dependence and bias dependence of R and MR of as-prepared MTJs and MTJs that have been intentionally shorted. We find that neither the T dependence nor the bias dependence of the MR shows any significant features useful to identify a shorted barrier. $R(T)$, on the other hand, clearly changes to weakly metal-like, at all bias levels, once the barrier is shorted. Barrier parameters extracted from fits to Simmons'[13] and the BDR[14] models also show an artificial T dependence in the case of a short. In addition, the shorted junctions exhibit a dramatic increase in noise level already at relatively low bias levels and are also much less stable at high bias.

The junctions were formed by sputter depositing the thin-film material stack on SiO_2-coated Si wafers and then processing the material to form the junctions and interconnects that allow a current to be passed perpendicular to the tunnel junction. Thick metal contact layers were used above and below the MTJ to provide low resistance conductors that eliminate possible current distribution artifacts. The bottom-pinned MTJ material used an IrMn exchange layer, a NiFeCo/CoFe bilayer for the bottom magnetic electrode, and NiFeCo alloy for the top magnetic electrode. The AlO_x tunnel barrier was formed by depositing ~10 Å of Al on the bottom electrode followed by oxidation in a rf-produced oxygen plasma to form a junction with a resistance-area product (RA) of ~8 k$\Omega\,\mu\mathrm{m}^2$. The wafer was annealed at 250 °C to improve the tunnel barrier[15] and then patterned by standard lithographic techniques.

Breakdown studies of these junctions showed a well-defined breakdown voltage V_{bd} with a narrow transition. Bits were exposed to progressively higher bias voltages as their resistance, measured at low bias, began to drop. The average V_{bd} was 1.15 V and the width of the transition from 5% loss of resistance to 90% loss of resistance was only a few tens of

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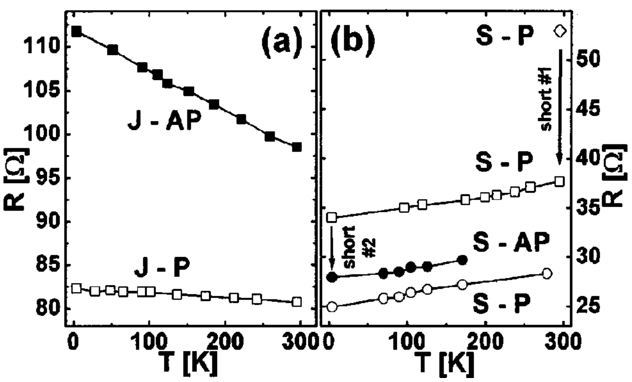

FIG. 1. (a) $R(T)$ for sample J in both the antiparallel (■) and parallel (□) magnetic states; (b) same for sample S. Open diamond and arrow show R before and after the first short was introduced. Small contact, P state (□); large contact, AP state (●); large contact, P state (○).

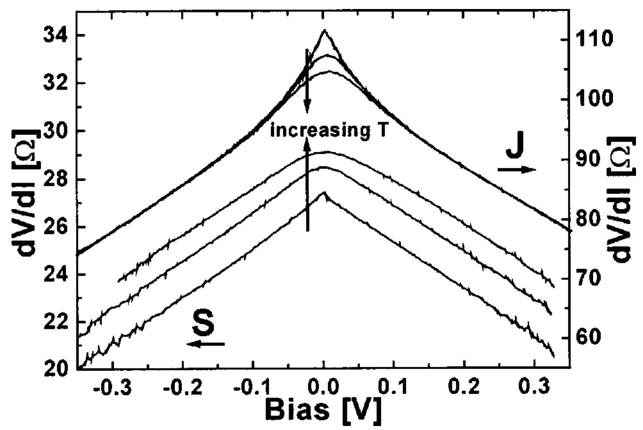

FIG. 2. Differential resistance vs applied bias at 4.2, 90, and 155 K, respectively. Three top curves: sample J; three bottom curves: sample S.

mV. Measurements on 30 different bits showed bit-to-bit standard deviation of only 0.1 V.

All samples had lateral dimensions of $10\times10\,\mu\text{m}^2$ and were taken from the same wafer. At room temperature (RT) and in the parallel state (P) $R=78\ \Omega$ for sample J (junction) and 53 Ω for sample S (short), corresponding to $RA=7.8$ and 5.3 k$\Omega\,\mu\text{m}^2$, respectively. Sample J had a MR of 36% at 4.2 K and 23% at RT. From the narrow distribution of same-wafer MR values[3] we assume that sample *S* had the same MR as *J* before being shorted.

Sample S was exposed to a voltage pulse above its breakdown voltage, which induced a short in the barrier and reduced R at RT to 38 Ω. After an initial cooldown to 4.2 K the same sample was again exposed to a voltage pulse which further reduced R to 25 Ω and all subsequent measurements on sample S were carried out in this shorted state.

Figure 1(a) shows $R(T)$ for sample J in both magnetic states. The weakly insulator-like T dependence proves[11,12] that sample J has an integral tunneling barrier and that electron tunneling dominates the conduction in this device. Figure 1(b) similarly shows $R(T)$ of sample S for two different number (or sizes) of shorts through the barrier. The open diamond marks the original R of 53 Ω before any short was induced. $R(T)$ of the shorted junction is in all cases weakly metal-like. These results corroborate the validity of $R(T)$ as a reliable criterion for tunnel junction barrier quality. It is noteworthy that $[1/R(0)]dR/dT$ of sample S in the P state is $3.6\times10^{-4}\,\text{K}^{-1}$ after the first short and $5.0\times10^{-4}\,\text{K}^{-1}$ after the second, i.e., the metallic behavior increases with increasing conductance contribution from the short.

The resistance of sample S in the P state is 24.9 Ω at 4.2 K, which corresponds to a short of about 47 Ω in parallel with the original junction. Assuming that the remaining junction area still has a MR of 36% one expects $R=28.4\ \Omega$ in the *AP* state, which is very close to the observed 27.9 Ω. The expected MR is 14%, again very close to the experimentally observed 12%. The short does not seem to introduce any significant MR on its own that would add to the tunneling MR. Since little is known about the magnetic nature of the short that forms upon breakdown of a tunnel junction barrier; we are not surprised by this loss of MR. For example, there may be many small shorts and they may have a complex morphology leading to complex domain states, or they may not be ferromagnetic at all.

Figure 2 shows $dV/dI-V$ for samples J and S in the *AP* state at 4.2, 90, and 155 K, respectively. Again $R(T)$ is completely different for the two samples. It is interesting to note that the evolution of $R(T)$ with increasing bias is entirely different for the two junctions. Above an absolute bias level of about 0.1 V, sample J exhibits a vanishing T dependence. The metal-like $R(T)$ of sample S on the other hand is equally apparent at all bias levels and consistent with a short with no bias dependence.

The short will inevitably alter the *apparent* barrier parameters that are extracted from fits to either Simmons'[13] or the BDR[14] model. It is important to note that the *apparent* barrier parameters are just fitting parameters with no real physical significance, especially for sample S. While the fitted barrier parameters of sample J are only weakly T dependent, both the barrier thickness and the barrier height of sample S vary more strongly with T (Fig. 3). The short effectively decreases the apparent barrier height and increases the apparent barrier width, more so as its conductivity increases with decreasing T. The observation of a sudden drop of the fitted barrier height accompanied by an *increase* in the fitted barrier width, in a study of barrier parameters versus insulator thickness, would consequently mark the first appearance of a pinhole through the insulator.

Figure 4(a) shows the T dependence of the normalized MR of both samples J and S. Although the absolute MR decreased from 36% to 12% as the short was introduced, the

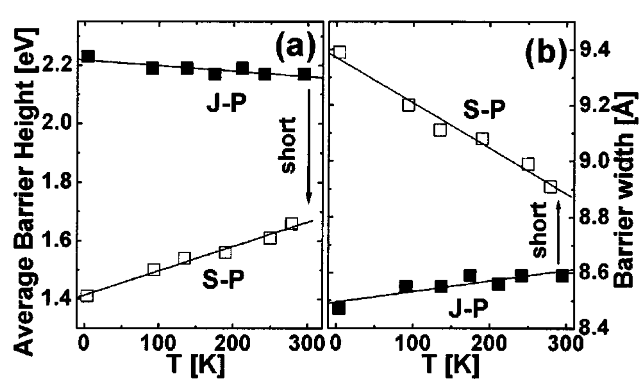

FIG. 3. Average barrier height (a) and barrier width (b) vs T for sample J (■) and S (□) in the parallel state. Straight lines are guides to the eye.

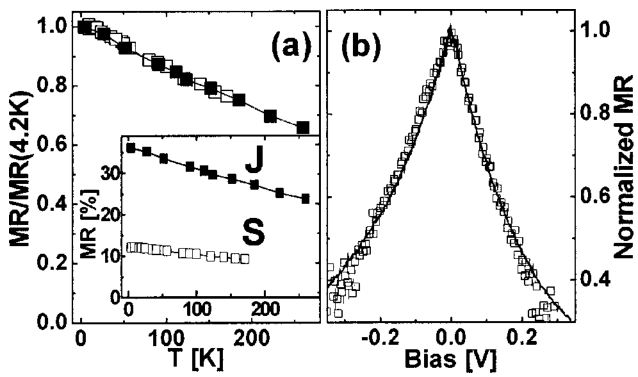

FIG. 4. (a) *T* dependence of the normalized differential MR for sample J (■) and *S* (□). Inset: same data before normalization; (b) bias dependence of the differential magnetoresistance of sample J (−), and S (□).

overall shape of the *T* dependence is still virtually identical. The short has an equally insignificant effect on the bias dependence of the MR [Fig. 4(b)]. The shape of the MR dependence is hence of very limited use as an indicator of the barrier quality, at least for the type of MTJs studied in this work.

A striking difference between samples J and S is the noise level at finite bias. While our measurement setup does not detect any bias dependence in noise level for sample J, sample S shows strongly increasing noise for $|V|>0.2\,\mathrm{V}$ (Fig. 2). The additional noise in sample S is likely to come from Johnson noise over the metallic contact. A contact with $\mathrm{RA}=10^{-3}\,\Omega\,\mu\mathrm{m}^2$ has to sustain a huge current density of $2\times10^{10}\,\mathrm{A\,cm}^{-2}$ at 0.2 V, which will raise the local temperature, hence the increase in noise with increasing bias.

Other shorted junctions also showed greater instability above 0.2 V and *R* could change dramatically both to lower and higher values if too high a bias was applied. If the bias is continuously increased, a weakly shorted junction will eventually breakdown completely at about 0.5 V leaving a fully shorted device with very low *R* and MR. Again, the huge current density is expected to lead to electromigration, which may alter the size of the contact.

In conclusion, our experimental results suggest the following criteria to ascertain whether an magnetic–insulator–magnetic trilayer contains a short in parallel with the insulator: (i) metal-like $R(T)$ at all bias levels, (ii) decreasing fitted barrier height and increasing fitted barrier thickness for decreasing *T*, (iii) increased junction noise at finite bias, and (iv) increased junction instability at finite bias.

Note added in proof: During corrections of the galley proofs of this manuscript, Zhang and coworkers reported that with decreasing oxidation of ultrathin tunneling barriers, both RA, TMR and the extracted barrier height decrease, while the apparent barrier width increases.[16] These results are in good agreement with criterion (ii), assuming the appearance of barrier pinholes as the true barrier thickness is decreased. A recent report by Versluijs, Bari, and Coey of MR in excess of 500% in Fe_3O_4 nanocontacts, gives further emphasis to the need for such criteria to distinguish between tunneling and direct metallic conduction.[17]

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