Electrical noise in hysteretic ferromagnet–insulator–ferromagnet tunnel junctions

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Low frequency noise has been measured in magnetic tunnel junctions that have Al_2O_3 tunnel barriers and magnetoresistance values up to 35% at 295 K. Fluctuations in voltage were found to cross over from Johnson noise to shot noise at low bias voltages, in quantitative agreement with theories of noise in quantum ballistic systems. $1/f$ resistance noise, where f is frequency, predominates at larger biases and is proportional to the mean current squared. This noise is attributed to trapping processes and it depends sensitively on the relative position of the oxide edge and the ferromagnet–Al interface. *© 1999 American Institute of Physics.* [S0003-6951(99)03304-5]

Only recently has it been possible to grow magnetic tunnel junctions reproducibly with large magnetoresistance (MR). Such junctions consist of two ferromagnetic (FM) metal layers separated by a thin insulating layer. The spin dependence of electron tunneling makes these junctions attractive candidates for magnetic sensor and digital memory storage technologies. For memory applications, it is desirable to have hysteretic junctions exhibiting sharp transitions between two magnetic states at small applied fields. Because the spin-polarized tunneling probability depends on the relative orientation of the magnetization vectors in the two magnetic electrodes[1,2] one can detect a ''recorded'' magnetic state by a simple measurement of the junction resistance. The detection sensitivity to resistance changes will be limited by the intrinsic noise of the junction. Identifying the origin of noise is then particularly relevant to fabricating junctions with optimal magnetoelectronic properties.

This letter reports measurements of voltage noise as a function of temperature, T, and direct current (dc) current bias, I, in junctions that show fractional changes in resistance with magnetic field in excess of 25% at 295 K. These junctions were prepared by dc sputtering through metal masks onto Si wafers, similar to previous studies.[3] A series of masks were used to define a cross geometry pattern; each junction had an area of about 3200 μm^2. The final layered structure is given by $Si/SiO_2/5Ti/15Pd/10Mn_{46}Fe_{54}/3Co_{84}Fe_{16}/Al_2O_3/8Co_{84}Fe_{16}/20Pd/5Ti$ where the numbers represent the nominal layer thicknesses in nanometers. A layer of Al with thicknesses, d, ranging from 1.2 to 3.0 nm, was deposited. An oxygen plasma was used to form the insulating barrier of Al_2O_3 and, for small d, some oxidized FM. We find that as the voltage, V, across the junction is increased, three characteristic regimes in the power spectral density of the voltage fluctuations, $S_V(f)$, emerge: (i) Johnson noise, (ii) current shot noise, and (iii) at low frequencies and for the highest biases, fluctuations in the tunneling resistance are apparent for which $S_V \sim I^2/f$, where f is frequency. The origin of the $1/f$ noise is consistent with charge trapping in the oxide. In particular, we find that the quality of the FM/Al interface has the greatest effect on the magnitude of the $1/f$ noise. We discuss implications of the $1/f$ noise at low frequencies and the shot noise at high frequencies for magnetic device applications.

Measurements of the dc and differential tunneling resistance ($R_d = dV/dI$) and the voltage noise were made using a four-terminal method with an applied magnetic field H in the plane of the junction and along the exchange-bias field direction. The magnetoresistance curves of these junctions at $T = 295$ K are hysteretic (square shaped) with sharp transitions at applied fields $H \approx \pm 20$ Oe. The high and low resistance states are associated with the top electrode's magnetization being oriented either antiparallel (AP) or parallel (P) with the bottom electrode's magnetization, which is pinned by exchange bias with the antiferromagnetic MnFe layer. The maximum MR ratio, defined as $(R_{AP} - R_P)/R_P$, was 35% at $T = 295$ K for a 1.6-nm-thick Al layer. Junction resistances ranged from 1.5 to 37 kΩ depending on the Al film thickness. Upon cooling to 4.2 K, the junctions showed a 25% increase in the zero-bias differential resistance. The current–voltage *(I–V)* characteristics were fit to Brinkman's theory of tunneling.[4] At $T = 295$ K, the fitted average barrier heights and asymmetries for the P orientation ranged from 3.2 to 4.2 eV and 0.6 to 1.0 eV, respectively. The high MR, weak temperature dependence of R_d, and the reasonable values of the barrier heights indicate that a good tunnel barrier between the FM metals is achieved.[5] Next, we will discuss features of the noise that are common to all junctions in either the P or AP configuration.

Voltage noise under constant current bias was generally found to be comprised of a frequency independent component (white noise) and a $1/f$ part, similar to results on nonmagnetic tunnel junctions.[6] Figure 1(b) shows that at $T = 4.2$ K, the power spectrum is white and increases linearly with the current, $S_V(f) \propto I f^0$, at moderate currents. $1/f$ noise

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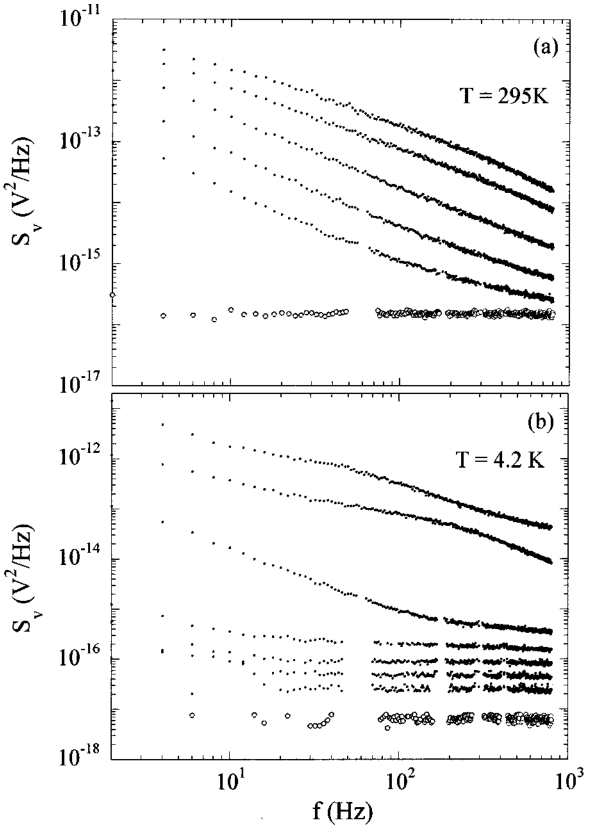


FIG. 1. Power spectra $S_V(f)$ of the voltage fluctuations are plotted as a function of dc current bias, I. Data is for a junction with Al thickness $d=2.0$ nm in the AP orientation. For successive spectra from bottom to top, $I=0$, 3, 6, 12, 24, and 36 μA in panel (a) and 0, 0.75, 1.5, 3, 6, 12, 24, and 36 μA in (b). At $T=295$ K, $1/f$ noise having $S_V(f)\propto I^2/f$ is the principal type of noise at low frequencies. Shot noise, $S_V(f)\propto If^0$, is the prevailing noise at 4.2 K and at low biases, but is outweighed by $1/f$-like noise at the higher currents.

becomes prominent at higher currents, scaling roughly as I^2/f. The dependence on I^2 indicates that the $1/f$ noise is due to resistance fluctuations in the junction. At $T=295$ K [Fig. 1(a)], nearly all the noise is $1/f$-like over the frequency range. The power spectral density of the measured noise is well described by

$$S_V(f)\cong 2eI\coth\left(\frac{eV}{2k_BT}\right)R_d^2+\alpha\frac{I^2R_d^2}{Af}, \qquad (1)$$

where e is the charge of the electron and k_B is the Boltzmann constant. α, a function of T, parameterizes the $1/f$ noise magnitude. If the $1/f$ noise comes from homogeneous local fluctuations, α will be independent of the cross-sectional area, A, of the junction for a fixed barrier thickness. This is a consequence of the usual statistics of independent random variables.

The white part of the power spectrum arises from a combination of Johnson noise and current shot noise. In the absence of interactions of the tunneling electrons with various excitations inside the tunnel barrier,[7] the tunnel junction may be viewed as a ballistic conductor for which all transmission probabilities are very small. In the low frequency limit ($f\rightarrow 0$) the spectral density of the voltage noise is given by the shot noise relation [the first term in Eq. (1)].[8–10] Hence, at low bias voltages $V\ll k_BT/e$ the noise is given by the Nyquist theorem, $S_V=4k_BTR_d$, and in the opposite case one finds the full shot noise, $S_V=2eIR_d^2$. The $1/f$ noise part, on the other hand, involves interactions of electrons with defects in or near the tunnel barrier.

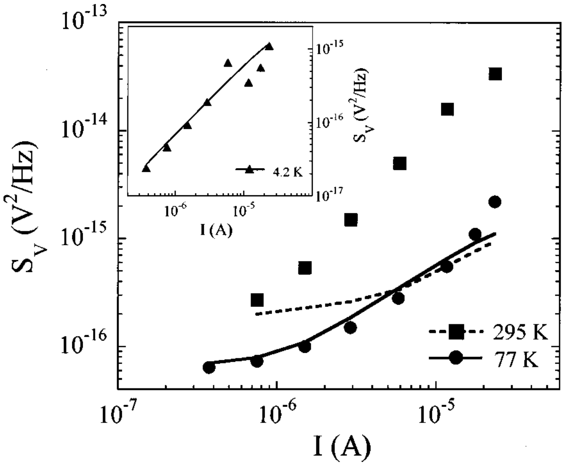
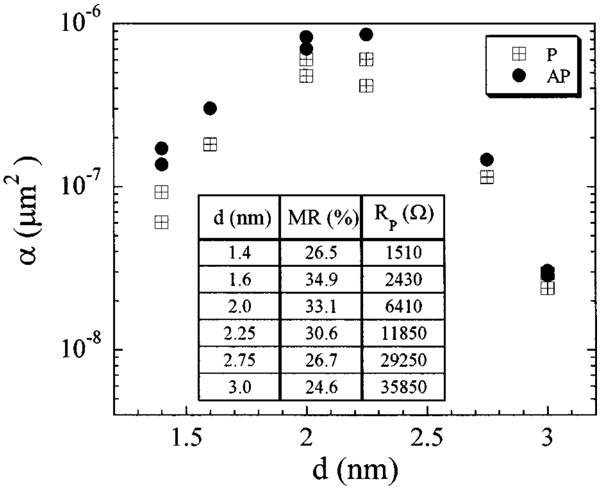


FIG. 2. Current dependence of $S_V(f\sim 1$ kHz) is shown for a junction with Al thickness $d=2.25$ nm in the P orientation and having $R_d\approx 14.5$, 14, and 12.5 kΩ at 4.2, 77, and 295 K, respectively. The lines in the main panel and inset are given by the shot noise relation [first term in Eq. (1)], evaluated at the corresponding temperature. Good agreement with this relation is obtained at low T. At $T=295$ K, resistance fluctuations having $S_V\propto I^2$ obscure the shot noise component (dashed line) over our experimental bandwidth. Crossovers from Johnson noise to shot noise and to $1/f$ resistance noise are evident at $T=77$ K.

In Fig. 2 we plot $S_V(f\sim 1$ kHz) versus I for three temperatures. Using the measured $R_d(I)$ for this junction, the first term in Eq. (1) was evaluated at the various temperatures and is depicted by the lines shown in Fig. 2. At $T=4.2$ and 77 K there is excellent quantitative agreement at low biases between the measured noise power and that predicted by the shot noise relation. Deviations from the shot noise relation at larger currents are due to $1/f$ noise which scales as I^2 and, for sufficiently large currents, comes to predominate over the white noise part at a given frequency. At room temperature, the $1/f$ noise greatly exceeds the Johnson noise and the shot noise at low frequencies (dashed line in Fig. 2), indicating that α increased sharply above 77 K. Because R_d is found to decrease with I, the dependence of the $1/f$ voltage noise power on current is somewhat weaker than I^2, exhibiting a roll off at large I.

Resistance fluctuations often displayed a featureless $1/f$-like power spectrum. Strong deviations from a $1/f$ spectrum [e.g., Fig. 1(b)] were associated with the presence of discrete, large amplitude fluctuators in the voltage-time traces, i.e., random telegraph noise. Telegraph noise was commonly observed for $V>100$ mV and often depended sensitively on bias conditions, see also Ref. 11. The sensitivity to bias conditions gives rise to peculiar dependences of S_V on I, such as the nonmonotonic behavior observed at 4.2 K in Fig. 2. The sharp drop in noise that occurs near 10 μA coincides with a predominant two-state fluctuator that was active in our frequency bandwidth only for a narrow range of currents above 10 μA. Such unusual behavior, however, depends on the details of the telegraph noise, which varies considerably among junctions. It is also much less pronounced at 295 K.[11]

Shot noise was sometimes found suppressed, e.g., see the inset of Fig. 2 where some data points lie below the line



d (nm)	MR (%)	R_P (Ω)
1.4	26.5	1510
1.6	34.9	2430
2.0	33.1	6410
2.25	30.6	11850
2.75	26.7	29250
3.0	24.6	35850

FIG. 3. Shown is the dependence of the normalized excess $1/f$ noise, $\alpha = f S_R A / R_d^2$, on the thickness of the Al metal. Data is for $T = 295$ K. The table lists the same dependence for the average MR and tunneling resistance. Both the MR and the noise exhibit a broad peak near 2.0 nm.

which corresponds to shot noise. This effect was always accompanied by large telegraph noise, discrete fluctuations as large as 0.1% of the tunneling resistance, indicating that current flow across the junction is inhomogeneous,[11] at least at these large biases. If the majority of current passes through localized regions in which the probabilities of transmission are high, then the suppression of shot noise is expected due to electron–electron anticorrelations.[12] Moreover, evidence for inhomogeneous current flow at high currents suggests that the resistance noise may not scale accurately with inverse area, contrary to the assumption in Eq. (1).

Several factors indicate that the origin of the telegraph and $1/f$ noise is charge trapping in the barrier or near the FM–insulator interfaces,[11] rather than magnetic domain fluctuations that couple to the resistance.[13] If magnetization fluctuations were driving the noise, then the effect of a magnetic field large enough to saturate the MR would be to suppress the noise. However, changes in field for a given magnetic orientation of the FM electrodes had no detectable effect on the noise. The absence of field dependence and the sensitivity of the telegraph noise to bias conditions support a charge trapping mechanism. The trapping of an electron at a defect in the barrier can locally raise the effective tunneling barrier height and directly affect the transmission of electrons.[14]

Reduction of the $1/f$ resistance noise relative to the junction's MR ratio may come with improvements in materials and processing. Since tunneling electrons come from the top few monolayers of the FM film, surface properties are important. It is not easy to completely oxidize the barrier Al film without oxidizing the underlying FM surface and thereby affecting the quality of the interface.[15] In Fig. 3, the normalized magnitude of the $1/f$ noise, $\alpha = f S_R A / R_d^2$, is plotted as a function of Al barrier metal thickness for a fixed oxidation condition. From the table in Fig. 3 it can be seen that both MR and α exhibit a broad maximum near $d = 2.0$ nm, and that the peak in the noise is not an artifact of the normalization. These values of α are up to 50 times lower than those previously reported in low-MR junctions.[11] We consistently find large α in the AP orientation, but typically by less than a factor of 2. We are uncertain as to the origin of this difference. Since the noise results from barrier fluctuations driven by charge trapping, the increased noise in the AP state may indicate stronger sensitivity of R_d to the barrier height, which may be related to the greater dependence of R_d on bias voltage observed in the AP state. More precise modeling is needed, however.

Noise can arise both at the boundaries and inside the barrier. Above some value of d, the oxide will not reach the FM–Al interface, leaving a nearly d-independent thickness of Al_2O_3 and a weakly d-dependent R. These samples appear to approach that regime near $d = 2.5$ nm. In that same regime, Fig. 3 shows that α drops dramatically indicating that an oxidized FM–Al interface is a major source of the noise. The increase in α as a function d at lower d is not understood since many factors (including the position of the interface within the barrier) may affect α. Another leading factor might be an increase in defect density associated with the FM and the interfacial region being less uniformly oxidized as d is increased.

An important consideration for magnetic device applications is that current shot noise can set the ultimate sensitivity to resistance changes at high frequencies. The optimal junction bias, corresponding to the maximum signal to noise ratio, will depend on how the MR decreases with bias.[5] A suitable bias may be a few times $k_B T / e$; it is small enough that it maintains a large value of the junction MR and keeps the shot noise and $1/f$ noise small. Although these devices had magnetic response optimized for hysteretic memory elements, very similar considerations for barrier thickness and avoidance of oxidation of the FM–Al interface should apply as well in minimizing noise of junctions optimized as field sensors.

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