

Noise properties of ferromagnetic tunnel junctions

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We report measurements of voltage fluctuations in magnetic tunnel junctions which exhibit both high and low magnetoresistance (MR). The voltage noise power normalized to the square of the junction bias voltage was 10^{-14} /Hz at a frequency of 1 Hz in a high MR junction. Low MR junctions had significantly higher noise power at 1 Hz and the origin of the noise was not magnetic. In these junctions, random telegraph noise was observed over a wide range of temperatures and junction biases. The results are consistent with a two-channel model of conduction, one of which is spin independent and gives rise to large noise. A noise measuring technique provides evidence for bias-dependent current-path rearrangements. The data support the existence of an inhomogeneous (filamentary-like) current-flow pattern across the tunnel junction associated with the spin-independent channel. © 1998 American Institute of Physics. [S0021-8979(98)09023-9]

I. INTRODUCTION

Recently, it has become possible to fabricate magnetic tunnel junctions, consisting of a thin insulating film sandwiched between two ferromagnetic electrodes, which exhibit magnetoresistance near the theoretical maximum.^{1–3} The magnetoresistance (MR) is attributed to the spin-polarized tunneling probability which depends on the relative orientation of the magnetization vectors in the two magnetic electrodes.⁴ In the parallel configuration, the density of occupied states of the majority carriers in one electrode is well matched with the density of unoccupied majority states in the other electrode. Hence, the tunneling probability is high and the tunneling resistance is low. In the antiparallel configuration, the mismatch between the number of occupied majority states and unoccupied minority states leads to a high tunneling resistance. The two electrodes can be “engineered” to have different coercive fields so that an applied field can alter the relative orientation of their magnetization vectors and thus affect the tunneling resistance.

The large magnetoresistance (25%–30%) at room temperature holds promising opportunities for the digital storage industry. The applications of these junctions depend on their noise properties, which in turn are expected to depend sensitively on the quality of the insulating barrier and the ferromagnetic–insulator interfaces. In this respect, noise studies can provide valuable information regarding both the nature of the tunneling conduction and the quality of the junctions. In this article, we report measurements of the voltage noise in junctions as a function of voltage bias, temperature, and magnetic field. We specifically draw a comparison between junctions having nearly equivalent magnetic electrodes but displaying markedly different MR. Junctions ex-

hibiting high MR were found to have significantly smaller noise power than low MR junctions. The results indicate that the ultimate noise floor of these junctions may be set by Johnson and shot noise, at least for low junction biases. When the measured MR falls below the theoretical maximum,^{4,5} the transport data are well described by a two-channel model consisting of a spin-dependent and a spin-independent conduction channel. In such junctions, large $1/f$ noise is typically found and occasionally random telegraph noise is observed. These properties are associated with the spin-independent channel. Moreover, measurements of the noise as a function of alternating voltage bias indicate that current flow through the low MR junctions is filamentary in nature.

II. EXPERIMENT

We choose to examine two types of layered structures: type A, Si(100)/50Ta/150Al/40Ni₈₁Fe₁₉/100Mn₅₄Fe₄₆/30Ni₈₁Fe₁₉/15Co/12Al₂O₃/150Ni₄₀Fe₆₀/200Al with MR < 5% and type B, Si(100)/50Ti/150Pd/100Mn₅₀Fe₅₀/40Co/12Al₂O₃/75Ni₄₀Fe₆₀/200Pd/50Ti with MR > 22%. The numbers represent the layer thicknesses in Å. Details of the fabrication process have been published elsewhere.^{3,6} Briefly, the junctions were prepared by dc sputtering through metal masks. A series of masks were used to define a cross-geometry pattern; each junction had an area of $80 \times 80 \mu\text{m}^2$. The tunneling barrier is formed by plasma oxidizing an Al layer, having a thickness $d = 12 \text{ Å}$, in 100 mTorr of O₂ for 4 min. The materials used to define the tunnel junctions in each structure are nearly identical, although factors that affect the quality of the junction may differ, for example, the degree of smoothness of the films or the presence of defects in the barrier. The 30Ni₈₁Fe₁₉/15Co layer and the 40Co layer comprise the bottom magnetic elec-

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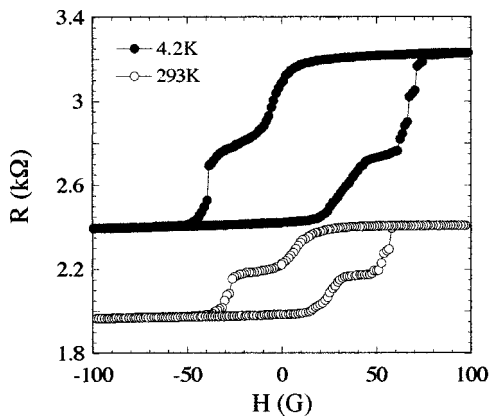


FIG. 1. The magnetoresistive response of a type B (Co/Al₂O₃/NiFe) tunnel junction is shown at two temperatures. The magnetic field is applied colinear with the easy axis as defined during the growth process. A dc current biases the junction at approximately 25 mV. The high resistance state corresponds to antiparallel alignment of the magnetization in the two ferromagnetic electrodes.

trode and their magnetizations are pinned by exchange bias from the antiferromagnetic MnFe layers. A NiFe layer having a low coercive field forms the “free” top magnetic electrode. Measurements of the dc and differential tunneling resistance ($R_d = dV/dI$) using a four-probe sample geometry were made as a function of temperature T , junction voltage bias V , and magnetic-field H parallel to the plane of the junction and colinear with the easy axis.

In addition, voltage noise with spectral density $S_V(f)$ was measured under ac and dc current biases. The low-frequency properties of the voltage noise in response to a current bias that alternated rapidly between two values were used to study the current flow pattern through the junction. The technique is described in detail elsewhere.⁷ Briefly, the junction is connected alternately to two current biases I_1 and I_2 using a 1 kHz oscillator that controls commercial electronic switches. Additional synchronized switches separate the voltage fluctuations across the junction under the different biases into two channels. To avoid saturation of amplifiers, a “noise-free” compensating dc voltage is applied to each channel during the half-cycle associated with the other bias. The two signals then pass through a low-pass filter and into a spectrum analyzer that accumulates time traces of the noise and computes the power spectrum of each channel as well as the coherence function.

III. RESULTS

The magnetoresistance of a typical, high MR, type B junction is shown in Fig. 1. The low resistance state R_p reflects the parallel alignment of the magnetization in each of the two ferromagnetic (FM) electrodes. Since the bottom electrode’s magnetization vector is pinned by the MnFe exchange bias layer, only the magnetization in the top electrode is free to reorient at these low fields. At high positive fields the magnetizations are antiparallel and the resistance R_{ap} is largest. The MR ratio is defined as $(R_{ap} - R_p)/R_p \approx 34\%$ and 22% at $T = 4.2$ and 293 K, respectively. The size of the MR

effect can be understood within the simple model proposed by Julliere.⁴ The MR ratio for these junctions should be given by

$$\Delta R/R_p = (R_{ap} - R_p)/R_p = 2P_{Co}P_{NiFe}/(1 - P_{Co}P_{NiFe}),$$

where P_{Co} and P_{NiFe} are the spin polarizations of the Co and NiFe electrodes. Using the low-temperature value for $\Delta R/R_p \approx 34\%$ and taking the value of 34% for P_{Co} , this expression gives $P_{NiFe} = 42\%$, which compares favorably to values reported in the literature.⁸

In comparison, the type A junctions by design had relatively low MR ratios ranging from 3% to 5%. A variety of factors can reduce the observed MR, such as interfacial and barrier spin scattering; direct coupling of the two electrodes ferromagnetically, which is mediated by surface roughness; surface degradation of the FM films, and domain walls in the junction areas. In addition, we have observed that junctions with reduced MR also had significantly lower tunneling resistance (by a factor ranging from 4 to 20) for nominally identical barrier thicknesses. This suggests the existence of an additional conduction mechanism (see discussion below).

The resistive transition as a function of field passes through an intermediate value of resistance, which is evident in Fig. 1. An intermediate state was also found in magnetization measurements using a superconducting quantum interference device magnetometer. The origin of this state is not clear, but it is not a generic property of all magnetic tunnel junctions. (Other junctions, not reported here, have shown very sharp transitions without such intermediate states.) The magnetic reversal mechanism can be complex, involving a combination of rotation and domain-wall motion and/or the nucleation of reversed domains that sweep through the whole electrode when the domain pinning force is exceeded. The intermediate state may be related to the orientation of the top electrode’s easy axis, which could be rotated relative to the exchange pinning direction induced during film deposition. Then, near zero applied field, the magnetization of the top electrode can revert to pointing along its easy axis, thereby affecting the tunneling probability. (Details are deferred to a future publication.) Two-step transitions were a common feature among both types of junctions studied. We next discuss the properties of low and high MR junctions separately.

A. Type A junctions

Generally, the tunneling resistance of these low MR junctions increased sharply below $T \approx 200$ K. Plotted in the inset of Fig. 2 is the resistance as a function of temperature at $H = 0$ G for a typical junction; application of a magnetic field had a negligible effect on the general form of this curve. The temperature dependence is not well described by either the usual T^2 dependence for an ideal junction,⁹ an Arrhenius form, or by the variable range hopping model¹⁰ in two or three dimensions with or without Coulomb interactions. This strong temperature dependence is to be contrasted with that for type B junctions for which the tunneling resistance increased only by tens of percent ($\sim 30\%$) on cooling down to 4.2 K. The $I-V$ curves of type A junctions were weakly nonlinear at room temperature and the tunnel conductance was parabolic at low biases ($V < \pm 20$ mV). Fits to the Sim-

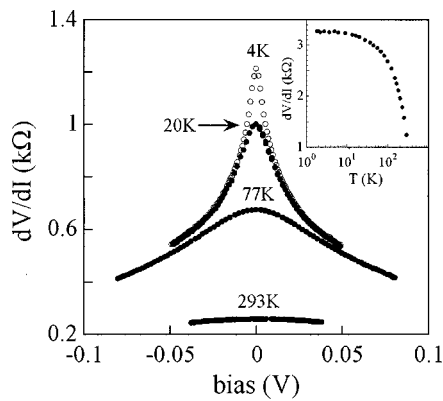


FIG. 2. Plot of the differential resistance spectra for a type A (NiFe/Co/Al₂O₃/NiFe) junction. For $T < 77$ K, the high-bias resistance remains temperature independent whereas a prominent resistance peak develops about zero bias. The relative orientation of the electrode magnetizations had negligible effect on the shape of these spectra. The inset shows the temperature dependence of the zero-bias resistance at $H = 0$ G for another type A junction.

mon's tunneling model⁹ yielded values for the barrier height and barrier thickness that were, respectively, much larger and considerably smaller than expected for Al₂O₃ barriers.⁹ At low temperatures the I - V curves were strongly nonlinear and the differential resistance R_d exhibited a sharp maximum at zero bias, often referred to as a zero-bias anomaly (ZBA). A ZBA was a common feature in the ten junctions studied, for an example, see Fig. 2. At $T = 4.2$ K the resistance maximum is nearly a factor of 2 larger than the background resistance. Below 77 K, R_d vs V shows both temperature-dependent and temperature-independent components with the temperature-dependent component occurring at low junction bias corresponding to the ZBA regime. The relative orientation of the electrode magnetizations had negligible effect on the overall shape of the R_d vs V curve. We also found that the shape of the resistance maximum was not sensitive to magnetic fields even at extreme conditions, $T = 1.8$ K and $H = 60$ kG. Instead, R_d remained linear with voltage bias, $V < \pm 50$ mV. Hence, scattering by a magnetic impurity in the barrier or at the interface is not a likely origin for the ZBA.^{9,11}

Figure 3 shows an example of the voltage fluctuations measured across a junction which was biased with a dc current at $T = 4.2$ K. The random telegraph character of the voltage fluctuations is clearly evident in our measurement bandwidth. Such behavior was typical over the entire range of temperatures measured, $4 < T < 295$ K. However, random telegraph signals were not reproducible under nominally identical conditions; either a distinct fluctuator would spontaneously become active or dormant, or undergo a significant change in its duty cycle over the course of seconds to hours. The two voltage versus time traces in Fig. 3 demonstrate that the predominant fluctuator is not sensitive to magnetic field; the two traces were taken immediately before and after a step change in field corresponding to a reversal of magnetization in the top electrode. The corresponding power spectra of these two traces were essentially identical and well described by the same, single Lorentzian superimposed on a $1/f$ back-

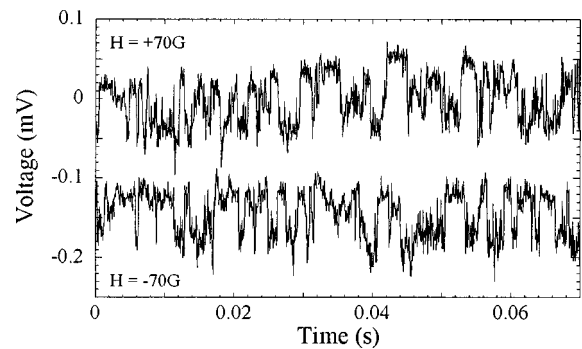


FIG. 3. Voltage fluctuations are shown at $T = 4.2$ K and for a bias voltage of 40 mV across the type A junction. The two time traces (offset for clarity) were taken immediately after a step change in field of 140 G, corresponding to a jump from the low to high resistance state. The noise was unaffected by the relative orientation of the ferromagnetic layers.

ground. Moreover, 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. One may expect an increase in noise near the transition region in the R - H curve, where dR/dH is large. However, no such increase was found at room temperature. At 4.2 K, the strong voltage bias dependence of the noise (discussed below) can cause the noise to change abruptly (either to increase or decrease) in the transition region.

The random telegraph character was less pronounced at higher temperatures. In these cases, the power spectrum had a $1/f$ -like power-law dependence at low frequencies and scaled nearly as the square of the current since the I - V relation was nearly linear. At higher frequencies no noise power was found above the Johnson noise of the resistance of the junction plus the leads. Two-probe voltage noise measurements of the electrodes demonstrated that the observed $1/f$ noise was entirely due to the tunnel junction. The typical normalized noise power at $f = 1$ Hz was quite large, $S_V/V^2 = 2 \times 10^{-9}$ /Hz.

The large noise power can be attributed to the presence of discrete, large amplitude fluctuators in the voltage-time traces. A superposition of many independent fluctuators with a broad distribution of characteristic switching time scales is well known to give rise to $1/f$ noise.^{12,13} We have observed discrete fluctuations in voltage as large as 0.3% of the junction bias. If we assume uniform current flow through the junction, then this implies a resistance fluctuation affecting an area of nearly $20 \mu\text{m}^2$ of the junction. Such a scenario is very unlikely, leaving inhomogeneous transport across the junction as a more plausible hypothesis.

We observed that a small change in the current bias would often replace a distinct fluctuator with another having a different amplitude and duty cycle. This behavior was particularly prevalent at low temperatures. A direct example of how different bias conditions can sample different fluctuators is shown in Fig. 4 for $T = 4.2$ K. In each panel the two time traces were measured simultaneously and correspond to the low-pass filtered voltage fluctuations at the two alternating biases. Figure 4(a) shows the time traces for $V_1 = 39$ mV and

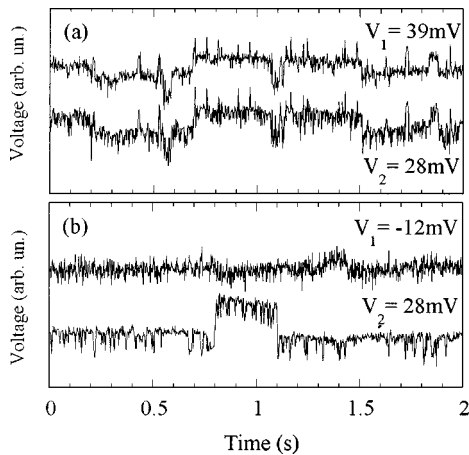


FIG. 4. Time traces of the low-frequency fluctuations when a fast alternating square-wave bias is applied across the junction. Data are for $T=4.2$ K and at $H=0$ G. In (a) the two alternating biases are nearly equal and the time traces are strongly correlated. In (b) a large fluctuator is present in the bottom trace but is absent in the top trace.

$V_2=28$ mV. Under these conditions the fluctuations in the two channels appear strongly correlated. However, in Fig. 4(b) the top trace shows a featureless fluctuating signal whereas the bottom trace indicates the presence of a large fluctuator. This fluctuator is only observed under V_2 and is not present at the lower bias in the upper time trace.

The correlation between noise signatures at different biases can be quantified using the coherence function. The coherence function is defined as

$$\gamma^2 = \frac{\langle S_{1,2}(f) S_{1,2}(f)^* \rangle}{\langle S_{1,1}(f) \rangle \langle S_{2,2}(f)^* \rangle},$$

and satisfies $0 \leq \gamma^2 \leq 1$ for all frequencies f . Here, $S_{1,2}$ is the cross-power spectrum, and $S_{1,1}$ and $S_{2,2}$ are the auto power spectra of channels 1 and 2. A high value of γ^2 indicates that the noise in both channels, corresponding to different biases, is coming from a common source. In Fig. 5 we plot the

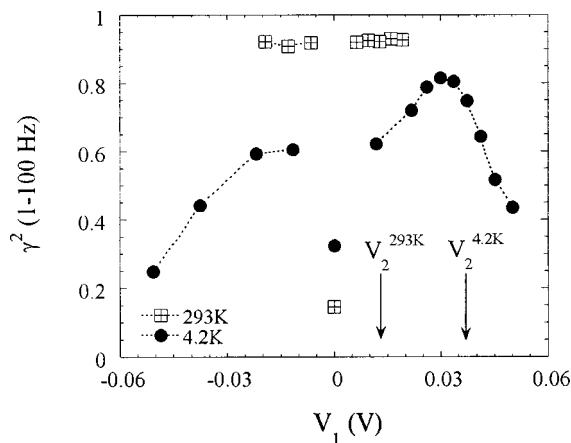


FIG. 5. The voltage bias dependence of the coherence function γ^2 averaged over frequencies $1 < f < 100$ Hz is shown for the type A junction. At each temperature, V_2 is held constant (indicated by arrows) while V_1 is varied. A large value of γ^2 for a particular bias V_1 indicates that the noise is due to a common source. At low temperatures, the noise signatures become less correlated as the difference between V_1 and V_2 increases.

coherence function, averaged over 1–100 Hz, versus voltage bias V_1 with V_2 held constant. At zero bias $V_1=0$, the coherence is small since there should be no correlation between the junction's $1/f$ -like resistance fluctuations and the thermal or amplifier noise. On the other hand, for $V_1=V_2$ we expect that $\gamma^2 \approx 1$ since this corresponds to a dc bias situation. Notably, $\gamma^2 \approx 1$ at $T=293$ K and is bias independent, so the noise at each bias comes from the same fluctuators. By comparison, $\gamma^2 < 1$ at low temperatures and it decreases strongly as the difference between the alternating biases $|V_2 - V_1|$ increases.

Values of γ^2 considerably less than 1 suggest that either the bias conditions affect the fluctuators, and thus give rise to different noise signatures, or that different fluctuators are responsible for noise at different biases. (Recall that the voltage bias is switched much more rapidly than the rate at which fluctuations are recorded.) Since rapid switching between V_1 and V_2 has no detectable effect on the amplitude or characteristic frequency of the fluctuators seen at either V_1 or V_2 , we can rule out the possibility that the applied voltage is significantly perturbing the local fluctuators. Thus, the appearance of different fluctuators at different biases requires that the current is sensitive to different local fluctuations as arising from distinct fluctuators located along either two entirely different current paths or two segments of a branching current path. By changing the bias between the two voltages we alternately probe the two paths or segments, each of which contains a different set of fluctuators. For example, the large fluctuation shown in the lower trace of Fig. 4(b) under V_2 must be due to a two-state fluctuator that cannot be probed under V_1 . The pattern of current flow must then rearrange according to the bias and probe the fluctuator's state only when a current path is close to it. The two signals are thus highly uncorrelated, which yields a low value for the coherence function. In general, different bias voltages may impose different current flow patterns that result in completely different noise signatures. The key point is that not only must the current be inhomogeneous, with nonlinear $I-V$ curves, but the form of the nonlinearity must vary substantially from site to site.

At high temperatures, the coherence is nearly equal to unity and independent of bias. This observation requires that the current pattern not depend on bias. Thus, the very nearly linear $I-V$ relation for the device at high temperatures must not result from a superposition of many local nonlinear $I-V$ curves, but rather reflects local linearity.

B. Type B junctions

Here, we report first results on the differential resistance spectra and noise properties of two junctions with high MR. Figure 6 shows the bias dependence of the differential resistance for the two relative orientations of the top electrode's magnetization. These data were taken on a $\text{Co}/\text{Al}_2\text{O}_3/\text{NiFe}$ junction at $T=4.2$ K. Although a zero-bias anomaly is evident, it is much less pronounced than for the type A junction in Fig. 2. Also shown in Fig. 6 is the ratio of differential resistances for the parallel and antiparallel orientations. This

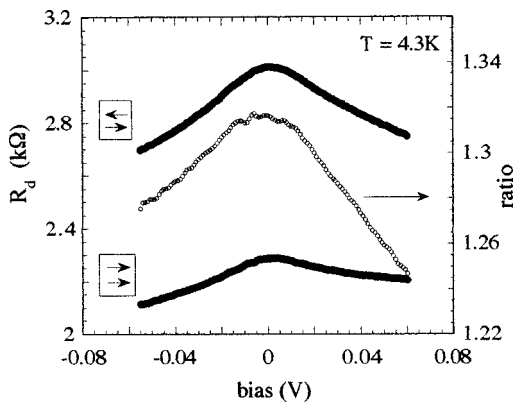


FIG. 6. The differential resistances for both the antiparallel and the parallel orientations and their ratio are shown for a type B junction. The pairs of arrows indicate the relative orientation of the electrode magnetizations.

ratio indicates that the MR falls sharply with increasing bias, as has been previously reported.^{1,14} At room temperature the tunneling resistance dV/dI was nearly independent of bias at low biases and approximately parabolic at biases greater than 40 mV. The conductance spectra were slightly asymmetric about zero bias, being shifted to positive biases corresponding to a higher potential for the bottom electrode.

In comparison to the type A junctions, the noise magnitude in this high MR junction was significantly smaller. In order to resolve excess noise without applying large and potentially damaging bias voltages, all noise measurements were performed at $T = 4.2$ K. We were unable to detect any random telegraph character in the voltage fluctuations, in sharp contrast to the type A junctions. In Fig. 7 we show the frequency dependence of the noise power taken at two dc currents $I_{dc} = 0$ and $16 \mu A$. Unfortunately, this junction was damaged after subsequently increasing the current. Another spectrum taken at $I_{dc} = 2 \mu A$ was nearly equivalent to that for zero current, i.e., to the background noise. The overall background noise level taken at zero bias is consistent with the junction's Johnson noise and amplifier noise. Narrow-

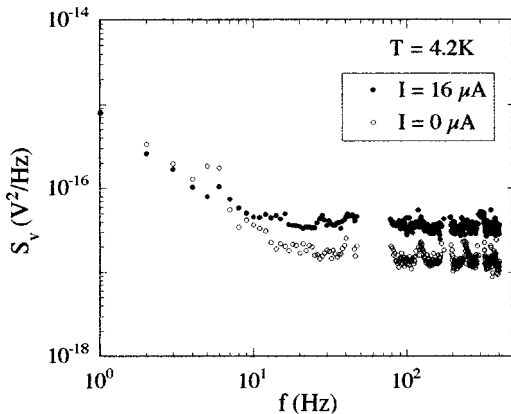


FIG. 7. The power spectra of the voltage fluctuations in the type B junction are shown at zero and 45 mV junction biases. The lower trace (open symbols) represents the background noise. Narrow-band spikes from interference pickup at 60 Hz and harmonics were removed. At nonzero bias, the power spectrum is nearly frequency independent and has significantly lower amplitude than found in type A junctions.

band spectral spikes from electrical interference, such as 60 Hz and its harmonics, were removed. Notably, the power spectrum at the higher current remains nearly independent of frequency and has a normalized magnitude of roughly $S_V/V^2 \sim 10^{-14}/\text{Hz}$. This value is over a factor of 10^5 smaller at $f = 1$ Hz than that found in the low MR junctions.

These results demonstrate the feasibility of fabricating low-noise, high MR tunnel junctions. Ultimately, the noise properties may quite possibly be set by the junction's Johnson noise and the shot noise resulting from current flow. In the simple independent electron model of shot noise, the power spectrum of the current fluctuations will be frequency independent with a magnitude $S_I = 2eI_{dc}$, where e is the charge of an electron. More specifically, it has been shown¹⁵ that at low bias voltages, $V \ll k_B T/e$ the noise is given by the Nyquist theorem, $S_V = 4k_B T R$, and in the opposite case it approaches the full shot-noise value. Figure 7 shows that the power spectrum measured in a high MR junction at a 45 mV voltage bias ($I_{dc} = 16 \mu A$) is nearly frequency independent. Since $k_B T/e \ll 45$ mV, a $16 \mu A$ current will give rise to current fluctuations with $S_I \approx 5 \times 10^{-24} \text{ A}^2/\text{Hz}$. This would correspond to a voltage noise of $S_V \approx 4 \times 10^{-17} \text{ V}^2/\text{Hz}$, which is less than a factor of 2 higher than the observed, background-corrected noise.

IV. DISCUSSION

Our results can be qualitatively described by a two-channel model of current conduction across the barrier: one channel having spin-dependent (SD) conduction and the other being essentially spin independent (SI) and responsible for reducing the MR. These two channels function in parallel and determine the magnetoresistive and noise properties of a junction. The existence of a SI conduction channel in the type A junctions is supported by the anomalously low tunneling resistance and its temperature dependence in comparison to a normal Al oxide barrier. The field independence of the noise also supports a source of spin-independent conduction. However, the marked temperature dependence of the resistance brings into question whether tunneling is the major source of conduction. One possibility is that the plasma oxidation step may have oxidized the surface of the bottom FM electrode to form a thin semiconducting layer. Alternatively, defects or impurities in the oxide or at the ferromagnetic/insulator interfaces, or inhomogeneities and pinholes in the barrier may form conductive paths. Continuous paths that bridge the barrier could also provide a source of ferromagnetic coupling across the barrier, which would further reduce the MR. However, metallic bridges would have linear $I-V$ relations rather than the very nonlinear $I-V$ curves associated with the noisy spin-independent channels. Occasionally, the tunneling resistance of a junction showing high MR would suddenly, and irreversibly, drop by a considerable fraction, presumably due to a breakdown in the barrier in a local region. In these instances, we found that the MR would also fall by a corresponding amount. This indicates that the new conducting channel is parallel with the spin-dependent channel.

The detailed nature of the SI channel is likely to be related to the quality of the junction. Since the two types of junctions are nearly identical but their noise signatures differ greatly and are independent of the applied field in detail, it is reasonable to attribute the large noise power to the SI channel. The large random telegraph noise and the bias dependence of the coherence function suggest that this channel involves extremely inhomogeneous current flow across the tunneling barrier. Recall that when discrete two-level fluctuators were resolved, fractional changes of 0.3% in the resistance were typical. It is well known that defects or impurities in oxide barriers can act as charge traps and thereby raise the effective tunneling barrier or impose a blocking potential on a current path.¹⁶ As a rule of thumb, a single trapped electron can effectively block conduction only through a volume of d^3 of the barrier,^{17,18} since the metallic electrodes can screen the trapped electron's Coulomb potential over longer distances. Recall, $d \approx 12 \text{ \AA}$ is the thickness of the barrier. Hence, the current through the junction must be nonuniform and perhaps filamentary. The charge population kinetics of a defect in or near such a current path can then significantly affect the amount of current flowing through it. A natural consequence of this is a random telegraph signal. Similar behavior can also be observed in disordered electronic systems in which conduction occurs primarily along inhomogeneous current filaments, for examples, see Refs. 19–21. Recently, random telegraph noise was found in electrodeposited Ni/NiO/Co heterostructures.²² Both the noise and magnetoresistance were attributed to spin-dependent trapping–untrapping of electrons by an impurity in the oxide barrier. Our results differ in that the noise is independent of field and the magnetoresistive state of the junction.

Inhomogeneous current flow may occur, for example, if there are lateral variations in the width of the tunneling barrier.¹⁸ Even for a uniform barrier, the presence of defects or impurities embedded in the oxide can introduce intermediate electronic states in the tunneling barrier, which can locally increase the tunneling or hopping probability, i.e., a current path. Then, conduction along a current path will be determined by the nature of the impurity, and so, one may expect different I – V characteristics for each current path. We found that the I – V curves in low MR junctions at low temperatures were nonlinear. Moreover, it was shown that changing the junction bias would cause rearrangements or selection of different current paths, resulting in changes of the noise signature. At room temperature, the I – V curves were nearly linear and rearrangements under varying biases were not observed, see Fig. 5. Thus, each current path must be nearly linear.

Additional insight into the nature of the current paths can be revealed from the differential resistance spectrum, and in particular, the zero-bias anomaly. Various causes of such anomalies have been discussed,⁹ including magnetic scattering in the electrodes or in the barrier, electron–electron interactions as in disordered media, and tunneling through an intermediate state. Recently, Zhang *et al.*¹⁴ proposed that the ZBA is due to “hot electrons” exciting magnons at the electrode interfaces. This model is successful at explaining the origin of reduced MR as a function of T and

V , and the zero-bias anomaly in high MR junctions in which the SD current dominates. However, we believe it is less appropriate for low MR junctions where the noise and the differential resistance spectra are predominately spin independent.

An alternative explanation for similar resistance peaks (ZBA) found to occur in Cr–I–Ag junctions²³ had been proposed by Giaever and Zeller.²⁴ The authors invoked a two-step tunneling process involving an intermediate state in the oxide barrier. The origin of the resistance peak comes from a distribution of threshold biases for transfer of an electron across the barrier via the intermediate state. A characteristic feature of this mechanism is that the zero-bias conductance varies linearly with temperature. The data shown in Fig. 2 are consistent with a linear temperature dependence for $T < 100 \text{ K}$. Moreover, a distribution of threshold biases could be the origin of current-path rearrangements seen in the noise.

Although metallic inclusions residing in the barrier have been shown to produce resistance peaks,²⁴ such a mechanism is very unlikely to occur in our junctions. On the other hand, perhaps the presence of charge traps and defects in the barrier can give rise to similar behavior. Detailed T and V dependence will allow comparison to theories and help identify the origin of spin-independent current in low MR junctions. Furthermore, the T and V dependence of the SI current are likely to require distinctly different inelastic tunneling models.

V. CONCLUSION

We have demonstrated that junctions with large magnetoresistive responses can also have low-noise power, as small as $S_V/V^2 \approx 10^{-14}/\text{Hz}$ for $80 \times 80 \mu\text{m}^2$ junction areas. Detailed bias and temperature dependences will help elucidate whether, for practical purposes, the noise floor is set by Johnson noise and current shot noise. In particular, device applications may require significantly higher bias voltages than we were able to explore, which may lead to excess noise. Low MR junctions, on the other hand, exhibited random telegraph noise and $1/f$ -like noise with substantially higher noise power. A two-channel conduction model consisting of a low-noise spin-dependent channel and a “noisy” spin-independent channel (that also reduces the magnetoresistive response) describes our data well. Although the detailed nature of the spin-independent channel is sensitive to the quality of the junction and is likely to vary among junctions, noise measurements under alternating bias conditions indicate that current flow in this channel is highly inhomogeneous. At low temperatures, the pattern of the inhomogeneous current flow is strongly bias dependent. The absence of any field dependence of the noise in low MR junctions indicates that the noise is not magnetic in origin. In this regard, an important factor in device performance will be controlling and maintaining the quality of the barrier.

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