

Electronic noise in magnetic tunnel junctions

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We have studied bias and magnetic field dependence of voltage noise in metallic magnetic tunnel junctions with areal dimensions on the order of $1 \mu\text{m}$. We generally observe noise with Gaussian amplitude distribution and pure $1/f$ power spectra at low frequencies. The $1/f$ noise scales with bias voltage as V^2 . Two kinds of deviations from this low frequency behavior have been observed. One is at fixed magnetic field when the junction bias reaches above a critical value, the other occurs at a fixed bias when the external magnetic field brings the sample to certain magnetic configurations. In both cases the noise spectra become dominated by Lorentzian noise and in both cases we have observed two level fluctuators in the time domain. We attribute the bias dependent noise to charge traps in the tunnel barrier. The field dependent noise is associated with the switching of the magnetization direction of portions of the top electrode, which we believe to be reversible. © 1999 American Institute of Physics. [S0021-8979(99)49308-9]

Extensive experimental work has been done on magnetic tunneling junctions (MTJs). Studies include bias and temperature dependence, composition of ferromagnets and sample shape,^{1,2} as well as theoretical attempts to explain the conduction mechanism involved.³⁻⁵ To our knowledge only a limited amount of work has been done in terms of noise in these devices. Noise characterization is of fundamental interest as it could reveal behavior that may be hard to detect in other experiments. Among potential applications of MTJs are nonvolatile memories and sensors, for which it is important to understand noise in relation to signal levels. Therefore noise characterization is extremely important from an application point of view.

In this work we report measurements of voltage noise on MTJs with sizes on the order of $1 \mu\text{m}$ and study their dependence on bias. Our tunneling junctions are defined in a stack of Ta(50)/Al(150)/Ni₈₁Fe₁₉(40)/MnFe(100)/Ni₈₁Fe₁₉(36)/Co(12)/Al₂O₃(12)/Ni₄₀Fe₆₀(75)/Al(200)/Ta(50) using optical lithography (the numbers within parenthesis are layer thicknesses in Å). A detailed description of the fabrication process is given elsewhere.¹ The junctions have magnetoresistance (MR) between 25% and 30% at room temperature. The thickness given for the oxide layer above is the thickness of the unoxidized Al layer, which subsequent to deposition was oxidized in an oxygen plasma. The MnFe layer serves the purpose of exchange biasing the magnetic moment of the “bottom” ferromagnetic electrode (the NiFe and Co layers) and effectively pinning it so that only the magnetization of the “top” electrode is affected by applying fields of less than 100 Oe. A schematic of a junction including only the antiferromagnetic pinning layer, the bottom and top ferromagnetic electrodes, and the oxide tunnel barrier is shown in Fig. 1. Samples discussed in this article have rect-

angular shapes. Antiparallel (parallel) alignment of the electrode magnetization gives high (low) resistive states of the junction, respectively. Resistance measurements are done using a four probe connection. Samples are current biased using a battery and a large bias resistor. The voltage fluctuations are amplified using a PAR113 preamplifier and recorded either as voltage noise power spectra using a HP3563A spectrum analyzer or as a time series using a National Instruments Data Acquisition card. All the measurements were made at room temperature. Figure 1 shows ten MR loops for sample 1. It clearly shows that the sample traces similar curves each time. From the discrete “Barkhausen” jumps one can conclude that there are a few domains involved in the switching of this sample and that the sample either follows a different sequence of domain reversal in each loop or, due to the stochasticity involved with switching of each domain and domain wall pinning, the jumps appear at different fields. Most likely both these processes are involved.

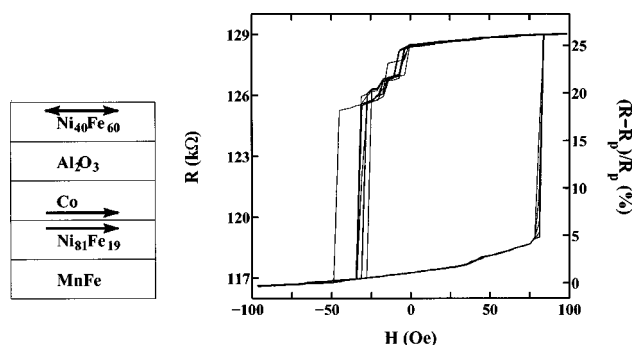


FIG. 1. Schematic of our tunnel junctions (left). The double headed arrow indicates the top electrode and the other two indicate the layers comprising the bottom electrode. Resistance as a function of applied field along the easy axis of the device (right) or MR loops for sample 1.

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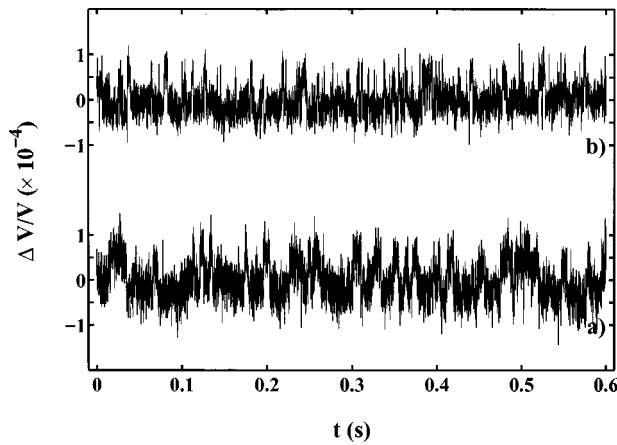


FIG. 2. Time series at two different bias levels for sample 2: (a) 288 and (b) 399 mV. Increasing the bias affects the population probability of the two states and favors the lower state in (b).

Figure 2 shows 0.6 s portions of time series measurements on sample 2 at a bias of (a) 288 and (b) 399 mV. The time series clearly reveals a two level voltage fluctuation within the bandwidth of the measurement at these bias levels. At bias levels of up to 204 mV no such fluctuators were observed and the amplitude distribution of voltage fluctuations was Gaussian. In the frequency domain at low bias values the noise spectra showed pure $1/f$ noise^{6,7} except in the bias region of the two level fluctuators, where Lorentzian spectra dominated. Lorentzian effects are already visible at 204 mV even though in the time domain we detected no fluctuators. A careful analysis of the power spectra involving fitting with Lorentzians and $1/f$ noise leads us to believe that there were three two level fluctuators active during this experiment although one of them completely dominates. Evidently in Fig. 2 the increase in bias causes the fluctuator to prefer the lower state to the upper one. The origin of the two level fluctuators is believed to be charge traps in the oxide barrier which when charged will block the conduction through an area $\propto d^2$, where d is the thickness of the oxide barrier. The sudden appearance of fluctuators at a certain bias value corresponds with the bias overcoming the charging energy of the trap, in the sense that the energy barrier becomes small enough that an electron has a non-negligible probability of either tunneling to the trap or getting there by thermal activation. As the bias is further affected, so is the barrier height and the charging probabilities and lifetimes of upper and lower states change. This is in perfect qualitative agreement with our observations both in the time and the frequency domain.⁶ Charge traps were studied long ago in nonmagnetic tunnel junctions.⁸⁻¹⁰ The lifetime distribution of the two levels in measurement (a) in Fig. 2 is shown in Fig. 3. It shows the exponential distribution characteristic of a Markov process. The average lifetime of such processes is normally found experimentally to follow¹¹

$$\bar{\tau} = \nu_0^{-1} \exp E/kT, \tag{1}$$

where $\bar{\tau}$ is the average lifetime of the state, ν_0 is an attempt frequency, and E is an activation energy. Lacking temperature dependent data we assume an equal attempt frequency

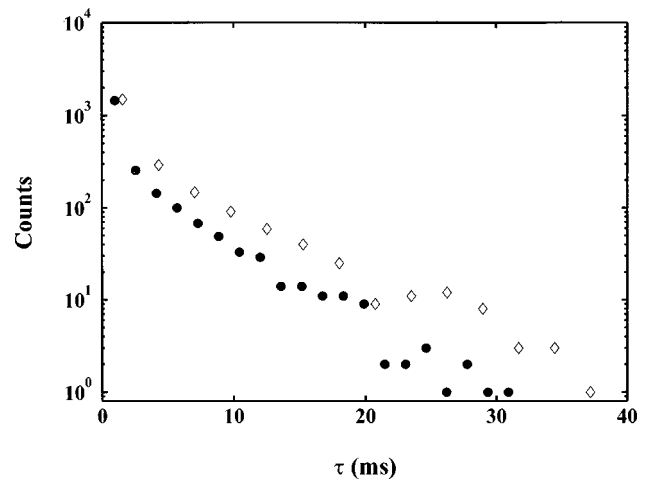


FIG. 3. Histogram showing the lifetime distributions of the two states in Fig. 2(a): (●) indicates the upper and (◇) indicate the lower state lifetimes. The distributions are approximately exponential, characteristic of a Markov process although the very shortest lifetimes are overcounted due to the noisy data.

for the two states of $\nu_0 = 10^{13}$ Hz (the energy E does not depend strongly on ν_0). This gives activation energies of approximately 0.60 and 0.61 eV for the upper and lower states, respectively.

Other explanations have been considered as the origin of these voltage dependent two level fluctuators in our experiment. They involve local switching of magnetization in the electrodes. This can be achieved either by fluctuating single domain particles or 180° domain walls that fluctuate between two different energetically favorable configurations and affect the area of the adjacent domains. All the fluctuators we have observed have had $\Delta V/V \propto 10^{-6} - 10^{-5}$. Assuming uniform conduction in the junction this calls for reversal of magnetization of area on the order of 10^2 (nm)² in the case of sample 2. Reversal of a single domain of such size in a uniform sample would require too much energy. Also domain wall motion back and forth over such distances must be considered extremely improbable. However if the current distribution is highly nonuniform and localized in small filaments in the oxide, these effects could explain resistance changes of such magnitude, but it is hard to imagine how biasing the junction can change the lifetimes of states of fluctuators of magnetic origin in the way we observe.

We have also observed noise that we do attribute to magnetic phenomena. Figure 4 shows results of noise measurements at different magnetic configurations of the junction. The sample is held at a fixed current bias and the top electrode is switched a number of times prior to the measurement so the resistance goes through a number of complete hysteresis loops and the measurement starts from a ‘‘known’’ state. The external field is then stepped slowly between the extreme field values and a voltage noise power spectrum recorded in each step. The left axis in Fig. 4 is noise power per octave in frequency, in this case from 128 to 256 Hz. The right axis is the junction voltage in each magnetic field step. The voltage was measured both before and after the noise spectra in each step and was virtually identical

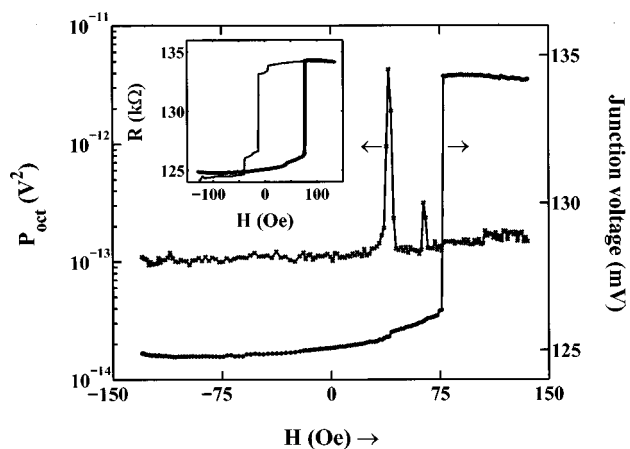


FIG. 4. Total noise power P_{oct} (left axis) of sample 1 in the octave 128–256 Hz at different field values and a fixed current bias of $I_b = 1.1 \mu\text{A}$. The right axis displays the voltage across the sample during the measurement. To each noise power measurement there correspond two voltage measurements, one measured before and one after the noise measurement. Only one of them is shown here but they are undistinguishable on this scale. This shows “exactly” the resistive state of the sample during the noise measurement. (Inset) The voltage loop followed by the sample during this measurement. The heavy line is the part shown in the main graph.

in all cases (within the resolution of the dc voltage measurement). The sample switches in three steps in this case, two minor and one major step. On the second plateau, at a field of around 40 Oe, there is a large peak in noise power. Viewed as a function of frequency, the peak has a Lorentzian structure whereas the noise at all other field values is pure $1/f$ noise. The knee frequencies of these Lorentzian spectra are bias voltage independent unlike the noise we attribute to charge traps. Apparently at a certain microscopic magnetic configuration a two level fluctuator is revealed. The fluctuator is very sensitive to magnetic field, i.e., a change in field insufficient to bring the sample to another plateau through

another Barkhausen jump causes it to show up and then disappear gradually. This has been observed in a number of samples. The noise peaks can sometimes be associated with very small changes in the $V-H$ curve but often there is no detectable change as in the case of Fig. 4.

In summary we have studied high MR magnetic tunnel junctions of small dimensions. At low frequencies we generally observe noise with a Gaussian amplitude distribution and a pure $1/f$ spectrum that scales as V^2 . In some samples the noise takes on a Lorentzian character above a critical bias value that can be attributed to charge traps in the oxide barrier. We have also observed evidence of magnetic field dependent noise that shows up as Lorentzians in the voltage noise power spectra at certain field values. We believe this noise is caused by magnetic dynamics such as reversible domain switching or domain wall jumps.

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