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Observation of full shot noise in CoFeB/MgO/CoFeB-based magnetic tunneling junctions

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The electron transport through the CoFeB/MgO/CoFeB-based magnetic tunneling junction (MTJ) was studied by the shot noise measurement. The obtained Fano factor to characterize the shot noise is very close to unity, indicating the full shot noise, namely, the shot noise in the Schottky limit, both in the parallel and antiparallel magnetization configurations. This means the Poissonian process of the electron tunneling and the absence of the electron–electron correlation in the low bias regime. The shot noise measurements will be a good guideline to make up tunneling criteria for designing MTJ-based spin devices. © 2010 American Institute of Physics. [doi:10.1063/1.3456548]

The tunneling magnetoresistance (TMR) is one of central topics in spintronics, which is invoking intensive studies on the realizations of sensitive magnetic sensors and microwave oscillators.1 In terms of the electron tunneling in magnetic tunneling junctions (MTJs), the spin-dependent electron tunneling based on the simple Julliere’s model2 is applicable in the transport through amorphous Al2O3 junctions,3 whereas the coherent tunneling is expected in epitaxial MgO (100) junctions.4–7 The large spin polarization plays a critical role in CoFeB/MgO/CoFeB junctions.8,9 In addition to the conventional resistance measurement, the shot noise measurement allows us to explore more the underlying physics of electron transport.10 For example, the shot noise has served to prove the fractional charge in the fractional quantum Hall regime11,12 and the Cooper-pair transport in the superconductor-normal junctions.13 Similarly, a spin-related electron dynamics such as spin transfer torque is expected to emerge itself in the shot noise.14–17

Generally, when the current I is fed to a junction with the resistance, the current noise S/N across it due to the shot noise can be expressed as $S/N = 2eIF$ (in the zero-temperature limit) with the Fano factor $F = 1$ in conventional Schottky-type junctions. Although there are several papers on the I/f noise in MTJs,18–22 so far only a few studies are available on the Fano factor. One of them reported a distinct suppression of Fano factor ($F \sim 0.45$) in Al2O3-based MTJs (Ref. 22) after reporting $F \sim 1$.23 Another group reported that the shot noise in Al2O3-based MTJs with Cr doped barrier shows $F \sim 0.65$.24 Thus, the Fano factor for the MTJs remains unsettled and also that for MgO-based MTJs is not known yet.

Here we report the systematic study on the shot noise in MgO-based MTJs. The observed Fano factor indicates the full shot noise in the MTJs, signaling that the spin-dependent Poissonian process governs the electron transport. We also revealed that the magnetization fluctuation is the main origin of I/f noise in MTJs.

Our MTJs consist of Ta(3)/Cu(50)/IrMn(10)/CoFeB(2.5)/Ru(0.8)/CoFeB(3)/MgO(1.5)/CoFeB(4)/Ta(2)/Ru(5)/Cu(3)/Au(100) multilayer stacks grown by magnetron sputtering on SiO2 layer on a silicon substrate [see Fig. 1(a)]. Here the numbers in () indicates the thickness of each layer in units of nanometer. The multilayer stacks are patterned into $2 \times 2 \times 5 \times 5 \, \mu m^2$ junctions by the electron beam lithography, then annealed in 0.6 T for 60 min at 350 °C to improve the crystallization of the amorphous ferromagnetic CoFeB layers,8,9 yielding high TMR ratios exceeding 150%. The area resistance (RA) ranges from 500 $\Omega/\mu m^2$ to 50 k$\Omega/\mu m^2$.

The shot noise measurements were carried out in a variable temperature insert (Oxford VTI) as schematically shown in Fig. 1(a). The dc current is applied to the MTJ through a 10 MΩ resistor. The two voltage signals across the MTJ in the cryostat are obtained through a pair of the voltage probes in an electronic circuits optimized for the present MTJ resistance (typically a few kilohm). Each signal is consecutively amplified by the room temperature amplifiers (NF corpora-

![FIG. 1.](image-url)
The resistance of the MTJ at the lowest resistance state (parallel magnetization configuration; P) is 2.05 kΩ, while the highest resistance state (antiparallel magnetization configuration; AP) is 5.61 kΩ [Fig. 1(b)]. The TMR ratio defined by \((R_{AP} - R_P)/R_P\) is 173%. The shot noise measurement is performed with changing a magnetic field around zero bias voltage,23,24 for the noise measurement we typically measured at P and AP states. The differential resistance in the AP configuration shows a peak feature at low frequencies well below 5 kHz as shown in Fig. 2(b). The center of the Gaussian fit of the obtained histograms gives a better estimation for the average noise power than just the average of the spectrum, since unwanted peaks, which accidentally appear in the spectra, do not very much contribute in the histogram. Thus from the histogram obtained for \(V_{sd}=0\) mV the electron temperature of the MTJ can be deduced by using the device resistance, as the thermal noise is given as \(S_V = 4k_BT\) where \(k_B\), \(T\), and \(R\) are Boltzmann constant, sample temperature, and resistance, respectively.

By increasing the bias voltage at a fixed temperature, the shot noise, which is also frequency-independent at a low frequency range as in the present study, appears as the increase of the noise power. Again, the shot noise on top of the thermal noise can be precisely evaluated by the histogram analysis. As an example, Fig. 2(b) shows the histograms obtained for \(V_{sd}=5\) and 10 mV, where the difference of the center position of the histogram from that at \(V_{sd}=0\) mV corresponds to the shot noise.

Figure 2(c) represents the noise power \(S_V\) for the same MTJ for three different temperatures (3.3, 6.8, and 12 K as estimated from the thermal noise). Here we express \(S_V\) by using the noise temperature \(T_{noise} = S_V/4k_B R\) to absorb the slight resistance difference for different temperatures. While the thermal noise contribution is dominant around \(V_{sd} = 0\) mV, the parabolic behavior at finite bias indicates the crossover from the thermal to the shot noise. At large enough bias voltages \((eV_{sd} \approx k_BT)\), the noise power increases linearly to the bias voltage as \(S_V = 2eFRV_{sd}\), where \(F\) is the Fano factor. To obtain the Fano factor, we performed the numerical fitting to take the crossover between the thermal noise and the shot noise into account by using the following equations:

\[
S_V = 4k_BT + 2FR\left[\frac{eV_{sd}}{2k_BT} \coth\left(\frac{eV_{sd}}{2k_BT}\right) - 2k_BT\right].
\] (1)

From the numerical fitting line, we deduced \(F=0.98\) for the three temperatures. The accuracy of the fitting also ensures that the effect of Joule heating in the MTJ is negligible.

The noise power spectra for the AP configuration for the same device are shown in Fig. 3(a). In contrast to the spectra obtained for the P configuration, they show a considerable 1/f contribution when the MTJ is voltage-biased. To obtain the frequency-independent contribution, we numerically fit the spectra by the function \((a + b/f)/(1 + (f/f_c)^2)\), which includes the frequency-independent contribution \(a\) representing the thermal noise and the shot noise, and the 1/f contribution \((b/f)\) with the RC-damping with the cut-off frequency \(f_c\).

The result of the fitting are superposed on the experimental curves by the function equations,10 for the bias voltages \((V_{sd})=0, 5, \text{ and } 10 \text{ mV at } 12 \text{ K. Except several spikes observed at certain frequencies, which are due to internal noises, the spectra are flat between 1 and 5 kHz. At high frequencies (\(\approx 10\) kHz) the RC damping of the voltage noise due to the finite capacitance (\(\approx 700\) pF) of the measurement lines occurs. The frequency independent contribution observed in the spectrum at \(V_{sd}=0\) mV is attributed to the Johnson–Nyquist (thermal) noise. To estimate the amplitude of this frequency-independent noise, we performed the histogram analysis of the number of the points between 1 and 5 kHz as shown in Fig. 2(b). The center of the Gaussian fit of the obtained histograms gives a better estimation for the average noise power than just the average of the spectrum, since unwanted peaks, which accidentally appear in the spectra, do not very much contribute in the histogram. Thus from the histogram obtained for \(V_{sd}=0\) mV the electron temperature of the MTJ can be deduced by using the device resistance, as the thermal noise is given as \(S_V = 4k_BT\) where \(k_B\), \(T\), and \(R\) are Boltzmann constant, sample temperature, and resistance, respectively.

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The first systematic study on the shot noise in MTJs suppression of the Fano factor was conducted by the group reported a strong suppression of the Fano factor. On the other hand, the present study indicated that the tunneling mechanism can be described as an ideal Schottky type.

In conclusion, the full shot noise is observed in the CoFeB/MgO/CoFeB-based MTJs, indicating that the tunneling mechanism can be described as an ideal Schottky type. By evaluating the Hooge parameter, the contribution of the shot noise is identified to be of magnetic origin.

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