Annealing effect on low frequency noise in MgO-based magnetic tunnel junctions

J. F. Feng, Z. Diao, and J. M. D. Coey
CRANN and School of Physics, Trinity College, Dublin 2, Ireland
E-mail: jfeng@tcd.ie

Abstract. The annealing temperature ($T_a$) dependence of the low frequency noise in exchange-biased magnetic tunnel junctions (MTJs) with an MgO barrier and CoFeB electrodes has been investigated for $200 < T_a < 425$ °C. An $1/f$ noise spectrum is observed for the parallel and antiparallel states, where the Hooge parameter ($\alpha$) for the parallel state remains unchanged with $T_a$ after the CoFeB electrodes are fully crystallized, while $\alpha$ for the antiparallel state increases over the range of $T_a$ from 275 to 425 °C. The $1/f$ noise for the antiparallel state is largely of magnetic origin, and it can be attributed to magnetization fluctuations of ferromagnetic electrodes due to the loss of the exchange bias, whereas there is little magnetic noise in the parallel state. An annealing temperature of 325 °C yields an optimized signal-to-noise ratio, as the CoFeB electrodes become fully crystallized. The bias dependence of $\alpha$ is discussed based on the Glazman-Matveev model, which considers both elastic and inelastic tunneling.

1. Introduction
Magnetic tunnel junctions (MTJs) were originally developed using amorphous aluminum oxide tunnel barriers [1-4]. These AlO$_x$-based MTJs with CoFeB magnetic electrodes have attained a tunneling magnetoresistance (TMR) value up to 80% ($[R_{AP}-R_P]/R_{AP}$) at room temperature and low field [4], where $R_P$ and $R_{AP}$ are the resistances of a MTJ when the magnetizations of the two electrodes are in parallel and antiparallel, respectively. More recently, MTJs with single crystalline MgO tunnel barriers have been found to exhibit much higher TMR values; more than 600% at room temperature and 1100% at low temperature, have been reported in poseudo spin valve structures [5]. This TMR ratio is close to the theoretical maximum [6,7]. MTJ devices have already found important applications in magnetic memory and as sensors [8, 9]. MgO-based MTJs present a seven-fold increase in their output signal compared to those with AlO$_x$ barriers at room temperature. However, sensor applications require not only a large output signal but also a good signal-to-noise ratio. Therefore, minimizing the noise in an MTJ becomes an important consideration.

Electrical noise in MTJs has various mechanisms, such as thermal noise, shot noise at nonzero current bias, and $1/f$ noise [10]. The thermal noise and shot noise are both frequency-independent, and together they define the ultimate noise floor. $1/f$ noise is often dominant in the low frequency range, and it is a performance-limiting factor for magnetic field sensors [11, 12]. The $1/f$ noise is quantified by the Hooge parameter

$$\alpha = AfS_V/V^2,$$

where $A$ is the junction area, $f$ the frequency, $S_V$ the noise power spectrum, and $V$ the voltage applied to the MTJ. The origin of $1/f$ noise in MTJs can be either magnetic or nonmagnetic. The magnetic contribution to the $1/f$ noise is attributed to thermally-activated magnetization fluctuations of the
ferromagnetic electrodes, which can be understood in terms of the fluctuation-dissipation theorem [12]. The nonmagnetic 1/f noise manifests itself as spin-independent resistance fluctuation [13] due, for example, to localized charge traps in the tunnel barrier or at the electrode/barrier interface [14,15]. Thermal annealing, which leads to a crystallized CoFeB layer, is widely used to improve the TMR ratio of MTJs [16]. However, the effect of thermal annealing on electrical noise in MTJs is more controversial. In the early report, Scola et al. [14] found no marked dependence of 1/f noise in MTJs on the annealing temperature. Liou et al. [17] and Stearrett et al. [18], however, found a significant drop of low frequency noise in MTJs after annealing.

In this work, we investigate the low frequency noise of MgO-based MTJs in a large $T_a$ range, from 200 to 425 °C in the parallel and antiparallel states. Noise in the perpendicular configuration, required for sensors, is expected to the intermediate between these two extremes. Micro-scale MTJs having high TMR ratio, with MgO tunnel barrier and CoFeB ferromagnetic electrodes, have been fabricated. The annealing temperature dependence of the magnetotransport properties is similar to that reported by Dimopoulos et al. [16]. Under a moderate bias of 10 - 30 mV, a 1/f noise spectrum is observed at low frequency in both $R_P$ and $R_{AP}$ states. It is well known that the annealing temperature $T_a$ can influence magnetotransport properties of exchange-biased MgO-based MTJs, i.e., TMR, resistance-area (RA) products, interface quality, and Mn diffusion. We further study the relation between these properties and the Hooge parameter ($\alpha$) of our MTJs under different annealing conditions.

2. Experimental detail

The typical layer structure of our bottom-pinned synthetic antiferromagnetic MTJ samples is Ta 5 /Ru 20 /Ta 5 / Ni$_{81}$Fe$_{19}$ 5 /Ir$_{22}$Mn$_{78}$ 10 /Co$_{90}$Fe$_{10}$ 2 /Ru 0.85 / Co$_{40}$Fe$_{40}$B$_{20}$ (CoFeB) 3 /MgO 2.5 /CoFeB 3 /Ta 5 /Ru 10 (from the bottom electrode to the top with thickness given in nanometers). All metallic layers were deposited by dc-magnetron sputtering in a Shamrock sputtering tool. The MgO barrier was deposited from a target-facing-target source using rf sputtering. The MTJ stack was patterned into square-shaped pillars, with an area of 24 × 24 and 24 × 48 µm$^2$, using UV lithography. High vacuum annealing of MTJ samples in the temperature range of 200 - 425 °C was carried out in a magnetic field of 800 mT in the sample plane for an hour. All magnetotransport and electrical noise measurements were performed by a four-probe method at room temperature. Further details on the sample fabrication and measurements can be found in Refs. [19, 20].

![Figure 1](image1.png)

**Figure 1.** (a) The TMR - $H$ curve for an MTJ at $T_a = 325$ °C. (b) The noise power spectral density ($S_n$) of the same device in the $R_P$ and $R_{AP}$ states.

![Figure 2](image2.png)

**Figure 2.** The annealing temperature $T_a$ dependence of the RA value (a) and TMR (b) for an MTJ measured at $V = 5$ mV. The insets in (a) and (b) show the $H_c$ and $H_{ex}$. 


3. Results and discussion

Figure 1 (a) shows the TMR - $H$ curve for an MTJ with RA = $1.8 \times 10^3$ $\Omega \cdot \mu m^2$, annealed at $T_a = 325$ °C. A TMR of 210% at 5 mV is obtained at room temperature, suggesting that the MgO barrier is of high quality. The well-separated switching of the pinned and free CoFeB electrodes creates well-defined parallel ($R_p$) and antiparallel ($R_{AP}$) states. Fig. 1 (b) shows the noise power spectral density ($S_P$) of the same MTJ below 1 kHz. Magnetic fields of 50 mT and -20 mT are applied to set the $R_p$ and $R_{AP}$ states, respectively. The amplifier noise and thermal noise have been subtracted from the measured $S_P$. Similar $1/f$ noise is always observed for both states of MTJs studied in this work. In the following, we focus on the influence of annealing temperature on the noise power of our MTJs, and correlate it with the magnetotransport and magnetic properties during annealing.

The annealing temperature dependence of RA and TMR for an MTJ with RA = $2.9 \times 10^3$ $\Omega \cdot \mu m^2$ is plotted in Fig. 2 (a) and (b). The RA values remain almost unchanged in the low $T_a$ range until the CoFeB begins to crystallize on the MgO; TMR changes from 15% at the as-grown state to 44% at $T_a = 200$ °C. The TMR value is 96% at $T_a = 250$ °C, and then it increases monotonically to reach 210% at $T_a = 325$ °C due to the improvement of the MgO/CoFeB interface. The crystallization process of the amorphous CoFeB electrodes with the increase of $T_a$ has been observed at the electrode/barrier interfaces [16, 21]. Crystallization of CoFeB is accompanied by a change in coercivity ($H_c$) of the free CoFeB layer, as shown in the inset of Fig. 2 (a). It is found that the crystallization process starts at $T_a = 250$ °C. Full crystallization of the free CoFeB is found at an annealing temperature of around 325 °C [16], which corresponds to the highest $H_c$. The $H_c$ value triples from 0.4 mT to 1.2 mT in this annealing temperature range. Together with the high TMR ratio at $T_a = 325$ °C, it suggests that the large TMR in MgO-based MTJs resides in the fact that the CoFeB layer at the electrode/barrier interface is of crystalline nature [21]. After that, the TMR ratio remains almost unchanged, though Mn has been found at the bottom CoFeB/MgO interface at around $T_a = 350$ °C [16]. However, a lower TMR ratio is obtained at $T_a = 425$ °C due to the enhanced Mn diffusion.

Figure 3 (a) shows the Hooge parameter ($\alpha$) for the $R_p$ and $R_{AP}$ states as a function of the annealing temperature. The lines are guided to the eye. For each $T_a$, at least three individual MTJs with similar RA were measured, and they all show a similar $\alpha$ value. The $\alpha$ values remain unchanged when $T_a$ is below 250 °C, where RA of the junctions remains steady as described above. Furthermore, $\alpha$ for the $R_p$ state is very close to that for the $R_{AP}$ state. This suggests that the electrical noise of these MTJs at low $T_a$ mainly comes from the amorphous CoFeB/MgO interfaces and the MgO barrier. When the interfaces improve with $T_a$, $\alpha$ for the $R_p$ state falls and reaches a roughly constant value of $2.0 \times 10^9$ $\mu m^2$, at $T_a = 300$ °C. This can be explained by the fact that defects formed at the CoFeB/MgO interfaces during the sputtering deposition are released from the system when the CoFeB layer crystallizes. Hence, thermal annealing reduces the electrical noise from these defects in the MTJs. The $\alpha$ values observed in this work are comparable to those reported in Refs. [22], but are higher than those in fully epitaxial Fe/MgO/Fe MTJs [23]. Above 300 °C, $\alpha$ for the $R_p$ state remains unchanged, despite Mn diffusion. However, the $\alpha$ value for the $R_{AP}$ state behaves differently. Firstly, $\alpha$ in the $R_{AP}$ state is larger than that in the corresponding $R_p$ state ($6.5 \times 10^9$ $\mu m^2$ at $T_a = 300$ °C, more than 3 times higher). Similar observations have been reported for junctions with an MgO or AlO$_x$ barrier [10, 14, 15, 20, 22-26]. The difference of $\alpha$ between two states increases to more than one order of magnitude at higher $T_a$. Above 350 °C, $\alpha$ increases significantly with $T_a$ for the $R_{AP}$ state. This may be attributed to the fact that Mn diffusion at high $T_a$ leads to the degradation of IrMn as the antiferromagnetic pinning layer. Hence, magnetization in the pinned layer becomes more vulnerable to thermal excitations. The decrease of TMR at $T_a = 425$ °C is not accompanied by a change in $\alpha$ for either $R_p$ or $R_{AP}$ state.

A high signal-to-noise ratio is desirable for sensor applications, which requires a high TMR ratio and low noise in the devices. The optimum annealing temperature of 325 °C for these MgO-based MTJs, corresponds to a full crystallization of the CoFeB ferromagnetic electrodes, and lower diffusion of Mn.
The bias dependence of $\alpha$ for the $R_{AP}$ state is shown in Fig. 3 (b) for another MTJ at $T_a = 325$ °C. The $\alpha$ value is practically constant in the voltage range of $\pm 100$ mV [14], but a three-fold decrease in $\alpha$ is observed under higher voltage bias. It may be related to the nonlinearity of the I-V curve of MTJs (as shown in the inset of Fig. 3 (b)), where a clear nonlinear behavior starts to appear beyond also about 100 mV [22-24, 27]. The Glazman-Matveev model [28] has previously been used to describe the nonlinear I-V curves in MTJs [22, 27],

$$I = G_1 V + G_2 V^{7/3} + G_3 V^{7/2} + \cdots,$$  \hfill (2)

where $G_1$ is the elastic contribution of direct and resonant tunneling via a single localized state, and $G_2, G_3, \cdots$ gives the inelastic contribution to the total current from tunneling involving 2, 3, \cdots impurity states [27, 28]. The direct tunneling and resonant tunneling are independent of bias, while the inelastic tunneling contribution is bias dependent. The fit in the inset of Fig. 3(b) shows that the nonlinear I-V curves of our MTJs can also be well described within the framework of this model. If we consider fluctuations both in the elastic and the inelastic tunneling conductance, Eq. (2) gives that

$$\delta V = V \frac{\delta G_1}{G} \cdot V^{7/3} \frac{\delta G_2}{G} \cdot V^{7/2} \frac{\delta G_3}{G} \cdot \cdots,$$  \hfill (3)

where the total tunneling conductance is $\tilde{G} = G_1 + 7/3 G_2 V^{\alpha_3} + 7/2 G_3 V^{\alpha_2}$ [27]. It can be shown from a simple analysis of Eq. (3) that a decrease in the normalized noise power under high voltage bias can be attributed to a mixing between the different tunneling channels. The bias dependence of $\alpha$ suggests that the voltage bias should always be specified when the $\alpha$ parameters in different junctions are compared.

A related point is that, under low voltage bias, the inhomogeneity of the tunneling barrier plays an important role in defining the noise of the device, since fewer localized fluctuators may contribute. While under high voltage bias, different localized fluctuators are active, which can lead to a decrease of the $\alpha$ value. Nowak et al. [29] have previously measured the correlation of low frequency noise signatures at different biases in MTJs. Their results suggest that there exists a current redistribution when the bias across the MTJ changes. This leads to the appearance of different fluctuators under different biases. This effect is closely related to the strong sensitivity of bias current to the defect distribution in MTJs [23].
1/f noise in magnetic devices has two origins -- magnetic and nonmagnetic. In the high field range (500 mT), only residual electrical noise is assumed to remain, and there is no noise of magnetic origin. We subtract the high field residual electrical noise from the measured power spectral density \( S_V \) to obtain the magnetic contribution \( S'_V \). Defining the magnetic Hooge parameter

\[
\alpha_{\text{mag}} = \frac{A}{S_V/V^2},
\]

this parameter allows to compare the noise level in different magnetic states [12,20]. In Fig. 4 (a), we plot \( \alpha_{\text{mag}-\text{AP}} \) for the \( R_{\text{AP}} \) state as a function of \( T_a \) in the range of 275 - 400 °C. Compared to the values of the conventional Hooge parameter \( \alpha \) (Eq. (1)) at \( T_a = 300 \) °C, \( \alpha_{\text{mag}-\text{AP}} \) at the same annealing temperature is \( 4.2 \times 10^{-9} \) \( \mu \text{m}^2 \), 3 - 4 times higher than the nonmagnetic contribution to the noise in these MTJs. This shows that during the magnetization switching, the noise source in a MTJ in its \( R_{\text{AP}} \) state is mainly of magnetic origin, whereas non-magnetic noise plays the major role when the MTJ is in its parallel state. The \( R_p \) state is much quieter magnetically and there is little hint of instability with \( T_a \) (see Fig. 3 (a)) [26]. It is found that the \( \alpha_{\text{mag}} \) value for the \( R_p \) state (\( \alpha_{\text{mag},p} \)) typically under a 50 mT magnetic field, is much lower (around 8 \( \times 10^{-10} \) \( \mu \text{m}^2 \)).

Figure 4 (a) also shows the difference of the conventional Hooge parameter \( \alpha \) between two magnetic states (\( \alpha_{\text{AP},p} \)). It is found that \( \alpha_{\text{AP},p} \) also increases with \( T_a \). This further supports our conclusion that magnetic fluctuations contribute very little to the noise of a MTJ in its \( R_p \) state. To understand the origin of the evolution of \( \alpha_{\text{mag}-\text{AP}} \) with \( T_a \), we use the definition of the sensitivity of an MTJ device, \( (1/R)(dR/d\mu H) \), but extend it to the part of the MR curve where the pinned layer switches. This can be treated as a characteristic of the pinning quality of the antiferromagnetic layer. As shown in Fig. 4 (b), an increase of \( (1/R)(dR/d\mu H) \) at \( \mu H = -20 \) mT is found with the increase of \( T_a \). From the inset of Fig. 2 (b), it is also found that the exchange bias (\( H_{\text{ex}} \)) decreases with \( T_a \). Hence, both facts suggest that the loss of the exchange bias, resulting in a loose pinning effect of IrMn, can increase the instability of the magnetic configuration of the pinned layer when the MTJ is in the \( R_{\text{AP}} \) state. This effect leads to more magnetization fluctuations in the pinned layer which increases \( \alpha_{\text{mag}-\text{AP}} \) with \( T_a \). Since an increase in \( T_a \) can change the noise behavior of MTJs at the \( R_{\text{AP}} \) state, the annealing conditions prior to noise measurements should be mentioned in order to allow the correct comparison of low-frequency noise.

4. Summary
The annealing temperature dependence of low frequency noise in MgO-based MTJs with high TMR provides some insight into the origin of the noise. Annealing at a moderate temperature helps reduce the defects in the MgO tunnel barrier and at the MgO/CoFeB interfaces, which leads to a decrease of the nonmagnetic noise level in these MTJs. A high annealing temperature is shown to significantly increase the noise of the MTJ device in its antiparallel state due to the degradation of the exchange-bias pinning, whereas it has little effect on its noise level in the parallel state. Our results suggest that magnetic stability of the pinned layer is a crucial factor in reducing the low frequency noise in MTJs. A carefully selected annealing temperature and an antiferromagnet with good thermal stability will improve the properties of MTJ sensors. Further improvement in the signal-to-noise ratio in MgO-based MTJs will depend on the ability to reduce the nonmagnetic noise level of the barrier which is mainly related to the parallel state.

Acknowledgements
This work was supported by Science Foundation Ireland as part of the MANSE project No.05/IN/1850. Some support was also provided by Enterprise Ireland, as part of the ‘Spin currents’ FoNE network. The authors would like to thank Prof. E. R. Nowak for advice on the measurement setup.

References
[1] Miyazaki T and Tezuka N 1995 J. Magn. Magn. Mater. 139 L231
[2] Moodera J S, Kinder L R, Wong T M, and Meservey R 1995 Phys. Rev. Lett. 74 3273
[3] Wang D, Nordman C, Daughton J M, Qian Z, and Fink J 2004 *IEEE Tran. Magn.* 40 2269
[4] Wei H X, Qin Q H, Ma M, Sharif R, and Han X F 2007 *J. Appl. Phys.* 101 09B501
[5] Ikeda S, Hayakawa J, Ashizawa Y, Lee Y M, Miura K, Hasegawa H, Tsunoda M, Matsukura F, and Ohno H 2008 *Appl. Phys. Lett.* 93 082508
[6] Butler W H, Zhang X-G, Schulthess T C, and MacLaren J M 2001 *Phys. Rev. B* 63 054416
[7] Mathon J and Umersky A 2001 *Phys. Rev. B* 63 220403
[8] Parkin S S, Xin J, Kaiser C, Panchula A, Roche K, and Samant M 2003 *Proc. IEEE* 9, 661
[9] Tondra M, Daughton J M, Nordman C, Wang D X, and Taylor J A 2000 *J. Appl. Phys.* 87 4679-81
[10] Weissman M B 1988 *Rev. Mod. Phys.* 60 537
[11] Stutzke N A, Russek S E, Pappas D P, and Tondra M 2005 *J. Appl. Phys.* 97 10Q107
[12] Ozbay A, Gokce A, Flanagan T, Stearrett R A, Nowak E R, and Nordman C 2009 *Appl. Phys. Lett.* 94 202506
[13] Reed D, Nordman C, and Daughtoon J 2001 *IEEE Tran. Magn.* 37 2028
[14] Scola J, Polovy H, Fermon C, and Pannetier-Lecoeur M, Feng G, Fahy K, and Coey J M D 2007 *Appl. Phys. Lett.* 90 252501
[15] Nowak E R, Weissman M B, and Parkin S S P 1999 *Appl. Phys. Lett.* 74 600
[16] Dimopoulos T, Gieres G, Wecker J, Wiese N, and Sacher M. D 2004 *J. Appl. Phys.* 96 6382
[17] Liou S H, Zhang R, Russek S E, Yuan L, Halloran S T, and Pappas D P 2008 *J. Appl. Phys.* 103 07E920
[18] Stearrett R, Wang W G, Shah L R, Gokce A, Xiao J Q, and Nowak E R, 2010 *J. Appl. Phys.* 107 064502
[19] Feng J F, Feng G, Coey J M D, Han X F, and Zhan W S 2007 *Appl. Phys. Lett.* 91 102505
[20] Feng J F, Diao Z, Feng G, Nowak E R, and Coey J M D 2010 *Appl. Phys. Lett.* 96 052504
[21] Hayakawa J, Ikeda S, Matsukura F, Takahashi H, and Ohno H 2005 *Jpn. J. Appl. Phys.* Part 2 44 L587
[22] Gokce A, Nowak E R, Yang S H, and Parkin S S P 2006 *J. Appl. Phys.* 99 08A906
[23] Aliev F G, Guerrero R, Herranz D, Villar R, Greullet F, Tiusan C, and Hehn M 2007 *Appl. Phys. Lett.* 91 232504
[24] Almeida J M, Wisniowski P, and Freitas P P 2008 *IEEE Tran. Magn.* 44 2569
[25] Jiang L, Nowak E R, Scott P E, Johnson J, Slaughter J M, Sun J J, and Dave R W 2004 *Phys. Rev. B* 69 054407
[26] Ingvarsson S, Xiao G, Parkin S S P, Gallagher W J, Grinstein G, and Koch R H 2000 *Phys. Rev. Lett.* 85 3289
[27] Philipp J B, Alff L, Marx A, and R. Gross 2002 *Phys. Rev. B* 66 224417
[28] Glazman L I, and Matveev K A 1988 *Sov. Phys. JETP* 67 1267
[29] Nowak E R, Merithew R D, Weissman M B, Bloom I, and Parkin S S P 1998 *J. Appl. Phys.* 84 6195