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Journal of Magnetism and Magnetic Materials 300 (2006) 132–135
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Low-frequency noise and inelastic tunneling spectroscopy in Fe(1 1 0)/MgO(1 1 1)/Fe(1 1 0) epitaxial magnetic tunnel junctions

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Available online 15 November 2005

Abstract

We report on tunnelling magnetoresistance (TMR), current–voltage (*IV*) characteristics and low-frequency noise in epitaxially grown Fe(1 1 0)/MgO(1 1 1)/Fe(1 1 0) magnetic tunnel junctions (MTJs) with dimensions from 2×2 to $20\times 20\,\mu m^2$. The evaluated MgO energy barrier (0.50 ± 0.08 eV), the barrier width (13.1 ± 0.5 Å) as well as the resistance times area product ($7\pm 1\,M\Omega\,\mu m^2$) show relatively small variation, confirming a high quality epitaxy and uniformity of all MTJs studied. At low temperatures ($T<10$ K) inelastic electron tunneling spectroscopy (IETS) shows anomalies related to phonons (symmetric structures below 100 meV) and asymmetric features above 200 meV. We explain the asymmetric features in IETS as due to generation of electron standing waves in one of the Fe electrodes. The noise power, though exhibiting a large variation, was observed to be roughly anti-correlated with the TMR. Surprisingly, for the largest junctions we observed a strong enhancement of the normalized low-frequency noise in the antiparallel magnetic configuration. This behavior could be related to the influence of magnetostriction on the characteristics of the insulating barrier through changes in local barrier defects structure.

PACS: 72.25.−b; 72.70.+m; 73.21.−b

Keywords: Magnetic tunnel junctions; Low-frequency noise; Inelastic tunneling spectroscopy

Very high (more than 200% at RT) values of TMR [1,2] achieved recently in epitaxial magnetic tunnel junctions (MTJs) indicate a possible different tunneling mechanism in these new types of MTJs in comparison with polycrystalline ones [3,4]. Therefore, the study of new types of MTJs with epitaxial MgO [5,6] is of special importance. The record increase of TMR was described in terms of coherent tunneling in the case of Fe(1 0 0)/MgO(1 0 0)/Fe(1 0 0) MTJs [7,8] and alternatively attributed to large spin polarization of CoFe ferromagnetic layers in CoFe/MgO(1 0 0)/CoFe MTJs with epitaxial MgO(1 0 0) layer [1].

We report here on TMR, low-frequency noise and inelastic tunneling spectroscopy in a novel type of epitaxial MTJs of Fe(1 1 0)/MgO(1 1 1)/Fe(1 1 0), yet unexplored for the (1 1 1) orientation of the oxide layer, as well as for the (1 1 0) orientation of Fe. Measurements of the noise and ITES in polycrystalline MTJs have provided a variety of new information such as: (i) observation of $1/f$ noise, independent of the relative orientation of ferromagnetic layers and related mainly to structural defects within the barrier [9,10], (ii) presence of a well-defined increase of the magnetic noise just near the transition regions between ferromagnetic and antiferromagnetic alignments [11,12], and detection of phonon and magnon modes [13].

The measurements have been carried out on 14 Fe(1 1 0)/MgO(1 1 1)/Fe(1 1 0) epitaxial MTJs grown on a single substrate, with 4 different sizes from 2×2 to $20\times 20\,\mu m^2$. All Fe/MgO/Fe multilayers have been grown in a UHV system (base pressure 1×10^{-10} mbar) by molecular beam epitaxy (MBE) using Al_2O_3(1 1 −2 0) substrates. Typically, 10 nm Mo buffer layers have been grown at $T = 1000$ K

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0304-8853/$ - see front matter
doi:10.1016/j.jmmm.2005.10.049

before the Fe deposition. The first 50 nm Fe electrode has been grown at room temperature with a subsequent annealing at $T = 600$ K for 30 min to improve the crystalline quality. The MgO(1 1 1) barriers have been grown at $T = 293$ K from bulk MgO placed in a crucible of the electron beam evaporator. The second Fe(1 1 0) electrode (5 nm) has been deposited subsequently at room temperature on the MgO(1 1 1) barrier. To prevent oxidation all samples were protected by a 5 nm Au cap layer. More details about growth and characterization of the MgO(1 1 1)/Fe(1 1 0) system may be found in Ref. [14]. Thin film structures were microstructured using a combination of optical and electron beam lithography and Ar^+ ion milling. A SiO_2 insulating layer was deposited to prevent shortcuts between the lower electrode and the upper contact layer. We used silver paste connected gold wires to contact the samples to four terminals on a chip carrier for the transport measurements. In order to obtain the first and the second derivatives of the current–voltage (IV) characteristics a modulated ($f < 77$ Hz) DC current was sent through shunt resistors R_s ($1 < R_s < 10$ MΩ) to the junction while the magnitude and phase of the AC response was detected by a lock-in amplifier. The typical frequency range of the voltage noise was $3 < f < 1000$ Hz. The low-frequency noise was measured with an auto-spectrum technique by using a two-step amplifier and spectrum analyzer.

Fig. 1a shows typical TMR measured in a sample of area size $10 \times 10\,\mu m^2$ between 300 and 1.5 K. The dependence of TMR on device dimension shows that due to fringing fields at the sample edges the coercive field of the hard Fe layers stays nearly size independent, while the switching of the soft layer starts even before the magnetic field inversion. The rather small variation in the RA parameter (7 ± 1 MΩ μm^2), which we obtain with an area change of order 100, indicates that the studied MTJs may be considered as nominally nearly identical and that pinholes are not the main factor affecting the TMR. The negative temperature coefficient in $R(T)$ curves observed in our MTJs, according to Ref. [15], also supports this point. Statistical analysis of the MgO barrier characteristics determined from differential conductance as a function of applied voltage (Fig. 1b) is shown in Fig. 1c. The MgO barrier parameters such as thickness and height of the MTJs vs. area were evaluated by using a parabolic Brinkman fit [16] of the IV curves.

Interestingly, the MgO barrier height has been found to be 0.50 ± 0.08 eV when averaged over all the samples studied. This value is about a factor of 5 lower than the expected value of bulk MgO [5]. Similar recent observations reported for Fe(1 0 0)/MgO(1 0 0)/Fe(1 0 0) were explained by the oxygen vacancy impurity band forming inside the wide (about 3 eV) energy gap of MgO [2]. The average width of the barrier was estimated to be reduced to about 13.1 ± 0.5 Å from the nominally grown 40 Å. In our view, the reduced effective barrier width could be due to a non-rectangular energy profile of the barrier. Some FeO

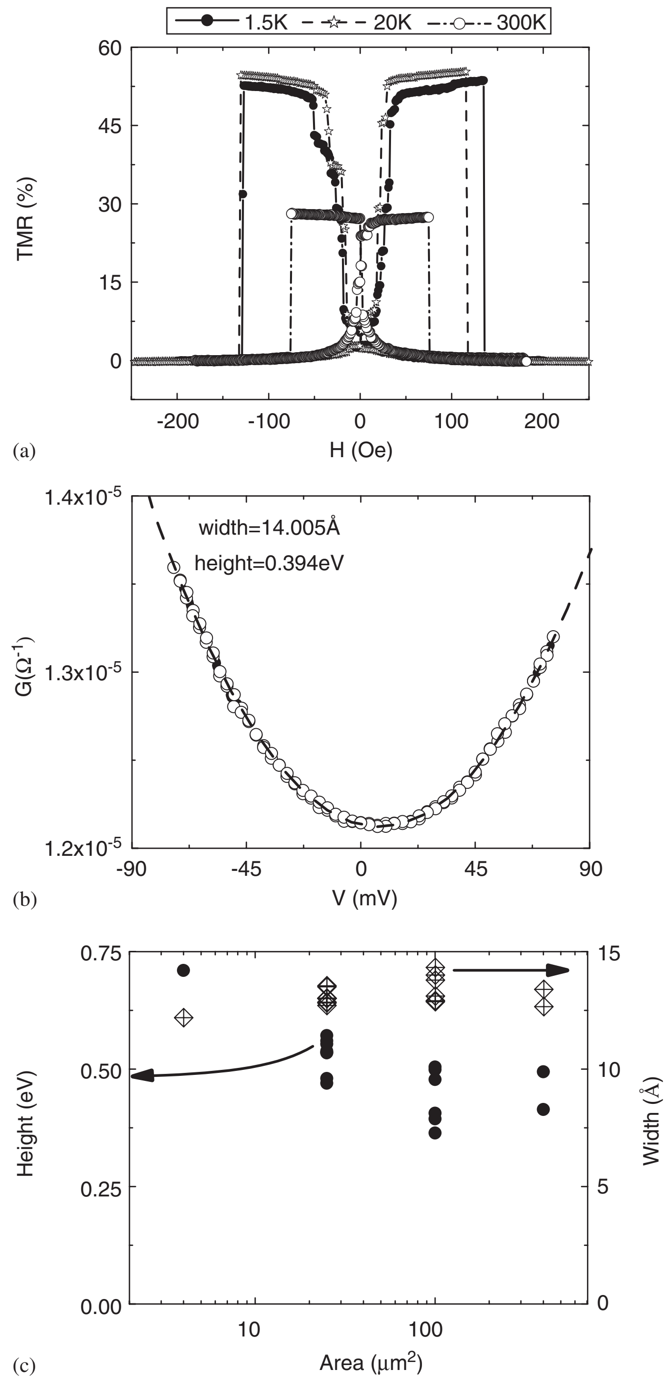

Fig. 1. (a) Tunnelling magnetoresistance between 300 and 1.5 K, (b) typical conductivity vs. voltage at 300 K and (c) statistical analysis of the MgO barrier in Fe(1 1 0)/MgO(1 1 1)/Fe(1 1 0) MTJs at 300 K (see text).

intermixing at the interface could also reduce the barrier width [14].

The spectral noise density follows, as expected, a linear dependence on the applied current (not shown). With suppressed $1/f$ noise at small current, frequency independent contributions, including thermal and shot noise, were observed at the highest frequencies. We shall analyze here only the $1/f$ noise which depends on the interaction of electrons with defects inside the barrier [17]. To characterize noise we use the Hooge parameter α which is defined [17] as $\alpha(f) = As^2(f)*f/V^2$, where A is the junction area, f is the frequency and V is the voltage applied to the junction. This parameter allows to compare samples with different sizes and resistances. Despite a rather large variation in the noise characteristics, there seems to be a general trend of lower noise with increasing TMR. Investigation of the noise spectra by changing the magnetic field in steps of 1 Oe, when driving the MTJ from parallel (P) to antiparallel (AP) and back to P alignment (Fig. 2a), shows, that the magnetic field dependence of the noise (Fig. 2b) may be qualitatively different for the studied samples compared to polycrystalline samples. Some MTJs showed a noise parameter nearly independent of the relative alignment of the magnetic layers, with the exception of a narrow transition region where some excess magnetic noise could be seen (Fig. 2b). Other MTJs, however, revealed the presence of unexpected additional noise in the AP state. A rather weak change of the form and the value of this extra noise with magnetic field in the AP state, points to its nonmagnetic origin. On the other hand, the strong variation of the noise (Hooge parameter) between P and AP configurations (Fig. 2b) indicates that the noise level should be linked to the magnetization direction of the soft Fe layer. In our view, the unusual enhancement of the noise in the AP state could be caused by magnetoelastic constriction/elongation of the soft Fe layer following the field inversion.

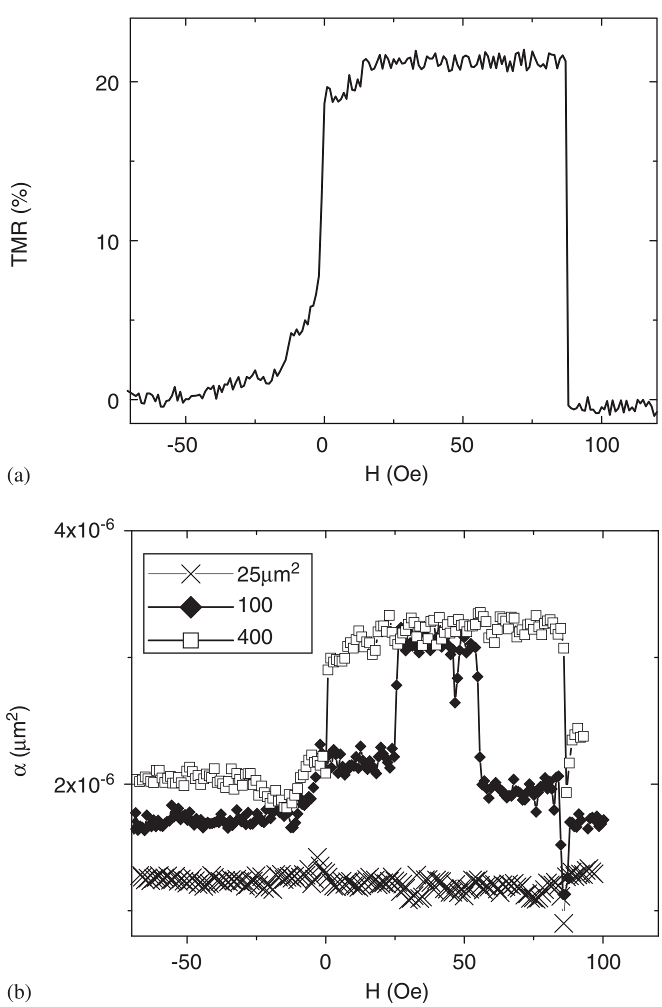

Fig. 2. (a) Typical TMR curve for a $20 \times 20\,\mu m^2$ MTJ and (b) dependence of the Hooge parameter on magnetic field for three MTJ samples with different sizes at 300 K.

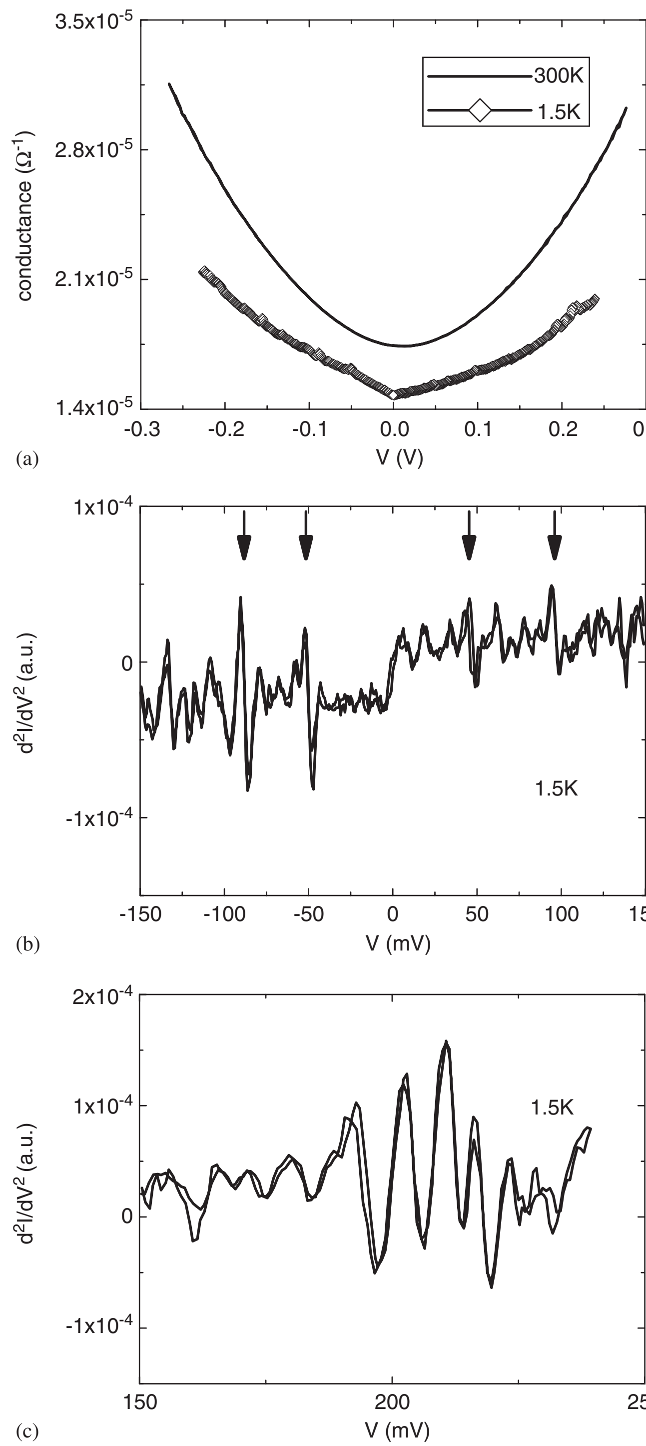

Fig. 3. (a) Differential conductance at 300 and 1.5 K and its derivative (b, c) at $T = 1.5$ K for $10 \times 10\,\mu m^2$ MTJ.

Interestingly, the field dependent noise has been found to be present in the largest samples ($20 \times 20\,\mu m^2$) and to be absent in the small ones ($2 \times 2\,\mu m^2$ and $5 \times 5\,\mu m^2$), while only some of the samples with intermediate dimensions ($10 \times 10\,\mu m^2$) demonstrated this behavior. This further supports the magnetostriction origin of the noise enhancement suggested above, because in smaller MTJs the stray fields change the sign of the coercive field, enhancing magnetization in the AP state and reducing therefore the influence of the magnetostriction.

At low temperatures ($T < 10\,K$) inelastic electron tunneling spectroscopy (IETS) (Figs. 3a–c) shows symmetric (50 and 90 meV) and asymmetric (210 meV) anomalies. The symmetric features, shown by arrows in Fig. 3b, are usually attributed to excitation assisted tunneling anomalies related to phonons, magnons or vibrational excitations of specific molecules inside the barrier [18] (Fig. 3c). Within our experimental resolution we could not detect molecules inside MgO [14], which indicates that the main symmetric anomalies in IETS (Fig. 3b) may correspond to excitation of phonons or magnons. Indeed, the 50 meV feature is close to the lattice phonon mode reported for MgO [19]. We attribute the asymmetric features in IETS to the generation of electron standing waves in one of the Fe electrodes, presumably the thinnest. Similar effects have been reported for ultrathin Fe(1 0 0) layers (below 10 ML) by Yuasa et al. [20] but for partially epitaxial Fe(1 0 0)/Al_2O_3/FeCo MTJs.

Authors acknowledge useful discussions with A.P. Levanyuk, S.S.P. Parkin, A. Vedyaev and E. Tsymbal. The work has been supported in parts by Spanish MEC (MAT2003-02600) and Spanish–German Integrated Action project (HA-2002-0015).

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