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Abstract. Tunnel resistivity $R (= V/J)$ as a function of voltage has been calculated for magnetic tunnel junction systems, such as ferromagnet-insulator-ferromagnet three-layer structures. Our early study [1] has been carried out for determining the barrier characteristics in the MTJs based on Ni$_{80}$Fe$_{20}$/Al$_2$O$_3$/Co systems, by fitting the experimental $I$-$V$ characteristics to Simmons’ and Brinkmann’s models without image force. In this paper, the image force is taken into account for approaching closely to a real barrier potential. The effect of dielectric constant, and temperature on the tunnel characteristics has also been investigated.

Keywords: Magnetic tunnel junction, three-layer structures, tunnel characteristics.

1. Introduction
Magnetic tunnel junction (MTJ) structures like ferromagnet/insulator/ferromagnet exhibit large tunneling magnetoresistance (TMR) which makes them attractive for magnetic-field sensors, non-volatile magnetic memory and other spintronics devices [1, 2]. It is known that heterogeneous junction surfaces between ferromagnetic metals and very thin isolating layers in the MTJ structures form a potential barrier. Spin-dependent electron tunnelling through the barrier has been studied theoretically and experimentally [3, 4]. Essentially this is an electron scattering process at the surfaces. Important factors in the electronic properties of surfaces are the bound states of the surfaces, so called surface states, localized in the direction normal to the surface [5]. Image potential states are formed from the quantized surface states that exist at metal surfaces with a band gap near the vacuum level.

In the last paper [1], a fitting procedure of our experimental $I$-$V$ characteristic data to theoretical Simmon’s equation [6] allowing the determination of the potential barrier’s thickness and barrier height in the MTJ Ni$_{80}$Fe$_{20}$/Al$_2$O$_3$/Co has been presented. The obtained reasonable values are proof of the fact that tunneling dominates the conduction. However in that study we have used the rectangular potential barrier without image forces of the Simmon’s model. That means the electronic properties of surfaces at the barrier were not concerned. Whereas the practical barrier is a rectangular barrier with the image potential included. The image potential states have been considered to provide a unique model system for studying the various scattering processes in detail with the available experimental capabilities [7].

In this paper, a new fitting procedure of the experimental data for the MTJs to Simmon’s model has been realized taking into account the image force in the potential formula applied for all voltage
ranges. The new mean barrier height in the insulating layer is adjusted to obtain the experimental data. The effect of the dielectric constant of the insulating film is discussed in detail, and, it is shown that this constant affects the temperature dependence of the $J$-$V$ characteristic of the tunnel junction.

2. Theory

2.1. Rectangular barrier

When two metallic electrodes are separated by a thin insulating film, the action of the film is to introduce a potential barrier between the electrodes which impedes the flow of electrons between them. Normally the potential barrier is an ideal rectangular if image forces are excluded, as presented in figure 1a for the case of biased voltage $V = 0$, where $\phi_0$ is the height of the barrier at zero bias and $s$ is the wide of the barrier. Under application of a biased voltage $V \neq 0$, the barrier deforms in to trapezium as seen in figures 1b and 1c. The generalized theory developed by Simmons is applied to a rectangular barrier with and without image forces. Theoretical calculated results from the Simmon’s model have indicated that, for a given $s$, $\phi$ and $V$, the tunnel resistivity is lower for the practical barrier (with image forces) than for the ideal barrier (without image forces) [6].

2.2. The image potential

The surface barrier potential can confine electrons in surface states. The Coulomb-like attractive image force, experienced by any charged particles in front of a conductive material, and the repulsive surface then form a potential well for weakly bound electrons. These surface states are quantized to form energy levels described by a Ryberg series similar to electrons in the hydrogen atom, and lead to form a long coulombic tail on this potential of the surface barrier [5]. The effect of the image force is to reduce the area of the potential barrier by rounding off the corners and reducing the thickness of the barrier (figure 2a) and, therefore, increasing the flow of current between the electrodes.

Figure 1. a) Rectangular tunnel barrier at $V = 0$; b) $V < \phi_0/e$; c) $V > \phi_0/e$.

Figure 2. Generalized barrier with image potential for $V = 0$ (a) and biased for $V \neq 0$ (b).
The image potential is readily determined using image force method and is given, in a good approximation, by $V_i = -1.15\lambda d^2/[x(s-x)]$, where $\lambda = e^2\ln 2 / 8\pi\varepsilon e d$ [6]. In these equations, $x$ is the distance of the electron from negatively biased electrode (electrode 1), $s$ is the insulating film’s thickness, $e$ - electron charge, $\varepsilon$ - permittivity of the insulating film.

When the image potential expressed by $V_i$ is taken into account, the potential barrier is written as: $\phi(x) = \phi_0 - eVx / s - V_i$, For this case, the mean barrier height above Fermi label of negatively biased electrode is

$$\overline{\phi} = \frac{1}{d_s} \int_{s_i}^{s} \phi(x)dx$$

(1)

where $s_i$ and $s_2$ are limits of barrier at Fermi level (see figure 2):

$$d = s_2 - s_i$$

(2)

is the width or the thickness of the barrier when image force is included.

The current-voltage characteristic of a tunnel junction in the Simmon’s model can be determined as

$$J(Acm^{-2}) = (6,2.10^{10} / d^2)\phi_j \exp(-1.025d \phi_j^{1/2}) - (\phi_j + V) \exp[-1.025d (\phi_j + V)^{1/2}].$$

(3)

where

$$\phi_j = \phi_0 - (V / 2s)(s_1 + s_2) - [5,75 / K(s_2 - s_1)]\ln[(s_2(s - s_1)) / s_1(s - s_2)]$$

(4)

and

$$\begin{align*}
    s_1 &= \frac{6}{K\phi_0} \\
    s_2 &= s[1 - 46 / (3\phi_0 Ks + 20 - 2VKs)] + 6 / K\phi_0 \\
    s_i &= \frac{6}{K\phi_0} \\
    s_2 &= (\phi_0 Ks - 28)KV
\end{align*}$$

$$V < \phi_0$$

$$V > \phi_0$$

The first term in the equation (3) can be interpreted as a current density flowing from electrode 1 to electrode 2 and the second – a current density from electrode 2 to electrode 1, resulting in a net current density $J$. It is clearly seen that its value is dependent on the barrier thickness, mean barrier height and the applied voltage. Thus, the fitting procedure of the $I-V$ experimental data to the mentioned above Simmon’s model should help to determine $d$ and $\overline{\phi}$.

3. Experimental

We have fabricated cross-shaped MTJ samples (three Ni$_{80}$Fe$_{20}$/Al$_2$O$_3$/Co samples) by rf sputtering technique and measured their $I-V$ characteristics. Figure 3 present the experimental current-voltage curve for the Ni$_{80}$Fe$_{20}$/Al$_2$O$_3$/Co (1.7 nm) sample. It is in good agreement with another experimental current-voltage presented in Ref. [8].

The barrier parameters were then extracted by fitting the experimental curve to the Simmon [6] and Brinkman [9] models. It is shown that the annealing process (60 minutes at 300°C for Ni$_{80}$Fe$_{20}$/Al$_2$O$_3$/Co (1.7 nm) sample, for example) strongly affects the barrier parameters, both the thickness and height, and in this way, on the conduction mechanism in these MTJ samples.
4. Results and Discussions

4.1. Barrier parameters

By using equations (1) and (3) and coupling them with experimental curve of figure 3, some parameters concerning the barrier in the insulating film have been obtained and summarized in table 1. The reasonable values of these parameters are proof of the fact that tunnelling dominates the conduction in MTJ samples. The thickness takes a value which is comparable with the one calculated from the calibrated curve (not shown here). Usually the thickness found with this approach is different from the structural one (TEM image, for example). One of the reasons for it is caused by a limit of field view which does not allow an accurate determination of the averaged thickness over the sample.

The fitting to the experiment has given a higher value for the height of the rectangular potential when the image force is included, that is a good approach because the effect of the image force is to enhance the current of electrons through the barrier by reducing its width which can be clearly seen from the Table 1 (from 31 to 28.51 Å). From now on, all theoretical calculations take the value of 9.8 for the dielectric constant $K$ of the Al$_2$O$_3$ insulating film of the MTJ sample.

Table 1. Barrier parameters extracted by fitting procedure for the rectangular potential without and with image force for Ni$_{80}$Fe$_{20}$/Al$_2$O$_3$/Co sample.

| Parameter | Rectangular potential without image force in the Simmon’s model (1) | Rectangular potential with image force in the Simmon’s model (2) |
|-----------|---------------------------------------------------------------|-----------------------------------------------------------------|
| $\phi_0$ (eV) | 1 | 1.26 |
| $\bar{\phi}$ (eV) | $\bar{\phi} = \phi_0$ | 1.14 |
| $s$ (Å) | 31 | 31 |
| $s_1$ (Å) | 0 | 0.48 |
| $s_2$ (Å) | $s_2 = s$ | 29.75 |
| $d = s_2 - s_1$ (Å) | $d = s$ | 28.51 |

4.2. Current voltage characteristic I-V

The current-voltage of the sample is calculated by substituting to the equation (3) of the Simmon’s model the values of the mean thickness and height of the barrier potential obtained when image force is included (data of column (2) in table 1). It is presented in figure 4.
4.3. Dependence of tunnel resistivity on applied bias
Tunnel resistivity \( R = V/J \text{ (A.cm}^{-2} \text{)} \) is calculated from equation (3) including the image force and is compared with the one case without image force. They are depicted in figure 5. It can be observed that, for given \( s \), \( \phi \) and \( V \), the tunnel resistivity is lower for the practical barrier, as anticipated, although the general shapes of the curves are preserved. Moreover, the difference of the resistivity between two cases becomes more apparent, because of the influence of the image force which is greater for small barriers. If the voltage applied to the junction is great enough, the barrier is lowered below the Fermi level of the negatively biased electrode, and then the current is not impeded in the insulator.

4.4. Influence of the dielectric constant on the electrical characteristics of the junction
Inspired by the idea of [8] who studied experimentally the temperature dependence of tunnel resistance and TMR ratio of a MTJ (the ratio TMR is defined as resistivity relative to the value at saturated magnetic field), we carried out a study of this dependence in our sample through the dependence of the dielectric constant \( K \) of the insulating film in equation (3). The theoretical results of the tunnel resistivity \( R \) as a function of the film thickness and applied bias are illustrated respectively in figures 6 and 7.
It is shown from these figures that the smaller the value of $K$, the lower the tunnel resistivity. As we have known that the dielectric constant of most materials changes when temperature changes, the electrical characteristics of the junction of MTJs depend therefore on temperature through dielectric constant. However, the law of the tunnel resistance’s dependence on temperature must need more study, because not only dielectric constant but also other parameters of the junction, for example film thickness [10], vary with temperature.

5. Conclusion
A Simmon’s model based approach, including image force, to practical tunneling image force in the magnetic tunnel junction Ni$_{80}$Fe$_{20}$/Al$_2$O$_3$/Co has been presented. The fitting procedure of the theory to the experiment allows determining barrier parameters such as effective thickness and mean height. The dependence of electrical characteristics of the tunnel on the dielectric constant and temperature has also been investigated. The derived results for the sample have shown useful to qualify the MTJs.

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