Solid-State Electronics 68 (2012) 8–12

Contents lists available at SciVerse ScienceDirect

Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse

Review

Effects of applied bias voltage in tunnel junctions with ferroelectric barrier

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ARTICLE INFO

Article history:
Received 17 February 2011
Received in revised form 1 September 2011
Accepted 17 September 2011
Available online 24 October 2011

The review of this paper was arranged by Dr. Y. Kuk

Keywords:
Applied bias voltage
Tunnel junction
Ferroelectric barrier
Tunneling electroresistance
Tunneling magnetoresistance

ABSTRACT

Effects of applied bias voltage on tunneling electroresistance and tunneling magnetoresistance in multiferroic tunnel junctions with ferroelectric barrier and dissimilar ferromagnetic electrodes are theoretically investigated. Taking into account the electric field effect on permittivity of ferroelectric films, the applied bias voltage could creates a sizable influence on the permittivity-dependent tunneling electroresistance and tunneling magnetoresistance. The calculations could indicate a prospective way for reading the states of tunnel junction with a pronounced difference in resistance, which may provide some contributions to practical applications in memories and spintronics.

Contents

1. Introduction

Multiferroic tunnel junctions (MFTJs) which are consisted of two asymmetric ferromagnetic electrodes separated by nanometer-thick ferroelectric barriers have been investigated with considerable interest due to its potential application in memories and spintronics [1–7]. Current investigations show that due to the presence of converse piezoelectricity in the ferroelectric barrier, the properties of MFTJs, such as tunneling magnetoresistance, vary with the reversal of electrical polarization [3]. Moreover, the magnetic configuration is potentially switched by reversing the polarization of the ferroelectric barrier layer due to the existence of interlayer exchange coupling between ferromagnetic and ferroelectric layers [2,5]. One electronic mechanism explains that atomic displacements at the ferromagnetic/ferroelectric interface caused by ferroelectric switching change the overlap between atomic orbits at the interface, which in turn affects the interface magnetization [8,9]. Another mechanism demonstrates that an accumulation of spin-polarized electrons or holes at the interface results in a change of the exchange splitting and interface magnetization [10,11].

To read out the tunneling states and depict the properties of the tunnel junctions, a small bias voltage should be applied across the barrier-layer which scarcely ever considered in previous theoretical works because it is much smaller than the height of the barrier and the permittivity of ferroelectric films is also considered as a constant. However, for the ferroelectric thin film, the permittivity is electric-field-dependent [12,13] and the permittivity of the ferroelectric barrier is one of the dominating factors affecting the

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0038-1101/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.sse.2011.09.005

properties of tunnel junctions with ferroelectric barriers. In addition, for a nanometer-thick thin film, the small bias voltage could create a strong electric field, which will influence the permittivity of the ferroelectric barrier-layer and in turn affects the properties of the tunnel junction. Consequently, taking into account the sensitivity of the permittivity of ferroelectric films to electric field, the applied bias voltage may be a key parameter affecting the properties of the tunneling junctions.

2. Device model and theoretical calculation

The key properties characterizing the MFTJs are the tunneling electroresistance (TER) and the tunneling magnetoresistance (TMR), both of which describe the difference of tunnel conductance among the states of tunnel junction. The TER ratio represents the difference of tunnel conductance related to the orientations of electric polarization in the barrier. The TMR ratio represents the difference of tunnel conductance related to relative orientations of magnetization in the electrodes.

To investigate the contribution of external applied voltage to the properties of MFTJs, we consider a junction which consists of a ferroelectric layer with the thickness of d sandwiched between two asymmetric ferromagnetic electrodes, shown in Fig. 1. In this model, the permittivity for ferroelectric thin films is electric-field-dependent and defined as [12,13].

$$\varepsilon_{\mathrm{FE}}(E) = \frac{b}{\sqrt{a^2 + E^2}}, \tag{1}$$

where a, b are appropriate constants which are independent of the electric field E. For $\mathrm{PbZr_{0.52}Ti_{0.48}O_3}$ (PZT) thin films $a = 2.1656 \times 10^5$ V/cm, $b = 9.35 \times 10^7$ V/cm, which are the empirical values for its parameters [13].

Employing the Thomas-Fermi model of screening and imposing short-circuit boundary conditions, the shapes of the electrostatic potential in the electrodes are given by [14].

$$\varphi(x) = \begin{cases} \frac{\sigma_s \delta_L e^{-|x|/\delta_L}}{\varepsilon_L}, x < 0 \\ -\frac{\sigma_s \delta_R e^{-|x-d|/\delta_R}}{\varepsilon_R}, x > d \end{cases} \tag{2}$$

where $\sigma_s = \frac{dP}{\varepsilon_{\mathrm{FE}}(\delta_L + \delta_R) + d}$ is the screening charge and δ_L, δ_R are the Thomas-Fermi screening lengths in the left and the right electrodes, respectively. $\varepsilon_{\mathrm{FE}}$ is the electric-field-dependent relative permittivity for the ferroelectric barrier-layer. ε_L, ε_R are the permittivity for the left and the right electrodes. In addition, the electrostatic potentials at the interfaces are given by Eqs. (3) and (4):

$$\varphi(0) = \frac{\sigma_s \delta_L}{\varepsilon_L}, \tag{3}$$

$$\varphi(d) = -\frac{\sigma_s \delta_R}{\varepsilon_R} + eV. \tag{4}$$

Here eV is the applied bias voltage across the ferroelectric barrier-layer. From the Eq. (4), it can be seen that even the permittivity of ferroelectric barrier-layer is constant, the effect of the applied bias voltage on the properties of tunnel junctions is also considered in our calculations. Following the conventional treatment, [1–4, 15–17] the conductance of tunnel junctions can be obtained using the Landauer formula,

$$G = \frac{e^2}{h} \int \frac{d\kappa_{||}}{(2\pi)^2} T(E_F, \kappa_{||}). \tag{5}$$

Here G is the tunneling conductance for per unit area, e is the charge of an electron and h is the Planck constant. $T(E_F, \kappa_{||})$ is the transmission coefficient evaluated at the Fermi energy E_F for a given value of the transverse wave vector $\kappa_{||}$.

In the calculations, for simplicity, we assume that all electrons have the free electron mass (m_e) in both electrodes and the barrier-layer. And other parameters are set as follows: $d = 2$ nm, the barrier height $U = 0.5$ eV for ferroelectric barrier-layer [18] and the ferroelectric polarization $P = 0.39$ C/m^2 which is a typical value for PZT films. The Thomas-Fermi screening lengths are $\delta_L = 0.09$ nm and $\delta_R = 0.07$ nm for the left and the right electrodes [19,20]. The Fermi energy $E_F = 0.1$ eV for the system and $\mu_L = 0.1$ eV and $\mu_R = 0.1$ eV for the left and the right electrodes [19]. The exchange splitting energies of the electrode are $\Delta_L = 0.05$ eV and $\Delta_R = 0.09$ eV for the left and the right electrodes [19,20].

3. Results and discussion

The calculated results are presented in Figs. 2–4. In the figures, the terms TER ↑↑ and TER ↑↓ represent the TER corresponding to the alignment of magnetization in the electrodes parallel and anti-parallel. The TER ratio is defined by $\mathrm{TER} = \frac{G_R - G_L}{G_L}$, G_L and G_R are the tunneling conductance corresponding to the electric polariza-

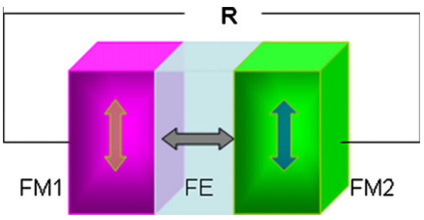

Fig. 1. Schematic diagram of MFTJs with symmetric ferromagnetic electrodes (FM1 and FM2) and ferroelectric barrier (FE).

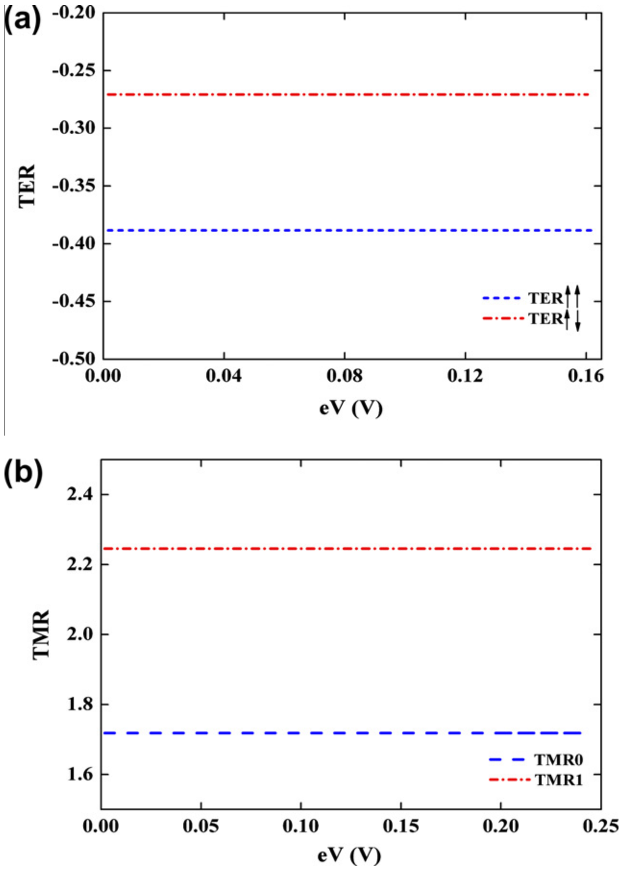

Fig. 2. The TER and TMR as functions of applied bias voltage while the relative permittivity is constant.