Magnetization Reversal of Magnetic Tunnel Junctions by Low-Current Pulses

Igor Yu. Pashen'kin, Nikita S. Gusev, Dmitry A. Tatarskiy, and Maksim V. Sapozhnikov

***Abstract*— The magnetization curves of highly resistive CoFeB/MgO/CoFeB/IrMn magnetic tunnel junctions (MTJs) are studied in dependence of the electrical field in the barrier. It is shown that the magnetoresistive hysteresis curve of the free layer (FL) is shifted by 6 Oe with the increase of the applied voltage from 50 mV to 1 V. The 100-ns voltage pulse of 2 V changes the magnetization of the FL by 50%. At that the current density of the pulse is small enough as 10^3 A/cm^2. The most probable explanation of the observed effect is the dependence of the exchange interaction between the ferromagnetic (FM) layers in the MTJ on the electric field in the barrier, which reaches a value of 10^7 V/cm. The architecture of the MRAM cell operating on the observed effect is proposed.**

***Index Terms*— Magnetic tunnel junction (MTJ), magnetoelectric effects, spintronics.**

I. Introduction

MAGNETIC tunnel junctions (MTJs) have a multilayer structure comprising of an ultrathin insulating layer (serves as a tunnel barrier) sandwiched between two ferromagnetic (FM) layers. One of the FM layers has the fixed magnetic orientation and is called a reference layer (RL). Another FM layer is called a free layer (FL) and it has a magnetic orientation, which can be either parallel or antiparallel to the RL. The resistance variation of these two states of the MTJ can be as large as 600% in the case of MgO barrier [1]. This way logical states can be coded as "1" and "0" for the parallel and antiparallel magnetization states, respectively. Whereas the process of the MTJ state reading can be organized quite easily due to the large magnitude of the tunnel magnetoresistive (TMR) effect, the process of writing is much more complicated because it is necessary to change the magnetic state of the system. The most researched and developed methods of magnetization reversal of FL involve the use of electric current. This can be the creation of a magnetic field by current flowing through the conductor next to the FL-field-induced magnetization switching (FIMS) [2] or a more sophisticated version is commonly known as toggle MRAM (T-MRAM) [3]. The field switching can be assisted with local heating—thermally assisted switching-MRAM (TAS-MRAM) [4]. It is also possible to use the effect of spin transfer torque when the spin polarized tunneling current reverses FL magnetization (STT-MRAM) [5], [6]. The STT mechanism can be assisted by spin Hall effect [SHE-MRAM or spin-orbit torque (SOT-MRAM)] [7], [8] when additional amount of spins are injected into FL from heavy-metal conductor carrying electric current. All these electric current assisted methods have their own advantages and disadvantages and are thoroughly discussed in [9] and [10]. Their common feature is the need for a high current density (10^7 A/cm^2 and higher), which associates with the problems of high power consumption and scaling.

This problem can be overcome if the switching of the logical state happens not due to the current but due to the application of an electric field. Such a mechanism can be realized using the so-called voltage-controlled magnetic anisotropy (VCMA) switching mechanism [11], [12], [13], [14]. The VCMA means that the electric field generated by the bias voltage applied to the MTJ leads to the charge accumulating or depleting at the metal/barrier interface. That modifies the spin-orbit interaction and changes the magnetic anisotropy of FL. The magnetization reversal takes place due to FL magnetization precession in the effective field of the changed anisotropy. In this case, the deterministic switching is possible only in the dynamic mode; therefore, the precise control of voltage pulse duration and shape is needed. A sufficiently lower switching energy is needed in VCMA-MRAM [15] because the current density stays lower than 2×10^5 A/m^2. The VCMA effect is also used to assist STT magnetization reversal [16], but the effect is an even function of the bias voltage and the switching barrier decreases only in one direction (e.g., from 0 to 1).

An alternative possibility of field control of the magnetic state in an MTJ is a variation in the exchange interaction between magnetic layers upon voltage application. This possibility has been demonstrated in a tunnel structure CoFeB/GdO$_x$/CoFeB due to the oxygen vacancies ability to move within the GdO$_x$ tunnel barrier. That is why such a MTJ can be reversibly switch between AFM and FM states by applied voltage [17]. This idea has not been developed further apparently due to not very large value of the TMR effect in such a structure (14%). Another magnetization state switching mechanism is demonstrated in [18], where the reference electrode of the MTJ structure includes a layer of a synthetic antiferromagnet (SAF) FePd/Ru/FePd. When an

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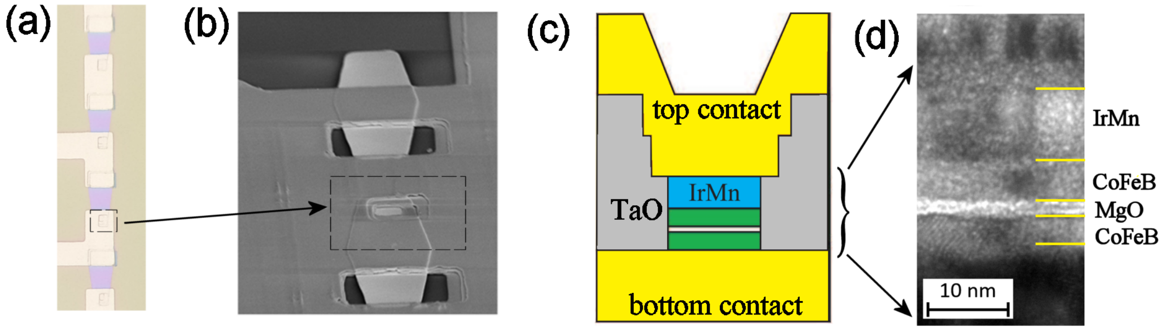

Fig. 1. (a) Optical photograph of a section of a serial chain of micrometer-scale MTJs. The MTJ region is highlighted by a dotted line and is shown in (b) in an enlarged form (the image is obtained using an electron microscope). (c) Schematic representation of the MTJ stack. (d) Bright field cross-sectional micrograph of the similar MTJ structure obtained with a transmission electron microscope (Color online).

electric current of $\sim 10^5$ A/cm^2 flows through SAF, it leads to the sign change of the exchange interaction in SAF and so to switching in the direction of the RL magnetization. Note that the current value is one order of magnitude lower than in the best reported STT devices.

In this work, we study the possibility of controlling the exchange coupling between FM layers through the MgO layer when an electrical voltage is applied to the junction. The idea is based on the fact that the exchange coupling of FM layers depends on the width of the tunnel barrier. It changes from $+5 \times 10^{-3}$ erg/cm^2 to -4×10^{-2} erg/cm^2 passing through zero at a thickness of $\sim$0.8 nm in Fe/MgO/Fe layered system [19]. The same behavior is observed in Co/MgO/Co junction [20]. The energy profile of the tunnel barrier, and hence its effective width, changes with the application of an electric voltage leading to the change of the exchange coupling [21]. In the following, we demonstrate that applying $\sim$1 V to the CoFeB/MgO/CoFeB MTJ leads to a shift of the FL hysteresis loop by $\sim$6 Oe. Partial (by 50%) magnetization reversal of the FL occurs when short voltage pulses of 2 V are applied. Since magnetization reversal takes place due to the application of the voltage to a structure with a resistance of 10$-$20 k$\Omega \times \mu$m^2, the accompanying current has an extremely small value of only $\sim 10^3$ A/cm^2. It is three orders of magnitude less than the current required for STT-MRAM. The demonstrated effect is unipolar; however, we propose a scheme that will allow bipolar switching.

II. Samples

For this work, a multilayer stack with the composition of Ta(20 nm)/Pt(10 nm)/Ta(20 nm)/CoFeB(2$-$4 nm)/MgO(1.5–2.5 nm)/CoFeB(4 nm)/IrMn(10 nm)/Ta(3 nm)/Pt(10 nm) is deposited on Si/SiO_2 substrates by high-vacuum magnetron sputtering at room temperature. The residual pressure in the growth chamber does not exceed 3×10^{-7} torr, and the working argon pressure during the deposition is 2×10^{-3} torr. The MgO layer is deposited by the RF sputtering of a MgO stoichiometric dielectric target. The IrMn layer is used to obtain unidirectional anisotropy of the FM RL. The layers are deposited in a magnetic field of 150 Oe for this purpose. In this case, the CoFeB RL is magnetized uniformly and causes the required ordered state of the AFM IrMn layer, which is deposited next. Correspondingly, after switching off the field, the RL layer turns out to be pinned in the uniform state on the IrMn sublayer. The typical value of the exchange bias in our samples is 150$-$300 Oe.

The deposited TMR stack is patterned into elliptical micropillars for transversal electrical measurements by using successive optical lithography and ion milling. As the result, the elliptical 2×3 μm^2 MTJs are fabricated. The MTJs are connected in a serial chain of 50 elements. It is possible to measure both individual MTJ from a chain and the entire chain [Fig. 1(a)]. The junction pads are formed from Au film to connect the sample to a measuring circuit. Finally, the MTJs are thermally annealed in vacuum at 330° for 2 h to form texture in CoFeB layers, which are initially amorphous. The annealing is carried out in the presence of the magnetic field of 4 kOe. This results a significant increase in the TMR effect from 10%–20% to 80%–220% for different samples.

III. Results and Discussion

We measure TMR effect at different applied voltages to understand the influence of the applied electric field on the interlayer exchange coupling in MTJ. Note that the barrier thickness must satisfy two conflicting requirements. On the one hand, the barrier should be thin enough, so that a noticeable variation in the exchange coupling is observed under the voltage application. On the other hand, it should be thick enough, so that its resistance allows significant voltages to be applied without large current and accompanying thermal effects. It is found that the MgO barrier thickness $t_b \sim 2$ nm best meets these requirements. This corresponds to MTJ resistance $R = 3.4$ kΩ. Here and in the following, we give the resistance of the parallel (FM) configuration of the samples. The thickness of the FL layer is chosen to be as thinner as possible (2 nm) to increase the possible interlayer exchange interaction, which is a surface effect.

Two main effects are found with the increase of the bias voltage from 50 mV to 1 V per MTJ (which corresponds to the electric field of $\approx 10^9$ V/m). At first, it is noticeable fivefold drop in the TMR effect [Fig. 2(a)]. Such effect was observed earlier in CoFeB/MgO/CoFeB MTJs [22], [23], [24], [25]. It is due to the fact that the probability of electron tunneling from the majority-spin band to the minority-spin band increases in the antiparallel magnetic configuration at high voltage [26].

The second effect is a shift of the magnetization curve of the FL by 6 Oe [Fig. 2(b)] for the sample with $R = 3.4$ kΩ per MTJ. This shift becomes smaller as the thickness of the MgO barrier increases, accompanied by an increase in junction resistance. The magnetoresistive loop for the sample with $R = 10$ kΩ ($t_b \sim 2.2$ nm) per MTJ shifts by 3 Oe

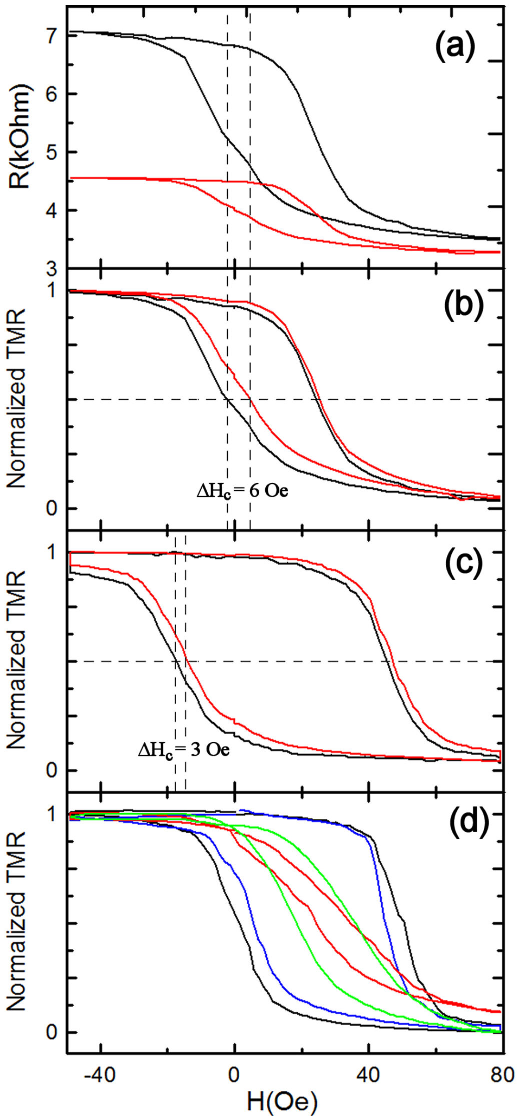

Fig. 2. Magnetoresistive curves of the samples. The FL hysteresis loops are presented. Black, blue, green, and red lines are for the dc voltage 0.05 V, 0.2, 0.8, and 1 V per junction correspondingly. The data are averaged over MTJ chain. (a) Magnetoresistive curve of the sample with resistance $R = 3.4$ kΩ per junction. (b) Same dependencies reduced to the same scale. (c) and (d) Loops for the samples with $R = 10$ kΩ and $R = 0.2$ kΩ (Color online).

at the voltage 1 V [Fig. 2(c)]. It is important to note that the magnitude and direction of the shift of the hysteresis loop do not depend on the polarity of the applied voltage. The data for the other samples are shown in Fig. 3(a). The possible mechanism of the observed shift is the change in the exchange interaction between the magnetic layers. The observed magnitude and the directions of the shift are in good agreement with the earlier measurements of the exchange coupling. Indeed, comparing the value of the Zeeman energy referred to the surface area and the range of the possible variation of the exchange coupling in MTJ (see [19, Fig. 1]), one can estimate the range of the possible variation in the effective exchange field between the layers as

$$H_{\text{coup}} = J/Md \approx +20\,\text{Oe} \sim -200\,\text{Oe}$$

where J is the interlayer coupling energy, $M \approx 1000$ erg × Gs^{-1} × cm^{-3} is the magnetization of FL, and $d \approx 2 \times 10^{-7}$ cm is its thickness. The measured hysteresis loop shift $\Delta H \approx 6$ Oe lies within this range. On the other hand, the shift of the magnetization loop of the FL to the region of higher magnetic field values indicates either a decrease in the exchange coupling or a change of its sign from FM to anti FM with applying of the voltage. Such variation in exchange coupling corresponds to an effective decrease in the width of the tunnel barrier upon application of a voltage. Let us note that the current flowing through the MTJ has a density of about 10^3 A/cm^2 (at the voltage of 1 V).

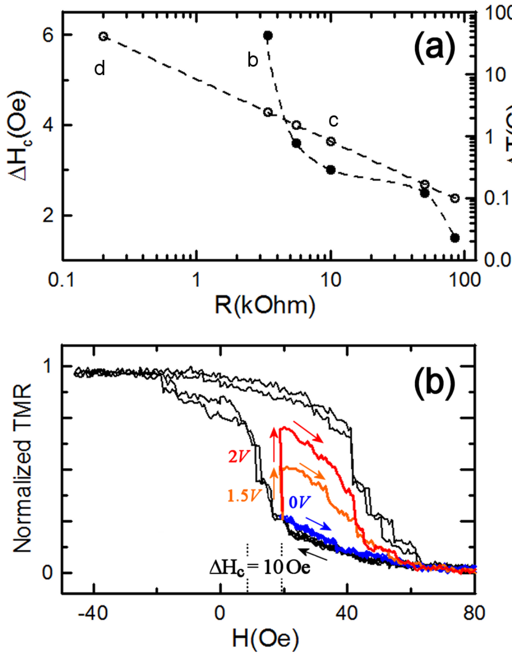

Fig. 3. (a) Solid circles are for the magnetoresistive loop shift value ΔH_c at dc voltage 1 V in the dependence on MTJ resistance. Open circles are for estimated maximal temperature increase of the MTJ when 1-V dc voltage is applied. Small letters "b," "c," and "d" correspond to the samples presented in Fig. 2. (b) Change in the resistance of a MTJ with $R = 3.4$ kΩ after applying a 100-ns voltage pulse. Blue line is for the minor hysteresis loop without voltage pulse, the orange one is for 1.5 V, and the red one is for 2 V pulse (Color online).

The discovered effect cannot be a manifestation of the known VCMA effect for two reasons. Due to magnetostatics, our samples have the effective easy-plane anisotropy. We do not observe a change of the anisotropy sign when the voltage is applied. VCMA can also lead to a change in the value of effective easy-plane anisotropy. In the latter case, the in-plane magnetization reversal loop should either expand or narrow depending on the sign of the applied voltage, since the VCMA itself depends on the sign of the voltage. Vice versa, we observe a loop shift, and the effect does not depend on the polarity of the applied voltage.

Can other nonpolar mechanisms, heating, for example, explain the observed effect? The power density can be estimated as $P = jV \sim 10^3$ W/cm^2 $= 10^{-2}$ mW μm^{-2}. The typical temperature coefficient in MTJs [27] lies in the range 1–50 K/(mW μm^{-2}). The possible heating of our MTJs estimated using the maximum value of the temperature coefficient (50 K/mW μm^{-2}) is shown in Fig. 3(a). The heating effects should be negligible in the samples with $R > 3$ kΩ. Besides, heating should lead to a narrowing of the magnetization hysteresis loop, since thermal fluctuations begin to initiate the magnetization reversal process in lower fields and not to its shift. This is exactly the effect observed in the MTJ with resistance 0.2 kΩ [$t_b \sim 1.5$ nm, Fig. 2(d)]. In this case, the estimated heating of the junction by the flowing current at an applied voltage of 1 V can reach 42°.

Another possible effect is related to the redistribution of the current flowing through the barrier. The shape of the hysteresis loops demonstrates that the magnetization reversal of our MTJs proceeds gradually through a sequence of inhomogeneous states. So, there are regions with different resistance values in the same MTJ depending on the local mutual orientation of the magnetizations in the nonuniformly magnetized FL and uniform RL. This leads to an inhomogeneous current distribution over the MTJ area. The application of voltage changes the magnitude of the TMR effect and, hence, the ratio of resistances of high- and low-resistive areas of the MTJ. In principle, this can lead to a redistribution of the current over the MTJ area with increasing voltage and, hence, to a shift in the magnetoresistive curve relative to the magnetization curve.

In order to avoid the effect of current redistribution and also the effect of heating, which can occur during dc measurements, we study how short voltage pulses applied to the MTJ change its magnetic state. The measurements are carried out according to the following protocol. First, we measure the hysteresis curve of the magnetoresistance during FL reversal [Fig. 3(b)] applying small (0.05 V) dc voltage. Then, the magnetization reversal process is stopped at a point close to the front of the transition to the highly resistive (anti FM) state of the system ($H = 19$ Oe). After that, without changing the magnitude of the external magnetic field, we apply voltage pulse with a value of 1.5−2 V and a duration of 100 ns to the MTJ. Then, by changing the direction of the sweep of the external magnetic field, we measure how the magnitude of the magnetoresistance changes as a result of the applied voltage pulse. Thus, irrespective of the magnitude of the pulse voltage, all the measurements of the magnetoresistance are carried out at the same low applied dc voltage (0.05 V). The results are presented in Fig. 3(c). If no voltage pulse is applied, then the magnitude of the magnetoresistance, and hence the magnetic state of the system, does not change [blue line in Fig. 3(c)]. Since the measurements before and after the application of the voltage pulse are carried out at the same low applied dc voltage, this also allows us to avoid the effect of reducing the magnitude of the magnetoresistance, as is in the case with the dc measurements [Fig. 2(a)].

The applying of the pulse with the voltage of 1.5 V to the MTJ leads to ∼30% a change of TMR [orange line in Fig. 3(c)], and the pulse of 2 V leads to ∼50% change [red line in Fig. 3(c)]. The corresponding change of the effective exchange field is 10 Oe. The most important fact is, that after the action of the voltage pulse is completed, the magnitude of the resistance remains at the new changed level. This means that the application of a voltage pulse leads to the permanent change in the magnetic state of the FL of the MTJ. The change in resistance can be estimated as

$$\Delta R \sim \int_S \vec{M}_{\mathrm{RL}} \vec{M}_{\mathrm{FL}} dS \sim < M_{\mathrm{FL}} >_x$$

where M_{RL} and M_{FL} are the magnetizations of the reference and FLs, and x is the direction of the RL magnetization, which is considered to be uniform. Thus, the shape of the magnetoresistive curve corresponds to the shape of the magnetization curve of the FL. So, the magnitude of the magnetization change can be estimated as $\Delta M = M_s$ at 2 V pulse. The MTJs used by us in the experiment do not allow to apply larger voltages to completely switch the magnetic state of the system from the parallel to the antiparallel state ($\Delta M = 2\ M_s$), since an avalanche electrical breakdown is observed in the system at the voltages above 2 V. Nevertheless, the very fact of a change in the magnetic state of the FL under the action of an electric voltage pulse can be considered reliably fixed. The density of the electric current in the pulse is only 10^3 A/cm^2. This magnitude is clearly insufficient for the manifestation of the spin-torque or heating effects.

The effect of the change in the magnetic state upon voltage pulse application is in good quantitative agreement with the effect of the shift of the FL magnetization reversal loop in the dc measurements. It is possible that changing the lateral geometry or the thickness of the MTJ layers will make it possible to achieve 100% magnetization reversal of the FL. In order for 100% switching of magnetization to occur, it is necessary that the width of the edge of the hysteresis curve be less than the observed change in the coercive field ($\Delta H_c =$ 10 Oe) under the influence of voltage. This can be achieved by reducing the MTJ size to the size corresponding to the dimensions of a single domain (∼200 nm). Such MTJ can be manufactured using electron lithography methods. In our MTJs (2 × 3 μm^2), magnetization reversal occurs through a sequence of inhomogeneous states, and therefore, the width of the inclined part of the magnetization curve exceeds the change in the coercive field (10 Oe). But even the effect of 50% magnetization reversal is significant enough, to encode logical states and so to think about possible practical applications.

Although our MTJs are not a ready-made memory cells, their thermal stability factor can be estimated. It is usually estimated as $M_s H_c V / 2 k_B T$, where $M_s \approx 1000$ Oe, $H_c \approx 40$ Oe, and V are the saturation magnetization, coercivity, and volume of an FL. Since in our case magnetization reversal occurs through a sequence of inhomogeneous states, this formula gives overestimation. For a more accuracy, H_c should be taken as the width of the steps on the magnetization reversal curve (≈5 Oe), and M_s should be replaced by the magnetization value change on the step (≈0.1 M_s) [see Fig. 3(b)]. Taking this into account, the value of the thermal stability factor of our MTJ is approximately 90. In accordance with the data given in [28] (Table I), this value is sufficient for required stability of 1-Gb memory operation.

An important obvious drawback of the observed effect for control MRAM elements is its unipolarity. We propose the following dual MTJ cell architecture to overcome such disadvantage and to continue future investigations (Fig. 4). In the presented circuit, logical "0" and "1" correspond to high and low resistance at the bottom junction (corresponding to the anti FM and FM configuration of the bottom MTJ). The entry "1" is performed by applying a voltage pulse to the lower junction, and the entry "0" is performed by applying a voltage pulse to the upper junction. The opposite directions of

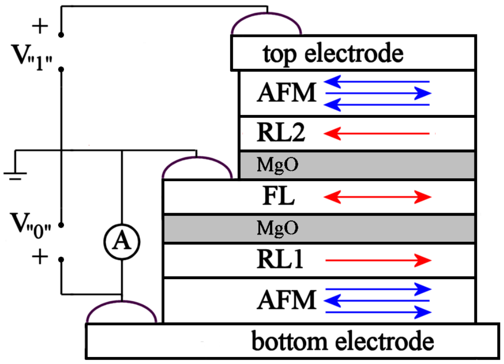

Fig. 4. Schematic design of the possible dual MTJ cell for MRAM operated by the effect of the voltage-controlled exchange shift. $V_{\text{"0"}}$ and $V_{\text{"1"}}$ indicate the points of application of the control voltage pulses that put the system in a state of logical 0 or 1. "A" denotes the circuit that reads the state of the MRAM cell (Color online).

the exchange bias in the upper and lower RL are essential for the operation of the proposed scheme. Besides, the proposed scheme provides two additional important advantages. First, due to the symmetry of the structure, the center of the FL magnetization reversal loop will shift to zero magnetic field and an external biasing magnetic field will not have to be applied to the MTJ to function. Second, in the case when CoFeB layer is surrounded on both sides by MgO layers, it has less crystallite size and its coercivity can be reduced to 5 Oe [29]. Thus, coercivity is lower than the change in the effective exchange field observed when a voltage pulse is applied. Under these conditions, the proposed dual MTJ scheme will be able to use the effect of a voltage-controlled exchange shift to switch between states "0" and "1" in both directions.

IV. Conclusion

In this paper, we present a novel method to control the magnetic state of MTJs by applying an electric field. The method is based on the effect of the dependence of the effective exchange coupling between the magnetic layers of the MTJ on the applied electric field which is observed and studied. Applying short pulses of electrical voltage to a junction changes its magnetization by 50%. At that the current density of the pulse is small enough as 10^3 A/cm^2. The discovered effect can be used to create energetically efficient MRAM.

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