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Investigation of the sensitivity of a TMR sensor based on magnetic tunnel junctions with uniaxial crystalline anisotropy in the free layer

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An approach to designing a tunnel magnetoresistive sensor based on magnetic tunnel junctions with uniaxial crystalline anisotropy in the free layer is presented. A detailed study of the influence of the shape, tunnel magnetoresistance and anisotropy field on the sensitivity and transfer characteristics of the TMR-sensor is performed.

Keywords: Magnetic tunnel junction, MTJ, TMR-sensor, sensitivity of TMR-sensor, spintronics, spintronic sensor.

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1. Introduction

Tunnel magnetoresistive sensors are becoming increasingly important in large industries nowadays, in particular, in the automotive industry. Magnetic field sensors based on the effects of anisotropic magnetoresistance (AMR) [1,2] and giant magnetoresistance (GMR) [3,4] are widely used as angular position sensors and current monitoring sensors. It is necessary to ensure the stability of the sensor output signal for such applications without unnecessary interference acting on the sensor element. This requirement is satisfied by designing the sensor using the Wheatstone bridge circuit. The replacement of AMR and GMR sensors with tunnel magnetoresistance (TMR) sensors [5–7], based on magnetic tunnel junctions (MTJ) [8–10], results in an increase of sensor sensitivity due to the effect of tunnel magnetoresistance, which reaches the order of 200%.

The resistance of the MTJ sensor element changes under the impact of an external magnetic field, due to which the magnetic field signal is converted into an electric one. The detection range of the external magnetic field is determined by the linearity of the magnetic resistance curve of the MTJ, and an MTJ design with a free layer with planar crystalline anisotropy directed orthogonally to the magnetization of the polarizer layer is used to achieve this characteristic (Figure 1, a). This MTJ design ensures a near-zero width of the hysteresis loop (Figure 1, b). This paper presents an analytical study of the impact of the shape of the MTJ, tunneling magnetoresistance and the crystalline anisotropy field on the sensitivity of the sensor and its transmission characteristic.

2. Sensitivity of the TMR sensor

The TMR sensor is an MTJ link in the Wheatstone bridge circuit (Figure 2), the magnetization of the polarizer layer of one pair of diagonal bridge elements is directed along the „+X“ axis, and the other — against „−X“. The resistance of the diagonal elements changes when the magnitude of the external magnetic field changes: increases $(R+\Delta R)$ or decreases $(R-\Delta R)$ depending on the direction of magnetization of the polarizer layer. Thus, the voltage at the differential output varies in proportion to the magnitude of the external magnetic field.

The sensitivity of the TMR sensor to the magnetic field is determined by the sensitivity of the magnetic tunnel junction, which has the following form

$$S = 100\% \, \frac{dR}{dH} \frac{1}{R_o} \, \%/\mathrm{Oe}, \tag{1}$$

where R_o — resistance in a zero external magnetic field, dR/dH — a nonlinear function of the dependence of the change in the resistance of the MTJ on the change in the magnitude of the external magnetic field.

It is necessary to deduce the dependence of the MTJ resistance on the external magnetic field $R(H)$ for an analytical study of the impact of external parameters on the sensitivity of the MTJ, for this we write down the energy of the system acting on the magnetization of the free layer (in spherical coordinates $\mathbf{m} = \{\cos(\varphi)\sin(\theta); \sin(\theta)\sin(\theta); \cos(\theta)\}$):

$$E = E_U + E_Z + E_{sh}, \tag{2}$$

where E_U — the energy of crystalline anisotropy, written in spherical coordinates $E_U = -k\sin^2(\varphi)\sin^2(\theta)$, where k — the constant of uniaxial anisotropy, and φ, θ —

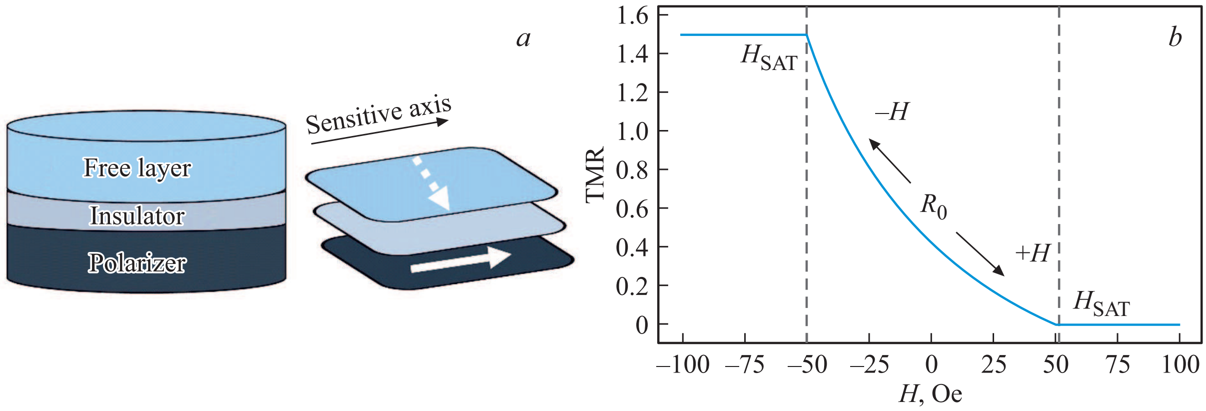

Figure 1. *a* — stack of a magnetic tunnel junction with a free layer, with planar crystalline anisotropy directed orthogonally to the magnetization of the polarizer layer; *b* — magnetic resistance curve of MTJ.

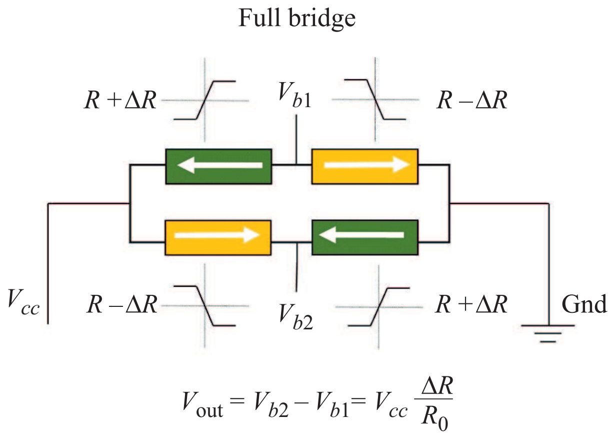

Figure 2. The MTJ link into the Wheatstone bridge, where the diagonal elements of the bridge have one direction of magnetization of the polarizer.

polar and azimuthal angles magnetization, respectively. A planar crystalline anisotropy directed orthogonally to the magnetization of the polarizer layer is considered in this paper (Figure 1, *a*). The Zeeman energy is written as $E_Z = -M_s H\cos(\varphi)\sin(\theta)$, where M_s — saturation magnetization, H — the magnitude of the external magnetic field. It is necessary to take into account the anisotropy energy of the shape, which has the form

$$E_{sh} = 4\pi M_s^2/2\big(N_x \sin^2(\theta)\cos^2(\varphi) + N_y \sin^2(\theta)\sin^2(\varphi) + N_z\cos^2(\theta)\big),$$

where N_k — demagnetizing factors.

Let us find the magnetization equilibrium state, which is determined by the condition

$$\frac{\delta E}{\delta\varphi} = \frac{\delta E}{\delta\theta} = 0. \tag{3}$$

Substituting the variational derivative of the energy (2) in (3), it was obtained that the azimuth angle is $\theta = \pi/2$, and $\cos(\varphi) = H/H_{SAT}$, where H_{SAT} is the saturation field equal to $H_{SAT} = -4\pi M_s(N_y - N_x) + 2k/M_s$. The stability of solutions can be verified using the determinant of the second derivatives of the Hesse matrix, which gives a sufficient condition for a minimum of energy.

Let us write down the conductivity of the MTJ:

$$\frac{1}{R} = G = \frac{G_{AP} + G_P}{2} + \frac{G_P + G_{AP}}{2}\frac{H}{H_{sat}}, \tag{4}$$

where $G_P(G_{AP})$ — the conductivity of the MTJ when the magnetization of the free layer relative to the magnetization of the polarizer layer is in a parallel (antiparallel) state.

We will differentiate the resistance by the external magnetic field dR/dH based on (4), then the sensitivity of the MTJ:

$$S = -\frac{TMR(TMR+2)H_{sat}}{(H_{sat}(2+TMR) + H\cdot TMR)^2}\,100\%. \tag{5}$$

Thus, the sensitivity of the MTJ is determined by the anisotropy of the shape, the uniaxial anisotropy constant and the magnitude of the tunneling magnetoresistance. An increase of the sensitivity of the MTJ to an external magnetic field is observed with an increase of tunneling magnetoresistance (Figure 3), while the sensitivity of the MTJ decreases with an increase of the saturation field (Figure 4). It should be noted that the range of operation of the sensor $\pm H$ should be less than the saturation field $H \ll H_{sat}$, since the magnetoresistance curve (Figure 1, *b*) becomes more nonlinear closer to the AP and P states of magnetization. It is necessary to take into account the magnetoresistance curve in a given field range of $\pm H$ to find the optimal combination of parameters: saturation field and tunnel magnetoresistance and this error should be less than 1% for the development of the TMR sensor.

Since the saturation field includes the difference between the field of crystalline anisotropy and the field of anisotropy of the shape, which are mutually compensated, it should be taken into account when developing the sensor that the crystalline anisotropy field is constant in the technological

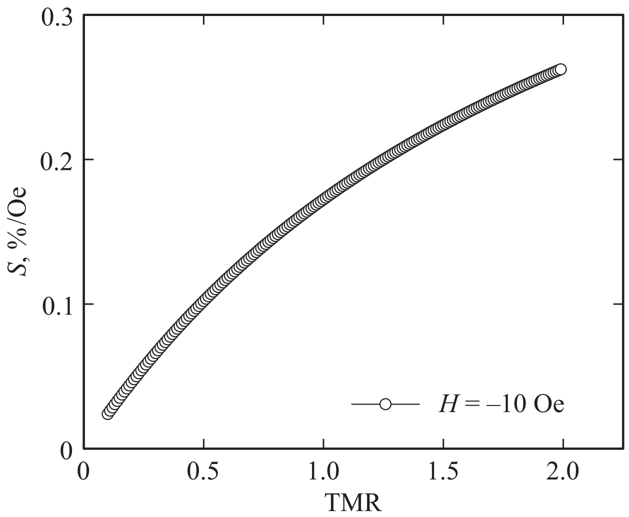

Figure 3. The dependence of MTJ sensitivity on its tunneling magnetoresistance with the saturation field of $H_{sat} = 200$ Oe and external magnetic field $H = -10$ Oe.

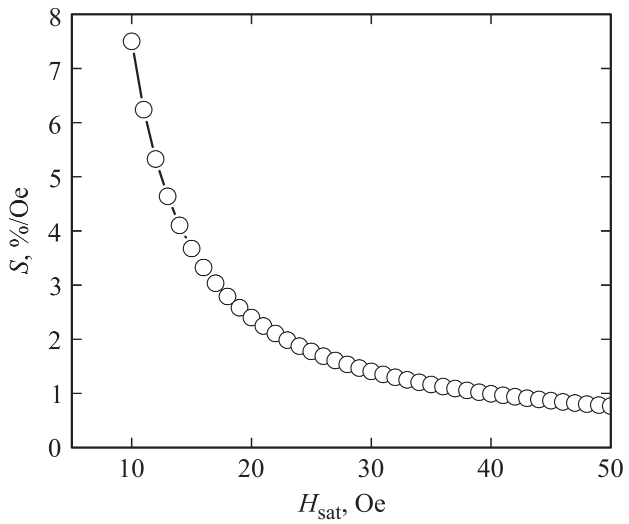

Figure 4. The dependence of the sensitivity of the MTJ on the magnitude of the saturation field with the tunneling magnetoresistance of 1.5 and the magnitude of the external magnetic field of $H = -10$ Oe.

process and it is necessary to control the shape of the MTJ for reducing (increasing) the saturation field of the MTJ according to customer requirements, that is, to produce a more elongated (rounded) sample.

3. Transmission coefficient of the TMR sensor

The main electrical characteristic of the sensor is the transmission coefficient K_{tr}, which determines the measure of conversion of the magnitude of the magnetic field into an electrical signal in the linear range $[-H; +H]$ of operation

$$K_{tr} = \frac{V_{out}(H) - V_{out}(-H)}{2HV_{cc}} 1000, \text{ mV/V/Oe}, \qquad (6)$$

where V_{out} is the voltage at the differential output of the Wheatstone bridge, which is written as $V_{out} = V_{cc}\frac{\Delta R}{R_0}$, V_{cc} — supply voltage. As a rule, the transmission coefficient is calculated with $V_{cc} = 1$ V and has the form

$$K_{tr} = 1000 \frac{TMR(TMR + 2)H_{sat}}{(H \cdot TMR)^2 - (H_{sat}(2 + TMR))^2}, \text{ mV/V/Oe}. \qquad (7)$$

Thus, the transmission coefficient of the TMR sensor based on MTJ with a free layer with planar crystalline anisotropy directed orthogonally to the magnetization of the polarizer layer depends on the saturation field and the tunneling magnetoresistance of the structure. An increase of the saturation field results in a decrease of the transmission coefficient. It should be noted that neither the sensitivity nor the transmission coefficient of the sensor depend on the number of MTJ in the sensor element.

4. Conclusion

The effect of such parameters as the uniaxial anisotropy constant, shape and tunneling magnetoresistance of MTJ on the sensitivity and transfer characteristics of the sensor was analytically studied for a magnetic tunnel junction with a free layer with planar crystalline anisotropy directed orthogonally to the magnetization of the polarizer layer. As a result of the study, it was found that the sensitivity and transmission coefficient of the TMR sensor in the Winston bridge circuit do not depend on the number of MTJ in the sensor array. It follows from this that the sensor in the bridge link occupies a smaller area on the plate, which reduces its cost. When developing a TMR sensor, it should be borne in mind that the sensitivity and transmission coefficient of the sensor increases when the tunneling magnetoresistance is maximum and the saturation field is minimal, that is, equal to the operating range of the sensor, however, the output characteristic of the sensor is nonlinear in this case. It is necessary that the of the linearity of the magnetoresistance curve in the operating field range is less than 1% for finding the optimal combination of parameters such as the smallest saturation field and the largest tunneling magnetoresistance. It should be noted that the uniaxial anisotropy constant is constant during the technological process, therefore, it is possible to control the value of the saturation field by the shape of the MTJ, that is, by making the sample more elongated or rounded.

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Conflict of interest

The authors declare that they have no conflict of interest.

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