LOOK ACADEMIC PUBLISHERS
OPEN ACCESS

INTERNATIONAL JOURNAL OF ENVIRONMENTAL & SCIENCE EDUCATION
2016, VOL. 11, NO. 18, 10923-10940

Straintronic Elements of the Basis of Magnetostriction

Vladimir Amelichev[a], Petr Belyakov[a], Dmitry Vasilyev[a], Dmitry Zhukov[a], Yury Kazakov[a], Sergey Kasatkin[b], Dmitry Kostyuk[a], Alexey Krikunov[c], Mariya Kupriyanova[a] and Evgeniy Orlov[a]

[a]Scientific-Manufacturing Complex «Technological Centre» MIET, Moscow, RUSSIA; [b]V. A. Trapeznikov Institute of Control Sciences of Russian Academy of Sciences, Moscow, RUSSIA; [c]Scientific-Manufacturing Complex «Fotron – Auto», Moscow, RUSSIA

ABSTRACT

Background/Objectives: The subject of the submitted article lies within the scope of the heightened interest for magnetostriction. This interest demonstrates itself through the idea of combining opposite effects in one device, whereas straintronics is on the forefront. Methods/Statistical analysis: An extended report is made on resonant-type and non-resonant magnetoelastic transducers, and within the first group actuators employing the effect of magnetic tunnel junction, cantilevers, sensors of mechanical quantities, and high-frequency sensors are dwelt upon. Findings: The paper offers a review of principal results of use of direct and reverse magnetoelastic effects in the development of straintronic devices. The author undertakes a detailed investigation into the structure and principles of functioning of different types of strainmeters. Actual and possible instances of their practical application are outlined, where biomedical use as most promising is paid particular attention.

KEYWORDS

Magnetoelastic films, tensile and compression strain, anisotropic magnetoscription, ferromagnetic layer, magnetization, mechanical deformation, strain gauge, hybridization, magnetoimpedance effect

ARTICLE HISTORY

Received 17 July 2016
Revised 25 August 2016
Accepted 29 September 2016

Introduction

Up to the present day, the interest that has actively manifested itself towards research into magnetostriction has been caused by two main incentives: a) search for materials with the largest possible value of the magnetostriction coefficient at a well-defined value of the external magnetic field; b) search for solutions to minimize the effect where it is needed.

The first research area has to do with development of various actuators, microelectromechanical systems (MEMS) and sensors. In this field, materials with a giant magnetostrictive effect (GMS) have been investigated and put to

CORRESPONDENCE Dmitry Zhukov D.Zhukov@tcen.ru

practical use. Within the second area, materials are being searched (both homogeneous and heterogeneous) that have a minimum magnetostrictive (MS) effect.

At present, the interest towards magnetostriction has increased quite significantly in connection with the idea of combining opposite effects in a single device. The idea gave rise to a new research direction - straintronics. Scientists involved try to use the connection between different physical phenomena that is realized through mechanical deformation or strain, which allows to employ more efficiently this or that function in such devices than in existing analogues. A most graphic example is hybridization of magnetoresistive (MR) effects and effects associated with magnetostriction. In the devices based on the effect of a giant magnetoresistive effect (GMR) and tunneling magnetoresistance (TMR), magnetostriction effect is undesirable. The reason is the occurrence of spurious signals caused by disturbances in the sound information recording / reproducing systems. In GMR and TMR devices the magnetostriction value is sensitive to changes in the magnetic state of the free layer. If the free layer has good MS properties, the device grows sensitive to mechanical deformations. The idea of hybridization of MS and MR effects is suggested in work of P. Grünberg (1986).

Straintronic devices based on MS can be divided into two groups: resonant and non-resonant. In resonant sensors placed under the influence of an external alternating magnetic field, a mechanical resonance arises, which can be registered by various physical methods. In non-resonant magnetoelastic (ME) transducers, the sensor detects the change in magnetic susceptibility, arising from changes in communication between the reader elements and the sensor. Susceptibility change takes place due to a new magnetic state of the sensor because of its deformation. In many cases, piezoelectric elements may be replaced by more effective GMS MS elements.

The paper presents an overview of the most encouraging results of the use of direct (Joule, 1842 effect) and reverse (Villari effect) magnetostriction in the development of various straintronic devices.

Magnetostriction in thin ferromagnetic layers

Magnetostriction effect (Joule, 1884 effect) was discovered in 1842 by George Joel (1842; 1884). This term implies elastic deformation of a ferromagnetic material at a changing value of the external magnetic field. Magnetostriction in general manifests itself in two ways: as volume (isotropic) magnetostriction and anisotropic magnetostriction (Joule, 1884 effects). The coefficient of volume magnetostriction $\omega = \Delta V / V$ describes the isotropic change in body shape in all directions. Anisotropic magnetostriction coefficient $\lambda = \Delta l / l$ describes linear changes in body size in the direction of the applied magnetic field. The physical cause for anisotropic magnetostriction is rotation of the magnetization vectors of the magnetic domains in the ferromagnetic material under the influence of an external magnetic field. This rotation causes internal strain in the material structure and, consequently, its elastic deformation. Volume magnetostriction by its value is significantly less than anisotropic magnetostriction ($\lambda \gg \omega$), so usually when assessing the value of magnetostriction it is not considered. Anisotropic magnetostriction (further magnetostriction) depends on the crystallographic direction, in which the crystal can be magnetized to saturation, and the direction of magnetostriction measurement; it is characterized by magnitude of saturation magnetostriction λs. For crystals of cubic system, saturation magnetostriction is characterized by magnitutdes λ100 and λ111. For isotropic single phase polycrystalline cubic materials, saturation magnetostriction λs can be estimated K.P. Belov (1987) by measurements of λ100 and λ111 of a single crystal having the same composition as the polycrystal:

$$\lambda_S = \frac{2}{5}\lambda_{100} + \frac{3}{5}\lambda_{111} \quad (1)$$

The correlation of the magnetostriction coefficient and the external field λ(H) is determined by magnetization curve, which in turn depends on the magnetic anisotropy energy. For the case of magnetization only by rotation:

$$\lambda(H) = \lambda_s \cdot \left(\frac{M(H)}{M_s}\right)^2 \quad (2)$$

where M(H) is the correlation between the magnetization and the applied field, and Ms is saturation magnetization.

Manifestations of magnetostriction in the layers with a very small crystallite size (> 100 nm) has its own peculiarities. In the case where the ferromagnetic grain size is less than the length of the exchange interaction, the role of magnetocrystalline anisotropy is reduced and the role of magnetoelastic anisotropy in the value of the effective macroscopic magnetic anisotropy is increased.

In nanocrystalline ferromagnetic layer the crystalline and amorphous phases can coexist. In this case, the effective macroscopic magnetostriction λeff can be defined as the simple average of the contribution of the two phases:

$$\lambda_{eff} = p \cdot \lambda_{cr} + (1 - p) \cdot \lambda_{am} \quad (3)$$

where p is the volume fraction of the crystalline phase.

Modern technological possibilities allow to create ferromagnetic, nanocrystalline and nanocomposite layers of different compositions, and the structural features of the layers (crystallite size, the presence of an amorphous phase and non-magnetic inclusions, particular properties of intercrystalline regions) have a significant effect on MS properties. MS properties of amorphous and nanocrystalline structures are described, for example, in work of G. Herzer (1992).

In the development of straintronic devices based on magnetostriction, most commonly used are the effects of forward and reverse magnetostriction. Fig. 1 shows the behavior of ferromagnetic layers under the influence of a constant external magnetic field and by applying a tensile stress.

It is obvious that in the case of direct magnetostriction, by increasing the strength of the external magnetic field, magnetic saturation in the layer can be achieved, and the relative deformation is λs. In the case of reverse magnetostriction, mechanical deformation of the layer with 180 ° domain boundaries in perpendicular orientation towards the magnetic anisotropy axis does not change the layer magnetization. Increasing of the deformation causes only domain rotation. This change in the magnetic state is of particular interest in conjunction with the magnetoresistive (Grünberg, 1986) or magnetoimpedans effects (Wilson, 2007).

Non-resonance elements based on magnetostriction

MS sensors on the basis of magnet tunnel junction

When searching for the material that can be employed in creation of a tensiometric device based on magnetic tunnel junction (MTJ), it must be borne in mind that such material should have a high value of the saturation magnetostriction coefficient at a sufficiently low value of the anisotropy field, whose magnitude is determined by conditions of specific application. Besides, technology of its production must be compatible with the technology of MTJ production. Sensitivity of the sensor can be represented by the expression (Wang et al., 2004):

$$S_e = \frac{dR/R}{\varepsilon} = \frac{1.5 \cdot TMR \cdot E \cdot \lambda}{H_k \cdot M_s \cdot (1-v^2)} \quad (4)$$

where Se is the sensitivity of the device (gaugefactor); ΔR /R - MTJ relative resistance change caused by deformation; ε - relative deformation of the sensitive layer; TMR - the maximum value of the magnetoresistance of the MTJ; E - Young's modulus of the sensitive layer; λ - coefficient of magnetostriction of the sensing layer; Hk - anisotropy field of the sensitive layer; Ms - saturation magnetization; v - Poisson's ratio.

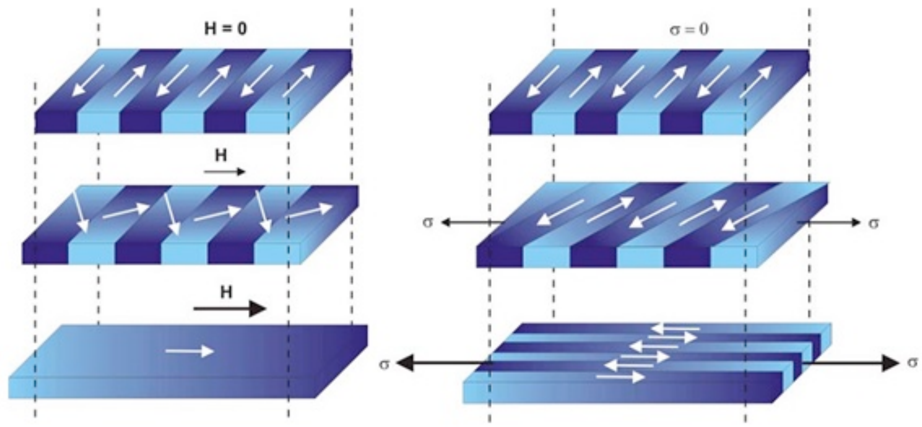

Figure 1. Schematic behaviour of thin layers with a positive magnetostriction in the external magnetic field (a) or under applied tensile stress (b). White arrows indicate the orientation of the domains (Wilson, 2007)

In addition, one must remember that elastic deformations within the permissible range are admissible for the sensitive layer.

With regards to the requirements to the sensitive layer a number of magnetostrictive materials can be considered.

a) Rare earth magnets and their alloys.

Giant MS effect (λs ~ 10-2 ... 10-3) in rare-earth metals Tb and Dy (Belov, Levitin, & Nikitin, 1961) is observed at very high values of the magnetic fields and low temperatures. Later N. Koon, A. Schinder & F. Carter (1971) giant magnetostriction was found in intermetallic compounds TbFe2i DyFe2. In these materials, a large magnetostriction was observed at temperatures close to indoor temperature. However, these materials are not widely used in electronic devices because of their specific temperatures and strong saturation fields.

b) layers based on FeGa alloy.

FeGa alloy was first studied in work of A.E Clark et al. (2003). The single crystal samples have shown magnetostriction (3/2) λ100 ~ 400 ppm at a Ga concentration in the alloy of ~ 19%. In work of A. Butera et al. (2005) a FeGa epitaxial layer on the surface of (100) MgO was first obtained. Correspondence of crystal lattices at their mutual rotation in the epitaxy plane by 45 ° was ~ 0.7%, which is important for the formation of MTJ nanostructures on the basis of MgO. Magnetostriction in thin FeGa layers, as evidenced by several authors (Basantkumar at al., 2006; Wang et al., 2008; Materials of Crystran company), makes 50 ... 150 ppm. Sufficient values of magnetostriction, and the possibility of soft magnetic epitaxial growth on MgO surface give reason to believe this material a promising one for use in strain gauge sensors on the basis of the MTJ.

In work of T.A. Fazir (2012) a nanostructure FeGa (30) / MgO (2) / FeGa (5) / Ta (10) is described, where film thickness in nm is indicated in parentheses. In the original (not annealed) samples the value of MR ΔR/R effect was about 9%. It is known that the value of ΔR/R can be significantly improved by annealing that follows. However, while being annealed the structures were being degraded, for example, by annealing at 350°C during 1 hour the value of ΔR/R was 0.1 ... 0.5%. Subsequent analysis of the samples showed that during annealing segregation of Ga takes place at the interfaces of the ferromagnetic layers with a barrier layer of MgO and its further diffusion into the dielectric layer. Perhaps, it breaks the spin polarization of the current flowing through the barrier.

Another nanostructure was investigated:

TaN(5)/Ta(5)/PtMn(25)/CoFe(2.5)/Ru(0.8)/CoFe40B20(4)/ Mg(1.5)/MgO(1.5)/CoFe40B20(2)/FeGa(20)/Ta(5)/Ru(10)

where thickness of the layer in nanometers in indicated in parentheses.

In this nanostructure, in order to avoid Ga diffusion, into the barrier layer between the layers MgO and FeGa a CoFe40B20 layer 2 nm thick was applied. For technological reasons, depressurization of the vacuum system was then performed. This was accompanied by the partial oxidation of the CoFe40B20 layer that affected the value of the MR effect of the whole structure. Stability of the fixed layer was ensured by the antiferromagnetic "sandwich" PtMn/CoFe/Ru/CoFe40B20. In the formed MTJ of 2500 mcm2 the sensitivity to mechanical deformations was explored. Sensitivity (Gauge Factor) was defined as: $GF = \frac{\Delta R/R}{\Delta \varepsilon}$, where ΔR is change in the electrical resistance of the junction; Δε is deformation.

Fig. 2 shows the results of magnetoresistance measurements and the conditions of fabrication and measurement of samples. The sensitivity of the given sample made 42.

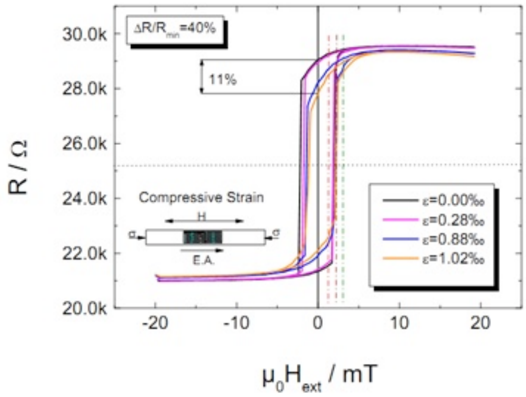

Figure 2. Magnetoresistance of MTJ of 2500 mcm2 area. The sample was annealed at 450 ° C and cooled in a magnetic field of 320 mT (Fazir, 2012)

Further enhancement of the technological process has made it possible to obtain the value of sensitivity equal to 51, which is higher than the sensitivity of the metal tensoresistive sensors and is the average for the class of semiconductor piezoresistive sensors (Handbook of modern sensors: physics, designs, and applications, 2010).

c) layers on the basis of CoFeB alloy

CoFeB layers are among the main functional layers in the production of MTJ with high values of MR effect. The study of the magnetic properties of layers made of this material 10 nm thick showed7 that it is a soft magnetic material with a saturation magnetization of ~ 1.5 T, with coercivity near zero in the hard axis direction and the coercivity of ~ 2 e in the direction of the easy axis. Fig. 3 shows the magnetization curves of the layer along the difficult and the easy axes.

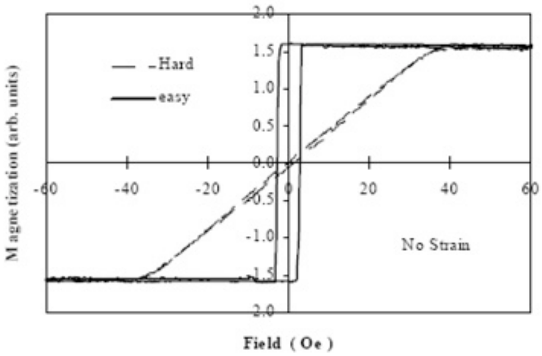

Figure 3. Magnetization curves along the hard and easy axes of the sample Si(100)/Si3N4/Ru/CoFeB/Al2O3 after annealing at 250°C for 1hour (Wang et al., 2004)

Fig.4 shows the variation of the hysteresis loop in the direction of hard magnetization under conditions of tensile and compressive stresses, as well as under no stress. Mechanical stresses were applied along the direction of the external magnetic field.

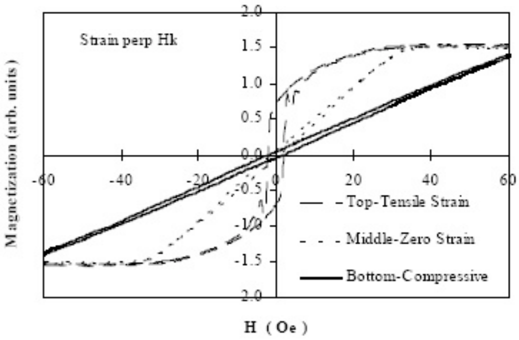

Figure 4. The magnetization curve of the sample (see Fig. 2) along the hard direction under deformation ± 230 ppm («+» - tensile stress, "-" - compressive stress) (Wang et al., 2004)

As is seen from Fig.4, CoFeB layer has good sensory properties and can be used as a sensitive MTJ layer. In tunnel nanostructures produced with the use of Al2O3 as a barrier layer and CoFeB as a free layer, the tensosensitivity made 1,416.

Cantilevers

This research area is relevant for advanced MEMS devices having a wide range of applications: sensors (magnetic, chemical, acoustic), medicine (ophthalmology), telecommunications and more.

In work D. Hunter et al. (2011) authors give results of the study of cantilever and enhancement of the Fe-Ga alloy deposition process for obtaining the maximum magnetosriction effect. The alloy deposition process has been optimized for 19/81 Ga- Fe alloy, which has the maximum effect of magnetostriction. The film was cut into strips of 1 × 5 mm2 (Fig. 5), the deflection was measured in the same plane as the magnetic field strength in the range of up to 60 kA/m. The maximum λ deformation ratio was 96 ppm for the magnetic field strength of 58 kA/m. The correlation between deflection of the cantilever of the studied samples and the field strength is shown in Fig. 6.

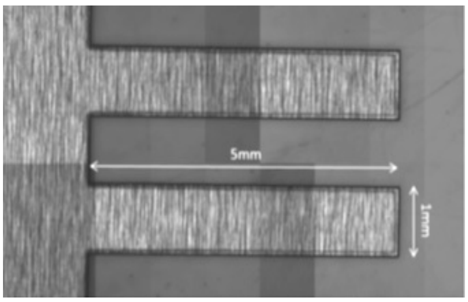

Figure 5. Foto of the cantilever (Jack et al., 2015)

In work D. Hunter et al. (2011) for an assessment of MS properties of thin films, on the cantilever of an atomic force microscope (AFM) a composite film Co1-xFex of 500 nm thick was formed. For investigation the three methods of forming samples were used: deposition of the structure; deposition of the structure and annealing at 800°C for 1 hour followed by natural cooling; deposition of the structure and annealing at 800°C for 1 hour followed by shock cooling.

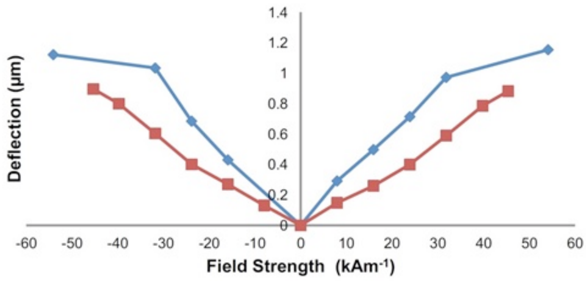

Figure 6. Deflection of the cantilever depending on magnetic field strength (Jack et al., 2015)

In the sample formed by the first method with the structure of Co44Fe56 the magnetostriction made 67 ppm, with the structure of Co73Fe27 - 84 ppm. The samples obtained by the second method with the structures Co40Fe60 and Co66Fe34 demonstrated magnetostriction values of 103 ppm and 156 ppm respectively. The samples formed with the third method with the structures of Co40Fe60 and Co66Fe34 had magnitostriction values of 180 ppm and 260 ppm respectively.

Magnetostriction in deposited thin film samples was measured with the aid of cantilever (Fig. 7). After the application of magnetic field the magnetostriction causes bending of the film, and the resultant displacement of the cantilever is captured by a position-sensitive detector and measured in relation to the applied field. The displacement measurements were carried out for the magnetic fields applied parallel and perpendicular to the length of the cantilever, but always parallel to the film plane.

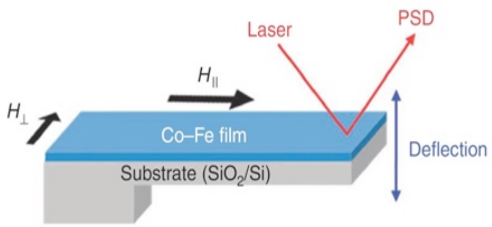

Figure 7. Scheme of the cantilever used for registration of magnetostriction (Hunter et al., 2011)

There were produced by M. Löhndorf et al. (2004) MS micro- and nanodotted arrays for MEMS such as membrane structures of different diameters (from 50 to 300 microns) of square or circular shape. These magnet MEMS devices can be used as local sensors for measuring deformation, since application of mechanical load to the membrane will change the direction of magnetization of the magnetostrictive points due to the inverse MS effect (Villari effect) depending on the position on the membrane. As Fig.8a shows, mechanical stress (compression or tension) is performed by means of pressure of air or vacuum on the membrane, and the magnetization switching is registered by magnetic force microscopy.

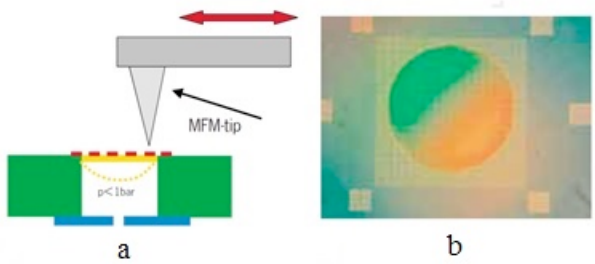

Figure 8. a) schematic representation of the experimental setup;
b) MS dot of the array on a round Si3N4 membrane (Löhndorf et al., 2004)

In work (Quandt et al., 2004a) combined micro-electro-mechanical systems (MEMS) fabrication processes and thin film technology in order to fabricate highly magnetostrictive micro-dot arrays on membrane structures with different diameters (50 to 300 μm) and forms. Application of mechanical loads leads to a change in the direction of the magnetization and magnetostriction of the free layer materials due to the inverse MS effect.

In work (Pereles, 2014) the results of development of cantilevers (Fig. 9) and bridge sensors are demonstrated. The devices measure the speed (Fig. 10) and pressure of gases (Fig. 11).

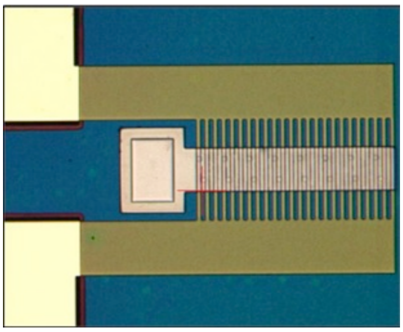

Figure 9. Cantilever photo (Pereles, 2014)

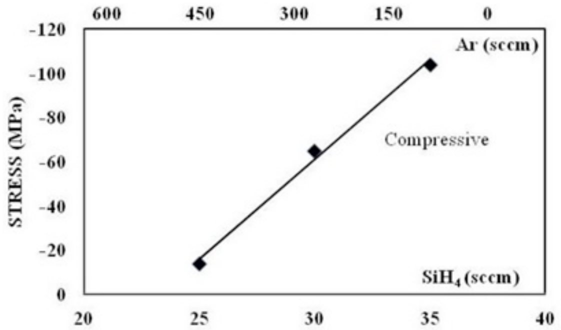

Figure 10. Correlation between the sensor stress and gas velocity (Pereles, 2014)

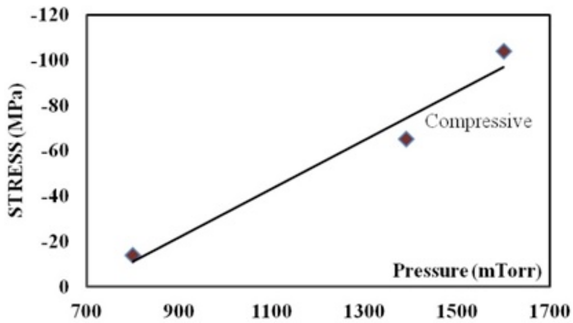

Figure 11. Correlation betwen the sensor stress and pressure (Pereles, 2014)

Sensors of mechanical quantities

For the measurement of mechanical quantities, such as deformation or rotation, miniature, reliable and, preferably, wireless sensors are required. The sensors based on MS films meet these requirements as they exhibit sensitivity that exceeds that of the most strain gauges (Quandt, Stein & Wuttig, 2007).

In work of R.S. Lakshmanan (2008) the results are describes of the development of non-resonant ME sensor system that measures the applied force for biomedical purposes with the aid of Metglas 2826MB strips, designed for long-term control of stresses and forces in medical devices, for example, for postsurgical control after the installation of a prosthesis. The system has four sensitive areas. The signal is detected by sensing a change in magnetic susceptibilities, in particular, by the appearance of new frequencies in the signal. The external appearance of the system is shown in Fig. 12. The system design is shown in Fig.13.

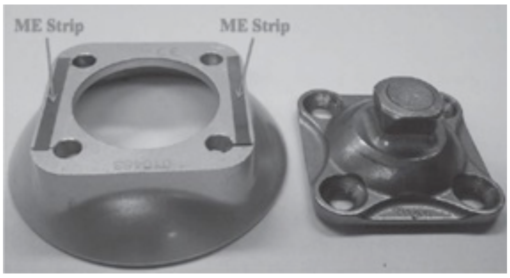

Figure 12. ME system (Lakshmanan, 2008)

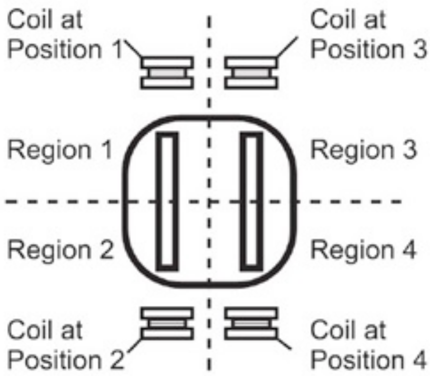

Figure 13. Design of the ME system (Lakshmanan, 2008)

High-frequency sensors

In small LC circuits MS films are used as the core material for inductors. Exerted deformation leads to a change in the permeability of M and, in this way, in the inductance and resonant frequency of the device. In order to understand the behavior of the thin film material, it is necessary to correlate the quasi-static (constant) magnetic properties with high frequency (HF) properties. Along with the influence of deformation on the formation of a static domain, observed was magneto-optical Kerr effect (Fig. 14). The initial vertical domain structure results from the induced anisotropy during sputtering under the influence of an inplane magnetic bias field of approx. 100 Oe. Increase of deformation rotates the domains in its own direction. With a positive MS material, for obtaining the maximum deformation the easy axis rotates by 90°, remaining parallel to the applied tensile strain in the direction of deformation (Quandt et al., 2004b).

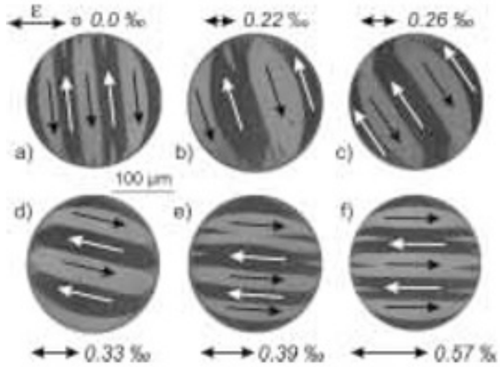

Figure 14. Effect of tensile deformation of FeCoBS thin film structure on Si (Quandt et al., 2004b)

The changes of permeability are different for constant and high-frequency cases (Fig. 15). A significant drop in high-frequency permeability at approximately 0.02% of deformation reveals the fact that the easy magnetic axis is now parallel to the high-frequency field. In this case magnetization reversal is performed through domain wall motion

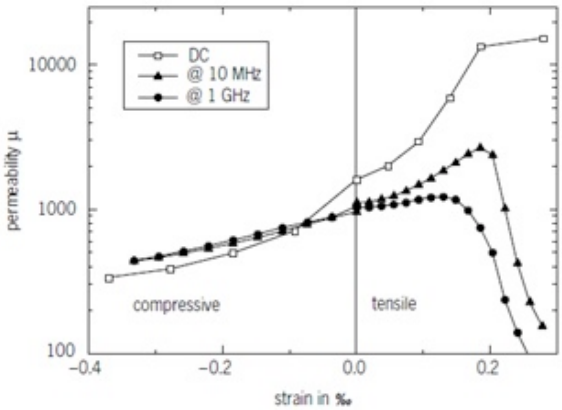

Figure 15. Correlation of current and HF-permeability and the deformation (Quandt et al., 2004b)

The device exhibits a stress sensor based on MS FeNiCoBSi thin films responsive to tensile and compression strain with electronic reading via inductive coupling (Fig. 16). The system allows the measurement of the LC resonance phase shift depending on the applied stress.

Figure 16. Stress sensor based on MS thin films (Quandt et al., 2004b)

Fig. 17 shows the phase shift of the strain dependent sensor signal in comparison to the AC permeability of a reference FeCoBSi thin film at 350 MHz operating frequency. Both curves show a similar correlation with the deformation, proving that MS material can be effectively integrated into the sensor (Quandt et al., 2004b).

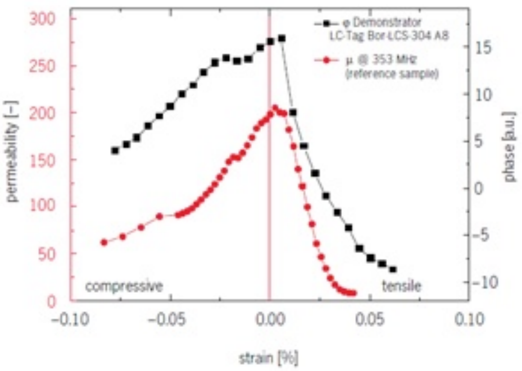

Figure 17. Correlation between AC deformation and permeability of the MS material (Quandt et al., 2004)

In FeCoBSi films, the quality factor was assessed 10 and a high coefficient ($\Delta\mu$ / $\mu 0$ / $\Delta\varepsilon$) of 2400 was obtained at 250 MHz. Further works will focus on the application and use of this sensor principle.

Investigations of Yu Ying et al. (2015) were carried out, in which Fe81Ga19 100 nm thick were evaporated on polyethyleneterephthalate (PET) with a bending R of 10, 15 and 30 mm. Then, the PET supports were straightened, but they retain the internal stress (Fig. 18 a). Uniaxial magnetic anisotropy is formed. Due to the internal stress the structure has a low structural perfection and λs = 20ppm.

The structure has the form: Ta (3 nm) - Fe81Ga19 (100 nm) - PET (150 microns). The stress was 0.26%, 0.52% and 0.78% for 30, 15 and 10 mm respectively. The aim of the study was to obtain high resonant frequencies for further use in HF flexible microwave devices. Fig.18 (b) and (c) shows the hysteresis loops measured along the easy and hard axes of FeGa films evaporarted with various preliminary deformations of the supports. The correlation between Ku uniaxial magnetic anisotropy of Fe-Ga films and the deformation is shown in Fig. 18 (d).

The best model for HF applications is the sample with the compressive strain of 0.78%, i. e., bend radius of 10 mm, which shows operation at 2 GHz.

In work A. Biswas, J. Atulasimha & S. Bandyopadhyay (2014) described are the principles of operation and construction of logic elements that constitute a combination of CTMR transition and a piezoelectric film (Fig. 19).

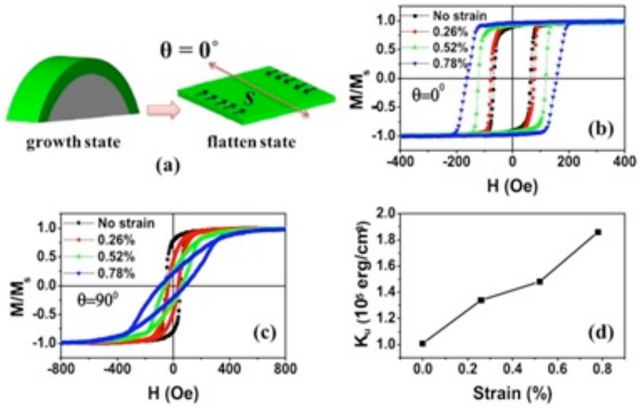

Figure 18. (a) The process of the structure formation: evaporating of Fe-Ga film and straightening of the structure; (b) hysteresis in the direction of easy and (c) the difficult axis of the film magnetization for different initial compressing conditions; (d) the correlation between Ku uniaxial magnetic anisotropy of Fe-Ga films and the deformation (Ying et al., 2015)

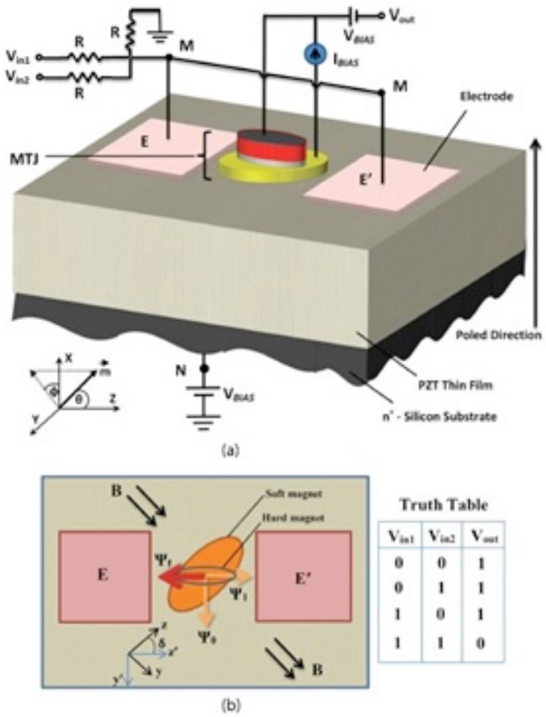

Figure 19. Design of a logic gate (Biswas, Atulasimha & Bandyopadhyay, 2014)

Resonant Sensors

Work C.A. Grims et al. (2011) provides an overview of ME thick-film resonance elements on the basis of Fe40Ni38Mo4B18 (Meglas 2826MB) alloy. Typically, such sensors are excited by magnetic field, and the reading is done by registering the magnetic field generated by the sensor by an optical or acoustic method. Such sensors are strips of a thick-film material, usually of Meglas 2826MB alloy. They are excited by an external magnetic field, wherein resizing takes place that depends on strip thickness and topology and that changes of the sensor resonance. Changing of the sensor resonance frequency is caused by the contact of sensor strip surface with the mass of another object, it depends on ambient pressure, temperature, fluid viscosity and density, moisture content, presence of a number of gases such as ethylene, CO2 NH3. Similar sensors can measure pH of a liquid and detect a number of biological objects, they are used to determine the quality of milk, blood clotting and anti-theft tags (Grims et al., 2011).

Use in biological areas

The connection of deformations of ME elements with magnetic field opens the way to numerous biomedical developments. A ME element inside an implant helps measure the stress existing therein. It can be used, for example, in an orthopedic implant with a planar sensing coil (Croh, Cros] & Courcimault, 2012). ME implants are used in treatment of severe cases of glaucoma (Chorits et al., 2010). In work V. Pepakayala (2015) described are the results of a research into RF ME elements properties with a view of their possible medical use. The author has developed a sensor and a differential ME sensor on a silicon substrate with a magnet (Fig. 20). The signal is transmitted to the planar coil.

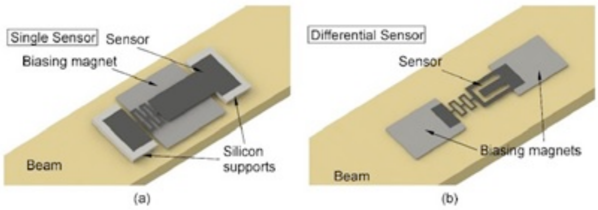

Figure 20. ME sensor (a) and a differential sensor (b) (Pepakayala, 2015)

In the same paper, they provide a description of a ME generator for blood flow activation in severe cases of glaucoma (Fig. 21). The generator is made of 29 micron Metglas 2826MB foil and is protected by a biocompatible material.

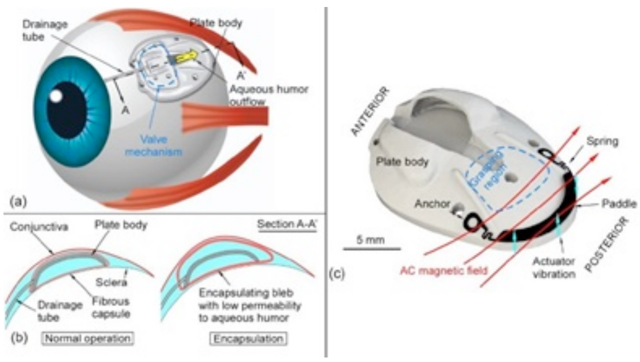

Figure 21. ME generator for activation of blood flow in glaucoma cases (Pepakayala, 2015)

In work R.S. Lakshmanan (2008) there is a description of the results of ME biosensor development for detection of salmonella bacteria with the aid of immunoassay. The surface of ME strip is immunized with phages, and when a biological object is attached to it, the surface mass is changed, which leads to a change in the resonance frequency of the biosensor. As an example, the data is provided on the change of resonance frequency of about 1 MHz to the order of 1 kHz.

Conclusion

The elements developed on the basis of mechanical stresses and strains, which use magnetostriction and other physical purely magnetic effects, such as MR effects, including giant magnetoresistance of nanostructures with the proven technology of their production, and which do not use piezoelectric effect, represent a forward-looking research area within the new field of micro- and nanoelectronics, which has been dubbed "straintronics" worldwide. These elements may have HF properties and are used as sensors of stress, pressure, magnetic field, as biosensors, primarily in analytical biology, medicine and other fields of science and technology. Research into straintronic elements and their development is on the forefront of world science, and new elements are being created basing on new operation principles and materials, which improve their parameters and extend the functionality of these elements themselves and systems employing them.

Acknowledgments

The work was financially supported by The Ministry of Education and Science of Russia Federation in the framework of the state task 8.533.2016 / CU.

and the total number of foreigners, traveling annually with various educational goals abroad exceeds 5 million people (Report on international migration of United Nations population Division, 2012). At present, the greatest amount of educational services to international students is given by higher educational institutions of the USA, UK, Austria, Germany, and France. Universities of these States form and coordinate the flows of international educational migration, subordinating them to their own goals, focused on pragmatic results: economic profit; improvement of the demographic and labor structure of society due to the influx of educated young people of reproductive age; getting of new citizens integrated into society through the educational system.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

Vladimir Amelichev, PhD, Head of a department, Scientific-Manufacturing Complex «Technological Centre» MIET, Moscow, Russia.

Petr Belyakov, Research associate, Scientific-Manufacturing Complex «Technological Centre» MIET, Moscow, Russia.

Dmitry Vasilyev, Research associate, Scientific-Manufacturing Complex «Technological Centre» MIET, Moscow, Russia.

Dmitry Zhukov, Engineer, Scientific-Manufacturing Complex «Technological Centre» MIET, Moscow, Russia.

Yury Kazakov, Junior research assistant, Scientific-Manufacturing Complex «Technological Centre» MIET, Moscow, Russia.

Sergey Kasatkin, PhD, Head of a laboratory, V. A. Trapeznikov Institute of Control Sciences of Russian Academy of Sciences Moscow, Russia.

Dmitry Kostyuk, Head of a laboratory, Scientific-Manufacturing Complex «Technological Centre» MIET, Moscow, Russia.

Alexey Krikunov, PhD, Leading researcher, Scientific-Manufacturing Complex «Fotron – Auto» Moscow, Russia.

Mariya Kupriyanova, Research associate, Scientific-Manufacturing Complex «Technological Centre» MIET, Moscow, Russia.

Evgeniy Orlov, Junior research assistant, Scientific-Manufacturing Complex «Technological Centre» MIET, Moscow, Russia.

References

Basantkumar, R., Stadler B.H., Robbins, W. & Summers, E. (2006). Integration of Thin-Film Galfenol With MEMS Cantilevers for Magnetic Actuation. *IEEE Transactions on Magnetics, 42(10),* 3102-3104.

Belov, K.P. (1987). *Magnetostriction effects and their technical application*. Moscow: Nauka, 266 p.

Belov, K.P., Levitin, R.Z. & Nikitin, S.A. (1961). *Physics of metals and metal studies*, Moscow: Nauka, 348 p.

Biswas, A., Atulasimha, J. & Bandyopadhyay, S. (2014). An errow-resilient non-volatilemagnetoelastic universal logic gate with ultralow energy-delay product. *Scientific Reports, 3,* 1-7.

Butera, A., Gómez, J., Weston, J.L. & Barnard, J.A. (2005). Growth and magnetic characterization of epitaxial Fe81Ga19/MgO (100) thin films. *J. Appl. Phys., 98(3),* 339-351.

Chorits, L., Koynov, K., Renieri, G. & Barton, K. (2010). Surface topographies of glaucoma drainage devices and humaintenonfibrablast adhesion. *Invest Ophthamol, 51(8),* 4047-4053.

Clark, A.E, Hathaway, K.B., Wun-Fogle, M., Restorff, J.B., Lograsso, T.A, Keppens, V.M, Petculescu, G. & Taylor, R.A. (2003). Extraordinary magnetoelasticity and lattice softening in bcc Fe–Ga alloys. *J. Appl. Phys., 93*, 8621.

Croh, J., Cros, F. & Courcimault, C. (2012). Strain monitoring system and apparature. *USA patent.* N. 8278941.

Fazir, T.A. (2012). *FeGa based tunneling magnetoresistance junctions and strain sensors.* Direct access: www.tu-ilmenau.de/fileadmin/media/mms/Aktuelles/IMN_Report_2013_small.pdf.

Grims, C.A., Roy, S.C., Rany, S. & Cay, Q. (2011). Theory, Instrumentations and Applications of magnetoelastic Resonance Sensors: A Review. *Sensors, 11,* 2809-2844.

Grünberg, P. (1986). Layered Magnetic Structures: Evidence for Antiferromagnetic Coupling of Fe Layers across Cr Interlayers. *Phys. Rev. Lett., 57*, 2442-2445.

Handbook of modern sensors: physics, designs, and applications. (2010). New York: Springer-Verlag: 437 p.

Herzer, G. (1992). Nanocrystalline soft magnetic materials. *Journal of magnetism and magnetic materials, 112,* 258–262.

Hunter, D., Osborn, W., Wang, K., Kazantseva, N. (2011*). Giant magnetostriction in annealed Co1 − xFex thin-films*. Direct access: http://www.nature.com/articles/ncomms1529

Jack, H.G., Record, P., Shang, X. & Wlodarczykat, K. (2015). Optimised co-electrodeposition of Fe–Ga alloys for maximum magnetostriction effect. *Sensor sand Actuators, 223*, 91–96.

Joule, J.P. (1842). On a new Class of Magnetic Forces. *Sturgeon's Annals of Electricity, 8*, 219.

Joule, J.P. (1884). *Scientific Papers.* London: Taylor and Francin, 367 p.

Koon, N., Schinder, A. & Carter, F. (1971). Giant magnetostriction in cubic rare earth-iron compounds of the type RFe2. *Physics Letters A, 37(5),* 413–414.

Lakshmanan, R.S. (2008). *Phage-based magnetoelastic sensor for the detection of Salmonella Typhimurium*. Direct access: etd.auburn.edu/bitstream/.../Lakshmanan_Ramji_26.pdf

Löhndorf, M., Bootsmann, M.T., Borowski, R., Dokupil, S. & Hout, J. (2004). Magnos: Magnetic-MEMS. Center of advanced european studies and research. *Annual Report, 1*, 78-79.

Pepakayala, V. (2015). *Micromachened Magnitoelastic Sensors and Actuators for Biomedical Devices and Other Applications*: PhD Thesis. Univer. Michigan, 252 p.

Pereles, B.D. (2014). *Design and Applications of wireless passive magnetowlastic resonance and magnetoharmonicforce sensors*: PhD Thesis. Michigan: Michigan Unver. Technol, 197 p.

Quandt, E., Dokupil, S., Bootsmann, M.T. & Stein, S. (2004a). Magnos: GMR/TMR Strain Sensors. Center of advanced european studies and research. *Annual Report*, *3,* 82-83.

Quandt, E., Frommberger, M., Glasmachers, S., Gorski, R., Schmutz, C. & Tewes, M. (2004b). MURI: Strain Dependence of a Remote Interrogatable Sensor Based on Magnetostrictive Thin Films. Center of advanced european studies and research. *Annual Report, 3,* 84-85.

Quandt, E., Stein, S. & Wuttig, M. (2007). MURI: Composite Magnetoelectric Effect for Magnetic Field Sensing. Center of advanced European studies and research. *Annual Report, 2,* 88-89.

Wang, B.W. (2008). Structure, magnetic properties and magnetostriction of Fe81Ga19 thin films. *Journal of Magnetism and Magnetic Materials, 320(5),* 769–773.

Wang, D., Norman, C., Qian, Z. & Daughton, J.M. (2004). 70% TMR at room temterature for sandwich Tunnel Junctions with CoFeB as free and pinned layers. *IEEE Trans. Magn, 40,* 22-69.

Wilson, C. (2007). New Materials for Micro-scale Sensors and Actuators. *An engineering Review. Materials science & engineering, 56,* 1-129;

Ying, Y., Qingfeng, Z., Jinwu, W., Jianbo, W., Guohong, D., Zhenghu, Z., Xiaoshan, Z., Yiwei, L., Huali, Y., Yao, Z., Shuhong, X., Baomin, W. & Run-Wei, L. (2015). Static and high frequency magnetic properties of FeGa thin films deposited on convex flexible substrates. *Applied physics letters, 106,* 162-185.