Mathematical Modeling of Switching Processes in Magnetically Controlled MEMS Switches

Sergey M. Karabanov, Dmitry V. Suvorov, Dmitry Yu. Tarabrin

Abstract—The operating principle of magnetically controlled microelectromechanical system (MEMS) switches is based on controlling the beam movement under the influence of a magnetic field. Currently, there is a MEMS switch design with a flexible ferromagnetic electrode in the form of a fixed-terminal beam, with an electrode fastened on a straight or cranked anchor. The basic performance characteristics of magnetically controlled MEMS switches (service life, sensitivity, contact resistance, fast response) are largely determined by the flexible electrode design. To ensure the stable and controlled motion of the flexible electrode, it is necessary to provide the optimal design of a flexible electrode.

Keywords—MEMS switch, magnetic sensitivity, magnetic concentrator.

I. Introduction

MAGNETICALLY controlled MEMS switches are a functional analogue of small reed switches and Hall sensors [1], [2]. The increase of the service life and switch magnetic sensitivity (magnetic field induction at which the electrodes are closed) on condition of maintaining resistance to applied shock (inertial resistance) is the critical task. The service life of magnetically controlled MEMS switches in the low current mode is determined by the mechanical resistance of MEMS switch parts (torsions by means of which electrodes are fixed), subjected to maximum deformation.

There are three main types of the electrode construction in MEMS switches: electrodes with end fixation, electrodes on torsions [3], [4] and two travelling electrodes as in reed switches [5], [6]. Each of these structures has its advantages and disadvantages. The general is that increase of the magnetic sensitivity by reduction of rigidity of the electrode fixation leads to the decrease of the G-force resistance. To solve these problems and determine the design parameters, a detailed calculation of MEMS switches and their comparative evaluation according to the magnetic sensitivity, impact resistance (the maximum acceleration applied to the system, which results in spurious contact closure) and mechanical stresses in the deformable parts of the structure are necessary.

II. Numerical Modeling Conditions

A MEMS switch consists of a travelling electrode fixed to a stationary ferromagnetic platform, a magnetic concentrator having the form of a trapezoidal or rectangular ferromagnetic plate, and a contact platform (Fig. 1).
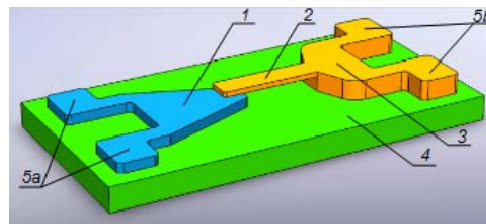

Fig. 1 The construction of a magnetically controlled MEMS switch: 1 – magnetic concentrator, 2 – travelling electrode, 3 – current-conducting base, 4 – dielectric substrate, 5a, 5b – contact pairs

The model for calculating the magnetic action on the electrode is based on solution of Gauss equations for magnetic fields with the use of a magnetic scalar potential as a variable.

The equations describing the distribution of the magnetic field inside magnetically controlled MEMS switches, as well as in the calculated volume around the structural elements, are as:

$$H = -\nabla \cdot V_m, \tag{1}$$

where H is the magnetic field strength, V_m - magnetic scalar potential.

$$\nabla \cdot \left(\mu_0 \mu_r H \right) = 0, \tag{2}$$

where μ_0 is the permeability of vacuum, μ_r – the material relative permeability.

$$B = \mu_0 \mu_r H, \tag{3}$$

where B is the magnetic induction.

$$B = f\left(|H|\right) \tag{4}$$

Equation (4) defines the magnetization of magnetic materials, i.e. hysteresis. Since the magnetic material in our design is permalloy, (4) corresponds to the magnetization function for this material (Fig. 2).

The equations describing the distribution of magnetic field forces acting on a travelling electrode have the form:

$$F = \int_{\partial \Omega} nTdS \tag{5}$$

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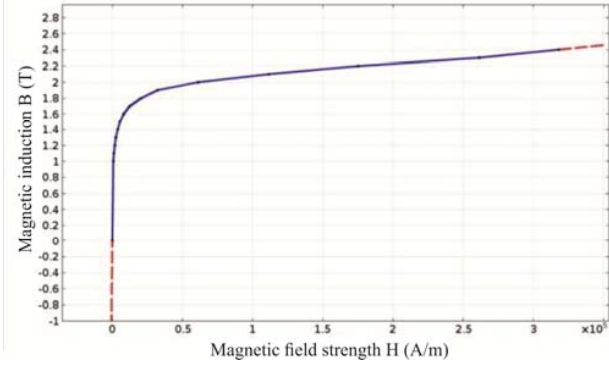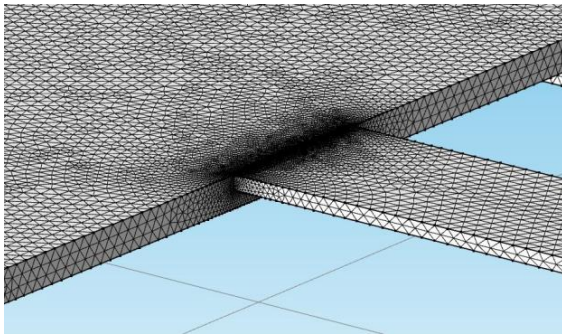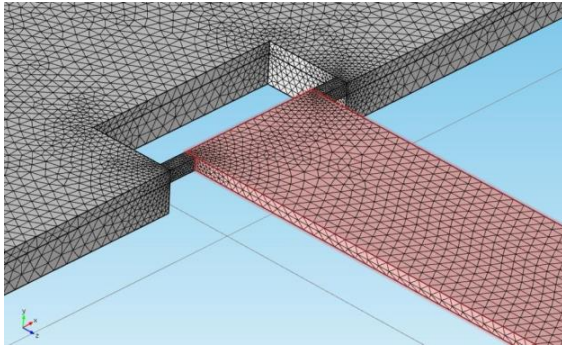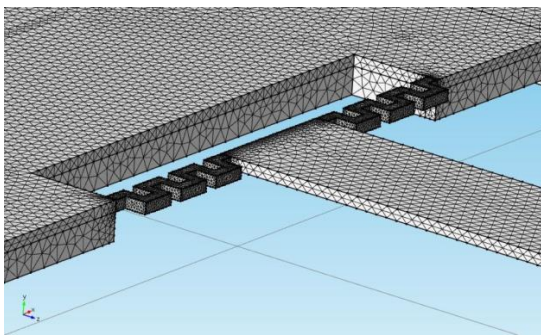
Fig. 2 The dependence diagram B=f(|H|) for permalloy

(a)

(b)

(c)

Fig. 3 Calculated fixation geometries of the travelling electrode of a MEMS switch: with a strip ferromagnetic plate (a), with a rectangular torsion (b), with an elbowed torsion (c)

$$\tau = \int_{\partial\Omega} (r - r_0) \cdot (nT) dS \qquad (6)$$

$$n_1 T_2 = -\frac{1}{2} n_1 (H \cdot B) + (n_1 \cdot H) B^T \qquad (7)$$

The equation describing mechanical stresses in deformable moving elements of magnetically controlled MEMS switches looks like:

$$\nabla \cdot \sigma = F \qquad (8)$$

In this work, the numerical model of MEMS switches is implemented in the COMSOL software package using the finite element method and a triangular adaptive grid (Fig. 1).

Fig. 3 shows the general geometry of a three-dimensional numerical model of a magnetically controlled MEMS switch.

In the work, the calculation of mechanical stresses in deformed torsions of MEMS switches of various shapes was made.

The magnetic sensitivity was calculated for the geometry with a triangular magnetic concentrator and various fixation geometries of the travelling electrode of a MEMS switch: with a terminal fixation electrode, with an electrode on a rectangular torsion and with an electrode on an elbowed torsion (Fig. 4). The electrode parameters for three geometry types were fixed: The thickness was 4 microns, the width - 50 microns, the length - 200 microns, the gap - 4 microns, the ferromagnetic plate width is 50 microns; the length varied within 200 microns. This condition provides the same magnetic force for all geometries. The geometry of a triangular magnetic concentrator is the ratio of width to length as 1:1. The material of electrodes, torsions and concentrator is permalloy.

The magnetic strength of magnetically controlled MEMS switches was determined on the basis of the time history data of the travelling electrode geometry during the process of switching up to closing. In this case, the magnitude of the magnetic field changed iteratively in the process of switching the electrode.

The calculation was made for three variants of the torsion design: with a fixed electrode, with an electrode on rectangular torsions and elbowed torsions. The torsions thickness was set equal to the electrode thickness of 4 μm, the number of elements in the elbowed torsion was equal to 3, the cross-sectional shape was square. The torsion material was permalloy.

III. RESULTS

In the process of modeling, the profiles of the magnetic field distribution inside the structure of the magnetic system of MEMS switches and the time history data of the moving parts geometry during switching were obtained (Figs. 5 (a), (b)).
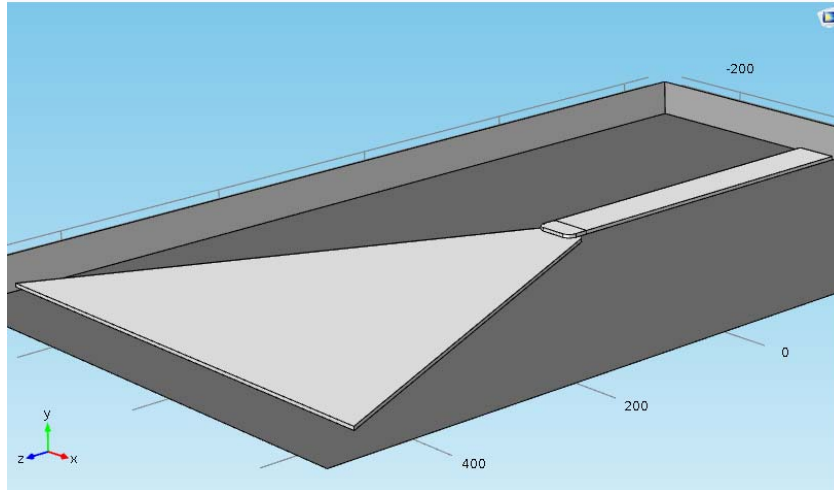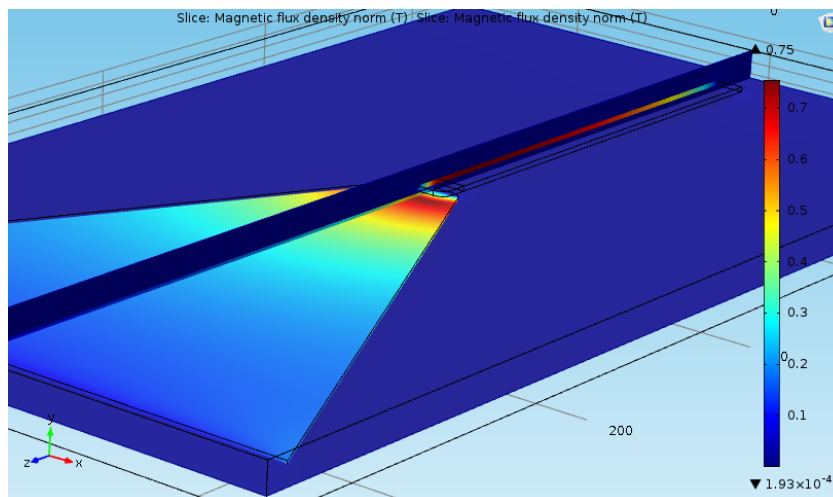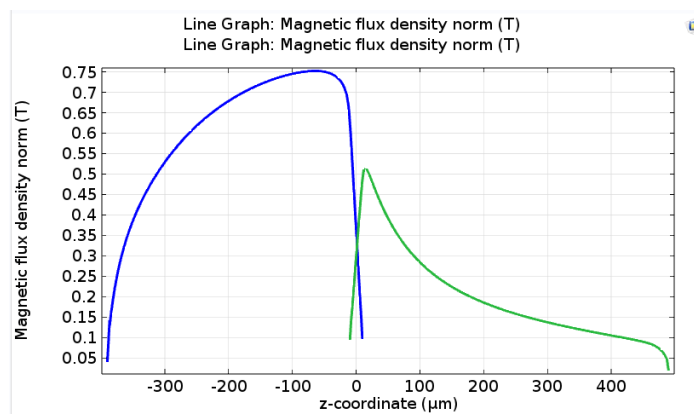
Fig. 4 Calculated geometry of a magnetically controlled MEMS switch with a triangular magnetic concentrator
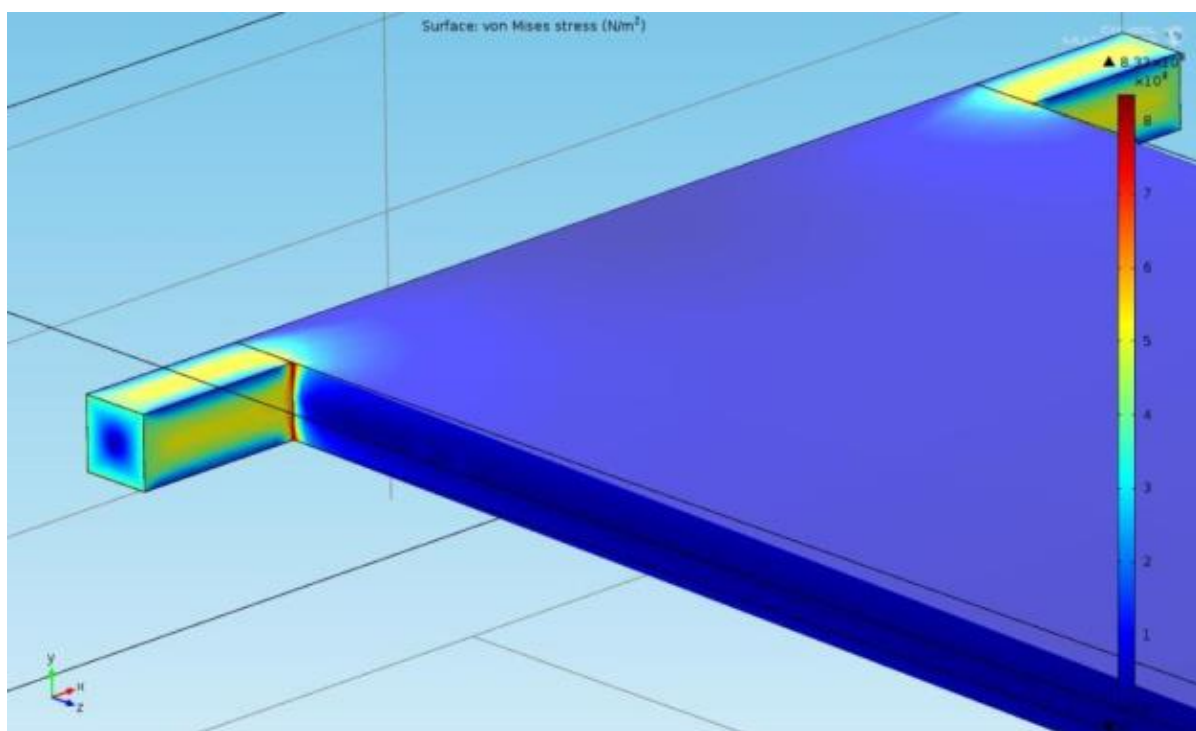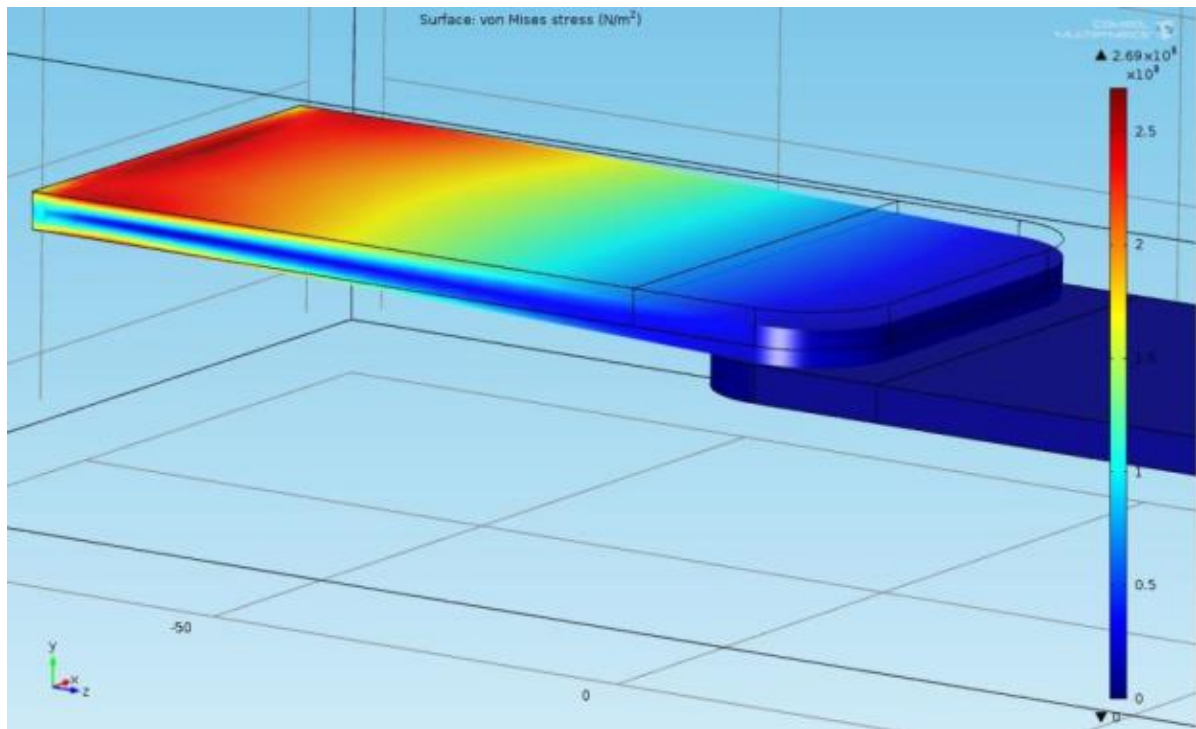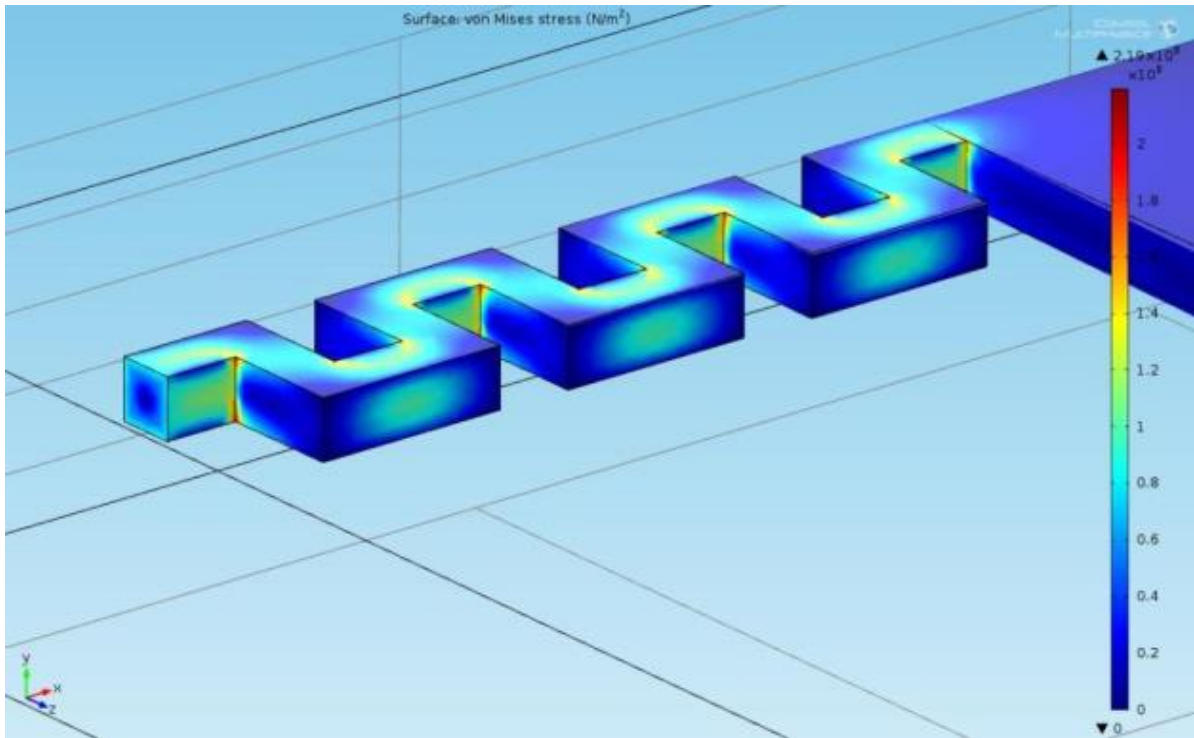

(a)

(b)

Fig. 5 Magnetic field distribution in a travelling electrode and a triangular magnetic concentrator: (a) flux distribution in the plane of a magnetic concentrator and a moving electrode; (b) distribution of the magnetic field in a travelling electrode and a magnetic concentrator along the central line

(a)

(b)

(c)

Fig. 6 Mechanical stresses distribution in a travelling electrode: (a) rigid fastening; (b) direct torsion fastening; (c) elbowed torsion fastening

It is shown that the use of magnetic concentrators is an effective method for increasing the MEMS switch sensitivity, as they provide the field amplification in the intercontact space, thereby increasing the contact pressure at a smaller external magnetic field value.

The analysis of the magnetic field distributions shows that the maximum magnetic field induction for all the performed calculations is less than the permalloy saturation induction ($\approx$ 1.8 T), what allows to conclude that there is no saturation effect in this numerical experiment.

The traditional solution for fastening a travelling electrode in magnetically controlled MEMS switches is to use either terminal fixation (similar to a reed switch - RedRock) [1] or direct torsions (MS-1) [7]. The disadvantage of these design solutions is the relatively low mechanical resistance and, accordingly, the limitation of the commutations number that is caused by the mechanical destruction of torsions as a result of long-term periodic deformation.

For optimization, a comparative calculation of the mechanical stresses in direct and elbowed torsions has been performed under the condition that the system provides the same magnetic sensitivity of 20 mT.

Fig. 6 shows the distribution of mechanical stresses for various geometry types of a travelling electrode.

In the course of calculations it was found that the use of elbowed torsions for fastening is an effective method for increasing the magnetic sensitivity, which provides less mechanical stresses value at electrode switching ($2.1 \cdot 10^9$ N/m^2

for rectangular torsions and $1.1 \cdot 10^9$ N/m^2 for elbowed torsions under the conditions of a numerical experiment) in comparison with direct torsions and terminal fastening of the electrode.

IV. CONCLUSIONS

The performed calculations show that an elbowed form of the torsion chosen by mathematical modeling provides the maximum commutation number of a switch as a result of significant decrease (more than twofold) of mechanical stresses level in it and the increase of the magnetic sensitivity. This allows to confirm that the use of elbowed torsions together with magnetic concentrators is an effective method to increase the operating characteristics of magnetically controlled MEMS switches.

The obtained results have been used for the design and production of magnetically controlled MEMS switches.

REFERENCES

[1] S. Day, T. Christenson, "A High Aspect Ratio Microfabricated Reed Switch Capable of Hot Switching", in *Proc. Holm Conference on Electrical Contacts (HOLM), 59th IEEE,* 2013.
[2] M. Tang, Y.H. Lee, R. Kumar, R. Shankar, O.L. Néel, "A MEMS Micro-reed Switch Designed for Portable Applications," in *Proc. 16th International Conference on Magnetism, Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS),* 2011, pp. 2847–2850.
[3] US6633158 B1 (Micro magnetic proximity sensor apparatus and sensing method) – 14.10.2003.
[4] US 8,327,527 B2 (INTEGRATED REED SWITCH) 11.12.2012.
[5] C. Coutier, L. Chiesi, A. Garnier, J.C. Fourrier, C. Lapiere, M.

Trouillon, B. Grappe, M. Vincent, A. Samperio, S. Borel, C. Dieppedale, E. Lorent, H. Sibuet, "A New Magnetically Actuated Switch for Precise Position Detection", *in Proc. International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS),* 2009, pp. 861 – 864.

[6] S.M. Karabanov, R.M. Maisels, V.N. Shoffa, "Magnetically Controlled Contacts (Reed Switches) and Reed Switch Based Products", Monograph under the editorship of V.N. Shoffa, Dolgopudniy, Publishing House "Intellect", 2011.

[7] S.M. Karabanov, A.S. Karabanov, D.V. Suvorov, B. Grappe, C. Coutier, H. Sibuet, B.N. Sazhin, "Magnetically controlled MEMS switches with nanoscale contact coatings", in *Proc. 26th International Conference on Electrical Contacts (ICEC),* 2012, pp. 359–361.