Ruthenium Based Nanoscale Contact Coatings for Magnetically Controlled MEMS Switches

Sergey M. Karabanov, Dmitry V. Suvorov

***Abstract*—**Magnetically controlled microelectromechanical system (MCMEMS) switches is one of the directions in the field of micropower switching technology. MCMEMS switches are a promising alternative to Hall sensors and reed switches. The most important parameter for MCMEMS is the contact resistance, which should have a minimum value and is to be stable for the entire duration of service life. The value and stability of the contact resistance is mainly determined by the contact coating material. This paper presents the research results of a contact coating based on nanoscale ruthenium films obtained by electrolytic deposition. As a result of the performed investigations, the deposition modes of ruthenium films are chosen, the regularities of the contact resistance change depending on the number of contact switching, and the coating roughness are established. It is shown that changing the coating roughness makes it possible to minimize the contact resistance.

***Keywords*—**Contact resistance, electrode coating, electrolythic deposition, magnetically controlled MEMS.

I. Introduction

THE magnetically controlled MEMS (MCMEMS) switch design consists of a silicon substrate with deposited contact metal pads, a travelling beam electrode that moves under the action of a drive magnetic field. The electrodes are placed in the cavity of a silicon substrate in inert gas (nitrogen, argon) atmosphere [1]-[3]. One of the main parameters of a MCMEMS switch is the contact resistance (R_c), the value and stability of which is largely determined by the contact coating material. Platinum group metals (Au, Rh, Ru) and gold-base alloys are used as the contact coating material [4], [5]. Currently, Ru films applied by magnetron sputtering [1] and electrolytic deposition [3] are used as the contact coating material. Ruthenium coating provides acceptable R_c value and stability [4]. For a MCMEMS switch, the R_c value is to be at the level of 1 Ohm, and must be stable during the service life (10^7–10^9 switching). For production, it is important that ruthenium has a minimal cost compared to other platinum group metals.

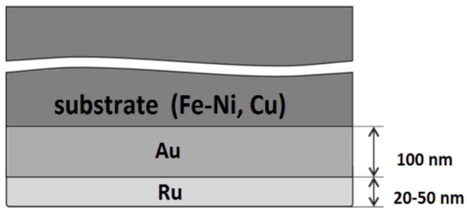
In reed switch production the ruthenium coating thickness is 0.5 - 1.5 microns. For MCMEMS switches the coating thickness should be 50-300 nm. In the present work, studies of nanoscale ruthenium contact coatings (50 - 300 nm) have been carried out. The paper studies the modes of ruthenium films deposition, the regularities of the contact resistance change depending on the switching cycle number and the coating roughness.

S. M. Karabanov is with the Ryazan State Radio Engineering University, 59/1 Gagarina St., Ryazan 390005, Russia (corresponding author, phone: +7 996-910-6387; e-mail: pvs.solar@ gmail.com).

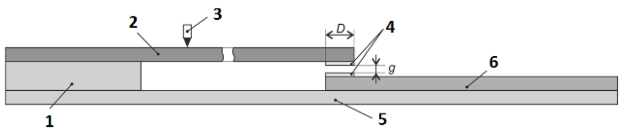
D. V. Suvorov is with the Ryazan State Radio Engineering University, 59/1 Gagarina St., Ryazan 390005, Russia (e-mail: Dmitriy_Suvorov@mail.ru).

II. Research Method

Fig. 1 (a) shows the contact coating structure. Ruthenium contact coatings are deposited by an electrolytic method from an electrolyte based on the ruthenium complex $[Ru_2N(H_2O_2)Cl_8]^{-3}$ on a ferromagnetic material – permalloy (FeNi - 80%/20%). This complex is obtained by the reaction of ruthenium chloride and amidosulfonic acid (NH_2SO_3H). In this work, the dependence of the ruthenium deposition rate on the ratio of ammonium sulfamate (SA) and ruthenium (Ru) concentrations in the solution at different current densities to select the optimum conditions for the ruthenium deposition was investigated. To study the effect of the deposition mode on the porosity of the ruthenium coating, the pulse deposition was used.



(a)



(b)

Fig. 1 The structure of the contact coating (a) and the scheme of the contact system (b) for the study of the contact coating properties

The coating roughness (h) varied by electrochemical substrate etching in the range of 30–60 nm.

The surface structure study and the measurement of the contact coatings thickness were carried out by atomic force microscopy using NTEGRA scanning probe microscope. The coating roughness was determined in a scanning electron probe microscope by NOVA special image processing program.

The study of the films in the switching mode of the electric current was carried out on a special model simulating the MCMEMS switch operation (Fig. 1 (b)). The studies were carried out in the switching mode of 1 mA – 5V DC at the frequency of 1 kHz, that corresponded to the real MCMEMS switch operating mode.

In this work, the dependence of R_c on the coating thickness and on the roughness of the permalloy substrate during the current switching process was investigated.

III. The Research Results and Discussion

A. Study of the Influence of Ruthenium Coating Deposition

Fig. 2 shows the dependence of Ru deposition rate on the ratio of ammonium sulfate (SA) concentrations to the ruthenium concentration in the solution at different current densities.

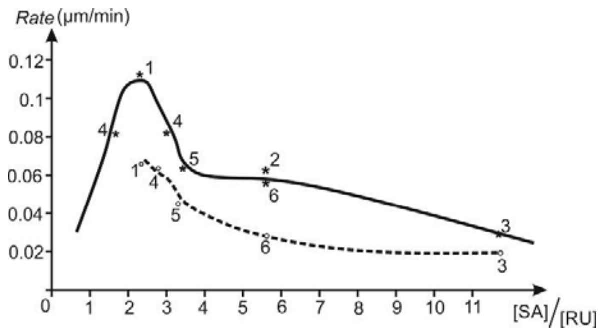


Fig. 2 Dependence of the ruthenium deposition rate on the concentration ratio of ammonium sulfate (SA) and ruthenium (Ru)

The rate of ruthenium exsolution with the increase of SA/ Ru ratio passes through a maximum at the ratio of about 2, and then decreases significantly (Fig. 2). This dependence remains unchanged within the studied range of current densities (up to 5 A/dm^2). Such behavior of the deposition rate is explained by the classical electrochemistry and the influence of the forces of electrostatic interaction of ions in solution.

According to the equation of electrochemical kinetics, when the delayed (limiting) stage is the discharge stage for the current density *i*, we have:

$$i = i_0\left[\exp\left(\frac{\alpha ZF}{RT}\eta_a\right) - \exp\left(\frac{-(1-\alpha)ZF}{RT}\eta_k\right)\right], \qquad (1)$$

if $|\eta_k|$ is large, then

$$\left|\exp\left(\frac{\alpha ZF}{RT}\eta_a\right)\right| \langle\langle \left|\exp\left(\frac{\beta ZF}{RT}\eta_k\right)\right|, \qquad (2)$$

where i_0 is the exchange current, α is the conversion factor, Z – the number of electrons participating in the delayed reaction stage, *F, R,* and *T* are the Faraday number, the gas constant and absolute temperature, accordingly, at which the process proceeds; η_k and η_a are the cathodic and anodic overvoltages, respectively.

Taking into account (2) from (1) we have:

$$i = i_0 \exp\left(\frac{\beta ZF}{RT}\eta_k\right). \qquad (3)$$

After taking the logarithm of the ratio (3), we get:

$$\eta_k = \frac{2.3RT}{\beta ZF}\left(\lg i - \lg i_0\right). \qquad (4)$$

At T=333 K, the value is $\frac{2.3RT}{F} = 0.0653$.

Differentiating (4) and entering $b = \frac{d\varphi}{d\lg i}$, where φ is the ruthenium electrode potential, we have:

$$\beta Z = \frac{0.0653}{b}, \qquad (5)$$

at i_0=const.

As follows from the analysis of the experiments, in the investigated range of current densities, the dependence of *lgi* from φ is not linear (*b* changes from 0.533 V up to 0.136 V). Since less than one electron (Z≥1) cannot participate in the elementary act, then using the value of *b* at the beginning of the dependence we can estimate β.

Assuming that β changes at low magnifications of φ insignificantly, we can observe an increase of the electron number *Z*, participating in one elementary act of the electrode potential φ growth, i.e. current density *i* increase.

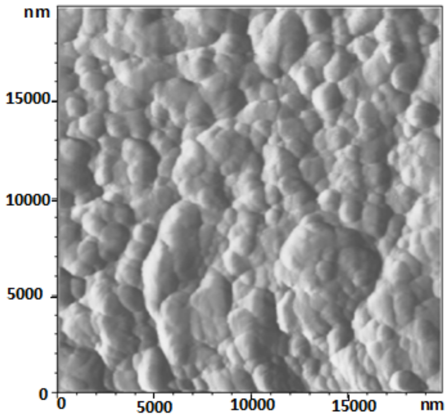
The obtained results are taken into account when analyzing the operation of ruthenium plating electrolytes.

It has been established experimentally that ruthenium coatings obtained in the pulsed deposition mode have a lower porosity. The optimum pulsed deposition mode is established: i = 1-6 A/dm^2, the pulse period is 1 ms, the porosity is 10%. For the use in MCMEMS switches, the ruthenium coating was deposited on the galvanic gold intermediate layer with the thickness of 50-100 nm to ensure stable adhesion. The thickness of the ruthenium coating was 50–300 nm.

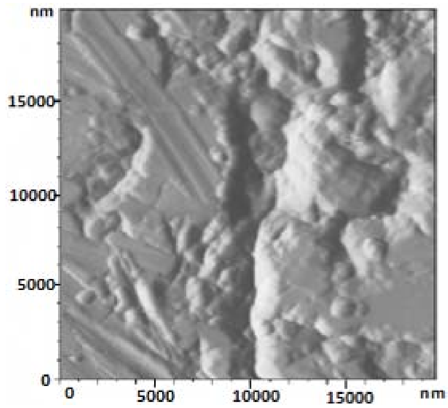
B. Study of the of Ruthenium Coating Properties

Fig. 3 shows the surface structure of electrochemically deposited ruthenium, which has a granular character. The elements of the surface structure have an average size of 1–3 μm (Fig. 3 (a). This growth form begins to appear at the small film thickness of about 40–50 nm. During the switching process, the surface structure of the contact coating changes significantly due to mechanical interaction (Fig. 3 (b)).

Fig. 4 shows the dependence of the contact resistance R_c change on the number of switching cycles for different values of the initial roughness level (h) of the contact surface for different coating thicknesses: 100 nm, 200 nm, and 300 nm. The studies have shown that in the first stage, an increase of the switching number is followed by the drop of the contact resistance R_c value. Then, after R_c reaching a certain minimum value, its growth begins, slowing down with a further increase of switching cycles.



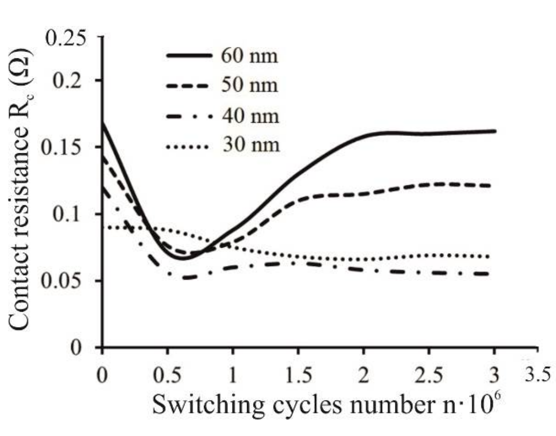
(a)



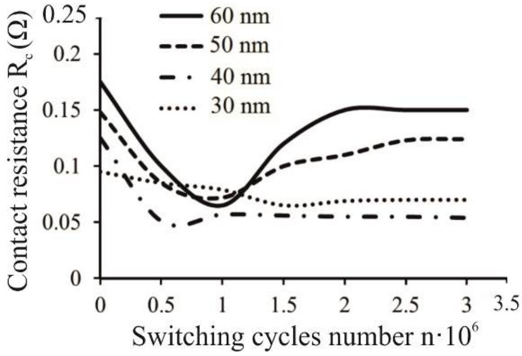
(b)

Fig. 3 Surface structure of the ruthenium contact coating before (a) and after 10^6 switching cycles (b)

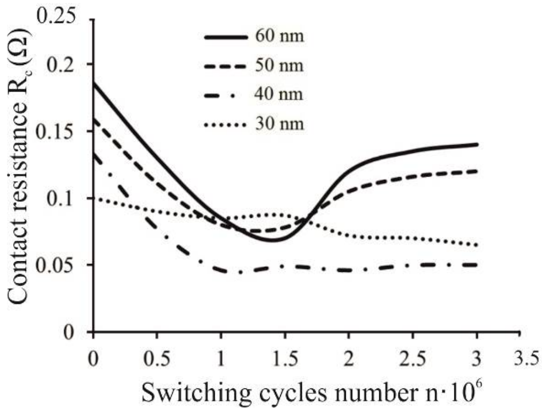
The obtained dependences were processed, and the dependences of the contact resistance R_c on the initial roughness level of the coating were constructed on their basis. Prior to switching tests, the curve describing the dependence of the contact resistance on roughness increases almost linearly (Fig. 5). In the process of switching, the resistance decreases, and the minimum contact resistance is achieved at the level of the initial roughness of the ruthenium coating at the level of 40 nm.



(a)



(b)



(c)

Fig. 4 Dependence of the contact resistance on the switching cycles number

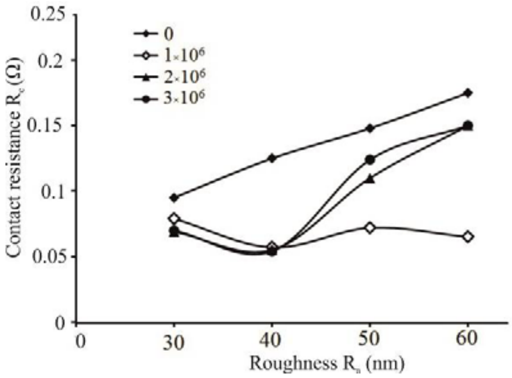


Fig. 5 Dependence of the contact resistance on roughness

The dependence of the contact resistance on the switching cycles number (Fig. 4) is determined by two opposite factors:

– an increase of the contact area due to the electromechanical interaction of the surfaces that results in a rapid decrease of the contact resistance at the initial stage;
– erosion processes that leads to a gradual increase of the contact resistance in the course of time.

The increase of the ruthenium film thickness results in the decrease of the electromechanical erosion processes intensity and the shift of the minimum contact resistance point to the minimum values area. Obviously, this is due to the fact that a thinner ruthenium film is more easily exposed to mechanical stress, since it is deposited on a plastic intermediate layer of gold.

Fig. 6 shows the roughness change of the contact pads in the switching process. It is seen that in the switching process the surface roughness of the contacts decreases. In this case, the higher the initial roughness level, the more significantly the surface roughness changes. From the experiment it can be seen that the minimum surface roughness is achieved at the initial surface roughness (h_0) of 40 nm.

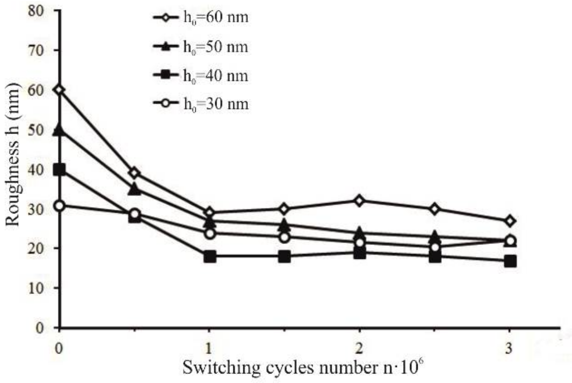


Fig. 6 Dynamics of the roughness change during switching

The presented research results show that there is an optimal value of the surface roughness, which ensures the minimum value of the contact resistance in the steady state. For the presented experimental conditions, the optimum roughness of the ruthenium coating is about 40 nm.

IV. Conclusion

The results of the work are important for the design of MCMEMS switches and the development of their production technology: the application of contact ruthenium coatings and the treatment of ferromagnetic permalloy electrodes.

References

[1] M. Vincent, L. Chiesi, J. C. Faurrier, A. Garnier, B . Grappe, C. Lapiere, C. Coutier, A. Samperio, S. Paineau, "Electrical contact reliability in magnetic MEMS switch", *Proceedings of the 54th IEEE Holm Conf.*, Orlando, October 27-29, 2008, pp 145-150.

[2] C. Coutier, L. Chiesi, A. Garnier, J. C. Faurrier, C. Lapiere, M. Trouillon, B. Grappe, M. Vincent, A. Samperio, S. Borel, C. Dieppedale, E. Lorent, H. Sibuet, "A new magnetically actuated switch precise position detection", *Proceedings of the 15th International Conf. Transducers 2009*, Denver, June 21-25, pp. 861-864.

[3] S. Day, T. A Christenson, High Aspect Ratio Microfabricated Reed Switch Capable of Hot Switching. Holm Conference on Electrical Contacts (HOLM), 2013.

[4] S.M. Karabanov, R.M. Maizels, V.N. Shoffa. Magnetically operated switches (reed switches) and products on their basis, Dolgoprudniy, Publishing House "Intellect", 2011, 408 pages.

[5] Karabanov, A.S., Suvorov D.V., Grappe B., Coutier c., Sibuet H., Sazhin B.N., "Magnetically controlled MEMS switches with nanoscale contact coatings," *26th International Conference on Electrical Contacts (ICEC 2012)*, 2012) IET Conference Publications 2012 (605 CP) PP. 359-361. doi: 1049/cp.2012.0675.