magnetizations of FM layers and their thickness, this maximum shifts to a region of higher values of h (in absolute value).

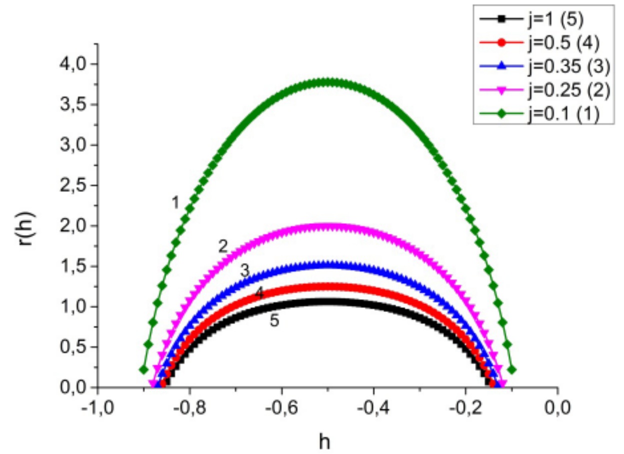


Figure 1 – Relative magnetoresistance of the AFM/FM/NI/FM structure as a function of the h parameter for different values of the j exchange constant.

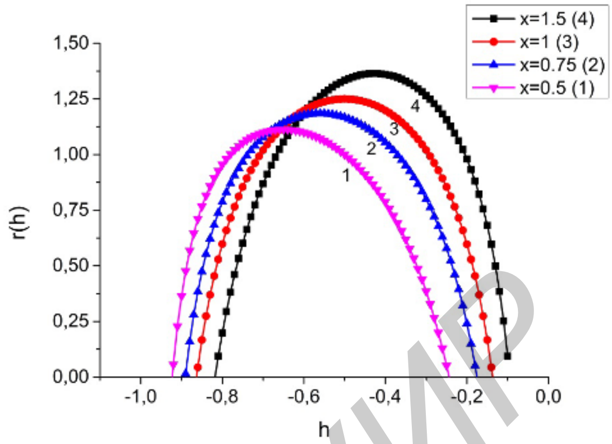


Figure 2. Relative magnetoresistance of the of the AFM/FM/NI/FM structure as a function of the h parameter at different values of x parameter.

IV.CONCLUSIONS

The simulation of the magnetoresistance of a spin valve containing an antiferromagnetic fixing layer is performed. It is shown that the effect of exchange bias that occurs at the contact of the ferromagnetic and antiferromagnetic layers with certain combinations of parameters of the spin-valve can lead to an increase in the magnetoresistance in several times (from 1.5 up to 4) due to the presence of the field of exchange bias.

REFERENCES

[1] A. Brataas, A.D. Kent, H. Ohno, Nature Mater. 11, 372 (2012).
[2] S. Loth, S. Baumann, C.P. Lutz, et al. Science 335, 196 (2012).
[3] F. Maca, J. Masek, O. Stelmakhovych, et al. J. Magn. Magn. Mater. 324, 1606 (2012).
[4] M.J. Grzybowski, P. Wadley, K.W. Edmonds et al. Phys. Rev. Lett. 118, 057701 (2017).
[5] X. Marti, I. Fina C. Frontera, et al. Nature Materials 13, 367–374 (2014).
[6] H. B-M. Saidaoui, A. Manchon, X. Waintal. Phys. Rev. B 89, 174430 (2014).
[7] Th.G.S.M. Rijks, R. Coehoorn, J.T.F. Daemen, W.J.M. de Jonge. J. Appl. Phys. 76, 1092 (1994).

ANALYSIS AND DIGITAL PROCESSING OF SEM IMAGES OF ANODIC ALUMINA FILMS WITH NANOPOROUS STRUCTURE

N. Lushpa, T. Dinh
Belarusian State University of Informatics and Radioelectronics, Minsk, Belarus

INTRODUCTION

The study of the morphology and structure of nanoporous materials is one of the important tasks of modern materials science. The creation and development of new nanostructured materials containing arrays of nanoscale pores are impossible without determining the pore sizes and density of their distribution. When you analyze images of an object with a nanoporous microstructure, it is first of all necessary to solve the following problems: performing segmentation, filtering the microstructure deficiencies, and isolating the objects from the background, determining the limits of objects, and pattern recognition. Correctness of the image segmentation is an important prerequisite for the success of the subsequent analysis.

Various application programs for image analysis are currently developed and available. Among the variety of software based on their functionality the most successful are Photom, Optimas, Image Expert Pro, ImageJ, Avizo and Smart-eye. In our work the ImageJ program was chosen for research. There are all necessary algorithms for image processing: high-frequency and low-frequency filtering, selection of image limits, arithmetic and logical operations, brightness / contrast correction [1, 2]. Digital image processing in this program was used to analyze the morphology of the surface of nanoporous anodic alumina.

The properties of anodic alumina films are of great interest due to self-organized nanoporous structure, as well as the possibility of controlling the structural parameters at the formation stage. These advantages provide wide application of nanoporous anodic alumina films in nanotechnology for the fabrication of various nanostructures, nanoporous membranes, memory cells and optical elements [3-5].

The purpose of this work is to use the ImageJ software, whose algorithms allow to analyze the characteristics of the films with porous structure using SEM images.

I. EXPERIMENTAL

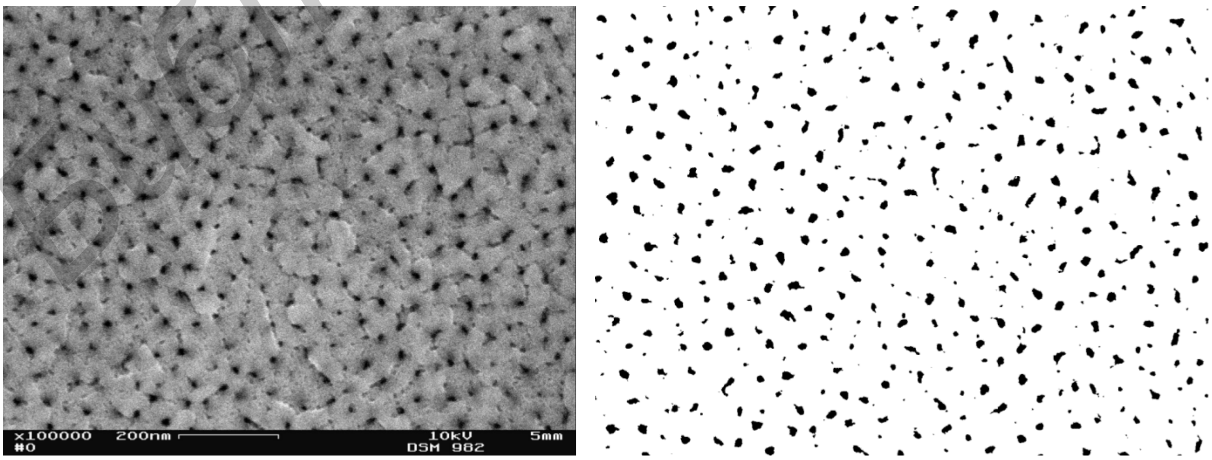
Thin aluminum films approximately 100 nm thick were deposited on silicon substrates with a silica film (SiO_2/Si plates) by thermal evaporation in a vacuum. Then, square samples of 4 cm2 were cut and anodized in a potentiostatic mode at 20 V in an aqueous solution of 0.3 M oxalic acid. The anodizing area of aluminum (about 0.22 cm2) was set with Viton-o-ring. The process was carried out in a two-electrode fluoroplastic cell at a constant temperature (18.0 ± 0.1) ˚C using a thermostat F 12 (Julabo). As DC power source was used PS-2403D (Voltcraft). The cathode was a platinum grid. The electrolyte was vigorously stirred using a mechanical stirrer. The morphology of the obtained samples was studied using SEM on a Zeiss DSM 982 microscope. The voltage on the accelerating electrode varied from 10 to 20 kV. To process and analyze the characteristics of the nanoporous structure of anodic alumina films, the following algorithm was used:

– filtering the image to exclude random noise;
– preliminary segmentation to isolate homogeneous regions;
– correction of the object for determining the brightness threshold;
– final segmentation using a certain background value, which allows to fully define objects;
– analysis of selected objects.

The ImageJ software allows us to calculate the areas and statistical indicators of the pixel values of the various areas selected manually or by means of threshold functions on the images. This software supports standard image processing functions, such as logical and arithmetic operations between images, contrast manipulation, convolution, Fourier analysis, sharpening, smoothing, border detection. The program also allows usto perform various geometric transformations, scaling, rotation or reflection. The ultimate task of image analysis is statistical processing of the results obtained throw measuring the characteristics of an object with a porous structure, determining the average values of pore diameters, and plotting graphs to visualize the analysis process.

II. RESULTS AND DISCUSSION

The investigated samples of porous anodic alumina films had a uniform distribution of pores over the surface (Fig. 1).



a b

Figure 1 – SEM image of the surface of porous anodic alumina films (a) and the final view (b) for identifying the pores after conversion to black and white graphics using ImageJ

To evaluate the geometric parameters of the porous anodic alumina films a technique based on the analysis of the surface morphology from SEM data with the help of Image J was used. We gave examples of the initial (Figure 1) and final (Figure 2) results of the software work for processing SEM images.

Operating with ImageJ program included several stages. At the beginning, the image area was calibrated to obtain information about the pore size. In the Settings menu, the function "Calibrate Spatial Measurements" was selected and a line of the specified length was drawn. As such a line, the marker in the lower right corner of the SEM image was selected. In the dialog that appears, the required dimension was selected and the length of the line was setted. After completing the calibration, the images went to the basic operations for measuring the pore sizes.

At the first stage, the shades of gray present on the SEM image into ImageJ were imported (Figure 1, a). Then we set the size of the analyzed area, cropped the image to the selected size, and the rest was converted to a real black and white image (Figure 1, b).

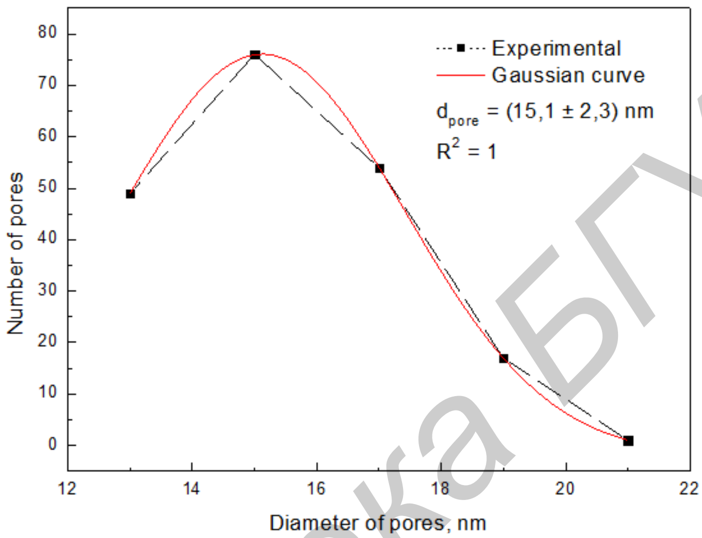


Figure 2 – The results of processing image in the ImageJ software of the porous alumina films obtained in 0.3 M aqueous solution of oxalic acid

In the second stage, before the transformation was started, a gray threshold was selected in ImageJ, above which the associated pixels were converted to black pixels, and below – to white. For the analysis, SEM images with a significant contrast of shades of gray between the round pores are best. In the third stage, by using the program settings, small dark objects were automatically deleted and thus the image was cleaned. At the end of the program cycle, data was obtained to construct a histogram of pore distribution of a certain diameter on the analyzed surface (Figure 2). According to the results shown in Fig. 2, the porous anodic alumina films had a pore size of (15.1 ± 2.3) nm. The obtained result agrees well with the data available in the literature for porous anodic alumina films formed in the electrolyte of an aqueous solution of oxalic acid at 20 V [6].

III. CONCLUSION

We concluded that the ImageJ software is a suitable tool for the quantitative analysis of the morphology of anodic alumina surface with nanosized pores. The processing results in the ImageJ program allowed to calculate the mean pore diameter for porous anodic alumina films. To visualize the analysis process, graphical dependencies of the pore diameter distribution on the sizes using the Origin package were plotted.

REFERENCES

[1] Bodla, K.K. Microtomography-based simulation of transport through opencell metal foams / K.K. Bodla, Y.M. Murthy, S.V. Garimella // Numerical Heat Transfer. – Part A. – 2010. – P. 527-544.
[2] Whitehouse, D. Handbook of Surface Metrology / D. Whitehouse. – Bristol and Philadelphia, 1994. – 988 p.
[3] Lee, W. Porous anodic aluminum oxide: anodization and templated synthesis of functional nanostructures / W. Lee, S.-J. Park // Chem. Rev. – 2014. – Vol. 114. – P. 7487-7556.
[4] Polymer nanoimprinting using an anodized aluminum mold for structural coloration / T. Kikuchi [et al.] // Appl. Surf. Sci. – 2015. – Vol. 341. – P. 19-27.

[5] Chemical and structural modifications of nanoporous alumina and its optical properties / A. Brzozka [et al.] // Springer Series in Materials Science. – 2015. – Vol. 220. – P. 219-288.
[6] Sulka, G.D. Highly ordered anodic porous alumina formation by selforganised anodizing and template-assisted fabrication of nanostructured materials / G.D. Sulka // Nanostructured materials in electrochemistry. – 2008. – P. 1-116.

BREAKDOWN AND CONDUCTIVITY SWITCHING IN NANOSIZED HAFNIUM DIOXIDE

D. Podryabinkin, A. Danilyuk
Belarusian State University of Informatics and Radioelectronics, Minsk, Belarus

I. INTRODUCTION

At the present time nanostructures based on hafnium dioxide are promising for use as gate insulators in MOSFETs (metal-oxide-semiconductor) and non-volatile resistive memory with random sampling (RRAM). Hafnium oxide has a high dielectric constant, a relatively high energy of the forbidden band, and forms a thermodynamically stable interface with silicon. It is worthwhile for resistive memory, since its dielectric breakdown leads to switching to a low-resistance state, and formation of high density of traps, that makes possible the long-term storage of charge (up to 106-107 s). Therefore, the methods for fabrication of nanosized hafnium dioxide on a silicon substrate and nanostructures based on it are being developing, and its electrical, structural and spectroscopic characteristics and parameters, as well as peculiarities of hafnium dioxide properties appearing as a result of electroforming, are being studied [1, 2]. In this area practical results have been already achieved, the main of which is the production of a stable nanosized layer of hafnium dioxide, switchable by a low potential. However, there are still many unsolved problems, the most important of which are the identification of a mechanism for switching of hafnium dioxide from a high-resistance to a low-resistance state, identification of mechanisms of current transfer in the presence of a high concentration of traps, and the determination of the contribution of thermal processes.

II. MODEL

In this paper, we propose a model of breakdown and a fast switching of the conductivity of nanosized hafnium dioxide containing bistable electronic states. Such states in hafnium dioxide are obtained by electroforming in an electric field with the formation of conductive current filaments. At electrical breakdown of nanosized hafnium dioxide, filaments with a diameter of about 50 nm are formed. A strong heating of the material up to its boiling point takes place. In fact, there is an electrical explosion of matter in the channel, which is limited by solid walls. Plasma is formed, a fast growth of pressure on the walls of the channel and its expansion occurs, as well as a certain release of matter from the channels due to local heating of the electrodes, which leads not only to a deficiency of oxygen atoms in the channels, but also to the release of the compound itself [3]. Due to the strong heating and the subsequent increase of pressure on the walls and electrodes, the substance in the channels is pressed against the walls, like spreading along them, some of it is pushed to the electrodes closer to the anode, and part of the electrode material, mainly the cathode, is pressed into the channels. After removing the electrical impulse and cooling down of the substance in the channel, i.e. after the finishing of the electroforming, the evaporated material sedimentate on the channel walls, is amorphized under pressure in the anode region and after cooling turns into a glassy nonequilibrium disordered system. Between the cathode and the glassy region, apparently, an area is formed in which the substance is absent, i. e. a vacuum cavity.

Upon further application of the electric field, the current transfer mechanism changes. Now we must take into account the thermal emission of electrons from the cathode, which have energy higher than the Fermi energy of the cathode and can be accelerated in the vacuum gap. These electrons, interacting with the glassy region near the anode, activate metastable trap states in it, facilitating the transition of this region to a high-conductivity state, but without heating the substance up its to melting and evaporation. The removal of the field leads to the return of the system to a low-conductivity state.

Such glassy region near the anode can capture electrons, forming a space charge after removing the field, or may not form it at all. In the first case, for the subsequent switching it is necessary to apply an external bias with the opposite sign, and this will be a bipolar switching. In the second case, the potential of the opposite sign is not required, and we obtain a monopolar switching.