Problems of the experimental implementation of MTJ

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Abstract. The results of experimental studies of MRAM technology based on standard magnetic tunneling junctions are presented. Basic steps of experimental fabrication of MRAM cell are considered. Experimental samples of MTJ with variable lateral sizes are fabricated. Current-voltage characteristics of the tunnel barriers are investigated. Main parameters of the tunnel barriers are estimated from comparison of the experimental data with the theory.

Magnetic Tunneling Junction (MTJ) is an important element of modern MRAM cell. It is believed that MRAM might be the next generation of computer memory. Therefore optimization of the technology for MTJ fabrication is of very important task. Achievement of high functional characteristics of MTJ requires intensive quality control at different stages of the technological route. In this work we discuss different aspects of quality control during this route. For this purpose we studied experimentally the technology of typical MTJ fabrication.

Standard spin-tunnel structure used to make MTJ consists of two magnetic layers separated by the layer of tunnel dielectric. This structure can be also used for magnetic field sensors [1]. MTJ fabrication involves complex technological route consisting of deposition of multilayer structure and subsequent MTJ pattern formation through lithography.

This work is devoted to the analysis of quality control methods at different stages of experimental fabrication of the MTJ samples. Two types of structures were considered: symmetrical Co(10 nm)/Al\textsubscript{2}O\textsubscript{3}(2 nm)/Co(30 nm)/SiO\textsubscript{2}(200 nm)/Si(100) and non-symmetrical Ta(3 nm)/FeMn(15 nm)/NiFe(8 nm)/Al\textsubscript{2}O\textsubscript{3}(2 nm)/NiFe(10 nm)/Ta(10 nm)/SiO\textsubscript{2}(200 nm)/Si(100). Multilayer structure was deposited by RF magnetron sputtering using industrial equipment Alcatel TETRA SCR-650. This machine is equipped with 4 magnetron sources, which allows depositing of multilayer structures in a single vacuum cycle. The magnetic layers were grown at external magnetic field of 100 Oe in the plane of substrate to promote easy axis formation.

Appropriate texture formation in the growing films is achieved through ion bombardment of the surface due to substrate bias potential. The layer of the tunnel dielectric was obtained by deposition of a thin Al layer (2 nm), which subsequently was oxidized in oxygen plasma. Low-energy ion bombardment in argon plasma was also used during antiferromagnetic (FeMn) growth to promote exchange bias effect in the underneath ferromagnetic (FeNi) layer and provide effective pinning of upper magnetic layer.
It was found that changing the conditions of ion bombardment at this stage of the growth greatly affects pinning potential in the layer. The growth of buffer layer (at the bottom of the structure) and encapsulating layer (on the top of it) were done in separate vacuum cycles (before and after deposition of the core layers of spin-tunnel structure). We have already tested this kind of technology before in studies of spin-valve structures [2].

The quality of multilayer structure has been studied using TEM. Cross-section of as deposited thin film structure is shown in figure 1. Bright color stripe in the center of the figure corresponds to the tunnel dielectric layer (Al₂O₃). Neighbor dark spaces correspond to magnetic and buffer layers. From this figure we can estimate the quality of tunnel dielectric layer (its thickness and homogeneity). Visual inspection does not find any major breaks in the dielectric layer. Another important characteristic, which could be obtained from the analysis of this figure, is roughness of the interface. It is well known that this parameter considerably affects magnetic characteristics of MTJ.

![Image](image1.png)

**Figure 1.** Cross-section of the multilayer spin-tunnel structure obtained using TEM. 1. FREE magnetic layer, 2. TUNNEL dielectric layer, 3. PINNED magnetic layer

![Image](image2.png)

**Figure 2.** Hysteresis loop of non-symmetrical MTJ structure obtained by magnetooptic Kerr effect

Magnetic properties of the multilayer structure were measured on the next stage using magnetooptic Kerr effect. For this purpose home-made experimental set-up (measuring orthogonal Kerr effect) has been used. Hysteresis loop of one of our nonsymmetrical structures is shown on figure 2. Presence of characteristic steps on this curve shows that different magnetic layers switch separately. From other
side we can see that loop is shifted to the area of large magnetic fields due to strong exchange bias effect.

Main problem in the formation of high quality MTJ is creating tunneling junction with appropriate transport characteristics. Pinholes and other defects could occur in a process of forming tunnel dielectric layer. Those defects deteriorate functional characteristics of the tunnel junction due to possible electric current short cuts. Usually, main source for those defects to appear is impurity inclusions (e.g. particles of dust). In case of high-class clean room facilities absent in the laboratory, one way to solve this problem (minimizing impurity inclusions) is the fabrication of MTJ with minimum lateral sizes.

![Optical microscope image of MRAM cell (Keyence VHX 2000)](image)

**Figure 3.** Optical microscope image of MRAM cell (Keyence VHX 2000)

On the next stage MTJ (in CPP geometry) with different shapes (rectangles, squares and circles) and lateral sizes (in the range from 3 µm to 45 µm) were fabricated using photolithography and ion beam etching methods. The whole technological route consisted of more than 15 operations [3]. Figure 3 shows optical microscope picture of sample MTJ structure at the final stage. As we can see circle-shaped tunnel junction is located in the center of two conducting wires crossing. Electrophysical properties of as-obtained structures were studied.

![Voltage-Current characteristic of symmetrical MTJ structures with rectangular shape and different lateral sizes](image)

**Figure 4.** Voltage-Current characteristic of symmetrical MTJ structures with rectangular shape and different lateral sizes
Figure 5. Voltage-Current characteristic of square-shaped non-symmetrical MTJ structure

Ratio of good MTJs in the experimental series was about 25%. In figure 4 typical voltage-current characteristics for symmetrical structures with rectangular shape MTJs (10x30 µm – bold line, 7x21 µm – dashed line, and 5x15 µm – dotted line) are shown. Similar curve but measured for non-symmetrical structure of square shape is shown in figure 5. We can see that I(V) dependence has similar nonlinear behavior as in Fig.4. Approximation of experimental curves using Simmons’s theory [4] let us to estimate height of the tunnel barrier (2 eV) and its thickness (3.8 nm). The results obtained agree well with TEM results (from 3 to 5 nm) [5].

Measurements of magnetoresistance of non-symmetrical structures gave us result that didn’t exceed 1.5%. Such low TMR values might be explained by degradation of magnetic films during fabrication process. Thus further work needed to improve the technology. In particular, magnetic annealing of MTJ sample could improve its performance.

In conclusion, we have studied typical MTJ fabrication process and developed methodology for quality control at different stages of the technological route. These results might be useful for optimization of MRAM technology.

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References
[1] Kasatkin S I, Meydan T, Murav’ev A M, Popadinec F F, Nikitin P I and Pudonin F A 2000 Microsystems engineering 4 23
[2] Trushin O S, Naumov V V, Barabanova N I and Bochkarev V F 2014 Bulletin of the Russian Academy of Sciences. Physics 78 13
[3] Gallagher W J, Parkin S S P, et.al. 1997 J. Appl. Phys. 81 3741-3746
[4] Simmons J G 1963 J. Appl. Phys. 34 1793.
[5] Trushin O S, Naumov V V, Mironenko A A and Mazalets'kiy L A 2014 J. Integral 77 10-11