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Method and Experimental Setup for the Study of the Local Current Distribution in Conducting Micro-and Nanostructures

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The method for the study of the spatial distribution of current in micro-and nanostructures on the measured magnetic field is presented. The methods of studies the magnetic field distribution of conducting nanostructures by passing a transport current are considered. The technique of current recovery from experimental data is offered.

Keywords: Nanostructures, The local current distribution, MFM, Conductive bridges.

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1. INTRODUCTION

At the present stage of development of nanotechnology is becoming increasingly important means of measuring various physical quantities in the nano range. The particular interest is the determination of the spatial distribution of current density in the micro- and nanosystems. Direct contact measurement of the spatial distribution of current density in the micro - nanosystems technically very difficult and often impossible due to the small dimensions and the need to manufacture a large number of electrical contacts. However, when the current flows, the magnetic field associated with them is appears, and therefore contains the information about the current distribution in the object of research. The implementation of experimental and theoretical approach of non-contact measurement of the magnetic field and recovery of the spatial distribution of the current in the object of study will provide qualitatively new physical data and undertake research into current paths with high spatial resolution, without the need for making electrical contacts.

2. EXPERIMENT

The experimental technique is based on a study of the magnetic field distribution above the sample, during the flow of transport current.

For the current flow through the sample were used two types of contacts: the pressure and glued using conductive glue based on silver. When using of lead wires and an external power source, go beyond the atomic force microscope, observed significant noise arising from the vibrations of air. In order to get rid of the influence of the wires was designed sample holder with the contacts and used an internal current source that is placed together with a sample under the vacuum protective cap.

The measurements were performed on an atomic force microscope using a probe with a magnetic coating with the following parameters:

Parameters of the cantilever:	
Thickness	3.0 μm
Mean width	28 μm
Length	225 μm
Force constant	2.8 N/m
Resonance frequency	75 kHz
Parameters of the tip:	
Cover	Co
The thickness of the coating	40 nm
Tip radius	less 50 nm

The samples was conductive copper bridges, with a width from 200 to 1000 nm, the film thickness is 150 nm.

The technique of magnetic force microscopy allows us to carry out measurements in two basic modes: static and dynamic. In the dynamic - the probe is shaking with the cantilever resonance frequency. During the current carrying sample measurement by the magnetic probe under the influence of a magnetic field force which changes parameters of vibration of the probe occurs and leads to the change of amplitude, phase and frequency of the probe vibration. Measuring these parameters, we obtain spatial distribution of the amplitude, the phase and the frequency.

In the static mode, we do not use the forced oscillations of the probe. The probe moves freely over the sample. Entering to the region of the magnetic field of the current, there is a force acting on the magnetic tip, which leads to bending of the cantilever. Thus, by measuring the amplitude of the deviation, we obtain the force distribution over the sample with the current.

MFM measurements allow us to investigate the distribution of the tip movement parameters of in the magnetic field of the current, but these data do not directly show us the pattern of current flow in the sample. In addition, the numerical values of the measured signal are inextricably linked with the parameters of the probe and the cantilever.

3. CALCULATION METHOD

In order to investigate the processes of current flow in nanostructures is necessary to recover the spatial distribution of the current components in a sample from the experimental data.

The main approach that have been used is the method of recovery current distribution from the magnetic field through the inversion of the Biot-Savart-Laplace equation:

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$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\int_V \frac{\mathbf{j}(\mathbf{r}')\times(\mathbf{r}-\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|^3} d^3\mathbf{r}',$$

where μ_0 is magnetic permeability of vacuum, V–region of the current localization of the sample

The solution to this problem allows to recover the current distribution under the condition of current flow along closed paths in a single plane by the magnetic field component perpendicular to this plane. In our case, the direct use of the approach is not possible, due to the flow of transport current through the sample. To solve this problem in a predetermined algorithm, we used an artificial closure of the flow lines outside the sample, by expanding the consideration area of current flow, assuming that in the area outside of the sample the current flows as well as in the sample. In case the current lines are closed in the sample. The usual technique to determine X, Y components of the current is a preliminary calculation of the magnetic moment of the film $g(X, Y) = (g_x, g_y, g_z)$, with subsequent determination of the current by the formula:

$$\mathbf{j} = \nabla \times \mathbf{g}$$

For the film can consider $g_x = g_y = 0$; $g_z = g(X, Y)$ [1,2]. Under the above assumptions, we obtain the relationship of the components of the magnetic field and the magnetic moment is the following:

$$B_Z(r) = \mu_0 \int_V K(\mathbf{r},\mathbf{r}')g(X',Y')d^3\mathbf{r}'$$

Using Fourier transform we obtain the equation:

$$\widetilde{B}(k_X,k_Y) = \mu_0 \widetilde{K}(k_X,k_Y)\cdot \widetilde{g}(k_X,k_Y)$$

, where the corresponding component of the magnetic field and the magnetic moment associated with their Fourier transforms by relations

$$\widetilde{B}(k_X,k_Y) = \int_{-\infty}^{+\infty} dX \int_{-\infty}^{+\infty} dY B_Z(X,Y)\exp(ik_X X + ik_Y Y),$$

$$\widetilde{g}(k_X,k_Y) = \int_{-\infty}^{+\infty} dX \int_{-\infty}^{+\infty} dY g(X,Y)\exp(ik_X X + ik_Y Y)$$

Fourier transform of the kernel of the integral operator defined by the following equation:

$$\widetilde{K}(k_X,k_Y) = \exp(-kh)\sinh(kd/2),\ k = \sqrt{k_X^2 + k_Y^2}$$

The detailed description is presented in [3].

Additional difficulty - is that when we use MFM as a result of the measurements we obtain the not the values of the magnetic field, and only derivatives [4].

Consider the first mode. The force of the magnetic interaction between the cantilever tip with the field of the sample is determined by the derivative of the vertical component of the magnetic field and current detection is based on the inversion of the following equation:

$$\widetilde{g}(k_X,k_Y) = \widetilde{B}'_Z(k_X,k_Y)\cdot\left[W'(k)/\left(\mu_0 \frac{\partial}{\partial h}\widetilde{K}(k_X,k_Y)\right)\right]$$

where $W'(k)$ – filter function required for correct recovery of the current distribution, in addition, it also filters the high frequency noise of the experimental data. Similarly, taking the second derivative, we are able to restore the current distribution by measuring the phase shift or frequency of the vibrational mode.

4. RESULTS

To test our methods were performed measuring the copper bridge with current. The size of the bridge width of 1 μm, length - 100 μm, thickness 150 nm. Passed a current of 10 mA.

It were obtained the distribution of the amplitude of the deflection of the probe in the static mode and change the amplitude and phase of the cantilever in dynamic mode. By the calculation was restored the distribution of the current in the sample in Figure 1. Thus, the technique has demonstrated its efficiency.

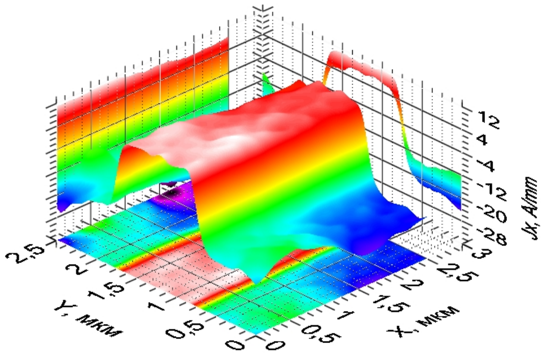

Fig. 1 – The surface distribution of the components of current along the bridge

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