Superconducting Film Flux Transformer for a Sensor of a Weak Magnetic Field

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Abstract. The object of study is a superconducting film flux transformer in the form of a square shaped loop with the tapering operative strip used in a sensor of a weak magnetic field. The magnetosensitive film element based on the giant magnetoresistance effect is overlapped with the tapering operative strip of the flux transformer; it is separated from the latter by the insulator film. It is shown that the topological nanostructuring of the operative strip of the flux transformer increases its gain factor by one or more orders of magnitude, i.e. increases its efficiency, which leads to a significant improvement of important parameters of a magnetic-field sensor.

1. Introduction

Ultra-sensitive instruments are the basis for solving many scientific and technical problems including these targeted to the study of biological objects. The magnetic field $B$ of the organs of the biological object is so small (e.g. the magnetic field produced by the human brain is of the order of $\sim 10^{-5}\text{ to } 10^{-4}\text{ nT}$) that it is close to the level of the magnetic vacuum, and only modern highly sensitive magnetometers and systems can be used to measure it [1].

Currently, the weak magnetic fields ($B \leq 10\text{ nT}$) are measured by different-type magnetometers: SQUIDs (SQUID – Superconducting Quantum Interference Device), optical and NMR magnetometers, etc. SQUID-devices based on the effect of superconducting electrons tunneling through a weak link (Josephson junction or transition) are the most sensitive of them, but they do not measure the absolute value of the magnetic field and only detect changes in it. The absolute value of the magnetic field can be measured with fluxgate sensors and numerous magnetometers based on them [2].

However, fluxgate sensors have a large weight and size, insufficient magnetic flux resolution $\delta \varphi \geq 100\varphi_0$, where $\varphi_0 = 2.07 \cdot 10^{-15}\text{ Wb}$ – magnetic flux quantum, and insufficient magnetic field resolution $\delta B \sim 10^{-2}\text{ nT}$, whereas for SQUIDs these values are $\delta \varphi \sim 10^{-6}\varphi_0$ and $\delta B \sim 10^{-5}\text{ nT}$.

Any material with sufficient non-linearity of its magnetic characteristic can be used as a magnetosensitive element (MSE). For example, these are the Hall sensors, materials and structures based on the effect of giant magnetic resistance (GMR), a granular conventional low-temperature superconducting (LTS) or ceramic high-temperature superconducting (HTS) material. However, in
order to improve important parameters of a magnetic field sensor (e.g. to reduce $\delta B$), it is necessary to use the measured (external) concentrators of the magnetic field, in particular, the so-called magnetic flux transformers (MFT). For this purpose, the property of superconductors to preserve magnetic flux in a closed circuit without loss is often used.

The variant MFT based on HTS film materials are used in many magnetometers, where MSE are: the Josephson junctions (for SQUIDs) [3], the Hall sensors [4], the sensors based on the GMR effect [5], the sensors based on the magnetoresistive effect in ceramic HTS materials [6], etc.

In this article, we present the results of the calculations intended for the efficient growth of the flux transformers based on the superconducting film materials.

2. Material and Methods
The object of study is the growth factor $F$ of the effective concentration of the magnetic field by MFT in MSE. We studied the geometry of a magnetic field sensor (MFS), which consists of a superconducting film MFT in the form of a square-shaped loop with the tapering operative strip, and a film MSE based on the GMR effect. The MSE is overlapped with the MFT operative strip and is separated from the latter by an insulator film. All the MFS elements are planar which is illustrated in figure 1 and figure 2.

![Figure 1](image1.png)  
**Figure 1.** Layout of MFS: 1 – superconducting square shaped loop of MFT, 2 – dielectric substrate, 3 – operative MFT-strip on a larger scale (ignoring aspect ratio), 4 – insulator film, 5 – MSE, 6 – connections to the contact pads.

![Figure 2](image2.png)  
**Figure 2.** Part of MFS: a – non-structured operative MFT-strip, i.e. with no slits, b – structured operative MFT-strip, i.e. with slits, where: 1 – superconducting loop of MFT, 2 – dielectric substrate, 3 – connections from MSE to the contact pads, 4 – branches, 5 – slits.

The value of the gain factor $F$ of the magnetic field in MSE was evaluated as follows. In the external magnetic field, the magnetic flux which shields the loop 1 in figure 1 is defined as $\varphi = A \cdot B$, where $A$ is the area inside the loop. The screening current $I_s$ is described by the formula $I_s = \varphi (L + M)^{-1}$, where $L$ is the inductance of the loop and $M$ is the total sum of mutual inductances between the parts.
of the MFT and MSE. It is known that $L$ is higher by one or more orders of magnitude than the total mutual inductance $M$.

The MFT loop inductance is mainly determined by the inductance $L$ of the operative MFT-strip since the ratio $D/\omega_i > 10^3$, where $D$ is the length of the square-shaped MFT loop side and $\omega_i$ is the width of the operative MFT-strip. If the latter is split into several branches, each with the inductance $L_i$ ($i = 1, 2, \ldots, n$, where $n \geq 2$ – the amount of branches in the operative MFT-strip), their total inductance grows insignificantly relative to $L$.

We carried out the search for the growth maximum of the gain factor $F_m$ by varying the widths of the slits and branches, their number and topological location, and the MFT superconducting material characteristics as well. During the search for the optimal splitting of the operative MFT-strip into parallel branches, corresponding to the maximum value of $F_m$ for a given configuration, we calculated the magnetic field in the MSE created by the superconducting currents in the branches of the operative MFT-strip, taking into consideration the non-uniform currents distribution. We considered only the component of the magnetic field parallel to the substrate plane since it has the most significant impact on the GMR MSE.

In the calculations, we used the following formulas:

$$B = \frac{\mu_0 \cdot I_s}{8\pi \cdot \lambda \cdot h} \cdot \left[ \int_{-\frac{h}{2}-l}^{0} \int_{-\frac{h}{2}}^{0} \frac{(y_0 - y) \cdot \exp(-\frac{x+l}{\lambda})}{(y_0 - y)^2 + (x_0 - x)^2} \, dx \, dy + \int_{-\frac{h}{2}-l}^{0} \int_{-\frac{h}{2}}^{0} \frac{+l (y_0 - y) \cdot \exp(-\frac{l-x}{\lambda})}{(y_0 - y)^2 + (x_0 - x)^2} \, dx \, dy \right],$$

$$F_m = \frac{<B>}{<B_0> - K_L^{-1}},$$

$$K_L = \frac{\sum_{i=1}^{n} L_i}{L} \approx \frac{\sum_{i=1}^{n} w_i}{n w_s},$$

where $l$ and $h$ are the half-width and half-thickness for the film of the operative MFT-strip, respectively; $\mu_0$ is the magnetic constant; $I_s/(2 \pi \cdot h) \leq J_c$ and $I_s$ are the screening superconducting current in the operative MFT-strip, flowing above the MSE and influencing it in the point $(x_0, y_0)$ (the reference point $(0, 0)$ is located in the center of the upper surface of the film); $J_c$ and $\lambda$ are the critical current density and London penetration depth for the MFT film material, respectively; $<B>$ and $<B_0>$ are the averaged values of the magnetic fields created by the operative MFT strip, for the structured operative MFT-strip and for the non-structured (no slits) operative MFT strip, respectively; $K_L$ – total inductance growth factor for the operative MFT strip; $L$ and $L_i$ are the inductance of the operative MFT-strip and its $i$-th branch, respectively; $n$ is the amount of the branches in the operative MFT-strip; and $w_s$ and $w_i$ are the width of the operative MFT-strip and its $i$-th branch, respectively.

3. Results

Here we present the results of calculations for a superconducting film MFT, which has the parameters: $J_c = 10^6 \, \text{A/cm}^2$, $\lambda = 50 \, \text{nm}$, $w_s = 7000 \, \text{nm}$ and $h = 75 \, \text{nm}$, and the minimum width of the slits $w_p = 175 \, \text{nm}$. Following the splitting of the operative MFT strip into parallel branches, we obtained the maximum value $F_m \approx 50$ for the optimal widths and topological location of the slits and branches in this sequence: $1050-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-175-350-175-150$. The widths of slits in nm are shown in bold italic, and the widths of the superconducting branches in nm are shown in capital letters.
Figure 3. Relationship $F_m(\lambda)$ if $w_p$ is: $\Box - 1400$ nm; $\Diamond - 700$ nm; $\Delta - 350$ nm; $\circ - 175$ nm.

Figure 3 illustrates the relationship of $F_m(\lambda)$ for varied values of the minimum width $w_p$ of the slits for the case of optimal splitting of the operative MFT-strip. Evidently the splitting leads to a significant increase in the gain factor – by more than one order of magnitude. Besides, in the range $w_p < 200$ nm the value of $F_m$ can reach several tens, while in the nano-sized range ($w_p \leq 100$ nm) – $F_m \geq 100$ for the LTS films, in particular, for niobium ($\lambda = 50$ nm). Although for the MFT based on the HTS film materials ($\lambda = 250$ nm) the increase of $F_m$ is less (~ 30), its efficiency remains significant. This tangible increase in $F_m$ is due to the fact that optimal splitting of the operative MFT-strip leads to a more uniform distribution of the screening current in it, and, hence, to the increased magnetic field concentration in MSE.

Authors of [8] proposed the MFS with the film HTS MFT made from the HTS material with the topologically nonstructured surface of the operative MFT strip (similar to figure 2, a), for which the resolution of the equivalent noise of $\sim 40$ fT/Hz$^{1/2}$ is attained. Applying our result to this MFS but having the topologically nanostructured surface of the operative MFT-strip (similar to figure 2, b), we found the improved resolution of up to $\sim 2$ fT/Hz$^{1/2}$ at $\lambda \sim 250$ nm and $F_m \sim 20$, which points to a considerable heightening of the sensor efficiency.

4. Summary

Thus, the topological nanostructuring of the operative strip of a superconducting film flux transformer increases its efficiency and improves important parameters of the magnetic field sensor.

It should be noted that the rise of the MFT efficiency due to its topological structuring in the submicron- and nanosized range can simplify the process of its manufacturing since the elements of MFT and MSE can be created using the same film HTS material. Nevertheless, MFT can be produced based on the films of Y-123 or Bi-2212 systems with high critical currents, while MSE can be produced on the basis of ceramic films with distinctive properties of the Josephson medium from systems [7] or Bi-2223 systems [8-10].

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