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A New Generation of the HTS Multilayer DC-SQUID Magnetometers and Gradiometers

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Abstract. We have optimized the preparation of submicrometer wide symmetric 20° bicrystal Josephson junctions on the basis of YBa₂Cu₃O₇₋ₓ (YBCO) films and integrated them in SQUID magnetometers and gradiometers with multilayer flux transformers. The achieved reduction of the curvature of the grain boundary leads to an improvement of the homogeneity of the current flow in the junction due to the d-wave symmetry of the order parameter in YBCO. The junctions have typical normal resistance $R_n$ above 10 $\Omega$ and a $I_cR_n$ product of about 0.4 mV at 77.4 K. The high resistance of the junctions has required an extensive use of low pass filters, rf-shields and microwave absorbers to protect the junctions from increased interference of high frequency electromagnetic fields. Integration of such junctions in SQUID magnetometers with a square 16-mm multilayer flux transformer allowed us for the first time to reach a field resolution of about 3.5 fT/Hz at frequencies above 10 Hz and about 7 fT/Hz at 1 Hz at an operation temperature of 77.4 K. SQUID gradiometers with a 10 mm base length of the planar multilayer flux transformer have achieved resolutions of about 15 fT/cmHz at frequencies above 10 Hz and about 30 fT/cmHz at 1 Hz and temperature 77.4 K.

1. Introduction
Sensitive SQUID-based magnetometers and gradiometers are required for many magnetic measurement applications in shielded and unshielded environment [1,2]. High-$T_c$ DC-SQUID magnetometers have achieved field resolutions better than 10 fT/Hz at an operation temperature of 77.4 K [3,4,5]. Such high-$T_c$ magnetometers can be combined in electronic gradiometer systems with gradient resolution $\sim$ 1 fT/cmHz at 77.4 K to obtain medically useful biomagnetic data in a clinical environment inside a standard magnetic shielded room having a shielding factor as low as $\sim$ 10 at 0.1 Hz (see, e.g., [6]). The remaining tasks are to increase the yield of the sensors and improve further their sensitivity and performance in unshielded magnetically and radio-frequency noisy environments. In this work, we present recent modifications in the Josephson junction technology, encapsulation, and matching circuitry of our high-$T_c$ DC-SQUID sensors, which significantly improved their overall operation properties.

2. Experimental
The best high-$T_c$ SQUIDs utilize bicrystal Josephson junctions because of their high resistance and largest $I_cR_n$ product [7,8]. One of the main obstacles limiting the reproducibility of the bicrystal junctions is the quality of the bicrystal grain boundary (GB) in the substrates. Even voids that are...
invisible in a transmission optical microscope can be present in the GB and prevent electrical contact between the electrodes in some parts of the GB in the superconducting film. To reduce the number of these and other defects in the GB and on other parts of the bicrystal substrate we have deposited a SrTiO₃ buffer layer ~ 300 nm thick prior to the deposition of the YBa₂Cu₃O₇₋ₓ (YBCO) film. TEM and AFM studies have shown that the microstructure of the SrTiO₃ films is better compared to the microstructural properties of the pristine substrates. Etching of the SrTiO₃ bicrystals buffered by SrTiO₃ films in HF acid revealed significantly improved quality of their surface: the etching rate decreased more than 2 times and less point defects were observed. Also the bicrystal grain boundary (GB) was much more resistant to the chemical etching in comparison with the GB in the pristine substrate.

The YBCO films were deposited with a high-oxygen-pressure dc-sputtering technique on symmetric 20° bicrystal SrTiO₃ substrates. These films have about 5 times larger grains and much less curvature of the grain boundaries compared to the films prepared by other deposition methods. The reduction of the voids and other surface defects has also reduced the meandering of the GB in the YBCO film. In particular the reduction of the curvature of the grain boundary [9] has lead to an improvement of the homogeneity of the current flow in the junction due to the d-wave symmetry of the order parameter in YBCO [10]. The use of symmetric 20° bicrystal SrTiO₃ substrates also resulted in an increase of the IₘRₙ product of the junctions compared to ones having larger misorientation angles [8] but has required a submicrometer width of the junctions. The normal resistance Rₙ of the junctions was ~ 10 Ω and an IₘRₙ product ~ 0.4 mV was measured for the junctions at 77.4 K. Reduction of the temperature down to the melting point of nitrogen ~ 63 K has resulted in an increase of Iₘ in about 3 times and the IₘRₙ product up to ~ 1 mV, but often has lead to nearly hysteretic current-voltage characteristics corresponding to the Steward-McCumber parameter βₐ = 2πIₘRₙ²C/Φ₀ ~ 1, where C ~ 20 fF is the capacitance of the junctions in agreement with [11].

The Josephson junctions are sensitive to electromagnetic radiation up to THz frequencies [12] and this feature can severely degrade properties of the DC-SQUIDs [13]. One needs to shield the SQUID sensors from all frequencies above the modulation frequency (~ 1 MHz) up to the THz region. This is especially important for the high-resistance (≥ 10 Ω) bicrystal junctions because of their better coupling to the vacuum impedance (377 Ω). The high resistance of the junctions has required an extensive use of low pass filters, rf-shields and microwave absorbers to protect the junctions from increased interference by high frequency electromagnetic fields. The parasitic electromagnetic signals can reach the SQUID directly through the cryostat or via the wires. We have found that it is advantageous to surround the SQUID magnetometer with a grounded conductive non-magnetic microwave absorber and to introduce low-pass filters (τ ~ 1 μs) on the electrical inputs for the heater and modulation-feedback coil (see Fig.1). The estimated Nyquist noise of the microwave absorber was ~ 1 fT/√Hz and the cut-off frequency was ~ 10 GHz at 77.4 K. We also successfully applied similar circuitry and packaging to the flip-chip gradiometers.

![Fig.1. Schematic representation of an encapsulated flip-chip SQUID magnetometer with filtered inputs for the heater and modulation coil.](image)
The junctions were integrated in SQUID magnetometers and gradiometers with multilayer flux transformers similar to ones described in [4]. The best 8-mm magnetometer ($\partial B / \partial \Phi \sim 1 \text{nT}/\Phi_0$) has reached the white noise level $\sim 15 \text{fT}/\text{Hz}$ and $\sim 35 \text{fT}/\text{Hz}$ at 1 Hz (see Fig.2). Outside shields these magnetometers had operated without suppression of the bias current nor the SQUID signal modulation amplitude. The white noise level remained unchanged, while the spectrum at low frequencies represents the environmental noise. Decrease of the operation temperature down to $\sim 63 \text{K}$ has sometimes resulted in about 2 times reduction of the magnetometer noise.

Integration of such junctions in SQUID magnetometers with a square 16-mm multilayer flux transformer ($\partial B / \partial \Phi \sim 0.5 \text{nT}/\Phi_0$) has, for the first time, allowed to reach a field resolution of $\sim 3.5 \text{fT}/\text{Hz}$ at the white noise frequencies above 10 Hz and $\sim 7 \text{fT}/\text{Hz}$ at 1 Hz and operation temperature 77.4 K (see Fig.3). The measurements of the intrinsic noise of the magnetometers were performed inside a 3-layer $\mu$-metal shield and a YBCO superconducting shield [14].

![Fig.2. Noise spectrum of 8-mm magnetometer.](image)

![Fig.3. Noise spectrum of 16-mm magnetometer.](image)

For the unshielded operation in noisy environment it is more practical to use hardware gradiometers. A photograph of our best type of the planar gradiometers produced with the above mentioned modifications in technology is shown encapsulated in the Fig.4. This HTG-10N gradiometer has a base length $L \sim 10 \text{mm}$ of the planar multilayer flux transformer ($\partial B / L \partial \Phi \sim 1.5 \text{nT}/\text{cm}\Phi_0$) and had achieved the gradient resolutions $\sim 15 \text{fT}/\text{cm}/\text{Hz}$ at frequencies above 10 Hz and $\sim 30 \text{fT}/\text{cm}/\text{Hz}$ at 1 Hz and the operation temperature 77.4 K (see Fig.5).

![Fig.4. Photograph of the encapsulated HTG-10N gradiometer.](image)

![Fig.5. Noise spectrum of a HTG-10N gradiometer.](image)
3. Discussion
The buffering of the bicrystals by SrTiO$_3$ has significantly reduced the number of structural defects on the substrate surface like screw dislocations and voids in the GB compared to the microstructure of the pristine bicrystal substrate. This has reduced meandering of the GB in the YBCO film and contributed to a better reproducibility and parameters of the Josephson junctions and DC-SQUIDs. Also the use of lower misorientation angle bicrystals and submicrometer junctions helped to achieve a higher $I_cR_n$ products and SQUID signal modulation amplitude. Further reduction of the temperature down to $\sim 63 \text{ K}$ improves noise of the sensors for relatively low resistance junctions with $\beta_c < 1$ at this temperature.

The extensive use of the low-pass filters, low conductivity rf-shields, and microwave absorbers had helped to avoid the degradation of the parameters of the Josephson junctions by parasitic electromagnetic interference in noisy environment and provided a reliable operation of the SQUID sensors inside different measurement systems.

The modifications of the Josephson junction technology and installation of the filters and shields in the encapsulation had together helped to improve further the resolution of the SQUID sensors.

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