High-T_c SQUID magnetometers with submicrometer bicrystal junctions for information technology.

INTRODUCTION

SQUID magnetometers have an ultimate combination of field and spatial resolution. Unsurpassed magnetic field sensitivity (see Fig. 1) and wide bandwidth of the SQUID sensors allows to create a large variety of measurement systems with unique resolution for different applications in non-destructive evaluation (*e.g.*, test of materials and integrated circuits) and biomagnetism (*e.g.*, magnetocardiography, magnetoencephalography, and other kinds of propagation of signals in neurone networks).

The high-T_c SQUID sensors, developed and produced in the Institut für Festkörperforschung (IFF) Forschungszentrum Jülich GmbH (FZJ) and distributed via Technologie-Transfer-Büro FZJ, show the world best sensitivity at the moment [1] and have already found many applications in scientific laboratories around the world. For example, a non-contact evaluation of 2D distribution of a photo-induced magnetic field from p-n junctions in semiconductor devices and wafers using a laser SQUID microscope was performed first time in Japan with such SQUID sensors [2]. Another example of a SQUID measurement system is a SQUID microscope, which can be used, *e.g.*, in failure analysis, yield, reliability, and design verification to identify critical defects in high density multilayer printed boards, multilayer structures for magnetoelectronics, multi-chip module substrates, in semiconductor packages, wafers, and processes [3].

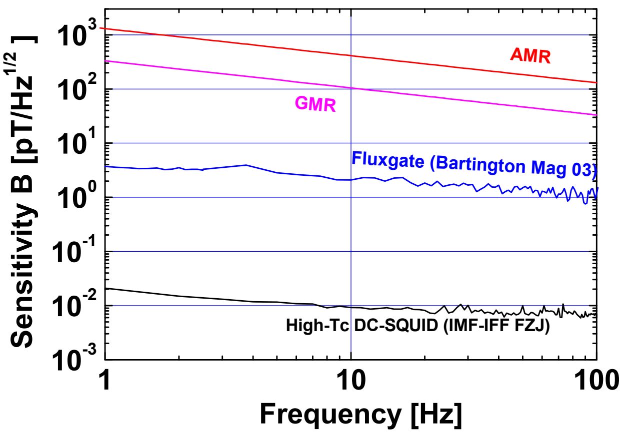


Fig.1. Comparison of the sensitivities of the high-T_c SQUIDs with conventional magnetometers.

Development and characterization of custom high-T_c SQUID sensors and SQUID-based measurement systems (*e.g.*, SQUID microscope) occurs in cooperation with Zentrallabor für Elektronik FZJ (E.Zimmermann, W.Glaas, H.Halling) as well as with international partners like Tristan Technologies Inc. (San Diego, CA, U.S.A.) and the Institute of Radio Engineering & Electronics of Russian Academy of Science (Moscow, Russia).

APPROACH

A demand to improve further the parameters of high-T_c SQUIDs has determined the present trend of reducing the width of the used Josephson junctions to a submicrometer scale [4]. To obtain the best field sensitivity of the SQUID sensors multiturn flux transformers are necessary, requiring a high quality multilayer high-T_c technology. Different SQUID microscope systems incorporating the developed SQUID sensors were found to be adequate for many information technology applications.

RESULTS

Submicrometer bicrystal junctions

The present 24^o bicrystal Josephson junctions (see Fig. 2) have a width between 0.4 μm and 1 μm, and a critical current density of about 2×10^4 A/cm^2 at 77.4 K. The junctions are prepared by optimized conventional photolithography and an Ar ion milling. Some inclusions of secondary phases serve as effective flux pinning centers in the high-T_c films.

It is important to achieve the highest possible microstructural quality of the high-T_c films and Josephson junctions. The average size of the growth spirals of the $YBa_2Cu_30_{7-x}$ films, deposited by the high-oxygen-pressure dc-sputtering technique, is about 1 μm compared to the about 0.3 μm grains of conventional laser-ablated films. By preparation of submicrometer Josephson junctions with sputtered films one can produce the junctions between individual growth spirals. This improves the homogeneity and increases the tunneling part of the critical current density of the Josephson junctions.

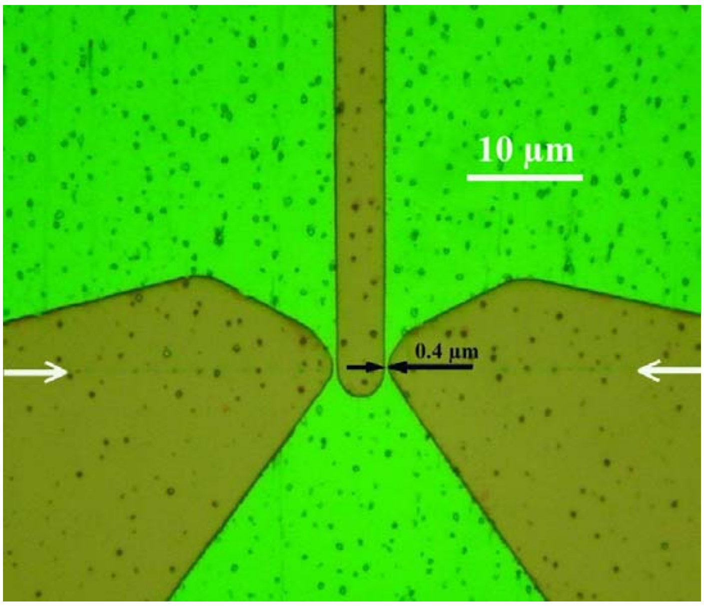


Fig.2. Optical image of the bicrystal junctions, obtained in a combination of transmission and reflective illumination. A magnification of x1000 and a green filter were used. The white arrows indicate the position of the bicrystal boundary. The black arrows determine the width of the 0.4 μm wide junction.

Multilayer high-T_c technology

The investigation of epitaxial heterostructures, like multilayer Josephson junctions, crossovers, and vias, helps to obtain the best field resolution of the sensors. Multilayer flux transformers are prepared by a technique developed in IFF FZJ using a $PrBa_2Cu_30_{7-x}$ insulation layer between the windings of the multi-turn input coil and the return strip. PMMA-photoresist and Br-ethanol chemical etching are used for surface-damage-free patterning of bottom layers.

The dynamic range of the sensitive magnetometers is mainly limited by the critical current of the flux transformer. Due to the damage-free interfaces and gently sloping edges produces by the Br-ethanol etching we have achieved a critical current for the transformer inner coil of about 100 mA at 77.4 K. The corresponding dynamic range of the magnetometer is about 60 μT (peak-to-peak), which allows sensitive measurements also after a movement of the magnetometers in earth's field. The vacuum-tight sealing in fiberglass epoxy encapsulations (see Fig.3 left) ensures the long-term stability of the sensors during multiple thermal cyclings between the storage (300 K) and operation (77.4 K) temperatures.

The development and optimization of HTS structures is very effective by incorporating them in a bio-magnetic measurement system, because it requires an ultimate combination of field- and spatial resolution achievable exclusively with SQUID sensors. The shown in Fig.3 (right part) test magnetocardiogramm (MCG) was measured under clinical conditions with a volunteer having reduced peak-to-peak amplitude of the magnetic signal of heart. The obtained with the high-T_c system field resolution is similar to the resolution of a standard low-T_c system. But the high-T_c system has at least an advantage of a more than 5 times longer cryogen hold time due to the possibility to use liquid nitrogen instead of liquid helium.

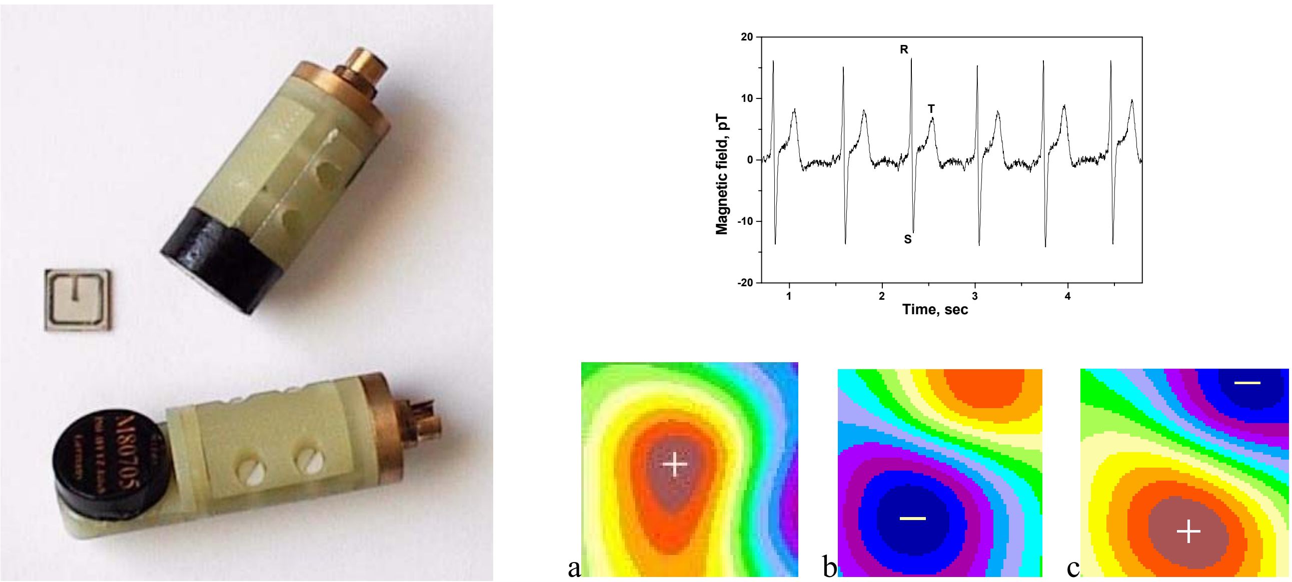


Fig.3. Multilayer flux transformer on 10 mm x 10 mm $SrTiO_3$ substrate and encapsulated dc-SQUID magnetometers (left). Shown on the right side are real-time magnetocardiogramm, obtained by an electronic gradiometer under clinical conditions, and the corresponding magnetic field distribution over the scan area at the moments of the (a) R-, (b) S- and (c) T-peaks of the heart beat.

SQUID microscope

The development of the SQUID systems in Jülich has achieved a level, which allows their application in laboratory prototypes [5]. A limited test production and characterization of custom high-T_c SQUID sensors and SQUID-based measurement systems is a significant part of the development process.

Compared to other magnetic evaluation methods for microscopic objects the scanning SQUID microscope has higher magnetic field sensitivity and a high linearity over a dynamic range up to about 200 dB. Different SQUID microscope measurement systems are presently under study in IFF FZJ. The goal of this research activity is a creation of a new generation of the high-T_c SQUID microscopes with an improved spatial resolution (< 1 µm) and sensitivity for room temperature samples.

Minimizing SQUID–sample separation for a better field- and spatial resolution becomes a problem for room temperature objects, which are placed outside the cryostat. The typical separation between the SQUID sensor tip (like one presented in Fig.4) and the room temperature sample is about 100 µm. This relatively large distance limits the space resolution of such type of SQUID microscopes to about 50 µm. Examples are commercially available scanning SQUID microscopes of U.S. firms Tristan Technologies Inc. and Neocera [3], which are already used for low spatial resolution failure analysis of multi-chip modules and other semiconductor packaging.

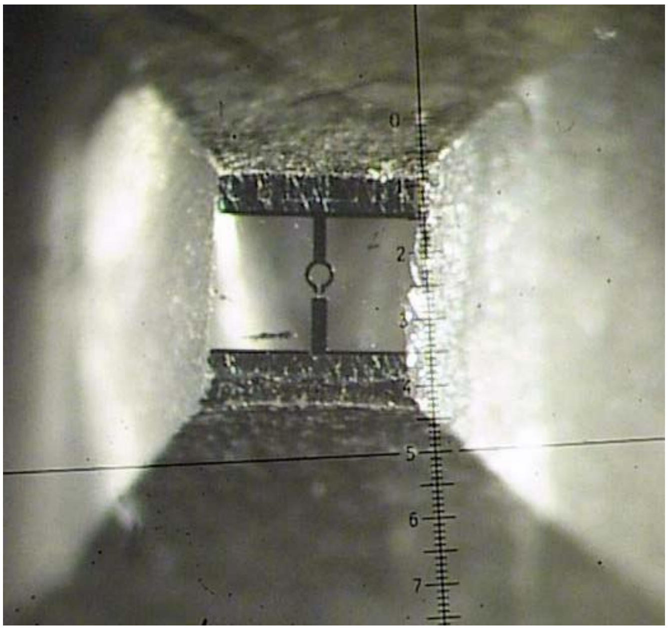
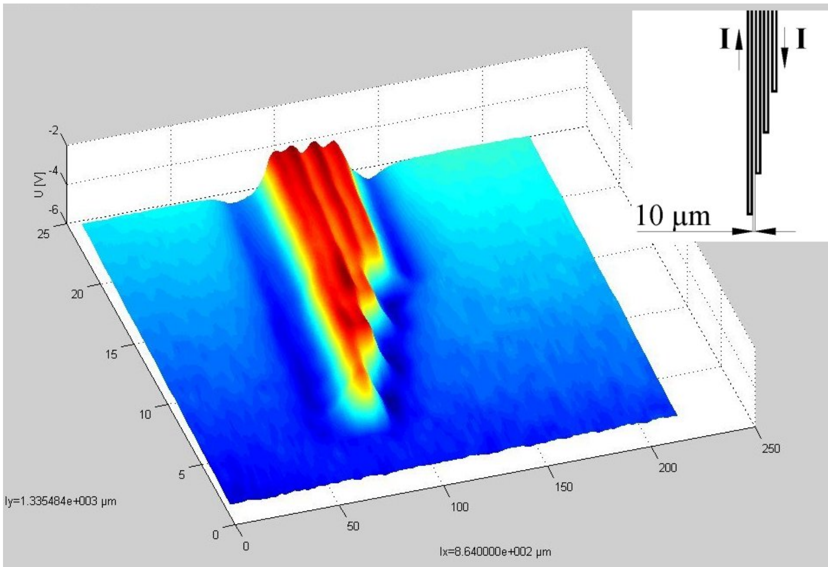
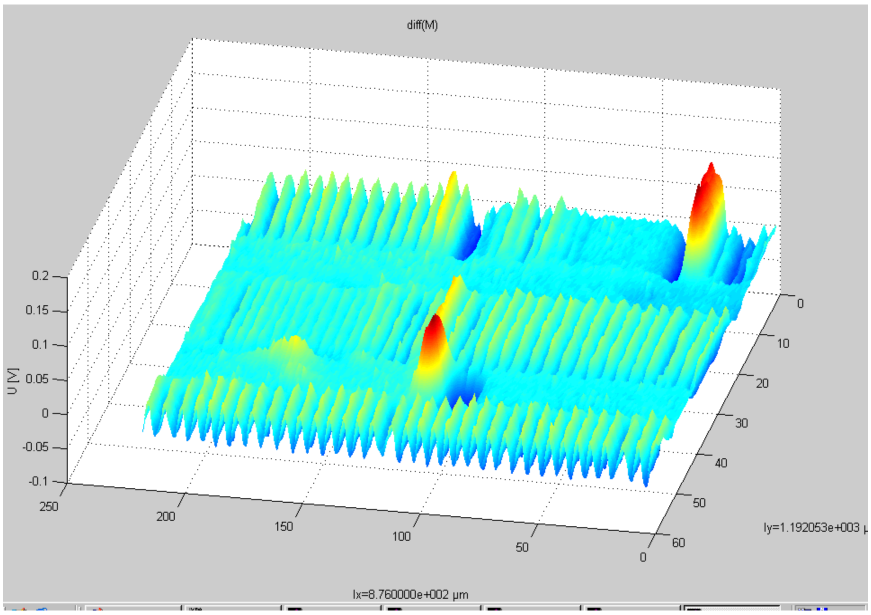


Fig.4. Optical image of the SQUID sensor tip. The diameter of the SQUID loop is 50 µm. The developed and produced in IFF/IMF SQUID sensor was used in commercial SQUID microscope of Tristan Technologies Inc.

Application of specially designed magnetic flux conductors can help to improve the space resolution to submicrometer values. Such development is currently under way in the IFF/IMF together with the Zentrallabor für Elektronik (ZEL). First examples of such sensors with soft magnetic flux guides, which demonstrate significantly improved spatial resolution are shown in Fig.5. The spatial resolution of SQUID microscopy for room temperature samples already could be enhanced by a factor of about 10 compared to existing state of the art magnetic microscopes without magnetic flux guides. Presently we are working on a further improvement of the sensitivity of such instrument. An optimized coupling of the magnetic flux to the SQUID can significantly enhance the sensitivity, which is very important for measuring speed in failure analysis of low level current distributions.



a.



b.

Fig.5. An example of the measurements of a 2D distribution of magnetic field above a thin-film current-carrying meander, which has 10 µm wide lines separated at 10 µm distance from each other (a) and of magnetic field above a floppy disk (b). Both objects were placed at room temperature outside cryostat. The measurements were performed with a SQUID microscope, developed by IFF and ZEL FZJ.

References

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