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REGULAR PAPER

Development of planar first order gradiometer coupled to HTS SQUID sensor

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Abstract
HTS SQUID sensors coupled to an on-chip integrated planar gradiometric pick-up loop were fabricated using highly reliable advanced micro-fabrication techniques such as: deposition of superconducting thin films by Pulsed Laser Deposition (PLD), UV photolithography and RF ion beam etching. It may be noted that the use of wire wound gradiometers and approaches based on an electronic subtraction of sensor outputs to realize synthetic gradiometers have not been entirely satisfactory. We have designed a first order planar gradiometer with two planar loops in opposition with the Josephson weak links in the form of microbridges located at the centre. Bicrystal $SrTiO_3$ substrates with a 24° misorientation angle were used for realizing the Josephson weak links using YBCO thin films, as well as HTS planar gradiometer coupled to an HTS SQUID sensor. The performance of these devices were evaluated.

1 Introduction

The Superconducting Quantum Interference Device (SQUID) using High Temperature Superconductors (HTS) is a promising sensor for the detection of extremely small changes in magnetic fields (in the range of fT to pT). SQUID sensors have been used in several exciting applications such as: recording of Magnetocardiogram (MCG) of human heart [Clarke & Braginski, 2004; Janawadkar *et al*. 2010; Hong-Chang *et al*. 2006], exploration of mineral resources by Time Domain Electromagnetic Method (TDEM) etc [Hato *et al*. 2013] and in Non Destructive Evaluation (NDE) of materials [Wikswo, 1996; Nagendran *et al*. 2007]. Since SQUID sensors are extremely sensitive to small changes in magnetic fields, some of the challenging applications of these sensors require the use of expensive magnetically shielded rooms. An alternative strategy to suppress magnetic noise due to distant sources is to use superconducting pick-up loops in the form of axial or planar gradiometers [Faley *et al*. 2002] to couple the signal of interest to SQUID sensor. So, for practical applications of HTS-SQUID in harsh environments in laboratory and at field sites, where the use of magnetically shielded room is not practical, the development of gradiometer based HTS SQUID [Borgmann *et al*. 1999] devices is essential. Compared to LTS SQUID [Janawadkar *et al*. 1999] sensors based on niobium, which require liquid helium temperatures for their operation, the use of HTS SQUID sensors has certain advantages such as: less stringent requirements on thermal isolation of the sensor, simpler cooling system and the possibility of minimizing the distance between the sensor at low temperatures to the actual specimen under investigation at room temperature. This paper reports the design and development of

HTS SQUID and first order gradiometer coupled to HTS SQUID sensor at Indira Gandhi Center for Atomic Research (IGCAR), Kalpakkam using highly reliable advanced micro-fabrication techniques such as: deposition of superconducting thin films by Pulsed Laser Deposition (PLD), UV photolithography and RF ion beam etching.

2 Fabrication of HTS SQUIDS and first order gradiometer SQUIDS

The detailed procedure used for the fabrication of HTS SQUID sensors on bicrystal $SrTiO_3$ (STO) substrates is described elsewhere [Vaidhyanathan *et al*. 2011]. Briefly, pulsed laser deposition process was standardized to yield high quality YBCO thin films with superconducting transition temperature (T_c) above 90 K and high J_c of ~10^6 A/cm^2. These high quality thin films were used for the fabrication of HTS SQUID sensors by photolithography and RF ion beam etching.

Bicrystal $SrTiO_3$ substrates with a 24° misorientation angle and step edge defined substrates on MgO and $SrTiO_3$ (STO) are the two kinds of substrates that are being used to fabricate HTS SQUID devices. Step edges were fabricated on the substrates by two different methods. Formation of step edge over MgO or STO substrates involves, deposition of Cr film by RF sputtering over photolithographically defined lift-off pattern and etching it at an angle of 60° by RF ion beam etching so that step heights of 150 to 250 nm could be realized. A thumb rule for fabricating high quality step angle is to use hard protecting mask with sharp profiles. Another method for creating step edge is to use photoresist AZ 5214 as the masking layer and define the step edge pattern by UV photolithography. The patterned photoresist mask was hard baked at 125°C in an oven for 1 h 30 min to reduce milling rate of the masking layer in the subsequent RF ion beam etching.

Ion beam etching involves using a 4 cm broad RF ion source to direct a stream of Argon ions to the surface of the substrate for etching. A three step etching process was adopted by varying RF power from an initial high value (68 W) to get smooth etching parameters which, could be confirmed using DEKTAK surface profile measurement system. RF power was kept at 68 W, gas pressure in the chamber was adjusted and dc accelerating voltage was kept at 300 V to get a stable plasma, which would strike the substrate. Step heights of 200 nm were realized and these substrates with step edges were used for producing HTS SQUID devices.

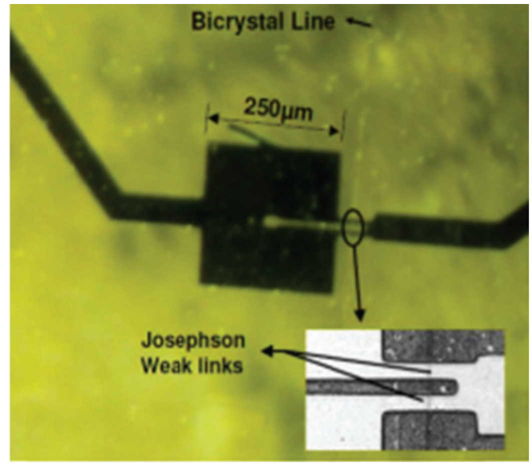

Figure 1. Type A SQUID fabricated on a bicrystal STO substrate.

Ten micron wide microbridges crossing either the bicrystal boundary in the case of bicrystal STO substrates or step edge substrates were used as the Josephson weak links. In the type A SQUID design, the Josephson weak links were placed outside the washer. SQUID had an inner sensing area of 25 μm × 25 μm and an outer superconducting washer with an area of 250 μm × 250 μm. Figure 1 shows Type A SQUID fabricated on a bicrystal STO substrate, and Figure 2 shows the photograph of Type A HTS SQUID with step edge line.

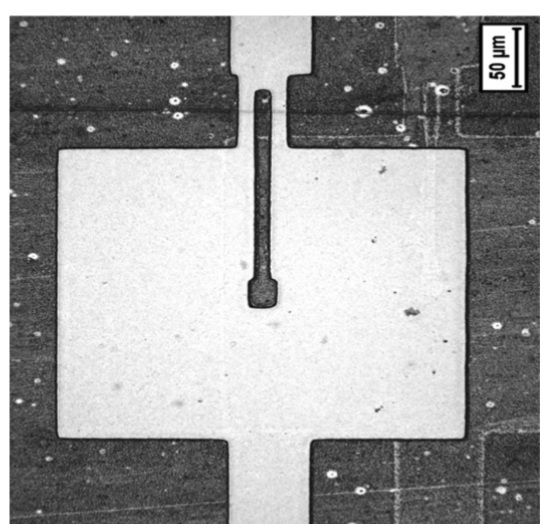

Figure 2. Photograph of Type A HTS SQUID with step edge line.

HTS SQUID sensors were mounted at the end of a dip-stick with the device surrounded by several layers of µ metal and a superconducting tube to provide the necessary magnetic shielding. Current voltage characteristic showed a behavior similar to that expected for a Resistively Shunted Josephson Junction (RSJ). Magnetic flux was coupled into the sensing area of SQUID using an external wire-wound field coil. AC current at relatively low frequencies were passed through the field coil, and voltage across HTS SQUID sensor was monitored as a function of time, which reflects V-Φ characteristic of SQUID sensor (Figure 3). Modulation depth was measured at various applied DC bias currents. Modulation depth was found to rise smoothly as DC bias current was increased upto the optimal value, at which a maximum modulation depth of ~180 µV was measured.

In order to use HTS SQUID sensors for practical applications, efforts were focused on the fabrication of an on-chip planar gradiometric pick-up loop coupled to HTS SQUID sensor. We have designed a thin film first order planar gradiometer with two planar loops in opposition with the Josephson weak links in the form of microbridges located at the centre.

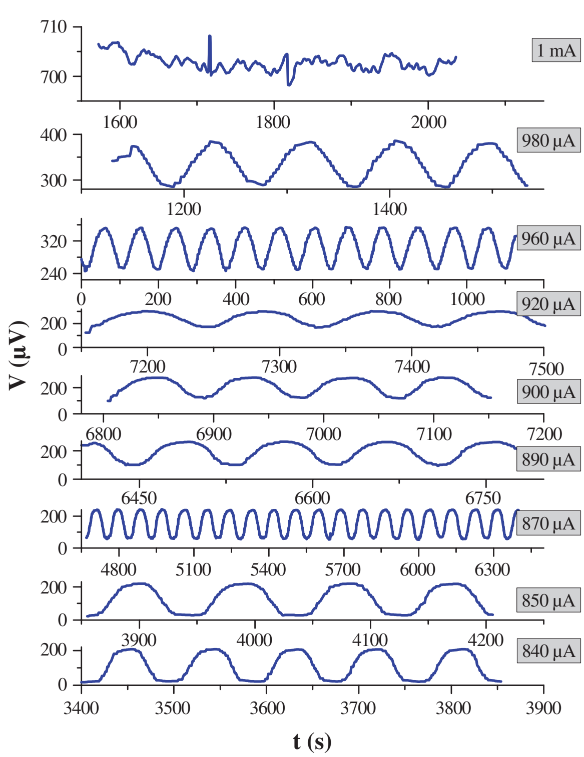

Figure 3. V-Φ characteristic of SQUID at 4.2 K for various applied DC bias currents.

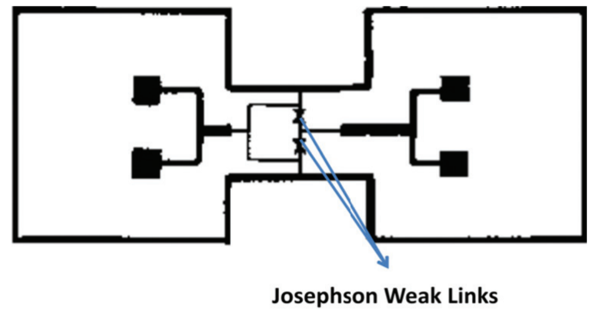

Figure 4. Schematic of an HTS first order planar gradiometer coupled to a SQUID.

The schematic of HTS first order planar gradiometer is shown in Figure 4.

Bicrystal $SrTiO_3$ substrates with a 24° misorientation angle were used for realizing the Josephson weak links using YBCO thin films, as well as HTS planar gradiometer coupled to an HTSC SQUID sensor.

The two pick-up loops in opposition constituting the planar gradiometer located on either side of SQUID device, had a line-width of 1 mm and an inner diameter of about 4 mm. All the necessary photomasks were designed and fabricated in-house. Using photolithography and three step etching process, the device geometries were patterned. The procedures yielded sharp definition of HTS planar gradiometers on 10 mm × 10 mm $SrTiO_3$ bicrystal substrates. Figure 5 shows the optical micrograph depicting the gradiometric loops and HTS SQUID geometry with contact pads; SEM image shows the bicrystal line of HTS SQUID.

SQUID sensor coupled to a planar first order gradiometer was mounted at the end of a

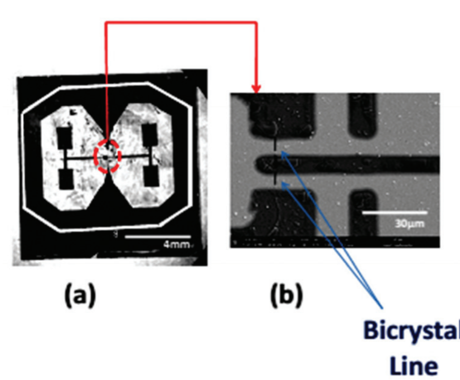

Figure 5. (**a**) Optical micrograph showing gradiometric loops and HTS SQUID geometry with contact pads. (**b**) SEM image showing the bicrystal line of HTS SQUID.

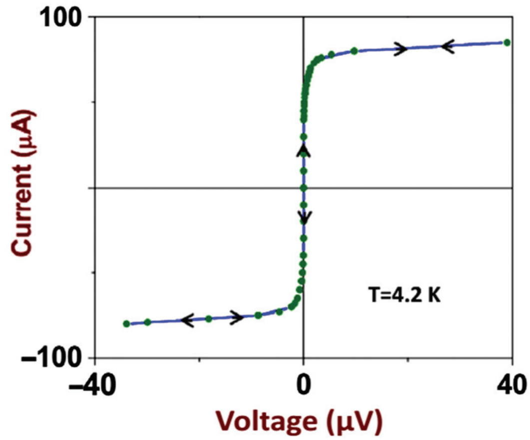

Figure 6. I–V characteristics showing RSJ like behaviour.

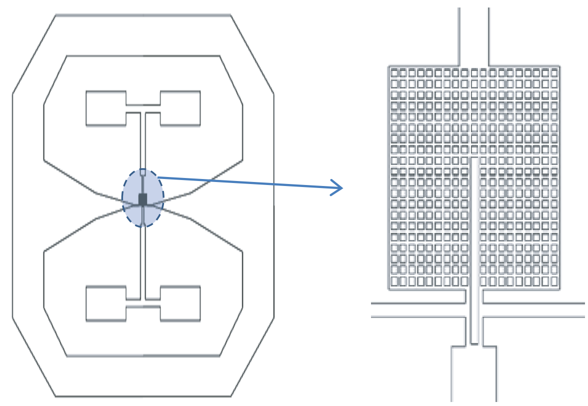

Figure 8. The schematic diagram of first order gradiometer coupled to HTS SQUID with a slotted design flux dam.

dip-stick, and the measured I–V characteristics showed Resistively Shunted Junction (RSJ) like behaviour (Figure 6).

Magnetic flux was coupled into the sensing area of SQUID using an external wire-wound coil. V-Φ characteristic showed that voltage across the device was a periodic function of applied flux with the periodicity of a flux quantum Φ_0.

Modulation depth was measured at various applied bias currents and a maximum modulation depth of 11.2 µV has been measured (Figure 7) at an applied bias current of 105 µA.

HTS SQUIDs have higher intrinsic noise in comparison to low T_c SQUIDs because of higher operating temperature. It is well known

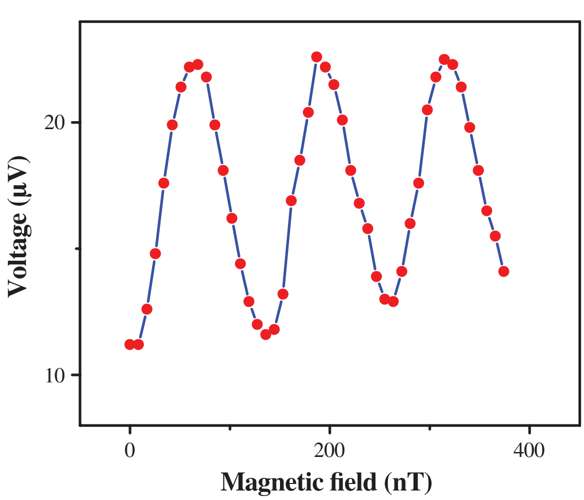

Figure 7. V-Φ characteristic indicates that output voltage across SQUID is a periodic function of applied flux with the periodicity of a flux quantum Φ_0.

that thermally activated vortex motion in superconducting thin films contribute to low frequency noise, and this problem especially manifests when SQUIDs are operated in an unshielded environment. Therefore, it is essential to eliminate the 1/f noise by designing HTS SQUIDs in a manner such that motion of flux vortices are restricted. The concept of flux dam [Oyama *et al*. 2001], is widely used in HTS SQUIDs to reduce flux trapping in thin films. The noise reduction technique in first order planar gradiometer can in principle be further enhanced by incorporating the slotted design to it. Clem [1996], has shown that it is energetically unfavourable for flux to penetrate into a film of width w provided $w \leq (\pi\phi_0/4B_0)^{1/2}$; where, B_0 is the perpendicular field applied on the film. Taking this into account, a slotted on-chip input coil has been designed for effective flux coupling and arresting the motion of vortices, which will reduce noise. The schematic diagram of first order gradiometer coupled to HTS SQUID with a slotted design flux dam is shown in Figure 8. It consists of 216 number of slots of 4 µm area each with an inter-spacing of 8 µm. A mask is made based on the above design, and further work is underway to characterize these devices to study the noise characteristics.

3 Conclusions

HTS SQUID sensors and HTS SQUID coupled to an on-chip integrated planar gradiometric pick-up loop were fabricated with YBCO thin films on bicrystal $SrTiO_3$ substrates using highly reliable advanced micro-fabrication techniques. The two pick-up loops in opposition constituting the planar gradiometer, located on either side of SQUID device, had a line-width of 1 mm and an inner diameter of about 4 mm. The various procedures adopted yielded sharp definition of HTS planar gradiometers on 10 mm × 10 mm $SrTiO_3$ bicrystal substrates. Modulation depth was measured at various applied bias currents and a maximum modulation depth of 11.2 μV has been measured. A slotted on-chip input coil has been designed for effective flux coupling, and further work is underway to characterize these devices to study the noise characteristics.

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He has also worked in the area of modelling and inverse problems in the context of Non-Destructive Evaluation of materials and Magnetoencephalography. He has several research publications in national and international journals to his credit. He has been jointly awarded S. N.Seshadri memorial award-2002 by Indian Physics Association. He is also a recipient of. Group Achievement award-2011 of DAE for the team work on "Indigenous repair and servicing of HPGe detectors".

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