Magnetic Field Behavior of YBCO step-edge Josephson junctions in rf-washer SQUIDs

M. Bick, J. Schubert, M. Fardmanesh, G. Panaitov, M. Banzet, W. Zander, Y. Zhang and H.-J. Krause

Abstract—**The suppression of the critical current in YBCO Josephson junctions by the Earth's magnetic field strongly affects the operation of SQUIDs outside magnetic shielding. Commonly, one observes a modulation of the SQUID flux-voltage transfer function amplitude, $V_{sq\text{-}pp}$, with a period of $\Delta B_{0\text{-}V}$ leading to an increased white flux noise level or unstable SQUID operation. Here, we report on the investigation of $\Delta B_{0\text{-}V}$ of rf-SQUID sensors based on step edge junctions (SEJ) operated in a flip chip configuration with coplanar resonators with integrated flux concentrators. To investigate the origin of the suppression of $V_{sq\text{-}pp}$, we opened the SQUID loop of some samples and measured the magnetic field dependence of the critical current $I_c(B)$ directly and compared it to $V_{sq\text{-}pp}(B)$. It is shown that a junction width in the submicrometer scale is required for operation of the sensors in the Earth's magnetic field.**

Index Terms—**Magnetic field dependence, rf-SQUID, SEJ**

I. INTRODUCTION

MANY SQUID applications require stable sensor operation in unshielded environments. This is especially important for SQUID devices opposed to magnetic field variations of up to 50 μT in the Earth's magnetic field which may result in an increased white noise level due to Josephson vortex penetration into the junction [1]-[3]. In the extreme case, the sensors cannot be operated in flux locked loop mode. This is due to an external magnetic field B, causing flux penetration into the junction area modulating the critical current, I_c. This modulation follows a Fraunhofer-like pattern $I_c(B)$ with a field period of ΔB_0 depending on the width of the junction [4],[5].

To obtain SQUIDs for stable operation in a given magnetic field, it is important to determine the range of the required junction width w. For planar junctions, flux focussing effects of the superconducting electrodes lead to a $1/w^2$ dependence of ΔB_0 [6]. For thick planar devices ($wt \gg \lambda_L^2$, thick film limit), due to strong demagnetization effects, $\Delta B_0 = \phi_0 t/(1.2w^2 2\lambda_L)$ is predicted where t denotes the film thickness and λ_L is the London penetration depth. For thin films, the magnetic field penetrates the film almost uniformly and the Meissner screening currents are neglected. The equation $\Delta B_0 = 1.84\phi_0/w^2$ has been derived for planar grain boundary junctions (GBJ) [6] and verified for SEJs [7],[8]. These formulae only apply to isolated junctions. In the case of washer-SQUIDs, additional flux focussing areas have to be taken into account when calculating ΔB_0. Assuming a homogeneous field distribution in the inner square hole of dimension, d, of an rf washer SQUID with an effective area, A_{eff}, the magnetic field at the first critical current minimum is:

$$\Delta B_0 = 1.84\ \phi_0\, d^2 / (w^2 A_{eff}) \tag{1}$$

in the thin film limit and in accordance to [3]. The corresponding expression for the thick film limit is:

$$\Delta B_0 = \phi_0\, t\, d^2 / (1.2 w^2\, 2\lambda_L\, A_{eff}). \tag{2}$$

By using (1) or (2), the optimum junction width for stable operation of SQUIDs in external magnetic fields, $B \ll \Delta B_0$, can be calculated. Larger effective areas of highly sensitive sensors will automatically lead to smaller field periods, ΔB_0. Therefore, to achieve stable operation in magnetic fields, the junction width has to be small [2],[3].

The stability of the amplitude of the flux-voltage transfer function, $V_{sq\text{-}pp}$, is the direct criterion for stable SQUID operation. A suppression of I_c leads to a reduction of the parameter $\beta_L = 2\pi L I_c/\phi_0$ (rf-SQUIDs), where L is the SQUID inductance. $V_{sq\text{-}pp}$ has a maximum at about $\beta_L = 1$ and for smaller values, $V_{sq\text{-}pp}(\beta_L)$ is monotonically decreasing [9]. Therefore, in the case of $\beta_L \sim 1$, a suppression of I_c should also lead to a suppression of $V_{sq\text{-}pp}$. However, for a reliable calculation of the optimum junction width using (1) or (2), the correlation between the field period of the critical current, ΔB_0, and the field period of the flux-voltage transfer function, $\Delta B_{0\text{-}V}$, has to be known. To our knowledge, this correlation has not been investigated before in detail for SEJ rf-washer SQUIDs.

In this paper, we report experimental investigations on the influence of external magnetic fields on $V_{sq\text{-}pp}$ depending on the junction width of SEJ rf-washer SQUIDs. The width dependence of $\Delta B_{0\text{-}V}$ is compared to different model predictions. Finally, the suppression of I_c will be correlated to the suppression of $V_{sq\text{-}pp}$ by direct measurements of I_c, β_L, and $I_c(B)$ using samples with opened SQUID loops.

II. SAMPLE PREPARATION AND MEASUREMENT SETUP

Washer-rf-SQUIDs based on step-edge junctions using YBCO films with t=200 nm were fabricated on $LaAlO_3$

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substrates with the pulsed laser deposition technique [10]. With a 3.5 mm washer diameter, the magnetometers have a loop of 150x150 μm^2 (L~225 pH) and an effective area of ~0.31 mm^2. Using conventional photolithography and wet chemical [11] or ion beam etching processes, junction widths of 3 μm down to the submicrometer scale were fabricated. The sensors showed a typical magnetic flux noise between 35 and 15 $\mu\phi_0/\sqrt{Hz}$ in the white noise regime. To investigate the period of the magnetic field dependence $\Delta B_{0\text{-}V}$ of the SQUIDs, $V_{sq\text{-}pp}$ was measured at the output of the SQUID readout electronics as a function of an external magnetic field applied to the zero field cooled (ZFC) SQUIDs at 77K. The field was produced by a calibrated solenoid. To check the influence of different effective sensor areas on the parameter $\Delta B_{0\text{-}V}$, the SQUIDs were also operated in flip chip configuration with two different coplanar resonators with integrated flux concentrators [12], with either a 8 mm rectangular (SR8) or a 13.4 mm circular (SR13) shape. Investigating the dependence of $\Delta B_{0\text{-}V}$ on w, 24 SQUIDs with different junction widths were characterized with the same setup. All measurements were performed inside a 3-layer mu-metal shield.

To find the correlation between the field dependence of the critical current and the flux-voltage transfer function, $I_c(B)$ and $V_{sq\text{-}pp}(B)$, respectively, four-probe current-voltage (I-V) measurements on 3 of the 24 already characterized SQUIDs were performed. For this purpose, the SQUID washers were opened mechanically with a diamond cutter. In order not to change the junction properties, processes like photolithography to open the loop and gold evaporation of contact pads were avoided. Instead, gold wires were bonded directly onto the YBCO surface yielding contact resistances of <5 Ω at 77 K. To check the stability of the junction properties, one sample was bonded but only partly scratched without opening the loop. Measurements of flux noise and $\Delta B_{0\text{-}V}$ showed no difference before and after this process. The ZFC SQUID samples with opened loops were characterized in a mu-metal shield with a setup allowing measurements at temperatures down to about 5 K. $I_c(B)$ was measured in a magnetic field normal to the film surface using a 30 μV criterion. To determine I_c and β_L in the presence of large thermal fluctuations ($\Gamma>1$) at T=77 K, measurements of the differential resistance, $R_d=dV/dI$, were performed with standard lock-in technique. As described in [13], I_c can be derived from the analytic expression of the normalized differential resistance $r_d(i)=1-\{1/[2(i^2+\Gamma^2)] - i^2/(i^2+\Gamma^2)^{2}\}$ at zero bias current where $i=I/I_c$ denotes the normalized current and $\Gamma=2\pi k_B T/(I_c\phi_0)$ is the junction noise parameter.

III. Results and Discussion

The magnetic field dependence of the transfer function $V_{sq\text{-}pp}$ of all sensors showed one main maximum enabling determination of the value of the magnetic field at the first minimum: $\Delta B_{0\text{-}V}$. For about 30% of the devices, a Fraunhofer-like dependence of $V_{sq\text{-}pp}(B)$ was observed. A typical example is shown in Fig. 1. Strongly irregular minimum spacings or even no side minima were found for the other sensors. This behavior and also the observed non-zero minima may be attributed to a nonhomogeneous current distribution in the junction [2],[4],[5] or to flux penetrating into a second grain boundary in series with the main junction as shown in [1] for bicrystal rf-SQUIDs.

Fig. 1 also illustrates the effect of different sensor areas on the field period $\Delta B_{0\text{-}V}$. As expected, coplanar resonators with larger effective areas have no influence on the shape of the Fraunhofer-like pattern but reduce the field period following a $1/A_{eff}$ dependence according to (1). This is shown in the inset of Fig. 1. When the magnetic field dependence of the washer-SQUID is known, $\Delta B_{0\text{-}V}$ can be calculated for every type of flip chip configuration.

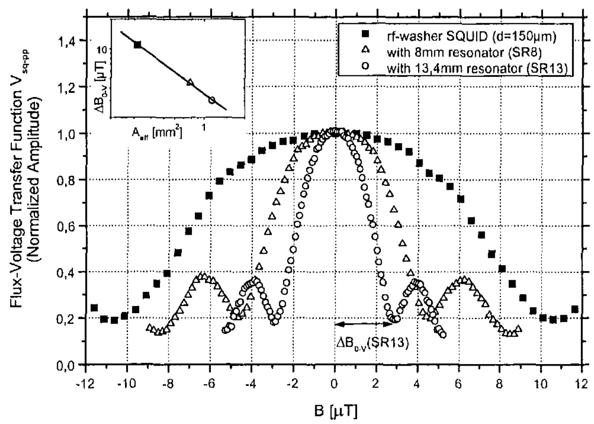

Fig. 1. Magnetic field dependence of $V_{sq\text{-}pp}$ of an rf-washer SQUID with w=3 μm, and effect of coplanar resonators with flux concentrators of two effective sensor areas, 0.78 mm^2 and 1.11 mm^2. The inset shows the $1/A_{eff}$ dependence of $\Delta B_{0\text{-}V}$ (solid line) compared to the experimental data.

A. Dependence of ΔB_0 on the Junction Width w

To investigate the influence of the junction width on the field period $\Delta B_{0\text{-}V}$, SQUIDs with different values of w were studied. In Fig. 2, the measured $\Delta B_{0\text{-}V}(w)$ dependence of single washer-SQUIDs without coplanar resonators (symbols) is shown in comparison with model predictions (lines). A clear $1/w^2$-behavior is observed as predicted in [6] for planar devices. The model for thin films was confirmed for isolated SEJs with t=200 nm similar to those used in our SQUIDs [7] (dashed-dotted line in Fig. 2). However, the observed field enhancement at the junction is larger than expected within the thin film model even when taking into account the flux focussing effect of the SQUID washer according to (1). In our measurements, the majority of data points is lying in the intermediate zone of thin and thick film limit described by (1) and (2) (thick solid and dashed line in Fig. 2). This may be explained by the fact that (1) and (2) are only exact in the extreme thin and thick film limit. Moreover, the derivation of (1) is based on the assumption of a homogeneous flux density in the SQUID hole. Based on the current distribution in a circular washer close to its inner hole, Sloggett et al. [3] derived a simplified expression for the estimation of the flux density, $B_{jj}(\xi)$, for points in the hole of a circular washer-SQUID close to the edge, i.e. close to the

Josephson junction (r_i-σ<<r_i). The expression is $B_{jj}(\xi)=B_m[r_i/(8\xi)]^{0.5}$ where B_m is the mean value of the flux density, σ denotes the radial distance (σ<r_i), r_i is the inner hole radius, and $\xi=r_i-\sigma$ is the distance from the loop edge [3]. They found the flux density in the middle of the hole to be half of its mean value B_m and a field enhancement >> 1 at the edge of the hole where the junction is situated. This principle tendency of a field enhancement B_{jj}/B_m at the junction is unlikely to change for SQUIDs with square holes and may be

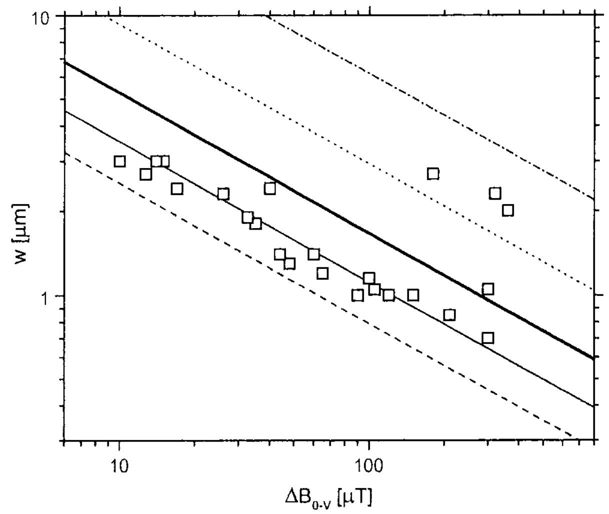

Fig. 2. Dependence of the field period $\Delta B_{0\text{-}V}$ on the junction width: comparison of our experimental data for single SQUIDs (symbols) with different model predictions for t=200 nm, λ_L=200 nm at 77 K, d=150 µm and A_{eff}=0.31 mm²: $\Delta B_0 = 1.84\phi_0/w^2$ (dashed-dotted line: isolated GBJ, thin film limit), $\Delta B_0 = \phi_0 t/(1.2w^2 2\lambda_L)$ (dotted line: isolated junction, thick film limit), $\Delta B_0 = 1.84\ \phi_0\ d^2/(w^2\ A_{eff})$ (thick solid line: SQUID, thin film limit), $\Delta B_0 = 1.84\ \phi_0\ d^2\ (B_m/B_{jj})/(w^2\ A_{eff})$ (thin solid line: SQUID, thin film limit, taking into account field enhancement of B_{jj}/B_m=2), and $\Delta B_0 = \phi_0\ t\ d^2\ /\ (1.2w^2\ 2\lambda_L\ A_{eff})$ (dashed line: SQUID, thick film limit).

the reason for the observed behavior. A fit of our experimental data using $\Delta B_0=1.84\phi_0 d^2(B_m/B_{jj})/(w^2 A_{eff})$ shows that a value of B_{jj}/B_m~2 (thin solid line in Fig. 2) is consistent with most of our samples. This enables us to estimate the necessary junction width for our rf-SQUIDs with coplanar resonators for operation in the Earth's magnetic field (B_{earth} ~50µT). A field period $\Delta B_{0\text{-}V}$ of ~100µT is necessary [3] in order not to significantly decrease the transfer function $V_{sq\text{-}pp}$, leading to an increased white noise level of the sensors. Taking into account the effective areas of the different sensor types, we obtain optimum junction widths of w ~ 0.6 to 1.2 µm. 'Magnetically stable' sensors can also be obtained accidentally at larger widths, as shown in Fig. 2 for some samples. This property can be attributed to a strong difference between geometric and effective junction width and has been observed by other groups before [2],[3]. However, for the reproducibility of stable devices, the fabrication of narrow junctions is essential.

B. Correlation of ΔB_0 and $\Delta B_{0\text{-}V}$

The analysis of the parameter $\Delta B_{0\text{-}V}$ in Section IIA – the period of the magnetic field dependence of the flux-to-voltage transfer function amplitude - was performed on the basis of (1) and (2). As pointed out in Section I, this approach is not strictly correct because these equations are for the period ΔB_0 of the magnetic field dependence of the junction's critical current $I_c(B)$. Therefore, in this section, the conformity of ΔB_0 and $\Delta B_{0\text{-}V}$ for SEJ-rf-SQUIDs will be checked. To exclude uncertainties in this analysis arising from strong junction inhomogenities, only samples with $V_{sq\text{-}pp}(B)$ curves showing no strong deviation from a Fraunhofer-like pattern were chosen for the investigation. In this case, the magnetic field behavior is dominated by the critical current of the main junction or by subjunctions in series with a similar field dependence.

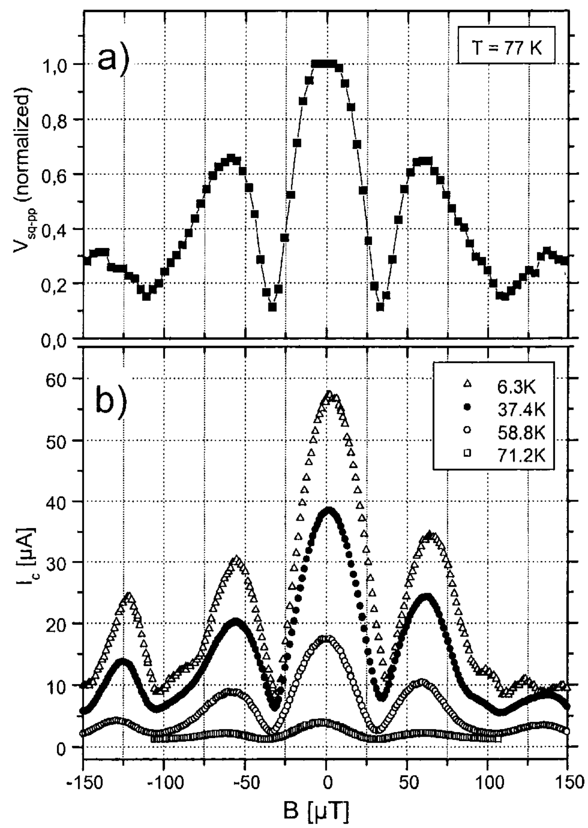

Fig. 3. Comparison of the field dependence of the transfer function $V_{sq\text{-}pp}$ of an rf-washer-SQUID and of its critical current I_c, respectively: a) $V_{sq\text{-}pp}(B)$ at 77K, b) temperature dependent 4-probe measurements of $I_c(B)$ on the same SQUID after opening the loop.

In Fig. 3, the $V_{sq\text{-}pp}(B)$ dependence of a SQUID is shown in comparison with four-probe measurements of $I_c(B)$ of the same SQUID after opening the loop. The periods of the Fraunhofer-like patterns - ΔB_0 and $\Delta B_{0\text{-}V}$, respectively - show reasonably good agreement including a good correlation of the side minima. A similar behavior was found for other devices as well.

The measurements of $I_c(B)$ at different temperatures (Fig. 3b) demonstrate that there is no strong temperature dependence of the period ΔB_0. Therefore, the $I_c(B)$ curves were acquired at low temperatures to reduce measuring errors as the determination of I_c using a voltage criterion is difficult in the presence of high thermal fluctuations at 77 K for I_c-values of a few μA.

All investigated SQUID junctions showed resistively shunted junction (RSJ) behavior. I_c was obtained at 77 K by fitting the junction noise parameter $\Gamma=2\pi k_B T/(I_c\phi_0)$ to the measurements of the differential resistance (see example in Fig. 4). From I_c, β_L was determined to be < 1.5 at 77 K for all samples. A list summarizing the investigated parameters of the samples is given in Table I.

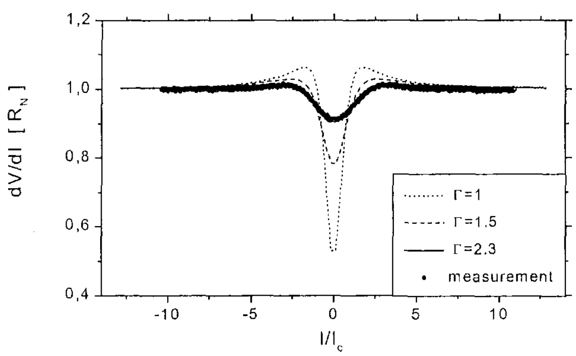

Fig. 4. dV/dI-measurement at 77 K (sample JS1712) to determine β_L: The measurement is in good accordance with the calculation of dV/dI on the basis of the RSJ model [13] for Γ=2.3.

TABLE I
COMPARISON OF SQUID PARAMETERS

Sample	w [μm]	I_c [μA] at 77K	β_L at 77K	$\Delta B_{0\text{-}V}$ [μT] $V_{sq\text{-}pp}(B)$	ΔB_0 [μT] $I_c(B)$
JSA12	2.7	2.1	1.4	12.7	14.2
JSA13	1.9	1.3	0.9	32.6	32.8
JS1712	1.4	1.4	1.0	59.5	56.0

The overall good agreement between ΔB_0 and $\Delta B_{0\text{-}V}$ in the case of the 3 investigated samples is confirmed by the fact that the values for β_L are not much larger than ~1 (Table I). In this case, a reduction of β_L caused by the suppression of the critical current due to an external magnetic field will also lead to a suppression of $V_{sq\text{-}pp}$. The conformity of ΔB_0 and $\Delta B_{0\text{-}V}$ was proven indirectly by the determination of β_L (<1.5) and directly by comparing the measured magnetic field dependences of I_c and $V_{sq\text{-}pp}$ (Fig. 4). We conclude that the equations described in the previous section can be applied to yield an estimation for the expected field period $\Delta B_{0\text{-}V}$ for different junction widths of our SQUID devices.

IV. CONCLUSION

We have investigated the magnetic field dependence of the flux-voltage transfer function, $V_{sq\text{-}pp}(B)$, for SEJ rf-washer SQUIDs and coplanar resonators with different effective sensor areas and junction widths. The suppression of $V_{sq\text{-}pp}$ by a magnetic field - commonly leading to an increased white flux noise level - was correlated to a suppression of the critical current in the rf-SQUID junction. This was shown for devices having a reasonable homogeneous current distribution according to their Fraunhofer-like pattern. The width dependence of the field period $\Delta B_{0\text{-}V}$ of the sensors was compared to different models taking into account the field enhancement at the junction due to the focussing washers. The measured field period, $\Delta B_{0\text{-}V}$, scales with $1/w^2$ as expected for planar devices. It was shown that, due to the large effective areas of SQUIDs with coplanar resonators, junction widths in the submicrometer scale are required for operation in the Earth's magnetic field. Future work will include a detailed characterization of the magnetic field behavior of isolated SEJs and their correlation to these results.

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