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YBCO STEP EDGE JUNCTIONS FOR MAGNETICALLY TUNABLE RESONATORS

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Abstract - Step edge junctions on $NdGaO_3$ substrates with a product $I_O R_N \approx 50\,\mu V$ and a promising rather uniform current density distribution along the junction width at 77 K have been fabricated. 196 magnetometer SQUIDs are integrated in a coplanar line resonator to tune its resonance frequency magnetically. The resonator quality factor and frequency shift near 10 GHz and 50 K are investigated experimentally.

Introduction

Microwave applications like radar and antenna systems will need phase shifters. Commercial products based on GaAs MMIC [1,2] could improve performance in bandwidth and insertion loss by using HTSC circuits [3..5]. To start the development of a phase shifter a coplanar line resonator with tunable inductance has been designed and simulated [6,7]. Step edge junctions on different substrates are used. They can be integrated easily in rf circuits and allow acceptable properties at 77 K [8,9]. The phase shifter allows for rather large tolerances of the maximum Josephson current and can therefore be implemented with the present state of technology.

Fabrication

YBCO films have been deposited by *off-axis sputtering* from a single stoichiometric target on (001) $NdGaO_3$ substrates in order to get almost untwinned *c-axis* films [10]. Current densities of $2x10^7\,A/cm^2$ and surface resistances of $25\,\mu\Omega$ at 10 GHz and 4.2 K have been achieved. The anisotropy ratio of the dc resistivities ρ_b/ρ_a and of the surface resistances R_{sb}/R_{sa} at 10 GHz in the *a-b*-direction of the YBCO films is about 2. The steps have been etched with Ar ion beam and a Nb mask.

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Measurements of junctions

Junctions have been fabricated on (110) $NdGaO_3$ substrates with a step height h = 380 nm and a film thickness t = 340 nm. Sometimes two Josephson currents are observed in the I_G-U_j- characteristic probably eminating from the upper and lower grain boundary at the substrate step. However, in contrast to step edge junctions on $SrTiO_3$ [11] the corresponding Josephson current ratio on $NdGaO_3$ substrates seems to be considerably larger. The I_G-U_j- characteristic of a step edge junction with 6 µm line width at 77 K in a swept external magnetic field is shown in Fig. 1. The maximum Josephson current is I_o = 75 µA and the product $I_o R_N$ reaches 50 µV. The Josephson current can be suppressed by a magnetic field.

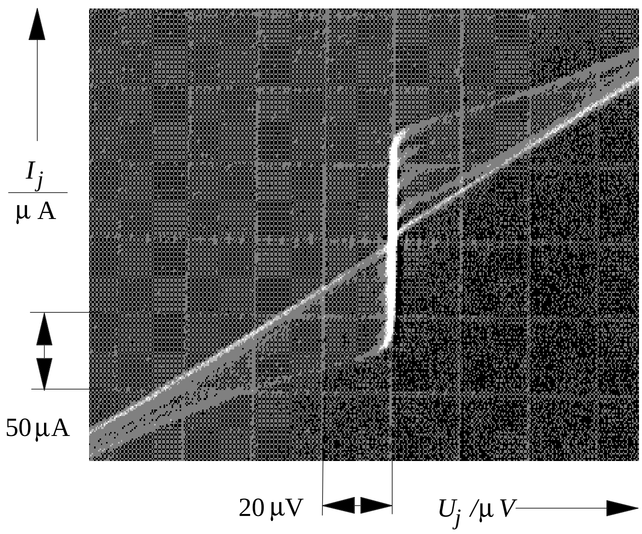

Fig. 1: The measured current-voltage characteristic of a 6 µm wide step edge junction in a swept external magnetic field at 77 K.

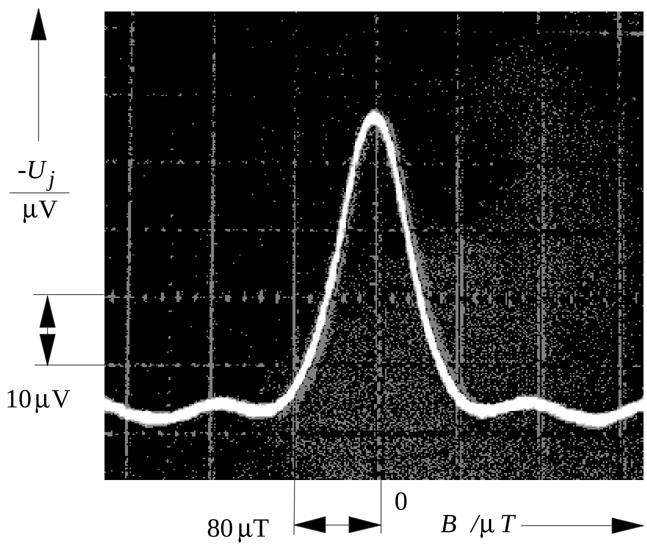

Fig 2: Voltage versus magnetic induction at 77 K of a 6 µm wide step edge junction according to Fig. 1 at constant current I_G.

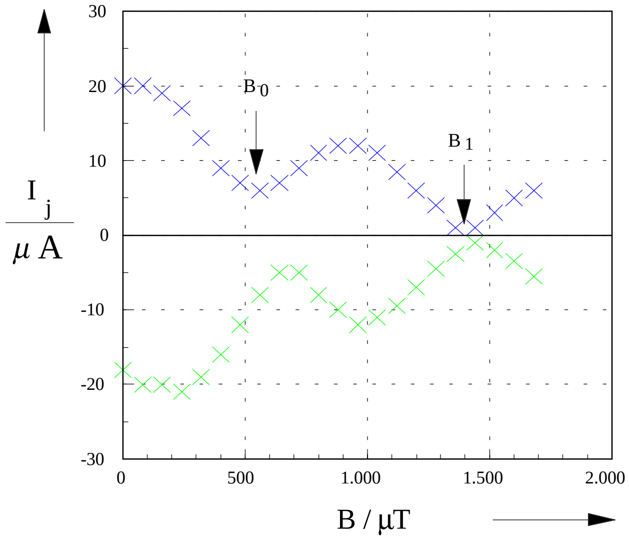

Fig. 3: The Josephson current I_j of a step edge junction at 77 K versus magnetic induction **B**.

The negative junction voltage U_j as a function of the external magnetic field or flux with a constant current I_G is presented in Fig. 2. The second minimum appears at about twice the magnetic field value of the first one.

The I_j **-B** characteristic at 77 K of a junction with smaller width w = 2.5 µm than in Fig. 1 and 2 is shown in Fig. 3. Since the I_G -U_j characteristic exhibits noise rounding the current I_G has been measured at constant voltage of 10 µV. The Josephson current I_j is calculated in subtracting the resistive component: $I_j = I_G - 10\ \mu V/\ R_N$ with $R_N \cong 1\ \Omega$. The Josephson penetration depth of these step edge junctions may roughly be approximated:

$$\lambda_J(T = 77\ K) = \sqrt{\frac{\phi_o}{2\pi\mu_o d\ j_{max}(T)}} \approx 2.3\ \mu m$$

where $j_{max}(T = 77\ K) \approx 4.7\ kA/cm^2$ and $d \approx 2\lambda$. The magnetic penetration depth is estimated for $\lambda(77\ K) \approx$ 520 nm. Hence, the junction width in Fig. 3 is in the same order than the Josephson penetration depth; self fields can be neglected. For both polarities in Fig. 3 there are pronounced minima. The second minimum is approximately zero. The ratios of the inductions at the minima of $|I_j|$ are $\mathbf{B_1/B_o}$ = 2.5 and 2.1, i.e. close to 2. The magnetic pene-

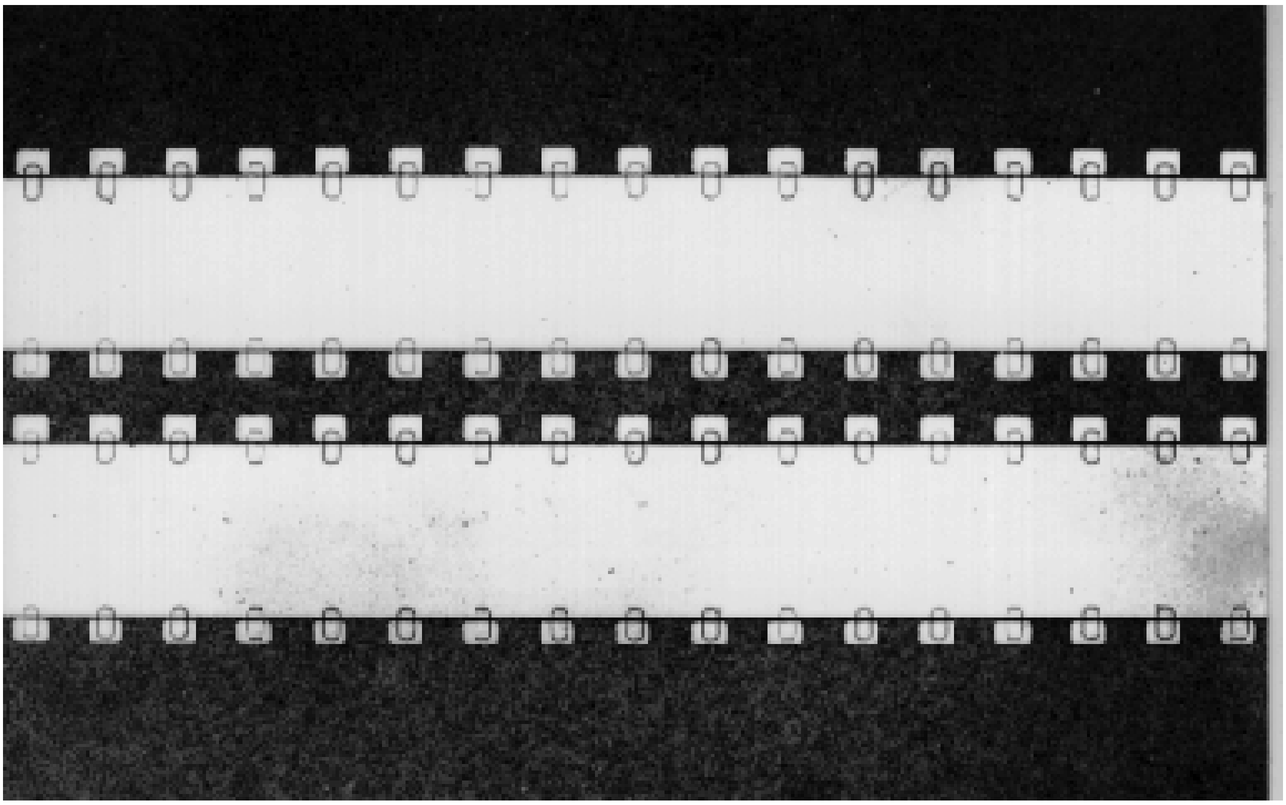

Fig. 4: Micrograph of a coplanar resonator section with magnetometers on a $NdGaO_3$ - substrate. The resonator has a length of 4 mm and a inner conductor width of 50 µm.

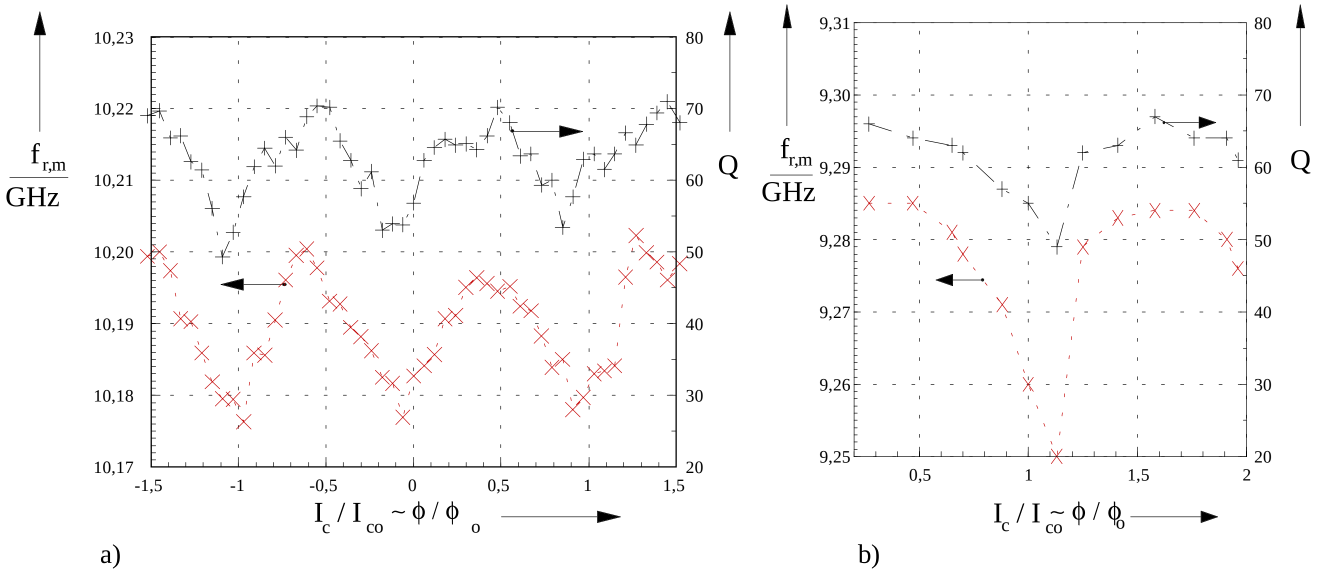

Fig. 5: a) Measurement results: Resonance frequency $f_{r,m}$ and quality factor Q versus the normalized control current. The center frequency $f_{r,m} = (f_1 + f_2)/2$ is calculated from the measured 3 dB - frequencies f_1, f_2. b) Simulated results with $I_o R_n = 135\mu V$ [7].

tration depth is larger than the film thickness so that the magnetic inductions $\mathbf{B_0}$ at the first minimum of I_j can be estimated [12]

$$\mathbf{B_o} \approx \frac{2\phi_o}{w^2}.$$

For $w = 6$ µm and $w = 2.5$ µm the inductions are $\mathbf{B_0} = 110$ µT and 660 µT in reasonable agreement with measurements according to Fig. 1 and 2, respectively. The observed magnetic field dependence may be explained rather by an uniform Josephson current density of a single short junction than by an interferometer with a few point junctions in contrast to that of step edge junctions usually found on $SrTiO_3$-substrates [11].

Measurement of the resonator

About 196 magnetometer SQUIDs with junctions of the discussed type on $NdGaO_3$ have been integrated in a coplanar line resonator according to Fig.4, however with a film thickness t = 165 nm and a step height h = 220 nm. Test - SQUIDs with hole area 46x46 µm^2 on the same chip have been characterised at $T = 50$ K by $I_O R_N = 590$ µV, a maximum slope $dU/d\phi_C = 65$ µV / ϕ_O and a critical junction temperature, where the Josephson current vanishes, $T_{cj} = 79.5$ K.

The resonator has been mounted in a closed gold plated brass housing and tested with a vector network analyser HP8720. A THRU calibration and time domain filters have been applied to eliminate the influences of small reflections. From S_{21} transmission parameter measurements the resonance frequencies and quality factors have been deduced. The coplanar resonator is capacitively coupled to 50 Ω-transmission lines. The SQUIDs are integrated in both the inner and outer strips of the coplanar line at small distances of 92 µm to increase the influence on the line inductance. The resonance frequency and the quality factor near 10 GHz in Fig.5a changes periodically as a function of the applied control current I_c or magnetic flux ϕ. The period ΔI_{co} = 430 µA should correspond to one flux quantum. Hence, within one flux quantum the maximum frequency shift is 24 MHz. This periodic frequency and quality factor dependence can be simulated with a simple model assuming $I_o R_n = 135\mu V$ as shown in Fig. 5b [7].

Conclusion

The magnetic field dependence of step edge junctions on $NdGaO_3$ can be approximated with a rather uniform current density inside the the junction. An integration of a large number of SQUIDs in a coplanar line resonator is feasible. The resonance frequency has been changed periodically with a magnetic field.

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