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Superconducting properties of magnesium diboride thin film measured by using coplanar waveguide resonator

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ABSTRACT

In this paper we demonstrate the superconducting properties of MgB_2 coplanar waveguide resonator patterned from 300 nm thin film fabricated by vapor deposition. We measured the temperature dependence of the quality factor and the resonant frequency of the resonator. Surprisingly, we also observed hysteretic periodic response of resonance frequency to external magnetic field, which is characteristic of bistable systems with double-well potential, such as superconducting RF SQUID or phase-slip flux qubits. This property seems to be peculiar for granular and disordered superconductors where a superconducting loop of large effective diameter with weak links can be formed.

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1. Introduction

The superconducting coplanar waveguide resonator (CPW) is a device with distributed elements created on a superconducting thin film. Thanks to their low parasitic capacitances and inductances, they have been recently used with great success in experiments with circuit quantum electrodynamics or kinetic inductance detectors. One of the crucial parameters, which allows them to be used for this purpose, is their high internal quality factor. The quality factor is temperature dependent and achieves its maximum value at temperatures close to one tenth of the critical temperature of the superconductor. Recently, superconducting ion traps with an integrated CPW resonator have been examined with aim to improve their performance. It is expected that the quality factors will increase by several orders of magnitude while heat dissipation will be reduced by making use of superconducting electrodes. The ion trap chips are cooled to temperatures ∼4 K. Magnesium diboride (MgB_2) has critical temperature of about ∼40 K, so the saturated value of internal quality factor can be achieved by cooling with liquid helium. Therefore MgB_2 seems to be a good candidate for this purpose and we have investigated its superconducting properties by microwaves.

2. Sample fabrication

Superconducting MgB_2 thin film was prepared by co-deposition of magnesium and boron from two separate sources on a mirror-polished sapphire substrate and ex situ annealing in vacuum chamber. The deposition chamber was evacuated to the limit vacuum 5×10^{-4} Pa. The resistive thermal evaporation and e-beam evaporation were used to make a precursor of MgB_2. Ex situ annealing process was realized in vacuum chamber evacuated to the base pressure of 1×10^{-3} Pa and consecutively filled with Ar up to working pressure of 700 Pa. The annealing temperature was 800 °C.

The resonators were patterned on the MgB_2 thin film with thickness of 300 nm by optical lithography using a 2.5 μm thick layer of positive tone resist AZ 6624 and by reactive ion etching in Ar and SF6 plasma.

3. Theoretical background

The quality factor and the resonant frequency of the CPW resonator can be recalculated from the complex conductivity $\sigma = \sigma_1 - i\sigma_2$ using analytic formulas [1,2]. The real part σ_1 arises

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from inertial losses in the superconductor, which determine the quality factor, while the imaginary part σ_2 influenced by London penetration depth λ_L, changes the kinetic inductance and therefore also the resonant frequency. The complex conductivity of the superconductor in alternating electromagnetic field can be calculated from equations derived by Mattis and Bardeen [3]

$$\frac{\sigma_1}{\sigma_N} = \frac{2}{\hbar\omega}\int_{\Delta}^{\infty}[f(E) - f(E+\hbar\omega)]g(E)\mathrm{d}E + \frac{1}{\hbar\omega}\int_{\Delta-\hbar\omega}^{-\Delta}[1-2f(E+\hbar\omega)]g(E)\mathrm{d}E \quad (1)$$

$$\frac{\sigma_2}{\sigma_N} = \frac{1}{\hbar\omega}\int_{\Delta-\hbar\omega,-\Delta}^{\Delta}\frac{[1-2f(E+\hbar\omega)](E^2+\Delta^2+\hbar\omega E)}{\sqrt{(\Delta^2-E^2)[(E+\hbar\omega)^2-\Delta^2]}} \quad (2)$$

where $f(E)$ is Fermi–Dirac distribution function, E is the excitation energy, Δ is the superconducting energy gap, ω is the angular frequency of external electromagnetic field. For a superconductor with two gaps, such as MgB$_2$, one has to take into account two-gap model in calculations of the complex conductivity. In our case, we used the method described in [4] and calculated the complex conductivity for the individual gaps and we made the weighted average of the calculated values.

4. Results and discussion

4.1. Quality factor and resonant frequency

The temperature dependences of the quality factor and the resonant frequency (Fig. 2) of the resonator were determined from the transmission measurement by a vector network analyzer at GHz frequency range at temperatures between 40 K and 0.3 K. Sample was placed in a cryogen-free ^{3}He refrigerator according to scheme shown in Fig. 1. The results were fitted by Eqs. (1) and (2) taking into account two energy gaps of MgB$_2$ [4]. From the fitting procedure we obtained two superconducting energy gaps and the critical temperature $T_c = 38$ K of the MgB$_2$ sample (Fig. 2).

4.2. Hysteretic detuning of resonant frequency

We also measured the response of the MgB$_2$ CPW resonator to external magnetic field, created by two NbTi coils (Fig. 1).

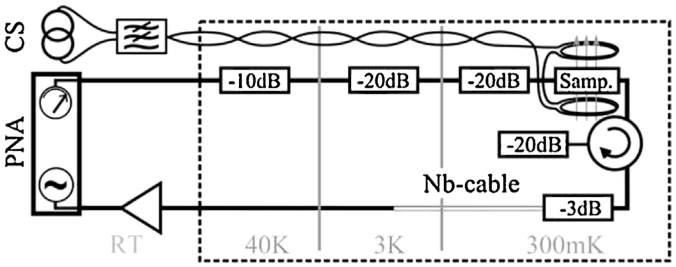

Fig. 1. Experimental measurement set-up. Sample is cooled down to 0.3 K in the refrigerator and connected to the microwave vector network analyzer. Magnetic field is created by two NbTi coils powered by DC current.

The transmission was measured by means of the technique described in the previous section. Surprisingly, the resonant frequency exhibited hysteretic periodic detuning (Fig. 3), which is characteristic for measurements of resonators with artificially patterned superconducting quantum interference device (SQUID) or phase-slip flux qubit [5–7]. Therefore we have analyzed the experimental results with theoretical model of hysteretic RF SQUID [8,5,7]. From the fitting procedure we determined the parameters of our virtual SQUID (Fig. 4) such as coupling coefficient k, critical current I_c and normalized inductance of the SQUID $\beta = 2\pi L I_c/\Phi_0$.

A superconducting quantum interference device (SQUID) is usually implemented as a superconducting loop interrupted by a Josephson junction with critical current I_c. The 'potential' energy U of this loop with inductance L can form a double-well potential

$$\frac{U}{E_J} = \frac{\beta i(\phi_e)^2}{2} - \cos(\phi_e - \beta i(\phi_e)) \quad (3)$$

if parameter β is larger than one. Here $E_J = \Phi_0 I_c/2\pi$ is Josephson energy and Φ_0 is the magnetic flux quantum. The presence of RF SQUID in CPW resonator causes the detuning of the inductance of the resonator which is dependent on the external magnetic flux. The effective inductance can be expressed as [5]

$$L_{eff} = L_r\left(1 - k^2\frac{\beta\cos\phi}{1+\beta\cos\phi}\right) \quad (4)$$

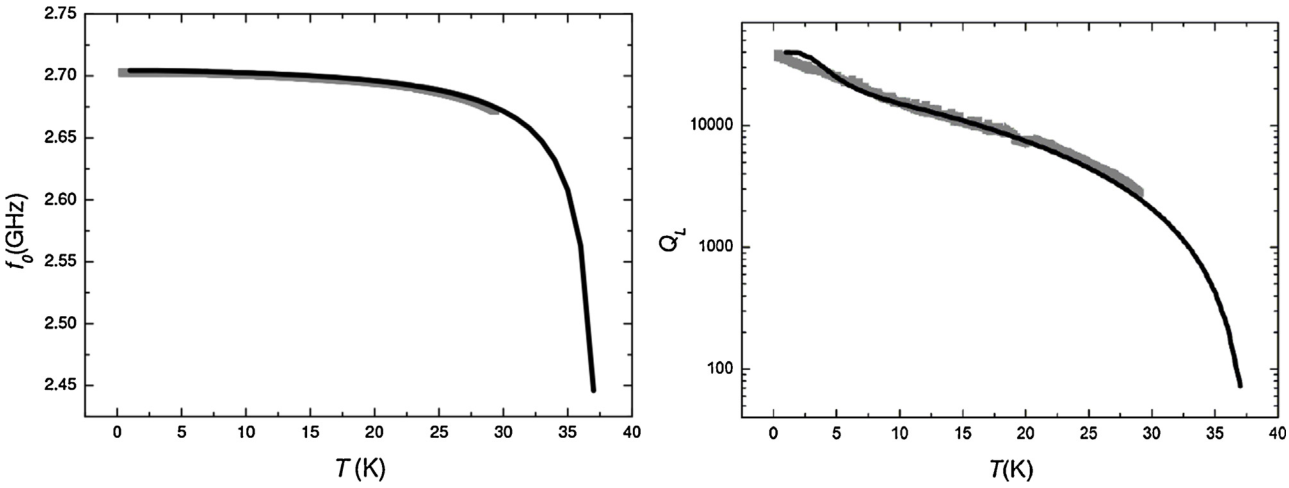

Fig. 2. The measured temperature dependence of the resonant frequency f_0 (left, gray points) and the loaded quality factor Q_L (right, gray points) compare with results, calculated by Mattis–Bardeen theory (both, solid line).

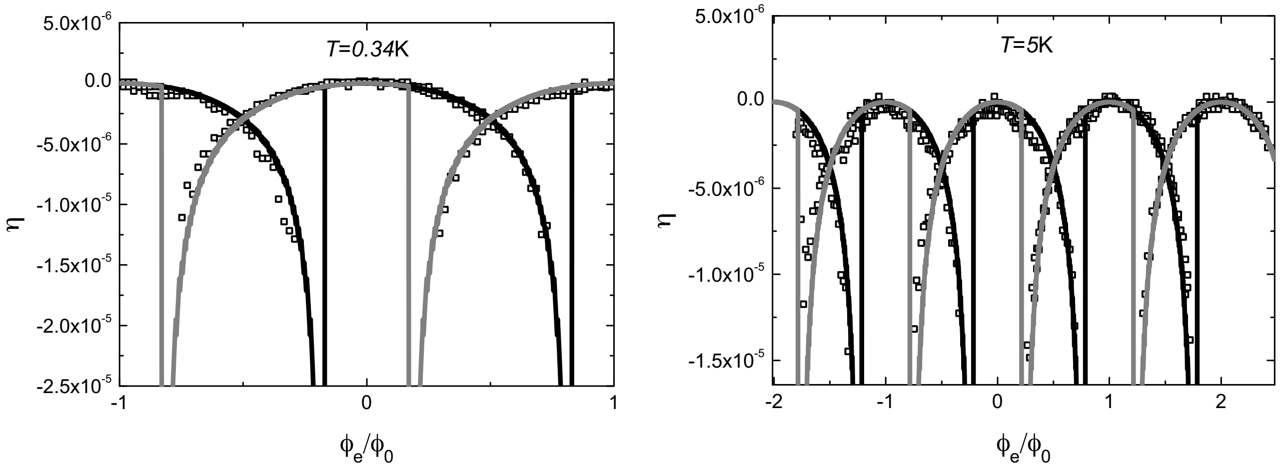

Fig. 3. Hysteretic periodic response of the resonant frequency to magnetic field for MgB_2 (squares – experiment, black and gray lines - numeric fitting) obtained parameters: $\beta = 3.5$, $I_c = 70\ \mu A$, $S \approx 170\ \mu m^2$, $k \approx 0.01$.

where $L_r \approx 10 nH$ is the inductance of a resonator without SQUID, k is a coupling constant between the resonator and the SQUID, $i(\phi) = \sin(\phi)$ is the normalized supercurrent in the loop, $\phi = \phi_e - \beta i(\phi_e)$ and ϕ_e are normalized internal and external magnetic flux, respectively. Change of the effective inductance leads to a detuning of the resonant frequency $f_0 = 1/(2\pi\sqrt{L_{ef}C})$. Normalized detuning η can be expressed as:

$$\eta = \frac{f_0 - f_{0\,\max}}{f_{0\,\max}} = \frac{1}{2}k^2\left(\frac{\beta\cos\phi}{1+\beta\,\cos\,\phi} - \frac{\beta}{1+\beta}\right) \tag{5}$$

where f_0 is the detuned frequency and f_{0max} is the maximal resonant frequency at zero magnetic flux.

If we suppose that a superconducting loop is formed in MgB_2 thin film among grains, one can determine its effective area from a fitting procedure using Eq. (5). The parameters of our 'virtual' RF SQUID, namely the normalized inductance, the effective surface, the critical current and the coupling constant between SQUID structure and CPW resonator are $\beta = 3.5$, $I_c = 70\ \mu A$, $S \approx 170\ \mu m^2$, $k \approx 0.01$ respectively.

The effective area was determined from the periodic response of the SQUID with period Φ_0. The magnetic field created by NbTi coils was calibrated according to measurement of RF SQUID with known geometry. The critical current I_c was determined from the value of the parameter β taking into account that the inductance of RF SQUID can be estimated as $L \approx \mu_0\sqrt{S}$, where μ_0 is the vacuum permeability. If we suppose that the mutual inductance between the resonator and the 'virtual' RF SQUID is equal to the Josephson inductance $M = L_J = \Phi_0/(2\pi I_c)$, we can calculate the coupling constant

$$k = \left(\frac{\Phi_0}{2\pi I_c}\frac{1}{L_r\beta}\right)^{\frac{1}{2}} \approx 0.012 \tag{6}$$

which is in agreement with the result obtained from fitting by Eq. (5) ($k = 0.01$). Therefore we can conclude that our assumption is justified and the model of the 'virtual' RF SQUID weakly coupled with the resonator gives us very reasonable results.

Our finding has also other implication. If the Josephson junction in the superconducting ring is replaced with a very narrow (~10 nm) but long (~100 nm) bridge, where phase slips can occur, the energy of the superconducting loop has the same dependence on external magnetic flux (Fig. 5). If the barrier between two states in crossing points is small, the degeneracy is lifted and anticrossing of energy levels occurs. It has been shown by Astafiev et al. [6] that this effect occurs in structures created on highly disordered superconductors and it was ascribed to quantum phase-slip. But is this effect really caused by coherent quantum phase slip?

One can equally well explain this effect by phase slip in the Josephson junction. We want to stress here that similar results were

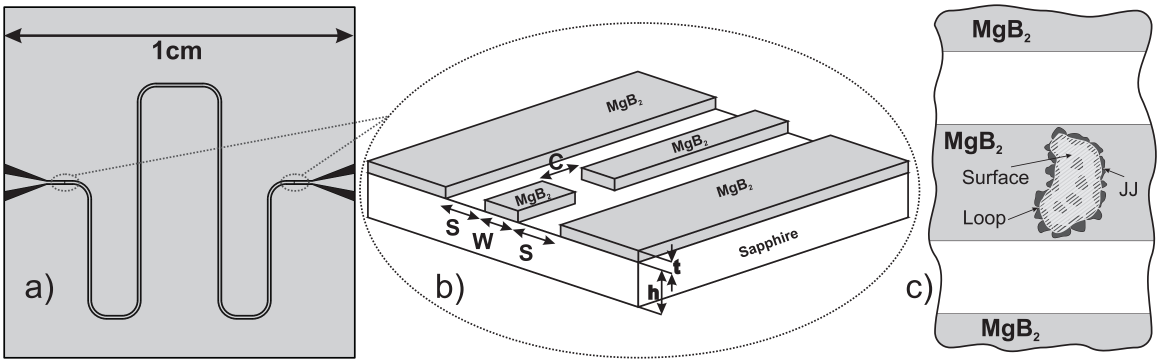

Fig. 4. (a) CPW resonator design – gray colored area for MgB_2, (b) detailed view of the input and output capacitor with marked dimensions: $W = 50\ \mu m$, $S = 30\ \mu m$, $C = 10\ \mu m$, $t = 300$ nm, $h = 430\ \mu m$, (c) model of superconducting loop formed between groups of grains inserted in central conductor of CPW resonator. Size of the individual grains is about ~10 nm [9].

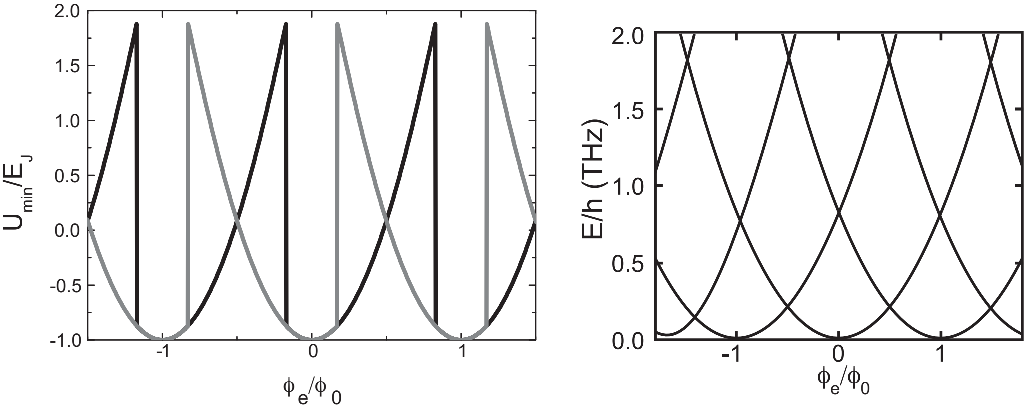

Fig. 5. Total energy of (a) RF SQUID with Josephson junction (b) RF SQUID with narrow bridge (phase-slip flux qubit) [10].

obtained on bulk MgB_2 material [11], where a low quality copper coil was used as pick-up tank.

5. Conclusions

We measured and analyzed behavior of MgB_2 superconducting material by microwave technique using a coplanar waveguide resonator. Internal quality factor is $\sim 10^6$, which indicates that it is a suitable material for quantum electrodynamics experiments [12].

We also demonstrated, that granular superconductors exhibit periodic response to external magnetic field like RF SQUID. For example response of the MgB_2 resonator can be fitted by the RF SQUID model. Therefore one should be very careful in concluding what really happens in disordered and granular superconductors.

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