Effect of magnetic fields on superconducting microwave coplanar resonators

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Abstract— **Coplanar microwave resonators made of NbN and $YBa_2Cu_3O_{7-\delta}$ show similar behavior under the influence of magnetic field. In particular, the two resonators exhibit marked difference between zero-field-cooled (ZFC) and field-cooled (FC) measurements, which is attributed to the presence of screening currents in ZFC but not in FC measurements.**

I. Introduction

Superconducting microwave resonators play an important role in a vast range of applications, such as quantum bits[1], [2], parametric amplifiers[3], [4], superconducting quantum interference devices [5], [6] and microwave kinetic inductance detectors (MKIDs) [7]–[9] designed as a microwave LC resonance circuit in which the inductance part includes the kinetic inductance, L_k, of the superconductor. In a previous work [8] we reported on fabrication of $YBa_2Cu_3O_{7-\delta}$ (YBCO)-based MKID, focusing on its behavior in magnetic field. It is well known that MKIDs are extremely sensitive to magnetic fields to a degree that a significant shift in the resonance frequency can be caused by changing the direction of the dewar relative the earth's magnetic field [10], [11]. Thus, it is important to understand the origin of the magnetic field effect in order to better design MKIDs in which this effect is minimized. The present article describes a continuation of the study of YBCO to a NbN-based MKID, comparing their behavior in magnetic field. The two materials are substantially different in structure, critical temperature, T_c (84 K compared to ~13.5 K in our YBCO and NbN samples, respectively), critical fields (estimated as 100 T and 10 T, respectively [12]) and in the symmetry of their order parameter (d-wave and s-wave, respectively). And yet, as we report below, the behavior of the YBCO and NbN resonators in magnetic field is qualitatively similar. In particular, in zero-field-cooled (ZFC) measurements (in which the superconductor is cooled in zero field from above T_c and the magnetic field is changed at low temperatures), the presence of screening currents arising from induction gradients gives rise to a sharp decrease of the resonance frequency, f_r, at low fields, up to the full penetration field, after which f_r continues to decrease only gradually due to the increase in the density of vortices. In contrast, in field-cooled (FC) measurements (in which the change in the magnetic field is done above T_c) screening currents are absent and, as a result, f_r, exhibits only a gradual decrease with field in the entire field range.

II. Experimental

Our fabricated resonator consists of a rewound spiral CoPlanar Waveguide (CPW) with length of 11 mm, yielding a resonance frequency of ~5 GHz as calculated using SONNET electromagnetic simulation software[13]. The resonator is coupled to a CPW 50 Ohm transmission line forming a microwave kinetic inductance detector. An optical picture of the fabricated MKID, including the relevant dimensions, is presented in figure 1. Using the same layout of figure 1, we patterned MKIDs from thin films of NbN and YBCO. The 50 nm thick M-Type YBCO film purchased from Ceraco Ceramic Coating GmbH [14] was deposited on MgO substrate with in-situ deposition of gold layer to protect the YBCO. Deposition of 300 nm NbN on R-cut sapphire was done in our Nano Center, using DC reactive magnetron sputtering. The YBCO pattering was made using e-beam lithography followed by Ar ion milling and gold etch processes. The NbN pattering was made using Maskless Laser Aligner (MLA) followed by Reactive Ion Etching (RIE) in a combination of BCl_3 and Cl_2.

The fabricated MKIDs were inserted into a 9 T "Quantum Design" Physical Properties Measurement System (PPMS). The superconducting critical temperatures, T_c, were measured using the internal current source and voltage-meter of the PPMS, yielding T_c^{YBCO} = 84 K and T_c^{NbN} = 13.5 K (similar to previously reported values, see, *e.g.*, [15]–[17]). The resonance frequency, f_r, and the quality factor, Q_i, were measured using Keysight Vector Network Analyzer (VNA) while applying magnetic field perpendicular to the MKID plane.

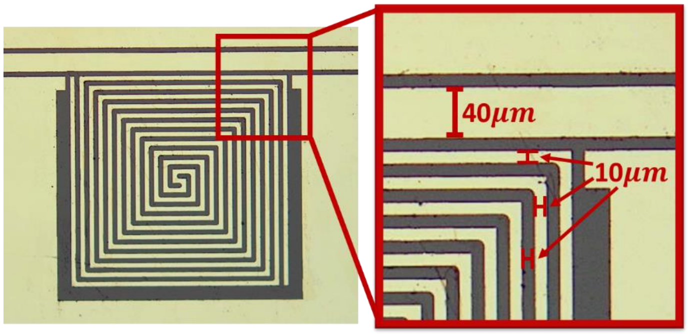

Figure 1. Optical picture of the fabricated MKID. The YBCO and NbN MKIDs have similar dimensions. (Superconducting material in white, substrate in black).

In ZFC measurements, the device was cooled in zero field to the measurement temperature and then the field was applied and ramped up to 5 T. In the FC measurements, the field was applied at a temperature above T_c and then the device was cooled down to the measurement temperature with the field on. Heating the device to above T_c and cooling it down to the desired temperature with the field on, was repeated for each field.

III. Results

Figures 2a and 2b describe the temperature dependence of f_r, in the NbN and YBCO resonators, respectively, measured in zero magnetic field. Apparently, the two resonators exhibit a similar behavior, namely f_r decreases monotonically with temperature. The inset in the two figures describe the temperature dependence of the quality factor, Q_i, in these two resonators, measured in zero field. Note that the value of Q_i at low temperatures are in excess of 10^4, in accordance with previously reported values, see, *e.g.,* [16], [17]. The behavior of Q_i is similar to that of f_r, namely it decreases monotonically with temperature. Also note that in contrast to YBCO, Q_i for NbN does not show a saturation at low temperatures. This may be due to experimental limitations of our system which prevents cooling down the NbN to achieve same reduced temperature as the YBCO.

The field dependence of f_r for NbN and YBCO resonators is presented in figure 3a and 3b, respectively. In the insets to figure 3, the field dependence of Q_i, measured in ZFC and FC, is presented. The behavior of the two resonators is again qualitatively similar, exhibiting a substantial difference between the FC and ZFC measurements. While the FC measurements show gradual decrease in f_r with increasing field, the ZFC measurements show initially a slow decrease of f_r, followed by a sharp decrease after which f_r continues to decrease gradually. The sharp drop of f_r starts at ~40 Oe and ~70 Oe for the NbN and YBCO based resonators, respectively, and it ends at 105 Oe and 135 Oe, respectively. The insets to Figures 3a and 3b present the field dependence of Q_i in ZFC and FC measurements. The behavior of Q_i in YBCO is similar to that of f_r, exhibiting lower values of Q_i in ZFC as compared to the FC data. This difference is not observed in NbN (inset to figure 3a), probably due to the lower absolute temperature value the influence of the screening currents on the quasiparticle density is less significant.

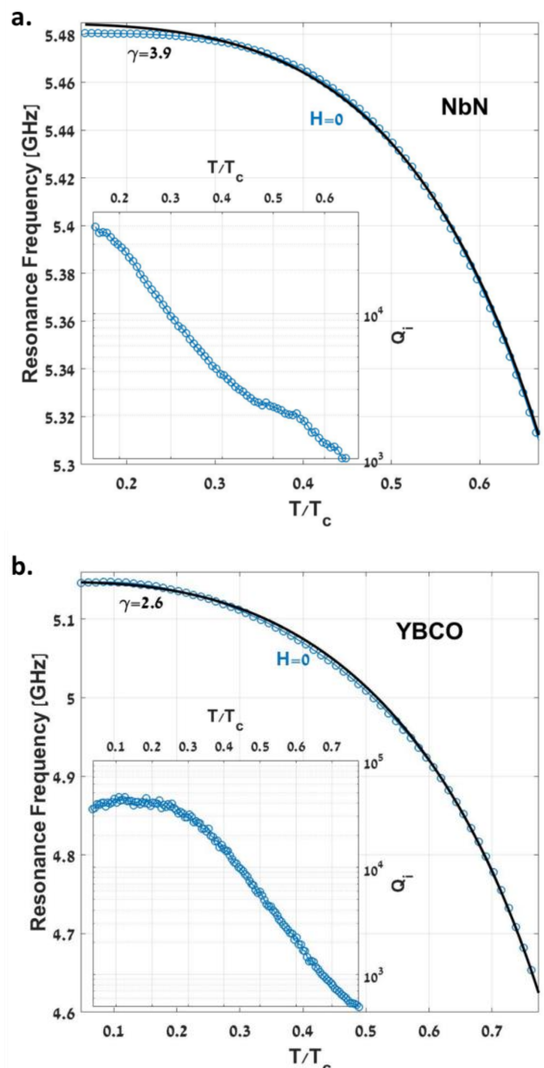

Figure 2. Dependence of the resonance frequency measured in zero field on the reduced temperature, $t=T/T_c$, for (a) NbN-based (T_c = 13.5 K) and (b) YBCO based (T_c = 84 K) MKID. (The data for YBCO is based on Ref [8]). The solid lines are fits of Eq. 2 to the data with γ as a fitting parameter. Note the different γ values found for the low-T_c and high-T_c materials. Insets: Quality factor Q_i *versus* temperature.

This article has been accepted for publication in IEEE Transactions on Applied Superconductivity. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TASC.2023.3247979

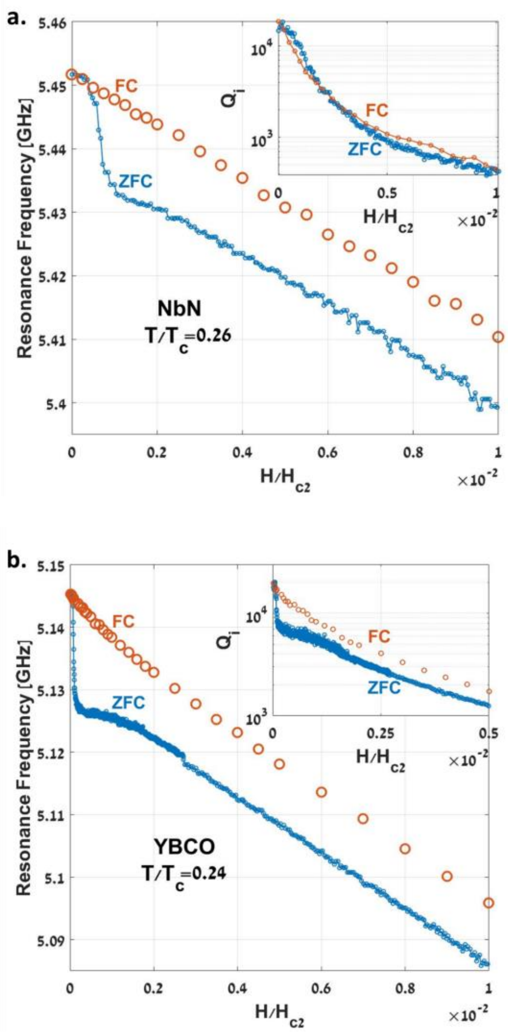

Figure 3. Resonance frequency as a function of reduced magnetic field, H/H_{c2}, in FC (upper curve) and ZFC measurements (lower curve) for (a) NbN at reduced temperature, t = 0.26 and (b) YBCO at t = 0.24. The critical field H_{c2} is estimated as 10 and 100 T for NbN and YBCO, respectively. (The data for YBCO is based on [8]). The insets present the field dependence of Q_i in ZFC and FC measurements.

IV. Discussion

The temperature and field dependence of f_r stem from the temperature and field dependence of the kinetic inductance, which is directly related to the London penetration depth, λ. Theoretically,

$$\lambda = \lambda_0 \left(1 - \left(\frac{T}{T_c}\right)^{\gamma}\right)^{-0.5} \quad (1)$$

where λ_0 is the London penetration depth at T=0 and γ is found experimentally to be 1.5-3 [18] for high-T_c materials such as YBCO and ~4 for low-T_c superconductors such as NbN [19]. λ depends also on the magnetic field, and basically increases as the field increases [20]. As shown in [8], the relation between λ and f_r for half-wavelength resonator is:

$$f_r = \frac{1}{2l\sqrt{CL_k(0)\left[\frac{1}{(1-(T/T_c)^{\gamma})}+\chi\right]}} \quad (2)$$

where l is the length of the resonator, C and $L_k(0)$ are the capacitance and kinetic inductance per unit length, respectively, and $\chi = L_m/L_K(0)$, where L_m is the magnetic inductance. We simulated the resonators using SONNET, taking surface inductance, $L_s = L_k w/l = \mu_0\lambda^2/d$ (w and d are the width and the thickness of the wire), values of L_s^{NbN} = 0.8 pH/square and L_s^{YBCO} = 1.31 pH/square, yielding $\chi_{NbN} = 3.6$ and $\chi_{YBCO} = 2.2$. The solid lines in figure 2a and 2b show a fit of Eq. 2 to the H = 0 data, yielding $\gamma_{NbN} = 3.9$ and $\gamma_{YBCO} = 2.6$. While γ_{NbN} is close to that predicted by the two-fluid model, γ_{YBCO} deviates from this prediction as was found experimentally in other YBCO films, see *e.g.* Ref. [21].

The field dependence of f_r and Q_i has been commonly ascribed to the presence of Abrikosov vortices and losses associated with their motion [22]–[25]. As the field increases the number of vortices increases, giving rise to a decrease in f_r and Qi. This scenario explains well the measured gradual decrease of f_r and Q_i with increasing field in the FC procedure, see Fig. 3. To explain the ZFC behavior of f_r and Q_i one must consider, in addition to vortices, the influence of screening currents on L_k. The origin of the screening current is the non-uniform induction distribution across the resonator in ZFC (but not FC) measurements. The influence of the screening currents is mainly pronounced at low fields up to the full-penetration field, H_p, causing a sharp decrease of f_r up to H_p. Above H_p, the influence of the screening current saturates and from now on one observes only the influence of vortices. As a result, the sharp fall is followed by a moderate decrease, similar to that observed in the FC data. In Ref [8] we ascribed the linear dependence to the fact that YBCO is d-wave superconductor. Our measurements in NbN (s-wave superconductor) which also exhibit linear dependence of f_r on the field, clearly show that the symmetry of the order parameter does not play a role.

V. Conclusions

The important role of screening currents in determining the field dependence of f_r was first demonstrated in our ZFC measurements of YBCO based MKID [8]. The present article describes a continuation of that work, showing similar results in NbN MKID although, compared to YBCO, it has a substantial different structure, critical temperature, critical field and order parameter symmetry. The role of screening currents on the kinetic inductance is apparent in the ZFC data. In FC measurements, where induction gradients are absent, the resonance characteristics are controlled only by vortices, exhibiting a moderate decrease with field.

ACKNOWLEDGMENT

This work was supported in part by the Israel Innovation Authority and by ELTA Systems LTD. The authors acknowledge important discussions with I. Finkelman, G. Lukovsky, N. Maskil and N. Teneh.

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