Giant parametric amplification of nonlinear response in single crystal Nb

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Abstract

We report the experimental observation of a giant parametric amplification of a nonlinear response in single crystal Nb in the surface superconducting state. Measurements of the nonlinear susceptibility of Nb ($T_c \approx 9.15$ K), have been performed as a function of temperature, applied dc and ac fields in the presence of parametric ac pumping. Non-monotonic changes of the nonlinear response have been found as a function of the dc, ac and pumping fields in a surface superconducting state of Nb.

Key words: Surface superconductivity;nonlinearity;parametric phenomena;

1. Introduction

Parametric phenomena in Josephson junctions have attracted attention since the middle seventies. Josephson junctions were used as a parametric amplifier with a low noise level (see, for example[1] and references therein). These experimental observations were possible because of the nonlinearity of the Josephson junction. In this paper we show that application of parametric pumping produces a giant enhancement of the nonlinear response of single-crystal Nb. Moreover, at magnetic fields $H_0 < H_{c2}$ the amplitude of the nonlinear response exponentially grows with the magnitude of the pumping field at low pumping level.

2. Experimental

The experiments were carried out on Nb single-crystal sample with sizes $10 \times 3 \times 1$ mm^3 and resistance ratio $R_{300K}/R_{10K} \approx 300$. The results of magnetization measurements of our sample have been published elsewhere [2]. The sample was exposed to dc H_0, ac $h(t)$ and pumping ac $h_p(t)$ magnetic fields applied parallel to the [100] crystalline direction which coincides with the longest dimension of the sample. The amplitude modulated ac field $h(t) = h_0(1 + \alpha cos\Omega t)cos\omega t$, where: $0 < h_0 < 0.3$ Oe, $\alpha \approx 0.9$, $\omega/2\pi = 3.2$ MHz, and $\Omega/2\pi \approx 1.5$ kHz, was obtained by excitation of the small primary copper coil from a high frequency generator operating in a constant current regime. Parametric pumping field $h_p = h_{2\Omega}cos(2\Omega t + \Psi_{2\Omega})$ was achieved using the copper solenoid of a commercial SQUID magnetometer system. The detailed description of the experimental setup has been given elsewhere [2].

Nonlinearity of a superconducting specimen excited by an amplitude modulated ac field results in oscillations of the magnetic moment at the frequencies of the harmonics of the fundamental frequency ω, and at the frequencies $\omega \pm \Omega$, as well as at the modulation frequency Ω, and its harmonics. The signal at the frequency Ω, its amplitude A_Ω and phase Ψ_Ω was processed by a lock-in amplifier as a function of the experimental parameters such as: temperature, H_0, h_0, $h_{2\Omega}$ and $\Psi_{2\Omega}$.

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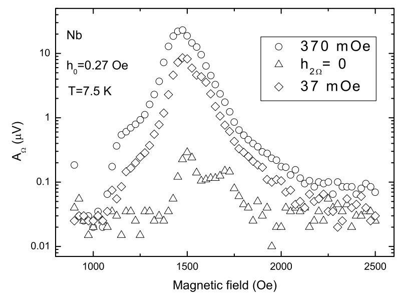

Fig. 1. $A_\Omega(H)$ dependence at different pumping amplitude $h_{2\Omega}$.

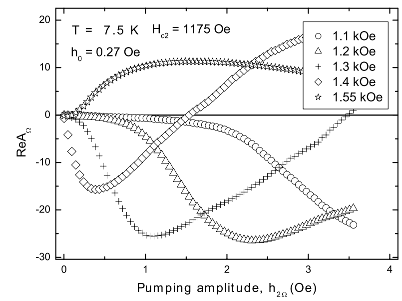

Fig. 2. Re$A_\Omega(h_{2\Omega})$ dependence at different dc magnetic field values.

3. Results and discussions

Fig. 1 shows the field dependence of the rectified signal A_Ω measured at T=7.5 K for different amplitudes of $h_{2\Omega}$. It is readily observed that application of parametric pumping leads to giant enhancement of the rectified signal. We showed recently that under stationary conditions the rectified signal exists in surface superconducting state only [2]. Present results confirm our previous observation. At the same time we can see that the rectified signal appears at $H_0 < H_{c2}$ and $H_0 > H_{c3}$. (H-T phase diagram of our sample was reconstructed in[2].) However we argue that in both cases surface superconductivity is responsible for the rectified signal. In the middle sixties H. Fink showed that surface superconductivity exists below H_{c2} [3]. We believe that even for $H_0 < H_{c2}$ the surface states defined a nonlinear response. In support of this experiment shows an absence of any sharp changes in $A_\Omega(H_0)$ near H_{c2}. We should emphasize that the sensitivity of the present experiment is in three order of magnitude higher than at previous one [2]. This is why we observe surface states in magnetic fields above H_{c3} measured in[2]. Fig. 2 presents the in-phase signal (ReA_Ω) dependence on $h_{2\Omega}$ (phase of the rectified signal was measured in respect to phase of the envelope of $h(t)$). One can see that at $H_0 > 1.6$ kOe ReA_Ω becomes positive at any pumping amplitude $h_{2\Omega}$. At $H_0 < H_{c2}$ the dependence of $A_\Omega(h_{2\Omega})$ is exponential at low pumping level, e.g. $A_\Omega \propto exp(\frac{h_{2\Omega}}{h^*})$. Fig. 3 presents field dependence of h^*. The h^* characterized some energetic barrier with height per unit length about $\varphi_0 \times h^* \approx 10^{-7}\frac{erg}{cm}$. And the barrier height goes to zero at $H_0 > H_{c2}$.

The phase of the rectified signal $\Psi_\Omega(h_{2\Omega})$ dependence at low $h_{2\Omega}$ is essentially different for the $H_0 > H_{c2}$ and $H_0 < H_{c2}$ cases. At $H_0 < H_{c2}$ Ψ_Ω is a weak function of $h_{2\Omega}$. But at $H_0 > H_{c2}$ Ψ_Ω grows rapidly with $h_{2\Omega}$.

A qualitative explanation of the observations for the case $H_0 > H_{c2}$ may be done in a frame of parametric amplifier model[4]. However a quantative theory has to be developed for the description of the experimental results presented in our work. To the best our knowledge this theory does not exist as yet.

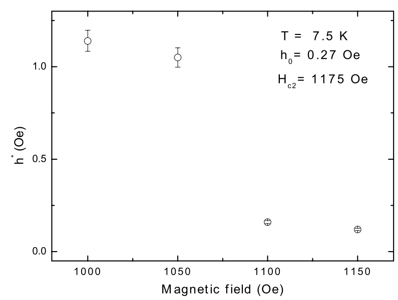

Fig. 3. $h^*(H_0)$ dependence.

Acknowledgements

The work was supported by the Klatchky foundation. The authors are deeply grateful to Dr. S.I. Bozhko and Dr. A.M. Ionov (ISSP RAS, Chernogolovka, Moscow district, Russia) for the sample preparation.

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