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Electron phase-breaking time in ultra-thin Nb films

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Abstract. Here we study the temperature dependences of the electron phase-breaking time τ_ϕ in ultra-thin superconducting niobium (Nb) films. In Nb films, passivated with a layer of silicon (Si), the observed temperature dependence of the phase-breaking time is $\tau_\phi \sim T^{-2.5}$, is resembling the electron-phonon scattering. However, in the uncovered Nb films, we observe the saturation of τ_ϕ at low temperatures, which may be a signature of the surface magnetic disorder, present in native Nb oxide on the film surface.

Keywords: magnetoresistance, thin films, inelastic scattering, magnetic disorder

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Материалы конференции
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Время сбоя фазы в ультратонких пленках Nb

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Аннотация. В данной работе мы представляем результаты экспериментального исследования времени сбоя фазы волновой функции электрона в ультратонких сверхпроводящих пленках ниобия (Nb). В Nb пленках, пассированных слоем кремния (Si), наблюдается сильная зависимость времени сбоя фазы от температуры $\tau_\phi \sim T^{-2.5}$, вероятно, обусловленная электрон-фононным рассеянием. Однако в непокрытых кремнием Nb пленках наблюдается насыщение времени сбоя фазы при низких температурах, что может быть обусловлено наличием поверхностного магнитного беспорядка, возникающий в естественном окисле Nb на поверхности пленки.

Ключевые слова: магнетосопротивление, тонкие пленки, неупругое рассеяние, магнитный беспорядок

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Introduction

Magnetic disorder, potentially present in the native oxides on the surface of thin superconducting films, can crucially suppress superconductivity due to breaking of the time-reversal symmetry in superconductors [1, 2]. However, distinction this mechanism from other mechanisms of superconductivity suppression is not straightforward. For example, it is well known that the native oxide of Nb is conductive and, hence, it can diminish superconducting properties due to the inverse proximity effect [3]. Meanwhile some experimental observations show signatures of magnetic disorder on the surface of Nb [4–5], one can to obtain additional information with magnetoresistance transport measurements. In particular, one can expect the saturation of phase-breaking time of the electron wavefunction in case of scattering on magnetic disorder [6–7]. In this work we investigate the dependence of phase-breaking time upon temperature by measuring magnetoresistance in ultra-thin superconducting Nb films. We observed a strong dependence of the phase-breaking time on temperature in Nb films, passivated with a layer of silicon (Si). Meanwhile, in uncovered Nb films, we observe the saturation of the electron phase-breaking time at low temperatures.

Materials and Methods

Ultrathin Nb films are sputtered using the magnetron sputtering system (AJA International Inc.) with a background pressure of 9×10^{-8} torr. The samples are deposited on r-cut Al_2O_3 and Si substrates by sputtering of the Nb target with diameter of 50.8 mm and purity of 99.95% in argon atmosphere (99.998% purity). The working pressure is 3.1 mTorr. During deposition the substrates are heated up to T_{dep}= 400 °C. This heating is controlled with a built-in PID controller, and T_{dep} is pre-calibrated using an analog thermometer (PTC Instruments). The rotation of substrates during deposition and the relatively large distance between substrates and the target (~ 10 cm) allows for fabrication on Nb films with high uniformity. The acquisition of thin Nb films is controlled by piezoelectric microweighting in the test process. The film growth rate is 0.11 nm/s, and the thickness is determined by the time of film deposition. The films investigated have thicknesses in the range of 3–6 nm. To prevent unintentional oxidation of Nb films in the atmosphere, two films are passivated with a 5-nm thick silicon (Si) layer. In this study, we prepare two passivated Nb samples (A1, A2) and two uncovered samples (B1, B2). In the latter case, the films are exposed to strong unintentional oxidation [8].

To study transport properties, we patterned the films into 500-μm wide and 1000-μm long Hall-bars. Electrical transport measurements are carried out with a 370 AC LakeShore resistance bridge at a bias current less than 1 μA. Normal-state resistance Rs is measured in a four-probe configuration. The measurements are carried out on a custom ^{4}He cryogenic insert immersed in a dewar in a wide temperature range (from 300 K to 1.7 K). At low temperatures we measure the magnetoresistance $R_S(B)$, the temperature dependencies of the second critical magnetic field $B_{c2}(T)$ and the Hall resistance R_H at 25 K by applying perpendicular magnetic field B up to 4 T. The latter allows to determine the carrier density $n = B/(edR_H)$. We determine the slope dB_{c2}/dT at T_c by measuring $R(T)$-dependencies on different values of B (not shown here). The latter allows to estimate the critical magnetic field $B_{c2}(0)$, the electron diffusivity D using the following expressions $B_{c2}(0) = -0.69T_c(dB_{c2}/dT)$, $D = -4k_B/(\pi e)\,(dB_{c2}/dT)^{-1}$.

For samples B1 and B2 we estimate the diffusion D coefficient by extrapolation from data for thicker films (not presented here). Here, the critical temperature T_c is determined as the temperature at $R_s = R_s^{10K}/2$. The parameters of the studied samples are presented in Table 1.

Table 1

Characteristics of niobium films

	With a Si layer		Without a Si layer	
	A1	A2	B1	B2
d, nm	6	3	5	3
Substrate	Al_2O_3	Al_2O_3	Al_2O_3	Si
T_c, K	7.53	3.26	1.10	0.92
R_s^{10K}, Ohm	20.0	137.3	186.4	363.8
R_s^{300K}, Ohm	48.57	181.9	186.8	363.8
D, cm^2/s	3.56	1.59	1.3	1.2
n, cm^{-3}	4.85×10^{22}	4.06×10^{22}	3.03×10^{22}	3.25×10^{22}
$B_{c2}(0)$, T	2.32	2.25	0.93	0.84
τ_0, fs	14.3	6.4	5.2	4.8
α_{e-e}^{-1}, ps	203	97	227	165
α_{e-ph}^{-1}, ps	7.5	20	100	20
p	2.5	1.5	0	0
τ_s, ps	inf	10	2.4	6.7

Theory

To determine the electron phase-breaking time τ_ϕ in thin films, one should experimentally study contribution of quantum corrections to magnetoconductance [9]. The dimensionless change in magnetoconductance at a fixed temperature T can be determined from the measured sheet resistance $R_S(B, T)$ using the expression:

$$\delta G(B,T) = \frac{2\pi^2\hbar}{e^2}[R_s(B,T)^{-1} - R_s(0,T)^{-1}]. \quad (1)$$

There are different contributions to the magnetoconductance: weak localization [10] and superconducting fluctuations (Maki-Thompson (MT), Aslamazov-Larkin (AL), and renormalization of density of states (DOS) contributions) [9]. Since the superconducting fluctuations are stronger than the weak localization in our samples, we refer only to the contribution of the superconducting fluctuations:

$$R_s(B,T)^{-1} = \sigma(B,T) = \sigma^{AL}(B,T) + \sigma^{DOS}(B,T) + \sigma^{MT}(B,T) + \sigma^{WL}(B,T), \quad (2)$$

where

$$\sigma^{AL}(B,T) = \frac{\pi^2\varepsilon}{4h^2}\left[\psi\left(\frac{1}{2}+\frac{\varepsilon}{2h}\right) - \psi\left(1+\frac{\varepsilon}{2h}\right) + \frac{\varepsilon}{h}\right],$$

$$\sigma^{DOS}(B,T) = -\frac{28\zeta(3)}{\pi^2}\left[\ln\left(\frac{1}{2h}\right) - \psi\left(\frac{1}{2}+\frac{\varepsilon}{2h}\right)\right],$$

$$\sigma^{MT}(B,T,\tau_\phi) = -\beta_{MT}(T,\tau_\phi)\left[\psi\left(\frac{1}{2}+\frac{B_\phi}{B}\right) - \psi\left(\frac{1}{2}+\frac{B_\phi}{B}\frac{\varepsilon}{\gamma_\phi}\right)\right],$$

$$\sigma^{WL}(B,T) = \frac{3}{2}\psi\left(\frac{1}{2}+\frac{B_2}{B}\right) - \psi\left(\frac{1}{2}+\frac{B_2}{B}\right) - \frac{1}{2}\psi\left(\frac{1}{2}+\frac{B_3}{B}\right).$$

Here $\psi(x)$ is the Digamma function, $\varepsilon = \ln(T/T_c)$ and $h = 0.69B/B_{c2}(0)$ are the reduced temperature and magnetic field, respectively, $\gamma_\phi = \pi\hbar/(8k_BT\tau_\phi)$ is the phase-breaking parameter

with τ_ϕ, which is used as a fitting parameter here. The characteristic fields are defined as $B_1 = B_0 + B_{so}$, $B_2 = B_\phi + 4B_{so}/3 + 2B_s/3$, $B_3 = B_\phi + 2B_s$, $B_{so} = \hbar/4eD\tau_{so}$, $B_o = \hbar/4eD\tau$. The coefficient in MT term $\beta_{MT}(T, \tau_\phi)$ can be found in [11].

In order to analyze the dependence of the phase breaking time upon temperature, it is useful to represent τ_ϕ as the sum of four different contributions, namely the scattering on superconducting fluctuations, the electron-electron scattering, the electron-phonon scattering and the scattering on magnetic moments:

$$\tau_\phi^{(-1)}(T) = \tau_{SC}^{-1} + \tau_{e-e}^{-1} + \tau_{e-ph}^{-1} + \tau_s^{-1}. \quad (3)$$

While magnetic scattering is independent of temperature, other terms are dependent on T in the following way:

$$\tau_{SC}^{-1} = \frac{\pi g k_B T}{\hbar} \frac{2ln2}{\varepsilon + \beta},$$

$$\tau_{e-e}^{-1} = \frac{\pi g k_B T}{\hbar} \ln\frac{1}{2\pi g} = \alpha_{e-e}\frac{T}{T_C},$$

$$\tau_{e-ph}^{-1} = \alpha_{e-ph}\left(\frac{T}{T_C}\right)^p,$$

where $\beta = 4ln2/[\sqrt{(ln^2(2\pi g) + 64/(\pi^2 g))} + ln(2\pi g)]$, $g = e^2 R_s/(2\pi^2\hbar)$, α_{e-e} and α_{e-ph} are material-dependent constants, p is the power index, which is in the range of 2-3 for Nb films, as shown previously in Ref. [12].

Results and Discussion

Fig. 1, *a* shows the dependence of the sheet resistance R_s upon temperature for all samples. One can see that the passivated samples have lower R_s and higher values of the critical temperature T_c than the uncovered samples. This observation means that 5 nm-Si layer protects films from unintentional oxidation.

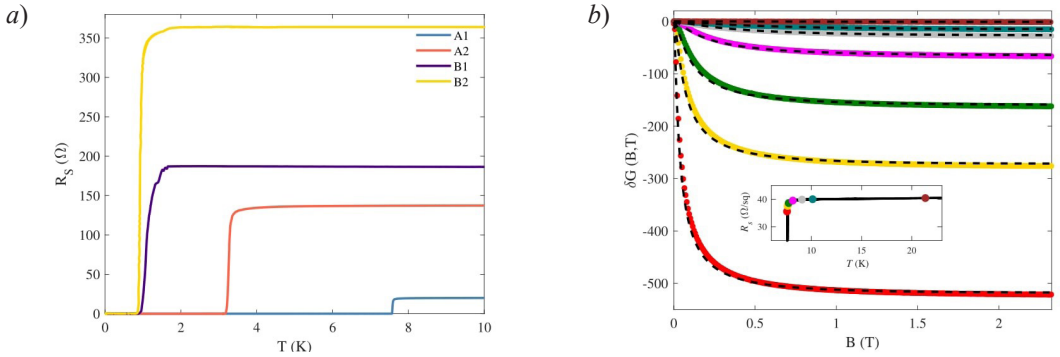

Fig. 1. The dependence of the sheet resistance R_S upon temperature for all investigated samples (*a*); The normalized magnetoconductance $\delta G(B,T)$ versus magnetic field for a representative sample (A1) (*b*); Different colors of the curves correspond to different operating temperatures marked on the $R_S(T)$-curve in the inset. The dashed black lines represent the fits by Eq.(2).

In Fig. 1, *b* we plot the normalized magnetoconductance for a representative sample A1. The magnitude of the phase-breaking time at each operating temperature is deduced from the fits of the experimental data by Eq.(2) (the dashed black lines in Fig. 1).

Fig. 2 shows the phase-breaking time τ_ϕ as a function of temperature for all studied samples. We fit the experimental dependence $\tau_\phi(T)$ with Eq.(3) (dashed black lines) using $\alpha_{e\text{-}ph}$, p, and τ_s as fitting parameters. The best-fit values, which defined the electron-phonon time $\tau_{e\text{-}ph}$ ($\alpha_{e\text{-}ph}^{-1}$ and p), are listed in Table 1. One can see that the best-fit values of electron-phonon time at the T range under study are much smaller than the estimated values of the electron-electron time. Thus we exclude electron-electron scattering from further analysis. Since τ_s is supposed to be a temperature independent parameter and $\tau_{SC} \sim \ln(T)/T$, we assume that the increase in τ_ϕ with

against decreasing of T is determined by the electron-phonon inelastic scattering time. First of all, we observe the close power-law T-dependence of τ_ϕ for the passivated samples ($\tau_\phi(T) \sim T^{-2.5}$ for A1 and $\tau_\phi(T) \sim T^{-1.5}$ for A2), meanwhile τ_ϕ for the uncovered samples does not show a pronounced dependence on T. The observed results for $\tau_{e\text{-}ph}(T)$ in the passivated samples are also close to previous reported data for thin Nb films [12]. The sign of saturation in T-dependence of τ_ϕ is observed for A2, B1, and B2 samples and can be explained by the finite value of τ_s (see Table 1). Now, we can compare τ_s derived from τ_ϕ with τ_s obtained from the quantitative analysis of suppression of T_c in Nb films [13].

The estimated value of τ_s for passivated sample A2 is an order of magnitude longer than value of τ_s reported in [13], which indicates that the magnetic disorder cannot be the dominant factor in this film. In additional, we assume that the suppression of T_c with the film thickness in the passivated samples can be related to the inverse proximity effect due to metallic silicide at the Nb-Si interface [3] rather than the magnetic disorder [13].

In contrast, we observe the enhanced phase-breaking rate τ_ϕ^{-1} for the uncovered samples B1 and B2, which evidences an additional phase-breaking mechanism. We also notice that the low-temperature value of $\tau_\phi \approx 1.5$ ps is consistent with the spin-flip scattering time τ_s in Nb reported in [13]. This result, together with the observed decrease of τ_ϕ and the saturation in $\tau_\phi(T)$-dependence, indicates that the electron dephasing in the uncovered samples may be caused by the magnetic disorder in the native oxide layer [6]. It is the worth remark that the magnetic disorder concentrated in native Nb oxide is known to be a source of parasitic magnetic flux noise in uncovered Nb-based superconducting quantum interference devices [14] and power-independent losses in Nb-based resonators [15].

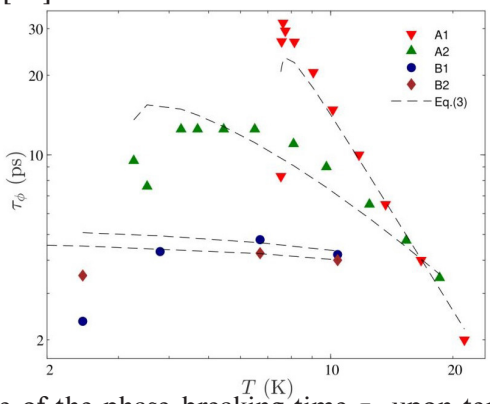

Fig. 2. Temperature dependence of the phase-breaking time τ_ϕ upon temperature extracted from the magnetoconductance measurements. The data are plotted with symbols on a log-log scale

Conclusion

We investigated the influence of the Si passivating layer on the electron phase-breaking rate in ultrathin Nb films. We observed the power-law type $\tau_\phi(T)$-dependence in the passivated Nb samples and a tendency towards saturation in the $\tau_\phi(T)$-dependence for the uncovered Nb samples. The latter may indicate the presence of the magnetic disorder in the native niobium oxide on the Nb surface. The study can be useful for the design of microelectronic Nb-based devices.

REFERENCES

1. **Tamir I., Trahms M., Gorniaczyk F., F. von Oppen, Shahar D., Franke K. J.,** Direct observation of intrinsic surface magnetic disorder in amorphous superconducting films, Physical Review B, 105 (2022) L140505.

2. **Abrikosov A., Gorkov L.,** Contribution to the theory of superconducting alloys with paramagnetic impurities, Sov. Phys. JEPT 12, 1243 (1961).

3. **Delacour C., Ortega L., Faucher M., Crozes T., Fournier T., Pannetier B., Bouchiat V.,** Persistence of superconductivity in niobium ultrathin films grown on r-plane sapphire, Physical Review B, 83 (2011) 144504.

4. **Rogachev A., Wei T.-C., Pekker D., Bollinger A.T., Goldbart P., Bezryadin A.,** Magnetic-field enhancement of superconductivity in ultranarrow wires, Physical Review Letters, 97 (2006) 137001.

5. **Proslier T., Zasadzinski J. F., Cooley L., Antoine C., Moore J., Norem J., Pellin M.,** Gray K.E., Tunneling study of cavity grade Nb: Possible magnetic scattering at the surface, Applied Physics Letters, 92 (2008) 212505.

6. **Vranken G., C. Van Haesendonck, Bruynseraede Y.,** Esshanced magnetic surface scattering of weakly localized electrons, Physical Review B, 37 14 (1988) 8502.

7. **Pierre Y F. Birge N.O.,** Dephasing by Extremely Dilute Magnetic Impurities Revealed by Aharonov-Bohm Oscillations, Physical Review Letters 89, 20 (2002) 206804.

8. **Hikita M., Tajima Y., Tamamura T.,** Weak localization, fluctuation, and superconductivity in thin Nb films and wires, Physical Review B, 42 (1) (1990) 118.

9. **Glatz A., Varlamov A. A., Vinokur V. M.,** Fluctuation spectroscopy of disordered two-dimensional superconductors Physical Review B, 84 (2011) 104510.

10. **Rosenbaum R.,** Superconducting fluctuations and magnetoconductance measurements of thin films in parallel magnetic fields, Physical Review B, 32 4 (1985) 2190.

11. **Lopes dos Santos J. M. B., Abrahams E.,** Superconducting fluctuation conductivity in a magnetic field in two dimensions, Physical Review B, 31 (1985) 172.

12. **Gershenzon E. M., Gershenzon M. E., Gol'tsman G. N., Lyul'kin A.M., Semenov A. D., Sergeev A. V.,** Electron-phonon interaction in ultrathin Nb films, JETP, 70 3 (1990) 505.

13. **Samsonova A. S., Zolotov P. I., Baeva E. M., Lomakin A. I., Titova N. A., Kardakova A. I., Goltsman G. N.,** Signatures of Surface Magnetic Disorder in Niobium Films, IEEE Transactions on Applied Superconductivity, 31 5 (2021) 7000205.

14. **Kumar P., Sendelbach S., Beck M. A., Freeland J. W., Wang Zhe, Wang Hui, Yu Clare C., Wu R. Q., Pappas D. P., McDermott R.,** Origin and reduction of 1/f magnetic flux noise in superconducting devices, Physical Review Applied, 6 (2016) 041001.

15. **Altoé M. V. P., et al.,** Localization and Mitigation of Loss in Niobium Superconducting Circuits, PRX Quantum, 3 (2022) 020312.

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