Experimental Evidence of One-Dimensional Plasma Modes in Superconducting Thin Wires

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We have studied niobium superconducting thin wires deposited onto a $SrTiO_3$ substrate. By measuring the reflection coefficient of the wires, resonances are observed in the superconducting state in the 130 MHz to 4 GHz range. They are interpreted as standing wave resonances of one-dimensional plasma modes propagating along the superconducting wire. The experimental dispersion law, ω versus q, presents a linear dependence over the entire wave vector range. The modes are softened as the temperature increases close the superconducting transition temperature. Very good agreement is obtained between our data and the predicted dispersion relation of one-dimensional plasma modes.

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Quantum phenomena in mesoscopic physics such as tunneling effects, quantum fluctuations, or decoherence processes are intimately related to the properties of the environment. Its effects on quantum systems were extensively discussed in the last two decades. The dissipative environment was taken into account in the seminal Caldeira-Leggett study in order to treat the macroscopic quantum tunneling in a titled washboard potential [1]. Slightly afterwards a quantum phase transition was predicted for Josephson junctions in the presence of a resistive environment [2].

In most Josephson junction experiments, the dissipative environment corresponds to the measurement circuits and is therefore extrinsic to the quantum system. In contrast, in thin superconducting wires, the environment is intrinsic to the system. The related modes are the one-dimensional (1D) plasma modes propagating along the wire. They were predicted for the first time in a superconducting wire by Kulik [3] and later analyzed by Mooij and Schön using a nonequilibrium superconductivity model [4]. The restoring force is the long-range Coulomb interaction. Because of the restricted geometry, the charge mode is not shifted to the bulk plasma frequency and has a soundlike dispersion relation with a velocity v_p. Because of the gapless dispersion law of the environmental modes, quantum fluctuations in superconducting thin wires are expected to show critical behavior [5] and a new quantum superconductor-insulator phase transition has recently been predicted [6]. The driving parameter of the phase transition is the friction term coming from the interaction between the quantum system and the environmental modes. When a finite length is considered, a gap in the plasma dispersion appears at low energy because the wavelength cannot exceed twice the wire length. The critical behavior is modified and a length criterion ($L_c \sim \hbar v_p / k_B T$) was proposed [6] separating the long wire regime where plasma modes are the environmental modes, from the short wire regime where a full analysis of the external circuit must be taken into account. To our knowledge, only three experiments [7–9] have observed critical behavior in very thin superconducting wires but finite length effects were not investigated.

In a thin superconducting loop closed by a Josephson junction, quantum fluctuations of the propagating plasma modes are predicted to renormalize the Josephson energy of the junction [10]. Furthermore, these collective excitations are expected to modify IV characteristics of normal metal-superconductor tunnel junction [11,12]. In Josephson junction arrays the plasma modes, also called spin waves, can affect the quantum dynamics of vortices [13–15].

Although many theoretical and experimental works have pointed out the importance of one-dimensional (1D) plasma modes in thin superconducting wires as environmental modes, no experiments have succeeded in observing them yet. Indeed up to now, to our knowledge, only two-dimensional plasma modes have been measured in superconducting granular aluminum films [16], later in YBCO films [17], and more recently in superconducting wire networks [18].

In this Letter, we report the first experimental evidence of propagating 1D-plasma modes in superconducting wires. The wires were deposited onto a strontium titanate ($SrTiO_3$) crystal. The configuration "superconducting film/$SrTiO_3$" has been proven to be a *model experimental system* to study general properties of plasma modes [16,18]: in fact superconducting properties give a very weak damping of plasma oscillations, moreover the high dielectric constant of the $SrTiO_3$ ($\epsilon_m \approx 10^4$ at low temperatures) reduces their energy by 2 orders of magnitude.

Three different wires, A, B, and C were measured. Each one was deposited onto a (110) $SrTiO_3$ substrate of thickness $H = 0.3$ mm. The wires were obtained from very thin niobium films of about 10 nm thickness evaporated in an ultrahigh vacuum chamber at room temperature. A

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5 nm-thin layer of silicon was then deposited in the same vacuum in order to protect the niobium during the lithography process and to prevent niobium oxydation (no aging was observed after 1 yr). The wire pattern was defined on a 130–200 nm thick negative Nover [19] resist layer by electron-beam lithography. Both silicon and niobium layers were etched in a SF_6 plasma. Next the Nover resist was removed by oxygen plasma leaving the niobium pattern. The dimensions of the wires such as their width W, thickness t, and total length L, are given in Table I. In order to perform electrical bonding, the wire is widened to a 30 μm width over a 100 μm length at its two extremities.

Table I summarizes the main geometrical parameters and physical properties of the three different measured wires. The critical temperature of the superconducting transition was obtained from transport measurements and taken at the midpoint of the resistive transition. The film resistivity ρ was measured just above the superconducting transition. The penetration depth $\lambda_{\mathrm{th}}(0)$ was derived from the BCS dirty limit model $\lambda_{\mathrm{th}}(0) = \lambda_{\mathrm{L}}(0)\,(\xi_0^l/l)^{1/2}$, where $\lambda_{\mathrm{L}}(0) = 37$ nm is the London length, $\xi_0^l = 62$ nm$(9.25\ \mathrm{K}/T_c)$ the modified Pippard coherence length [20], and l the mean free path deduced from the resistivity by taking for niobium $\rho l = 0.72\ 10^{-5}\ \mu\Omega\ \mathrm{cm}^2$ [21].

In order to observe plasma mode resonances, reflection coefficient measurements were performed in the 130 MHz to 4 GHz range using an HP8720B vector analyzer. A cryogenic 50 Ω coaxial cable guides the microwave between the vector analyzer and the sample. The excitation of plasma modes is realized by injecting external charges into one extremity of the superconducting thin wire at the microwave frequency. The electrical contact between the wire and the inner conductor of the coaxial line is made by means of a 20 μm-diameter aluminum bonding wire. The "superconducting wire/$SrTiO_3$" block is isolated from electrical ground plane by a thin Teflon slab.

Since similar results have been obtained on the three different samples, only sample A will be reported in detail. Typical reflection coefficient versus frequency is plotted in Fig. 1 between 130 MHz and 2 GHz. Resonances show two distinct behaviors. Above about 1.5 GHz, large resonant peaks are observed. They are weakly temperature dependent and exist both in the normal and the superconducting state. These resonances are related to dielectric modes inside the $SrTiO_3$. They appear above the cutoff frequency of the transverse-electric mode which is estimated at about 1.5 GHz for the configuration used in this experiment. Much more interesting are the resonances which appear below 1.5 GHz. Their amplitude and frequency are strongly temperature dependent. As the temperature increases, their peaks shift towards lower frequency, their amplitude decreases, and their width increases. In the normal state, these resonances disappear.

Only two possible modes could explain the resonances below 1.5 GHz: the transverse electromagnetic (TEM) modes and the 1D plasma modes. Confusion between these two modes could be made because they both have similar properties such as a quasilinear dispersion law and a temperature dependence related to the superfluid density. However, fundamental differences exist between them. TEM modes need two conductors to propagate. Their dispersion relation does not depend on the conductors' dimensionality. In the case of two superconducting thin films the dispersion relation of propagating TEM modes has been derived for the first time by Swihart [22] and later observed by Mason *et al.* [23]. For such systems the long wavelength charge fluctuations in one conductor are coupled to charge fluctuations in the other conductor, leading to a short-range Coulomb interaction of the dipole type. On the contrary, plasma modes need only one conductor to propagate. In the case of a wire the long wavelength charge fluctuations are screened inside the wire itself, giving an effective long-range Coulomb interaction corresponding to the 1D case.

The following analysis of the experimental configuration can explain why TEM modes should not be taken into account to interpret our experimental results. The superconducting wire/$SrTiO_3$/teflon slab/ground plane structure [24] corresponds to a microstrip whose inner conductor is the wire and is separated from the ground plane by $SrTiO_3$ and Teflon slab dielectrics. The TEM mode related to this structure is determined by the unit-length inductance L_l and capacitance C_l [25]. The capacitance corresponds to the capacitance between the wire and the ground plane through the two dielectrics. By measuring the impedance of the wire at 130 MHz using the network analyzer, the capacitance could be deduced, $C_l \approx 0.45$ nF/m. Since the wire is superconducting, the inductance L_l is the sum of two terms: one is related to the kinetic inductance, estimated at about $L_K \approx 5.2\ \mu$H/m for a penetration depth of about 0.5 μm; the other is related to the magnetic inductance of the microstrip ($L_m \approx 1.3\ \mu$H/m) [25]. For such parameters, the phase velocity of the TEM modes, given by $1/\sqrt{L_l C_l}$, is roughly 2×10^7 m/s. Thus, the first resonance related to the TEM mode propagating along the wire is expected at about

TABLE I. Characteristics of the different niobium wires.

Samples	t (nm)	W (μm)	L (mm)	T_c (K)	ρ ($\mu\Omega$ cm)	l (nm)	ξ_0^l (nm)	$\lambda_{\mathrm{th}}(0)$ (μm)	$\lambda_{\mathrm{exp}}(0)$ (μm)
A	12	5.0	2.2	5.19	55	1.3	110	0.34	0.50
B	11	3.0	2.25	6.68	32.4	2.2	86	0.23	0.21
C	10	6.0	2.38	8.84	16.8	4.3	65	0.14	0.14

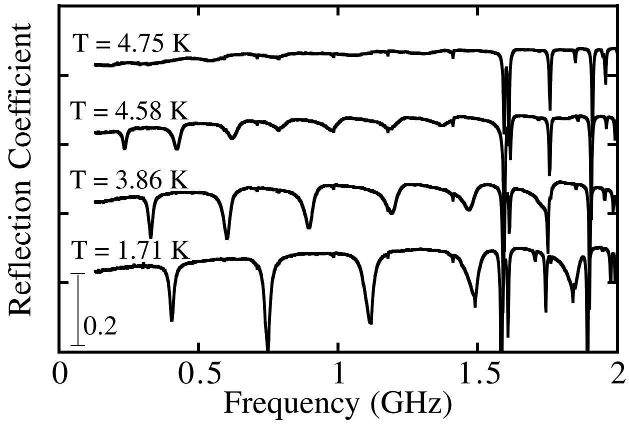

FIG. 1. Reflection coefficient versus frequency at different temperatures. A vertical shift of the different curves has been introduced for clarity.

4 GHz, 1 order of magnitude higher than the observed ones. Therefore standing wave resonances of TEM modes cannot explain the resonances measured below 1.5 GHz.

Hence we will discuss the observed resonances as standing wave resonances of 1D plasma modes. Indeed as it was already shown in a previous study [16], the wave vectors associated to plasma resonances obey the $qL = n\pi$ selection rule for standing waves, where n is an integer indexing the different resonances. An experimental ω vs q plasma dispersion relation is therefore obtained. Figure 2 presents the dispersion law of sample A for different temperatures. The linear dependence of the dispersion relation is observed over the entire wave vector range and for temperatures going from 1.5 K to very close to T_c. As the temperature increases, the modes are strongly softened. The mode velocity varies from 2×10^5 m/s near T_c up to 1.5×10^6 m/s at low temperature, but is always slower than the light velocity in the $SrTiO_3$. Above T_c, no dispersion curve exists because of the disappearance of the resonances.

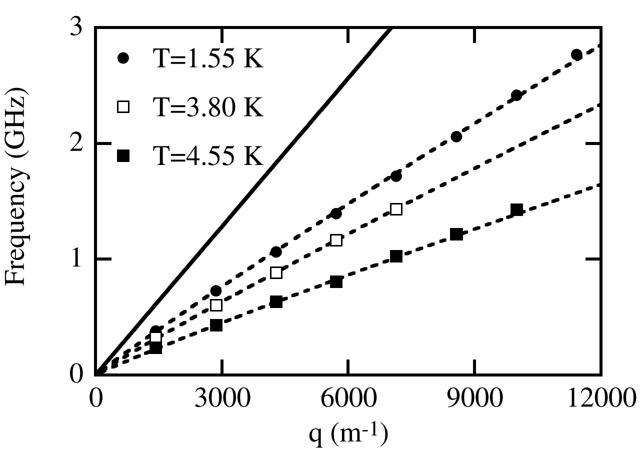

FIG. 2. Dispersion relation of sample A measured at three different temperatures (points) and fitted by the theoretical dispersion law given by Eq. (1) (dashed lines). Light dispersion inside the $SrTiO_3$ (continuous line) is plotted for comparison.

Theoretical studies on plasma modes in superconducting wires [34] predict a quasilinear dispersion relation if the radius r_0 of the wire is much thinner than the penetration depth, $\lambda(T)$, and the wavelength [$r_0 \ll \lambda(T)$ and $qr_0 \ll 1$]. The dispersion relation of the plasma modes is then given by

$$\omega_p^2 = \frac{{r_0}^2}{\epsilon_0 \mu_0 \epsilon_m \lambda^2(T)} \tilde{q}^2 \ln[1/(\tilde{q} r_0)], \qquad (1)$$

where $\tilde{q} = \sqrt{q^2 - \mu_0 \epsilon_0 \epsilon_m \omega_p^2}$ is the parameter characterizing evanescent length inside the dielectric, taking into account retardation effects. Such theoretical results were obtained for a cylindrical shaped wire embedded in an infinite isotropic medium of dielectric constant ϵ_m.

The experimental configuration presented here shows some important differences with the one considered in the theoretical derivations. Indeed the $SrTiO_3$ is finite size and a ground plane is present close to the superconducting wire. One-dimensional plasma modes are very sensitive to the finite dimension of the sample because of the long-range Coulomb interaction which extends up to a few millimeters if very low energy plasma modes are considered. Their propagation may thus be expected to be strongly modified.

In order to take into account these perturbations we have derived, in a previous work [24], plasma modes dispersion relation of a wire in the real experimental configuration. Two simplifications were applied. First, the $SrTiO_3$ dielectric constant was assumed isotropic with an average value $\epsilon_m = (\epsilon_{001}\epsilon_{110}\epsilon_{1\bar{1}0})^{1/3}$. Second, the rectangular wire was approximated by a cylindric wire of radius r_0 with cross section $\pi r_0^2/2 = Wt$ and half-immersed in the semispace occupied by the $SrTiO_3$. Because of the very high dielectric constant of $SrTiO_3$ ($\epsilon_m \approx 12\,500$ for sample A), it was possible to take into account the finite size of the experimental configuration. As a result, the derived dispersion relation of our sample configuration [24] was proven to be well described by the predicted 1D plasma modes one, Eq. (1), as long as the evanescent length is smaller than twice the $SrTiO_3$ thickness ($2\tilde{q}H > 1$). This allowed us to conclude that the experimental setup represents an optimal configuration for the study of plasma modes in superconducting wires.

The comparison between the experimental dispersion law and the theoretical one given by Eq. (1) is shown in Fig. 2. The theoretical quasilinear 1D plasma mode dispersion fits very well the experimental one for all the temperatures and over the entire wave vector range. The deviation between the predicted square root logarithmic dependence and the linear one is about 2.5% in the range of wave vectors accessible by the experiment. It is thus too small to be clearly observed in the experimental dispersion curves.

Since ϵ_m is measured independently using the dielectric resonances [26], $\lambda(T)$ is the only free parameter. The

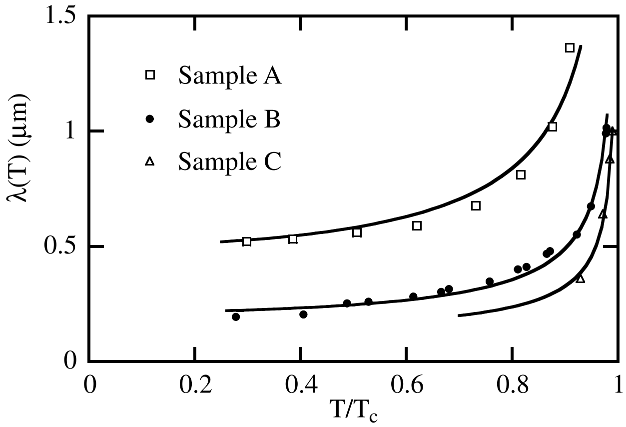

FIG. 3. Experimental penetration depths (dots) deduced from the fit of Eq. (1) as a function of the reduced temperature T/T_c. Solid lines are obtained from $\lambda(T) = \lambda_{\exp}(0)/\sqrt{1 - (T/T_c)^2}$ with $\lambda_{\exp}(0)$ as adjustable parameter (see values in Table I).

experimental penetration depth extracted from the fit versus the reduced temperature T/T_c is plotted in Fig. 3 for the three different samples. We notice that the required condition $2\tilde{q}H > 1$ is fullfilled for samples A and B over all the temperature range but not for sample C below 8 K justifying that the penetration depth of sample C is plotted only near T_c. As the temperature increases close to T_c, the penetration depth diverges. At low temperatures ($T/T_c < 0.5$), $\lambda(T)$ saturates. The temperature dependence cannot be well fitted by the Gorter-Casimir law but by an equivalent one: $\lambda(T) = \lambda_{\exp}(0)/\sqrt{1 - (T/T_c)^2}$ where $\lambda_{\exp}(0)$ is the only free parameter. The same temperature dependence has also been found in previous studies on niobium wire networks [18,26]. The penetration depths at $T = 0$ K obtained from the fit, $\lambda_{\exp}(0)$, are summarized in Table I for the three samples. These experimental values are consistent with the penetration depth derived using the BCS dirty limit.

In the following, we will explain why our system can be regarded as one dimensional. The wire is not 1D in the sense of the superconductivity because the estimated coherence length using the dirty limit [$\xi(0) \approx 8$ nm] is very small compared to the wire width. It is no more 1D for transverse charge distribution since the Thomas-Fermi length (about 0.4 nm for niobium) is always very small compared to the thickness and the width of the wire. The 1D behavior appears for the longitudinal charge distribution and can be explained by the two following properties. The supercurrent distribution is homogeneous in the wire section [$Wt \ll \lambda^2(T)$]. Moreover the Coulomb interaction which generates the observed plasma modes is due to its very long-range part ($q^{-1} \approx 1$ mm) and therefore can be described by its one-dimensional Coulomb potential [$U^{1D}_{\text{Coulomb}} \approx ln(1/qr_0)$].

In conclusion, one-dimensional plasma modes have been observed for the first time by measuring the reflection coefficient of thin niobium wires. By using a very high dielectric constant substrate, the strontium titanate, the long-range Coulomb interaction is strongly weakened, reducing by 2 orders of magnitude the plasma modes energy. A dispersion law has been obtained which shows a linear dependence. Moreover, the plasma modes are softened as the temperature increases close to the superconducting transition temperature. Both the dispersion law and the temperature dependence are well explained by the predicted plasma modes dispersion given by Eq. (1).

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