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Tunneling into thin superconducting films: Interface-induced quasiparticle lifetime reduction

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ABSTRACT

Scanning tunneling spectroscopy measurements of superconducting thin lanthanum films grown on a normal metal tungsten substrate reveal an extraordinarily large broadening of the coherence peaks. The observed broadening corresponds to very short electron-like quasiparticle lifetimes in the tunneling process. A thorough analysis considering the different relaxation processes reveals that the dominant mechanism is an efficient quasiparticle relaxation at the interface between the superconducting film and the underlying substrate. This process is of general relevance to scanning tunneling spectroscopy studies on thin superconducting films and enables measurements of film thicknesses via a spectroscopic method.

In tunneling experiments with superconducting electrodes, the differential conductance dI/dV is related to the superconducting density of states (DOS). In early studies, planar tunnel junctions with oxide layers [1–5] or point contacts [6] were utilized to determine superconducting properties like the energy gap Δ. With the ability to perform low-temperature scanning tunneling spectroscopy (STS) in ultra-high vacuum (UHV), it has become possible to probe *in situ* fabricated superconducting thin films with unprecedented control over the properties of the tunneling barrier interface, and to determine Δ with atomic-scale spatial resolution [7–12].

In such experiments, dI/dV is broadened at the coherence peaks if the lifetime τ of the quasiparticle states the electrons tunnel into is on the order of $\hbar/\Delta$. Such lifetime effects have been observed since the 1960s [1–4] and are often ascribed to electron-phonon (e-ph) coupling-induced relaxation and recombination of quasiparticles into the superconducting condensate of Cooper pairs [1,13].

However, there are a number of additional effects which lead to a similar broadening in dI/dV: thin film effects [14], thermal fluctuations [10], anisotropic energy gaps [5], electron–electron scattering [15], and inelastic scattering in dirty superconductors [11]. In modern STS literature, there is often confusion about the origin of lifetime broadening [8,9], motivating a thorough investigation.

In this work, we present an STS study of the quasiparticle lifetime effects in thin lanthanum films grown on W(110) as a model system. In an earlier publication [12], we presented our findings about Δ_{La} and the superconducting transition temperature T_c for La films between the bulk limit and the thin film limit. Here, we focus on the broadening parameter Γ_{La} [1]. We observe surprisingly large values of Γ_{La}, a monotonous increase with the inverse film thickness $1/d$, and a decrease with Δ_{La}. These findings are evaluated taking into account the different physical phenomena mentioned above. We conclude that the dominant effect is an efficient relaxation of the quasiparticles at the interface to the normal metal substrate.

La films were prepared *in situ* as described in Ref. [12] and studied in a commercially available UHV STM [16] at a base temperature of $T = 1.2$ K and at an elevated temperature of $T = 4.3$ K using normal metal tungsten and superconducting Nb tips [17]. During the annealing, La forms flat-top (0001) islands in the dhcp phase in a Stranski–Krastanov growth, with a wetting layer of one monolayer in between the islands. Islands with thicknesses d in the range between $d = 2.5$ nm and $d = 140$ nm were grown [12], which covers a wide range compared to the superconductor coherence length of lanthanum (36 nm) [18]. In order to avoid lateral finite size effects, we only investigated islands with a lateral dimension much larger than the thickness and the coherence length. For the STS spectra, the differential conductivity dI/dV was recorded using standard lock-in technique, adding a modulation voltage $V_{\mathrm{mod}} = 0.04$ to 0.07 mV (RMS value, modulation frequency $\nu_{\mathrm{mod}} = 0.93$ kHz) to the bias voltage V, stabilizing the tip at a current of $I_{\mathrm{stab}} = 100$ to 150 pA and a voltage of $V_{\mathrm{stab}} = -6$ mV, opening the feedback and ramping V.

STS on La islands using normal conducting [Fig. 1(a)] or superconducting [Fig. 1(b)] tips reveals symmetric gaps with a width of $2\Delta_{\mathrm{La}}$ or $2(\Delta_{\mathrm{La}} + \Delta_{\mathrm{tip}})$, respectively, around the Fermi level E_{F} due to the superconductivity of the probed islands. Note that by the use of the superconducting tip, the energy resolution is strongly enhanced with respect to the thermal limit [19,20]. The facts that the coherence

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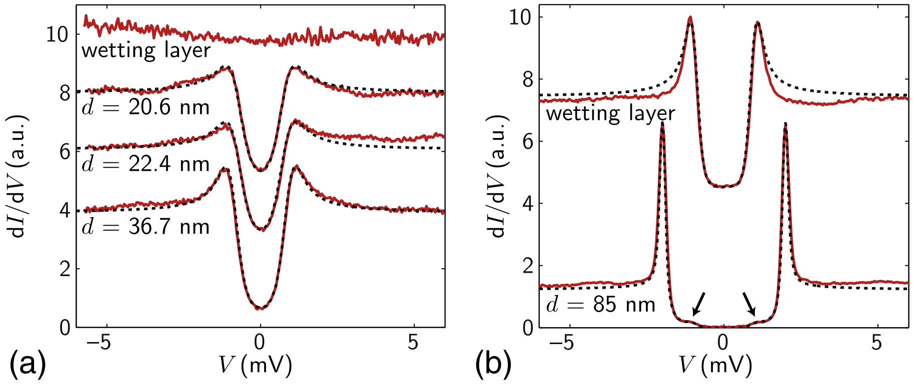

Fig. 1. STS spectra (red solid lines) were taken on La islands with thicknesses d as indicated and on the wetting layer to characterize the tip DOS, using (a) normal metal and (b) superconducting tips. Fitted calculations (dotted curves) are in excellent agreement with the experimental data and yield $\Delta_{\mathrm{La}}(T, d)$ and $\Gamma_{\mathrm{La}}(T, d)$. (a) Experimental parameters: $V_{\mathrm{mod}} = 0.06$ mV, $T = 1.23$ K. Model parameters: $V_{\mathrm{mod,eff}} = 0.10$ mV, $\Delta_{\mathrm{La}} = 0.79$, 0.80, 0.89 meV, $\Gamma_{\mathrm{La}} = 0.25$, 0.25, 0.14 meV (from top to bottom). (b) Experimental parameters: $V_{\mathrm{mod}} = 0.07$ mV, $T = 1.14$ K. Model parameters: $V_{\mathrm{mod,eff}} = V_{\mathrm{mod}}$, $\Delta_{\mathrm{tip}} = 0.94$ meV, $\Gamma_{\mathrm{tip}} = 0.01$ meV, $\Delta_{\mathrm{La}} = 1.05$ meV, $\Gamma_{\mathrm{La}} = 0.07$ meV. The curves are vertically shifted for better visibility by (a) 2 a.u. and (b) 4.5 a.u. Arrows: see text. (© IOP Publishing. Reproduced with permission from Fig. 2 in [12] All rights reserved). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

peaks are rather wide and that there is considerable zero-bias conductance indicate strong broadening effects. In order to quantify the superconductivity and broadening via Δ_{La} and Γ_{La}, respectively, the experimental curves were each fitted with a numerically simulated dI/dV, in analogy to the working principle of the lock-in amplifier [17],

$$\frac{\mathrm{d}I}{\mathrm{d}V}(V) \propto \int_{-\pi/2}^{+\pi/2} \sin(\alpha)\, I\left(V+\sqrt{2}\,V_{\mathrm{mod,eff}}\,\sin(\alpha), T\right)\mathrm{d}\alpha. \qquad (1)$$

In this formula, I is the tunneling current,

$$I(V,T) \propto \int_{-\infty}^{+\infty} N_1(E) N_2(E+eV) \times [f(E+eV,T) - f(E,T)]\,\mathrm{d}E\,, \qquad (2)$$

$N_1(E)$ and $N_2(E)$ are the DOSs of the two electrodes, and $f(E, T)$ is the Fermi function. For the normal metal electrodes, we assume a constant DOS on the relevant energy scale. The superconducting electrodes are modeled by a Dynes-like DOS [1],

$$N_{sc}(E,\Gamma) \propto \Re\left(\frac{E - i\,\Gamma}{\sqrt{(E - i\,\Gamma)^2 - \Delta^2}}\right) \qquad (3)$$

with a lifetime broadening parameter Γ, where $\Re$ indicates the real part. The excellent fit quality (Fig. 1) permits an accurate determination of Δ and Γ for both tip and sample. While most STS studies on superconductors [8–10] fit dI/dV-curves with the derivative of Eq. (2), the approach of Eq. (1) considers a finite modulation voltage, which enables to explicitly take into account the experimental broadening induced by the temperature, the lock-in technique, and additional electronic noise via an effective modulation voltage $V_{\mathrm{mod,eff}} \geq V_{\mathrm{mod}}$. The latter has been determined for each data set by fitting spectra taken with a Nb tip on the wetting layer, which have negligible values of Γ. This allows us to accurately determine the *intrinsic* broadening parameters Γ. The resulting values of Γ_{La} [Fig. 2(a)] are of the same order of magnitude as Δ_{La} [12] and vary between 0.1 and 0.6 meV depending on the thickness d of the island with a monotonous increase as a function of 1/d.

The almost perfect reproduction of the STS spectra in the gap region by the Dynes-DOS (Eq. (3)), particularly of the in-gap shoulders which stem from the overlap of the coherence peak of one electrode with the broadening-induced non-zero in-gap DOS of the other electrode [see arrows in Fig. 1(b)], strongly suggest an unusually short quasiparticle lifetime τ as the origin of the large Γ_{La}. Other effects that lead to such a broadening, i.e., averaging over different values of Δ due to anisotropic [5] or multigap [7] superconductors, lead to an order of magnitude smaller values. Moreover, these effects offer no explanation for the Γ(d) dependence. The extracted Γ_{La} of the La islands are 10 to 60 times larger as compared to typical Γ_{tip} values found for the Nb tips [cf. Fig. 1(b)], substantiating that the broadening stems from the sample exclusively. Therefore, the measured Γ_{La} can be directly converted into the quasiparticle lifetime in the sample via $\tau_{\mathrm{La}} = \hbar/\Gamma_{\mathrm{La}}$. This lifetime is plotted logarithmically as a function of the experimentally determined $\Delta_{\mathrm{La}}(T, d)/k_BT$ in Fig. 2(b), showing a monotonous increase. In the remaining part of this article, the dominant mechanisms leading to the measured quasiparticle lifetime in La will be discussed. The extracted lifetimes are considerably smaller than the typical lifetimes found for other conventional bulk superconductors [1,2,10,21] but comparable

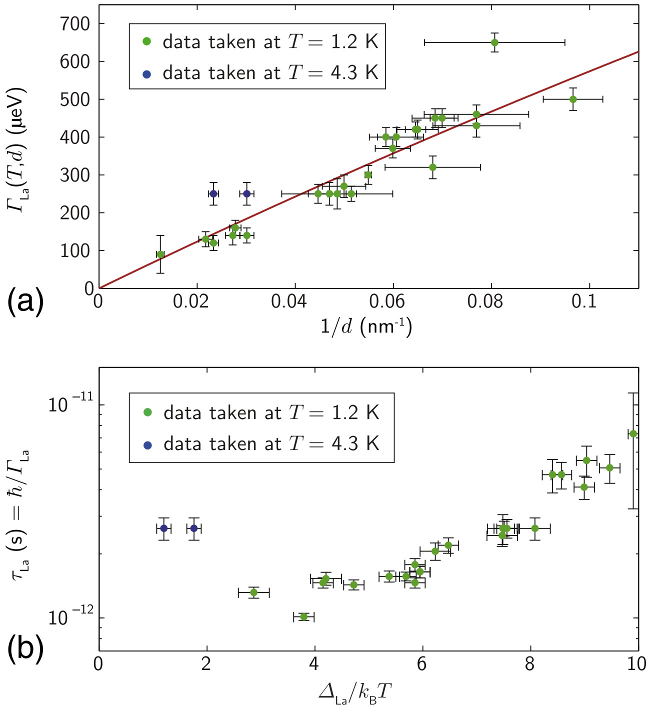

Fig. 2. (a) Dependence of $\Gamma_{\mathrm{La}}(T, d)$ on the inverse film thickness 1/d. The fit (red line) is discussed in the text. (b) Experimentally determined quasiparticle lifetime $\tau_{\mathrm{La}} = \hbar/\Gamma_{\mathrm{La}}(T, d)$ plotted logarithmically vs. $\Delta_{\mathrm{La}}(T, d)/k_BT$. Green and blue data points indicate measurements taken at 1.2 K and 4.3 K, respectively. The error bars are due to uncertainties in the measured film thickness and in the fit parameters. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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