Reactance at the superconducting transition due to dissipation

David Perconte, 1 Samuel Mañas-Valero, 2 Eugenio Coronado, 2 Isabel Guillamón, 1, 3 and Hermann Suderow 1, 3

1 Laboratorio de Bajas Temperaturas y Altos Campos Magnéticos, Departamento de Física de la Materia Condensada, Instituto Nicolás Cabrera and Condensed Matter Physics Center (IFIMAC), Universidad Autónoma de Madrid, E-28049 Madrid, Spain
2 Instituto de Ciencia Molecular (ICMol), Universidad de Valencia, Catedrático José Beltrán 2, 46980 Paterna, Spain
3 Unidad Asociada de Bajas Temperaturas y Altos Campos Magnéticos, UAM, CSIC, Cantoblanco, E-28049 Madrid, Spain

The superconducting transition leads to a sharp resistance drop in a temperature interval that can be a small fraction of the critical temperature $T_c$. A superconductor exactly at $T_c$ is thus very sensitive to all kinds of thermal perturbations, including the heat dissipated by the measurement current. Here we show that the interaction between electrical and thermal currents leads to a reactance at frequencies of order of tens of Hz at the resistive transition of single crystals of the layered material 2H-NbSe$_2$. We obtain the bolometric parameters of layered 2H-NbSe$_2$ and show that it can be used as a sensitive detector. We find that understanding the resistive transition requires taking into account the electric and thermal environment of the sample. By measuring the reactance under magnetic fields and at high currents, we obtain the heat generated by out of equilibrium quasiparticles.

INTRODUCTION

Since the discovery of superconductivity by H. Kamerling-Onnes over a century ago, the resistive transition continues to fascinate researchers, in spite of being now a routine measurement in many laboratories all over the world[1, 2]. A usual way of observing the resistive transition is to use a current source and measure a voltage that drops to zero at the transition. This drop occurs over a finite temperature interval, whose size depends on the characteristics of the superconductor, in particular the relevance of dissipation in form of fluctuations. The size of this temperature interval can be estimated through the Ginzburg-Levanyuk number $G_i \sim \left( \frac{T_c}{H_c} \right)^{\frac{3}{2}}$, which compares the critical temperature $T_c$ with the superconducting condensation energy of a volume of order of the superconducting coherence length ($= H_c^2 \xi^3$, with both the coherence length $\xi$ and the thermodynamic critical field $H_c$ at zero temperature)[3–5]. In low dimensional superconductors with a high $T_c$, such as for example the cuprate materials, $G_i$ increases to $10^{-1}$ and the transitions are considerably broadened, with a resistivity dropping over a temperature range as large as a several % of $T_c$[6]. However, in low $T_c$ superconductors, $G_i$ can be as small as $10^{-14}$[5]. Even in layered low $T_c$ materials such as 2H-NbSe$_2$ (where $T_c = 7.2$ K), $G_i$ is of order of $10^{-6}$ and the transition is sharp, usually occurring over a temperature interval below the % level of $T_c$[7, 8].

Sharp transitions provide a situation that has a number of consequences. First, the sample becomes an extremely sensitive thermometer. This is used in superconducting transition edge sensors (TES) for X-ray and $\gamma$-ray detection[9–14]. TES are usually based on superconducting amorphous alloys[9, 10, 15–19]. Energy resolution, operating temperature and other parameters are tuned to obtain the optimal properties in each application. Arrays of TES detectors are planned to be used for astrophysical X-ray imaging in space[20] where detector size and weight are critical. Second, heat dissipation does not occur immediately but with a, usually slow, time constant. In principle, this might lead to the appearance of AC effects. Although such effects have been used to characterize TES[21, 22], they have remained largely unaddressed in the literature of the resistive transition until now[5, 23]. And third, at the transition it’s easy to create out-of-equilibrium quasiparticles in an applied magnetic field and with a finite current[24–26]. Then, normal quasiparticles coexist with Cooper pairs in a quantum liquid out of equilibrium whose thermal behavior is still largely unknown[27].

Here we present impedance measurements of a 2H-NbSe$_2$ single crystal. We find a sharp peak in the reactance at the transition in a frequency range between 1 Hz and 1 kHz. We study the evolution of the peak with applied current and magnetic field. We find that the peak is due to heat dissipation. We study the electrical and thermal properties of the whole environment and determine how the reactance is influenced by current and magnetic field. We obtain the parameters of 2H-NbSe$_2$ for its use in a TES device and show that the reactance measures the heat deposited by out of equilibrium quasiparticles in the superconductor.

EXPERIMENT AND METHODS

2H-NbSe$_2$ crystals were grown by iodine vapor transport, the crystals display the usual 2H-NbSe$_2$ properties: a feature at the charge density wave transition in
FIG. 1. We show in (a) a schematics of our experiment. In the central panel, we show voltage vs current curves in the superconducting phase (blue) and in the normal phase (red). The sample (rectangle at the left) is connected to the circuit and has a resistance $R$ that strongly varies with current and temperature. The sample is coupled to the a fixed temperature bath through the connections at the sample holder and eventually a small amount of exchange gas. This coupling is schematically indicated by the blue arrow. The heat flowing through this coupling is $\delta Q$. The current source used for the impedance measurement is schematically represented on the bottom right. The AC current used for the measurement produces Joule heating ($P_{\text{Joule}}$) in the sample (green arrow). In (b) we show the electrical scheme of our setup. A current source ($I_{\text{source}}$) is connected to the 2H-NbSe$_2$ sample $R(I,T)$ through wiring which has a finite resistance $R_{\text{circ}}$ and an inductance $L_{\text{circ}}$. In (c) we show the thermal scheme. An electrical power $P_{\text{Joule}}$ is introduced in the 2H-NbSe$_2$ sample and flows to the thermal bath ($P_{\text{th}}$) through the thermal connection $G$. The temperature of the bath is modified using separate heater and thermometer (not shown).

FIG. 2. In (a) we show the voltage vs current for different temperatures from blue to red: 7.08 K, 7.11 K, 7.14 K, 7.16K, 7.17 K, 7.4 K. The resistance vs temperature at 20 mA is shown in (b) in a logarithmic scale, the inset shows the reactance.

RESULTS

A typical superconducting and normal current vs voltage characteristic is shown in Fig. 1(a). As we shall see in detail below, the resistive transition is very sharp for small currents and its width increases considerably when increasing the current. The highest applied currents correspond to a current density of about $2 \times 10^6$ A/m$^2$, which is five orders of magnitude below the de-pairing current density $J_d \approx 10^{11}$ A/m$^2$[29]. The power used is of about 50 nW at the largest currents. Furthermore, we observe that, at large currents, the shape of the transition depends on the amount of the exchange gas present in the vacuum chamber. We thus have to consider heating carefully. We describe schematically the situation in Fig 1. There is a heat exchange $\delta Q$ between the sample and the Helium bath produced by the Joule power $P_{\text{Joule}}$ deposited on the sample. Both, $P_{\text{Joule}}$ and heat exchange $\delta Q$ are oscillating with time, as the current and thus Joule heating does so. The thermalization of the sample is however not immediate and does not follow exactly the oscillation in heating. Thus, $\delta Q$ can lag behind $P_{\text{Joule}}$, so that heat and electronic transport are interconnected to each other.

As we will show below, the electrical response of the sample is actually dephased by the thermal behavior.
To see this, we show in Fig. 1(b,c) a schematics of the electrical (Fig. 1(b)) and thermal (Fig. 1(c)) circuits. In Fig. 1(b) we show that the current is provided by the current source through the resistance and inductance of the wires (R_{air} and L_{air}). The inductance L_{air} is of the order of a few µH. In Fig. 1(c) we show a schematic of the sample with its heat capacity C and receiving a power P_{Joule}. The power is dissipated in form of heat P_{th} and is transferred to the thermal bath through the thermal link, whose conductivity is G. The latter is mostly related to the connection between the sample and the bath through glues and wiring.

In Fig. 2 we show voltage vs current curves as well as the real and complex parts of the impedance (resistance and reactance respectively) close to the superconducting transition. Data are taken with a frequency of 90 Hz. The I-V curves shown in Fig. 2(a) are made by increasing the AC excitation current and measuring the voltage. We find a transition from an ohmic behavior at 7.3 K to a superconducting non-linear behavior below 7.2 K. When we measure the impedance vs temperature at 20 mA, we observe the transition shown in Fig. 2(b). The transition width in the resistance is very sharp: the resistance falls about 60% of its normal phase value in merely 40 mK and then drops much more steeply. At the same time we also observe a sizeable reactance (Fig. 2(b) inset). The reactance slowly increases when the resistivity starts falling, at about 7.3 K. Then, there is a sharp increase which peaks roughly at the midpoint of the superconducting transition in the resistance and then, when the resistance shoots down in a very small temperature interval, the reactance also disappears in the same temperature interval. The reactance reaches 3.5 mΩ, when the normal state resistance is of 17 mΩ.

In Fig. 3(a,b) we show the effect of the magnetic field on the transition. The magnetic field reduces the superconducting critical temperature and broadens the resistive transition (Fig. 3(a)). The entry of vortices produces dissipation due to vortex motion[5, 7]. The bottom of the transition loses the sharp exponential drop observed at zero field and shows instead a smooth decrease with temperature. The reactance is shown in Fig. 3(b). Instead of the asymmetric slow increase and sharp decrease when decreasing temperature observed at zero field, the curve is broader and more symmetric under magnetic fields. The absence of a sharp exponential decrease on the low temperature side of the resistive transition is accompanied with a slow decrease of the reactance for decreasing temperature. Thus, the reactance seems to reflect directly the behavior seen in the resistance. The amplitude of the reactance decreases considerably with magnetic field, although this decrease saturates for high magnetic fields.

In Fig. 3(d,e) we show the effect of the current on the resistance and on the reactance. When increasing current, the resistive transition is different than with increasing magnetic field. There is a shift of T_c due to heating while the shape of the initial drop does not change. The final sharp drop when cooling becomes a shoulder at higher current and with further cooling there is an exponential decrease of the resistance. The reactance considerably increases its size when increasing the current.

Finally, in Fig. 3(g,h), we show the effect of modifying the frequency at a fixed current and for zero magnetic field. The resistance vs temperature remains with the same shape, but the reactance first increases up to about 70 Hz and then decreases when approaching 1 kHz. Thus, there is a frequency range, of the order of a few tens of Hz, where the reactance is largest.

The exchange gas pressure influences the shape of the transition. When introducing He exchange gas, we observe that the reactance vanishes for a given applied current. As we discuss below, this is due to the improved heat transport with the thermal bath due to convection by the exchange gas.

COUPLING BETWEEN THERMAL AND ELECTRONIC CONDUCTION

First, let us discuss the usual electrodynamic frequency response of superconductors. The kinetic inductance L_K provides a finite reactance in the superconducting phase[30]. We can estimate the kinetic inductance L_K using L_K = (4πλ^2)/d = 3.6 × 10^{-8} H with λ = 200 nm the penetration depth of 2H-NbSe_2[31] and d the thickness of the sample. This provides a contribution to the reactance three orders of magnitude below our observations of 3.6 × 10^{-8} mΩ at 100 Hz. Furthermore, the maximum of the kinetic impedance occurs at frequencies in the GHz range, whereas we work here at frequencies well below a kHz and the maximum in the reactance occurs at merely 70 Hz (Fig. 3(h,i)). Thus, the kinetic inductance does not explain the observed behavior.

We now consider the coupling between electronic and heat transport. When the sample is at the resistive transition with a temperature close to T_c, the oscillatory AC current going through the sample modifies the temperature of the sample. The thermal time dependent behavior is governed by the sample's heat capacity C and the thermal conductance G due to the coupling between the sample and the thermal bath. The oscillatory variations in the sample’s temperature then lead to oscillatory variations of the sample’s resistance that are dephased with respect to the applied current, leading to an out of phase voltage and thus a finite reactance at the transition.

To understand this further, let us consider the variation of the power with time, given by C dT/dt. This distributes over the heating power P_{sample}I^2 and the power going through the thermal link to the bath P_{th}. The voltage induced by the oscillatory current is given by L dI/dt (L is the sum of the inductance of the wiring and of the ki-
FIG. 3. In (a) we show the resistance vs temperature for different magnetic fields (as lines from blue to red: 0 Oe, 150 Oe, 300 Oe, 760 Oe, 1500 Oe, 2300 Oe, and 3040 Oe). In (b) we show the reactance vs temperature for the same magnetic field values. In (c) we show the reactance calculated using the model described in the text. Data in (a,b) are taken at 20 mA and a frequency of 70 Hz. In (d) we show the resistance for different values of the current (from blue to red: 5 mA, 10 mA, 15 mA, 20 mA, 25 mA, 30 mA, 40 mA and 50 mA). In (e) we show the reactance vs temperature for the same current values. In (f) we show the reactance calculated with the model described in the text. Data in (d,e) are taken at zero magnetic field and a frequency of 70 Hz. In (g) we show the resistance vs temperature for different frequencies (from blue to red: 7 Hz, 32 Hz, 64 Hz, 89 Hz, 289 Hz, 689 Hz, 989 Hz). In (h) we show the reactance for the same frequencies. In (i) we show the calculated reactance for the model in the text. Data in (g,h) are taken at zero magnetic field and a current of 20 mA.

Magnetic inductance $L_K$ of the sample). The voltage equals the voltage drop at the sample, $R_{\text{sample}}I$ plus the voltage drop at the resistances of the circuit, composed by the resistance of the current source $R_{\text{Source}}$ and the resistance of the wires $R_{\text{cir}}$. Thus, the mutual influence between heat and electronic transport can be summed up in two coupled equations, following Refs. [21, 22]:

$$-L\frac{dI}{dt} = (R_{\text{Source}} + R_{\text{cir}})I + R_{\text{sample}}I,$$  \hspace{1cm} (1)

$$C\frac{dT}{dt} = R_{\text{sample}}I^2 - P_{\text{th}},$$  \hspace{1cm} (2)

It is useful to introduce the parameters $\alpha = \frac{T}{R} \frac{\partial R}{\partial T}$ and $\beta = \frac{I}{R} \frac{\partial R}{\partial I}$, which are the logarithmic derivatives of $R$ with temperature and current [21, 22]. As shown in Ref. [22], one can then find the impedance versus frequency $Z(\omega)$:
The calculated frequency dependence of the reactance is shown in green. The order of magnitude of the reactance and its temperature dependence is similar than the ones observed in the experiment.

In the inset of Fig. 4 we show the thermal conductance \( G \) between the 2H-NbSe\(_2\) sample and the bath as a function of exchange gas pressure. We extract the thermal conductance from the dependence of the maximum in the reactance at a given exchange gas pressure. The size of the reactance is considerably affected by the pressure of the exchange gas and strongly decreases when the exchange gas pressure increases, being almost suppressed for pressures above 5 mbar. The measured dependence of the thermal conductance \( G \) due to mass flow (convection) of gas in vacuum as a function of the pressure shows a similar increase as we observe here\[33, 34\]. The order of magnitude of \( G \) corresponds to a distance of the order of a cm, which is comparable to the size of our set-up.

**DISCUSSION**

The remarkable result of our work is that we obtain a reactive response at low frequencies at a sharp superconducting transition. The reactance is the result of the mutual coupling between thermal and charge transport at the transition and can be described by a model taking into account the thermal environment.

**Measurement of the resistive transition**

This implies that the resistive transition cannot be understood solely on the basis of measurements of the resistance. The resistive transition of superconductors has been studied in depth in the limit of vanishing current, or when heat dissipation in the sample can be neglected\[5, 23, 35, 36\]. The discussion has focused on the influence of fluctuations on the conductivity. When approaching the transition from higher temperatures, fluctuations modify the conductance gradually from the normal state value until it diverges at some point. The

\[
Z(\omega) = i \omega L + R_{\text{cir}} + R(1 + \beta) + \frac{2 + \beta}{1 + i \omega \frac{CT}{CT - I^2 R \alpha}} \frac{R^2 I^2 \alpha}{(GT)^2}.
\]

The reactance is the imaginary part of \( Z, Y \):

\[
Y(\omega) = \omega L - \omega \frac{CT(2 + \beta)}{1 + \omega \frac{CT}{CT - I^2 R \alpha}} \frac{R^2 I^2 \alpha}{(GT)^2}.
\]

The reactance has a maximum at a frequency of \( \frac{CT - I^2 R \alpha}{CT} = \frac{G}{C} - \frac{I^2 R}{CT} \alpha \), which is the difference between the inverse of the thermal time constant of the system \( \frac{G}{C} \) and the ratio between the power \( I^2 R \) and \( CT \). The maximal value of the reactance vs frequency is \((2 + \beta) \frac{R^2 I^2 \alpha}{2CT}\). \( \beta \) remains below one outside the voltage and current range where the V-I curve is very steep and \( G \) remains constant with temperature, as it is related to the coupling between the sample and the thermal bath. Thus, the value of the reactance at a frequency \( \omega \) is mostly related the shape of the resistive transition, \( \alpha \) and \( CT \).

Let us discuss the frequency dependence of the impedance (Fig. 4). We present results (points) obtained roughly at the middle of the transition, at zero field and with an exchange gas partial pressure below 0.01 mbar. The calculated frequency dependence of the reactance (green line) accounts well for the observed behavior. The reactance first increases and then decreases with increasing frequency (Fig. 4) with a peak around 70 Hz.

To obtain the green line in Fig. 4 we use \( C = 4.09 \times 10^{-8} \text{ J/K}, G = 1.5 \times 10^{-5} \text{ W/K}, \alpha = 65, \beta = 15 \). The heat capacity \( C \) of our sample can be estimated through the sample size (1.6 mm \( \times \) 0.8 mm \( \times \) 14 \( \mu \)m) and the molar heat capacity of 2H-NbSe\(_2\) 400 mJ/(mol K) \[32\], we obtain \( C \approx 1.7 \times 10^{-7} \text{ J/K} \). With the value of \( G \) used we can estimate the \( dT \) produced by the Joule power in the sample and obtain about 20 mK. Using \( \alpha \), we can again estimate \( dT \) and obtain approximately the same value. The obtained \( \alpha \) and \( \beta \) are compatible with the values expected at the conditions shown in Fig. 4.
temperature range for influence of fluctuations in thermodynamic properties is approximately given by \( \frac{T_c - T}{T_c} > G_i \), which in 2H-NbSe\(_2\) is practically negligible\[37\]. However, in the conductivity fluctuations appear much earlier due to nonlinear effects, at about \( \frac{T_c - T}{T_c} > \sqrt{G_i} \), which leads to a temperature range that can cover a few tens of mK\[38\]. Indeed, at the smallest currents we observe that the resistance starts to drop a few tens of mK before the actual transition. Different contributions might modify the conductivity at zero magnetic field and zero frequency around the superconducting transition in a superconductor. First, strongly time dependent fluctuations of the superconducting order parameter, that lead, averaged over time, to bubbles with higher conductance due to time fluctuating preformed Cooper pairs and is termed the Aslamazov-Larkin contribution\[5\]. Second, the normal state density of states might show a dip already above \( T_c \)\[5\]. Third, the Maki-Thompson contribution, due to the formation of Cooper pairs at self-interfering trajectories caused by scattering at impurities\[39–41\]. In the clean limit (as we mention above, \( \ell >> \xi \) in 2H-NbSe\(_2\)), only the Aslamazov-Larkin contribution is relevant and leads to the observed decrease in the resistance above \( T_c \). Our results show that there is a finite reactance which remained unnoticed in the fluctuation range, and that this reactance considerably increases at lower temperatures and in presence of magnetic field or a current.

The reactance appears at low frequencies and thus in transport experiments that are not made exactly in DC conditions. All kinds of electronic measurements imply a change of the parameters with time, either to remove thermoelectric voltages in a usual four-wire measurement \[42, 43\] or simply to vary the temperature in regular steps. Through the power used to measure, there is a connection between the resistance and temperature, which induces a reactance when the resistance is strongly temperature dependent.

**Dissipation under magnetic fields with an applied current**

The model we use traces back the behavior of the reactance from the resistance, taking into account heating effects. And it does so remarkably well on the qualitative level, particularly at low currents and low magnetic fields.

When applying a magnetic field, vortices enter the sample. Vortices are pinned at defects and move in between pinning centers in presence of a current\[6\]. During vortex motion, the Lorentz force is compensated by a drag force which is dissipative\[24, 44–48\]. Moving vortex cores requires transforming normal quasiparticles into Cooper pairs and produces out of equilibrium quasiparticles along their path\[49\]. At large driving currents, vortices move at very high velocities, even higher than the speed of sound\[50–52\]. They can be unstable at high driving velocities, leading to additional quasiparticles\[50, 53–57\]. Their energy can be quite high and the relaxation into Cooper pairs occurs through phonon scattering and requires thus large length scales\[25, 58\].

As we have seen, when the temperature oscillates due to the AC current through the sample, the reactance is related to the heat capacity \( C \) of the sample and the thermal conduction \( G \) to the bath. We can expect that out of equilibrium heat the sample, because the thermal diffusion length scale \( L_{thermal} = \frac{\kappa}{\tau C T} \) (where \( \kappa \) is the samples’ thermal conductivity, \( \tau \) the time scale for the oscillations and \( \rho \) the density) is much larger than the sample size (about 3 mm at 70 Hz and a cm at 1 Hz). The parameter \( C \) in the reactance then measures the heat deposited by dissipation inside the superconducting phase.

We can calculate \( C \) as a function of temperature from Eq.4 by taking the temperature dependence of \( \frac{dR}{dT} \) obtained from the resistance. We start with a smooth initial curve for \( C(T) \) and vary it numerically until we obtain the measured temperature dependence of the reactance. In Fig. 5 we show \( C(T) \) at zero magnetic field (Fig. 5(a)) and under magnetic fields for low currents (Fig. 5(b)) and with large applied currents at zero field (Fig. 5(c)).

It is useful to discuss the obtained \( C(T) \) together with the temperature dependence of the resistance and of its derivative. At zero magnetic field and with a small current (Fig. 5(a)), we observe that the resistance drops continuously with decreasing temperature. But \( \frac{dR}{dT} \) does not increase smoothly until it diverges at the transition. There is in particular a small peak in \( C(T) \). For temperatures higher than this peak, the resistance is dominated by fluctuations. Below this peak, we enter the superconducting phase, but there is dissipation induced by the current. The value we find for \( C \) in the fluctuation region is comparable to the estimated heat capacity of our sample. Its temperature dependence is similar as the one observed in the heat capacity of 2H-NbSe\(_2\) using macroscopic measurements (the heat capacity of the sample increases by the same amount in the temperature range above the peak shown in Fig. 5(a) \[32\]). At the peak in \( \frac{dR}{dT} \), we also observe a small peak in \( C \). For lower temperatures, we find a finite \( C \) until the resistance and reactances become zero. When applying a magnetic field, the temperature range with a finite \( \frac{dR}{dT} \) inside the superconducting phase becomes considerably larger (Fig. 5(b)). The peak in \( C \) also becomes larger and there is a finite \( C \) inside the (larger) temperature range with vortex motion induced dissipation. If we apply a strong current at zero magnetic field, (Fig. 5(c)), the peak in \( C \) becomes even larger and there is a finite \( C \) over a substantial temperature range.

In all cases, the value of \( C \) inside the low temperature region remains of the same order. Remarkably, it is also about the same order as the expected electronic
contribution to the value of $C$ approximately at the transition temperature. In 2H-NbSe$_2$, thermal conductivity and specific heat of the sample are approximately in equal parts due to phonons and electrons in the temperature range studied here [59]. The observed value of $C$ shows that the sample is heated via the electronic excitations. Thus, via out of equilibrium quasiparticles inside the superconducting phase. When applying a strong current, we furthermore observe that $C$ remains roughly temperature independent well inside the superconducting phase (at low temperatures in Fig. 5(c)). However, when decreasing temperature, pinning becomes more effective and the resistance decreases. Thus, the power dissipated in the sample decreases too. But this does not lead to a temperature dependence of $C$, which remains of the same order (Fig. 5(c)), indicating that the heat released inside the sample remains roughly temperature independent. Thus, there is a dissipative mechanism that develops when decreasing temperature which adds up to the Joule dissipation associated with vortex motion. Dissipation by vortex motion creates local modifications of the temperature in front and at the trailing edge of moving vortices associated to the transformation between normal and superconducting regions. This provides a source of heat that add ups to Joule heating[48]. It has been shown that taking this term into account yields a better account of the flux flow resistivity[60].

We can hypothesize that this contribution becomes more important when decreasing temperature, compensating for the absence of Joule heating, although this remains a speculation without more calculations about dissipation during vortex motion. Thus, the value of $C$ inside the superconducting phase is comparable to the electronic specific heat, showing that it is due to out of equilibrium quasiparticles. It has however a constant temperature dependence, which remains difficult to explain, in view of the decreasing influence of dissipation when decreasing temperature.

On the other hand, there is a clear peak at the onset of superconductivity which develops particularly at large driving currents. We note that the observed oscillatory reactance bears some similarities to the behavior reported in two-dimensional electron gases. In that case, the oscillatory component is used to obtain the differential electronic entropy, or the energy derivative of the chemical potential[61]. The presence of a peak in $C$ could be here due to a strong change in the particle density when crossing the superconducting transition, due to the quasiparticles driven out of equilibrium by vortex motion. Again, this idea is at present just a speculation. However, the presence of the peak is clear and it certainly reflects the onset of Cooper pairing and the associated modifications in the electronic density due to dissipative phenomena.

Thus, we can conclude that there is a strong and hitherto undetected influence of heat dissipation in the transport properties close to the superconducting transition that appears in the reactance and reflects the behavior of out-of-equilibrium quasiparticles.

**2H-NbSe$_2$ as a Transition Edge Sensor**

We obtain parameters for the use of the single crystalline superconductor 2H-NbSe$_2$ as a TES, $\alpha$ and $\beta$[21, 22]. Both are comparable to the values reported in TES. This shows that 2H-NbSe$_2$, and probably other homogeneous crystalline superconductors too, can be used as TES.

Note that in our experiment $C$ and $G$ are orders of magnitude larger than in usual TES. This is understandable, given the fact that our sample is much larger. Thinning further down our sample can easily values much closer to the ones in usual TES. Note that going to the single layer limit would considerably increase $G_1$ and thus decrease $\alpha$ and $\beta$. However, samples with a few layers show already sharp superconducting transitions[62–65]. For instance, a flake of $10\mu m \times 10\mu m$ and thickness of $10$ nm provides a heat capacity decreased by $8$ orders of magnitude. $G$ can be also decreased considerably by depositing a flake on a membrane with a controlled link to the thermal bath, as usual in TES.

**CONCLUSION AND OUTLOOK**

In conclusion, we have measured the reactance of high quality 2H-NbSe$_2$ single crystal. We observe a strong mutual influence between heat and electronic transport in the superconducting transition. The frequency for the appearance of the coupling can be tuned to the tens of Hz regime and is given by the sample heat capacity and the heat conductance between the sample and the bath. The behavior as a function of magnetic field is explained by a decreased sharpness of the superconducting transition for higher fields. The behavior for increasing current and varying frequency is also captured by the thermal model. We suggest that 2H-NbSe$_2$ single crystals are very promising for bolometric applications. The figure of merit is comparable to available bolometers and can be further improved by decreasing the size of the sample.

We also observe that the thermal link through residual exchange gas is a relevant issue in measurements having a strong temperature dependence of the resistance. Recent measurements of the dissipation in quantum systems are made through exchange gas mediated thermal contact between a sensor (a Josephson junction) and the sample[66, 67]. The sensor is scanned using a scanning probe microscope to obtain spatially dependent images of the dissipation. Here we show that the thermal link can produce variations in the measurements if the sensing signal is temperature dependent. Furthermore, our
measurements show the highly non-linear effect of the exchange gas, suggesting that the needed link between sensor and sample can be obtained with small variations in the amount of exchange gas, as observed in the said experiments.

There are a number of experiments about the superconducting transition showing effects that have remained unexplained for long times. This might be not surprising, as the criticality at the transition enhances the sensitivity to fluctuations. For example, in [68–71], steps were observed at the transition of Pb and in 2H-NbSe$_2$, interpreted as evidence for dissipation related phenomena. In Pb very thin wires, a negative magnetoresistance was found at low fields in wires, due to fluctuations [72] and in Pb films and other two-dimensional superconductors, an enhancement of the critical temperature was observed by applying a magnetic field [73]. The superconducting resistive transition decreases its width when increasing the magnetic field, an effect that has been associated to a transition to the normal state due to the paramagnetic exchange field instead of the increase in the vortex density [74]. Our data suggest that the measurement of the reactance could be useful in better characterizing the resistive transition.

Furthermore, our work opens the route to TES detectors made of few layers or two-dimensional superconducting materials. The increasing number of exfoliated crystals [75–77] is a promise towards even more efficient single crystal based tunable TES. In particular, Yan et. al. [78] have shown that bilayer graphene has a very small heat capacity due to electron-phonon decoupling ($10^{-19}$ J/K for their device) which makes layered systems both an ideal platform for bolometric detection and for unveiling new phenomena related to electronic and thermal transport in superconductors. It would be interesting to measure the reactance in transitions occurring in devices with bilayer graphene [79, 80] or other two-dimensional systems [81, 82].

A fundamental aspect in two-dimensional systems is the presence of out of equilibrium dissipation and coherence [27]. For example, very recent measurements suggest thermally driven vortex blockade in ultra thin devices of 2H-NbSe$_2$ [83]. Measurements of the critical current in 2H-NbSe$_2$ contacted with graphene show strongly reduced values with respect to a metallic electrode, suggesting that electron flow in graphene generates heat that is transferred to 2H-NbSe$_2$ [84]. These measurements consider only the resistance, which just shows electronic transport. The reactance found here is instead related to dissipation and can serve as a new method to measure the thermal behavior with an applied current.

**FIG. 5.** In the top panels of each figure we show the temperature dependence of the resistance (left y-axis, red color) and of $\frac{dR}{dT}$ (right y-axis, blue color). In the bottom panel we show the value of $C$ obtained as discussed in the text (black line). Notice that the temperature range shown in each figure corresponds to the range where the reactance is finite. In (a) we show results obtained at 10 mA and zero magnetic field (blue curve in Fig.3(a,b)), in (b) at 10 mA and 2300 Oe (orange curve in Fig.3(a,b)) and in (c) results at 40 mA and zero magnetic field (orange curve in in Fig.3(d,e)). Green shaded temperature range corresponds to the temperature region where we consider coherent Cooper pairing and rosa shading to the normal, fluctuation dominated region.
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