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MEASUREMENTS OF $I-V$ CURVES OF SUPERCONDUCTORS WITH SUBNANOVOLT RESOLUTION

ŽELJKO MAROHNIĆ

Institute of Physics of the University, P.O.Box 304, 41 001 Zagreb, Croatia

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A simple method for the measurements of I-V curves of superconductors with the voltage sensitivity of about 0.1 nV is described in some detail. The superposition of a very low sinusoidally varying alternating current I_A on much larger computer controlled direct current I_D is fed into the sample and the resulting signal from the phase sensitive amplifier numerically integrated yielding the I-V curve. The sensitivity of the method is demonstrated by measuring the I-V curve of an Ag-clad $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10+y}$ tape. The experimental set-up employed in these measurements is also described and some possible uses of the method discussed.

1. *Introduction*

The investigation of the dissipation in the mixed state is very important for the understanding of the flux line pinning [1] and motion [2,3] in the type II superconductors. For the conventional (low-T_c) superconductors such studies are relatively simple because the large lengths of the wire or tape enable to achieve in transport (I-V) measurements the required sensitivity at voltages which can easily be measured with the conventional methods.

At the present the high-T_c superconductors are prepared as small samples. Therefore, the conventional methods of the voltage measurements cannot yield the required sensitivity [4]. In order to circumvent this problem the low dissipation range (associated with low electric fields E developed across the sample) is studied by means of the magnetic measurements [4]. However, in addition to some ambiguities associated with the interpretation of such measurements for small, thin, often irregularly shaped and strongly anisotropic samples, these measurements cannot be extended to the region of higher E. Because of this the overlap between the transport and magnetic measurements of $E-J$ curves is poor and therefore their mutual consistency cannot be verified.

In what follows we shall describe a simple method which, using the conventional and inexpensive equipment (available in every laboratory), enables one to increase the sensitivity of I-V measurements to 0.1 nV level. Therefore, one can achieve the sensitivities typical for long lengths of conventional superconductors on small samples of either high-T_c or low-T_c materials. The sensitivity of the method is demonstrated by measuring the I-V curve of an Ag-clad $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10+y}$ tape. The employed experimental set-up is described, and some possible applications of the method outlined.

2. *The principle of the measurements*

In the conventional *dc* measurements (i.e. without using the superconducting quantum interference devices) of I-V curves one seldom reaches the voltage sensitivity δV better then 10 nV [5]. Therefore, the electric fields E_c used to define the critical current density I_c for short samples (typical lengths $L \leq 1$ cm) are several orders of magnitude below of those employed for the standardization of conventional type II superconductors. Furthermore, when employing the *dc* techniques the current through the sample must be reversed during the measurements in order to avoid the spurious voltages. Because of this, even at low magnitudes of direct current, the measurement of I-V curves by the use of *dc* techniques is an involved and time consuming job. In order to speed up the measurements quasi-*dc* pulsed measurements of I-V curves are performed. Due to induced voltages this further limits the voltage resolution to about 0.1-1 μV [6].

The sensitivity of the present-day *ac* techniques for the transport measurements can be made up to hundred times better then that of the *dc* ones. However, these techniques cannot be applied for the measurements of the I-V curves (and in general resistances) of the superconductors. In order to illustrate this we consider a case in which the current $I = I_A \sin\alpha$ ($\alpha = \omega t$) flows through the superconducting sample having the critical current I_0. Obviously, the voltage will appear across the sample only if $I_A|\sin\alpha| > I_0$. In order to be specific we will assume $I_A > I_0$ and a power law I-V characteristic:

$$V = V_c \left(\frac{I}{I_0} - 1 \right)^n . \tag{1}$$

Here n is an exponent which in polycrystalline high-T_c samples at not too large currents ($I \gtrsim I_0$) often takes on the value $2 \leq n \lesssim 3$ [7]. Under these circumstances the voltage on the sample will obey the following relations:

$$V(\alpha) = \begin{cases} V_c\, SGN\,(\sin\alpha) \left(\dfrac{I_A|\sin\alpha|}{I_0} - 1 \right)^n, & \alpha_0 < \alpha \leq \pi - \alpha_0,\ \pi + \alpha_0 < \alpha \leq 2\pi - \alpha_0; \\ 0, & \text{elsewhere} \end{cases} \tag{2}$$

where α_0 is the phase angle for which $I_A|\sin\alpha_0| = I_0$.

Since the output of the phase sensitive amplifier (hereafter PSA) gives the integral V_L of the input signal $V(\alpha)$, one will have:

$$V_L = \frac{1}{4\sqrt{2}} \Big[\int\limits_0^{\pi} V(\alpha)\mathrm{d}\alpha - \int\limits_{\pi}^{2\pi} V(\alpha)\mathrm{d}\alpha \Big]. \tag{3}$$

Obviously, because of relations (2), V_L will deviate systematically from the voltage V_D which would be obtained if the direct current I_D with the magnitude I_A were flowing along the sample. In particular, V_L will increase slower with I_A then V_D with I_D and an erroneous I-V curve will result.

In order to take the advantage of a better sensitivity associated with the *ac* techniques, and yet to avoid the described inconsistency between V_D and V_L, we employed a combination of the *ac* and *dc* technique. In particular, we used the direct current $I_D \gtrsim I_0$ with superposed very low alternating current $I_A \ll I_D$ (typically $I_A \lesssim 1$ mA). The alternating voltage on the sample V_{ac} was processed with PSA. It can be shown that for $I_A \ll I_D$ and $I_D - I_0 > I_A$:

$$V_L \approx \Big(\frac{\mathrm{d}V}{\mathrm{d}I_D} \Big) I_A. \tag{4}$$

The total voltage across the sample $V(I) = V(I_D + I_A \sin\alpha)$ can be expressed as:

$$V(I) = V(I_D) + \Big(\frac{\mathrm{d}V}{\mathrm{d}I}\Big)_{I_D} I_A \sin\alpha + \frac{1}{2}\Big(\frac{\mathrm{d}^2V}{\mathrm{d}I^2}\Big)_{I_D} I_A^2 \sin^2\alpha + \frac{1}{6}\Big(\frac{\mathrm{d}^3V}{\mathrm{d}I^3}\Big)_{I_D} I_A^3 \sin^3\alpha + ... \tag{5}$$

Ignoring the higher order terms in Eq. (5) and applying Eq. (3) one finds

$$V_L = \Big(\frac{\mathrm{d}V}{\mathrm{d}I}\Big)_{I_D} I_{RMS} \tag{6}$$

where $I_{RMS} = I_A/\sqrt{2}$. Therefore, V_L is simply proportional to the dynamic resistance of the sample $(\mathrm{d}V/\mathrm{d}I)_{I_D}$. In our measurements with $I_D > 50$ mA we did not observe any signal at 2 ω for $I_A \leq 2$ mA which shows that already at such sizeable I_A the higher order terms in Eq. (5) can be safely neglected.

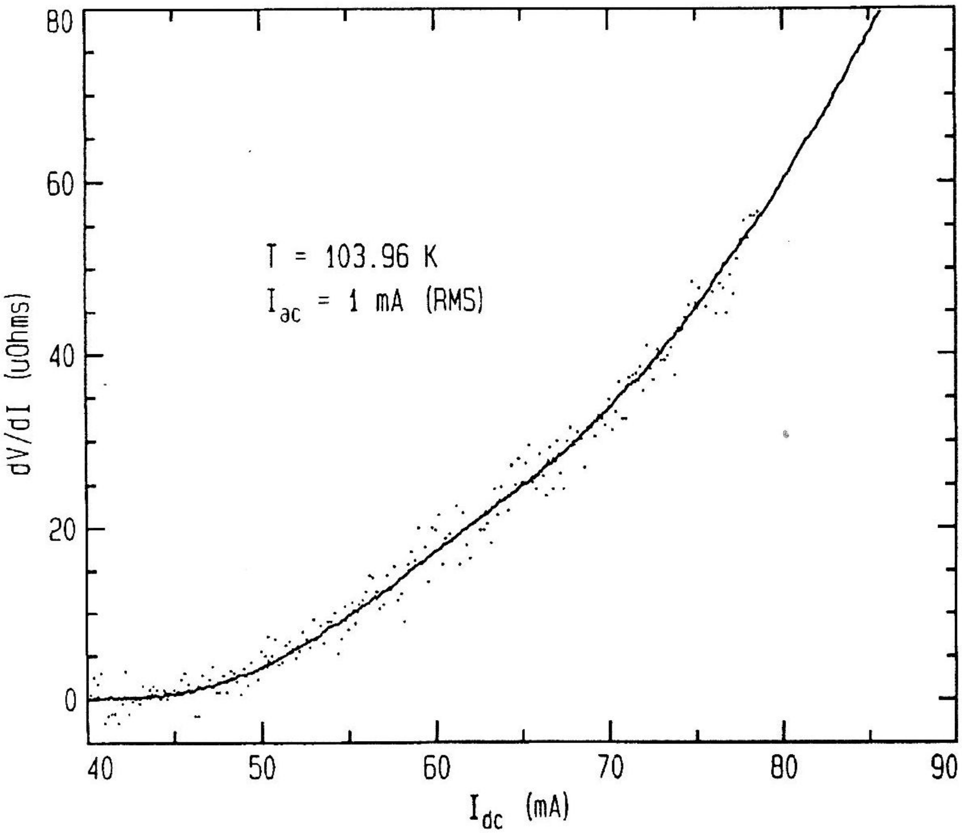

Fig. 1. Dynamic resistances dV/dI *of an Ag-clad* $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10+y}$ *tape obtained with new method (full line) and conventional dc method (dots) vs. direct current* I_{dc} *flowing along the sample at* $T = 103.96$ K.

The sensitivity of the method was tested on an Ag-clad $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10+y}$ tape [6] with the length of about 1 cm. The variation of $(\mathrm{d}V/\mathrm{d}I)$ with I_D at 104 K and zero applied field is shown in Fig. 1. The amplitude of the alternating current was $I_A = 0.2$ mA. Fig. 2 compares the I-V curve obtained by the numerical integration of the $(\mathrm{d}V/\mathrm{d}I)$ data of Fig. 1 (full line) with that obtained with the conventional *dc* technique (dots) at the same temperature. Obviously, both measurements yield (or better to say represent) the same I-V curve, but due to the noise there is a scatter of several nanovolts in the data points obtained by the *dc* technique. The voltage sensitivity obtained with the combined technique was over ten times higher i.e., about 0.2 nV (as shown below we used the low noise transformer before the input of PSA in order to increase the overall sensitivity).

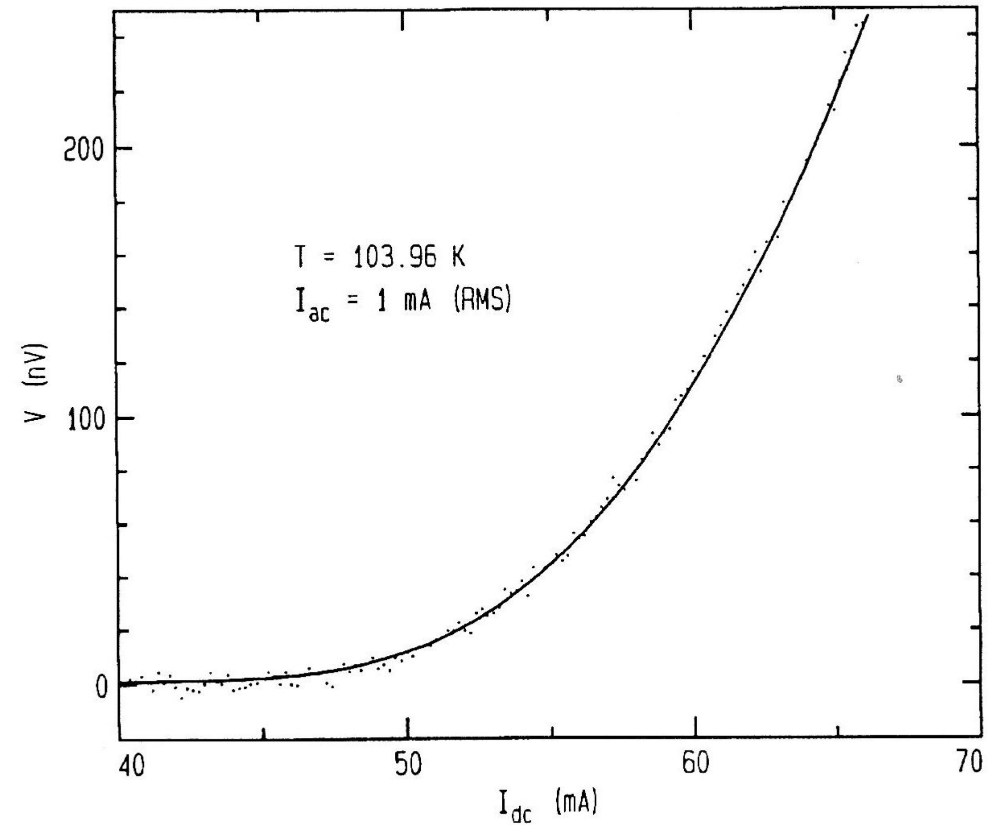

Fig. 2. $V - I$ characteristics for the sample from Fig. 1 at 103.96 K *obtained with new method (full line) and conventional dc method (dots).*

The difference in the sensitivity of two methods becomes particularly clear if one compares the dynamic resistances obtained with two methods. In Fig. 1 we have also plotted the numerical derivatives of the I-V data obtained by *dc* technique in Fig. 2. Obviously because of the scatter in the I-V data the *dc* technique is incapable to give the details of the evolution of the resistance in the superconducting sample with I whereas this is what is directly obtained with the combined technique. We note that $(\mathrm{d}V/\mathrm{d}I)$ is particular important in order to deduce the mechanisms of dissipation in different ranges of I. The similar results have also been obtained at other temperatures and hence different values of I_0 and I_D [8].

3. *Experimental arrangement*

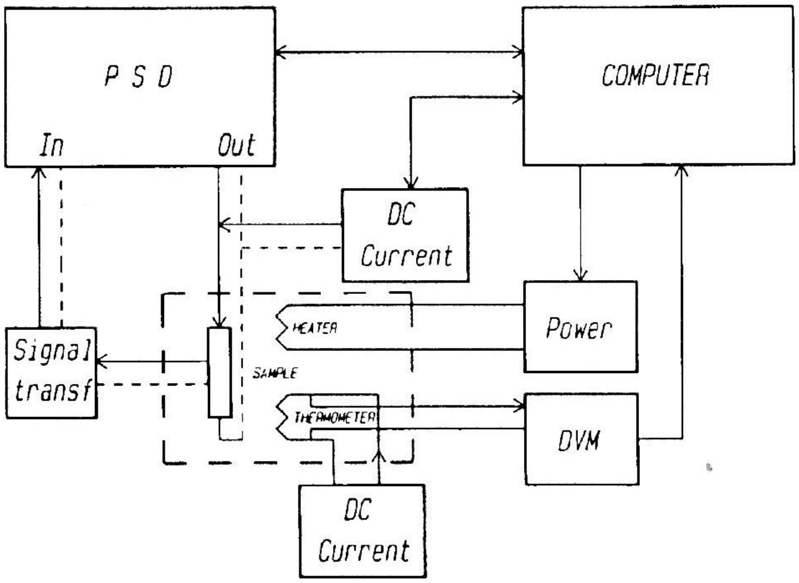

Fig. 3. Basic set-up for dynamic resistance measurements.

As seen from Fig. 3, the experimental set-up employed in the measurements illustrating the efficiency of the combined method (Figs. 1 and 2) is very simple and quite inexpensive. The current I_D is obtained from the computer controlled constant current source (*dc*). For temperatures close to T_c we used a programmable current source with the current range $0 - 100$ mA. The alternating current with frequency 28.4 Hz and amplitude $I_A = 0.2$ mA was obtained directly from the oscillator of PSA. Since the output resistance of PSA is over 600 Ω and the total resistance in the sample circuit was less then 1 Ω, I_A was sufficiently constant in all the measurements. We have also verified that the *dc* current source has sufficient impedance for the low frequency *ac* component ($I_{AC} = I_A \sin \alpha$) so that its presence in the circuit does not produce an observable change in I_{AC}. As seen from Fig. 3, the signal from the sample was first amplified with the low noise transformer and then fed into PSA.

Apparently, during the accurate measurements of $(\mathrm{d}V/\mathrm{d}I)$ the temperature of the sample should be constant. This requires a good temperature control. The temperature was measured with thin film Pt thermometer situated in the immediate vicinity of the sample on the pure copper sample holder. The temperature resolution was 1 mK and its control was achieved via the same computer which was used for I_D control (by means of a negative feedback on the current through the heater). The stability of temperature during the measurements (typically 0.5 hours) was always within ± 3 mK. The sample holder was inside of a vacuum cryostat immersed in the liquid nitrogen. All the wires were thermally anchored and arranged in a loop free manner.

4. Conclusion

A novel method for very accurate measurements of I-V curves has been described and its sensitivity demonstrated with the measurements performed on an Ag-clad $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10+y}$ tape. The method is a combination of the conventional *ac* and *dc* techniques and enables one to achieve the voltage sensitivity of about 0.1 nV by using the inexpensive equipment which could be found in almost every laboratory. Further advantage of this method is that it directly yields the accurate information on the evolution of the dissipation within the sample ($\mathrm{d}V/\mathrm{d}I$) and therefore enables a detailed investigation of the mechanisms dominating dissipation in a given range of I. The technique could be very useful for the investigation of high-T_c superconductors (where short samples prevented so far the investigation of $E-J$ relationship at very low E) and also for the studies of a local structure-property relationship in low-T_c superconductors [1]. The method can also be applied for the very accurate measurements of $\mathrm{d}I/\mathrm{d}V$ in the tunnelling junctions. In this way it can help to solve the fundamental question of the high - T_c superconductivity ie. the pairing mechanism (d- or s-).

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MJERENJE $I - V$ KARAKTERISTIKE SUPERVODIČA SUBNANOVOLTNOM REZOLUCIJOM

ŽELJKO MAROHNIĆ

Institut za fiziku, P.P. 304, Zagreb, Hrvatska

UDK 537.311

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Opisana je jedinstvena metoda direktnog mjerenja dinamičkog otpora ($\mathrm{d}V/\mathrm{d}I$) supravodiča sa rezolucijom od oko 0.1 nV. Istosmjerna struja I_D sa dodatkom male sinusne komponente amplitude I_A prolazi kroz uzorak. Izmjenična komponenta napona V na uzorku, proporcionalna sa $\mathrm{d}V/\mathrm{d}I$, pojačava se fazno-osjetljivim pojačalom, a numeričkim integriranjem dobiva se I-V krivulja. Osjetljivost ove metode demonstrirana je na uzorku $(BiPb)_2Sr_2Ca_2Cu_3O_{10+y}$.