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Experimental method for controlling the overheating of superconducting films under the action of a pulsed current

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Using time sweeps of the current through a sample of a superconducting film, the effect of the current sweep rate on the process of heat propagation from current contacts is investigated. The samples used were NbN films with temperatures below and above the temperature of transition to the superconducting state. A method for determining the critical heating of key zones of the sample is proposed. The propagation velocities of the resistive front and normal domain in a superconductor are estimated at different temperatures.

Keywords: niobium nitride films, time sweep of the current, resistive front, normal domain.

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One of the most important tasks in studying current−carrying properties of superconductors is to ensure the absence of sample overheating. Analysis of volt−ampere characteristics measured by the conventional four−contact method often cannot provide clear distinguishing between the contributions to the superconductor resistive state from thermal and non−thermal mechanisms. Therefore, we propose to use in determining overheated regions the time sweeps of voltage at potential contacts on the sample and on the reference resistance connected in series with the sample (current sweep). The difference of potentials at the reference resistance is used to control the circuit current; just the shape of the current time sweep is the main tool for analyzing variations in the sample resistance. The matter is that the sample resistance can increase also when the voltage at potential contacts remains zero. This is associated with inevitable heating of the region of current contacts. This critical heating is clearly seen in the current sweep because an increase in the total circuit resistance results in the sweep deviation from linearity (reduction of growth). In this case, if the permissible current growth reduction is ensured (due to an increase in the current sweep rate, temperature decrease and enhancement of heat removal), it is possible to guarantee the absence of overheating in the vicinity of potential contacts (in the zero magnetic field).

When magnetic field is applied, the sweep analysis becomes more complicated; however, in this case it is also possible to distinguish the thermal heating contribution by analyzing the character of the sample resistance growth until the resistive state gets realized. This is associated with two characteristic features: 1) an increase in the sample resistance due to the resistive area spreading; 2) a decrease in the flux creep resistance due to reduction of the sample superconducting region with simultaneous increase in the flux creep resistance due to an increase in the current through the sample. Whether the second mechanism contribution to the resistance increases or decreases, depends on temperature, magnetic field, and character of defects on which vortex pinning takes place. This may be estimated experimentally.

The above−described method was tested by using the niobium nitride (NbN) films. NbN films have a high specific resistance in the normal state and are at present used in many applied and fundamental researches. Ultrathin NbN films and fibers are used in producing logical devices [1], bolometers [2], resonators [3], terahertz radiation receivers [4], voltage standards [5] and other devices widely used in measurement instrumentation. Wide and relatively thick (units of micrometers) niobium nitride films are used in energy storage devices [6].

In our experiments we studied NbN films obtained by reactive cathode sputtering of a niobium target in a glow discharge in the nitrogen and argon atmosphere on fused−quartz substrates [7,8]. In the case of films 400−600 nm thick, the temperature of transition to the superconducting state is $T_c = 16.2-16.5$ K, and the transition width is $\Delta T_c \approx 0.1$ K. The film samples were $l = 9$ mm long and $b = 5$ mm wide. The electrical characteristics were studied by using the four−contact method; the contacts were made from beryllium bronze ensuring extra heat removal from the samples [9]. To form a single pulse and detect responses from the potential contacts and reference resistance connected in series ($R = 1\,\Omega$), generator ASK-4106 and oscilloscope ASK-3107 with the transmission frequency bands no less than 100 MHz were used (Fig. 1). The measurement technique and film parameters are described in more details in [10]. Experimental data presented here were obtained on the sample 400 nm thick at $T_c = 16.3$ K.

The experiments were conducted in the absence of external magnetic field (field strength $H = 0$) at such temperatures when currents able to transfer the sample

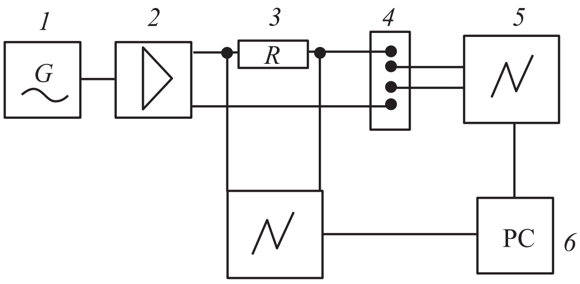

Figure 1. Electrical circuit of the experiment. *1* — generator ASK-4106, *2* — amplifier, *3* — reference resistance ($R = 1\,\Omega$), *4* — NbN sample, *5* — oscilloscope ASK-3107, *6* — personal computer.

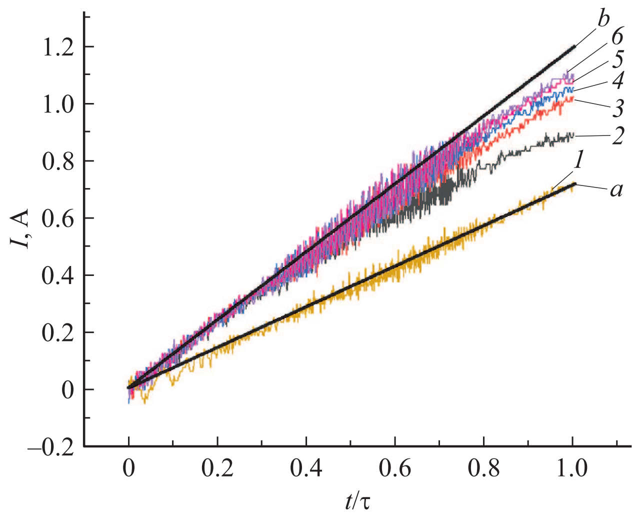

Figure 2. Current through the NbN film ($T_c = 16.3$ K) versus sweep time τ in the absence of external magnetic field. *1* — above T_c ($T = 17$ K), $\tau_1 = 0.25$ ms, *2* — $\tau_2 = 1$ ms, *3* — $\tau_3 = 0.25$ ms, *4* — $\tau_4 = 0.1$ ms, *5* — $\tau_5 = 0.05$ ms, *6* — $\tau_6 = 0.025$ ms. Dependences *2–6* were obtained at film temperature $T = 13.5$ K. Line *a* is a straight line approximating the experimental dependence *1*. Line *b* is a dependence that is to be observed in absolute absence of heating of the sample in the superconducting state.

to the resistive state were much lower than the depairing current.

Fig. 2 presents experimental dependences $I(t)$ of current in the circuit consisting of the NbN film and reference resistance connected in series on the time of its growth (the pulse/sweep time τ) at the film temperature $T = 13.5$ K ($H = 0$). The current was measured via the voltage at the reference sample. Prior to reaching current value $I = 0.4{-}0.5$ A (with the respective current density $j = (1.3{-}2.5) \cdot 10^4$ A/cm^2), dependences $I(t)$ coincide within the measurement error, i.e. the sample heating may be neglected below the indicated values. With further increase in current, a significant discrepancy between the $I(t)$ dependences is observed, which may be estimated based on the current values at the end of pulse $I_{\max}(t)$.

The current takes minimal values at the end of the $I_{\max N}$ pulse when the sample as a whole transits to the normal state at temperature $T = 17$ K at which the circuit resistance becomes maximal (dependence *1*). Dependence *1* does not change its shape with changing sweep time. Thereat, $I_{\max N} = 0.7$ A and dependence *1* is linear (approximation *a*), which evidences, for instance, that it is possible to neglect the influence of variation in the leading wire resistance during the current passage. The maximum possible $I_{\max S}$ may be determined by extrapolating the linear dependence common for all $I(t)$ to the point where the pulse time is over (ideal line *b* that is to be observed in the absolute absence of the sample heating, i.e. when all the sample is in the superconducting state). In this case, $I_{\max S} = 1.2$ A.

Therefore, real values of $I_{\max}$ range from 0.7 to 1.2 A; the shorter is the pulse time, the higher is $I_{\max}$. Since at such high currents absolute absence of the sample heating during contact measurements can hardly be ensured, it is important to estimate the pulse time upper limit at which the resistive front propagates to the potential contacts, i.e. the moment when the sample regions between the current and potential contacts have already transited to the resistive and normal state due to heating, but the region between the potential contacts still remains superconducting.

To make this estimate, it is necessary to determine the $I_{\max}$ value at which the sample resistance R_s equals 8/9 of its normal–state resistance ($R_m \approx 12\,\Omega$; assume that the sample is homogeneous, distances between neighboring contacts are identical, and the region length between the inner edges of potential contacts is 1/9 of the sample length). Then, using values $I_{\max N}$, $I_{\max S}$ and assuming dependence $R_s(I_{\max})$ to be linear in the region between $I_{\max N}$ and $I_{\max S}$, obtain for our case $I_{\max 8/9} \approx 0.77$ A ($j \sim 3.5 \cdot 10^4$ A/cm^2). This value of current corresponds to sweep time $\tau \approx 1.6$ ms. If $\tau < 1.6$ ms, the thermal wave has no time to reach the potential contacts; therefore, the overheating effect on the shapes of volt–ampere characteristic is excluded.

Fig. 3 demonstrates time sweeps of voltage at the sample potential contacts for different temperatures at sweep time $\tau = 0.25$ ms. One can see that, while the temperature decreases from $T = 17.0$ K (dependence *6*) to $T = 15.0$ K (dependence *1*), the onset time of overheating of the region between the potential contacts increases. In case $T = 15.2$ K (dependence *2*), overheating of this region does not promote its total transition to the normal state, a part of the region remains in the resistive state. When $T = 15.0$ K, the entire region remains in the superconducting state.

If the distance between the neighboring current and potential contacts (3–4 mm) and sweep time (0.25 ms) are known, it is possible to estimate velocity v of the resistive front propagation in the sample at different temperatures at the beginning of the voltage growth. At $T = 15.2$ K (dependence *2*), $v = 20{-}27$ m/s; at $T = 15.5$ K (dependence *3*), $v = 30{-}40$ m/s; at $T = 15.9$ K (dependence *4*), $v = 60{-}80$ m/s; at

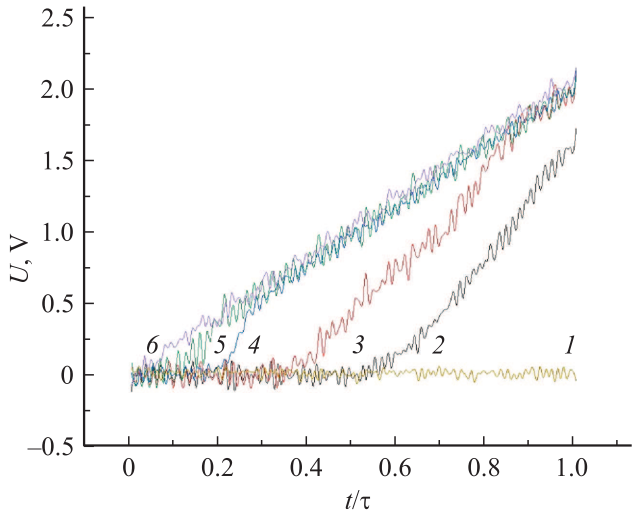

Figure 3. Time dependence of voltage at the sample potential contacts ($T_c = 16.3$ K) for different temperatures at sweep time $\tau = 0.25$ ms. T, K: *1* — 15.0, *2* — 15.2, *3* — 15.5, *4* — 15.9, *5* — 16.0, *6* — 17.0.

$T = 16.0$ K (dependence *5*), $v = 120-160$ m/s. When $T = 15.9$ K (dependence *4*), it is possible to estimate the propagation velocity of the normal domain front [11] via the time necessary for the signal to reach the linear section (when the entire sample transits to the normal state): $v = 4.5$ mm/0.08 ms=56.25 m/s.

Thus, the paper shows that knowledge of time sweeps of current and voltage during contact−type investigation of superconductors makes it possible to establish the sample overheating criterion depending on temperature and current growth rate. The current time sweep data obtained at a certain temperature clarifies the pattern of the resistive front propagation and defines the pulse time limit below which overheating of the region between the potential contacts may be neglected.

Conflict of interests

The authors declare that they have no conflict of interests.

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