CM-P00056435

MAY 1990

CERN-EP 90-51
c2

ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/90-51

23 April 1990

**OBSERVATION OF SUBNANOSECOND TRANSIENTS IN A
SUPERCONDUCTING MICROSTRIP EXPOSED TO
MINIMUM-IONIZING RADIATION**

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ABSTRACT

We report the observation of very fast pulses (rise-time < 300 ps) generated by irradiating a NbN microstrip with a ^{106}Ru β -source. We discuss the physical mechanisms which underlie the possible thermal and non-equilibrium models, and which could explain our results.

(To be published in Physics Letters B)

1. INTRODUCTION

Future large hadron colliders need to operate at very high luminosities. This, combined with the large multiplicity at high energies, will entail severe problems for any existing vertex detector. Radiation damage, spatial resolution, and readout are among the most evident.

One possible approach to the solution of these problems is the application of superconducting strip detectors made of suitable radiation-hard materials, such as niobium nitride (NbN).

A fast, high-resolution strip detector could also find many uses in tracking-applications in intense secondary beams. A typical example is the deep-inelastic scattering of high-energy muons, probing the parton structure functions of free and bound nucleons. Extending these experiments to very small angles, to spin structure, and to small fractional momentum carried by the constituent, demands a good statistical accuracy and therefore intense beams. In view of this and of the requirement of a high vertex resolution, neither silicon microstrip detectors nor gas-filled track chambers could achieve meaningful results in these applications.

Since Sherman [1] proposed superconducting tin strips as a new class of particle detectors, several materials have been tested [2–5]. In all these experiments, α -particles were used, and it is only recently that Gray et al. [6, 7] could demonstrate the applicability of superconducting Nb microstrips for the detection of X-rays and fast electrons. The pulses detected had amplitudes between 250 μ V [2] and 60 mV [7], and rise-times between 5 ns [5] and 150 ns [6]. All these authors resorted to the thermal model of Sherman to describe their results. This model, based on the difference in the enthalpy between the superconducting and the normal states, will be discussed below.

The aim of the present work is to demonstrate the existence of self-recovering voltage pulses in superconducting microstrip lines, with d.c. bias currents well below the critical value. Existing knowledge regarding non-equilibrium phenomena in superconductors would indicate that voltage transients following the local heating of the electronic system should be very fast (picosecond time-scale). Recovery from such pulses should be possible, provided certain stability criteria are satisfied.

The shape of these very fast transients should be well conserved in the superconducting microstrip line, because signal propagation is virtually free from dispersion up to terahertz frequencies. Our aim was also to find information about the propagation of the expected fast pulses along the length of the strip.

2. EXPERIMENTAL SET-UP

The NbN microstrip was prepared at the University of Salerno. A film with a thickness of 350 nm was deposited on a sapphire substrate by magnetron sputtering. The patterning of the actual strip geometry (see inset in fig. 2) was made by chemical etching. The resistivity of the film was about 120 $\mu\Omega$ -cm, and the dimensions of the strip were 3.4 μ m (width) by 18 mm (length).

The substrate was mounted on a Cu heat sink in an RF-tight housing, which itself was placed in a closed-cycle ^3He refrigerator precooled by a cryocooler. The upper face of the strip was in vacuum.

We used a ^{106}Ru source that had a diameter of less than 1 mm and an activity of about 400 kBq; it emits β radiation with characteristic energies of 3.5 MeV (79%), 3.0 MeV (12%), and 2.4 MeV (2%), accompanied by two γ -transitions of 511.4 keV (20.6%) and 621.6 keV (10.7%). The source was placed as close as possible to the strip, and was separated from it by

only the thickness of the layer of varnish (0.8 mm) that was necessary to prevent contamination of the cryostat.

Handling of the substrate caused some breaks on the strip; the longest uninterrupted piece was about 2.2 mm. Contacts to this remaining strip were made by pressing small In pearls directly onto the NbN film (see the lower inset in fig. 4).

In addition, a Nb sheet was placed on top of the strip to act as a superconducting ground plane. One end of the strip was shorted to ground by a small piece of copper.

The biasing current was fed into the strip through the same cryogenic coaxial line as was used to transmit the signals to the room-temperature electronics. A block diagram of the electronics is shown in fig. 1. The preamplifier has a gain of 20 dB and its passband extends from 10 MHz to 2 GHz. The Tektronix 7104 oscilloscope, with a 7A29 vertical amplifier and a 7B10 time base, has a bandwidth of 1 GHz.

The signals were recorded with a Tektronix CCD digitizing camera, triggered by the light from the oscilloscope. In this way, single-shot signals, with rise-times down to 300 ps, could be digitized, stored, and studied in a personal computer.

The characterization of the strip was done by measuring the maximum current $I_{\max}$ that could be passed through it before switching to the normal state, as a function of temperature. The results are shown in fig. 2, where the open symbols represent different sets of measurements without the radiation source and the full circles show one set of data taken with it. When approaching lower temperatures, $I_{\max}$ levels off owing to the heating of the strip by the bias current. This point of view is corroborated by the measurement of the voltage drop and d.c. resistance of the strip below the critical temperature, yielding contact resistance values between 3 Ω and 10 Ω . It should also be mentioned that, although the values measured for $I_{\max}$ were reproducible in each single run, thermal cycling to room temperature generally resulted in a different curve, indicating that the contacts had changed.

We also determined the critical current of the In contacts. The results, as a function of temperature, are shown in the upper inset in fig. 4.

One surprising effect was that the room-temperature d.c. resistance of the remaining 2.2 mm of the strip decreased during thermal cycling. In the beginning, a value of 2 k Ω was measured, whereas after several cooling cycles we found resistances below 900 Ω .

3. OBSERVATION OF FAST PULSES

The fast pulses were observed immediately after mounting the source for the first time, but were recorded only after all the measurements of $I_{\max}$ versus T_a had been performed. At a temperature of about 5 K and a bias current of 18 mA, which is close to the maximum current (see fig. 3), negative pulses were found with an amplitude of about 60 mV and positive pulses with about 10 mV. Figure 3 shows three typical signals. The overall shape of these signals was determined by the passband of our detection electronics (10 MHz–1 GHz).

The fact that the pulses persisted up to the critical temperature is a strong hint that they are definitely originating from the NbN.

After thermal cycling and cooling down to 3 K, a check was performed to see if these signals could be found also at currents lower than 18 mA. They could indeed be detected at currents down to 6 mA — even though there had been no signal — when the current had been ramped-up the first time. When the current was ramped-up once more from a value lower than 6 mA, the above finding was confirmed, i.e. no pulses were detected at low currents. This

hysteretic behaviour indicates that the existence of these fast signals is somehow dependent on the history.

In addition to the above pulses, equally fast signals, but with smaller amplitude, were observed at a very low bias current. During the determination of the lower threshold of the bias current at which these pulses were generated, the strip stopped operating. After that, even at high currents, signals could no longer be detected.

Suspecting that the In contacts were the culprits, new contacts were fabricated. The $I_{\max}$ was then found to be 18 mA, as for the previous run, and fast pulses were detected again, but the amplitude was reduced to about 3 mV. Also the range of currents over which these signals could be found was significantly reduced (18 mA to 16 mA). With reversed bias current, these signals disappeared.

However, the fast pulses at very low bias current were still present with a rate of about 200 s^{-1} . A typical signal is shown in fig. 4. The currents and temperatures, at which these pulses were observed, always corresponded to points below the curve of the critical current versus temperature for In, as determined *in situ* in our apparatus (upper inset in the same figure). These pulses, but with reversed sign, were also present with reversed bias current.

Our results show that with the present set-up we are detecting two different kinds of fast, self-recovering signals. The larger ones are correlated with the curve $I_{\max}$ versus T_a of the NbN; we call them the ‘NbN signal’ for short. The others are correlated with the $I_{\max}$ versus T_a of indium; they are called the ‘In signals’.

The most striking thing about the NbN signal is its presence, or absence, depending on the history of the bias current and possibly of the temperature. Notably, the signal could not be detected when the biasing current was reversed. Contrary to this, the In signal was present for both signs of bias current and changed sign when the current was reversed. The non-recovering signals clearly manifest themselves as a reduction of the maximum current $I_{\max}$ when the strip is exposed to the source (see fig. 2). As the aim of our work was to demonstrate the presence of self-recovering fast signals, and to study them, the design of our electronics and source was such that the study of the non-recovering signals was not practical.

4. DISCUSSION

4.1 Steady-state operation

In order to describe the steady-state behaviour of our strip, we developed a model, taking into account the theoretical dependence of the critical current on temperature, $I_c/I_{c0} = 1 - (T/T_c)^2$; the ohmic heating of the contact areas, $dQ/dt = RI^2$; and the heat conducted from these regions to the substrate, $dQ/dt = \alpha A_{th}(T_s^4 - T_a^4)$. In these expressions I is the current through the strip, T_s is the temperature of the strip in the contact area, T_a is the temperature of the substrate, R is the electrical resistance of the contacts, A_{th} is the area over which heat is conducted to the substrate, and α is assumed to be a constant. These yield the following expression for $I_{\max}$ as a function of the substrate temperature T_a :

$$\frac{I_{\max}(T_a)}{I_0} = \frac{1}{2 - I_{c0}/I_0} \left[1 - \sqrt{\left(2 - \frac{I_{c0}}{I_0}\right) \left(\frac{T_a^4}{T_s^4} + 1\right)} \right] \quad (1)$$

where we have introduced the parameter I_0 defined by

$$\frac{R}{\alpha A_{th}} = T_c^4 \left(\frac{1}{I_0} - \frac{1}{I_{c0}} \right)^2 \quad (2)$$

A first value for I_0 is obtained from the measurements of I_{max} by extrapolating to zero substrate temperature. As shown in Fig. 2, the flattening of the curve I_{max} versus T_a at lower temperatures is fairly well reproduced by this model. By fitting the above expression to our data, using I_0 , I_{c0} and T_c as variable parameters, we found consistent and reproducible values for I_{c0} and T_c , yielding the intrinsic critical current of our strip, $I_{c0} \approx 120$ mA, and the critical temperature, $T_c \approx 13.8$ K. This gives a critical current density of 10^7 A/cm², which is close to the values published in refs. [8] and [9]. Furthermore, a value for α can be deduced assuming that A_{th} is equal to the strip area covered by the In contacts; we get $\alpha = 190$ W·m⁻² K⁻⁴. This can be compared with results from direct thermal experiments; the values of $\alpha = (4R_K T^3)^{-1}$ vary between 60 W·m⁻² K⁻⁴ and 140 W·m⁻² K⁻⁴ [10] for combinations of materials similar to ours.

4.2 Thermal model for transients

According to the thermal model of Sherman [1], the radius r_0 of the ‘normal current zone’, created by a traversing particle is given by

$$r_0 = \sqrt{\frac{dE/dx}{\pi(\Delta H/V)}} \quad (3)$$

where $\Delta H/V$ is the difference between the specific enthalpies in unit volume, between the superconducting and normal states, and can be deduced from the critical field according to

$$\frac{\Delta H_0}{V} = \frac{B_{cth0}^2}{2\mu_0} \quad (4)$$

The thermodynamic critical field at zero temperature B_{cth0} can be calculated from the upper critical field B_{c2} and the Ginsburg–Landau parameter κ . In ref. [11] both values are given for a sputtered NbN thin film with $T_c = 14$ K and $\rho = 130$ $\mu\Omega\cdot\text{cm}$: $B_{c2} = 16.3$ T and $\kappa = 52$; therefore $\Delta H_0/V = 1.2 \times 10^{11}$ MeV/cm³, corresponding to 2.6 mJ/g. This estimate can be verified by comparison with the electronic energy difference, which is due to the superconducting gap, according to ref. [12]

$$\frac{\Delta E}{V} = \frac{m^* \Delta_0^2}{4\pi^2 \hbar^3} \sqrt{2m^* E_F} \quad (5)$$

From ref. [13], $2\Delta_0 = 4.08kT_c$ for sputtered NbN, so the energy gap in our case ($T_c = 13.8$ K) is $\Delta_0 = 2.42$ meV. Assuming that the effective mass is $m^* = m_e$, the mass of the free electron, and taking the Fermi energy E_F to be 12.5 eV (ref. [14]), eq. (5) yields $\Delta E/V = 3 \times 10^{10}$ MeV/cm³. The agreement between the values given by eqs. (4) and (5) is

thus reasonable since the averaged mass at the Fermi-surface is higher than m_e . For the temperature dependence of $\Delta H/V$, we assume the simple $(1 - t^2)$ form.

The energy loss dE/dx of 1 MeV electrons is about 12 MeV/cm in NbN, so the radius of the cylindrical volume, which becomes normal, should be $r_0 = 61$ nm for $T_s = 5$ K. The assumption that the whole strip is at 5 K (the temperature of the substrate) is justified because the heat originating from the contact areas can be assumed to be conducted directly to the substrate. This is due to the rather short thermal healing length of the strip, which will be discussed below.

The thermal healing length η , as defined in ref. [15] is given by

$$\eta = \sqrt{\frac{\kappa d}{\alpha'}} = 1.5 \mu\text{m} . \quad (6)$$

Here d is the thickness of the film, and κ is the thermal conductivity of NbN in the normal state (at $T = 14$ K) given by terms from the electron and phonon conduction, $\kappa = \kappa_e + \kappa_{ph}$. We estimate κ to be less than $1 \text{ W}\cdot\text{m}^{-1} \text{ K}^{-1}$.

The constant α' is related to the Kapitza conductivity α —introduced for modelling the behaviour of the I_{max} versus T_a data—by $\alpha' = 4\alpha T^3 = 1.5 \times 10^5 \text{ W}/(\text{m}^2\cdot\text{K})$. The result, $\eta = 1.5 \mu\text{m}$, is very short compared with the length of the strip (2.2 mm) between the In contacts; it is thus justified to assume that the strip is in good thermal equilibrium with the substrate, apart from a length of a few micrometres in the vicinity of the contact(s) generating the heat.

The minimum bias current $I_{b\text{min}}$ at which the strip would switch to the normal state over the whole width (according to the model of Sherman) is given by

$$I_{b\text{min}} = I_{c0} \frac{w - 2r_0}{w} = 93 \text{ mA} , \quad (7)$$

where w is the width of the strip. As the strip was biased with currents between 6 mA and 18 mA only, the critical current around the initial hot spot was not exceeded. It is then inconceivable that the observed voltage signals could result from transition to normal state over the full width of the strip.

In addition, if the strip would switch to the normal state over the whole width in the region of the initial hot spot, one would expect to observe an expanding normal zone. This can be seen by considering the bias current, which can balance the heat losses of a normal zone of length x_0 , given by ref. [15]:

$$I(x_0) = \sqrt{\frac{\alpha' w^2 h (T_c - T_a)}{\rho}} \sqrt{1 + \sqrt{\frac{\kappa_S}{\kappa_N}} \coth\left(\frac{x_0}{\eta_N}\right) \coth\left(\frac{L/2 - x_0}{\eta_S}\right)} . \quad (8)$$

In our case, $x_0 = 2r_0 = 120$ nm, κ_S and κ_N are the thermal conductivities of the superconducting and normal regions of the strip, η_S and η_N are the corresponding healing lengths, and L is the length of the strip. Therefore a bias current of about 2.1 mA would be

sufficient to make the original normal region grow, and one could not expect to see self-terminating pulses under any circumstances. As the signals do recover at bias currents up to 18 mA, which is almost one order of magnitude more than the above result [eq. (8)] we can rule out the simple model of Sherman for the description of our signals.

The magnitude of our larger signals, however, is not in such serious contradiction with the thermal model. The signal amplitude of 5.5 mV corresponds to a length of 300 nm of the normal zone; this is only two to three times larger than the $2r_0 = 122$ nm given by eq. (3).

4.3 Non-equilibrium models

One possible way of explaining the observed behaviour of our strip is to assume that current injection happens through many parallel tunnel junctions in the contact areas. These junctions are of the superconductor–insulator–superconductor (SIS) type when the temperature is lower than the critical temperature of the In. At higher temperatures we may be confronted with a superconductor–insulator–normal conductor (SIN) junction. This would make plausible the fast rise-time of our signals and could also allow for the absence of the NbN signal under reversed bias current. The size of our NbN signal, however, is more than twice as large as what one would expect in a SIN junction, and we are led to conclude that only the In signal may be due to tunnelling of non-equilibrium quasi-particles created by radiation from the source.

One could also speculate that, owing to its columnar structure, the NbN film basically consists of an array of weakly linked grains. In a simplified model the strip could then be represented by a network of tunnel junctions. If the incoming particle deposits enough energy in one of the columns to flip it to the normal state, then two or more junctions are switched, and one would observe a voltage of at least twice the gap-voltage.

In order to fully understand the transient behaviour of a superconducting microstrip in a very short time-scale, a theoretical model would have to include Maxwell's equations, in addition to the dynamic equations describing the non-equilibrium electronic and phonon systems in the type-II superconductor. From the gap energy, it is possible to deduce that the shortest time-scale for non-equilibrium phenomena is in the range of tens of femtoseconds for NbN. In addition, the recovery from non-equilibrium pulses becomes possible at currents well above the limit given by the thermal equilibrium model of eq. (8).

5. CONCLUSIONS

Very fast pulses produced by electrons of a ^{106}Ru source have been detected on a NbN microstrip. Although there were problems with the contacts, we could show that electrons with energies in the MeV range produce signals with mV amplitudes and rise-times of less than 300 ps. For a full clarification of the origin and underlying physics of the signals, further experiments are necessary using strips with better contacts.

A steady-state model was developed that describes reasonably well the stability of the strip under steady bias current, in both the presence and the absence of the source. The model gives the contact resistance, which agrees with d.c. resistance measurements, and yields the intrinsic critical current density of 10^7 A/cm² and critical temperature of 13.8 K, in good agreement with other work on the best available NbN films. Our model also yields the value $\alpha = 190$ W·m⁻² K⁻⁴ for the Kapitza thermal boundary conductance between the strip and the substrate. This boundary conductance allows us to deduce the thermal healing length

$\eta = 1.5 \mu\text{m}$ for our experimental conditions, which enables the comparison to be made with the thermal transient model of Sherman [1].

Our experimental data are in a serious conflict with many features of the thermal transient model. In particular, the model predicts thermal stability and signal recovery at bias currents below 2.1 mA only, in contrast with our observed signal recovery at currents up to 18 mA. The thermal model also predicts no self-recovering signals, because our strip would develop a normal zone across the whole width of the strip at currents above 93 mA only [see eq. (7)]. These contradictions with the predictions of the thermal transient model of Sherman lead us to suggest that only a more refined treatment of the non-equilibrium phenomena in a granular superconductor can describe our observations.

Acknowledgements

We would like to thank D. Caldwell, A. Gabutti and A. Zehnder for interesting discussions, and F. Dydak for encouragement and support. We are grateful to R. Vaglio for supplying us with the NbN strip.

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Figure captions

- Fig. 1: Block diagram of the electronic circuit for biasing the strip and amplifying the signals. The bias current is fed into the $50\ \Omega$ coaxial line, which transmits the signals to room-temperature electronics via a specially designed diplexer.
- Fig. 2: Maximum current $I_{\max}$ that could be passed through the strip before switching to the normal state occurred, as a function of temperature. The lines represent the least squares fits of the theoretical function, eq. (1), to each set of experimental results. The open symbols show results from different measurement runs, made while the strip was not exposed to the source. Full circles show the one set of data taken with the source mounted on the strip. The inset shows the cross-section of the strip.
- Fig. 3: A set of three different signals detected at a substrate temperature of 5 K and a bias current of 16.5 mA. The overall shapes of the signals are determined by the frequency response of the amplifiers. The signals are believed to originate from the NbN strip, because they persisted up to its critical temperature $T_c = 13.8$ K.
- Fig. 4: A positive pulse detected at $T_a = 2.35$ K and $I_b = 130\ \mu\text{A}$ recorded with two preamplifiers in series yielding a total gain of 40 dB. Pulses at such low currents were attributed to the In contacts. The inset in the top right-hand corner shows the $I_{\max}$ versus T for the In contacts (no irradiation). Pulses with a shape similar to the one shown were detected at a bias current close to $I_{\max}$. The lower left-hand inset shows the contact configuration.

Fig. 1

Fig. 2

Fig. 3

Fig. 4