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Test of superconducting Nb/Al bilayers as particle detectors☆

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Abstract

Superconducting thin film particle detectors can be very attractive due to the low sensitivity to radiation damage. We describe the fabrication procedure and the characterization of Nb/Al bilayers as particle detectors. First steady and dynamical results are reported from tests of 5 MeV alpha-particle detection.

1. Introduction

Superconducting thin film strip detectors have been thoroughly studied since the 1960s [1–3]. It has been shown that the detection of α-particles and X-rays is in principle possible using strips made with *soft* superconducting materials, such as In, Pb and Sn [3–5]. However, these materials suffer severe limitations due to their bad mechanical properties, which makes impractical their use for the fabrication of real devices. On the other hand, *hard* superconductors such as Nb, Al, Ta and W, appear to be better suited because of their high resistance to thermal and mechanical stresses, good electrical properties, stability, reliability, ease of fabrication and reproducibility of their properties over different deposition runs. The technology of Nb and Al in particular is well known and used worldwide for the fabrication of a wide array of superconductor-based devices. The main limitation of Al is its low critical temperature, ~ 1 K for the pure material and up to ~ 2 K for granular Al, which rules out the possibility of using liquid He cryostats [6]. On the other hand, Nb has a critical radius in the submicron range and a lower critical temperature is actually desirable because it gives larger hot-spots for a given energy of the ionizing particle [7].

We have therefore decided to investigate the feasibility of a Nb/Al strip detector, made by superposing an Al and Nb film, 5 μm wide, well within the allowed range of the photolithographic process used in most laboratories working on low-T_c superconducting devices. We report here our first results with α-particle irradiation of such devices at temperatures between 4.2 and 9 K. These results, although preliminary, clearly show the occurrence of self-recovering transitions in these Nb/Al detectors. The main limitation of present experiments is the slowness of the self-recovering events, occurring in a time scale of several hundreds of ms.

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2. Detector fabrication

The Nb/Al bilayers are RF-sputtered from single targets on Corning glass substrates through a photoresist stencil mask. The sputtering system is evacuated by a turbomolecular pump and the base pressure is about 4×10^{-7} mbar. Nb is deposited at an Ar pressure of 5×10^{-3} mbar and an RF voltage of 1500 V, a sputtering rate of 10 Å/s, while the Al film is deposited at a rate of 5 Å/s with the same Ar pressure and an RF voltage of 1000 V.

The film thickness d ranges between 500 and 2000 Å for Nb and between 0 and 2000 Å for Al. The deposition of each layer is followed by patterning the samples according to two different geometries using standard optical photolithography and either reactive-ion etching or lift-off. Different geometries have been made (Table 1).

Fig. 1 sketches the side-view and the top-view of the geometry A.

3. Detector operation

Heating caused by energy loss of an incident particle produces a normal conducting cross section, *hot-spot*, of radius r_c (critical radius). The superconducting–normal (s–n) transition propagates across the width of the strip and the resistive region thus created produces a detectable voltage pulse. The device can stay in the normal state (full-propagation regime) or recover the superconducting state (self-recovering regime).

Table 1
Detector geometries

Geometry	l (μm)	w_{Nb} (μm)	w_{Al} (μm)
A	100	5	2000
B	100	5	5

3.1. Steady-state tests

The critical current is determined by measuring the maximum current that can be passed through the strip before switching to the normal state as a function of temperature. The temperature dependence of the measured critical current follows the expected behavior for narrow strips [8]. For the hot-spot production, a ^{241}Am source has been used, whose favored decay (90%) is by a 5.47 MeV α-particle (intensity around 740 kBq). The source and the bilayer have been mounted in close proximity and placed in liquid ^{4}He. The irradiation can be treated as uniform, since the active area of the source is 2 mm in diameter. In Fig. 2, the critical currents I_c without alphas and $I_{c\alpha}$ with alphas are plotted versus temperature for a bilayer.

The effect of the α-particle flux onto the strip is to lower the critical current to the value [4]

$$I_{c\alpha} = I_c\frac{w-2r_c}{w}. \quad (1)$$

The reduction is between 30% and 90% at helium temperature. The r_c values extracted from these

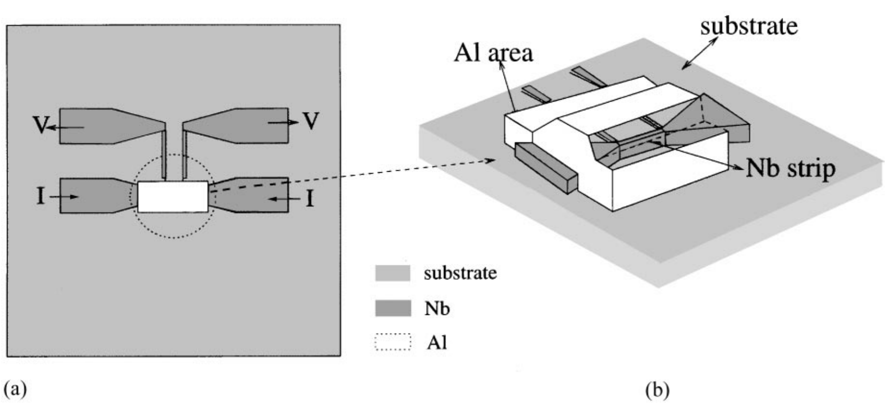

Fig. 1. Sample geometry A: (a) top-view, (b) expanded perspective view of the circle region in (a).

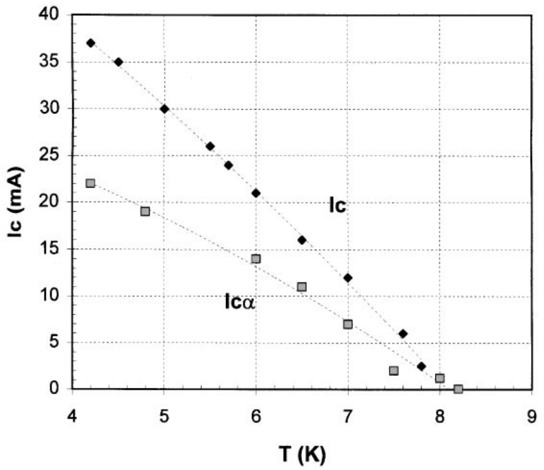

Fig. 2. Critical current versus T without (I_c) and with the Am α-source ($I_{c\alpha}$). Lines are used as a guide to the eye.

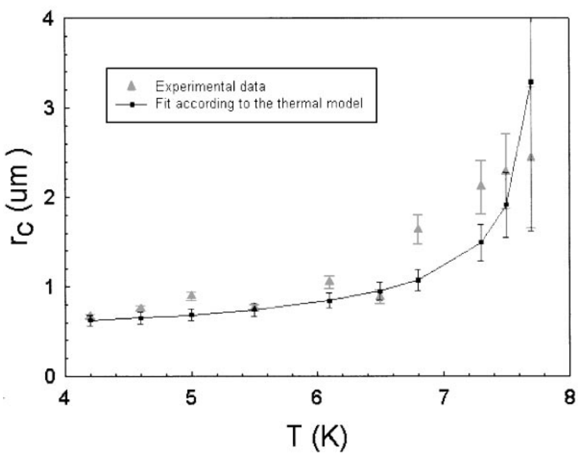

Fig. 3. Critical radius. Values extracted from experimental data compared to the thermal model fit.

measurements have been compared to the prediction of the thermal diffusion model [3]. According to Spiel, the relation between the radius of the hot-spot and the ionization energy is given by

$$r_c = \sqrt{\frac{2\mathrm{d}E/\mathrm{d}x}{\pi e \rho \gamma (T_c^2 - T_b^2)}}, \quad (2)$$

where $\mathrm{d}E/\mathrm{d}x$ is the stopping power, e the Neperian base, ρ the mass density, γ the Sommerfeld constant, T_b is the bath temperature. The α stopping

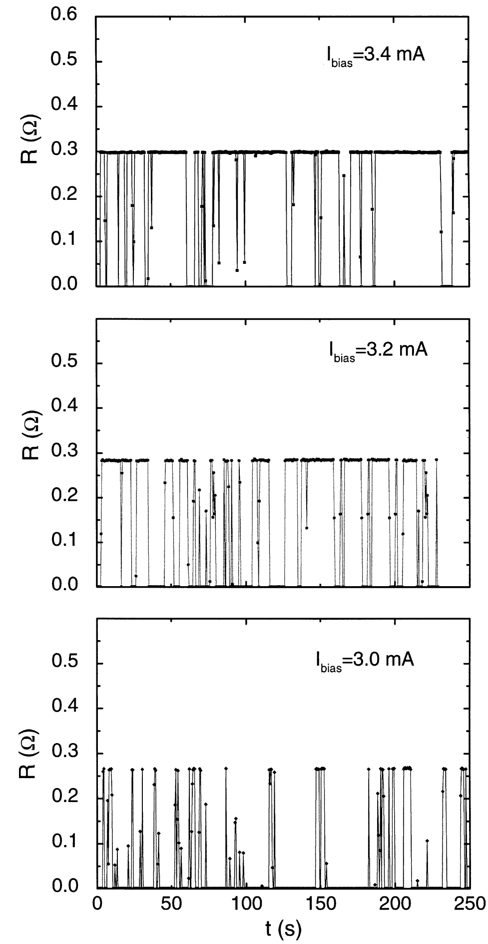

Fig. 4. Self-recovering signals due to α-particle irradiation at $T = 7.4$ K.

power in the Nb strip has been estimated using the Bethe– Bloch formula [9]. The comparison is shown in Fig. 3. Error bars take into account the energy loss dispersion about the mean value [10]. The data are in good agreement with the theory.

3.2. Dynamical response

We have detected both voltage pulses which fully propagate in the Nb/Al bilayers and self-recovering pulses, as shown in Fig. 4. When we bias the device between 85% and 95% of $I_{c\alpha}$, in a temperature range of 1–2 K below T_c, we observe a succession of transitions between the normal and the

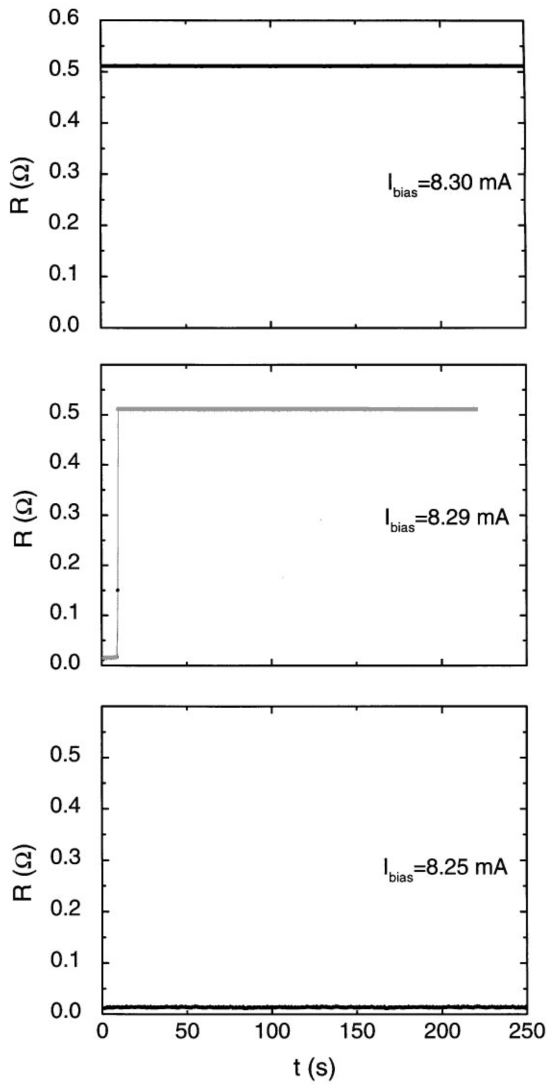

Fig. 5. No *s–n* transitions without the α-source at the same temperature $T = 7.4$ K.

superconducting state. No similar behavior is seen without the α-source at the same temperature (Fig. 5). We note that the device is not fully driven into the normal state by α heating, being its maximum resistance nearly half of that without alphas.

In our opinion, these transitions are related to the cumulative effect of the excess heat generated by several local transitions, which sum up leading to the transition to the normal state. When the accumulated heat is dispersed through the substrate and the cool helium gas, the strip cools down recovering its superconducting state. The recovery time becomes longer increasing the bias current. The slow recovery time is probably due to the thermal coupling at the bilayer/substrate and at the Nb/^{4}He boundaries.

The *s–n* transitions are not due to thermal fluctuations of the bath. Without the alpha source the sample does not become normal if biased with $I_b = 99\% I_c$.

4. Conclusions

Further efforts will focus both on the improvement of the experimental setup to detect the single local transitions of the Nb/Al strip, and on the further improvement of the fabrication process, using substrates having better thermal properties in order to avoid the accumulation of local heat and to shorten the recovery time.

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