Nb-based overdamped junctions with improved performance for measurement applications

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Abstract. Optimization of the performance of Nb-based overdamped Josephson junctions for applications to superconducting electronics is a major issue today. The use of cryocoolers, thus avoiding liquid helium refrigeration, with junctions working at temperatures higher than 4.2 K, could greatly increase the use of these devices in applications such as fundamental metrology and measurement sensors. The question we address here is how to maximize the characteristic voltage and minimize the temperature influence on the current-voltage curves of overdamped junctions enabling their use at $T > 4.2$K. To optimize the properties of a single Josephson heterostructure, we propose a type of overdamped junction that consists of a relatively thin insulating layer and a thick (tens of nm) normal-metal film between two superconducting electrodes. Measurements of the dependence of the critical current and characteristic voltage as function of temperature for different electrodes configurations show how it is possible to improve the design of these junctions.

1. Introduction
While conventional Josephson arrays of highly hysteretic tunnel junctions working at 4.2 K can generate maximum dc voltages up to 10 V, special Josephson junctions technologies were suggested to realise programmable quantum voltmeters and standards. These devices use only the first voltage step $V_1$ of each junction and, depending on the rf frequency $f$, even for a maximum output voltage of only 1 V, a large number of junctions with an extended microwave distribution circuit is needed \cite{1}. The research for an improved Josephson junction technology is relevant also for other superconducting electronic circuits such as fast A/D converters. For all these applications a mandatory feature is that the $I-V$ characteristic must be non-hysteretic, in order to avoid overlapping of the rf-induced voltage steps corresponding to the different voltage levels. This aspect is also necessary for fast electronic circuits, to have a symmetrical response with nearly equal rise and fall times, of the order of a few ps. Other basic requirements are an high noise immunity, a low power dissipation and reduced dimensions, in order to achieve the best measurement performance.

In terms of the junctions parameters, these requirements influence the critical current density $J_c$ and the characteristic voltage $V_c = I_c R_N$, where $R_N$ is the normal tunnelling resistance. Both $J_c$ and $V_c$ should be as high as possible, in order to obtain circuits capable of a sufficient...
span of the voltage output for metrology, or of sufficient speed for A/D converters, without requiring an excessive complexity of the fabrication process. However, the data on the various types of Josephson junctions developed so-far indicate, with a few exceptions, that this is rarely achieved, since high values of $J_c$ or $V_c$ usually lead to different classes of junctions. A further aspect which represents the next most challenging problem for voltage metrology, and also of other superconducting electronics applications, is the use of these devices in cryocoolers at a temperature greater than 4.2 K. In fact, to make precise dc and ac voltage reference standards available to a wider market than Universities and National Laboratories, less expensive and more compact refrigeration systems are needed.

The possibility of using large arrays of high-temperature superconductors or of MgB$_2$ is not yet available, since the technology of these junctions does not allow one to fabricated arrays of more than few hundred junctions. Moreover, of all the Nb- and NbN-based technologies currently available, only NbN/TiN/NbN Josephson junctions tackle this issue, at the cost of a top-level fabrication process. Nb/Al-AlO$_x$/Nb junctions with non-hysteretic $I-V$ fabricated at INRIM, are a possible solution to this problem.

2. Experimental
The junctions derive from the trilayer process described by Gurvitch et al. in 1983 [2], but have an Al thickness of 30 – 100 nm, one order of magnitude larger than the value used for the standard hysteretic SIS junctions. Because of this thick Al film, which is a normal metal at the liquid helium temperature, these devices could be better described as Superconductor-Normal metal-Insulator-Superconductor (SNIS) junctions. However, differently from other SIS or SNIS devices, these junctions become overdamped, thus showing a non-hysteretic $I-V$ curve when the aluminum oxide is sufficiently thinned. This is obtained by keeping the oxidation exposure $E$, oxygen pressure times oxidation time, below 500 Pa.s.

In detail, reproducible overdamped junctions with hysteresis at 4.2 K ranging from 0 to a few % were fabricated for Al = 30 – 100 nm and $E$ ranging between 40 and 475 Pa.s, with the best results being obtained for 100 – 300 Pa.s.

In order to test the use of these junctions at $T > 4.2$ K, we have studied the temperature behaviour by measuring their $I_c(T)$ dependence from 2 K to the transition temperature $T_c$. This

Figure 1. (a) Temperature dependence of the normalized critical current for two different Nb/Al-AlO$_x$/Nb Josephson junctions. The main fabrication parameters of the junctions are listed in the left panel. (b) Temperature derivative of the dotted line, which is the best approximation for the two sets taken together. The solid lines are the corresponding curves calculated from the Ambegaokar-Baratoff model.
transition temperature was typically from 7.5 to 9 K, depending on the relative thickness of the Nb base electrode and the Al normal layers. A detailed account of the experimental results can be found in [3].

3. Results and discussions

We shall demonstrate below the feasibility of ensuring in our junctions at $T$ above the liquid helium temperature both a high damping at the Josephson characteristic frequency $\omega_c = 2eV_c/\hbar$ and also the temperature stability, due to a specific gap voltage vs. temperature dependence of the Al film placed in proximity with the base Nb layer. The intrinsic damping properties of a single Josephson tunnel junction are determined by the product of $\omega_c$ and the characteristic decay time $\tau = R_N C = \rho_N c$ (where $C$ is the junction capacitance, $\rho_N$ and $c$ are the specific junction resistance and capacitance, respectively) that is known as the Stewart-McCumber damping parameter

$$\beta_c = \frac{\omega_c \tau}{\hbar}.$$  

The damping parameter should be less than unity to ensure non-hysteretic $I-V$ curves. To fulfill the condition $\beta_c < 1$, we need to fabricate either ultra-high transparency barriers in Nb-based junctions with $\rho \sim 1 \Omega \mu m^2$ [1, 4, 5], or to replace Nb-based junctions with Al-based devices [6], where $V_c$, that is proportional to the product of superconducting energy gaps in both electrodes [7], is nearly 10 times smaller than the corresponding value in Nb.

Unfortunately, in the first case the barrier quality was found to be rather poor, due to a noticeable density of pin-hole defects [5]. On the other hand, Al/AlO$_x$/Al Josephson junctions show non-hysteretic behavior up to $\rho = 30 \Omega \mu m^2$ but need ultra-low temperatures for their operation [6].

In this paper we show another way to obtain a self-shunted junction. We suppress the value of $\beta_c$ by increasing the temperature to reduce the critical current $I_c$. Of course, such a suppression can be realized in a standard Nb junction when the temperature is close to $T_c$ but, as it follows from the conventional Ambegaokar-Baratoff (A-B) expression for the temperature dependence of the critical current [7], in this region the values of $I_c$ are strongly influenced by the temperature variation. This means that a small temperature drift will cause an unstable operation of the Josephson circuitry.

Our idea is to obtain a relatively flat temperature dependence $I_c(T)$ above 4.2 K using a proximity-coupled superconducting Al/Nb bi-layer with comparable thickness of the two films, where the energy gap changes very slowly at temperatures close to $T_c$ compared with the AB

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.png}
\caption{Temperature dependence of the critical current, normalized to $I_c(5\,\text{K})$, for Josephson junctions with different ratios of $d_{\text{Al}}/d_{\text{Nb}}$, compared to the curve calculated from the Ambegaokar-Baratoff model.}
\end{figure}
regime (see, for example, Fig. 5a in Ref. [8] for an Al/Nb bi-layer or Fig. 2 in Ref. [9] for a Sn/Pb bi-layer).

We start by discussing the temperature stability of the Josephson current in our samples. Fig. 1(a) shows the $I_c - T$ behavior for two junctions with $d_{Al} = 100$ nm, $d_{Nb} = 120$ nm and two different oxidation exposures $E$.

The temperature stability of the Josephson junction can be characterized by the derivative $d[I_c(T)/I_c(0)]/dT$. To find the $I_c$ value at $T = 0$, we have used the ratio $I_c(T = 0.45T_c)/I_c(0) \approx 0.48$, that was determined in Ref. [3] from the low-temperature data. Fig. 1(b) shows this characteristic for the experimental data of Fig. 1(a), compared with that calculated for the AB model. It is evident that for $T > 0.7T_c$ our junctions are more stable to temperature variations than SIS heterostructures.

Fig. 2 shows the temperature dependence of the critical current for three junctions with different ratios of the Nb and Al thickness. The solid line is calculated from the Ambegaokar-Baratoff model. The critical current has been normalized to that measured at $T = 5$ K, which is roughly correspondent to $0.5T_c$. From the Figure, it is evident that, as the ratio of the Al and Nb thickness becomes smaller, the temperature dependence of the critical current becomes closer to the predictions of the A-B model. Also, the departure from the A-B model is larger at intermediate temperatures, i.e., around $0.6 - 0.8 T_c$, while at the extrema of the temperature range considered here, $T \sim 0.5T_c$ and $T \sim T_c$ the experimental results are very close to the A-B curve for any ratio of $d_{Al}/d_{Nb}$.

The measured $I_c(T)$ permits us to reconstruct the $\Delta_{Nb/Al}(T)$ dependence. Using Eqs. (3.2.5) and (3.2.9) from [7] we obtain that

\[
\frac{I_c(t)}{I_c(0)} = \frac{\pi t d + 1}{\alpha K(\delta)} \times \sum_{l=0,\pm 1,\pm 2,...} \left\{ \left[ f_1^2(T) \frac{\Delta_{Nb}(t)}{\Delta_{Nb}(0)} \right]^{-2} + 1 \right\} \left[ d^2 f_1^2(T) \frac{\Delta_{Nb/Al}(t)}{\Delta_{Nb/Al}(0)} \right]^{-2} + 1 \right\}^{-\frac{1}{2}}. \tag{2}
\]

Here $t = T/T_{c,Nb}$, $d = \Delta_{Nb}(0)/\Delta_{Nb/Al}(0)$, $\delta = (d - 1)/(d + 1)$, $K(x)$ is the complete elliptic integral of the first kind, $f_1(T) = 2\pi(2l + 1)t/\alpha$ and $\alpha = 2\Delta_{Nb}(0)/k_BT_{c,Nb}$.

The best fitting to our experimental data from Fig. 1 is shown in Fig. 3 where we present the resulting temperature behavior of the energy gap for Al/Nb electrodes.

Measurements of the $I - V$ characteristics in the whole temperature range from 1.7 K to $T_c$ have shown a peculiar feature of the junctions, namely, a transition from a non-hysteretic to an hysteretic behaviour for decreasing temperature, such as for the junction of Fig. 4, having...
Figure 4. Effect of the temperature on the $I-V$ characteristics of a Nb/Al-AlO$_x$/Nb junction with $d_{Nb} = 100$ nm, $d_{Al} = 50$ nm and $E = 160$ Pa-s.

an Al thickness of 50 nm and an oxidation exposure of 160 Pa-s, where a gradual increment of the hysteresis from nearly zero (< 1%) for $T$ higher than 4.2 K up to 28% at $T = 1.7$ K was observed.

Here the hysteresis is defined as the percentage of the difference between the retrapping current $I_r$ to the switching $I_0$ current $\Delta I = I_0 - I_r$. An hysteresis of 20–40% at low temperature when the energy gaps of both electrodes are not changed significantly means that the Stewart-McCumber parameter (Eq. 1) at $T = 0$ in our case is slightly above 1 [6]. Increasing the temperature, we strongly suppress $V_c$ in Eq. 1 and, as a result, above 4.2 K our $\beta_c$ is less than unity, as becomes evident in the absence of hysteresis. In our opinion, this is the main reason of the transition from hysteretic to a non-hysteretic behavior with increasing $T$. Let us also note that our junctions can show an hysteretic or non-hysteretic $I-V$ also at 4.2 K by changing the fabrication parameters [10]. Preliminary measurements of the rf-induced quantized voltage steps at temperatures from 4.2 K to 8 K confirm the possible use of these junctions for voltage metrology, without expensive liquid helium refrigeration [11].

4. Conclusions
We have shown for our Nb/Al-AlO$_x$/Nb overdamped Josephson junctions the feasibility of stable operation at temperatures above liquid helium and close to $T_c$. This opens the possibility of using these junctions for voltage standard circuits in cryocoolers, avoiding the expensive use of liquid helium refrigeration systems, opening to a wider market the use of precise dc and ac voltage reference standards.

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References

[1] Hu E L, Howard R E, Jackel L D, Fetter L A and Tennant D M 1980 IEEE Trans. Electron. Dev. 27 2030
[2] Gurvitch M, Washington M A and Huggins H A 1983 Appl. Phys. Lett. 42 472
[3] Lacquaniti V, Andreone D, Leo N D, Fretto M, Maggi S, Sosso A and Belogolovskii M 2007 IEEE Trans. on Appl. Supercond. 17 609
[4] Jackel L D, Hu E L, Howard R E, Fetter L A and Tennant D M 1981 IEEE Trans. Magn. 17 295
[5] Patel V and Lukens J K 1999 IEEE Trans. Appl. Supercond. 9 3247
[6] Lotkhov S, Tolkacheva E, Balashov D, Khabipov M, Buchholz F I and Zorin A 2006 Appl. Phys. Lett. 89 132115
[7] Barone A and Paternò G 1982 Physics and Application of the Josephson Effect (New York: Wiley)
[8] Bramertz G, Polaert A, Golubov A A, Verhoeve P, Peacock A and Rogalla H 2001 J. Appl. Phys. 90 355
[9] Gilabert A, Romagnan R and Guyon E 1971 Solid State Commun. 9 1295
[10] Lacquaniti V, Cagliero C, Maggi S and Steni R 2005 Appl. Phys. Lett. 86 042501
[11] Lacquaniti V, De Leo N, Fretto M, Maggi S and Sosso A 2007 (To be published)