Response to "Comment on 'High T_c superconducting quantum interference devices made by ion irradiation' " [Appl. Phys. Lett. 90, 136101 (2007)]

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In his comment,[1] Tinchev mentions that High T_c superconducting quantum interference devices (SQUIDs) made by ion irradiation have been already made successfully[2] and even tested in the American Space Shuttle.[3] He is right, of course, and we have only quoted in our letter the most recent works in this field. He also stresses that this "promising technique" suffers from two drawbacks: a strongly temperature dependent critical current and a restricted range of RSJ-like behavior. Although this last point needs to be clarified (the resistively shunted junction (RSJ) range is short for a 77 K operation, but can be 20–30 K for a low temperature one), Tinchev points out the true weaknesses of the method and at the same time, what needs to be done to cure them. If his fabrication method allows us to make irradiated Josephson junctions (IJJs) with *predictable* and *reproducible* characteristics $[T_J, \mathrm{Ic}(T), \mathrm{Rn}(T)]$, then for a given operating temperature chosen for a specific application, these values will be known in advance and set once and for all. If the dispersion in JJ characteristics is low enough, the temperature dependence of the critical current is no longer an issue. We do think that our method for making JJ is "new" in a sense that we have achieved an accurate control of their characteristics, with an extremely small dispersion from one JJ to another. For example, we can design SQUIDs for 77 K operation and we have shown that they indeed behave as predicted.[4]

What are the differences with the previous published work? They are twofold, related to the two main steps in the process.

Firstly, the great majority of the reported IJJ (Refs. 5–9) has been made in the middle of narrow channels realized by etching (wet or dry) high T_c superconducting (HTSc) films. Uncontrolled disorder and oxygen out-diffusion strongly impair the reproducibility of this method, and is a major source of poor thermal cycling of the devices. We fabricate the channels by ion irradiation, without removing the matter, leaving the whole device encapsulated. To the best of our knowledge, only one team (Kahlman and co-workers)[10,11] have used a similar trick, and therefore our technique is new compared to most of the references quoted by Tinchev.

Secondly, since the reproducibility of the IJJ is intimately related to the control of the irradiated zone defining the junction and therefore to the precision of the trench opened in the mask, the technique used to define it appears to be essential. In the 1990s Tinchev's group used a single layer polymethyl methacrylate (PMMA) photoresist as a shadow mask, with apertures of 100 nm and wider. The IJJs were working more in the weak link regime rather than in the superconducting-normal-superconducting (SNS) one, and therefore must be operated in a very restricted range near T_c', the critical temperature of the irradiated zone. Later on, the Jülich group explained and showed that the best results are obtained with smaller JJs,[11] working in the SNS limit. To make smaller apertures (down to 40–50 nm), this team developed a complex trilayer mask but had to anneal the devices after the process in order to obtain good characteristics, probably to cure the uncontrolled disorder introduced during this step. We have used a single PMMA photoresist with a nominal aperture of 20 nm designed by a LEICA EBPG 5000+ machine. No further annealing is needed to get the predictable and reproducible results described in our letters.[4,12]

In conclusion, HTSc IJJs have been made for many years, but not widely used in real applications. We have developed a new and rather simple process at a nanoscale (20 nm) to make them reproducible enough to open perspectives again for this technology. However, the authors agree with Tinchev that more work still needs to be done in this field.

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