Radiation Hardness of Josephson Junctions and Superconductive Digital Devices

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Abstract—We have investigated the response of Nb-based Josephson junctions and RSFQ digital devices to a beam of 6.5 MeV protons. We have reached a total fluency of $10^{16}$ p/cm$^2$. Both the junctions and the digital devices have showed practically no permanent damage after the irradiation, with no change in the I-V characteristic, in the magnetic field dependence of the critical current, and, in the case of the digital circuits, in the operation margins. These results indicate a very interesting potential for application of low Tc devices as fast detectors and signal processors in large accelerator (e.g. LHC) detectors, where semiconductive devices experience serious radiation damage problems.

I. INTRODUCTION

The response of superconductors to high energy particle has been widely investigated mostly in view of applications in particle accelerator environments. Most of the study has been focused on the material properties (critical current density $J_c$, residual resistivity $\rho_0$, critical magnetic field $H_c$), as the applications envisaged were mostly "material" applications, as high field magnets and accelerating cavities.

With the development of fast and reliable large scale integration superconductive electronics, new areas of application are possible in the field of particle accelerators, namely vertex pixel detector electronics and sensors, where superconductive electronics may provide a competitive substitute of the current semiconductive one [1],[2].

The possible application of superconductive electronics to satellite-based communications also requires a knowledge of the effects of high energy radiation, as satellites are subject to bombardment of a number of high energy particles, from cosmic ray, solar wind, solar flares, etc.

So far very few studies have been done on the effect of ionizing radiation on Josephson junctions [3],[4], and only two on junctions made using state of the art Nb technology [5],[6].

In this paper we have extended the previous work to higher radiation doses, and we have included in our tests also complete digital circuits, made using RSFQ logic.

II. SAMPLES IRRADIATION

The samples were irradiated with 6.5 MeV protons and fluences ranging from $5 \times 10^{11}$ to $10^{16}$ p/cm$^2$, at room temperature and in high vacuum at the APT scattering chamber [7] of the 7 MV Van de Graaf CN accelerator of INFN Laboratori Nazionali di Legnaro. In our case the beam diameter was about 5 mm. The target support frame consists of a 1 cm diameter tantalum sample holder. The tantalum sample holder allows the thermal connection between the sample and the surrounding ambient. Moreover the whole target assembly serves as a Faraday cup for beam current integration. The estimated error in this calculation is less than 10%.

In order to estimate the total radiation dose released into the junction, Monte-Carlo simulations were performed on the impact of 6.5 MeV protons on a Nb film and on a Si substrate. The energy loss profile in niobium (calculated using TRIM-95 code) is fairly flat to a depth of 850 nm, corresponding to the total junction thickness. On the basis of TRIM Monte Carlo [8] calculations, the total energy loss in the Nb film, $E_{loss Nb}$, was of about 27 KeV/μm and protons implant in the Si substrate at a depth of about 330 μm.

It is possible to distinguish two different interaction mechanisms between the protons and the target. The former one is the proton coulombian elastic scattering against target nuclei and it is responsible for the displacements of atoms from their initial positions. The second one is the proton electronic anelastic scattering against target electrons and it is responsible for the phonon productions and points out the energy loss rate of the particles in the target. With 6.5 MeV protons, the main source for damage creation in the target lattice is the first mechanism even if the energy lost for this mechanism is about three orders of magnitude lower than the energy lost for the second mechanism. Apart from statistical noise, the damage is quite uniform.

With a Nb density $D_0 = 8.57 \text{ g/cm}^3$ and a fluence $= 10^{16}$ p/cm$^2$ the total junction radiation dose, computed as $E_{loss Nb} = 4.3 \mu\text{J}$ as calculated by $E = E_{loss Nb} \cdot A$, where $t$ is the junction thickness (1 μm) and $A$ is the junction area ($10^4$
As the irradiation time was about 32000 s, the power released into the junction was 135 nW, and the corresponding power dissipated in the whole 25 mm$^2$ chip was 65 mW, low enough to prevent unwanted heating.

### III. RESULTS

In Figs. 1 and 2 are shown two micro-photographs as example of the chips used for the irradiation tests. The first one (Fig. 1) is a standard test chip realized for particle detection applications. It has been fabricated using state of the art Nb technology at the Electrotechnical Laboratory, Tsukuba, Japan, and employs a number of Josephson junctions of various size and shape, single and connected in series to form large (100 junction) arrays. The junction used in our test were all high quality samples ($V_m>60$) and had a low critical current density ($J_c = 60 \text{ A/cm}^2$).

The junctions have been characterized before and after the irradiation by measuring the I-V curve at $T=4.2$ K and at $T=1.2$ K (in order to suppress the thermally excited quasiparticles), and the magnetic field dependence of the critical current. Both single junctions and arrays configurations have been tested.

The second chip (Fig. 2) is an example of complex RSFQ digital circuit realized at HYPRESS, Elmsford, USA, and contains six 48-bit shift registers. This chip, realized with a technology of $J_c = 1 \text{ KA/cm}^2$, includes also the necessary interface circuits to convert the external voltage-based logic control signals into the internal very fast (few ps wide) quantized voltage pulses. In Fig. 2 is shown a detail of one of the shift registers, in particular the voltage comparator of the data input is shown (on the left) together with the first two cells (on the right) of the shift register.

The shift registers were characterized by measuring the bias margins ensuring the correct operation of the device both before and after the irradiation.

In previous work [6] high quality Nb-based Josephson junctions were investigated under the same irradiation conditions but only up to a total fluence of $10^{15}$ p/cm$^2$, corresponding to a total dose of about 500 Mrad. As result no evidence of permanent damages were observed both in single junctions and in arrays.

By analyzing the characteristic of the junctions after the irradiation with $10^{16}$ p/cm$^2$ only a slight change in the I-V curve could be observed. In particular in a large area junctions ($10^4 \text{ m}^2$) a threefold increase of the subgap current was observed, while the critical current and the tunnel resistance at $V > 2\Delta/e$ were essentially the same. Junctions of smaller size were basically unaffected by the radiation, indicating that the damage mechanism is of statistical nature, has a low probability and is proportional to the junction area. The same consideration results from the analysis of the I-V curve of a 100 elements array of large area junctions. Indeed the only visible effects were an increase of the critical current and of the subgap current in a small subset (<10) of junctions.

The investigation of the digital chips showed no significative change of the operating margins for each device. This result is consistent with the previous consideration about the junction area, as these devices employ very small area junctions (few $\mu$m$^2$), thus raising the effective damage threshold for digital circuits to values significatively larger than those tested in this work.
IV. CONCLUSIONS

High quality Nb/Al2O3/Nb Josephson Junctions and RSFQ devices have been irradiated by 6.5 MeV protons with a fluence up to 10^{16} p/cm^2, corresponding to a radiation dose of 5 Grad.

The junction characterizations, both at 4.2 K and 1.2 K, show no appreciable changes due to the radiation. A deterioration effect can be seen on few large area junctions belonging to the large size array of the chip, and can be ascribed to barrier damages induced either by the impinging particles or by the thermal cycling.

The digital circuits, which employ much smaller junctions, showed no changes in their operating margins.

As the overall radiation dose employed (5 Grad) exceeds that of damage of typical semiconducting devices (even the recent RadHard DMILL technology) used in particle experiments and space applications we can conclude that Nb-based superconducting devices are good potential candidates for operation in radioactive environments.

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