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# UPSET EVENTS IN JOSEPHSON DIGITAL DEVICES UNDER ALPHA PARTICLE IRRADIATION

by

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## Abstract

Preliminary results on the effects of 5 MeV alpha particle irradiation on the electrical characteristics of large area (approximately 60 $\mu m^2$) Josephson Nb-amorphous Si-Nb tunnel devices indicate that these particles are effective in producing upset events when the device is operated in a switching mode. For bias currents very close to the critical current, $I_C$, upset rates are near 0.1 per alpha. At a reduced bias current of 0.65 $I_C$ the upset rate is decreased but is still finite (0.002 per alpha). In addition, an hysteretic effect was observed for the critical current of the device under alpha irradiation. A simple heating model does not appear adequate to explain the observed upset rate as a function of bias current and the hysteretic effect.

## Introduction

Complex electronic circuits based on Josephson tunneling between two superconductors are being developed for use in signal processors and computers[1,2,3] where high speed, high device densities and low power consumption are required. Before these circuits can be considered for use on satellites or in other high radiation environments, it is imperative that their sensitivity to single event upsets and their radiation hardness be determined. The work reported here is the beginning of an effort to determine the sensitivity of Josephson junction devices to a variety of energetic nuclear particles.

The basic Josephson tunnel device consists of two superconductors separated by a barrier, as illustrated in Figure 1a. The barrier for the devices reported here was a 10 nm thick layer of silicon, as shown in the schematic in Fig. 1a. Usually, a native oxide layer about 2 nm thick is used for the barrier. A Josephson junction can function as a digital switch because it exhibits zero resistance when the current through it is less than the critical value, $I_C$, and a finite resistance when the current exceeds $I_C$. A schematic diagram of a current-voltage characteristic is shown in Figure 1b to illustrate one possible switching mode. As the bias current, $I_B$, is increased from zero, the voltage across the junction is zero until the bias current exceeds $I_C$. At $I_B = I_C$, the device switches to a finite resistance state with a voltage $V_{gap}$ (of the order of millivolts) across the junction. The junction will remain in the finite resistance state until the current is reduced to zero. Thus, an upset event will be defined to be an unwanted switching from the zero to the finite resistance state. In general, the Josephson critical current depends upon the superconductors used for the electrodes, the temperature, magnetic field, barrier thickness, height of the potential barrier and the junction's area.

Local heating is one possible cause of an upset event in a Josephson device. If a small portion

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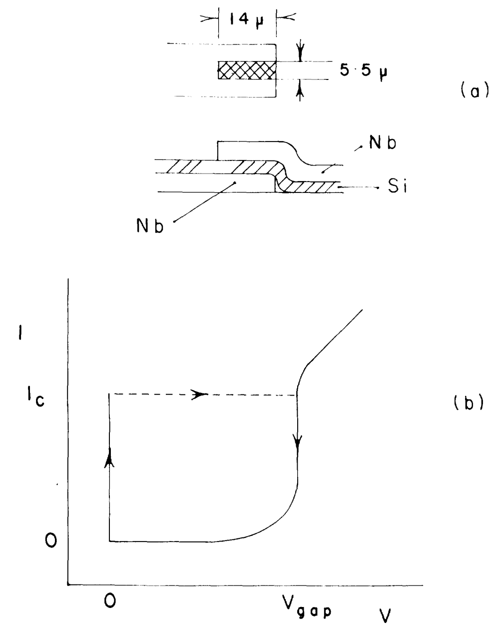


Figure 1. Schematic of basic Josephson tunnel device (a) and typical current-voltage characteristic (b).

of a junction's area is heated above the superconducting transition temperature, that part of the junction has a finite resistance and the current redistributes itself through the remainder. If the critical current density in the superconducting part of the junction is exceeded, the entire junction would switch to the finite-voltage normal state. This type of local heating could be caused by an ionizing particle passing through the device and losing energy to the lattice which results in localized heating. Such a heating model was used several years ago to explain how superconducting ribbons and superconducting tunnel devices (not operating in the Josephson mode) could be used as alpha particle detectors.[4,5,6]

Upset events could also occur if the devices are operated in weak magnetic fields, and if magnetic flux vortices were trapped in the vicinity of the device. The passage of an alpha particle could result in a redistribution of these vortices thus changing the effective magnetic field at the junction which would result in a variation of the critical current.[2,3]

The critical current could also be changed by varying the height of the potential barrier. This may happen if the alpha particles excite carriers which then become trapped by defects in the barrier. When the bias current is near the critical current it is also possible that the alpha particles could break the Cooper pairs required for superconductivity, creating a non-equilibrium state with an electron bath temperature higher than that of the lattice.[7]

## Experimental Details

Initial experiments involved irradiating Josephson tunnel junctions with alpha particles from a 562 microcurie americium-241 source. Since this source was relatively thick, the average energy of the alphas was degraded from 5.5 MeV to 4.7 MeV. The source was mounted so that it could be placed within 4 mm of the junction or moved entirely away to determine background noise. The alpha particles entered the junction with a wide distribution of angles because the source was large, 6 mm by 37 mm, as compared to the junctions which were about 5.5 μm by 14 μm. This source and sample geometry resulted in a flux of about one alpha every three seconds through the junction. Four terminal techniques and a constant current source were used to measure the current-voltage characteristics out to 3 mV, a voltage at which the device was clearly in the normal state. The devices were mounted on a copper block inside a sealed container which was immersed in liquid helium. The container was filled with helium gas to maintain the sample at the helium bath temperature of 4.2K.

A typical upset measurement cycle is shown in Fig. 2. At time zero, the current is slowly increased until a bias level $I_B$, where $I_B < I_C$, is reached at time $T_1$. Under this condition, the

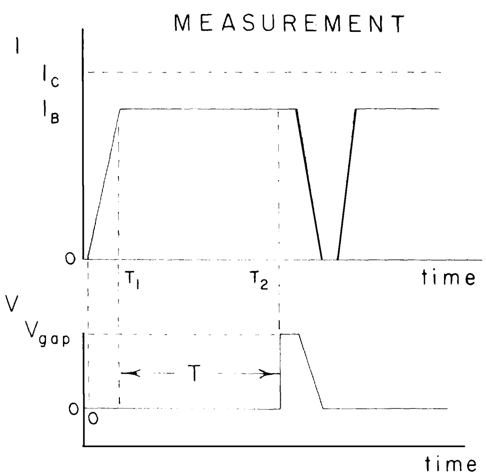


Figure 2. Experimental procedure for determining the upset time where I is the current and V is the voltage for the junction.

voltage across the junction will be zero. The voltage will remain zero until an upset occurs at time $T_2$ when the device switches to a finite voltage state, $V_{gap}$. The time $T_2 - T_1 = T$ is a measure of the time for an upset event. Following an event, the junction will remain in a finite resistance state until the current has been reduced to zero.

This cycle was repeated in order to obtain reasonable statistics for determining the upset rate with and without the alpha source. The critical current was checked after each upset, and if it changed, the junction was heated above its superconducting transition temperature to restore the critical current to its initial value. Measurements of the mean time for upset were made for several values of the bias current between 0.65 $I_C$ and 0.95 $I_C$.

## Results

The results for a series of measurements on the device with $I_B$ = 0.95 $I_C$ are summarized by the histogram in Figure 3. The number, N, of upsets occurring between T and T + ΔT is plotted both for the alpha source present and removed. It is clear from this plot that the mean time for upsets with the alpha source is shorter than the mean time for upsets due to background noise. An exponential form, $\exp(-T/T_i)$ was assumed to calculate the mean time for an upset, $T_i$. For the data shown in Figure 3, $T_N$ = 195 seconds was found from the background noise data and the mean time with the alpha source present (including noise) was T = 31 seconds. Recognizing that the total rate is $1/T_O = 1/T_N + 1/T_M$, a value of $T_M$ = 37 seconds was obtained for the mean time for upsets with the alpha source present.

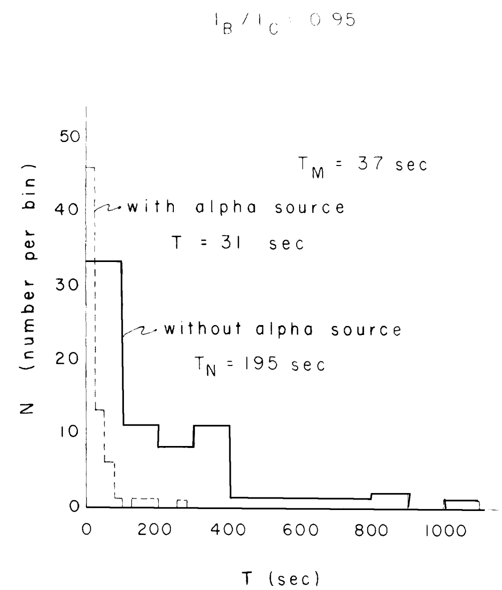


Figure 3. Number of events measured within the time interval between T and T + ΔT with and without an $^{241}$Am source present. $I_B/I_C$ = 0.95.

Several values of $I_B$ were used to obtain the variation of $T_M$ with bias current shown in Figure 4. The long mean times for upset made it difficult to obtain good statistics, but it is possible to set some limits on the sensitivity of the device. These results indicate that $T_M$ increases with decreasing bias current. At high bias currents, one in every 10 alphas results in an upset event, while only one in 500 causes an upset event at lower biases.

No permanent changes to the device characteristics were observed which could not be reversed by thermal cycling. However, results indicate there is an hysteretic effect in the critical current after an upset event during alpha particle irradiation. Because of this observation, tests were carried out to determine whether the critical current was changed by the alpha particle irradiation even before an upset was observed. The experiment consisted of exposing the junction to the alpha particles and then periodically removing them to measure the critical current. The critical current was determined by slowly increasing the bias current until a voltage appeared across the device.

Sometimes the value determined after alpha irradiation was close to the previously determined value, but most of the time the values of $I_C$ were smaller. Generally $I_C$ decreased on the order of 10% for 100 alphas penetrating the junction. When the control experiment with the alpha source removed was carried out, the critical current reproduced within 1% from one current induced switching event to the next. The changes to the critical current produced by the alpha particles could be completely erased if the bias current were set to zero and the device heated above its superconducting transition temperature. After a thermal cycling of this type,

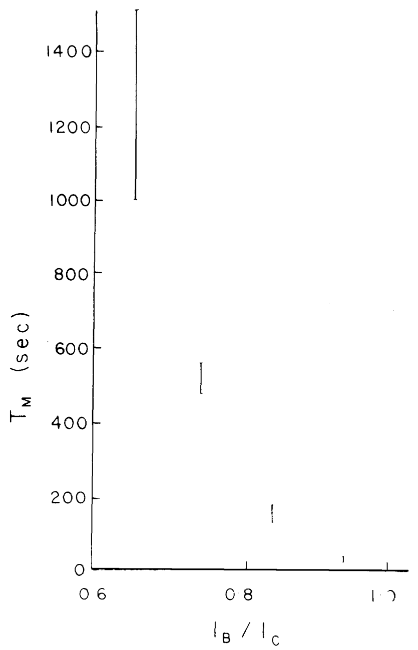


Figure 4. The mean time for upset due to alphas, $T_M$, as a function of bias current through the Josephson tunnel junction, $I_B/I_C$.

the measured value of $I_C$ agreed to within 1% of the value obtained before the alpha particle irradiation. Additional studies of this hysteretic effect are underway and the preliminary data suggest that it is associated with the trapping of magnetic flux in an ambient magnetic field.

## Discussion

On several occasions a heating model has been used to explain the effects of ionizing particles on the properties of superconducting ribbons and devices.[4,5,6] In this model, it is assumed that the particle interacts with the lattice transferring energy to the specimen as it passes through. Thus, the region of the specimen surrounding the particle track may be heated above the superconducting transition temperature depending on 1) the magnitude of the energy loss in the specimen, 2) the specific heat and thermal conductivity of the materials forming the specimen and 3) the geometry of the interaction. In this model, a region with area A, around the particle track would be in a finite resistance normal state and the bias current, $I_B$, would redistribute itself to flow through the superconducting part of the junction with area $A_o$-A, where $A_o$ is the junction area. The entire device would switch into the normal state and a voltage would appear across the junction if the current density through $A_o$-A exceeds the critical current density, $J_C$. That is, an alpha induced upset event will occur when

$$I_B/(A_o-A) \geq J_C = I_C/A_o$$

or,

$$I_B \geq I_C\,[(A_o-A)/A_o]$$

The data in Figure 3 were obtained with $I_B = 0.95\ I_C$. According to the heating model, switching would happen if 5% of the area of the device were heated to the normal state. For this device, the normal region would have to have a diameter of at least 2 μm. This size is consistent with the sizes of the normal regions previously obtained for alpha particles incident on indium and tin devices.[4]

However, the heating model by itself cannot explain the upset rate as a function of bias current as shown in Figure 4. At $I_B = 0.65\ I_C$ there should be no upsets if the normalized region produced by an alpha is only 4 $\mu m^2$ as calculated above. Upsets would occur though if the area of the normal region were about 1/3 of the device's area or about 25 $\mu m^2$ in this case. Since the source is much larger than the device, it is necessary to consider the possibility that alpha particles entering at a large angle of incident may normalize more than 4 $\mu m^2$. This possibility is ruled out because the particles would have to enter the device nearly parallel to its surface and the number of particles at these glancing angles is too small to account for the upset rate.

The changes observed in the critical current after exposure to the alpha particles suggest another explanation for the high upset rate at $I_B = 0.65\ I_C$. If the device is operating in the presence of a weak field (of the order of 10 μT) it may be possible for the alpha particles to change the amount of trapped flux and thus the critical current. The cumulative effect after many alphas may be a net decrease in the critical current to a value $I_C' < I_C$ which would go without notice until $I_C' = I_B$ when an upset would occur. This model is supported by the observation of changes in the critical current measured after exposure to a number of alphas, but before an upset event. It is also supported by the fact that the original critical current may be recovered by heating the device above its superconducting transition temperature and then recooled.

## Summary

In summary, we have observed upsets events in Josephson junctions induced by alpha irradiation. These upsets are not necessarily always single particle upsets because at low bias currents they may result from the cumulative effect of many alpha particles. These changes do not involve a change in the device's material makeup but they remain until the device is subjected to a heating cycle. A simple heating model by itself has been ruled out because it is unable to explain the upset rates at low bias currents and the hysteretic effect under alpha particle irradiation.

Experiments are continuing to determine the nature of the alpha upset mechanism and the upset sensitivity of various types of smaller Josephson devices. Experiments to study the sensitivity of these devices to neutrons and protons are planned.

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