Integration density of ion-damaged barrier Josephson junction and circuits

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Abstract. We investigate on the integration density limit of the superconducting technology for Josephson devices and circuits based on ion-damaged barrier. This technology is suitable for very large integration of superconducting circuits as the footprint of the Josephson junction is of the order of 40 nm by 2 µm. Series arrays of Josephson junction can be designed for high voltage amplitude at the device terminals. We have fabricated single Josephson junctions and arrays of 2 and/or 10 Josephson junctions connected in series with equal spacing. This spacing was varied on different devices from 100 nm to 1.6 µm. We observe a strong change in the parameters characterizing the DC transport in the arrays with the highest density of the Josephson junctions. It shows that the scaling behavior of Josephson array DC properties strongly depends on the distance separating 2 consecutive Josephson junctions. We discuss the origin of these effects presumably due to defects created at long distance during the ion irradiation process. Comparison of magnetic field responses for an array and single Josephson junctions shows a reduction of the Meissner effect in the array.

1. Introduction.
It is widely recognized that the performance of sensors can be improved by using a large number of elementary detectors. This approach is used for example in imagers with focal plane arrays instead of single elements. Very sensitive magnetic sensors can be made with superconductive components because of their very low noise, with the additional advantage of very large bandwidth. A recent review for Josephson junctions (JJ) arrays has been published by Cybart et al. [1]. Arrays of Josephson junctions connected in series can be used not only for magnetometry, but also for voltage standard [2] and neural networks [3]. Among several technologies used to fabricate Josephson junctions, one of the most promising for very dense integration is the ion damaged barrier technology [4], which uses High Temperature Superconductors (HTS). Basically, the barrier of the JJ is made by ion irradiation of a thin region separating the electrodes of an HTS microbridge, thereby degrading the superconducting properties of the barrier and giving the equivalent of a tunnel barrier for normal electron transport. The footprint of a single JJ made with this technology is of the order of 40 nm x 2 µm, less than 10⁻⁹ cm². In this paper, we present an experimental study of the behavior of arrays of JJ connected in series with various distances separating the JJ. The first section is devoted to the description of sample design and fabrication. The next section reports on the experimental results and finally, we discuss the results and consequences on the foreseen integration density for different applications.

2. Sample design and fabrication.
A view of the mask lay-out used to fabricate the devices is given on figure 1. The dark area is the insulating region of the circuit. The vertical strip is a 5 µm-wide superconducting microbridge. A collection of contacts are provided at the end of the microbridge and between the devices (on the right part of the layout). Labels on the right part of figure 1 give the names of the devices and the spacing
between the JJ (except for the 3 top devices made with a single JJ). A 20 nm-wide window, represented by a thin horizontal line running across the superconducting microbridge is made by e-beam lithography in a PMMA layer. It is used to make the barriers by full wafer Oxygen ion irradiation of the 150nm thick YBCO film supplied by CERACO [5]. Five arrays contain only 2 JJ, separated by a distance $d_{JJ}=100$ nm, 200 nm, 400 nm, 800 nm and 1.6 µm. Three arrays contain $M=10$ JJ each, separated by $d_{JJ}=100$ nm, 400 nm and 1.6 µm. Because of image resolution, individual JJ in an array can be observed only for arrays with $d_{JJ}=1.6$ µm. Details on the fabrication process can be found in a previous publication [6].

Figure 1: Layout of series arrays of JJ in one sample.

3. Results.

We have fabricated 4 wafers with similar process parameters and characterized by DC transport measurements 7 samples of 11 devices. The same testing procedure is applied for all the samples: first a temperature scan below 100 K is made to measure the voltage across each device under a constant probe current of 10 µA. Then, a temperature range is defined where the voltage versus bias current characteristics are measured. For each temperature, the critical current $I_C$ and the normal resistance $R_N$ introduced by the RSJ (Resistively Shunted Junction) model [7] are extracted. For the large majority of the applications the main figure of merit of the JJ is the $I_C R_N$ product, we report on figure 2 the variation of the $I_C R_N$ product versus temperature $T$ (for a single sample). We observe a maximum because the critical current $I_C(T)$ vanishes at temperatures approaching the superconducting transition, while the normal resistance $R_N(T)$ vanishes at low temperatures, when the barrier material becomes superconducting. The maximum occurs in the temperature range 62...66 K and is typical of all the samples tested. Its amplitude depends both on the number of JJ in the array and on their spacing $d_{JJ}$. For large values of $d_{JJ}$, the $I_C R_N$ product increases almost linearly with the number of JJ. However,
for both $M=2$ and $M=10$, the $I_C R_N$ product degrades when $d_{JJ}$ is equal to or smaller than 400 nm. For $d_{JJ}=100$ nm, the $I_C R_N$ product does not depend on $M$. This behaviour is qualitatively observed for all the samples tested.

We measured the response to a magnetic field of some of these arrays. The magnetic field is applied using a pair of coils, with the sample located midway between the centers of the coils, as is done in the Helmholtz configuration. A DC coil current $I_B$ is fed to these coils to create a DC magnetic field $B$. Results for only 4 devices are presented on figure 3, where the transfer factor, i.e. the derivative of the device voltage $V$ with respect to $B$, is plotted versus $I_B$. None of the arrays have transfer factors scaling with $M$, the number of JJ in the array. The best response is obtained for J10c, the array of $M=10$ JJ and the largest spacing $d_{JJ}=1.6 \, \mu$m. However, its response is approximately 3 times larger than for single JJ, i.e. 3 times weaker than expected. Also, the positions for the extrema of the transfer factor are separated by approximately 7 mA for single JJ, and by about 12 mA for the array of 10 JJ.

### Figure 3: Variation of the transfer factor for 4 devices (J1a, J1b, J1c and J10c) versus coil current.

#### 4. Discussion.

Clearly in an array of JJ connected in series, the JJs interact when their separation $d_{JJ}$ is small. When the Cooper pair current exceeds the critical current $I_C$, part of the Cooper pairs are broken into quasiparticles, adding to the quasiparticle current. The critical current $I_C$ is a characteristic of the barrier, which is defined by a density of defects in the vicinity of the barrier [8]. On figure 4, we show a SRIM simulation [10] of the irradiation used for the barrier fabrication process. The horizontal plane is a section of the film in a plane perpendicular to the edge of the mask defined by e-beam, used for O$^+$ irradiation. The top surface of the film is located at $y=0$, while the interface between the film and the substrate is located at $y=150$ nm. The direction of current transport, perpendicular to the barrier, is in the Ox direction. In the $(x=0, y=0)$ half plane is located an opaque part of the mask. In other words, one of the edges of the mask defining the window opened in the PMMA layer is located at $x=0$ (and $y=0$). The vertical axis is used to display the density of defects induced in the YBCO film versus depth and horizontal position as a 3D plot. Integrated values are presented as 2D graphs: on the Oxz plane.
(or \(y=0\) plane), the defect density per unit area vs. distance from the edge of the mask; and on the \(O'yz\) plane (or \(x=80\) nm plane), the defect density per unit area vs. depth.

Figure 4: SRIM (Stopping and Range of Ions in Matter) simulation of oxygen ion irradiation of a 150 nm thin YBCO film at 110 keV. The curve representing the defect density per unit area vs. distance from the edge of the mask limits the green area on the \(Oxz\) plane.

We observe that although the edge of the mask is ideally sharp, the defect density per unit area is a smooth function of the distance from the edge of the mask, creating a tail in the \(x<0\) region. As previously reported [6], the effective barrier thickness may be larger than designed, depressing the order parameter on a wider region. This in turn, will reduce the \(IcR_N\) product of the JJ [9]. The order parameter will be even more depressed if the JJs are close enough for Cooper pairs to interact simultaneously with 2 tails instead of one. For all the samples tested, the \(IcR_N\) product was strongly degraded for \(d_{JJ} = 100\) nm, and not degraded, i.e. it was scaling linearly with \(M\) the number of JJ, for \(d_{JJ} > 400\) nm.

For the array J10c, the response to the magnetic field is weaker than expected by a factor 3, and its width (the distance between the extrema of the slope \(\partial V/\partial B\)) is larger by a factor 2, compared to single JJ. Both effects can be explained by a weaker local field around the JJ placed in the array. As the superconducting strips used for the contacts are much further away in the case of device J10c, one may expect a weaker local field focused by the strips. Quantitative evaluation with InductEx [10] demonstrates that the effect is less than 5%. Thus, we conclude that the reduction of the local magnetic field is due to the density of JJ. As the barriers are essentially non-superconducting regions, the field can penetrate them, causing a reduction of the Meissner effect, i.e. a reduction of the local magnetic field. Modeling the flux penetrating the barriers over a distance \(d\) by a simple magnetic dipole indicates that the mean local field along the edges of the superconducting microbridge should depend on \(d_{JJ}\):

\[
B_{\text{local}} = \frac{D\cdot d_{JJ}}{d_{JJ} + d'} B_a
\]

where \(D\) is a depolarisation factor (or focusing factor due to Meissner effect in the electrodes), \(B_a\) is the macroscopically applied field. By comparing the performance of array J10c (\(d_{JJ}=1.6\) \(\mu\)m) with
those of the 3 single JJs ($d_{JJ} \sim \infty$), we estimate $d \sim 2...3 \mu m$.

In order to estimate the best performance for a given substrate area, we evaluate the achievable dynamic range on a 1cm$^2$ substrate, optimizing $L_{JJ}$ and $d_{JJ}$. We assume a meander layout for the chain of SQUIDs, with a spacing $g=2\mu m$ between each straight segment. The transfer factor is proportional to the JJ length $L_{JJ}$:

\[
\frac{\partial V_s}{\partial B_a} = \frac{L_{||}}{L_0} \frac{\partial V_0}{\partial B_a}
\]

where $V_0$ is the output voltage of a reference junction of length $L_0$. We assume that the noise in a long JJ scales as $1/L_{JJ}$ [11]:

\[
N_1 = N_0 \left( \frac{L_0}{L_{JJ}} \right)
\]

with

\[
\frac{\partial V_M}{\partial B_a} = \frac{M d_{JJ} \partial V_s}{d_{JJ} + d'} \frac{\partial V_s}{\partial B_a}
\]

(4)

to account for the degradation of the depolarisation factor. Assuming no noise correlation between the JJ,

\[
N_M = M N_1
\]

(5)

and the total number of JJ, $M$ is limited by the size of the substrate (square, with side $A$)

\[
M = \frac{A}{L_{||} + g} \frac{A}{d_{||}}
\]

(6)

Combining equations 2..6 gives

\[
\frac{(\delta V_M)^2}{N_M} = (\delta B_a)^2 \left( \frac{\partial V_0}{\partial B_a} \right)^2 A^2 \frac{L_0^2}{N_0} \frac{d_{||}}{(L_{||} + g)(d_{||} + d)^2}
\]

(7)

Maximum is obtained for $d_{JJ} = d$

\[
\frac{(\delta V_M)^2}{N_M} = (\delta B_a)^2 \left( \frac{\partial V_0}{\partial B_a} \right)^2 A^2 \frac{L_0^2}{N_0} \frac{1}{4d(L_{||} + g)}
\]

(8)

The parameter $d$ was experimentally estimated only for $L_{JJ} = L_0 = 5 \mu m$. It is expected that $d$ depends on $L_{JJ}$. If we assume this dependence to be linear, then $d= L_{JJ}/2$, and the maximum signal to noise ratio becomes:

\[
\frac{(\delta V_M)^2}{N_M} = (\delta B_a)^2 \left( \frac{\partial V_0}{\partial B_a} \right)^2 \frac{A^2}{N_0 L_0^2} \frac{L_{||}^2}{2(L_{||} + g)}
\]

(9)

and the maximum value is obtained for the largest technologically feasible $L_{JJ}$. Following Cybart [12], we choose a maximum value of $L_{JJ} = 2L_0 = 10 \mu m$.

\[
\frac{(\delta V_M)^2}{N_M} = (\delta B_a)^2 \left( \frac{\partial V_0}{\partial B_a} \right)^2 \frac{A^2}{N_0 L_0} \frac{2}{L_0(2L_0 + g)}
\]

(10)

With $A=1cm$, $L_0=5\mu m$ and $g=2 \mu m$, the dynamic range of the array is ~ 3.10$^6$ times larger than for a single junction. We observe that as long as $d$ does not decrease with $L_{JJ}$, optimal value of $d_{JJ}$ is well above 1 $\mu m$, i.e. the performance of such an optimized array for magnetic field detection is not limited by the degradation of the $L_{R_0}$ product presented in the previous section. This indicates that the oxygen ion straggling observed in irradiation process is not detrimental for the fabrication of magnetic field detectors based on arrays of JJ. However, for applications such as RF detection and metrology (Voltage Standard), where $d_{JJ}$ can be reduced below 1 $\mu m$, the fabrication process may have an importance.

5. Conclusion.

We have evaluated the performance of series arrays of $M$ Josephson junctions made with the ion damaged barrier technology, with variable integration density by changing the distance separating the junctions. For performance criteria basically linked to electronic transport through the barrier, such as
RF detection and Voltage Standard, deviation from linear dependence on $M$ is visible for a spacing less than 400nm. We assume that this limitation is linked to the fabrication process, and plan to investigate by using Helium ions instead of Oxygen ions, expecting a better definition of the barriers. For performance criteria linked to Meissner effect in the electrodes, such as magnetometry, deviation is observed for JJ spacing less than 1.6 µm. We interpret this as a consequence of the weakening of the superconducting properties of the bridge (because of the “normal” material in the barriers), leading to a weakening of the Meissner effect and reduction of the screening currents in the electrodes. An optimum in integration density is expected at different values depending on the application.

6. References.
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