Induced change of critical current density profile in Nb/Al-AlOx/Nb Josephson junctions.

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Abstract. A technique to induce spatial modulation of critical current density in niobium based Josephson devices by using a selective thermal annealing is reported. By depositing a carbon film onto selected region of the Josephson element it is possible to induce a localized heating, with a spatial resolution less than 1µm, exploiting the much higher absorbance coefficient of carbon than the niobium one. The effectiveness of such technique is demonstrated by experimental measurement of the critical current vs. magnetic field, measured at T = 4.2 K, showing that the change of critical current density occurs only in the region corresponding to the absorber film area. Furthermore, the theoretical behaviour, by modelling a suitable step-like junction barrier shape, has been carried out to fit the experimental data in order to verify the selective modulation of critical current. This technique can be very useful in view of quantum computing experiments, Majorana fermions detection and superconducting magnetic sensors.

1. Introduction
Josephson junctions are widely employed in superconducting circuits for both applications and basic physics research, so the possibility to control the main parameters of a Josephson device like the critical current density can be very useful. As the Josephson critical current density depends mainly on the thickness of insulation barrier, typically obtained by oxidation process, it is possible to modify the critical current density after the sample fabrication by using thermal or selective laser annealing [1-4]. However, these techniques allow us to modify the critical current density of the whole chip or, at most, of the single Josephson element in the case of selective laser annealing [5]. In any case, the critical current decreases as a consequence of tunnelling barrier thickness expansion produced by thermal effect. The increase of AlOx barrier thickness is due to several phenomena, thermally activated, such as diffusion through channels formed in Nb granular structure of oxygen coming from surface niobium oxide, reaction of Al atoms with free oxygen embedded at interstitial places close to the tunnel barrier and dissociation of aluminium hydroxides formed during the oxidation process. Here, a technique to change the critical current density within the single niobium based Josephson junction with a good spatial resolution by a selective annealing is presented. This technique allows us to induce spatial modulation of critical current density in Josephson elements paving the route to the control of critical current density profile and/or to the production of controlled “defects” inside the junction area. It is

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worth to note that a technique based on Ion implantation could be also employed to modify the critical current density profile, but with an unavoidable degradation of the involved superconducting films, leading to a local depression of the critical temperature and energy gap [6,7].

2. Methods and experimental results

The localized heating inside a single circuit element is made possible by depositing a carbon film on the desired region exploiting the larger absorbance coefficient of carbon (close to 1) with respect to niobium (about 0.2). At later stage, the Josephson junction is uniformly exposed to a heating radiation generated by an Argon laser beam aligned by an optical system. The difference in the power absorption by the different surfaces under irradiation allows reaching higher temperatures under the carbon film than in the surrounding areas, leading to a selective annealing with good spatial resolution down to 1 µm. In figure 1, the basic principle and the picture of the sample under investigation are shown.

![Figure 1](image)

Figure 1. (Left) Scheme of basic procedure for selective annealing in a Josephson device. Thanks to absorber film, the heating radiation produces a selective annealing only under carbon covered area. It is also reported the expected critical current density profile with a step-like behaviour after annealing process. (Right) Picture of the Josephson junction subject to selective annealing process.

The sample fabrication process, based on trilayer (Nb/Al-AlOx/Nb) technology, is well described elsewhere [8, 9]. High quality window type junctions with different sizes have been fabricated having a critical current density of about 50 A/cm$^2$.

The Josephson junction of presented experiment has a rectangular shape with a side length of 80 µm and 20 µm. The carbon absorber has been deposited by thermal evaporation and patterned by lift off process resulting in a film thickness of 300 nm. It has a length of 30 µm and is centred at middle of the junctions covering about the 37% of its length.

To heat the Josephson element, an argon laser beam ($\lambda$=514.5 nm), has been used at room temperature. The laser power and time exposition was 2W and 30 s respectively. The laser spot of 200x80 µm$^2$ has been focused on the junction by using an optical system [5]. It is worth noting that the laser spot is larger than the junction size being the device annealed region determined by the absorber dimensions, therefore a different radiation heating source could be also employed such as an UV lamp. In these conditions a temperature of about 330 °C was estimated in correspondence of insulating tunnel barrier in the region covered by the absorber.

In figure 2, the current to voltage characteristic of the junction before annealing process is shown, measured in a shielded cryostat containing liquid helium [10,11]. In the same figure, the critical current as a function of magnetic flux is also shown, where the very good agreement with the Fraunhofer pattern (black line) is evident, indicating an uniform current density profile and a good junction quality. The measured critical current is of about 900 µA in the untreated Josephson junction.
Figure 2. Critical current as a function of magnetic flux before thermal annealing of the Josephson junction measured at \( T = 4.2 \) K; the continuous line represents the calculated Fraunhofer pattern. In the inset, current-voltage characteristic before the annealing process is shown.

After the selective annealing process, the measurements of the critical current as a function of magnetic flux treading the junction and current to voltage characteristics of the device have been performed again and the results are displayed in figure 3. From the current to voltage characteristic a reduction of the overall critical current is measured which, after exposition, has a value of 630 \( \mu \)A corresponding to a decrease of about 30\%. In figure 3, the critical current vs. magnetic flux is shown in which the increase of secondary slope's height is observed, due to the change of the current density profile and, in particular, to a depression of the critical current in the middle area of the junction. In order to better verify that the modification area corresponds to the absorber one the experimental data have been compared with theoretical predictions obtained by using a suitable junction barrier model based on step-like barrier shape taking into account the possible asymmetries due to imperfect alignment of the absorber with respect to junction centre [12]. The fitting curves (continuous line in figure 3) are obtained fixing all values to the experimental ones and using \( \xi \) (see figure 1) as free parameter [13].

Figure 3. Critical current vs. magnetic flux after thermal annealing of the Josephson junction measured at \( T = 4.2 \) K. The continuous line represents the theoretical behaviour of a step-like shape junction model. The inset shows current-voltage characteristic after the annealing process showing a reduction of the critical current of about 30\% compared to non annealed junction.
The good agreement obtained for $\xi = 0.2$ demonstrates that the critical current density was changed only in the absorber covered region, leaving unchanged the critical current density outside that region ensuring the capability to locally modify the Josephson critical current density. Finally, by fixing $\xi$ to obtained value and leaving free the asymmetry parameter $\Delta s$, the absorber misalignment has been estimated finding that its value is about of 10 $\mu$m which is comparable with the misalignment measured on the junction under investigation. It is worth noting that it is possible to vary the annealing parameters, although in a very narrow range to avoid damage to the insulating barrier. In particular, by varying the timing of exposition different values for the parameter $\xi$ are obtained. Such results demonstrate that it is possible to control some fundamental parameters of the Josephson device (junction and SQUID) after the fabrication process, obtaining a very tunable device. This peculiarity could be very useful in view of interesting applications in quantum computing, Majorana fermions detection and superconducting magnetic sensors.

3. Conclusions
In conclusion, the spatial modification of the profile of critical current density within a Josephson device has been obtained by using a selective annealing technique based on the use of a carbon film acting as heat absorber deposited on the device region to modify. The effectiveness of such method has been proved by experimental results and confirmed by theoretical predictions based on an asymmetric step-like barrier profile model. It has been demonstrated also that the change of current profile, with an estimated resolution of about 1 $\mu$m, occurs only in the region of the Josephson junction corresponding to the area covered by the absorber.

On the basis of these results, the here reported selective annealing technique provide the possibility to control some fundamental parameters of the devices based on Josephson effect after the fabrication process, obtaining a very tunable device. This peculiarity is very useful in view of recent basic physics research and applications involving the Josephson devices. The results have been obtained making use of the different material absorption coefficients and, with a suitable choice of reflecting/absorbing materials, the reported method could be also applied on other materials and devices whose properties can be modified by thermal annealing [14, 15].

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