TRIMMING OF CRITICAL CURRENT IN NIOBIUM JOSEPHSON DEVICES BY LASER ANNEALING

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Abstract. The authors report a new thermal annealing technique for Nb/Al-AlOx/Nb Josephson devices based on laser heating. This technique allows to “locally” modify the Josephson critical current density. In fact, it is possible the heating of a single circuit element with a good spatial resolution using a focused Ar+ laser beam which is aligned by an optical system on a selected junction of the sample. During the procedure, performed at room temperature, a thermal camera provides a monitoring of the temperature distribution on the whole chip. A continuous reduction of the critical current density up to about 40% has been observed on high quality Josephson junction measured in liquid helium. Neighbouring junctions have not exhibited any measurable change ensuring the effective capability to locally modify the Josephson critical current density. The new technique has been employed to recover noisy dc SQUID magnetometers with non optimal critical current values obtaining a reduction of the spectrum density of magnetic field noise from about 30 to 2.5 fT/Hz½.

1. Introduction

Josephson devices based on niobium technology are very reliable and are employed in basic physic experiments and in several small scale applications. The critical current density is one of the most important parameter of a Nb based Josephson device. So, the study of critical current stability with respect to annealing processes at high temperature has been widely investigated [1-5]. During thermal annealing, an increase of the tunneling barrier thickness (AlOx), due to reacting oxygen, causes a decrease of the critical current. The reacting oxygen is provided by: diffusion of oxygen coming from surface niobium oxide through channels formed in Nb granular structure [2]; reaction with Al atoms of unbound oxygen embedded at interstitial places close the tunnel barrier [3] and dissociation of aluminum hydroxides formed during the oxidation process [4]. These experiments have showed that a substantial change of the Josephson critical current caused by thermal annealing process can be observed. However, this process involves the whole chip, producing the same effect on all Josephson element belonging to the chip. Therefore, it is not suitable to modify a single Josephson junction. Furthermore this technique requires to remove the chip from the its carrier, increasing the risk of
Here, the authors present a novel technique based on a focused laser beam annealing, showing preliminary measurements on high quality Nb based Josephson junctions and dc SQUID magnetometers. With respect to the standard technique based on oven or hot plate, it allows to get a localized trimming of the Josephson critical current with a micrometric resolution. So, it is possible to obtain a chip with a controlled non-homogeneous density of the Josephson critical current. Note that during the laser exposure, the chips are not removed from their carrier saving all the bonding wires and limiting the mechanical stress. Hence, the present technique is clearly less invasive with respect to the standard thermal annealing and can be used to correct the critical current of single Josephson elements after their low temperature testing. Hence, it is a helpful tool for both experiments and applications.

2. Experimental set up and sample fabrication

The experimental set up is schematically sketched in Fig. 1. A beam expander enlarges the light beam from a Ar+ laser at wavelength $\lambda = 514.5$ nm, producing a beam of 0.8 cm in diameter. Light is then focused by means of lens placed on the sample; the beam waist is measured by a micrometric graduated rule. The beam waist is given by the formula $d = \frac{4\lambda f}{\pi D}$, where $f$ is the focal length of the converging lens and $D$ is the diameter of the incident beam; the measured value is in good agreement with the estimation one. A beam waist of a few $\mu$m is obtained using suitable lens. Furthermore changing the distance between the target and the lens at a fixed position, it is possible to get different spot diameters. An optical microscope allows us to target the focal point on the selected Josephson device. In order to get a local heating ranging from 160°C to 170°C (after a two-minute illumination of the sample) the input power is kept sufficiently high (it ranges from $2.00 \times 10^5$ to $2.22 \times 10^5$ W/cm²). Varying the light intensity on the sample it is possible to obtain different temperatures. In order to exactly align the chosen area in the light focus, the chip is mounted on an XYZ stage (1$\mu$m step). An IR thermal camera (Land FT16 with a detector thermoelectrically cooled HgCdTe, with a temperature range between 20 to 2000°C, a spectral range 3.2-4.2 $\mu$m and a thermal resolution of 0.1°C) monitors the heating dynamics of the sample, during annealing procedure.

Figure 1. Experimental set-up for Josephson device annealing based on an Argon laser source ($\lambda = 514.5$ nm). The sample is mounted on the x-y actuator with one-micron steps in order to align exactly the chosen area in the light focus. The heating of the sample is continuously monitored by an IR thermal camera.
The absorbed incident light on the target gives rise to a local increase of the temperature producing a selective laser annealing. A picture of a \((10 \times 10) \text{ mm}^2\) silicon chip containing some Josephson junctions and the relative thermographic curve are reported in Fig. 2. From the figure it is evident the possibility to perform a quite localized heating. Note that, keeping fixed the output power of laser, the final temperature depends on the size of chips and on the device geometry indicating that the thermal properties of the sample play an important role. Variations up to 10 °C have been observed in chip having sizes ranging from \((10 \times 10) \text{ mm}^2\) (coldest) to \((3 \times 3) \text{ mm}^2\) (warmest). Such temperature variations produce significant critical current modifications, therefore before starting with the exposure of the target chip, the power laser is set using a test chip. However, it is useful to get a thermographic imaging during laser trimming as control parameter; also because it allows us to monitor the temperature distribution and its time evolution giving useful information about annealing efficiency. Usually, the increasing rate of the temperature is higher at the beginning and reaches the 80% of the required temperature in 30 s and the final temperature after about 90 s. An evident smaller rate at the beginning of the procedure indicates coupling problems. The optical system and the procedure has been tested on single Josephson junctions and SQUID magnetometer.

The samples were fabricated with all refractory niobium technology [6]. The Nb/AlOx/Nb trilayer was deposited by dc-magnetron sputtering on a 3" Si crystalline wafer in a UHV system, without breaking the vacuum. The base and top Nb electrodes were 200 nm and 35 nm thick respectively. They were deposited at a rate of 1.5 nm/sec. The Al film, about 7 nm thick, was deposited at a rate of 0.09 nm s\(^{-1}\); a fine control of the thickness is achieved by rotating the substrate carrier during the deposition. The tunneling barrier is obtained by thermal oxidation of the aluminum layer in a pure oxygen atmosphere for 1 h at room temperature. The trilayer geometric patterning was performed by a lift-off process. The junction geometry (window type) is obtained by standard photolithography and a Selective Niobium Anoditation Process (SNAP). The \(\text{Nb}_2\text{O}_5\) insulation layer also provides the insulation of the flux transformer and the integrated coils. A further insulation is provided by a SiO\(_2\) film (120 nm thick) deposited by rf-sputtering at a rate of 0.38 nm/s and patterned by a lift-off process. Shunt and damping resistors are obtained by a Au-Pd film deposited by dc-magnetron sputtering and defined by lift-off. Before the deposition, a buffer layer of molybdenum film (7 nm thick) has been deposited in order to improve the film adhesion. The sheet resistance of a 300 nm thick Au-Pd film, deposited at a rate of 2.0 nm/s, is resulted 0.7 Ω/sq at \(T = 4.2\) K. The wiring and the washer layer are obtained, after a ion-etch cleaning process, by depositing a Nb film (500 nm thick) by dc-magnetron sputtering at a rate of 1.0 nm/s, and then defined by a lift-off procedure.
3. Experimental results and conclusions

The measurements were performed, in a \(^4\)He cryostat with two copper and three \(\mu\)-metal coaxial shielding cans, using a low-noise 4-contact current-voltage technique [7] to obtain the current-voltage (I-V) characteristics and the dependence of the Josephson current on the external magnetic field (Ic-H). In the present experiments window Josephson junctions having the following main parameters have been used: area \(A_J=(10 \times 10) \, \mu m^2\), critical current density \(J_c=120 \, A/cm^2\), and junction capacitance \(C=6.0 \, pF\), as estimated from the Fiske step voltage position.

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In Fig. 3a current-voltage characteristics of a Josephson junction before and after the laser annealing are reported. A reduction of 40% of the critical current \(I_c\) going from 120 \(\mu A\) to 70 \(\mu A\) after the laser illumination (30 s at \(T=170^\circ C\)), is observed. As a consequence, an increase of the normal resistance \(R_{NN}\) which goes from 13.6 \(\Omega\) to 21.6 \(\Omega\) is also observed. The high quality factor of the junction remains about the same before and after the laser treatment (\(V_m=I_cR\sqrt{2mV}\approx 70 \, mV\)). In order to get a clear evidence of the local effect, a Josephson junction very close to the exposed junction and having the same dimensions and critical current has been measured before and after the annealing procedure. The I-V curve has not shown any measurable modification. Finally, magnetic patterns (Ic-H) relative to the same junction pair have been measured (Fig. 3b). The results show a Fraunhofer-like for both junction guaranteeing the integrity of the tunnel barrier and the absence of any tunnel barrier disomogeneity in the annealed junction.

Since the laser energy can be continuously varied, this technique allows to get a few percent \(J_c\) decrease. The procedure has been applied on several Josephson junctions with the same area and critical current belonging to different chip and in the same laser trimming conditions. A spread of relative \(I_c\) change less than 10% has been observed. Even if such a spread value indicates a good reproducibility, it is not due to the intrinsic limit of the technique but it depends on small differences among the chips leading slight different experimental circumstances.

The present technique has been preliminarily used to recover a noisy SQUID device due to a non-optimal critical current value. The SQUID device employed in the experiment is a high sensitive fully integrated dc SQUID magnetometer for biomagnetic measurements [6]. The basic structure of the SQUID magnetometer is Ketchen type [8]. The planar dc-SQUID is based on a square washer configuration with an inductance of 260 \(\mu H\), and is coupled to a 12-turn thin film input coil with a 33 \(nH\) inductance; the input coil is connected to a square single turn pick-up loop, of 67 \(mm^2\) area and

![Fig. 3a. Josephson junction current-voltage characteristics at T=4.2K before (open circle) and after laser annealing (full circle).](image1)

![Fig. 3b. Critical Josephson current as a function of the external magnetic flux relative to the laser annealed junction (grey circle) and to the not exposed close junction (black circle).](image2)
having an inductance of 27 nH. The SQUID critical current before the laser trimming is $2I_0 = 30 \, \mu A$ giving a shielding parameter $\beta_L \approx 3.7$ and a McCumber parameter $\beta_C \approx 1$. The Josephson junctions are window-type with an area of $(4 \times 4) \, \mu m^2$ and $14 \, \mu m$ separated. A beam spot of $30 \, \mu m$ in diameter has been used in order to expose both junctions. An integrated additional positive feedback (APF) circuit including the coil, a thin film resistor network and a bipolar feedback coil for low cross-talk operations are also integrated on the same silicon chip of $85 \, mm^2$ [9].

In order to understand the recovery mechanism of a noisy SQUID magnetometer, a short description of APF is given. This circuit renders the $V \Phi$ characteristics asymmetric; so, if the SQUID is biased on the steeper side, it is possible to achieved an effective increase of the SQUID responsivity $V_\Phi$ [10]. However if the APF gain $G_a$ is very close to 1, the positive reaction becomes unstable causing hysteretic flux-voltage characteristics and an evident magnetic flux noise increase [11]. Here the Josephson critical current play an important role because the APF gain is proportional to intrinsic responsivity $V_\Phi = 4I_0\Phi_0/(1+\beta_L)$ [12], where $\Phi_0$ is quantum flux.

Voltage–flux characteristics ($T=4.2$ K) of the SQUID magnetometer before and after laser annealing are reported in Fig 4a. Due to a too strong APF effect, the SQUID magnetometer before the illumination showed a very sharp characteristic and the spectral density of magnetic noise was quite high ($30 \, fT/Hz^{1/2}$) (Fig. 4b). After laser annealing ($30 \, s$ at $T= 160 \, ^\circ C$) a reduction of the SQUID critical current $I_0$ and consequently of the SQUID responsivity is obtained, giving a decrease of the APF effect. From Fig 4a it is possible to observe a reduction of the voltage amplitude from $60 \, \mu V$ to $40 \, \mu V$ due to a decrease of the SQUID critical current $2I_0$ from $30 \, \mu A$ to $20 \, \mu A$. It is worth noting that the voltage-flux characteristic becomes smooth allowing the sensor to work in a wide region of bias points and, hence, guaranteeing a good stability when SQUIDs operate in Flux Locked Loop (FLL). The Fig 4b shows the magnetic field noise spectral density of the sensors before and after annealing. As expected the removal of unstable condition produces a substantial decrease of the field noise, reaching a magnetic field noise as low as $2.5 \, fT/Hz^{1/2}$.

![Figure 4a. dc-SQUID magnetometer flux-voltage characteristics measured at T=4.2K. The upper curve is relative to the magnetometer before annealing; the lower curve shows the V-\Phi characteristic after laser annealing.](image1)

![Figure 4b. Magnetic field noise spectral density of a dc-SQUID magnetometer before (upper curve) and after (lower curve) the laser annealing.](image2)

In conclusion, a new tool to induce controllable and localized change of Josephson current density in niobium based Josephson device is presented. It is based on thermal annealing by a focused laser beam. The experimental data on window type Josephson junctions $(10 \times 10) \, mm^2$ measured in liquid
helium have shown a substantial reduction of density critical current of about 40% while an identical neighboring junction does not show appreciable changes. Such measurements evidently shows the effective capability to locally modify the main characteristics of the Josephson devices avoiding any mechanical stress and preserving the intrinsic quality factors. So, we believe that such a technique is a helpful tool for several applications.

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