Inductance measurement of YBCO strip-lines made by ion irradiation

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Abstract

We have investigated the electrodynamic properties of High-Tc strip-lines made by ion irradiation, in order to evaluate the potentialities of such a technology for RSFQ superconductor digital electronic. SQUID loops of different length and width have been fabricated by ion bombardment of 70 nm thick films through e-beam lithographed shadow masks, and measured at different temperatures. The voltage modulations have been recorded by direct injection of a control current in the SQUIDs arms. The corresponding line inductances have been measured and compared with 3D simulations. A quantitative agreement has been obtained leading to typical values of 0.4 pH/μm without ground plane.

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Superconductor digital electronics and its implementation of the Rapid Single Flux Quantum (RSFQ) logic are currently the subject of intensive research due to its exciting properties. It is assessed to be the most advanced alternative technology to silicon-based systems in order to reach the 100+ GHz operating frequency [1]; it has an extremely small energy consumption and its viability has been proven through the successful development of highly complex low-Tc electronics (for a review see [2, 3]). For specific applications like ADCs (Analog-to-Digital Converters), there is a need to develop High-Temperature RSFQ devices, which would operate beyond 400 GHz in the 30-80 K temperature range [4, 5]. While several competing technologies are currently been developed for this goal, there has been recent interest in the ion-irradiated Josephson Junction technology [6–8] which allows to design rather complex structures suitable for high speed electronics [9]. In that context, mastering the loop and line inductances in the circuits appears to be a key point. In this paper, we present measurements of the inductance of superconducting lines patterned using our all-planar ion-irradiation process [6–8], by direct current injection in SQUIDs arms. We compare the obtained values with numerical simulation of the kinetic and magnetic components. Given the good agreement observed, we then discuss the potential of this technology for RSFQ and high-frequency devices.

Starting from a commercial 70 nm thick YBa$_2$Cu$_3$O$_7$ (YBCO) film ($T_c$ = 86 K) grown on sapphire covered by an in-situ 100 nm gold layer, a three steps fabrication process is performed. Firstly, contact pads are defined in the gold layer through optical photoresist patterning followed by a 500 eV Ar Ion Beam Etching (IBE). Secondly, contact lines and SQUIDs arms are patterned in a AZ5214 image-reversal photoresist followed by 110 keV oxygen ions irradiation. A dose of $5 \times 10^{15}$ ions/cm$^2$ ensures that the surrounding matrix is deeply insulating. Eventually, Josephson junctions are fabricated: 20 nm slits in a 600 nm thick poly(methylmethacrylate) (PMMA) photoresist are patterned using a LEICA EBPG 5000+ electronic beamwriter and irradiated with 110 keV oxygen ions. We used a dose of $3 \times 10^{13}$ ions/cm$^2$ suitable to operate in the temperature range 40 to 65 K. Different geometries for the SQUIDs arms carrying the injection current have been studied: width $w$ of 4 µm and 10 µm, and five different lengths $l$ for each width: 10, 20, 30, 50 and 80 µm. Figure 1 displays the layout of a typical sample showing five different SQUIDs (width of 10 µm and lengths from 10 to 80 µm) sharing a common ground electrode, together with current injection lines.
Figure 1. (Color online) Upper left panel: Picture of a sample before the fabrication of the junctions. Five SQUIDs sharing a common ground electrode are seen, with length $l$ ranging from 10 to 80 $\mu$m. The control arm has a width $w$. Upper right panel: close up of the $l = 20 \, \mu$m SQUID. A scheme of the measurement geometry showing the bias current $I_b$ and the control one $I_{ctrl}$ is displayed. The junctions are symbolized by a cross. The dashed line shows the actual geometry used to compute the inductance using the 3D-MLSI code. Lower panel: Voltage modulation (shifted for clarity) for 10 $\mu$m-wide SQUIDs as a function of the control current $I_{ctrl}$ measured at 4.2 K. From bottom to top, SQUIDs length are respectively: 80, 50, 30, 20 and 10 $\mu$m.

Measurements were conducted in an Oxford Variable Temperature Insert using four-probe method and two extra-leads on one electrode of SQUIDs for current injection in the superconducting wire (Upper right panel of [1]). After measuring the critical current as a function of $T$, the SQUID was biased at its optimal point (1.1 $\times$ $I_c$) while the control
Figure 2. (Color online) Inductance as a function of the nominal length $l$ for two different widths ($w = 4 \, \mu\text{m}$ blue squares, and $w = 10 \, \mu\text{m}$ red circles), measured at 4.2 K for a $4.5 \times 10^{13}$ ions/cm$^2$ irradiated sample. Open symbols linked by a solid line are the corresponding values calculated with the 3D-MLSI code using $\lambda(0) = 0.135 \, \mu\text{m}$. The dashed line is the calculation including a correcting parameter (see text). The inset displays the Fourier transform of the SQUID modulations shown in Figure 1 for different lengths (from left to right : 10, 20, 30, 50 and 80 $\mu\text{m}$).

The current was swept. This results in oscillations in the SQUID’s voltage (Lower panel in 1) with a current periodicity that can be related to the inductance of the superconducting line through the simple formula

$$\delta I_{\text{ctrl}} = \Phi_0 / L$$

where $\Phi_0 = \frac{\hbar}{2e} \simeq 2 \times 10^{-15} \, \text{Wb}$ is the magnetic flux quantum and $L$ the inductance of the superconducting line [10–14].

A first set of data was extracted from SQUIDs with highly irradiated junctions measured at 4.2 K in order to extract the zero temperature London penetration depth $\lambda(0)$. The injection current was swept from -1 mA to 1 mA giving 20 to 50 oscillations of the SQUID voltage which were enough for reliably Fourier transform the data as displayed in the inset of 2. The corresponding inductances (solid symbols) are displayed in 2 for the two widths as a function of the SQUID arm nominal length. As expected, the total inductance increases slightly more rapidly than linearly, since it is the sum of the kinetic contribution $L_k = \mu_0 \lambda^2 l/wt$ [15] and the geometric one $L_m = 0.2 l \left[1/2 + \log(2l/(w + t))\right]$ [16], where $\lambda$ is the London penetration depth and $t$ the thickness of the film. A more accurate estimate of $L$...
Figure 3. (Color online) Inductances as a function of temperature measured for a $3 \times 10^{13}$ ions/cm$^2$ irradiated sample of width $w = 10$ μm, and length 10, 20, 30 and 80 μm from bottom to top. The solid lines are the best fit to the data with $\lambda(0) = 0.135$ μm and the correction factor $G = 0.78$ (see text), with respective $T_c$ of 70.5 K, 75.5 K, 75.5 K and 69 K.

has been computed with the 3D-MLSI software [17] on the actual geometry of the SQUIDs (dashed line of figure [1]). The results are given as open symbols in [2]. The agreement for the 4 μm wide superconducting lines is very good given the zero temperature $\lambda(0) = 0.135$ μm, which is exactly the film supplier’s data, thus indicating that our fabrication process preserves the superconducting properties of the films. Concerning the 10 μm wide superconducting lines, the numerical simulations needs to be renormalized by a factor of $G = 0.78$ to yield to correct results (dashed line in [2]). This numerical factor accounts for all the measured samples with this geometry. We do not have a clear explanation for this 20% discrepancy. However we should stress that most of the reported data in the literature using this DC SQUID method, do not provide quantitative agreements between measured and calculated inductances with such a precision.

The second set of SQUIDs were operated in the temperature range of interest 40-65 K and allowed us to extract the temperature dependence of the London penetration depth. The injection current was swept up to 10 mA to give the precision needed to measure the slight variation in inductance with temperature. [3] summarizes our results together
with fits of the temperature dependence of the inductance controlled by the penetration depth. Here we have used the Gorter-Casimir two fluids models with an exponent $\alpha = 2$: $\lambda(T) = \lambda(0) \frac{1}{\sqrt{1 - \left(\frac{T}{T_c}\right)^\alpha}}$ [11, 13, 14]. Given the values $\lambda(0) = 0.135 \mu m$ and $G = 0.78$ measured previously for the 10 $\mu m$ wide sample, we found a good agreement providing that $T_c$ is adjusted within 5 K or so (see caption of [3]). This uncertainty has two origins related to the measurement method itself. Firstly, the Josephson regime of the irradiated junctions is limited in temperature [6]. Therefore, our measurements are restricted in a temperature range (40-65 K in this case) well below the bulk $T_c$, in a region where $\lambda(T)$ does not strongly vary. Secondly, as the sensitivity of the measurement decreases when we approach this coupling temperature, one has to use high current density exceeding $10^6$ A/cm$^2$, that is the critical one in our samples at 77 K. The actual $T_c$ in the wire might therefore be lowered.

The overall measurements of inductances give us a value of 0.6 pH/$\mu m$ for a 10 $\mu m$ wide line and 0.9 pH/$\mu m$ for a 4 $\mu m$ wide line. These numbers compare favorably with the best one reported in the literature [13]. They do not change if the strip-line is embedded in a coplanar wave guide geometry with a typical gap of 4 $\mu m$ with respect to the ground plane. However, a factor of three improvement is expected when a ground plane is added [13, 18]. Such a desirable situation could be realized by adapting the ion irradiation process to trilayer films [8, 19].

Ion-irradiated junctions have typical critical current values in the range 100 $\mu A$ - 1 mA which leads to a screening parameter $2LI_c/\Phi_0$ ranging between 0.6 and 6 for a 10 $\mu m$ long and wide strip, or 0.36 and 3.6 for a 4 $\mu m$ one. Since RSFQ logic requires screening parameters around 1 for transmission lines and around 3 for storage cell [20, 21], the above mentioned inductances values fit well. Therefore, the irradiated junction technology seems suitable for RSFQ circuits applications.

In conclusion, we have measured the inductance of YBCO strip lines made by ion irradiation using direct current injection in SQUIDs arms. The measured values agree well with the calculated one using 3D simulation of our circuits. Such a line inductance combined with the typical critical currents of ion irradiated Josephson Junctions opens the route towards the realization of RSFQ logic circuits using this new technology.

This work has been supported by the Region Ile-de-France in the framework of C’Nano IdF and by the Délégation Générale de l’Armement (DGA) through a doctoral grant.
C’Nano IdF is the nanoscience competence center of Paris Region, supported by CNRS, CEA, MESR and Region Ile-de-France. Authors would like to thank Y. Legall at INESS Strasbourg for the ion irradiations.

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Figure 4. Fabrication process. Starting from a 70 nm thick YBa$_2$Cu$_3$O$_7$ (YBCO) film grown on sapphire covered by an in-situ 100 nm gold layer supplied by THEVA (a), pads are defined in a AZ5214 negative photoresist (b). A 500eV Ar Ion Beam Etching (IBE) removes the gold layer leaving only contact pads (c-d). Squids current and voltage lines are then defined using again a AZ 5214 photoresist patterning followed this time by a 110 keV oxygen ion irradiation (e). The use of a high dose of $5 \times 10^{15}$ ions/cm$^2$ ensures that the surrounding material is changed into an insulator (f). Eventually, josephson junctions are patterned as 20 nm wide slits in a 600 nm thick poly(methylmethacrylate) (PMMA) photoresist. A subsequent irradiation with 110 keV oxygen ions and a low dose of $3 \times 10^{13}$ ions/cm$^2$ gives working junctions in the temperature range 40-75 K. The electronic beamwriter used in this process is a LEICA EBPG 5000+. 