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Niobium and Aluminum Josephson Junctions Fabricated with a Damascene CMP Process

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Abstract

We report on the fabrication of Josephson junction and superconducting bridges using a damascene CMP process applied for a first time to superconductors. The demonstrated industrial reliability of damascene CMP processes on large scale semiconductor circuits is a major incentive for our research that should allow large numbers of nanometric Josephson junctions to be fabricated in both Nb and Al, the two main material employed in superconducting quantum computing (qubit) and RSFQ electronics fabrication.

We carried out a Chemical-Mechanical Polishing (CMP) process on Nb and Al films deposited on a SiO₂ layer patterned with trenches of 100 to 300 nm of nominal depth. The process formed long bridges, 1 to 4 μm wide. The susceptibility and resistive transitions showed that CMP has no observable influence on superconductivity.

We have also developed a hybrid technique that uses Al/Al₂O₃/Al shadow evaporation in the trenches before the damascene CMP process. This allows for high quality "in-situ" junction oxidation with the size reduction benefit provided by the damascene CMP process. We easily reach junctions sizes near 0.5 μm² which are difficult to fabricate by other methods.

We describe these techniques and report on measurements on large bridges and junctions and on the fabrication and measurements of Al and Nb nanobridges.

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1. Introduction

Ultrafast superconducting electronics such as Rapid Single Flux Quantum (RSFQ) [1, 2] and the superconducting quantum bits (qubits) [3-6] are based on the use of Josephson junctions of micro and nanometric dimensions. The two main techniques used to fabricate Josephson junctions, i.e. tri-layers and shadow evaporation, unfortunately have weaknesses. The tri-layer technique is based on a conventional microfabrication approach (deposition and pattern etching sequence) and used for the fabrication of RSFQ logic circuits. Though producing very large number of junctions, the size of the junctions created by this technique is limited to the constraints typical of lithography and etching. Although, CMP has been used with superconducting technology (e.g. [7-9] in conjunction with tri-layer technique), the junction is horizontal and the CMP is only used to planarize the surface for further processing like it is done in the semiconductor industry. On the other hand, the shadow evaporation technique allows shrinking the junction size by a geometric strategy. Extensively used for aluminum Josephson junctions fabrication for example for superconducting quantum bits (qubit) and for rather large number of junctions in voltage standards, this technique is not reliable with refractory materials such as niobium.

Nanobridges or nanoconstrictions have been studied for many years. Applications of nanobridge based SQUID have been proposed and investigated extensively [10-14]. Such nanobridges are expected to behave as weak links [15] between two electrodes of larger size and show Josephson effect [16]. More recently, the study of low dimensional superconductivity and phase slip physics [14] justify the need for a reliable nanofabrication technique.

We present a brief description of the three damascene type techniques [17] using a chemical-mechanical polishing (CMP) step applied for the first time to superconducting metals. We note that the CMP step is used directly on Josephson tunnel junctions and nanobridges to set their geometry. Results on the impact of the damascene CMP process on the superconducting properties of the patterned metal are also presented.

These techniques offer the possibility to use niobium ($T_c = 9.4$ K) instead of aluminum ($T_c = 1.4$ K) for the fabrication of qubits and also to reduce the size of the junctions. It presents the opportunity to unify the fabrication of RSFQ circuits and of qubit by the same procedure. These techniques also change the way the barrier is fabricated and engineered and part of the geometry of the junctions. In the case of nanobridges, the absence of tunnel junction certainly changes properties such as noise sources. As pointed out by many authors in the race for long qubit decoherence time (e.g. [11]) the intrinsic properties of the junctions play a crucial role. Our techniques could contribute in understanding these if not controlling them.

2. Fabrication techniques

The damascene type reference process by Dubuc *et al.* [17] was developed for metallic single electron transistors (SET) and demonstrated above room temperature operation of the SET. The process consists in etching a pattern into an insulator, silicon oxide in our case, which serves as a rigid mould for the definition of the metal structures (junctions, nanobridges, leads, etc.). The pattern is then filled with one or two layers of superconductors (in our case instead of normal metal) to form the junction, and finally the excess material (that outside the etched pattern) is removed from the surface of the oxide by CMP leaving the superconducting structures in the trenches. Performed on a single layer of metal, this allows the fabrication of nanobridges. We have applied this to Ti, Nb and Al layers.

To produce tunnel junctions, the first superconductor layer is patterned and the barrier is formed by "ex-situ" oxidation and the second superconductor layer deposited (no pattern required). Details can be found in [15]. We applied this technique for Nb and Al Josephson junctions. We note that although this

technique does not easily allow fabricating the junction "in-situ", i.e. without breaking the vacuum during metal deposition, we argue that with proper equipment the barrier could be engineered in similar ways as done in the tri-layer Nb processes.

The RSFQ roadmap [1] for de Nb technology required $2\ \mu\text{m}$ junction linewidth for 2006 and below $1\ \mu\text{m}$ linewidth for 2016. More recently, reference [7] in 2009 presents state-of-the-art junction size of $0.6 \times 0.6\ \mu\text{m}^2$. Our technique using only photolithography can pattern junctions of $0.5\ \mu\text{m}$ wide by far below $0.2\ \mu\text{m}$ depth reaching the very small junction area limit of $0.1\ \mu\text{m}^2$.

We have also developed a hybrid process based on the fabrication of junctions by shadow evaporation before the damascene process (Fig. 1). This hybrid approach allows "in-situ" tunnel barrier formation and thus combines the technological advantages of both techniques.

All fabrication is done on $1 \times 1\ \text{cm}^2$ samples with many tens of devices patterned. The CMP is performed using two types of pads, IC1000 and Chempol with slurries Sillica 20 and 50 nm.

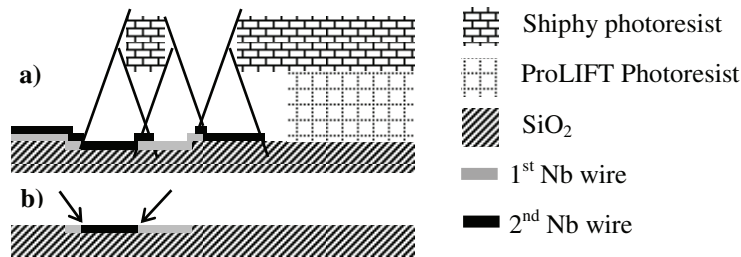


Fig. 1. Hybrid process. (a) Shadow evaporation in a trench; (b) The CMP step removes film overlaps leaving only two vertical junctions in the trench (arrows).

3. Chemical-mechanical polishing and superconductivity

To verify the impact of the CMP step on the superconductor properties, we performed polishing on Al (see Fig. 2. (a)) and Nb (see Fig. 2. (b)) deposited, by evaporation and sputtering, respectively. The patterns etched in a SiO₂ layers have a nominal depth of 100 to 300 nm with various width (from 1 and $4\ \mu\text{m}$) and length (from 15 and $150\ \mu\text{m}$). Figures 2 also shows design techniques needed to ensure large scale uniformity of the CMP process by use of filling patterns (basket weaving in this case) and meshed contact leads and pads.

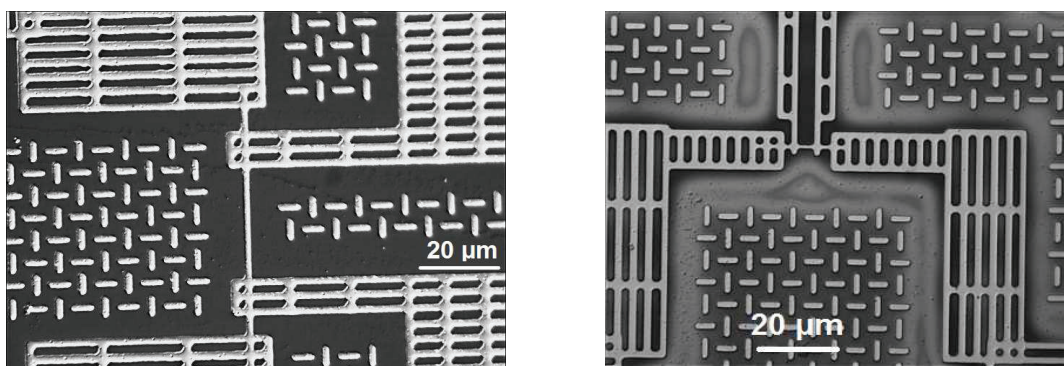


Fig. 2. . (a) Al wire (left) of $1.25\ \mu\text{m}$ width. Al is removed of the surface but remains that in the patterned trenches; (b) Nb wire (right) of $1.25\ \mu\text{m}$ width. Traces of the Nb still remain on the surface but no short-circuits are measured. The two wires have nominal depth of 300 nm. Surrounding the wires are filling patterns. The leads and contact pads are meshed ($2\ \mu\text{m}$ wide) to promote uniformity of the damascene process.

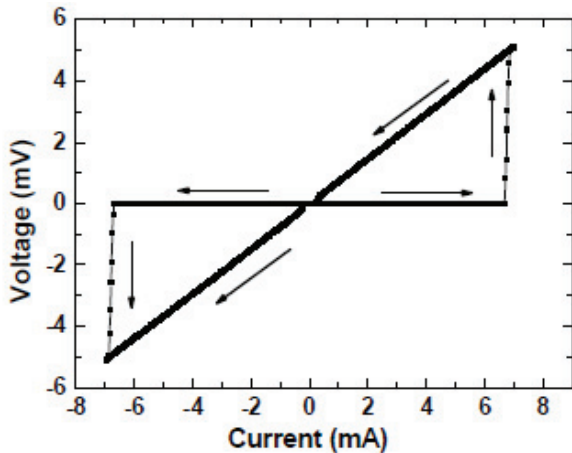


Fig. 3. V - I characterisation at 400 mK of an Al wire $1.5 \mu\text{m}$ wide, $30 \mu\text{m}$ long and 300nm of nominal thickness. The critical current density is $\sim 1 \text{ MA}/\text{cm}^2$.

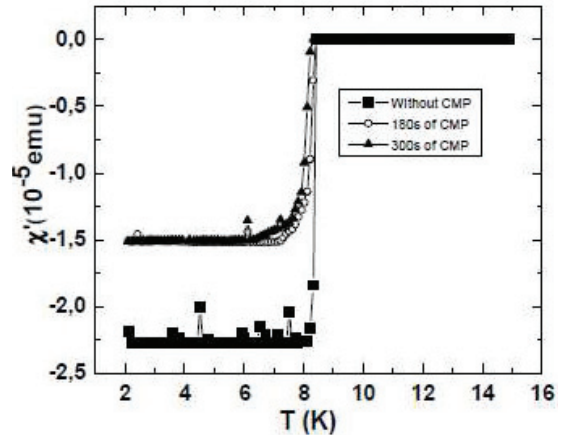


Fig. 4. Susceptibility of Nb films before and after 3 min and 5 min of CMP. The nominal thickness of the Nb layer before CMP is 250 nm .

The figure 3 shows the V - I characterisation of an Al wire fabricated by this technique ($30 \mu\text{m}$ long by $1.5 \times 0.3 \mu\text{m}^2$ of cross section) at 400 mK. The critical current density approaches $1 \text{ MA}/\text{cm}^2$. Tunnel junctions fabricated up to now do not show Josephson effect but have showed very high current densities and wire like behavior. We are working on a better control of the "ex-situ" barrier formation procedure.

The susceptibility measurements on layers without pattern (see Fig. 4) have shown that polishing has no remarkable influence on the superconductivity, thus confirming the viability of the process.

4. Hybrid fabrication process

We have also produced tunnel junctions with a hybrid process using both shadow evaporation to create the tunnel junction "in-situ" and CMP for the final pattern formation (Fig. 1.). The figure. 5 shows a SEM picture of the shadow evaporation Al/Al₂O₃/Al junction fabricated before CMP. The hybrid process allows eliminating film overlaps and thus reducing the size of the junction. Although the metal layers are wide ($5 \mu\text{m}$ in Fig. 5), the final junction size after CMP is determined by the width ($1 \mu\text{m}$ in this case) and the depth of the trench (grey area). For this reason, to fabricate nanometer size junctions, only the trench needs to be done by high resolution lithography while the shadow evaporation resist stack could be of micron size. To demonstrate this point, an arrangement of resists has been optimized to allow the use of photolithography to pattern the films as demonstrated in Fig. 1. High temperature or plasma tolerant resist could therefore be used in such a process if required.

The Figure 6 shows the I - V curve of a $1 \times 0.1 \mu\text{m}^2$ Al/Al₂O₃/Al junction made with the hybrid process with $I_c R_n = 0.57 \text{ mV}$ and $J_c = 3 \text{ kA}/\text{cm}^2$ at 400 mK.

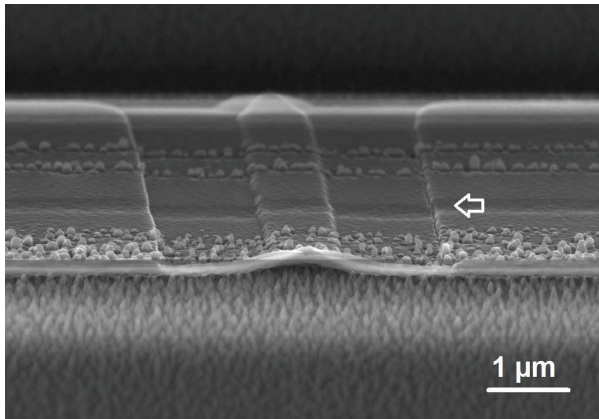


Fig. 5. Al/Al-oxide/Al Josephson junction fabricated by the hybrid process shadow evaporation/damascene. The trench are $3.5 \mu\text{m}$ wide but the shadow mask was made by photolithography (bridge $1 \mu\text{m}$ wide by $4 \mu\text{m}$ long). The arrow indicates the trench.

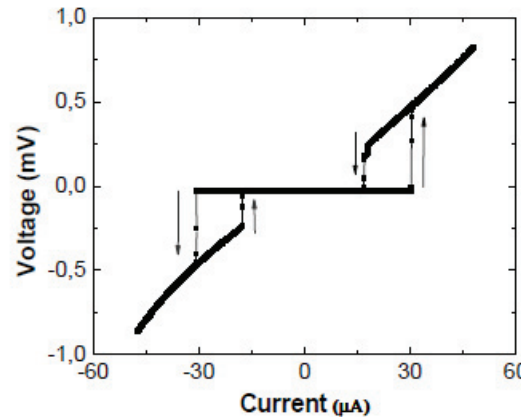


Fig. 6. $V-I$ of the Al/Al-oxide/Al Josephson junction with photoresist bridge of section $1.5 \mu\text{m}^2$. J_c and $I_c R_n$ are, respectively, 3 kA/cm^2 and 0.57 mV at 400 mK .

5. Nanobridges

The damascene CMP process also enables to realize nanobridges that behave as weak links between larger sized electrodes of the same material that provide proper superconducting phase anchoring (see [15]). Such simple devices have received much attention for various applications [10, 13] and for the study of low dimension superconductivity and quantum phase slip [12, 14]. For this, only the trenches need to be patterned and etched while the metal layer can be deposited over the whole sample without resist. This could increase the quality of the superconductor films providing the CMP slurries and process do not alter them. The process should also allow for “3D” nanobridges [16] to be fabricated.

Fig. 7 shows (a) a single nanobridge and (b) a SQUID type structure. These Nb nanobridges are approximately 100 nm wide and long and 20 nm thick. Similar structures have been fabricated in Ti and Al. Although the Nb and Ti nanobridges in most of the devices are conductive (~ 100 to 2000Ω) at all temperatures, none have shown superconductivity down to 300 mK . We are working at increasing the quality of the deposited films especially in the initial phase for this is the material that remains after CMP and forms these very thin nanobridges.

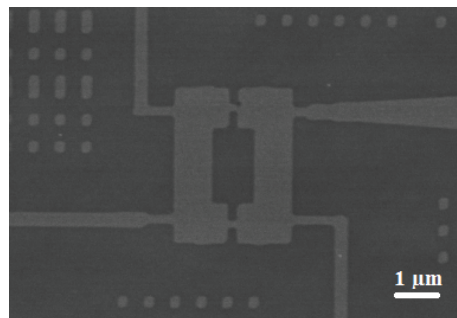
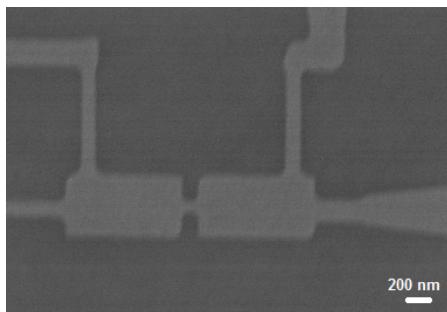


Fig. 7. (a) Josephson junction (weak link) formed by a 2D nanobridge of niobium between two electrodes of size more larger (left). Nominal depth of 20 nm ; (b) SQUID formed by two nanobridges 2D of niobium. The area of the SQUID is $2 \times 1.1 \mu\text{m}^2$ (right). Nominal depth of 20 nm . The width of the nanobridges is $\sim 100 \text{ nm}$.

6. Conclusions

We have developed new fabrication techniques to fabricate Josephson junctions and nanobridges in Al, Nb and Ti. We have shown that these chemical-mechanical polishing based process have minimal impact on Al and Nb superconducting properties as demonstrated on long microbridges. Using a hybrid process (shadow evaporation followed by CMP), we have fabricated and measured Al/Al-oxide/Al Josephson junctions. We have fabricated nanobridge structures in very thin Nb and Ti but none were superconducting. In these very thin structures, it is critical to have high quality material being deposited from the very start of the deposition process as it is those initial layers that are left as a device after CMP. We are addressing this issue which was known and controlled for thicker films (e.g. for 300 nm thick structures) but need optimisation for very thin films (e.g. 20 nm for nanobridges).

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