Investigation of three-dimensional digital circuits with nanometer Josephson junctions made by Focused Ion Beam
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INTRODUCTION
Fabrication processes dedicated to superconducting digital electronics were significantly improved during the last five years. These lithography-based processes allow to reach nearly one million junctions per cm² [1-2], opening the way to integrate more complex circuits on a single chip. Specific applications such as superconducting analog-to-digital interfaces require locally an outstanding performance. This 3D FIB (Focused Ion Beam) technique allows to precisely customize specific parts by locally etching the films. The presented work is focused on modelling nanometer-size Josephson junctions made by 3D FIB from a Superconductor-Normal Metal-Metal-Superconductor (SNIS) multi-layer process. An electrical model of the three-dimensional nano-SQUID was extracted with the InductEx® software, based on physical parameters of the 3D FIB SNIS technology. Expected behavior was simulated with the SPICE-based JSM simulator.

3D FOCUSED ION BEAM SCULPTING
The SNIS multilayer structure developed at INRiM is realized by multiple steps of argon-ion sputtering on a Corning glass wafer in high vacuum (≤10⁻⁷ mbar). The thin Au layer is grown in situ by oxidation of the spotted Al layer or by plasma oxygen pressure and with gas exposure of about 250 to 600 Pa a. The patterning process is done by 3D FIB milling of the SNIS multilayer to define Josephson junctions.

Features of 3D FIB sculpting of SNIS multilayers:
- Self-aligned Josephson junctions (suitable for VLSI)
- 300-300 nm maximum junction size
- Tunable critical current density (from 10 kA/cm² to 200 kA/cm²)
- 3D milling with focused Ga⁺ ion beam
- Characteristic voltage up to 0.7 V (Vbias = 70 GHz)
- Multidimensional rotation of the sample for sculpting junctions and lines

Fig. 1 : Patternning of a nano-junction by 3D FIB [1]
Fig. 2 : Fabrication steps of a 3D nano-SQUID [6]

DESIGN OF NANO-SQUIDS
The investigation of the technological process is done by implementing and characterizing SQUIDs. The smallest possible nano-SQUIDs were designed:

- 300 x 300 nm² Josephson junctions
- 200 x 1000 nm² SQUID loop
- Control lines at given locations (to estimate accurately the loop inductance)

Fig. 3 : 3D layout of nano-SQUIDs V1 (left) and V2 (right) with dimension given in cm
Fig. 4 : 3D layout of a nano-SQUID (left) and microphotography of the fabricated nano-SQUID V1 (middle) and V2 (right)

ELECTRICAL MODEL OF THE 3D NANO-SQUID
Physical parameters of the 3D FIB SNIS process given in figure 5 were input in InductEx® [5]. The two designed versions junctions were simulated with InductEx®. The corresponding electrical schematics and values are reported in figure 6. This three-dimensional structure was supposed to be symmetrical, which explains the identical values for a couple of inductances.

Table: Physical parameters used for InductEx® simulation

<table>
<thead>
<tr>
<th>Layer Name</th>
<th>Type of Layer</th>
<th>Layer Thickness</th>
<th>Physical parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb1</td>
<td>S (superconductor)</td>
<td>300 nm</td>
<td>Lambda = 85 nm</td>
</tr>
<tr>
<td>Nb2</td>
<td>S (superconductor)</td>
<td>50 nm</td>
<td>Lambda = 85 nm</td>
</tr>
<tr>
<td>AOX</td>
<td>A (insulator)</td>
<td>60 nm</td>
<td>-</td>
</tr>
<tr>
<td>LAl</td>
<td>L (alloy)</td>
<td>0 nm</td>
<td>-</td>
</tr>
<tr>
<td>Nb3</td>
<td>S (superconductor)</td>
<td>50 nm</td>
<td>Lambda = 85 nm</td>
</tr>
<tr>
<td>Nb4</td>
<td>S (superconductor)</td>
<td>300 nm</td>
<td>Lambda = 85 nm</td>
</tr>
</tbody>
</table>

Inductances Nano-SQUID V1 Nano-SQUID V2
L1 & L2 0.118 pH 0.156 pH
L3 & L4 0.115 pH 0.169 pH
L5 & L6 0.127 pH 0.035 pH
L7 & L8 0.360 pH 0.360 pH

Expectation of a nano-SQUID (1.44 pF) is lower than the Josephson junction’s static inductance (2x1.65 pH), the equivalent inductances extracted from the IV characteristic, which include the static inductances of the junctions, are higher by 25% than the expected geometrical values obtained by InductEx®.

- A novel method for retrieving the IV characteristics of a SQUID from SPICE simulations was developed, in order to include the junction’s dynamic behavior and predict more accurately the IV characteristics.
- Series of measurements of a few samples needs to be done in order to validate the InductEx® model of the 3D FIB SNIS process.

CONCLUSION
• Due to spatial constraints, the design and fabrication of SFO circuits by FIB with many junctions is complex. Despite this complexity of fabrication, design and fabrication of an SFO comparator or small test circuits can be realized.
• As the loop inductance of the nano-SQUID (1.44 pF) is lower than the Josephson junction’s static inductance (2x1.65 pH), the equivalent inductances extracted from the IV characteristic, which include the static inductances of the junctions, are higher by 25% than the expected geometrical values obtained by InductEx®.
• A novel method for retrieving the IV characteristics of a SQUID from SPICE simulations was developed, in order to include the junction’s dynamic behavior and predict more accurately the IV characteristics.
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EXPECTED BEHAVIOUR OF THE 3D NANO-SQUID
The physical parameters presented in figure 1 were extracted from SPICE simulations of the electrical schematics presented in figure 6. The simulated critical current of the 300x300 nm² Josephson junction is 200 μA with an R0K of 320 μV and an estimated McCumber parameter g = 1.

Fig. 7 : IV characteristics extracted from figure 3 and corresponding electrical schematics for the 3D FIB SNIS technology and static inductance (1.44 pF), CL is equivalent to “Controleur”

<table>
<thead>
<tr>
<th>SQUID version</th>
<th>Al</th>
<th>Equivalent Inductance</th>
<th>Expected Inductance</th>
<th>Difference in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1 CL1</td>
<td>8.16 mH</td>
<td>0.238 pH</td>
<td>0.224 pH</td>
<td>5%</td>
</tr>
<tr>
<td>V1 CL2</td>
<td>4.44 mH</td>
<td>0.460 pH</td>
<td>0.420 pH</td>
<td>11%</td>
</tr>
<tr>
<td>V2 CL1</td>
<td>6.43 mH</td>
<td>0.312 pH</td>
<td>0.291 pH</td>
<td>7%</td>
</tr>
<tr>
<td>V2 CL2</td>
<td>2.18 mH</td>
<td>0.567 pH</td>
<td>0.560 pH</td>
<td>1%</td>
</tr>
</tbody>
</table>

Fig. 8 : IV characteristics of the nano-SQUID V1 (left) and the nano-SQUID V2 (right) for current control injected only on control line 1 (top graph) and only on control line 2 (bottom graph). The SQUIDs bias current starts at 320 μA and ends at 350 μA with a step of 45 μA.

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