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 process 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 analogue/digital interfaces require locally an outstanding performance. The 3D FIB (Focused Ion Beam) technique allows to precisely customize specific parts by locally etching the films. The presented work is focused on modeling nanometer-size Josephson junctions made by 3D FIB from a Superconductor-Normal Metal-Insulator-Superconductor (SNIS) multi-layer process. An electrical model of the three-dimensional nano-SQUID was extracted with the InductEx© [5] software , based on physical parameters of the 3D FIB SNIS technology. Expected behavior was simulated with the SPICE-based JSIM simulator.

3D FOCUSED ION BEAM SCULPTING

The SNIS multilayer structure developed at INRiM is realized by multiple steps of magnetron sputtering on a Corning glass wafer in high vacuum [3-4]. The thin AlO_x barrier is grown in situ by oxidation of the sputtered Al layer, in pure oxygen pressure and with gas exposure of about 200 to 600 Pa.s. The patterning process is done by 3D FIB milling of the SNIS multilayer to define Josephson junctions.

Features of 3D FIB sculpting of SNIS mutlilayers:

- Self-shunted Josephson junctions (suitable for VLSI)
- 300x300 nm² minimum 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 mV (f_{MAX} = 70 GHz)
- Multidimensional rotation of the sample for sculpting junctions and lines

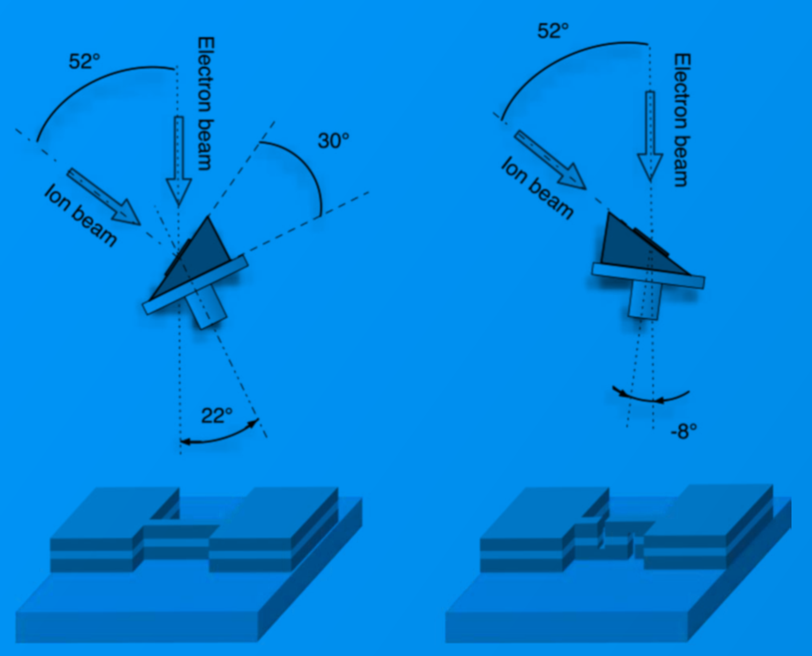

Fig. 1 : Patterning of a nano-junction by 3D FIB [4]

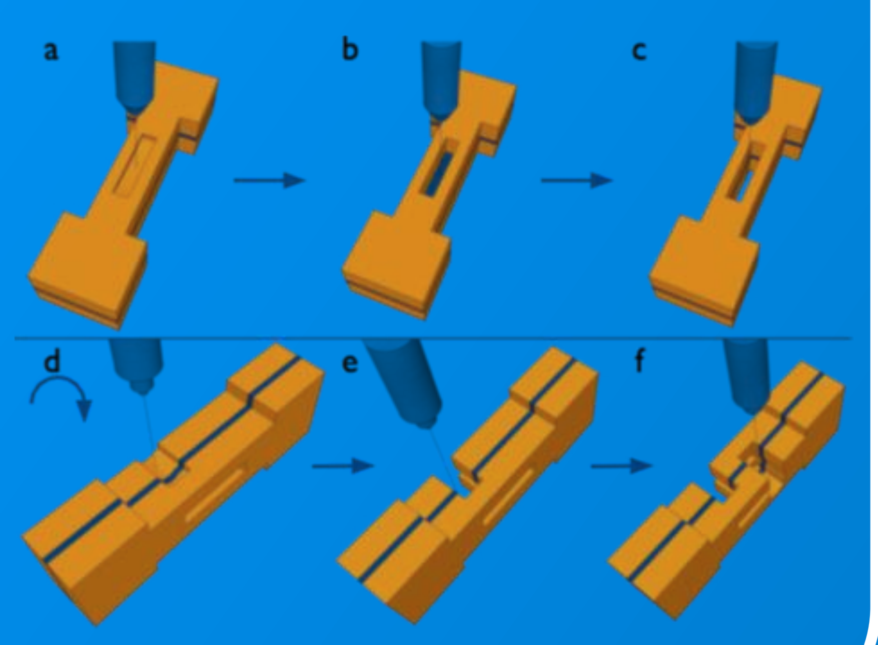

Fig. 2 : Fabrication steps of a 3D nano-SQUID [5]

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 1 000 nm² SQUID loop
- Control lines at given locations (to estimate accurately the loop inductance)

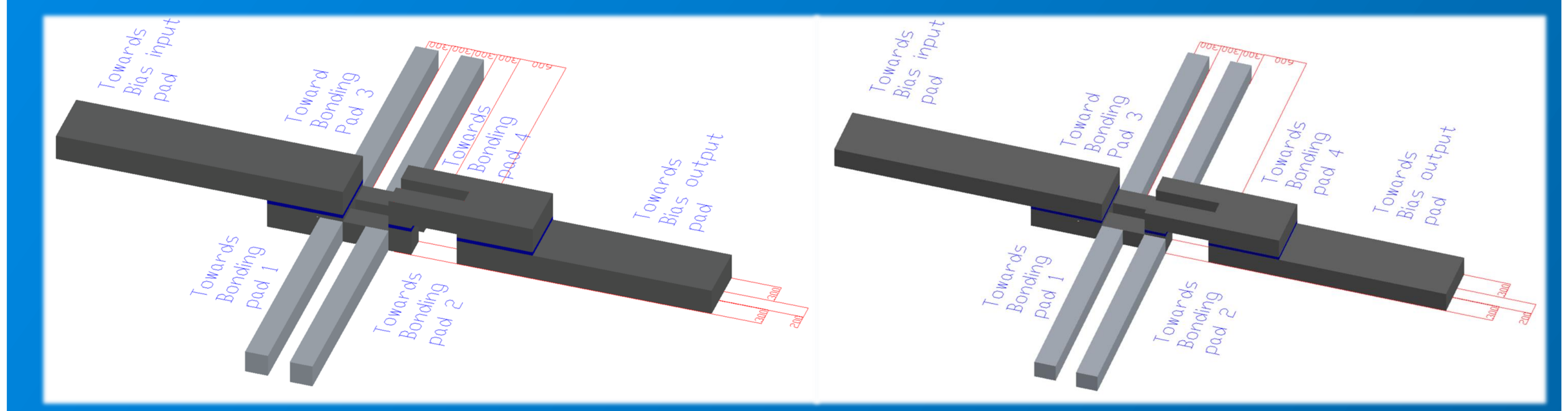

Fig. 3 : 3D layout of nano-SQUIDs V1 (left) and V2 (right) with dimensions given in nm

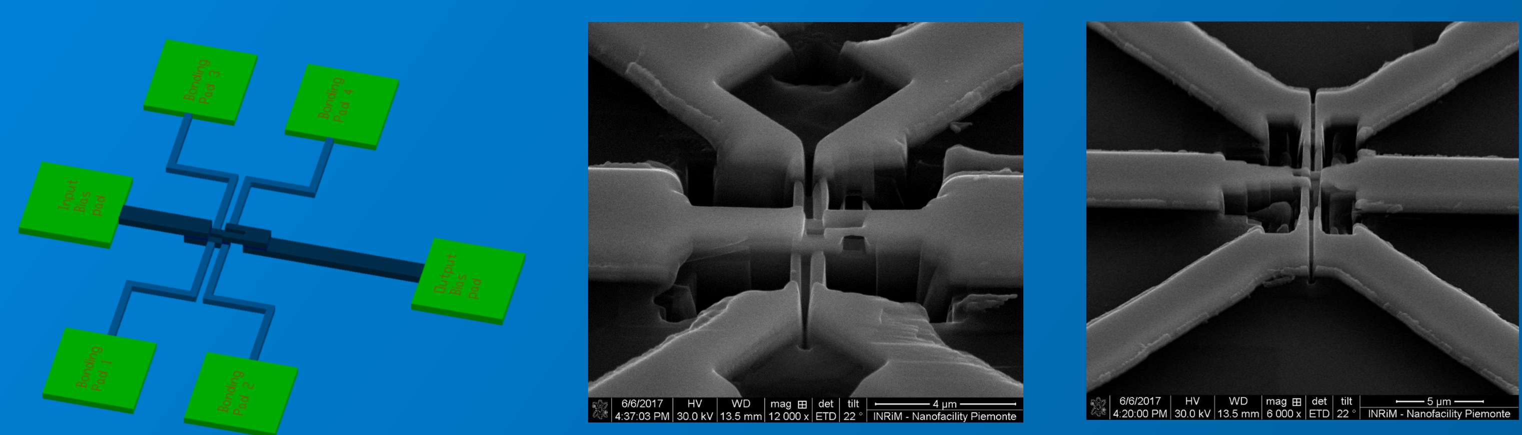

Fig. 4 : 3D layout of a nano-SQUID (left) and microphotography of the fabricated nano-SQUID V1 (middle) and V2 (right)

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 version's inductances were extracted in multiple steps with InductEx©. The corresponding electrical schematics and values are reported in figure 6.
The three dimensional structure was supposed to be symmetrical, which explains the identical values for a couple of inductances.

Layer Name	Type of Layer	Layer thickness	Physical parameters
Nb1	S (superconductor)	300 nm	Lambda = 85 nm
Nb2	S (superconductor)	50 nm	Lambda = 85 nm
AlOX	A (auxiliary)	80 nm	-
I0A	I (isolator)	0 nm	-
Nb3	S (superconductor)	50 nm	Lambda = 85 nm
Nb4	S (superconductor)	300 nm	Lambda = 85 nm

Fig. 5 : Physical parameters used for inductance extraction with InductEx ©

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

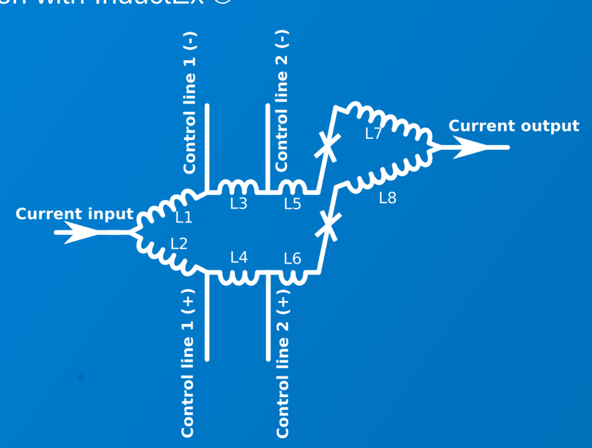

Fig. 6 : Extracted inductances with InductEx© for the 2 versions of designed SQUID (left) and corresponding electrical schematics (right)

EXPECTED BEHAVIOUR OF THE 3D NANO-SQUID

IV characteristics presented in figure 7 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 RnIc of 320µV and an estimated McCumber parameter βc =1.

SQUID version and current path	ΔI	Equivalent inductance	Expected Inductance	Difference in %
V1 CL1	8.76 mA	0.236 pH	0.224 pH	5%
V1 CL2	4.44mA	0.466 pH	0.420 pH	11%
V2 CL1	6.63 mA	0.312 pH	0.291 pH	7%
V2 CL2	3.18 mA	0.651 pH	0.560 pH	16%

Fig. 7 : Inductances extracted from figure 8 with expected inductance including the Josephson junction's static inductance (1.65pH). "CL" is equivalent to "Control line"

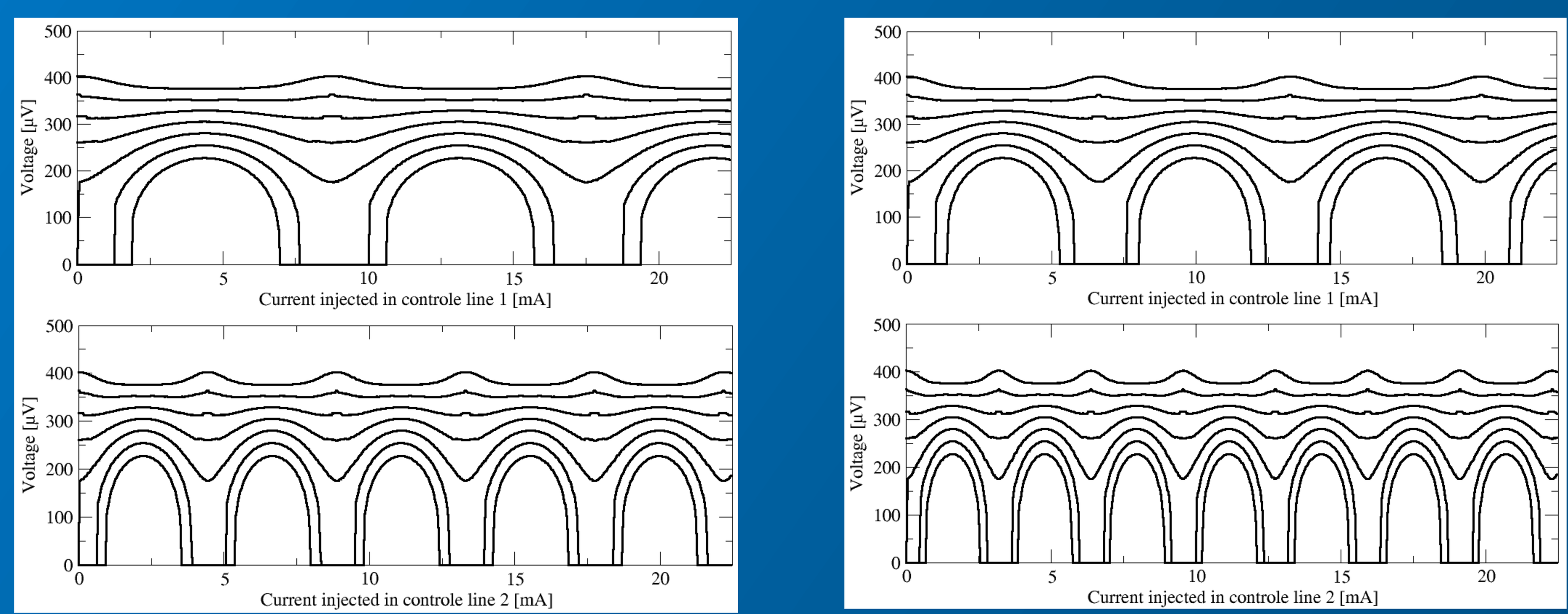

Fig. 8 : IV characteristic of the nano-SQUID V1 (left) and the nano-SQUID V2 (right) for control current injected only on control line 1 (top graph) and only on control line 2 (bottom graph). The SQUIDs bias current starts at 320µA and ends at 560µA with a step of 40µA.

CONCLUSION

- Due to spatial constraints, the design and fabrication of SFQ circuits by FIB with many junctions is complex. Despite this complexity of fabrication, design and fabrication of an SFQ comparator or small test circuits can be realized.
- As the loop inductance of the nano-SQUID (1.44pH) 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 20% 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.

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