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New developments in textured and epitaxial NbN superconducting layers for ultimate sensors and RSFQ digital circuits

J.-C. Villégier, N. Hadacek, C. Jorel, J.-L. Thomassin, V. Bouchiat[1], M. Faucher[1], P. Febvre[2], A. Rousy[2] and G. Lamura[3]

CEA Grenoble, SPSMS/LCP, 38054 Grenoble cedex 9, France
[1] CRTBT, CNRS, BP. 166, 38042 Grenoble cedex 9, France
[2] LAHC, Université de Savoie, 73376 La Bourget du Lac cedex, France
[3] LPS-ESPCI, 75231 Paris, France

Abstract: Nitride superconductors and specially niobium nitride are key materials for developing high performance optoelectronic and digital circuits We are presenting a way to achieve such high frequency devices on R-plane sapphire or MgO substrates Deposition of thin and flat NbN films with Tc above 10 K, low and reproducible penetration depth (λ_L~250 nm) and surface resistance (Rs) values up to 1 THz, is required and obtained by sputtering on a substrate heated in the 300-600°C range Simple sub-micrometer size HEB bridge structures where patterned even in a very thin (2-5 nm thick) NbN layers offering relaxation times below 30 ps It is then possible to achieve fast optoelectronic data links and sensors on-chip with high clock frequency NbN RSFQ digital circuits

1. INTRODUCTION

Important interest has been found recently in the possibility to achieve very low noise, large IF bandwidth Hot Electron Bolometric (HEB) heterodyne mixers in the THz signal frequency range as well as fast photo-detectors sensitive to a single photon in the IR-UV wavelengths [1], by using the transient electro-thermal properties of a simple sub-micrometer size bridge structure patterned in a very thin superconducting NbN layer In the same time THz cut-off frequency Josephson junctions can be fabricated with NbN electrodes and thin barriers made of MgO or of nitride materials such as AlN, NbN*x* or TaN*y*. Such layers can be sputter deposited in a multilayer stack [2] in order to achieve fast optical sensors or data links and high clock frequency (~100 GHz) Rapid Single Flux Quantum (RSFQ) logic circuits on the same chip High device performances imply relatively low penetration depth (λ_L) and surface resistance (Rs) values which require a good control on NbN cristalline texture and on superconducting properties.

2. ELABORATION OF EPITAXIAL NBN SUPERCONDUCTING LAYERS ON R-PLANE SAPPHIRE AND MGO (100) SUBSTRATES

NbN layers are DC-magnetron sputtered from 6 inch diameter high purity Nb target in a reactive mixture of argon and nitrogen with a total pressure of about 1,9 Pa and a background pressure of 10^{-5} Pa We are using both 3 inch diameter R-plane sapphire and 2x2 cm^2 area (100) MgO substrates which show correct (but not excellent) lattice matching with the cubic BCC phase NbN (a=0 44 nm), good surface quality in regard to epitaxial growth, low dielectric losses up to the infrared frequency range and good thermal conductivity at low temperature The NbN film texture is found strongly dependant on the substrate choice and on the substrate temperature during deposition

- (100) oriented NbN is found epitaxially grown on MgO, even when films are deposited at room temperature but the film quality increase with the deposition temperature up to 650°C, and film resistivity values are around 60 µΩ cm at 300 K
- Thin NbN is also found epitaxial when deposited at 600°C on blank R-plane sapphire, below some critical thickness value (~ 100 nm) where the low Tc HCP-phase nucleate and propagate across the layer

[2] When the NbN films are deposited below 400°C, a strong (100) texture can be also achieved when a 8-12 nm thick MgO buffer layer is RF sputter deposited on the sapphire substrate

Under theses conditions, very thin layers of NbN, in the range of 2-5 nm with 8K< Tc<13 K and $2\Delta_0$> 2 5 meV are obtained in a reproducible way by heating the wafer at 600°C both on MgO and on R-Sapphire (see fig 1) Films observed by grazing angle X-ray diffraction at ESRF are found epitaxial, surface morphology observed by AFM is very flat, showing single NbN lattice steps plateaus (0 4 nm thick) and the replica of vicinal steps present on both substrates. Very thin NbN layer are found electrically stable upon months when the surface is passivated by a few nm thick rf-sputtered semi-insulating AlN layer.

Thicker NbN layers (120-400 nm), used as junction electrodes, strongly (100) textured with Tc=16 K and low λ_l value can be achieved on top of a thin MgO buffer or by using a thin epitaxial NbN template sputtered at 600°C before lowering the temperature during deposition to prevent the HCP phase formation.

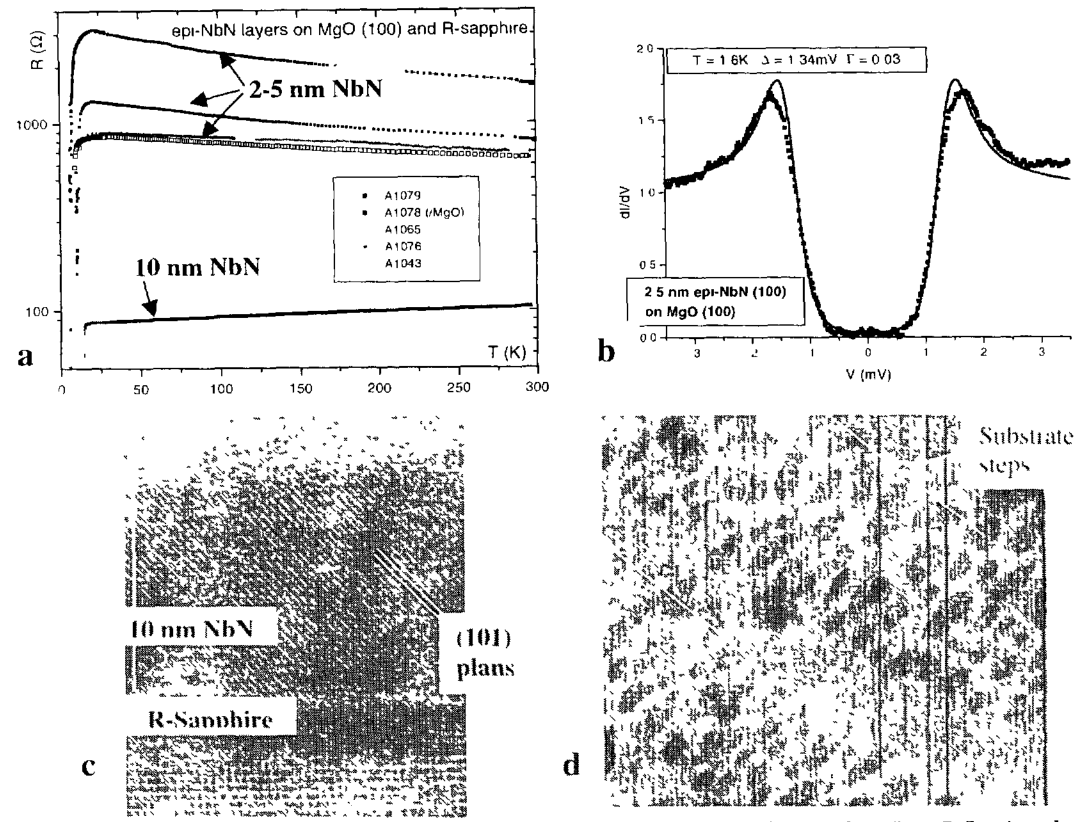

Figure 1. a- Resistance versus temperature variation for NbN films deposited at 600°C on MgO (100) or R-Sapphire, **b-** STM gap spectroscopy of a 2 5 nm thick film at 1 5 K, **c-** TEM cross-section of a 10 nm thick epi-NbN film on R-plane sapphire **d-** 4 µm x 4 µm STM observation of the NbN nucleation islands (0 4 nm step thick) for a 2 5 nm thick film (same film as in c)

3. PROCESSING OF THIN NbN NANOSTRUCTURES AND APPLICATIONS IN SENSORS AND RSFQ DIGITAL CIRCUITS

As reported in the table 1, different kind of RF devices could take advantage of textured NbN thin films.

- **HEB THz mixers** have been achieved in collaboration with Chalmers from our 2-5 nm epi-NbN on MgO layers, showing a low receiver noise temperature T_N~400K at 650 GHz [5] We are also developing a new

NbN-(Au) patterning process combining e-beam and UV lithography and a superposition of AlN and MgO hard masking layers, obtaining a small 3x 400x 800 nm^3 bridge volume (*see C. Ulysse et al, this volume*).

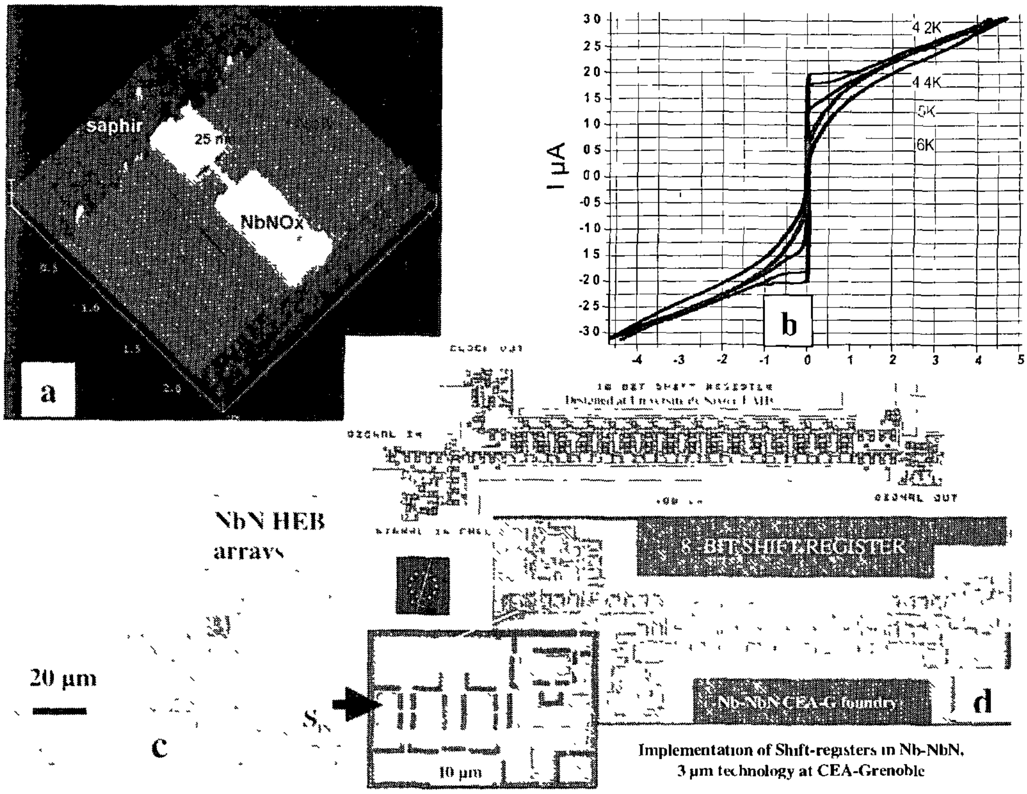

Figure 2. a- (2x25x250 nm^3) NbN nano bridge patterned by AFM anodization, **b-** I-V curve of the bridge shown in a, **c-** antenna structure developed for free space optical data link coupling and THz HEB mixers, **d-** implementation of a NbN RSFQ 8 bits shift-register compatible with the electro-optical signal input at the DC-SFQ gate (detailed picture)

Table 1. Various kind of device performances made possible with thin epitaxial NbN layers

NbN devices	Number of textured NbN layer / T_{dep} and thickness	Typical performance
HEB mixer [1],[5]	1 epi-layer (600°C)/(2-5 nm)	T_N< 700 K @ 1 5 THz /BW_{IF} >4GHz
Photodetector[1]& **photoswitch**	1 epi-layer (600°C) / (2-5 nm)	10 GHz BW, single photon counter / 20 GHz photo-switch
JFFO (Josephson flux flow oscillator)	2 epi-layer (600°C / 100 nm)	~ 1 THz LO with a broad band tuning
Hilbert spectrometer[7]	2 epi-layer (600°C / 100 nm)	~ 2 THz Band, on-chip SFQ spectrometer
NanoSQUIDs [4]	1 epi-layer (600°C / 2-5 nm) + 1 coupling coil	0 5 µm size, single layer SQUID front-end of a digital SQUID
On-chip RSFQ, sensors & data links *[2], [6]*	2 epi +3 textured layers	100 GHz clocked gates / 40 Gbits/s link or integrated sensor array read-out

- NbN Dayem bridges and 2.5x10x100 nm^3 Josephson VTB (Variable Thickness Bridge) with Jc above 100 kA/cm^2 at 4K and DC-SQUIDs operating up to 7K have been patterned by AFM local anodization method [4] into very thin (2-5 nm) epi-NbN layers grown at 600°C on R-Sapphire or MgO substrates. Large kinetic inductance is measured in such junctions and SQUIDs. Such single layer **NbN nanoSQUID** device working at 5 K looks important for RF applications in the fields of magnetic imaging, phase qubits-RSFQ hybrid gates and make possible the realization of a compact NbN RSFQ digital SQUID technology
- **JFFO** (Josephson Flux Flow Oscillators) and **Hilbert Spectrometers** based on epi-NbN Josephson tunnel junctions are also presently investigated with other devices useful for fast on chip diagnostic of RSFQ circuits they take advantage of an all epitaxial NbN/MgO/NbN junction [7]
- Fast **NbN RSFQ circuits** with high current density, high IcRn product, junctions, have been studied on-chip compatible with a fast epi-NbN electro-optical data link two (100) NbN layers are sputtered epitaxially on sapphire up to 600°C a 350 nm thick NbN layer (λ_I~250 nm at 6K) acts for the ground-plane and a GHz BW HEB micro-bridge electro-optical modulator is patterned in a 2 5-6 nm thick NbN epilayer with T_c above 11 K Innovative dielectrics formed of 10 nm thick MgO sputtered on top of 200 nm SiO_2 layers are found to improve significantly the superconducting and inductive properties of NbN wiring lines deposited below 300°C [3] Good quality, self-shunted NbN/MgO/NbN or NbN/TaN/NbN junctions with high Jc (up to 50 kA/cm^2) are obtained with large IcRn (up to 2 mV) at 4 2 K and with IcRn above 0.5 mV at 11 K (J_c~10 kA/cm^2) Jc can be trimed (reduced) without any detrimental effect on the junction quality or spread by annealing at 250°C. Recent achievements of hybrid Nb-NbN RSFQ circuits on 3 inch diameter R-plane sapphire substrates, also take advantage of the NbN texture control through the use of MgO buffers Examples of a 8 bits shift-register designed by LAHC-Université de Savoie and fabricated by the CEA foundry under FLUXONICS network are given in fig 2 The actual circuit technology is compatible with a 20 Gbits/s data modulation coming through the NbN HEB at the RSFQ signal input

CONCLUSION

The progress in superconducting NbN texture control and sub-micrometer patterning techniques should have a strong impact on high frequency device performances and open new functionality (on-chip fast circuit diagnostic tools, GHz bandwidth optical links), higher operating temperature (5-10 K) for RSFQ LSI circuits (ADC DAC, processors, digital filters,), but also for fast single photon detectors, THz HEB mixers, nanoSQUIDs,..

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