Characterization Measurements of Sapphire and Diamond based KIDs for Polarimetric Plasma Diagnostics

[1]F. Mazzocchi, [2]K. Ilin, [2]S. Kempf, [3]A. Kuzmin [1]D. Strauß and [1]T. Scherer
[1]Institute of Applied Materials – Applied Materials Physics, Karlsruhe Institute of Technology (KIT IAM-AWP)
[2]Institute of Micro- and Nanoelectronic Systems, Karlsruhe Institute of Technology (KIT – IMS)
[3]Laboratory for Applications of Synchrotron Radiation, Karlsruhe Institute of Technology (KIT - LAS)

Abstract— **In this work we present the study and characterization measurements of Kinetic Inductance Detectors prototypes based on NbN thin films on diamond and sapphire substrates. The detectors are polarization sensitive, have multi-pixel design and are meant to be employed as the detecting element in a polarimetric fusion plasma diagnostic system operating at a probing frequency of 1.3 THz.**

I. INTRODUCTION

KINETIC Inductance Detectors (KIDs) have proven to be a very versatile cryogenic detector technology, with applications in various fields like astrophysics [1,2], neutrino physics [3], material sciences in synchrotrons [4] and imaging [5]. We have recently proposed the use of a polarization sensitive Lumped Elements KID (LEKID) as sensor for an innovative polarimetric diagnostic system based on Quantum Cascade Lasers (QCL) for application in nuclear fusion reactors [6]. LEKIDs are particularly attractive since they don't require any antenna structure to couple the radiation into the detector and they are easily readable with Frequency Division Multiplexing (FDM) techniques. The detectors are composed by four pixels in a cross-polarized configuration, with each resonator tilted by 90 degrees with respect to its adjacent neighbors. This design was chosen to make a single device natively capable of measuring both the s and p components of the radiation impinging on it at the very same time. In order to avoid substrate events [7] and improve the resilience of the detector to radiation-flooded environments, we decided to study high-transparency low-losses radiation-hardened substrate materials in the form of sapphire and diamond. The superconducting thin film of choice is NbN, with a bulk critical temperature generally comprised between 12 and 16 K [8], allowing operation at liquid He temperatures. The thin film thickness was set to 15nm for radiation – detector coupling optimization purposes.

II. PROTOTYPES DESIGN AND CHARACTERIZATION

Each detector unit is made up by four resonators, arranged in a crossed configuration. Each pixel is composed by two distinct parts, a 1x1 mm^2 inductor and an interdigital capacitor (IDC). All the NbN tracks composing the resonators are 10 µm wide with a 40 µm separation between two adjacent inductor lines. The inductor geometrical configuration is shared among all the pixels, with the tuning of the resonator's resonant frequency for FDM read-out obtained by changing the number and length of the IDC fingers. To validate the design and to investigate the occurrence of detrimental phenomena like cross-talk, we performed an extensive set of simulations of single, dual and quadruple pixel systems. While sapphire is naturally birefringent, we nevertheless used an isotropic model, since our substrate samples were all r-cut and could be modeled with the use of an effective ϵ_r with a value of 10.06 [9]. The value of the loss tangent was pre-set to $5 * 10^{-6}$ in the Sonnet software suite [10] used for the calculations. Diamond is, in this regard, naturally isotropic and presents a lower value of ϵ_r equal to 5.67 [11]. The tanδ was set equal and 10^{-5} to simulate the losses associated with polycrystalline material produced through chemical-vapor-deposition (CVD) techniques [11]. The substrate thicknesses at our disposal were 330 µm for sapphire and 700 µm for diamond. The other material-related parameter used as input in the simulation was the value of the kinetic inductance L_k of the thin films. Computations of the current distribution inside the resonators at resonance outlined how the inductor of the pixels is characterized by a uniform value of the current density J. This leads to uniform detector responsivity, allowing detectable photons to fall naturally onto the device instead than having to couple to a specific, high responsivity point to maximize the response [12]. The polarization selectivity is given by the geometrical design of the unit that greatly favors absorption of waves polarized parallel to the long sides of the inductor. Following the design and simulation phase, we produced the prototypes by depositing the NbN thin films via DC reactive magnetron sputtering and patterning them with UV photolithography. The etching was then performed with a reactive ion process. The patterned films were first characterized by measurements of critical temperatures and currents. Films deposited on sapphire (T_C = 13.5 K, $J_c = 9.3 * 10^6$ A/cm^2, R_s = 70.6 Ω/□, *RRR* = 1.07, L_k = 7.28 pH/□,) showed higher quality compared to those on diamond (T_C = 9.5 K, $J_c = 5.6 * 10^5$ A/cm^2, R_s = 156.53 Ω/□, *RRR* = 0.91, L_k = 22.77 pH/□). We then tested the resonators response to a read-out tone, with an input power for all the measurements set at -20 dBm to avoid saturation, with a 20 dB attenuator added to port 1 of the VNA to limit the thermal noise injected in the system. Resonance frequencies in the range of 1.4-1.9 GHz were obtained for the sapphire substrates, in line with the simulations previously performed. The recorded resonances were quite deep and very sharp, an additional sign of the good quality of the deposited thin NbN film. For the diamond samples, simulations predicted resonance dips in the 1.2-1.7 GHz range that were absent in our measurements. Excessive resonator losses caused by the increased presence of quasi-particles at 4.2 K in the low-quality film resulted in extremely shallow first order resonances that ended up being embedded in the baseline noise and, therefore, could not be detected. Measurements related to the response of the detectors to THz radiation were carried out with a Backward Wave Oscillator (BWO) equipped with a Schottky frequency tripler. The source was operated at 900 GHz, since it corresponded to the maximum emitted power, and the radiation was chopped at a frequency of 23 Hz. The samples were inserted in a liquid helium bath cryostat, with 10 and 20 dB attenuators attached to the input port of the detector box and a cryogenic low noise amplifier at the output port. An additional room temperature amplifier was inserted between the cryostat output and the VNA. With a measured power of 47 µW

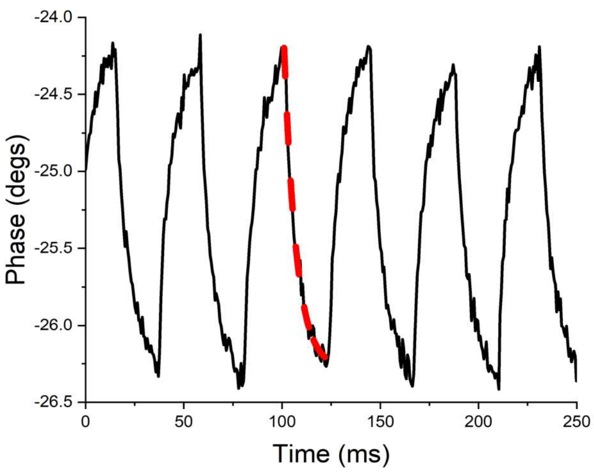

Figure 1 Phase response of one of the LEKID prototypes on sapphire substrate (black solid curve), together with the exponential decay fit (red dashed curve) used to extract the value of the response time.

emitted right after the tripler, we estimated roughly 20 µW falling onto the detector after passage of the generated THz signal through quasi-optical coupling system and the cryostat window. The measurements of the sapphire samples were performed at the temperature of 4.5 K. The phase responsivity of these devices is in the order of 0.1 degrees/ µW (Fig.1), with a response time scale in the order of 6 ms, as determined by an exponential decay fit over the recorded trace. The diamond sample was measured at a temperature of 5.5 K and presents a lower responsivity of 0.03 degs/µW but faster response at roughly 1 ms. The response time is orders of magnitudes above the typical dynamics of Cooper pairs generation-recombination and more in line with a bolometric regime. The detectors nevertheless fulfill the International Thermonuclear Experimental Reactor (ITER) response time guidelines of 10 ms [13] that have been taken into consideration during the design phase. We also checked the response of the pixels to radiation of two orthogonal polarizations. The measurements showed (Fig.2) well pronounced modulation of the phase response of a pixel to polarization along inductor long sides and almost no oscillations of the response to perpendicular one, validating the adopted design for a polarimetric application.

III. CONCLUSIONS

In this work we presented the design study and first characterization measurements of an innovative Kinetic Inductance Detector unit with a lumped element design based on sapphire and diamond substrates, and niobium nitride superconducting thin films. The detector has been designed to be part of a polarimetric diagnostic system for nuclear fusion application, taking into consideration the guidelines specified for the upcoming ITER tokamak machine. The thin film and microwave characterization measurements outlined the great difference in quality of the superconducting thin films deposited on the two substrates, with the films on diamond suffering from lattice and thermal expansion mismatch and from a rough surface finish of the substrate. Measured response to THz radiation showed in both cases bolometric nature, with response times in the order of the millisecond. Measurements

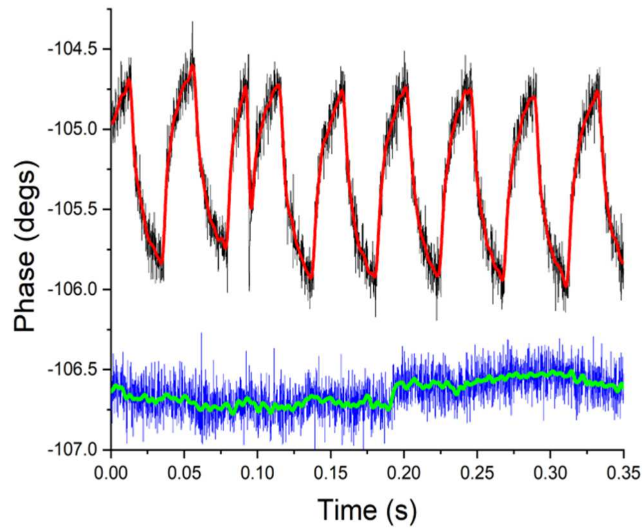

Figure 2 Phase response of one of the pixels deposited on sapphire substrate to two orthogonal polarization planes. In black, the response for polarization parallel to the inductor main lines, in blue the one for the perpendicular direction. Both tracks have been smoothed-out with an FFT algorithm for clarity purposes (red and green traces correspondingly).

of the response to radiation polarized along perpendicular directions validated the adopted polarimetric design and the choice of high optical quality materials as base for the devices. The prototypes fulfill the response time requirements specified by ITER for a polarimetric diagnostic and represent a good starting point for the optimization of these devices for the application at hand.

IV. REFERENCES

[1] S. Shu, M. Calvo et al., Optical Response of LEKID Arrays, IEEE Transactions on Terahertz Science and Technology, vol.8, no.6, Nov 2018.

[2] A. Monfardini, L.J. Swenson et al., NIKA: A millimeter-wave kinetic inductance camera, A&A 521, A29 (2010).

[3] N. Casali, C. Bellenghi, et al. Cryogenic Light Detectors for Background Suppression: The CALDER Project. J. Low Temp. Phys. 2020, 200, 206–212.

[4] T. Cecil, A. Miceli et al., Kinetic Inductance Detectors for X-Ray Spectroscopy. In Proceedings of the 2nd International Conference on Technology and Instrumentation in Particle Physics (Tipp 2011), Chicago, IL, USA, 9–14 June 2012; Volume 37, pp. 697–702.

[5] S. Rowe, E. Pascale et al., A passive terahertz video camera based on lumped elements kinetic inductance detectors, Rev. Sci. Instrum. 87 (2016).

[6] F. Mazzocchi, G. Grossetti, and A. Mlynek. THz multi-line of sight polarimeter for fusion reactors. Fus. Eng. Des. Vol. 130, p 1-5, 2018.

[7] D. Marsden, B.A. Mazin, et al. Optical lumped element microwave kinetic inductance detectors, High Energy, Optical, and Infrared Detectors for Astronomy V, volume 8453, pages 62-70 SPIE, 2012.

[8] Y.M. Shy, L.E. Toth, and R. Somasundaram. Superconducting properties, electrical resistivities, and structure of NbN thin films. J. App. Phys., 44(12):5539–5545, 1973.

[9] I.B. Vendik, O.G. Vendik, and S.S. Gevorgian. Effective Dielectric Permittivity of r-Cut Sapphire Microstrip. In 24th European Microwave Conference, volume 1, pages 395–400, September 1994.

[10] https://www.sonnetsoftware.com/

[11] H. Yamada, A. Meier et al. Dielectric properties of single crystalline diamond wafers with large area at microwave wavelengths. Diam. Rel. Mat., 58:1–4, September 2015.

[12] S. Doyle. Lumped element Kinetic Inductance Detectors. PhD thesis, Cardiff University, 2008.

[13] R. Imazawa, Y. Kawano et al.. Polarization measurement techniques suitable for ITER poloidal polarimeter. In Proceedings of the 41st Plasma Physics Conference on Plasma Physics (EPS2014).