Characterization of NbN Thin Films produced on Quartz Substrates using MgO Seed Layers for phonon cooled Hot-Electron Bolometer Devices

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INTRODUCTION

NbN phonon-cooled hot-electron bolometer (HEB) mixer devices have turned out to be very useful for space terahertz applications. High intermediate frequencies in the range of several GHz are demanded for those applications. The intermediate frequency bandwidth of phonon-cooled HEBs can be increased by reduced film thickness [1].

Thin NbN films of about 3 nm produced on fused quartz substrates are not superconducting at liquid helium temperature [2]. To improve the film properties, one can use crystalline substrates as MgO, silicon or sapphire but those high-ε materials pose particular problems in terms of electromagnetic impedance matching and are fairly expensive.

We present an investigation on NbN thin films deposited on MgO seed layers on 2" fused and crystal quartz substrates. This MgO layer improved significantly the superconducting properties of our NbN films, sputtered at ambient temperature. Atomic force microscopy and x-ray diffraction were used to examine the surface properties and crystallinity of our thin films.

We present preliminary results using small angle x-ray reflectometry to determine the thickness of our sputtered NbN/MgO bilayers. The results are compared to ellipsometry and anodization measurements.

Phonon-cooled NbN/MgO HEBs have been produced with a new process, using a negative resist for the definition of the width of the microbridge by electron beam lithography.

First results, obtained at a frequency of 800 GHz showed an IF-gain bandwidth of 1.8 GHz and a receiver noise temperature of 670 K (corrected for beam splitter loss).

I. Crystalline Properties of the Bilayer

The influence of an MgO seed layer on fused quartz and crystal quartz on the crystalline properties of the NbN thin films has been investigated by x-ray diffraction measurements.

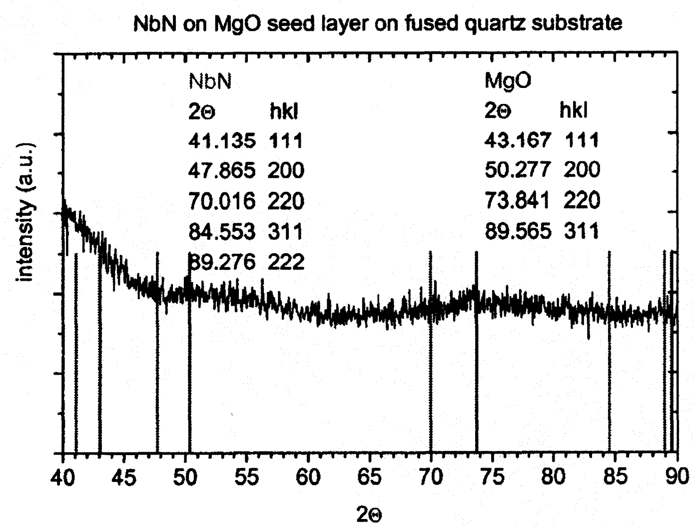

Fig.1.1.: θ/2θ scan of an NbN/MgO bilayer on a fused quartz substrate

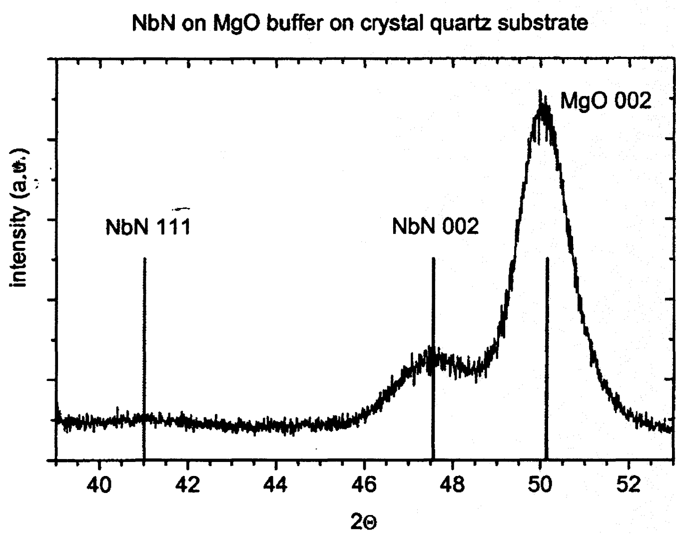

Fig.1.2.: θ/2θ scan of an NbN/MgO bilayer on a crystal quartz substrate.

The pictures show x-ray diffraction data (Co K_{α} 1.789 Å) of an approximately 5 nm thick NbN film on a 45 nm MgO seed layer on a fused (fig.1.1) and crystal quartz substrate (fig.1.2). On the fused quartz substrate the films are growing amorphously. The crystalline substrate allows the MgO and the NbN layer to grow mainly in (002) orientation. From the full width half maximum value of the (002) peak of NbN (fig.1.2) we can estimate a NbN grain size of 5 nm.

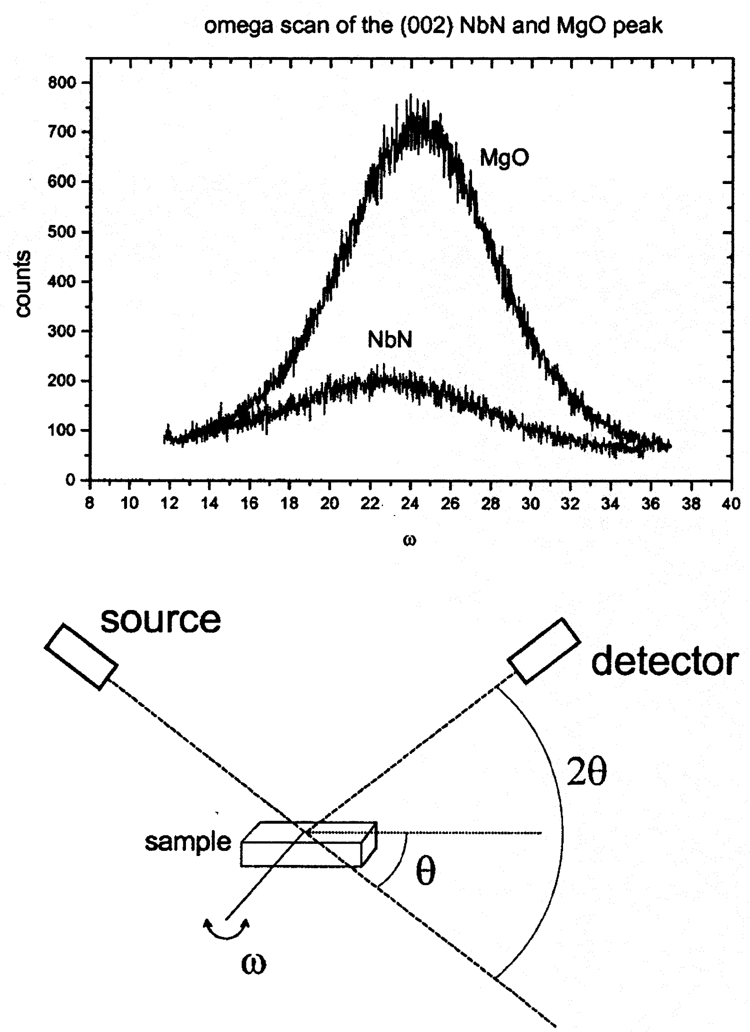

Fig.1.3.: Omega scan on the (002) peak of NbN and MgO

If one fixes the θ/2θ geometry for a given peak and turns the sample around the angle ω (= θ), one obtains a so called omega scan. The omega scan is a measure of the desorientation of the crystallites in the deposited layers. Figure 1.3 shows a scan, carried out on the NbN and MgO (002) peaks which confirms that the NbN growth is following the MgO seed layer.

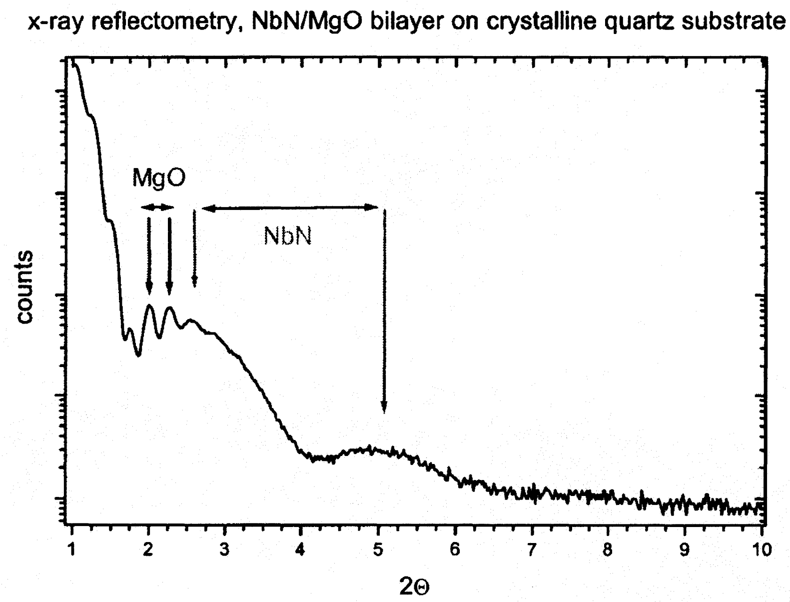

Fig.1.4.: Kiessig fringes of the NbN/MgO bilayer on a crystal quartz substrate.

As the equipment at DRFMC (Department of fundamental research on condensed matter) allowed also small angle measurements, we observed the Kiessig fringes of an NbN/MgO bilayer on crystal quartz (fig.1.4). The small oscillations correspond to the thicker MgO film and give a thickness of about 46 nm. The large oscillation is due to the ultrathin NbN layer and results in a thickness of 4 nm ±1. Surface, interface and substrate roughnesses determined from the x-ray small angle measurements could be estimated as 0.5 nm. This is about twice the RMS values obtained by AFM measurements carried out individually on a crystal quartz substrate, an MgO layer on crystal quartz and an NbN/MgO bilayer on crystal quartz.

II. THICKNESS CONTROL BY ELLIPSOMETRY AND ANODIZATION

The MgO layer thickness obtained by the reflectivity measurement was verified by ellipsometry of a film sputtered on a 2" Si wafer with the same deposition parameters. We obtained an average seed layer thickness of 42 nm in good agreement with the x-ray results (fig.2.1).

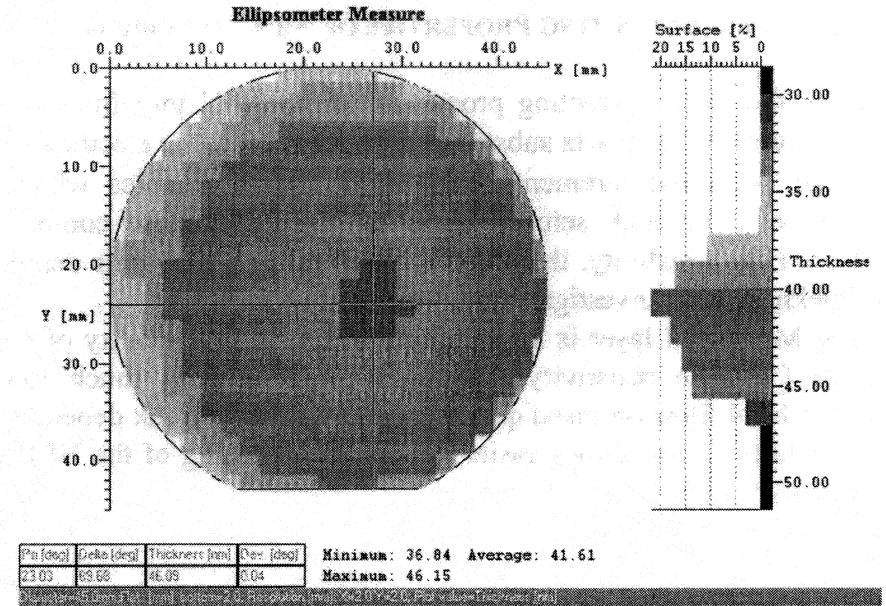

Fig.2.1.: MgO film thickness control by ellipsometry. Mapping of the hole 2" Si wafer.

The thickness of our NbN layers is always measured directly after deposition by anodization [4]. The graph in figure 2.2 shows an anodization curve of a 5 nm ±1 NbN film. The thickness of the superconducting layer determines the resistivity of the film in the normal conducting state and so the length and the width of the final NbN microbridge of a HEB.

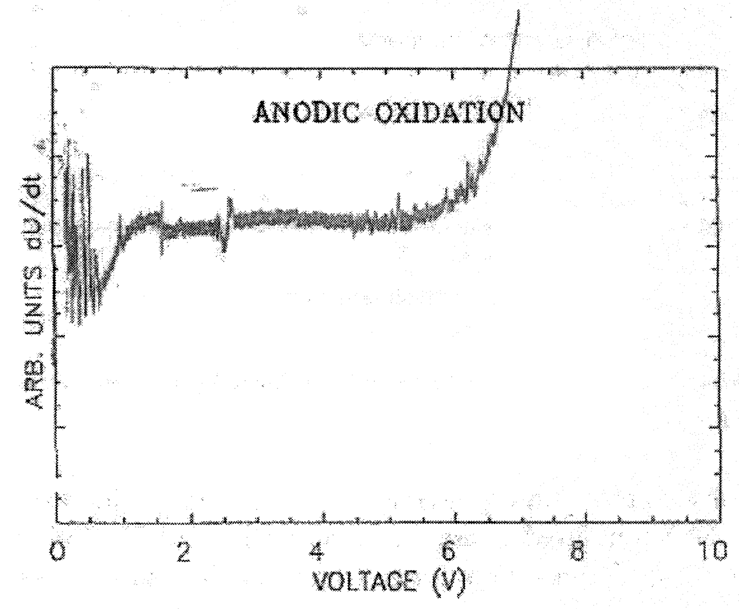

Fig.2.2.: NbN film thickness control by anodization. The plot shows the curve of a ~5 nm NbN thin film.

III. Superconducting Properties of NbN/MgO bilayers

To examine the superconducting properties of our NbN thin films, samples have been fabricated on quartz substrates. We determined the electrical properties by four point measurements on 1 mm × 10 mm samples which were carried out in a dip-stick setup. The film thicknesses were controlled by anodization. Film resistivity, the critical temperature T_c and their dependence on film thickness were investigated.

The MgO seed layer is substantially increasing the quality of our thin NbN films [3]. The resistivity (shown in figure 3.1) is much lower as compared to NbN films on fused quartz and shows only a weak dependence on the film thickness. This allows easier impedance matching of the HEB to the planar antenna.

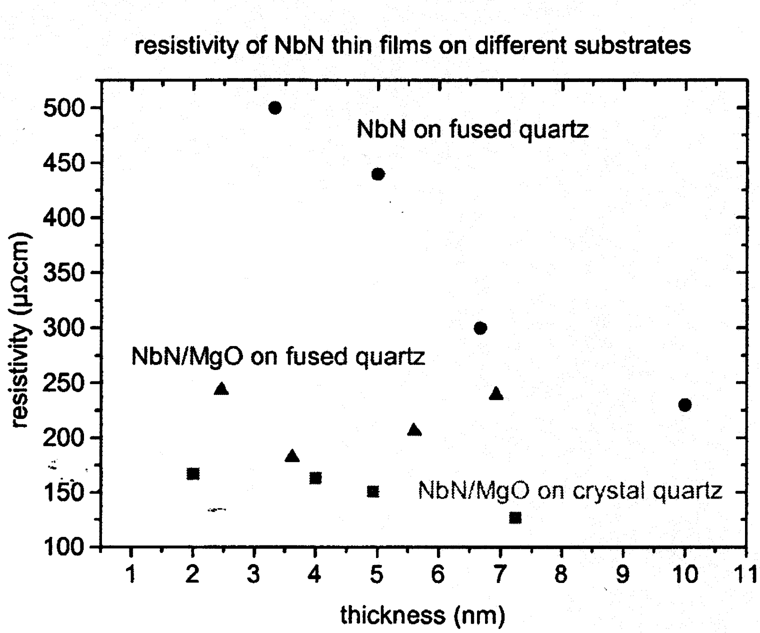

Fig.3.1.: Resistivity vs. NbN film thickness of NbN/MgO bilayers compared to NbN on fused quartz substrates.

We observed a strong increase of the critical temperature T_c as compared to NbN on fused quartz substrates (figure 3.2). The increased T_c allows working with thinner NbN films, which should result in a larger IF-gain bandwidth.

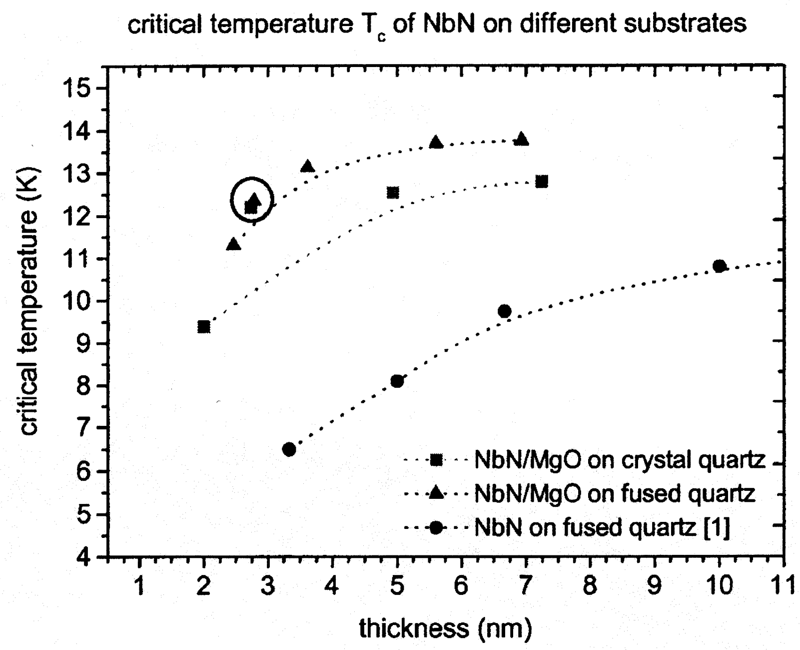

Fig.3.2.: Critical temperature vs. film thickness of NbN/MgO bilayers compared to NbN on fused quartz substrates.

The thickness of the MgO seed layer was 42 nm for the tested films, except for the two encircled points shown in fig.3.2. The latter were measurements on NbN films using a 15 nm thick MgO seed layer, showing that this thickness already provides a better film quality of NbN [5]. The spread in the data is mostly due to the uncertainty of the NbN layer thickness [4].

IV. DEVICE FABRICATION

In order to investigate the influence of an MgO seed layer on the properties of a phonon-cooled NbN HEB we first produced devices on fused quartz substrates. The HEBs have been produced with a new process, using a negative resist for the definition of the width of the microbridge by electron beam lithography.

After an overall deposition of a 42 nm MgO seed layer, the NbN film is deposited *in situ*. Antenna and filter structures are defined by photolithography. To define the lateral dimensions of the microbridge we use

Ebeam lithography. In a first step we fix the microbridge length by defining the Au contact pads by a single PMMA layer lift-off process.

In a second Ebeam step we generate a thin resist line using a negative Ebeam resist (Microsresist ma-N 2405) [6,7]. This resist line is used as an etch mask. We remove the surrounding NbN by reactive ion etching (CF_4, O_2). The resist etch mask is removed in aceton. Finally the substrate is diced and the individual devices are characterized by dc-measurements.

V. CHARACTERIZATION OF AN NBN/MGO HEB ON A FUSED QUARTZ SUBSTRATE

We determined the noise temperature of our NbN/MgO HEB by a Y-factor measurement. The improved film quality (as compared to NbN on fused quartz [2]) increased the critical current of our standard 5 nm NbN thin film and made higher pumping power necessary. With a beam splitter of 60% transmission at 300 K the best receiver noise temperatures were of the order of 670 K (corrected for beamsplitter loss) at 798 GHz and 1 GHz IF.

The IF-gain bandwidth was measured in a heterodyne mixing experiment with two local oscillators (LO), using LO1 to pump the device and LO2 as a signal. The variation of the IF was obtained by changing the frequency of LO2 and observing the output signal with a frequency analyzer. The NbN/MgO HEB showed a -3 dB IF-gain bandwidth of 1.8 GHz, as shown in figure 5.1.

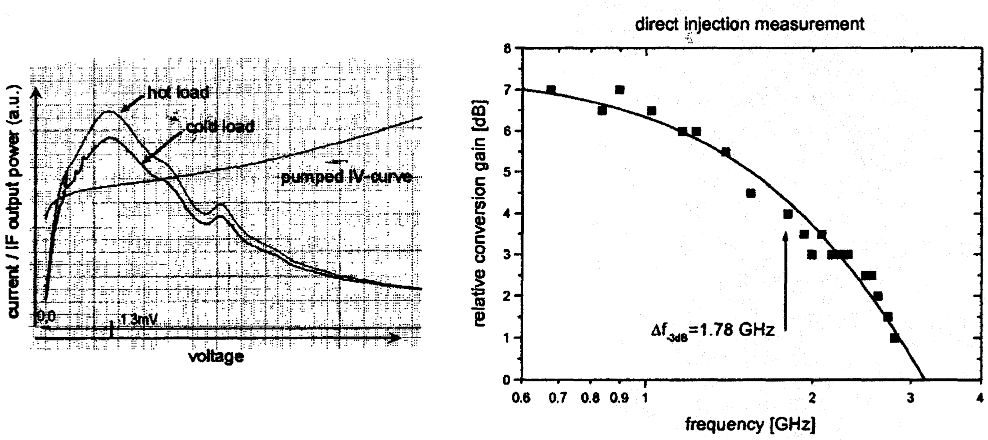

Fig.5.1.: Pumped I(V)-curve and conversion curves of an NbN/MgO HEB; IF bandwidth determined by double local oscillator injection.

VI. Conclusion and Outlook

An MgO seed layer on fused quartz, or crystal quartz substrates, provides a better crystal growth of our NbN thin films, resulting in lower normal state resistivity and higher critical temperature.

High frequency measurements on phonon cooled NbN HEBs fabricated on fused quartz substrates using an MgO seed layer showed a better noise temperature and a higher IF-gain bandwidth than comparable devices on fused quartz [2].

We are currently investigating the influence of the MgO seed layer on the acoustic matching between the bolometer and the substrate.

NbN/MgO HEBs were produced on crystal quartz substrates showing critical currents of about 150 µA and a T_c of 10 K. The high frequency properties of such devices are currently investigated.

Acknowledgement

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