Deposition of high-quality ultra-thin NbN films at ambient temperatures

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***Abstract*—This paper discusses the possibility of growing NbN ultra-thin films on Si-substrates and $Al_xGa_{1-x}N$ buffer-layers by means of DC magnetron sputtering without intentional substrate heating. Resistance-temperature measurements were carried out and the superconducting properties such as Tc, ΔTc and R□ were deduced while HRTEM gave insight into the crystal structure and film thickness. The adjustment of the partial pressure of argon and nitrogen was found to be critical in establishing a reliable deposition process. The quality of the interface between the NbN film and the substrate was improved by optimizing the total pressure while sputtering, and is therefore particularly valuable for phonon-cooled HEB heterodyne receivers. NbN films of 5 nm thickness were obtained and exhibited a Tc from 8 K on Si-substrates, and up to 10.5 K on the GaN buffer-layers. This result is significant since the absence of a high-temperature environment permits the establishment of more complex fabrication processes for intricate thin-film structures without compromising the overall integrity of e.g. dielectric layers, or hybrid circuitries with e.g. SIS junctions.**

***Index Terms*— NbN ultra-thin films, HEB, epitaxial growth**

I. Introduction

ULTRA sensitive receivers based on superconducting materials provide the basis for the detection of terahertz radiation, both for ground-based and space-born radio astronomical observations [1-2]. For more than two decades, NbN has been used as material for hot electron bolometers (HEB) due to its large energy gap and short electron-electron and electron-phonon interaction times, which yield a decent IF bandwidth of typically 4 GHz [3]. Ultra-thin NbN films with thicknesses 3.5 to 6 nm are usually required and are typically grown by means of DC magnetron sputtering at elevated substrate temperatures in a reactive argon/nitrogen gas mixture. This process is dependent on numerous parameters and has been investigated with the purpose to maintain the quality of the NbN films while reducing their thickness. However, only a few studies exist to date on the investigation of deposition techniques which do not require high substrate temperatures. More complex processing techniques could be applied by addressing this issue, hence enabling NbN to be e.g. used in other receiver technologies such as SIS junctions [4] or in general multilayer structures based on superconducting materials.

This paper demonstrates the deposition of 5 nm NbN films on Si-substrates and AlGaN layers with excellent crystallographic properties on the GaN epi-layer, confirmed by HRTEM microscopy. The suitability to grow NbN on GaN buffer-layer, was recently demonstrated at elevated temperatures [5] and is here applied for ambient temperature depositions. Superconducting properties of the ultra-thin films were determined by resistance-temperature measurements and Tc, ΔTc and $R_\square$ were deduced. Furthermore, micro-bridges with dimensions ranging from 4*4 µm to 4*20 µm were fabricated and characterized. The results of the NbN/GaN compound strongly point towards prospective applications in THz electronics, taking advantage of the enhanced superconducting properties of epitaxially grown NbN films combined with the favorable non-heat growth environment.

II. Experiment

A. Substrates

AlGaN epi-layers were grown by means of MOCVD on sapphire substrates (0002) and exhibited a hexagonal crystal structure. The Al content in the compound was gradually increased in order to investigate the influence of changing lattice parameter within the range of GaN and AlN. The epi-layers exhibited similar thicknesses of approximately 1.2 µm. Furthermore, bare silicon substrates with native oxide layer served as a reference. All substrates were ultra-sonically cleaned in acetone prior to loading, and treated in an argon-plasma before the sputtering of NbN.

B. Deposition

The deposition was carried out in an AJA Orion-6UD DC magnetron sputtering tool. Particular attention was paid to achieving optimal adjustment of the partial argon/nitrogen pressure, and the total pressure while sputtering from the Nb target. The optimal partial pressure is dependent on the total pressure and had to be adjusted accordingly.

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C. Characterization

All films were first characterized by R(T) measurements in a dedicated four-point-probe measurement set-up. The best films on silicon substrates and GaN buffer-layer were used to fabricate micro-bridges using photo-lithography techniques and dry etching in CF_4 to pattern the bridges. Investigation of the structural properties and the confirmation of the targeted thickness was conducted by HRTEM.

III. Results

A. R(T) measurement

Characteristic properties of the deposited films were extracted from resistance versus temperature measurements. **Ошибка! Источник ссылки не найден.** depicts the evolution of Tc for different Al content in the AlGaN compound and relates it to the film properties on bare silicon. A high Tc of 10.5 K has been obtained for low Al content of up to 20 % in the AlGaN layer. Above this, the Tc slowly deteriorated and approached the value of bare silicon.

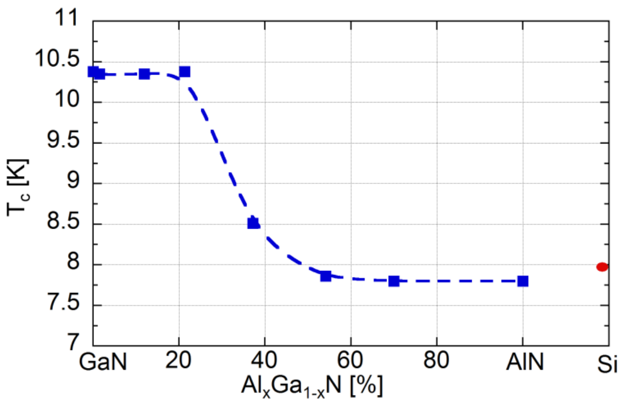

Fig. 29. Critical temperature versus Al content on AlGaN and Si substrates deposited at room temperature

B. Structural properties - HRTEM

After their electrical characterization, specimens of the NbN films were prepared both on the Si-substrate and the GaN epi-layer. Therefore, a thin Ti/Au layer was evaporated on the silicon substrates and a Nb-layer on the GaN sample in order to provide sufficient contrast.

The NbN film on silicon exhibits a poly-crystalline structure, and is arranged in differently sized grains. The ultra-thin NbN grown onto the GaN buffer-layer on the other hand, features epitaxial growth, as seen in **Ошибка! Источник ссылки не найден.**.

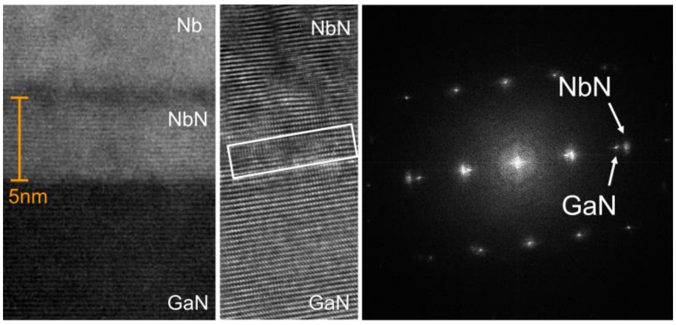

Fig. 30. Epitaxilly grown NbN films of 5 nm thickness. Indicated interface with very few defects. The Fourier transformed diffraction pattern supports the lattice match to the underlying GaN buffer-layer.

The left-hand side confirms the thickness of 5 nm, whereas the interface between the GaN layer and NbN match perfectly within one atomic layer. Furthermore, analysis of segments within the NbN and GaN layer yield the Fourier transformed diffraction pattern which supports the epitaxial nature of the NbN and its high quality.

IV. Conclusion

The presented properties of 5 nm thick NbN films grown at ambient temperatures on GaN buffer-layer are in accordance with the results from [5], presenting the growth at elevated temperature above 525 °C on GaN buffer-layers. A critical temperature of 10.5 K was achieved on AlGaN layer with Al content of up to 20 % and is therefore comparable with other lattice matched substrates, such as MgO [6]. Apart from its advantageous processibility over MgO, is it resistance to chemicals. Optimization of both the total pressure and the partial pressure of argon and nitrogen can improve the quality of the interface to NbN, thus, may benefit the phonon-escape in HEBs. The demonstration of the possibility to grow NbN without intentional substrate heating on AlGaN layer in high quality may pave the way for the integration of NbN in more complex multi-layer structures.

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