Conference materials
UDC 535.231.62
DOI: https://doi.org/10.18721/JPM.183.225

Study of low temperature reactive magnetron sputtering NbN films for fabrication of an ultra-high sensitive detector

I.V. Ivashentseva[1,2]✉, N.S. Kaurova[1], B.M. Voronov[1], G.N. Goltsman[1], I.V. Tretyakov[3]

[1] Moscow Pedagogical State University, Moscow, Russia;

[2] National Research University Higher School of Economics, Moscow, Russia;

[3] Astro Space Center of P.N. Lebedev Physical Institute of the RAS, Moscow, Russia

✉ irinivas22@yandex.ru

Abstract. This paper focuses on the study of reactive magnetron sputtering thin NbN films for sensitization of hot electron bolometers. HEB will be utilized in the Millimetron space observatory. The main principle of operation is a superconductivity that is experimentally observed when NbN film is cooled to the temperature of a liquid helium. At a critical temperature of superconductive transition a resistance of the film falls to zero and film becomes sensitive to light radiation of infrared and millimeter wavelength range. It is important to note that a thickness of film greatly affects on the sensitivity of film. When the thickness of film is decreased, the heat capacity decreases and with it the sensitivity of detectors based on superconductive film increases. In this research dependencies of the critical temperature from various parameters of fabrication technology were identified. Subsequently, parameters of reactive magnetron sputtering with the highest critical temperature at the lowest thickness of film were discovered.

Keywords: NbN films, critical temperature, superconductive transition, HEB, reactive magnetron sputtering, thin films, superconductivity, atomic force microscope

Funding: RNF 23-12-00187.

Citation: Ivashentseva I.V., Kaurova N.S., Voronov B.M., Goltsman G.N., Tretyakov I.V., Study of low temperature reactive magnetron sputtering NbN films for fabrication of an ultra-high sensitive detector, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 18 (3.2) (2025) 129–133. DOI: https://doi.org/10.18721/JPM.183.225

Материалы конференции
УДК 535.231.62
DOI: https://doi.org/10.18721/JPM.183.225

Изучение низкотемпературного реактивного магнетронного распыления пленок NbN для изготовления детектора с высокой чувствительностью

И.В. Ивашенцева[1,2]✉, Н.С. Каурова[1], Б.М. Воронов[1], Г.Н. Гольцман[1], И.В. Третьяков[3]

[1] Московский педагогический государственный университет, Москва, Россия;

[2] Национальный исследовательский университет "Высшая школа экономики", Москва, Россия;

[3] Астрокосмический центр Физического института им. П.Н. Лебедева РАН, Москва, Россия

✉ irinivas22@yandex.ru

Аннотация. Сверхпроводящие пленки NbN, изготовленные методом реактивного магнетронного распыления, являются чувствительным элементом болометров на эффекте электронного разогрева HEB. Основной принцип HEB устройств основан на свойстве сверхпроводимости, которое проявляется при понижении температуры детектора до температуры жидкого гелия. В таком состоянии детектор очень чувствителен к инфракрасному и миллиметровому диапазону волн, характерному для излучения многих элементов в нашей вселенной. Данная работа посвящена повышению чувствительности болометров на эффекте электронного разогрева благодаря уменьшению толщины пленки NbN при сохранении максимально возможной температуры сверхпроводящего перехода.

Ключевые слова: пленки нитрида ниобия, критическая температура, сверхпроводящий переход, болометр на эффекте электронного разогрева, реактивное магнетронное распыление, тонкие пленки, сверхпроводимость, атомно-силовой микроскоп

Финансирование: РНФ № 23-12-00187.

Ссылка при цитировании: Ивашенцева И.В., Каурова Н.С., Воронов Б.М., Гольцман Г.Н., Третьяков И.В. Изучение низкотемпературного реактивного магнетронного распыления пленок NbN для изготовления детектора с высокой чувствительностью // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 129–133. DOI: https://doi.org/10.18721/JPM.183.225

Introduction

Astro Space Center of P.N. Lebedev Physics Institute is working on the scientific program of the Millimetron space observatory [1]. The main goal of this program is observation of H_2O molecules for studying the evolution of life in the Universe. The equipment of space observatories with broadband and sensitive receivers makes it possible to study many water emission lines. Therefore, such space observatories, including Millimetron, make it possible to study water abundances and the entire chain of water transformations in the interstellar medium. The High Resolution Spectrometer incorporates heterodyne array receivers, one of which will be based on niobium nitride hot electron bolometers (NbN HEB) [2]. The sensitive element of NbN HEB is a superconductive niobium nitride film (NbN films on Si) produced by using the reactive magnetron sputtering [3].

NbN is a well-known material with comparatively high critical temperature from 14 to 16 K in bulk material [4]. The critical temperature depends on the proportion of niobium Nb to nitrogen N_2 [5–7]. NbN films on Si are fabricated with different sputtering technologies such as reactive magnetron sputtering [8], pulsed laser deposition [9], high-temperature chemical vapor deposition [10] and etc. Due to the existing technology and the high potential of reactive magnetron sputtering, this method of deposition of NbN films was chosen. The key parameters for evaluating film quality is critical temperature T_c, thickness. T_c is temperature at which a resistance of the film drops to zero.

The technology of superconducting NbN film deposition remains relevant, with numerous research groups regularly publish new research findings, for example, T_c is 9.6 K for 50 nm film [8] and T_c is 13 K for 100 nm [11]. The thicknesses of these films are very high and sensitivity is very low. Increasing the sensitivity of film is possible via reduction of film thickness, for instance, for 5.5 nm NbN on Si T_c is 7.8 K [12]. This work is devoted to optimisation of reactive magnetron sputtering process to achieve the most thin film with the highest possible critical temperature T_c.

Materials and Methods

The magnetron sputtering system Leybold Z400 was implemented for deposition of superconductive NbN films, the scheme of set up is depicted in Fig. 1. The vacuum chamber was pumped out to $2\cdot10^{-6}$ mbar using a two-stage pumping system. The inert gas Ar intrudes in the vacuum chamber. Then the voltage is applied to the magnetron with the Nb target in constant current mode, and N_2 is intruded. N_2 gas reacts with the Nb target, and NbN film deposition occurs [13]. In this work several parameters of the reactive magnetron sputtering are changed, such as current on glow discharge I, nitrogen gas pressure P_{N_2}, sputtering time τ.

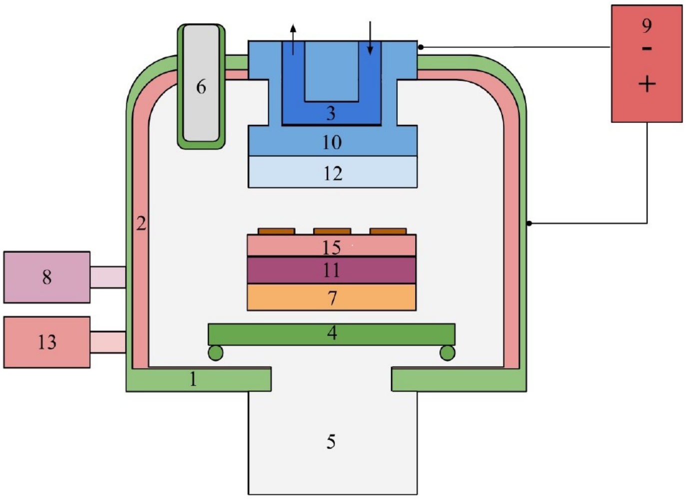

Fig. 1. Scheme of the magnetron sputtering system: vacuum chamber (1); heat jacket (2); cooling water (3); high vacuum valve (4); two-stage pumping system (5); nitrogen trap (6); heater of substrate holder (7); Ar gas intruder (8); sputtering power supply (9); magnetron (10); substrate holder (11); Nb target (12); N_2 gas intruder (13)

Several parameters of the fabricated film were investigated including critical temperature T_c, surface resistance R_s and the thickness film d. NbN film is cooled in Dewar with liquid helium and at T_c [14]. R_s and d are measured with Four-point method and atomic force microscope in half-contact regime, respectively.

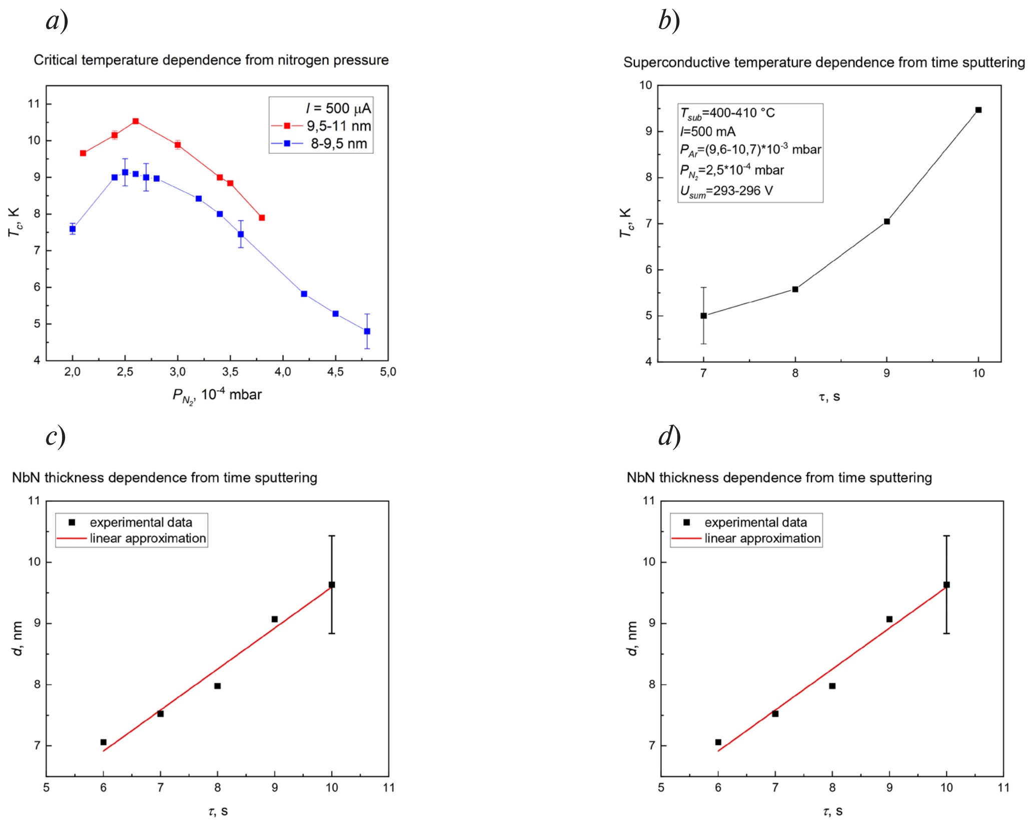

Fig. 2. Main dependences of the reactive magnetron sputtering technology:
T_c on nitrogen pressure (*a*); T_c (*b*) and film thickness on sputtering time, respectively (*c*);
surface resistance on film thickness (*d*)

Results and discussion

During this work, several dependencies were revealed (Fig. 2). The key parameter in this work is the nitrogen pressure. The final critical temperature depends on the ratio of nitrogen to niobium in the film. The highest superconducting transition temperature, T_c, was achieved at P_{N_2}=2.5·10^{-4} mbar (Fig. 2, *a*).

After raising the critical temperature, it was necessary to reduce the film thickness to increase sensitivity. From Fig. 2, *b*, the minimum sputtering time is τ = 7 s. At lower values of τ, the surface resistance R_s > sharply increases, which leads to increased film islanding and drastically reduces T_c.

Therefore, it was important to understand the dependence of the film thickness on the specific sputtering time, as demonstrated in Fig. 2, *c*. A sputtering time of 7 s corresponds to a 7 nm film. The final parameter is the surface resistance of the film, which determines the final geometry of NbN-based devices. The dependence of R_s on thickness was determined (Fig. 2, *d*).

All the final properties of the superconducting film were obtained to characterize the specific magnetron sputtering system that will be used for future work.

Conclusion

In this work the reactive magnetron sputtering technology was optimized for superconductive 7 nm NbN film with T_c = 7–8 K.

Acknowledgments

Work was conducted in Moscow State Pedagogical University.

REFERENCES

1. **Tretyakov I.V., Khudchenko A.V., Rudakov K.I., et al.,** Development of Mixers for the High-Resolution Spectrometer of the Millimetron Space Observatory, IEEE Transactions on Terahertz Science and Technology. 15 (2) (2025).

2. **Semenov A.D., Goltsman G.N., Sobolewski R.,** Hot-electron effect in superconductors and its applications for radiation sensors, Supercond. Sci. Technol. 15 (4) (2002) R1.

3. **Minakov V.I., Kogan M.Z.,** Production of thin-film microcircuits, Energia. Leningrad Branch. (1973).

4. **Matthias B.T., Geballe T.H., Compton V.B.,** Superconductivity, Rev. Mod. Phys. 35 (2) (1963) 414.

5. **Rogener H., Physik Z.,** Zur Supraleitung des Niobnitrids, Springer Nature. 132 (446) (1952) 446–467.

6. **Matthias B.T., Hulm J.K.,** A Search for New Superconducting Compounds, Phys. Rev. 87 (5) (1952) 799.

7. **Ziegler W.T., Young R.A.,** Studies of Compounds for Superconductivity, Phys. Rev. 90 (1) (1953) 115.

8. **Marquardt R., Cipo J., Schlichting F., et al.,** Correlation between properties of direct current magnetron sputtered thin niobium nitride films and plasma parameters, Thin Solid Films. 742 (2022) 139046.

9. **Treece R.E., Horwitz J.S., Claassen J.H., Chrisey D.B.,** Pulsed laser deposition of high-quality NbN thin films, Appl. Phys. Lett. 65 (22) (1994) 2860–2862.

10. **Hazra D., Tsavdaris N., Jebari S., et al.,** Superconducting properties of very high quality NbN thin films grown by high temperature chemical vapor deposition, Supercond. Sci. Technol. 29 (10) (2016) 105011.

11. **Kosutova T., Yao Y., Fernandes D., et al.,** Ion-assisted sputter-deposition of superconducting NbN thin films on silicon, Supercond. Sci. Technol. 38 (9) (2025) 095010.

12. **Sidorova M., Semenov A., Hьbers H.-W., et al.,** Electron energy relaxation in disordered superconducting NbN films, Mariia Sidorova, Phys. Rev. B. 102 (5) (2020) 054501.

13. Leybold. Technical documentation. Cathode sputtering Process. General information. UC 533/29.3.88

14. **Tinkham M.,** Introduction to superconductivity. McGraw-Hill, IncM. (1996).

THE AUTHORS

IVASHENTSEVA Irina V.
irinivas22@yandex.ru
ORCID: 0009-0000-7663-1149

KAUROVA Natalia S.
nkaurova@yandex.ru
ORCID: 0000-0002-3707-0649

VORONOV Boris M.
bmvoronov@mail.ru

GOLTSMAN Gregory N.
goltsman10@mail.ru

TRETYAKOV Ivan V.
phystret@gmail.com
ORCID: 0000-0002-8334-8752

Received 31.08.2025. Approved after reviewing 28.10.2025. Accepted 29.10.2025.