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Electron diffusivity measurements of VN superconducting single-photon detectors

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Abstract. The research of ultrathin vanadium nitride (VN) films as a promising candidate for superconducting single-photon detectors (SSPD) is presented. The electron diffusivity measurements are performed for such devices. Devices that were fabricated out from 9.9 nm films had diffusivity coefficient of 0.41 cm²/s and from 5.4 nm – 0.54 cm²/s. Obtained values are similar to other typical SSPD materials. The diffusivity that increases along with decreasing of the film thickness is expected to allow fabrication of the devices with improved characteristics. Fabricated VN SSPDs showed prominent single-photon response in the range 0.9-1.55 μ m.

1. Introduction

Since 2001 when Gol'tsman *et al.* [1] demonstrated the first superconducting single-photon detector, its performance has been improved greatly [2, 3, 4]. This SSPD improvement led to the wide spread of the devices and now they are involved in many applications [5, 6]. Partly this improvement was related to the appearance of new materials. When the first devices were fabricated using niobium nitride films, the modern ones could involve new for this sphere materials such as NbTiN, WSi, MoSi [7, 8, 9]. On the one hand, exploration of new materials allows to improve SSPD technology. For example, modern devices have detection efficiency of ~90% in wide spectrum range [3, 10], GHz counting rates [11], temporal resolution around tens picoseconds [2]. On the other hand, researches in this field allow further understanding of physical operation principles for such devices. Indeed, despite the fact that SSPDs are one of the most popular single-photon detection technologies, there is no comprehensive theory that explains its functioning principles [12]. Therefore, the search of the new SSPD materials remains an actual problem, which involves many scientific groups. With this work we begin a presentation of results of VN SSPDs fabrication and further research of its characteristics. Here we present the electron diffusivity (D) measurements of the VN devices. This parameter determines many features of SSPDs and therefore it remains one of the defining material parameters that shows the prospects of the superconducting materials for the implementation in the SSPDs. Specifically, as shown in [13], diffusivity plays a significant role in formation and subsequent dynamics of resistive region when a photon is absorbed by nanostripe. Hence, it defines the efficiency of the SSPD and its operation wavelengths range. It can be noted that diffusivity also has its contribution to the depairing current [14], which influence on the performance of the detectors.



2. Fabrication of VN structures, experimental methods and setup

2.1 VN structures and methods

The films for our work were deposited over silicon substrates with additional 250 nm thick thermally grown SiO₂ layer. The deposition was performed in AJA International Inc. sputtering system with typical background pressure $\sim 5 \cdot 10^{-8}$ Torr.

In order to study the effect of the deposition rate of VN films on its characteristics and in particular on the electron diffusion coefficient, we conducted several processes with different deposition rates of the films. The deposition rate was changed by variation of the discharge current and was controlled by atomic force microscopy measurements of the thickness of the deposited films. The thicknesses (h) of obtained films were set by sputtering time. We should note that along with decrease of the deposition rate, the transition temperature (T_c) decreased as well for the films with the same thickness. For the diffusivity measurements we selected two films 5.4 and 9.9 nm thick that had the same transition temperature, but were deposited with different rate (see table 1).

Table 1. VN films' parameters

Film #	h , nm	Deposition rate, nm/min	$R_s(300\text{ K})$, Ohm/ \square	T_c , K
1	9.9	2.2	111	5.5
2	5.4	3	202	5.5

To carry out measurements VN structures with standard topology for the SSPD [3] were made. The superconducting stripe was manufactured by electron-beam lithography in the form of meander had width of ~ 110 nm and filled up square area of $15 \times 15 \mu\text{m}^2$ with filling factor of ~ 0.6 . It should be noted that the T_c of SSPDs has significantly decreased compared to the values of the uniform films and amounted to 2.9 and 4.65 K for detectors based on 5.4 and 9.9 nm films respectively. This decrease could be related to the equal oxidization of the films, which resulted in more apparent T_c reduction in thinner film. It also could be caused by the local constrictions of the films on the scale comparable to the nanostripe width of the devices. These hypotheses are confirmed by the differences in the calculated and real values of the detectors' resistances, which are in better correspondence for the devices made of thicker film. The single-photon detection performance of such VN devices at different wavelengths could be found elsewhere [15].

The diffusivity was determined directly in SSPDs using the standard method [16] – measurements of dependence of resistance (R) on temperature in magnetic field and further estimations of the D as:

$$D = -\frac{4k_B}{\pi e} \left[\frac{dB}{dT_c} \right]^{-1} \quad (1),$$

where k_B is Boltzmann constant, e is the elementary charge and dB/dT_c is derivative of magnetic field with respect to superconducting transition temperature.

2.2 Experimental setup

For the measurements of $R(T)$ dependences in magnetic field the SSPDs were placed into special holder of cryogenic insert. The insert was put into double-walled cryogenic dipstick. The dipstick was placed into standard liquid helium storage Dewar. Liquid helium entered the inner volume of the dipstick through capillary. This construction allowed reaching minimal temperature of 1.6 K by pumping of helium vapors out from inner volume of dipstick. In addition, the detector holder had a heater for increasing temperature above 1.6 K and temperature sensors, which could operate in magnetic field. To create magnetic field up to 4 T a superconducting magnet coil was used. The samples were oriented normally to lines of magnetic field. We managed values of the magnetic field B

by regulating of superconducting magnet coil current. We biased a sample with direct current which was much smaller than critical current of the device (about $0.1 \mu\text{A}$ at 1.6 K and at $B=0 \text{ T}$). Such low value of bias current did not shift critical temperature of sample. We measured voltage values from the device by Lakeshore Temperature Monitor 218 and then we were calculating the R . The scheme of the experimental setup is presented at figure 1.

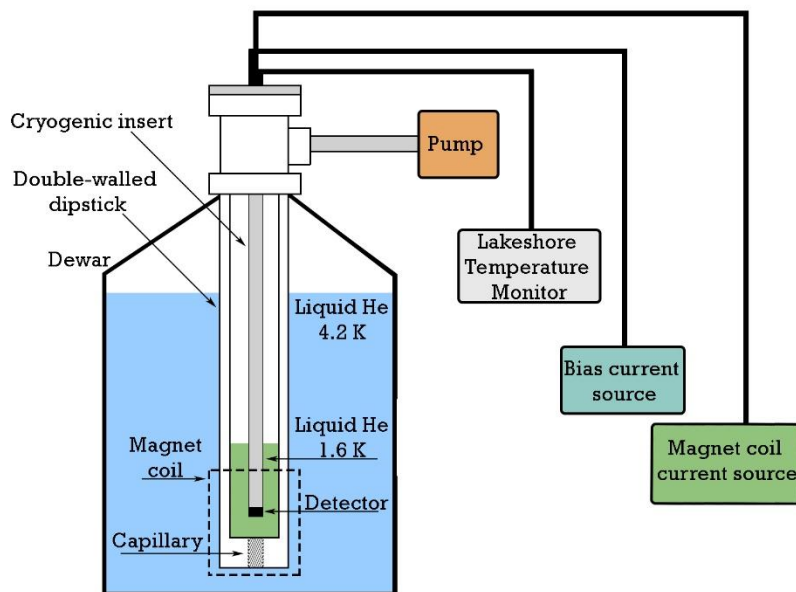


Figure 1. Scheme of the experimental setup for diffusivity measurements.

3. Experimental results

We carried out series of $R(T)$ measurements for samples with two different thicknesses at various values of magnetic field. Normalized to 1 at R_{20K} dependences of $R(T)$ of the SSPD sample with thickness of 5.4 nm is presented on figure 2a. As it was expected superconducting transition temperature, which was determined as $0.5 \cdot R_{20K}$, reduced along with increasing of magnetic field. The similar dependences of $R(T)$ in magnetic field were measured for VN SSPD with thickness of 9.9 nm . According to presented $R(T)$ measurements we plotted curves showing the variation of the T_c with respect to the magnetic field (see figure 2b). Calculated from these dependences values of dB/dT_c and the D (according to equation 1) for two samples are shown in table 2. Diffusivity values were $0.54 \text{ cm}^2/\text{s}$ for 5.4 nm VN SSPD and $0.41 \text{ cm}^2/\text{s}$ for 9.9 nm VN device

First of all, we note that the specified diffusion coefficient values have shown that the D of ultrathin superconducting VN SSPDs are close to values for other materials used for SSPD fabrication. It confirms that the VN films are potentially applicable for creation of SSPDs. It is noteworthy that the SSPD based on thicker superconducting VN film had lower diffusivity coefficient. Typically, as the thickness of the film increases the electron diffusion coefficient increases as well. That is usually associated with decreased influence of quantum corrections to the conductivity for thicker films. Let us note that the obtained $R(T)$ dependences in the magnetic field demonstrate qualitative behavior typical for films in which quantum corrections to conductivity have a noticeable effect. For both detectors increasing of the magnetic field did not led to the $R(T)$ curves shifting by parallel transfer towards decreasing of the transition temperature, but showed a significant increase in the width of the superconducting transition associated with the displacement of its lower temperature boundary. However, equal values of the transition temperatures of the unstructured films may indicate that the degree of disorder of the film with thickness of 9.9 nm is higher in comparison with the 5.4 nm thick film.

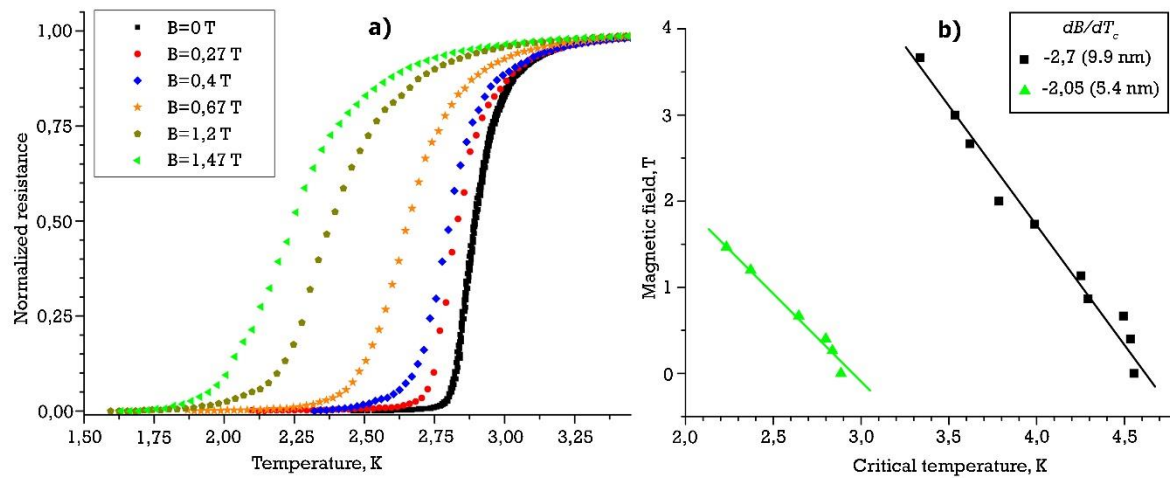


Figure 2. a) Dependences of R vs T for 5.4 nm sample. Critical temperature T_c was determined as temperature where $R=0.5 \cdot R_{20K}$; b) Dependences of B vs T_c for two samples with thicknesses of 5.4 nm and 9.9 nm.

Table 2. The values of dB/dT_c and the D for used samples

Detector #	h , nm	dB/dT_c	D , cm^2/s
1	9.9	-2.7	0.41
2	5.4	-2.05	0.54

Doubtless further researches of diffusivity variation at different thicknesses of VN films are necessary. At the same time present study demonstrated that: a) diffusivity of VN SSPD detectors are close to values for other materials used for SSPD fabrication; b) by changing the deposition rate of VN films it is possible to obtain thicker VN films with reduced diffusivity. Likewise, for thicker superconducting films (and/or films with a lower value of R_s) the radiation absorption coefficient increases. Moreover, with respect to the results presented in work [13], probability of appearance of voltage pulse in the superconducting stripe must increase after an absorbance of a photon with reduction of diffusivity. Authors [13] considered a fact based on both reduction of possibility of hot electron thermalization by diffusivity at initial stage of hot spot formation as well as decreasing of time of inelastic electron-electron interaction τ_{e-e} . It reduces both superconductor's volume in which energy of an absorbed photon is distributed and electrons thermalization time through their interaction.

In conclusion we want to note that two samples presented in this work had single-photon responses in the spectrum range 0.9-1.55 μm . Therefore, we experimentally demonstrated suitability of the VN films for the implementation as SSPD material. More detailed research of the influence of sputtering parameters on the VN films, quantum efficiency, typical jitter values and counting rates of VN SSPDs will be presented by the authors elsewhere soon.

4. Conclusion

We investigated the electron diffusivity for SSPDs based on vanadium nitride ultra-thin superconducting films. Obtained values of 0.41 cm^2/s for devices made out of 9.9 nm film and 0.54 cm^2/s for 5.4 nm film device show similar results with the other popular SSPD materials. Atypical decrease of the diffusivity along with increase of the VN film thickness we associate with the change of the film deposition rate, which influence on the superconductor's properties. Presented results allows us to consider vanadium nitride as a promising candidate for superconducting devices fabrication.

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