Conference Paper

Superconducting Single-photon Detectors Made of Ultra-thin VN Films

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Abstract

We optimized technology of thin VN films deposition in order to study VN-based superconducting single-photon detectors. Investigation of the main VN film parameters showed that this material has lower resistivity compared to commonly used NbN. Fabricated from obtained films devices showed 100% intrinsic detection efficiency at 900 nm, at the temperature of 1.7 K starting with the bias current of $0.7 \cdot I_c$.

Keywords: thin vanadium nitride films, superconducting single-photon detectors

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1. Introduction

Superconducting single-photon detectors (SSPD) combine near-unity quantum efficiency, ultra-high timing resolution and ultra-low dark count rates [1–3]. These devices are involved in many research areas ranging from singlet oxygen luminescence to development of single-photon sources [4–6]. However, a full description of detectors' operation principles is still under the study [7]. Despite the fact that SSPD operation was shown on a wide range of materials, the link between its performance and material properties is not clear yet. As it was shown before [8], the new materials are implemented for improving the detector's characteristics. After a decade of SSPD modifications it was suggested that commonly used polycrystalline niobium nitride (NbN) thin films could be replaced with amorphous tungsten silicide (WSi) films in order to obtain high detection efficiencies (DE) of the devices. Thanks to its lower superconductor gap (Δ) and low critical current density (j_c) larger hotspots were expected for WSi devices [8]. This fact allowed creating the detectors with higher yield and higher saturation of the DE than for devices fabricated of NbN films at that time. WSi SSPD set a new record of the system detection efficiency value of 93% at telecom range [9] and therefore WSi was considered as the main material for high-efficiency superconducting single-photon detectors fabrication.

In addition to DE some of the implementation areas require high timing characteristics of the detectors. The timing resolution (jitter) of the device signifies variation of the time that pulses from the detector take to arrive at the recording equipment. This parameter is crucial in such applications as quantum cryptography and life-time characterization of the quantum dots. The results [10] that recently showed the dependence of this parameter on critical current of the devices suggest that WSi SSPDs, that are usually characterized by low critical currents, lose their versatility and therefore further exploration of the new materials for SSPD is required.

To explore the possibility of creating universal SSPDs we present our study on vanadium nitride (VN) based devices. This material has been chosen due to its transition temperature (T_c) of ~9K, which is in between of the usual T_c values of WSi (~4.2 K) [2, 8] and NbN or NbTiN (13-15 K) films [11, 12]. We also assume that this material could help to understand how the detection mechanism of the device is evolving between the materials with similar structure and rather different T_c [13].

2. Fabrication Methods

In order to obtain high uniformity of the nanostrip of SSPD the superconductive film ideally should have homogeneous structure [14]. Film's thickness and nanostrip width establish quantum efficiency itself and its spectral dependency [15]. Therefore, to create an efficient device we started with the optimization of the deposition process of thin VN films. In most cases, thin and ultra-thin films for superconducting detectors are achieved by using of the magnetron spattering technique. Some deep investigations were performed to find the dependency of the films quality from deposition parameters on a wide range of materials and with that sputtering is the most promising technique when the new materials are studied in form of ultra-thin (<10 nm) films.

In the previous works, films of VN were obtained using the same method. For 500 nm-thick films best value of T_c was 8.9 K. As well as for other polycrystalline films, deposition was performed with relatively high substrate temperature of 600 °C [16]. In our case, we've focused on films with thicknesses less than 50 nm. Our films were deposited in a dedicated AJA International Inc. Orion-8 system in DC regime with a typical background pressure of $8{\cdot}10^{-8}$ Torr (~$1{\cdot}10^{-7}$ mbar). As the target we used V (99.9 % purity) disk with diameter of 50.8mm and thickness of 6.35 mm. We used Si and Al_2O_3 wafers in order to perform thickness, T_c and resistivity measurements of our films. For the optimization of film deposition process, we varied such parameters as substrate temperature, N_2 concentration and deposition rate. We should note that during our experiments we did not notice any pronounced dependency of films T_c from N_2 concentration (portion of the nitrogen in working gas mixture that also contains argon), which is crucial for instance during NbN deposition [13]. We believe that this fact could be related to adsorption properties of the material. Therefore, the most visible effect was observed for processes with the variable substrate temperatures and deposition rates, where the latter is defined by the value of the discharge current. From our experimental study we found that the optimal temperature for thin VN deposition was 500 °C and the discharge current – 700 mA. Fig. 1 presents the sheet resistance (R_s) at room temperature dependency of the T_c of VN films. T_c was defined as $0.5 \cdot R_{s20}$, where R_{s20} is the sheet resistance of the film at 20 K.

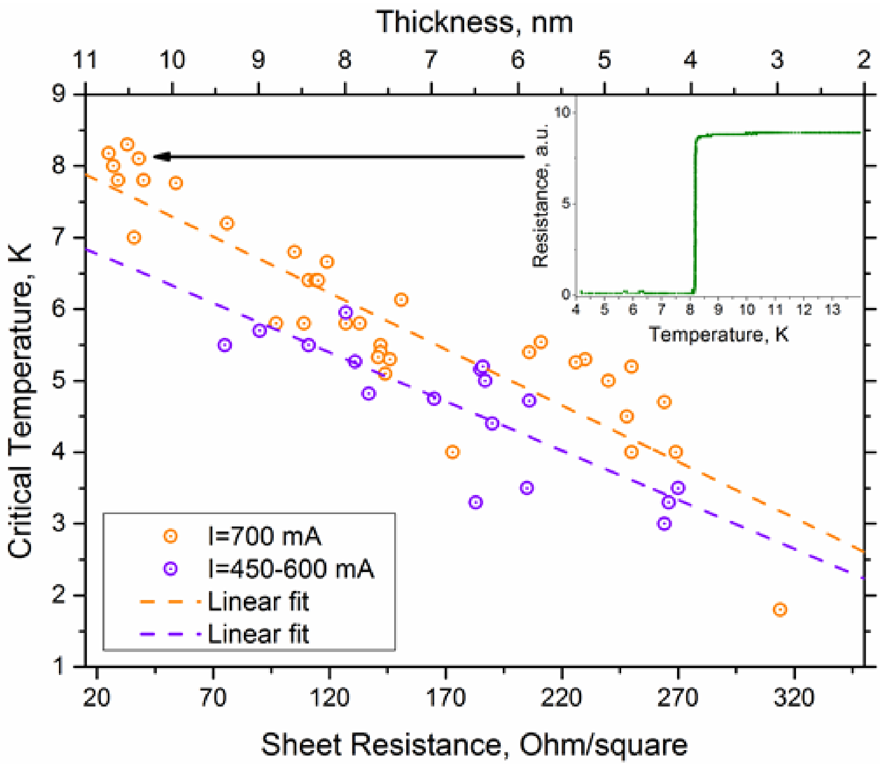

Figure 1: Dependency of the critical temperature of the film from sheet resistance. The results are divided into two arrays – 700 mA and 450-600 mA discharge current regimes. Dashed lines present linear fits of the data, presented in dotted circles. Inset to the graph shows the R(T) dependency for one of the data points from the graph.

As it follows from the presented graph the highest value of the critical temperature (8.3 K) was achieved for the film with R_s ~33 Ohm/square. For the highest R_s(314 Ohm/square), which is needed in terms of small thickness of the nanostrip, T_c was 1.8 K. As a first step towards implementation of VN films as SSPD material we fabricated the detectors out of the film with R_s=202 Ohm/square and T_c=5.5 K. The devices had active area of 15 by 15 μm^2, the filling factor was ∼0.5 and the width of the nanostrip was ∼115 nm. We used the same fabrication route as for our NbN SSPD detectors [17] with one slight modification – instead of PMMA A3 electron-beam resist we used ZEP 520 A7 because of its higher resistance to plasma-chemical etching process in SF_6, which proved to be less selective to VN with respect to the NbN films.

3. Experimental results and discussion

To perform a characterization of fabricated devices we aimed to measure one of the main for SSPD characteristics – intrinsic detection efficiency. This parameter allows calculating which amount of absorbed by the nanostrip photons led to the output voltage pulse. In case when the intrinsic DE is equal to 1 the dependency has a clear plateau region and the DE of the device does not change with the current. As it was shown before [18], intrinsic DE along with the absorbance of the structure are two most important parameters for achieving high DE. As the absorbance could be easily improved for desired wavelength range with an optical cavity, we decided to measure intrinsic DE on the first place, and thus give an overall estimate of possible capabilities of the VN SSPD.

As the main purpose of this article was an exploration of the main parameters of the VN films applicably to SSPD fabrication, we didn't pursue any chance of measuring maximal system detection efficiencies for such devices. Although, we intend to do this study and publish the results elsewhere soon. To estimate saturation of the intrinsic DE of the devices, we used a free-space coupling scheme, which consisted of the detector holder aligned with the output from single-mode fiber radiation. The gap between the detector and the tip of the fiber was ∼30 mm. The value of the optical power was picked to provide ∼10^5 counts from the device. The scheme was placed inside the cryogenic dipstick, that allowed us achieving minimal temperature of 1.7 K. The bias current dependency of the counting rate was investigated for three wavelengths: 900, 1310 and 1550 nm. Typical values of the bias current dependency of the counting rate for devices made out from selected film are presented on fig. 2 a). In order to estimate the values of the intrinsic DE of the presented device we've found the derivatives $\frac{dCPS}{dI_b}(I_b)$ for each curve (fig. 2 b) and followed with calculations similar to those we've presented earlier [17]. Obtained values of intrinsic DE are presented on fig. 3 c)

Graphs clearly show that the intrinsic quantum efficiency saturates at 900 nm and at 1310 nm the dependency ends at near-unity value of 97 %. This results show closer similarities of VN devices with NbN-based SSPDs than with WSi-based detectors. This

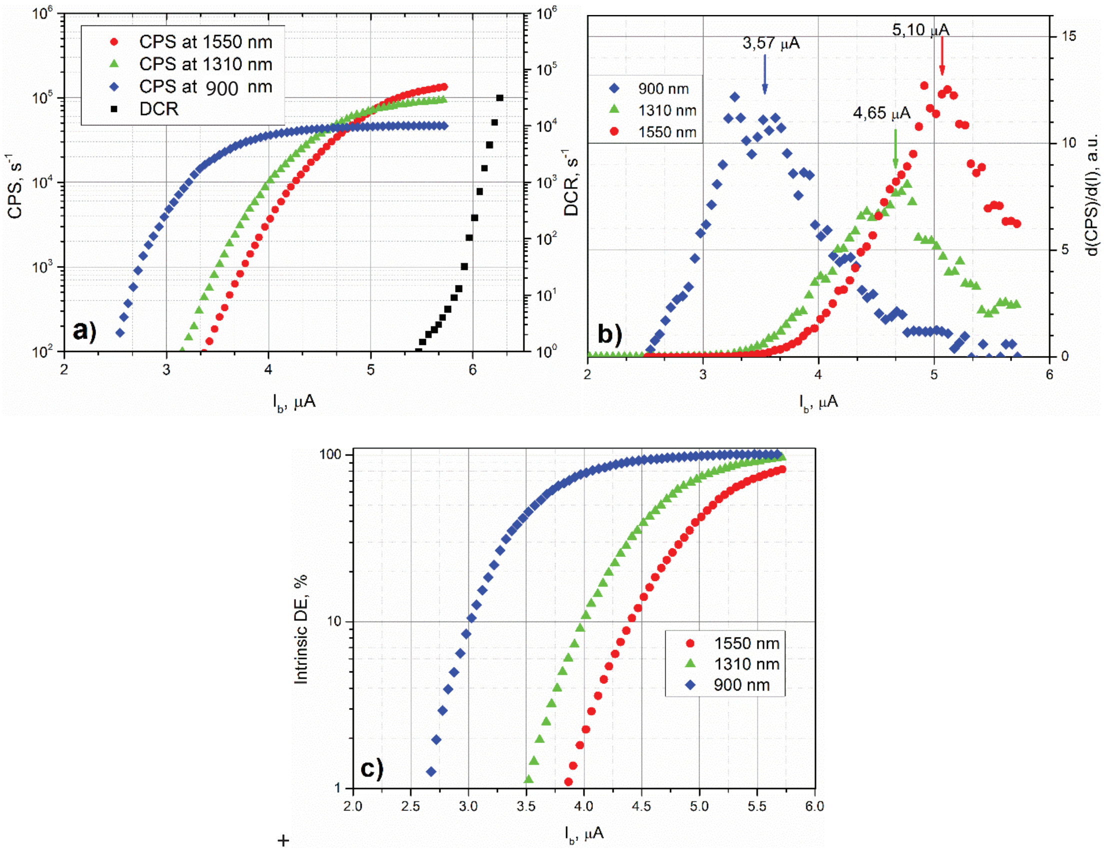

Figure 2: Bias current dependencies of the: a) photo counting and dark counting rates, b) derivatives of the counting rate and c) intrinsic DE of the VN SSPD at 900, 1310 and 1550 nm from the bias current. Section b) also presents values of the bias currents (marked with the arrows) at which 50% of the intrinsic DE is achieved.

could be because VN films are expected to have similar with NbN polycrystalline structure. Although VN has advantage over NbN films in its lover resistivity which results in lower sheet resistance per nanometer of its thickness. We believe that this could have its upsides. For instance, this could lead to the better coupling with the impedance of free space. We also assume that this material will lead to clarification and better understanding of the detecting mechanism of the device and as a result will help to improve bandwidth of the device, its timing resolution, counting rate, or to develop the devices combining all of the aforementioned parameters.

4. Conclusion

We introduced superconducting single-photon detectors made of ultra-thin vanadium nitride films. Obtained values of T_c of our thin films are with the good agreement with previously reported values and first ever presented ultra-thin (~5 nm) VN films had T_c=5.5 K, which allows creating photon counting solutions based on closed-cycle refrigerators. We discovered that VN SSPDs show saturation of the dependency of the photo counts from bias current at 900 nm and close-to-saturation dependency at 1310 nm. Thus, we proved that VN is a suitable material for developing high-performance SSPDs.

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