Fabrication and Properties of an Ultrafast NbN Hot-Electron Single-Photon Detector

G. Gol’tsman, O. Okunev, G. Chulkova, A. Lipatov, A. Dzardanov, K. Smirnov, A. Semenov, B. Voronov, C. Williams, and Roman Sobolewski

Abstract—A new type of ultra-high-speed single-photon counter for visible and near-infrared wavebands based on an ultrathin NbN hot-electron photodetector (HEP) has been developed. The detector consists of a very narrow superconducting stripe, biased close to its critical current. An incoming photon absorbed by the stripe produces a resistive hotspot and causes an increase in the film’s supercurrent density above the critical value, leading to temporary formation of a resistive barrier across the device and an easily measurable voltage pulse. Our NbN HEP is an ultrafast (estimated response time is 30 ps; registered time, due to apparatus limitations, is 150 ps), frequency unselective device with very large intrinsic gain and negligible dark counts. We have observed sequences of output pulses, interpreted as single-photon events for very weak laser beams with wavelengths ranging from 0.5 μm to 2.1 μm and the signal-to-noise ratio of about 30 dB.

Index Terms — ultrafast single-quantum detector, ultrathin superconductor film, infrared photon counter, superconducting optoelectronics.

I. INTRODUCTION

Currently, visible photon counting is a commonplace for advanced optical imaging and spectroscopy. Several types of devices, including photomultiplier tubes [1], quantum semiconductor avalanche photodiodes [2], and superconducting tunnel junctions [3], have been successfully implemented. In general, such detectors work by a cascade mechanism: an incident single photon is absorbed, releasing an electron, which then instigates a multiplication process leading to a measurable electron current pulse. Unfortunately, vacuum photomultipliers are slow and bulky and have an extremely low quantum efficiency for longer-wavelength photons. The major drawback of the most popular and most successful silicon photodiodes is the wavelength sensitivity limited to below 1 μm, restricted by the Si bandgap. In addition, the single-photon avalanche photodiodes exhibit low detection rates, due to complicated Geiger-mode readout schemes.

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G. N. Gol’tsman (tel +7(095) 246-1202 e-mail: goltsman00@mail.ru), O. Okunev, G. Chulkova, A. Lipatov, A. Dzardanov, K. Smirnov, A. Semenov, B. Voronov are with Moscow State Pedagogical University, Moscow 119435, Russia.

R. Sobolewski, C. Williams, G. N. Gol’tsman, A. Lipatov are with University of Rochester, Rochester, NY 14627, USA.

R. Sobolewski is also with the Institute of Physics, Polish Academy of Sciences, PL-02096 Warszawa, Poland.

The current most-pressing need is to develop practical infrared single-photon detectors, operational at either 1.3 μm or 1.55 μm, for novel quantum communication and quantum computation systems. The problem is that infrared photons carry significantly less energy than those of visible light do, so it is difficult to engineer in this case an efficient electron cascade. Avalanche photodiodes based on narrow-gap semiconducting materials exhibit unacceptably large dark counts, while recently proposed single-electron transistors [4] are slow and require millikelvin temperatures and tesla-level magnetic fields.

We present a simple-to-manufacture and easy-to-operate, NbN hot-electron photodetector with picosecond response time, high intrinsic quantum efficiency, the capability to detect single photons from ultraviolet to infrared wavelength range, and negligible dark counts. Our photodetector is a conversion of a well-known unselective superconducting hot-electron bolometer [5] into optical and infrared wavebands [6]. The detector consists of an ultrathin, submicron-width NbN stripe, maintained at 4.2 K and current-biased close to the critical value. The detection mechanism is based on supercurrent-assisted, temporary formation of a resistive barrier across the stripe due to photon-induced hotspot generation. Practical implementation of our device should lead to a revolutionary progress in areas ranging from ultrafast free-space satellite communication [7], through quantum computation [8] and quantum cryptography [9], to semiconductor integrated circuit testing [10].

II. DEVICE FABRICATION

NbN films were sputtered onto sapphire substrates by reactive magnetron sputtering in an argon–nitrogen gas mixture. Using an optimized sputtering technique, our NbN samples exhibited a superconducting transition temperature of $T_c = 10.5$ K for 60-Å-thick films and 11 K for 100-Å-thick films, respectively. The superconducting transition width was equal to $\Delta T_c = 0.3$ K. A more detailed description of the NbN film deposition can be found in [11].

The fabrication process of our HEP’s included several deposition and patterning manufacturing stages, resulting in the devices shown in Figs. 1 and 2. After the NbN film sputtering, TiAu alignment marks for the future lithography steps and interior TiAu contacts with dimensions 5 μm by 16 μm were formed using the e-beam lithography and e-beam evaporation. Exterior contact pads for wire bonding of the entire structure were fabricated by a vacuum evaporation of 2000 Å of Au.
The final, desired geometry of the NbN microbridge was achieved by ion milling the NbN film through a 200-Å-thick Ti mask placed inside the gap between the inner TiAu contacts. For a straight bridge (Fig. 1) this mask was a single 0.2-μm-wide stripe, while in the case shown in Fig. 2, it was a 0.2-μm-wide meander-type line covering the 4-μm × 4-μm area. After ion milling of the NbN detector, the remaining Ti layer was chemically removed.

After the fabrication, each device was very carefully inspected using both the AFM (Fig. 1) and SEM (Fig. 2) microscopes for the bridge uniformity. In addition, we selected only the samples in which room-temperature resistance was almost equal to the value calculated according to the structure dimensions and measured sheet resistance of the unpatterned NbN film. This procedure assured homogeneity and quality of the superconductor microbridge, with minimal, if any, variations along its width.

III. EXPERIMENTAL SETUP

Our experimental setup and the device connections inside an optical liquid-helium cryostat are shown schematically in Fig. 3. The NbN HEP was mounted on a cold plate and maintained at \( T = 4.2 \) K. We used two cold glass filters to prevent the room-temperature thermal radiation from falling onto the device. The device was mounted on a rigid coplanar transmission line and connected with a cold bias-tee through a stainless steel semirigid coaxial cable. The ac output of the bias-tee was connected to a cryogenic low-noise amplifier. Outside the dewar, the signal passed through a second power amplifier, connected to a single-shot oscilloscope and pulse counter (not shown). The oscilloscope was either externally triggered by laser pulses or self-triggered. Our experiments were performed using 20-ps-wide, \(-3\)-pJ-energy, 0.85-μm-wavelength pulses generated by a GaAs laser with the repetition rate ranging from 1 Hz to 100 kHz, or 100-fs-wide optical pulses from a modelocked Ti:sapphire laser. In this latter case, the wavelength could be varied quasi-continuously from 0.5 μm to 2.1 μm, while the repetition rate was either 76 MHz or 1 kHz. The intensity of the laser pulses was attenuated using banks of neutral density filters. The diameter of the beam incident on the device was always at least 200 μm, assuring stable (no “beam walking”) and uniform illumination throughout the experimental session.

IV. EXPERIMENTAL RESULTS

An experimental \( I-V \) curve for meander-type HEP, measured using a two-point method, is presented in Fig. 4. The curve is
typical for a long superconducting microbridge and shows that depending on the biasing condition (either purely current-bias or voltage-bias) our device switches from the superconducting, zero-resistance state to the switched, resistive state. This particular device exhibits \( I_c = 80 \, \mu A \) and the switched-state resistance \( R = 46 \, k\Omega \). The dashed line between points A and B in Fig. 4 represents the switching condition, when the device is connected to a 50-\( \Omega \) microwave transmission line. For a HEP biased close but below \( I_c \) (point A in Fig. 4), the photon absorption leads to a temporary switch along the dashed line to the metastable resistive point B. As a result, we observe a voltage pulse, whose amplitude corresponds to the point B voltage value, while the duration depends on the dynamics of formation and destruction of the resistive state induced by the photon absorption (see Sec. VI).

The time-resolved HEP response to a 0.85-\( \mu m \)-wavelength, 20-ps-wide optical pulse, captured using a single-shot, 6-GHz-bandwidth digitizing oscilloscope is shown in Fig. 5. We see that the width of the photoresponse is equal to \( \sim 150 \) ps and, based on our earlier electro-optic time-domain measurements [12], is limited by the upper cutoff frequency of our amplifier chain. The signal-to-noise ratio is \( \sim 30 \) dB. Qualitatively, the same response pulses, with the same \( \sim 150 \)-ps pulse widths and essentially the same amplitudes, were obtained at all the studied photon energies, independently of the incident optical pulse width, or the laser repetition rate. In addition, the response amplitude did not depend on the laser beam intensity.

V. DEVICE OPERATION

Fig. 5 shows the quantum nature of our detector, but it does not indisputably show that our HEP is indeed a single-photon counter. To demonstrate the latter, we measured the statistical dependence of the number of recorded photoresponse pulses on the number of input quanta per pulse per unit area. We progressively attenuated the intensity of laser pulses, using calibrated neutral density filters, and observed the decreasing number of response pulses. The experimental data allowed us to calculate the probability of recording a detector output for a given photon flux input, which is shown in Fig. 6 for two different device types. Curves a and b correspond to a simple, 1-\( \mu m \)-long microbridge, biased at the current value \( I_b = 0.92 \, I_c \) and \( I_b = 0.8 \, I_c \), respectively. Curves c and d are taken for a meander-type device, under the same conditions as curves a and b, respectively.

We note that while for high photon fluxes both HEP’s are saturated, showing 100% efficiency in photon counting, the significant decrease in the number of photons \( m \) per pulse results in lower probability of recording a photon. Based on simple statistics, one can expect that for very weak photon fluxes, the probability of detecting one photon should be proportional to \( m \), while the probability of simultaneously detecting two photons depends as \( m^2 \), the three-photon counting should obey the \( m^3 \) law, and so on. Indeed, we observe the linear decrease of response pulse probability versus number of quanta per unit area for curves a and c. At the same time, curve b follows a clear \( m^2 \) dependence, indicating a two-photon detection. Thus, the 0.92 ratio of \( I_{bias}/I_c \) is required for the single-photon operation. In general, photon detection probability versus \( I_{bias} \) was an exponentially decreasing function, indicating that the \( I_{bias} \) redistribution from the uniform state to the side-walk-restricted flow, rather than the hotspot formation, is the dominant factor of the device response.

The other characteristic parameter of a single-photon detector is its quantum efficiency, defined as the ratio of the number of response pulses to the number of incident photons per area for the device in the linear regime (Fig. 6, curves a and c). The quantum efficiency for our microbridge (curve a) may be estimated as 20%. The meander-type HEP’s have been designed to increase both the active area of the device and its total quantum efficiency. As was expected, the absolute quantum efficiency for the meander device is significantly higher than that
for the 1-\mu m device, but the detector’s active area was increased by the factor of 80, while the quantum efficiency increased only 20 times. Thus, the intrinsic quantum efficiency for the meander HEP is equal to approximately 5%. The reason for the observed decrease in the meander device performance might be associated with the limited uniformity of the device width over the very long length of the meander stripe. We also note that in the case of the lower bias current (Fig. 6, curve b), the meander device exhibits a nonlinear probability dependence on the photon flux.

VI. DISCUSSION AND CONCLUSIONS

The physical mechanism of operation of our NbN HEP optical single-photon counter is based on supercurrent-assisted, temporary formation of a resistive barrier across the stripe due to photon-induced hotspot generation and is presented in [13]. A single optical photon is absorbed by an ultrathin, very narrow stripe of a NbN superconductor, maintained at a temperature well below $T_c$ and biased with $I_{bias}$ close to the device $I_c$. The photon absorption generates a very high number of excited, hot electrons, leading to local suppression of superconductivity and hotspot formation. The resistive hotspot pushes the supercurrent out of the center of the stripe, causing it to exceed the critical value for the remaining superconducting part, and leading to the formation of a resistive barrier across the entire width of the device. For the current-biased sample, this resistance results in a large, easily measurable voltage signal. The subsequent hot-electron out-diffusion and cooling, leads to hotspot healing and the collapse of the resistive barrier. The superconductivity is restored in approximately 30 ps [12], and the detector is ready to register another photon.

The main difference between our detection mechanism and the earlier proposed hot-sot mechanism [14] is that our response is due to a collaborative effect of the bias current and the radiation quantum, leading to a large voltage output signal. To a certain extent the magnitude of the voltage pulse does not depend on the quantum energy, although the pulse shape does, providing the basis for the spectral sensitivity of the device. The rate of photon counting, which can be defined as the inverse of the total photon response time, is also a direct function of the operating parameters and can be as fast as tens of gigahertz. Finally, as we have demonstrated, depending on the device’s operating parameters, our HEP can act as a single-photon, two-photon, or even three-photon quantum counter.

Our device should be able to find immediate applications primarily in the area of ultrafast near-infrared photon counting, where there are currently no competing technologies. The 1.3-\mu m to 1.55-\mu m wavelength range is important for optical communication. Already identified applications of our superconducting HEP’s range from sensing ultrawake electroluminescence from submicron complementary metal-oxide-semiconductor VLSI circuits, to quantum cryptography and quantum computation.

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