Multi-photon Response of Photon-number-resolving Superconducting Single Photon Detector

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***Abstract*—A new photon-number-resolving superconducting single photon detector is fabricated and tested. To integrate the resistors connected to the nanowire, we used one step of electron-beam lithography and four subsequent photolithography steps. A micro cavity was introduced to the structure in order to gain relatively high quantum efficiency. The device fabricated could resolve 6 photons.**

I. Introduction

Superconducting nanowire single photon detectors (SNSPDs)[1] have been characterized to be with high sensitivity, short dead time, and low time jitter. Photon number resolving detectors using SNSPD array[2] with the capability of photon-positioning has very promising application prospect, especially in fluorescence imaging and quantum communication[3]. To achieve imaging using SNSPD in the near-infrared range, we need to build up a 2-D array of SNSPDs and its auxiliary readout system. However, fabrication and wiring became an obstacle when the readout circuits of the array were introduced. Hence, how to reduce the number of readout circuits needed is the key to construction of the SNSPD array imaging system. The results previously reported on a 12-pixel SND (series nanowire detector) [4] have shown clear evidence of detection of n-photons with n ranging from 1 to 12.

However, the fabrication method proposed in [4] has several shortcomings because of its four electron-beam lithography steps. For a batch of devices, the alignment of electron-beam lithography is difficult and time-wasting with high cost; the electron-beam lithography itself will affect the lattice structure of the NbN film which is the key to the overall system quantum efficiency. Based on that, we took one electron-beam step and four photolithography steps to accomplish the device. As depicted in figure 1, the device consists of 6 elements of detectors.

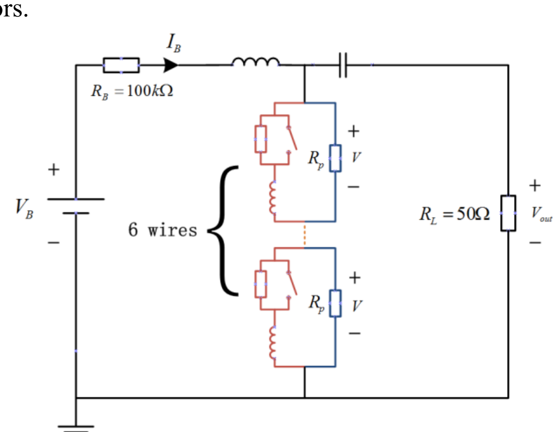

Fig. 1. The schematic diagram of the experimental circuit.

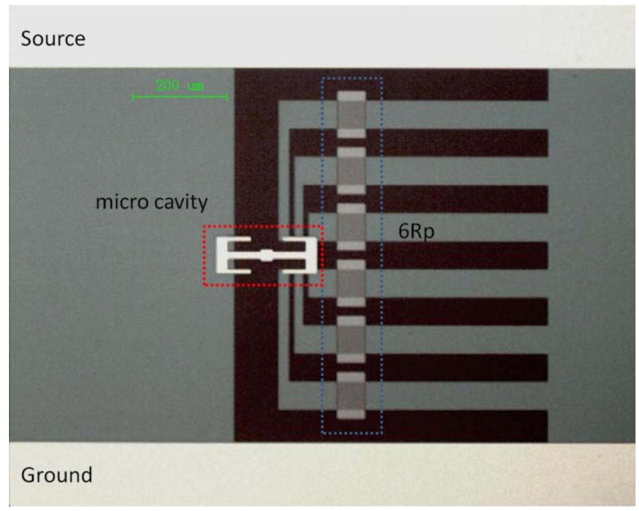

Fig. 2. Optical micrograph of the device. The NbN meander is under the central of the cavity with an area of 10μm × 10μm.

II. Results

We fabricated the structure on Si substrate with a 250-nm-thick thermally oxidized SiO_2 layer. The structure consists of 6 NbN nanowires on the top of which an optical resonator is introduced so as to raise up the whole system efficiency. After the NbN film was grown on SiO_2 layer by reactive DC-magnetron sputtering, one step of electron-beam lithography and four steps of photolithography were taken to fabricate the 6-SND structure. First, the NbN meander and alignment markers was patterned by reactive ion etching using polymethylmethacrylate (PMMA) as etching mask. The meander was resided in a 10μm × 10μm area with a filling factor of 50% and its width was about 100nm. Second, the electrical contact pads [Ti(10nm)/Au(100nm)] were fabricated by reactive DC-magnetron sputtering and lift-off using positive photoresist(AZ1500) as stencil mask. Third, with positive photoresist(AZ1500) as etching mask, we removed the unnecessary part of NbN film so as to pattern the pad for the resistors connected to nanowire by reactive ion etching. Fourth, the 6 resistors were grown through reactive DC-magnetron sputtering and lift-off using positive photoresist(AZ1500) as stencil mask. In the last step, to integrate an optical resonant cavity, we used plasma enhanced chemical vapor deposition to deposit a 240 nm-thick SiO2 on NbN meander, after which, a 100 nm-thick Au layer was sputtered on the SiO2 layer by reactive DC-magnetron sputtering. Positive photoresist(AZ1500) was used as stencil mask for lift-off. Fig.2 shows the optical micrograph of the device. The NbN meander is under the central of the cavity with an area of 10μm × 10μm.

A batch of devices were fabricated and tested at the temperature of 2.5 K in a Gifford-McMahon cryocooler and the schematic is shown in figure 1. The NbN film was 6.5 nm thick and the critical temperature was 7.1K. The device was biased by a voltage source V_B and a resistor R_B through the DC arm of a bias-T at room temperature. The response signal of the device was collected through the RF arm of the bias-T, then amplified by a low-noise amplifier. The I-V characterization of the device is depicted in Fig.3, as well as its linear fit. The I_c of the device is about 10.6 μA, and the device became a resistor as I_B exceeded I_c, the resistance of which was ~ 660 Ω. Since the normal NbN meander has much larger resistance than R_p fabricated with 50nm thick Ti, the fitted value R_{fit} could be considered as $6 \times R_p$, namely $R_p = 110\Omega$.

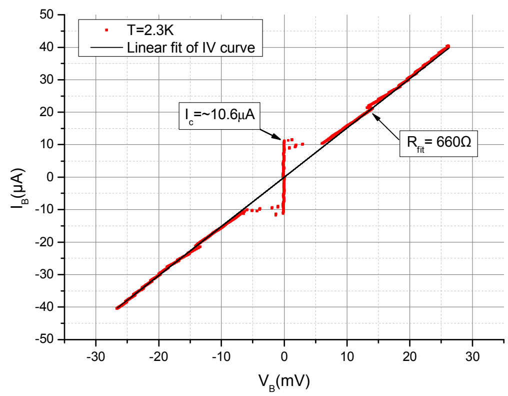

Fig. 3. IV characterization of the 6-SND at T=2.3K. The Ic of the device was 10.6 μA. The linear fit of the IV curve (solid black line) shows that the value of the six resistor is about 660Ω, making the single one 110Ω.

A low-noise amplifier with gain 50dB and bandwidth 1GHz was used to amplify the photon responses of the device. The wavelength of the laser was 1521 nm and the laser was triggered at a repetition rate of 2 MHz . The output pulses were observed by a 50 GHz sampling oscilloscope which is synchronized with the trigger signal of the laser. Fig 4 shows two different screen shot captures of different input light power, 20pW(~76 photons per pulse) and 10pW(~38 photons per pulse) respectively. Different colors indicate different times of occurrence. The phenomena were obvious and different pulse heights meant different number of elements of the device triggered by incident photons, from 1 to 6 respectively.

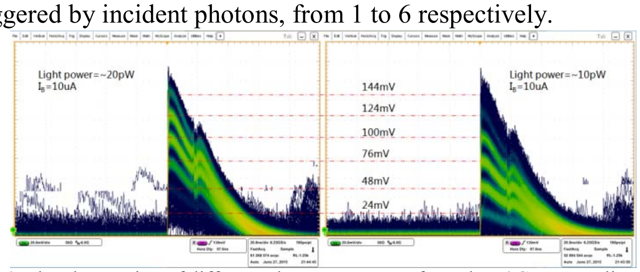

Fig. 4. The observation of different photon responses from the 50GHz sampling oscilloscope. The color indicates the density of the pulses.

As marked in Fig.4, the 6 categories of pulse levels are 144mV, 124mV, 100mV, 76mV, 48mV and 24mV. To study the photon number resolving functionality, we took the middle of the category voltages as the trigger level so that the counter would only record the '≥n-photon' pulses. we measured the relation between the count rates and light power of different category of pulses and showed the results in Fig.5. According to [5], when the light power is low, the count rate would be approximately proportional to $(\eta\mu)^n$ where η is the device quantum efficiency and μ is the average photon number per light pulse incident on the active area of the device. In Fig.5, we could see the slope of the curves agrees with the value of 1,2,3,4,5 and 6 for the corresponding photon regimes.

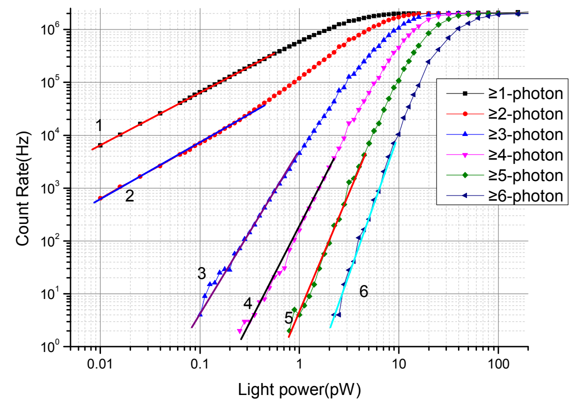

Fig. 5. Different count rates at different counting level and different input light power. The slope of the curve at low light power fits $(\eta\mu)^n$ well.

III. Summary

In this article, we presented a new method to fabricate a 6-SND photon number resolving detector. The new method is relatively time-saving, easy to realize and has little influence on the NbN film. We also analyzed the performance of the PNR devices with 6-SND fabricated in the new method. The overall system efficiency at low light power could exceed 20%. The further result indicates that the device has the functionality of resolving up to 6 photons and complies with the previous reports well.

References

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