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Photon-detections via probing the switching current shifts of Josephson junctions

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ABSTRACT

Phenomenally, Cooper pairs can be broken up by external energy and thus the Cooper-pair density in the superconducting electrodes of a Josephson junction (JJ) under radiation can be lowered accordingly. Therefore, by probing the shift of the switching current through the junction, the radiation power absorbed by the superconductors can be detected. Here, we experimentally demonstrate weak optical detections in two types of JJs: $Al/AlO_x/Al$ junction (Al-J) and $Nb/AlO_x/Nb$ junction (Nb-J), with the superconducting transition temperatures $T_c \approx 1.2$ K and 6.8 K respectively. The photon-induced switching current shifts are measured at ultra-low temperature ($T \approx 16$ mK) in order to significantly suppress thermal noises. It is observed that the Al-J has a higher sensitivity than the Nb-J, which is expected since Al has a smaller superconducting gap energy than Nb. The minimum detectable optical powers (at 1550 nm) with the present Al-J and Nb-J are measured as 8 pW and 2 nW respectively, and the noise equivalent power (NEP) are estimated to be 7×10^{-11} W/$\sqrt{\text{Hz}}$ (for Nb-J) and 3×10^{-12} W/$\sqrt{\text{Hz}}$ (for Al-J). We also find that the observed switching current responses are dominated by the photon-induced thermal effects. Several methods are proposed to further improve the device sensitivity, so that the JJ based devices can be applicable in photon detections.

1. Introduction

Superconducting photon detectors at near-infrared wavelengths, with photon-number resolving power, have shown great promises in quantum optics and quantum information applications. The superconducting detectors now extensively studied mainly include: the superconducting nanowire single-photon detectors (SNSPDs) [1–4], the transition-edge sensors (TESs) [5,6], the superconducting tunnel junctions (STJs) [7,8] and the microwave kinetic inductance detectors (MKIDs) [9–11]. Here we propose and demonstrate an alternative approach to achieve photon detections, by measuring the changes of the switching current of a Josephson junction (JJ) under radiation.

If a photon with sufficient energy $h\nu$ ($h\nu > 2\Delta$ with Δ being the superconducting gap) is absorbed by the superconductor, the number of $\eta h\nu/2\Delta$ Cooper-pairs can be broken apart, where η is the absorption efficiency. This implies that, when a photon is incident on the junction area, excess quasiparticles will be excited and the Cooper-pair density on the irradiated superconductors will decrease. This will lead to an abrupt reduction in its critical current I_c (the maximum magnitude of the supercurrent), based on the density–current relation: $I_c \propto \sqrt{\rho_1\rho_2}$, where ρ_1 and ρ_2 are the Cooper-pair densities in the two superconducting electrodes [12]. On the other hand, phonons in the substrate around the radiation center may be excited and thus cause a local temperature increase. The thermal effects can also reduce I_c based on the temperature-dependence of the critical current [13]: $I_c \propto \Delta(T)\tanh[\Delta(T)/2k_BT]$, where T is the bath temperature. Therefore, both pure pair-breaking effects and thermal effects can lead to a reduction in the critical current, which provides a feasible way to detect the incident photons via measuring the radiation-induced changes in the critical current of a Josephon junction.

Note that the *ac* Josephson effect was utilized to detect the microwave and far-infrared radiation several years ago [14]. Later, the superconducting gap voltage shifts due to visible and infrared radiation were measured in $Nb/AlO_x/Nb$ junctions [15] and junction arrays [16] at temperatures around 4.2 K.

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Particularly, the junctions immersed in superfluid helium were observed to have lower optical responsivity compared to those in vacuum. This is because the heating effect is suppressed in liquid helium and thus the optical responses of the devices are entirely due to the pair-breaking mechanism. Other experiments [17–20] had also observed similar optical responses of the gap voltage in Nb junctions due to both pure pair-breaking and thermal effects.

However, the previous experiments were all done with Nb junctions. In our experiments, we study the optical responses of both Al/AlO$_x$/Al junction (Al-J) and Nb/AlO$_x$/Nb junctions (Nb-J). We find that the Al-J has a higher optical responsivity than Nb-J. This is a reasonable observation since Al has a smaller superconducting gap energy, and thus a certain radiation energy can break more Cooper pairs on Al electrode. Besides, in all of the previous experiments the Josephson junctions were biased at constant currents and the gap voltage shifts were measured as the optical responses. Alternatively, we sweep the bias current through the junction and measure the switching current responses to a continuous radiation at 1550 nm. This detection approach is relatively simple and has not been reported before, as far as we know. Moreover, the previous experiments were all done at temperatures around 1–4.2 K while our system works in an ultra-low temperature regime, i.e., the bath temperature $T \approx 16$ mK. Thermal noises in the circuit are minimized at such low temperatures so that our devices are expected to have lower noise levels.

2. Device fabrications and measurement scheme

Our Al-J devices were fabricated by using electron beam double-angle evaporation technique, and the Nb-J devices were fabricated by using the magnetron sputterings and ion etchings. The junction areas of both devices are designed to be $\sim 6\ \mu m^2$ and the top electrodes exposed for illumination are ~100 nm thick. The measured superconducting transition temperatures (T_c) of Al-J and Nb-J are 1.2 K and 6.8 K respectively. The chips are cut to the size of 2 mm × 2 mm, with Si-substrates of 0.5 mm thick. Both junctions are slightly damped [21], thus showing hysteretic IV curves with small retrapping currents and sharp onsets of a finite voltage at certain bias currents (i.e., the switching currents).

The schematics of our measurement setup are shown in Fig. 1. The measured junctions are placed in an aluminum sample cell, mounted at the mixing chamber in a dilution refrigerator. Four-probe technique is used to measure the current–voltage characteristics of the devices. The waveform generator can output a voltage signal, which is applied to a resistor to generate a bias current through the junction. The voltage response is amplified by a battery-powered pre-amplifier and then fed into a timer. All electrical leads, connecting the sample cell to room temperature electronics, are filtered by low-pass RC filters (with a cutoff frequency ~10 kHz) and copper powder microwave filters. A laser source provides a steady radiation with the wavelength of 1550 nm. A single-mode optical fiber with controllable attenuation is used to illuminate the device. The bottom end of the fiber is carefully aligned and fixed, so that the laser beam can focus on the top superconducting electrodes of the junction. The fiber end is estimated to be about 200 μm vertically away from the chip surface and the irradiated area is about 80 μm in diameter. Therefore, the junction area is completely covered by the incident light beam.

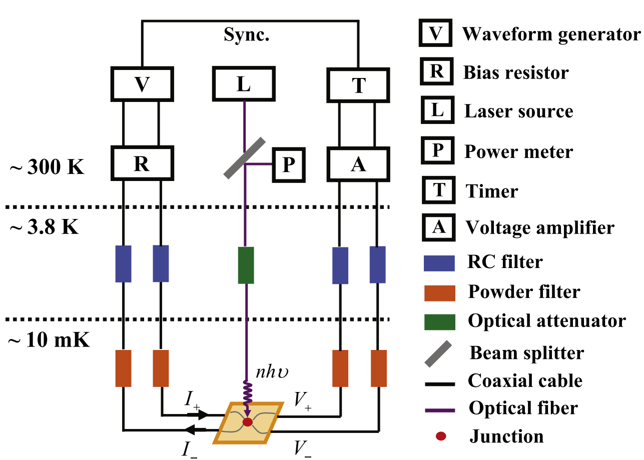

Fig. 1. Schematics of the measurement setup. Four-probe method is used to measure the junction current–voltage characteristics. The tested junctions are placed in a sample cell at ~16 mK and irradiated by 1550 nm laser beam with attenuation.

Due to the presence of thermal fluctuations and quantum tunneling, the junction switches from the zero-voltage state to the finite voltage state at a bias current I_s, which is practically smaller than its theoretical critical current I_c. Since this switching is a deterministic random process, the switching current I_s shows a Lorentzian distribution [22,23], which can be mainly characterized by the distribution width σ_s and mean value $\langle I_s \rangle$. In our experiment the switching current distribution $P(I_s)$ is measured by using the time-of-flight method [24]. For each switching event, the bias current is ramped linearly from a value below zero up to a value slightly higher than the critical current I_c. When the junction switches from the zero-voltage state to the finite-voltage state, the timer will be triggered to record the switching time and the corresponding switching current I_s can be calculated from the current ramping rate. The bias current is then reduced to below zero, resetting the junction to the zero-voltage state. The repetition frequency is 71.3 Hz and the measurement cycle is repeated 2×10^3 times to obtain an ensemble of I_s, from which the distribution of switching current $P(I_s)$ can be obtained.

3. Measurement results

Fig. 2 plots the measured switching current distributions, i.e., the switching probability $P(I_s)$ as a function of the switching

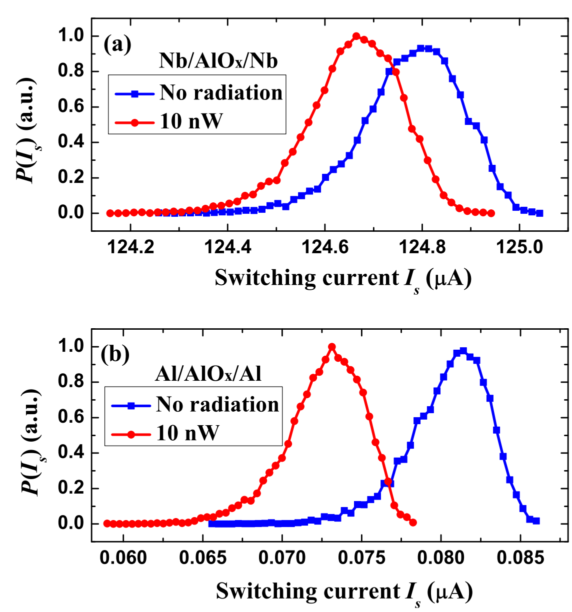

Fig. 2. (a) The measured distributions of the switching currents of Nb/AlO$_x$/Nb junction. Blue squares correspond to the data in the absence of radiation and red dots correspond to a 10 nW radiation on the junction. (b) The switching current distributions of Al/AlO$_x$/Al junction without radiation and with a 10 nW radiation respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

current I_s, with and without the photon radiation. Fig. 2(a) shows the switching current measurements on the Nb-J at 16 mK. The blue curve is the distribution in the absence of radiation, from which one can calculate the mean switching current $\langle I_{s0}(Nb)\rangle = 124.78$ μA, and the distribution width (standard deviation) $\sigma_{s0}(Nb) = 102.73$ nA. The red curve corresponds to a 10 nW radiation on the junction top electrode. In this situation the mean switching current shifts down to $\langle I_s(Nb)\rangle = 124.66$ μA and the distribution width $\sigma_s(Nb) = 98.00$ nA. For comparison, Fig. 2(b) shows the same measurements on the Al-J, which has a much lower critical current than Nb-J. It is shown that, without the radiation, the mean switching current is $\langle I_{s0}(Al)\rangle = 80.44$ nA and the distribution width $\sigma_{s0}(Al) = 2.53$ nA. However, in the presence of 10 nW photon radiation, the mean switching current is $\langle I_{s1}(Al)\rangle = 72.65$ nA and the distribution width $\sigma_{s1}(Al) = 2.47$ nA.

Two quantities can be introduced to describe the optical responsivity of the switching current for the junctions measured above. One is the ratio of the singal to noise, i.e., $R_a = \Delta I_s/\sigma_{s0} = (\langle I_{s0}\rangle - \langle I_{s1}\rangle)/\sigma_{s0}$. By this way, we have $R_a = 1.17$ for the Nb-J and $R_a = 3.08$ for the Al-J, showing that the Al-J device has a higher photon responsivity. The second way to define optical responsivity is the relative shift of switching current, i.e., $R_b = \Delta I_s/I_{s0} = (\langle I_{s0}\rangle - \langle I_{s1}\rangle)/\langle I_{s0}\rangle$. In this way, we obtain $R_b = 9.6 \times 10^{-4}$ for the Nb-J and $R_b = 9.7 \times 10^{-2}$ for the Al-J, showing again that the Al-J device has a more sensitive response to radiation. We take the second definition of the switching current responsivity in the following discussions.

We now investigate the optical responses of the switching currents under different radiation powers. To this aim we vary the light intensity and measure the corresponding average switching current at the bath temperature $T \approx 16$ mK. Fig. 3 shows the relative switching current shift $\Delta I_s/I_{s0}$ (i.e., the responsivity R_b) as a function of the radiation power. The black squares and red circles correspond to the responsivity of Al-J and Nb-J respectively. It is shown that the logarithmic switching current shift increases linearly with the logarithmic radiation power in the applied power range. By fitting the line slope, one can find that R_b is approximately proportional to $P^{0.6}$ for Al-J while proportional to $P^{1.2}$ for Nb-J. The minimum optical power that the Al-J device can detect is about 8 pW (corresponding to 8×10^5 incoming photons per measurement cycle), which is much smaller than the minimum power of 2 nW that Nb-J device can detect. With the switching current distribution width and local optical responsivity, we can also characterize the sensitivity of our devices by estimating [25] its noise equivalent power (NEP, which is the signal power in a 1 Hz bandwidth at which the signal-to-noise is unity), which are 3×10^{-12} W/$\sqrt{\text{Hz}}$ (for Al-J) and 7×10^{-11} W/$\sqrt{\text{Hz}}$ (for Nb-J). This clearly shows that as a detector, the Al-J has a higher sensitivity than Nb-J.

The behavior that switching current shift increases with the radiation power, is qualitatively similar to its bath temperature dependence. The inset of Fig. 3 shows $\Delta I_s/I_{s0}$ as a function of the bath temperature in the range of 30–400 mK, where the measured switching current shift also increases with the bath temperature. This suggests that the thermal effects might be dominant in the observed radiation power dependence of the responsivity R_b at the nominal bath temperature $T \approx 16$ mK. Experimentally, most of the photons are incident on the substrate rather than the superconducting electrodes of the junctions since the light spot is much larger than the junction area. As we are continuously pumping energy into the system, the chip will be mainly heated and achieve an effective local temperature higher that the bath temperature. To verify that the thermal effects could dominate the radiation power dependence of switching current, we move the fiber to radiate directly on a small area of the bare substrate, which is about 0.7 mm away from the Al junction area. We then perform the same switching current measurements and obtain the radiation power dependence of R_b, shown in Fig. 3 (black circles). It is shown that the responsivity is apparently weaker, when radiating on the bare substrate of a certain distance away from the junction than that when focusing on the junction area. This is a reasonable result, which can be attributed to a nonuniform temperature distribution around the irradiated area. The local temperature at the junction area is lower when the light spot is moved 0.7 mm away. The R_b of Al-J exhibits the same radiation power law dependence (the same slope) for both cases of radiation on the junction and the substrate, indicating that the thermal effect is the main factor in shifting the switching current.

Furthermore, we measure the variations of the switching current distributions due to the changes in bath temperature and radiation power independently. Fig. 4 plots the distribution width σ_s as a function of the average switching current $\langle I_s\rangle$ for the Nb-J device. Here, the black squares correspond to the data at different bath temperatures and without radiation, while the red circles correspond to different radiation powers and at the lowest bath

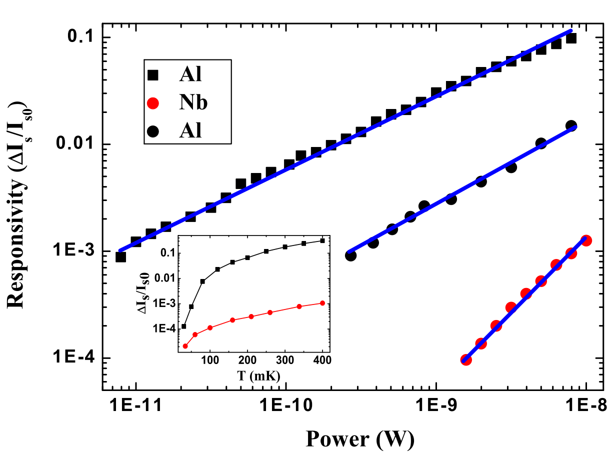

Fig. 3. The logarithmic $\Delta I_s/I_{s0}$ as a function of logarithmic radiation power. Black squares and black circles are the experimental data for focusing the light on junction area and nearby substrate of Al-J respectively. Red circles correspond to radiation on the Nb junction. The blue lines are the linear fitting, from which one can obtain the optical power law dependence of the responsivity. The inset shows $\Delta I_s/I_{s0}$ as a function of the bath temperature. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

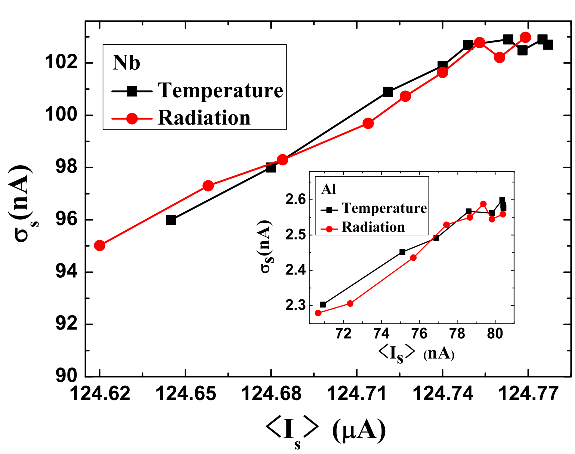

Fig. 4. The list plots of the measured distribution width σ_s versus the average switching current $\langle I_s\rangle$, for the Nb-J, due to independent changes in bath temperatures (black squares) and radiation powers (red circles) respectively. The inset shows the same measurements for the Al-J. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

temperature. The inset shows the same plots for the Al-J device. It can be seen that for both Nb-J and Al-J, σ_s approximately follows the same function of $\langle I_s \rangle$ by varying the bath temperatures or radiation powers: the distribution width has a plateau for higher switching current and then decreases with decreasing switching current monotonically [26]. In another word, one can obtain a certain switching current distribution $P(I_s)$ by radiating the junction with a certain power at a fixed bath temperature, and the same $P(I_s)$ (i.e., the same σ_s and $\langle I_s \rangle$) can also be obtained with a dark junction by setting the bath temperature at a certain value. This confirms that for the present devices, the optical responses of the switching current are indeed mainly due to thermal effects, suggesting the Josephson junctions could be used as a desirable bolometer.

4. Discussions and conclusions

Our experiment is meant to be a quick demonstration of weak optical detections by measuring the radiation-induced switching current shifts of Josephson junctions. Although the detection sensitivity (NEP) reported here for the present junction devices is obviously lower than that of other superconducting detectors (e.g., the NEP of a MKID is on the order of 10^{-17} W/$\sqrt{\text{Hz}}$ [27]), many aspects in the experimental configuration can be improved to achieve a better performance. The first one is to enhance the coupling between the superconducting electrode of the junction and the incident photons. To this aim, one can use a lensed fibers to focus the light on the junction so that a maximum incident energy could be absorbed directly by the Cooper pairs on the electrode. Besides, the top electrode can be fabricated as thin as possible so that a certain radiation power can cause a more reduction in the Cooper-pair density. The second method to raise sensitivity is to reduce the thermal conductance between the chip and the sample cell to maximize the energy absorption by the whole chip. For instance, one can fabricate the junction on the substrate with lower thermal conductivity (e.g., amorphous glass) or etch the back of the substrate wafer, to reduce the path of heat conduction from the chip to the sample cell. By this way the unwanted radiation energy loss can be avoided effectively. The third method is to select materials with lower gap energies as the superconducting electrodes. Moreover, for our experiments the fluctuations in the mean switching currents are limited by the low-frequency electrical noises in the circuits, not by intrinsic noises in the junctions. We definitely have rooms to further reduce the noise level, e.g., by new filter designs and readout with a lock-in amplifier, etc.

Besides the detection sensitivity, there are two main challenges to our system. Firstly, the detection (i.e., measure the switching currents through the JJs) can not be made very fast, since it takes time to sweep up the current and then sweep down to reset the junction to zero voltage state. The present measurement can be done at the rate up to several kHz, which is still a lower rate. By widening the circuit bandwidth, the measurement rate can be faster but may not easily get up to MHz. In addition, a faster measurement (i.e., a faster current ramping rate) will broaden the distribution width of the switching currents, which will then increase the noise level and decrease the sensitivity. Secondly, thermal activation is greatly suppressed at ultra-low bath temperatures, but the distribution of the switching currents still has a finite width σ_q due to quantum tunneling. For the present Nb-J device, one can calculate [28] $\sigma_q = 101.87$ nA, which is very close to the observed distribution width $\sigma_{s0}(Nb) = 102.73$ nA at $T \approx 16$ mK. This indicates that the quantum tunneling is dominant at the ultra-low bath temperatures. This finite distribution width may be translated to high dark counts for photon counting experiments (as shown in Fig. 2, the blue and red curves have overlaps). However, this problem disappears when the junction is only used as an optical power meter. One can statistically average the switching currents to determine the incident energy. If one can significantly suppress the fluctuations in the average switching currents, then the junction device can practically serve as a very sensitive radiation power meter.

Principally, the optical detection scheme in time domain is straightforward. One can bias the junction at a current slightly smaller than its switching current in the absence of radiation. If a light pulse with sufficient energy is applied, the switching current of the junction is reduced to below the bias current and then the junction will switch to a finite voltage state. Otherwise the junction will stay in zero voltage state. In this way one can judge if there are incoming photons or not.

In summary, we have experimentally demonstrated the optical responses of the switching currents through the Al/AlO_x/Al and Nb/AlO_x/Nb junctions at ultra-low temperatures ($T \approx 16$ mK). The radiation power dependence of the relative switching current shifts are measured. We find that the Al-J has a higher optical responsivity than Nb-J, which can be explained by the relatively lower gap energy of Al. The minimum powers that the Al-J and Nb-J can detect are 8 pW and 2 nW, and the noise equivalent powers for Nb-J and Al-J are estimated to be 7×10^{-11} W/$\sqrt{\text{Hz}}$ and 3×10^{-12} W/$\sqrt{\text{Hz}}$ respectively. Moreover, the Al-junction has been irradiated directly and indirectly through the substrate. In both situations, the relative switching current shifts follow the same radiation power law dependence, indicating that the thermal effects are dominant in the optical responses. Hopefully, the junction devices demonstrated here can be applied to implement photon detections in the future, once the device sensitivity can be greatly improved.

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[25] We can roughly estimate the NEP of our devices by simply assuming a flat noise spectrum up to 10 kHz (the circuit bandwidth). In this case the noise power spectrum of the switching current is simply given by the variance (the square of switching current distribution width) divided by the circuit bandwidth. One thus can obtain the noise power spectrum: 1.0×10^{-18} A^2/Hz for Nb-J and 6.4×10^{-22} A^2/Hz for Al-J. From Fig. 3 one can read the switching current responsivity $(\delta I_{sw}/\delta P_{opt})$ at weak optical power loading, which is about 14.3 A/W for Nb-J and 7.6 A/W for Al-J. Then the detector NEPs can be determined by dividing the square root of the noise power spectrum by the optical responsivity, which are 7×10^{-11} W/$\sqrt{\text{Hz}}$ (for Nb) and 3×10^{-12} W/$\sqrt{\text{Hz}}$ (for Al).
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[28] The theoretical distribution of switching currents due to quantum tunnelling is given by the equation: $P(I_s) = \frac{\Gamma_q(I_s)}{dI/dt} \exp\left[-\frac{1}{dI/dt}\int_0^{I_s} \Gamma_q(I) dI\right]$, where $dI/dt = 1.63 \times 10^{-2}$ A/s is the bias current ramp rate and $\Gamma_q(I)$ is the well-known macroscopic quantum tunnelling (MQT) rate at bias current I. To calculate Γ_q, one needs to know the critical current I_c and shunt capacitance C of the Nb junction. In our experiment, we obtain $I_c = 126.66$ μA by fitting to the average switching current and C = 0.26 pF from independent microwave resonance experiment. The distribution width $\sigma_q = 101.87$ nA can then be extracted once the distribution $P(I_s)$ is obtained.