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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.

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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 $\sim$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 $\times$ 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

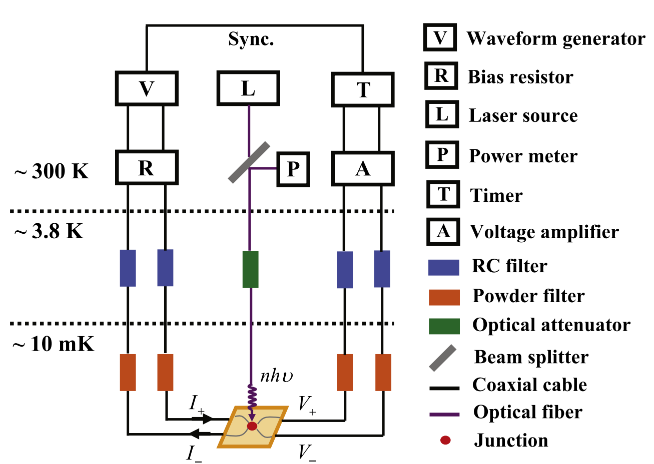

Fig. 1. Schematics of the measurement setup. Four-probe method is used to measure the junction current–voltage characteristics. The tested junctions are placed in a sample cell at $\sim$16 mK and irradiated by 1550 nm laser beam with attenuation.

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 $\sim$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.

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

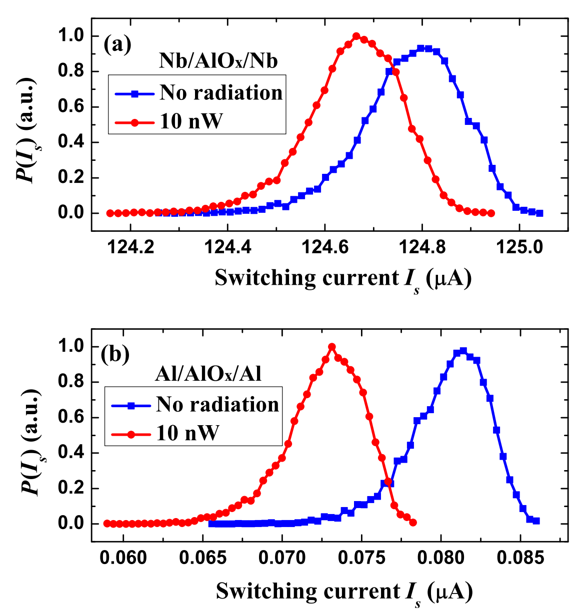

Fig. 2. (a) The measured distributions of the switching currents of Nb/AlO$_x$/Nb junction. Blue squares correspond to the data in the absence of radiation and red dots correspond to a 10 nW radiation on the junction. (b) The switching current distributions of Al/AlO$_x$/Al junction without radiation 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.)

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