# Experimental investigation on two-photon absorption in silicon avalanche photodiode

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**Abstract**: Two-photon absorption (TPA) in Si avalanche photodiode (APD) was investigated for infrared photon in 1550-nm telecom band with different frequencies, intensities, under different bias voltage. By measurement of the TPA efficiency for photon frequency from 186.3 to 196.1 THz in detail, it was found that it decreases when the photon frequency goes up while a certain optimal TPA efficiency is around 190.5 THz for the APD under test. It can be observed from the experiments that the TPA efficiency increases until a certain intensity (The peak value of light intensity in this experiment is less than 10 mW) and then it decreases.

**Key words**: two-photon absorption; single photon detection; Si-APD

**CLC number**: TN929.11 **Document code**: A **Article ID**: 1007-2276(2014)12-3928-04

# 基于硅雪崩光电二极管的双光子吸收实验

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**摘 要**：研究了硅雪崩光电二极管(APD)对光通信波段近红外光子在不同频率、强度，以及 APD 不同偏压下的双光子吸收效应(TPA)。通过实验详细测量了光频率从 186.3 THz 到 196.1 THz 变化时 APD 的 TPA 效率，结果表明：随着入射光频率的不断增加，TPA 效率呈现出先增大、后减小的规律，并且在 190.5 THz 附近达到最优效率。此外，在实验中观察到，随着入射光强的增大，TPA 效率也呈现出先增大、后减小的现象(此实验中的峰值光强度约 10 mW)。

**关键词**：双光子吸收； 单光子探测； 硅雪崩光电二极管

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**收稿日期**：2014-04-10； **修订日期**：2014-05-15

**基金项目**：国家自然科学基金(11274037)；新世纪优秀人才支持计划(NCET-12-0765)；全国优秀博士学位论文作者专项资助(201236)

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## 0 Introduction

Quantum communications based on fiber network are developing rapidly these days, which greatly promote the improvement of infrared single photon detection technology[1-7]. Directly detecting the infrared photons at the wavelength range of 1.3-1.6 μm, the InGaAs/InP avalanche photodiodes (APDs) are usually be employed, but their quantum efficiency is relatively low, while dark-count rate is high. To solve these problems, frequency up-conversion method has been proposed to convert the telecommunication-wavelength photon by a nonlinear crystal to short wavelength less than 1 000 nm, and then detected in a Si APD with high efficiency[5-7]. However, the up-conversion is relatively weak, and requires complex dispersion compensation techniques-phase matching, thus seriously restrict its application.

Recently, A. Hayat et al. propose a scheme for infrared single-photon detection based on two-photon absorption (TPA) in Si -APD, where the detected photon's energy is lower than the band gap and the energy difference is complemented by a pump field[3]. However, it is only analyzed theoretically, and up till now there are not any experimental reports. In this paper, we investigate in detail the TPA in Si-APD by experiment, and observe, for the first time according to our knowledge, that the TPA efficiency increases when the pump power is less than 10 mW, and then it decreases although the pump keeps going up, which agrees well with the theoretical analysis in Ref.[3].

## 1 Theoretical model

Based on the dressed-state solution for TPA in Ref[3], the system comprised of a semiconductor electron and an applied strong external field can be treated by the Volkov function approach, and the model is derived of a single-particle approximation which is reasonable for a room-temperature carrier-depleted bulk absorption region of the detector under reverse bias voltage. Here, we describe the TPA in Si - APD by a second-order perturbation applied to dressed states. For simplified expression, the relationship between the input optical power and the absorption rate can be presented by:

$$\mathbf{W}=\mathbf{C}|\mathbf{J}_1(\sqrt{\mathbf{x}})|^2 \quad (1)$$

where $\mathbf{W}$ is the absorption rate; $\mathbf{C}$ is a constant; $\mathbf{J}_1$ is the first order Bessel function of the first kind; and $\mathbf{x}$ represents the pump power. The simulation result is shown in Fig.1, from which we can find that an optimal pump power exists for a certain Si-APD.

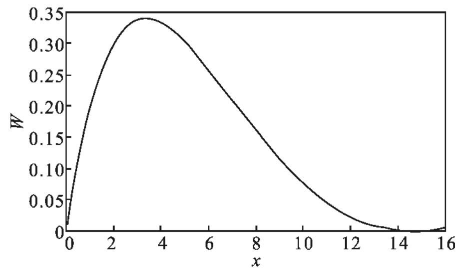


Fig.1 Simulation result of relationship between pump power and absorption rate

## 2 Experimental results and discussion

Figure 2 shows the principal of experiment investigation on TPA in Si-APD.

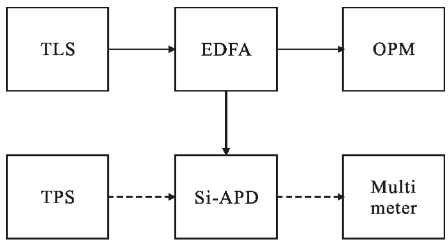


Fig.2 Experimental set-up of Si-APD measurement system

In order to facilitate the measurement, we weld the Si-APD in the specially designed circuit board. And then we investigate the properties of Si-APD by using the experimental scheme shown in Fig.3, while measure the output voltage response when bias voltage of APD increasing without light input, and subtract the influence of dark counts to get results.

Since the bias voltage upon the Si-APD approach the avalanche voltage (~200 V), the tunneling effect becomes much more remarkable as the theory model predict. Results show that the TPA efficiency increases until bias voltage rises up to about 198 V and then decreases when bias continues to go up, while the optimal bias changes as the photon frequency or intensity varies.

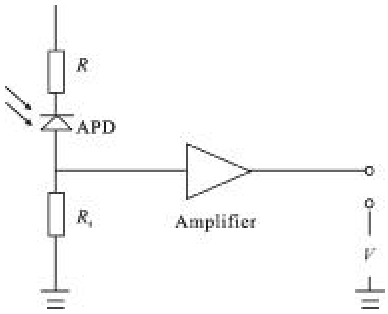


Fig.3 Si-APD detection circuit diagram

Firstly, we use the laser with different frequencies (range from 186.3 THz to 196.1 THz) generated by the TLS with fixed optical power(20 mW), and measure the output response curve of the APD with bias voltage increasing. We find that the output voltage decreases when the photon frequency goes up while a certain optimal TPA efficiency will be obtained around 190.5 THz, which is shown in Fig.4.

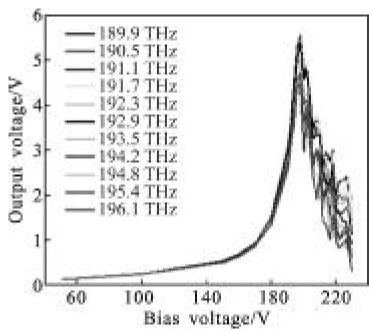


Fig.4 Output response curves of APD vs bias voltage for different frequencies

Secondly, we change the power of the laser from 10 mW to 35 mW with fixed frequency (192.8 THz), and measure the output voltage of the APD. We find that the output also goes up and then turns down, while reaches the highest value at about 198 V, which is shown in Fig.5.

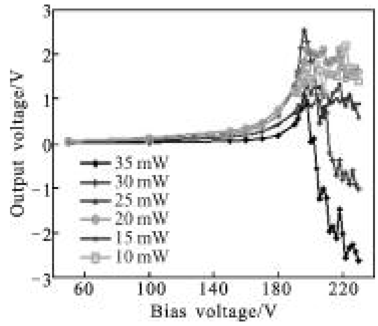


Fig.5 Output response curves of APD vs bias voltage for different pump powers

Besides, we also observe the nonlinear Franz-Keldysh effect of Si-APD, that is to say, the photon transition in the semiconductor near the band edge under the action of electric field, ignoring the electron-hole coulomb interaction, will make the absorption edge move to the low-energy side. The absorption curve develops an exponential tail characteristic when its energy is lower than the band edge without electric field, while the absorption coefficient presents an oscillatory behavior when it goes up over the band edge. In our investigation of Si-APD, oscillatory behavior occurs when the bias voltage is higher than the avalanche voltage (>200 V) with different optical powers and different frequencies.

Furthermore, we investigate the relationship between the TPA efficiency and the pump power by experiment at a certain bias voltage for a fixed wavelength. The TLS is set to 192.8 THz, and bias voltage of the APD is 198 V. When we adjust the optical power increasing from 0-40 mW, we find that the TPA efficiency increases when the pump power is less than 10 mW, after that it decreases, as shown in Fig.6. This result is satisfied with the simulation in

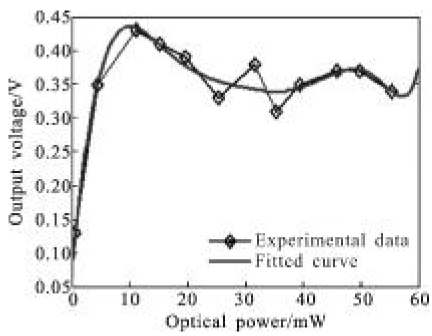


Fig.6 TPA efficiency vs optical power (bias voltage: 198 V)

Fig.1 and the theoretical analysis in Ref. [3], which demonstrates that the photon absorption probability is affected by the dressing-induced energy level detuning.

## 3 Conclusion

In summary, the TPA in Si-APD has been investigated in detail for the infrared photon in telecom band. Results show that the TPA efficiency decreases when the photon frequency goes up while an optimal TPA efficiency exists around 190.5 THz for the APD under test. And we further observe that the TPA efficiency increases until certain pump intensity (less than 10 mW) and then decreases, which is satisfied well with the theoretical analysis. By using two-photon absorption in Si-APD, the infrared single-photon can be detected with simpler configuration and higher quantum efficiency at room temperature.

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