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Optical Rectification Induced by Al-Si Schottky Barrier Potential and Mechanism of Two-Photon Response*

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Abstract: By observing two-photon response and anisotropy of the light-induced voltage in Al-Si Schottky barrier potential, it is certified from the experimental and theoretical analysis that the built-in electric field generated by the Schottky barrier potential will induce the phenomena of optical rectification in Si photodiode. Thus, it is deduced that there must be double-frequency absorption caused by phase-mismatch in the mechanism of two-photon response of Si photodiode. If the intensity of the built-in electric field is strong enough, the double-frequency absorption will be the main factor of the two-photon response, which is different from the conventional opinion that the two-photon response is just the two-photon absorption.

Key words: optical rectification; double-frequency; two-photon absorption

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1 Introduction

The conventional autocorrelation setup widely used to measure the ultra-short optical pulse usually consists of Michelson interferometer, double-frequency crystal and photomultiplier tube[1] which is very expensive, large, and hard to operate. In recent years, there has been a rapid expansion activity in the field of nonlinear optics. It is also a hot topic to substitute double-frequency crystal and photomultiplier tube with two-photon response[2] (including two-photon absorption and double-frequency absorption) semiconductor photodiode in autocorrelation setup[3,4]. When a beam from the laser to be measured is incident on a photodiode and photons possess energy $h\nu$ less than the semiconductor energy gap E_g, but greater than $E_g/2$, an electron can be excited from the valence band to the conduction band by the absorption of two photons or double frequency absorption, thus photocurrent is generated. Since the photocurrent is proportional to the incident intensity, it can be used to constitute autocorrelation setup. The nonlinear photoelectric detector with a very small volume conjoins the working of double frequency crystal and photomultiplier, so two-photon response detector and Michelson interferometer can be assembled to constitute an autocorrelation setup with low price, compact structure, convenience of using which can be applied in a wide wavelength range.

However, the principle of two-photon response is not well known[5,6] and there is no conclusion on whether direct two-photon absorption or double-frequency absorption dominates, or both exist. The conventional opinion is that the two-photon response is just a two-photon absorption[3,4]. We observed two-photon response and anisotropy of the

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light-induced voltage in Al-Si Schottky barrier potential, and found that the anisotropy is well correspondent with the theoretical analysis of optical rectification. So the existence of optical rectification is verified and double-frequency absorption exists can be concluded. In Section 2, how to measure the anisotropy in an appropriate experimental setup is introduced. In Section 3, a theoretical analysis is conducted, and one conclusion is presented in Section 4.

2 Experimental setup and measurement

The experimental setup is shown as Fig. 1. The laser is InGaAsP semiconductor with wavelength of 1.3μm and the chopper frequency is 140Hz. The specification of the objective lens is 12/0.3. The polarizer is used to generate linear polarization light and the λ/2 plate can change the polarization direction of linear polarization light without changing its intensity. The sample in the experiment is intrinsic silicon slice of 10mm length, 4mm width and 0.4mm height as shown in Fig. 2, whose upper and nether surface are vaporized with Al to form electrode.

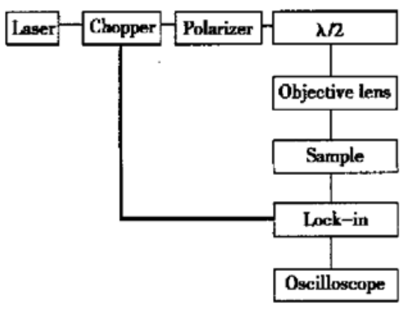

Fig. 1 Experimental setup

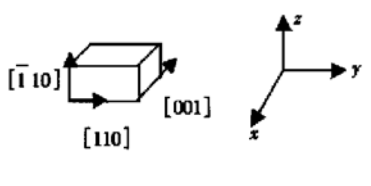

Fig. 2 Sample and coordinate in analysis

The laser beam is incident normally to (110) and (001) respectively in the experiment. The polarization direction of radiation changed but the intensity not when the λ/2 plate rotated. The lock-in amplifier would measure the photo-voltage generated by the incident light beam. Then the dependence of voltage on the polarization direction of incident light was obtained. When the laser beam is incident normally to (110), the dependence relation was shown in Fig. 3, where θ was the angle between direction [001] and polarization direction, V_A, V_B indicated the photo-voltage when the laser beam was incident on the upper Al/Si interface of the sample and the nether one respectively. When the laser beam was incident normally to (001), the dependence of photo-voltage on the polarization was shown in Fig. 4, where θ was the angle between direction [110] and polarization direction.

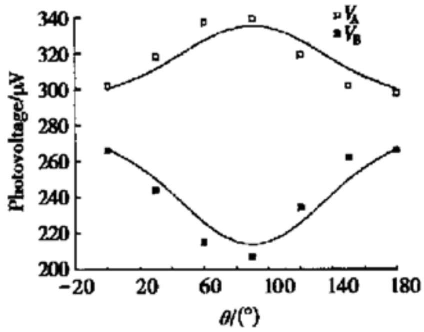

Fig. 3 Dependence of photo-voltage on the polarization direction when the laser beam being incident normally to (110)

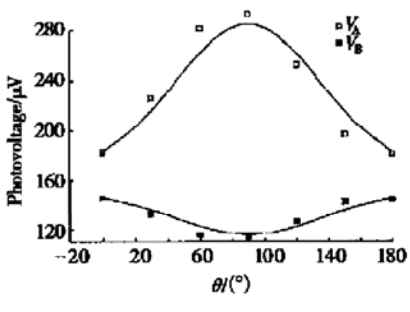

Fig. 4 Dependence of photo-voltage on polarization direction when the laser beam being incident normally to (001)

3 Theoretical analysis and discussion

It is well known that Si belongs to O_h and possesses symmetrical center, so the second-order susceptibility tensor is zero. But when it is under very strong electric field E, the symmetry will be broken and there will be an effective second-order susceptibility tensor $\chi^{(2)}$ that can be expressed as product of the third-order susceptibility tensor $\chi^{(3)}$ and the applied field E, namely[4]

$$\chi^{(2)} = \chi^{(3)} \cdot E \tag{1}$$

For the sample in the experiment, there is a Schottky barrier potential between the intrinsic Si and Al electrode, and the direction of built-in field is along $[\bar{1}10]$, so the $[\bar{1}10]$ effective second-order susceptibility can be deduced from Eq. (1). It should be noticed that the axis coordinate changes and a new one is shown in Fig. 2, so the expression of $\chi^{(2)}$ should be transferred into the new coordinate. At the same time, the expression of $\chi^{(2)}$ can also be obtained from the theory of group. Applied by an electric field along $[\bar{1}10]$, the symmetry of Si will decline into C_{2v} and the form of two-order susceptibility is

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & xzx & xxz & 0 & 0 \\ 0 & 0 & 0 & yyz & yzy & 0 & 0 & 0 & 0 \\ zxx & zyy & zzz & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{2}$$

where a simplified form is adopted, such as χ_{xxx} is written as xxx.

When the laser beam is incident normally to (110), the lightwave field can be written as

$$\bar{E}(\omega) = E_0(\omega)\cos\theta\hat{x} + E_0(\omega)\sin\theta\hat{z} \tag{3}$$

Because there is a effective two-order susceptibility, optical rectification will be generated, and the polarization intensity of optical rectification can be written as

$$\begin{aligned} P_{0z} &= \sum_{ij} \chi^{(2)}_{zij} E_i(\omega) E_j^*(\omega) \\ &= \chi_{zxx} E_x^2(\omega) + \chi_{zzz} E_z^2(\omega) \\ &= \chi_{zxx} E_0^2(\omega)\cos^2\theta + \chi_{zzz} E_0^2(\omega)\sin^2\theta \\ &= c_1\sin^2\theta + c_2 \end{aligned} \tag{4}$$

where $c_1 = E_0^2(\omega)(\chi_{zzz} - \chi_{zxx})$, $c_2 = E_0^2(\omega)\chi_{zxx}$

In Fig. 3 the solid curves are fitting curves. For V_A, the fitting equation is:

$$(300.11 \pm 4.47) + (38.07 \pm 7.9)\sin^2\theta \tag{5}$$

For V_B, it is:

$$(266.78 \pm 4.84) - (57.81 \pm 8.5)\sin^2\theta \tag{6}$$

It is well correspondent with the experimental data in Fig. 3. The directions of the built-in field at the upper and nether are reverse, so while optical rectification weakens one built-in field, it enhances the other. Thus, the maximum point of Curve A is the minimum point of Curve B, and vice versa.

For Fig. 4, the laser beam is incident normally to (001), so the lightwave electric field can be written as

$$\bar{E}(\omega) = E_0(\omega)\cos\theta\hat{y} + E_0(\omega)\sin\theta\hat{z} \tag{7}$$

Then the polarization intensity of optical rectification can be written as

$$\begin{aligned} P_{0z} &= \sum_{ij} \chi^{(2)}_{zij} E_i(\omega) E_j^*(\omega) \\ &= \chi_{zyy} E_y^2(\omega) + \chi_{zzz} E_z^2(\omega) \\ &= \chi_{zyy} E_0^2(\omega)\cos^2\theta + \chi_{zzz} E_0^2(\omega)\sin^2\theta \\ &= c_1\sin^2\theta + c_2 \end{aligned} \tag{8}$$

$$c_1 = E_0^2(\omega)(\chi_{zzz} - \chi_{zyy}),\ c_2 = E_0^2(\omega)\chi_{zyy}$$

It is the same as shown in Fig. 3, the solid curves are fitting curves. For V_A, the fitting equation is:

$$(183.00 \pm 7.05) + (112.00 \pm 13.23)\sin^2\theta \tag{9}$$

For V_B, it is:

$$(145.67 \pm 2.73) - (31.89 \pm 4.80)\sin^2\theta \tag{10}$$

The concrete analysis is the same as the former.

So the obtained photo-voltage is caused not only by the photovoltaic effect, but also by the optical rectification. Because both the optical rectification and the double-frequency effect are the second-order nonlinear optical effects, they must exist at the same time.

From the above analysis, we can draw a conclusion that the Schottky barrier potential can break the symmetry of Si, and make Si have the second-order nonlinear optical effect. So we can deduce that there must be the double-frequency absorption caused by phase-mismatch in the Si Schottky barrier photodiode. If the intensity of the built-in electric field is strong enough, the effective second-order nonlinear susceptibility of Si will be much larger than its third-order nonlinear susceptibility. Thus the double-frequency absorption will be the major factor of two-photon response. This is different from the conventional opinion that the mechanism of the two-photon response is just the two-photon absorption.

4 Conclusion

We measured the dependence of photo-voltage on the polarization direction of the incident linear polarization light. The experimental data is well correspondent with theoretical analysis. From the experimental and the theoretical analysis, it is concluded that optical rectification that is second-order nonlinear effect exists in Si devices when there is built-in electric field. According to the theory of nonlinear optics, optical rectification and double frequency effect appear simultaneously, so it can be said that double-frequency absorption caused by phase-mismatch must exist when there is built-in electric field. If the intensity of the built-in electric field is strong enough, the double-frequency absorption will be the main mechanism of two-photon response, which is different from the conventional opinion.

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Al-Si 肖特基势垒诱导的光整流与双光子响应机制*

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摘要: 通过观测硅光电二极管的双光子响应和 Al/Si 肖特基势垒处的光生电压的各向异性, 从实验和理论两个方面证实了肖特基势垒所产生的内建电场在硅光电探测器中诱发光整流现象, 从而推论硅光电二极管的双光子响应机制中必然存在相位失配的倍频吸收. 如果内建电场足够强, 倍频吸收将成为双光子响应的主要机制. 这与传统的认为双光子响应就是双光子吸收的观点不同.

关键词: 光整流; 倍频; 双光子响应

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