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Influence of electric field on two-photon absorption transition in HgCdTe photodiode

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Abstract: An experimental study of two photon absorption(TPA) in the HgCdTe pn junction detectors was reported. The excitation light source was a picosecond pulsed infrared laser. Even the incident photon energy was about 60% of HgCdTe (MCT) bandgap, an obviously photo-response was still observed. Quantification dependence of the peak amplitude on the incident intensity presented a slope of 2 by linear fitting to the experimental data in log-log coordinate, which indicated that the photo-response exhibited a quadratic power dependence on the incident intensity, suggesting a typical TPA process. The two photon absorption coefficient(TPAC) inside the space charge region(SCR) is as high as 130 times that of outside the depletion region which can be attributed to the TPA Franz-keldysh effect.

Key words: HgCdTe; two-photon absorption coefficient; photovoltaic-response

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电场对碲镉汞光电二极管双光子吸收跃迁的影响

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摘要: 实验研究了具有pn结结构的碲镉汞光电二极管的双光子吸收.激发光源采用了皮秒红外脉冲激光.尽管入射光子能量仅为碲镉汞材料带隙的60%左右,在光电二极管两电极端仍然观察到了显著的光伏响应信号.利用线性关系拟合双对数坐标系下光伏响应与入射光强的关系,发现两者呈现二次幂函数增强趋势,表明这种光伏响应是一种典型的双光子吸收过程.通过调节光电二极管两端的反向偏压,空间电荷区内的双光子吸收系数可比耗尽层外的强致130倍,这种双光子吸收系数的场致增强现象可归因为双光子吸收的FK效应所致.对比空间电荷区内外双光子吸收产生的光生载流子数量,证实空间电荷区内的双光子吸收会强烈地影响器件的光伏响应.

关 键 词: 碲镉汞;双光子吸收系数;光伏响应

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Introduction

Two-photon absorption (TPA) is an effective process to fulfill the nonlinear optical devices[1] owing to its high transparency at low incident intensity while blocking the transmission at high intensities. Despite strong interest of this non-linear optical absorption mechanism, the effects of electric fields have not received much attention in experiment[2]. The reason is that the field-induced TPA can only be observed in bulk devices applied by a strong electrical field(on the order of a few kilovolts)[3]. This is not always easy in a bulk device to create such a strong electric field. The main conclusion of the existing theory[4] and experiment[3] about electric field effect is the two-photon absorption coefficient(TPAC) of the semiconductor mate-

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rials can be modulated by a strong electric field, which can be attributed into TPA Frank-Keldysh Effect (FKE). Needless to say, this effect is very attractive for making a new high-performance optical power limiters(OPLs) because the modulation of TPAC make the TPA in nonlinear optical material be manipulated(thus the clamping output intensity) without changing the absorption length of the material or the structure of the devices. However, the reports about the influence of the field-induced changes of TPA on photoelectric conversion process are scarce in the literature. This lack of research is detrimental to the application of the effect for the nonlinear optical devices.

As an important non-linear optical material, mercury cadmium telluride(MCT) is a technologically important Ⅱ-Ⅵ semiconductor which has a Zinc-blende structure and narrow direct band gap[5-7]. Its energy band structure can be influenced by the strong electric field significantly. This will provide the possibility for observing the field-induced TPA modulation on the photovoltage, especially, in the space charge region (SCR) of a pn junction structure photodiode(PD). In this paper, we measured the TPA of MCT PD first. Using an effective RC circuit module, the TPAC inside and outside of the SCR is extracted respectively. It shows that the manipulation of TPAC can be realized by modulating the electric field of the SCR. Then, by comparing the OPA and TPA photovoltaic properties versus the incident light intensity, it was concluded that the TPA in SCR is the key factor enhancing the photovoltaic response of MCT PD at different electric fields. Also we will discuss the dramatic influence of TPA FKE on photo carrier transition in this work.

1 Experiment

The $Hg_{0.695}Cd_{0.305}Te$ n^+p photodiode was grown by MBE[8], and the acceptor concentration and donor concentration are $8(10^{15}\ cm^{-3}$ and $1(10^{17}\ cm^{-3}$, respectively. The active area of PD is $2.5(10^3\ \mu m^2$. From the Ⅰ-Ⅴ characteristics measurement, the PD breakdown voltage of -1 V was determined. The E_g obtained from the response spectrum is 0.258 eV(IFS-66v Fourier transform spectrometer). The equivalent junction capacitances C at different bias voltages were determined by C-V characteristics measurement (HP4194A impedance analyzer) at the device responding frequency(~0.5 MHz). The incident laser pulse ($\lambda = 7.92\ \mu m$, the photo energy $\hbar\omega$ is about 60% energy band gap E_g) was provided by a picosecond Nd:YAG laser (30 ps pulse duration, 10 Hz repetition rate). The laser beam was reflected by a beam splitter and measured using an energy detector in order to monitor the exciting energy. The pulsed photo-response of the MCT PD was measured from the voltage drop across a 10 kΩ load-resistor. Both signals from the energy detector and the MCT PD were input into an Agilent Infiniium 54832B oscilloscope to monitor and record the pulse profiles. The weak light illumination measurement was carried out using a tungsten halogen lamp. A tunable dc power supply was used for adjusting the bias on the pn junction.

2 Results and discussion

Fig. 1 shows the pulsed photovoltaic response profiles from MCT PD illuminated with 7.92 μm laser pulses at different incident intensities. The exponential decay time constant τ of the photovoltage is about 2.2 μs. At this response frequency 5×10^5 Hz($f = 1/\tau$), the equivalent junction capacitances C is determined to be 17 pF. Quantification dependence of the peak amplitudeof the photovoltaic response on the incident intensity presents a slope of 2 by linear fitting to the experimental data in log-log coordinate which indicates that the photo-response exhibits a quadratic power dependence on the incident intensity, suggesting a typ-

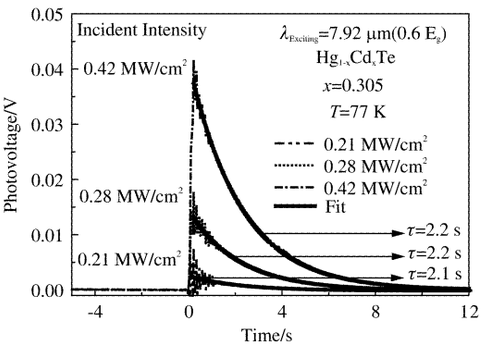

Fig. 1　Pulsed photovoltaic profiles of MCT photodiode illuminated with 7.92 μm laser pulses at different intensities.
图 1　7.92 μm 脉冲激光照射下，在不同入射强度下碲镉汞光电二极管的脉冲光伏信号

ical TPA process[4].

Neglecting the detailed photo carrier generation and recombination mechanisms, the photo-response profiles can be described with charging and discharging processes in the effective capacitor of the pn junction[9]:

$$\Delta V_p = \frac{qA}{C}\frac{\Delta t}{\hbar\omega}\left[\alpha I L + \frac{1}{2}\beta_1 I^2 l + \frac{1}{2}\beta_0 I^2 (L - l)\right] \quad , \quad (1)$$

where q, A, C, Δt, α, I, L, l, $\hbar\omega$ and β are electronic charge, pn junction area, equivalent capacitance, pulse duration time, OPA coefficient, incident intensity, total thickness of the MCT absorption layer excluded the SCR width, SCR width, photon energy, and TPAC, respectively. $\beta_0 = 1.5$ cm/MW has been previously determined by using photoconductivity technique[10]. β_1 is TPAC of SCR in pn junction, which can be determined to be 10.5 cm/MW using Eq. (1) to fit the photovoltaic peak amplitude on the incident intensity. TPAC inside SCR β_1 is found 7 times bigger than outside SCR β_0 from the comparison of the experimental data. When the electric field intensity of SCR varies from 13 kV/cm to 30 kV/cm (by adjustment the bias voltage changes from 0 V to 1 V), the TPAC inside SCR β_1 can be changed from 10.5 to 198 cm/MW (18.9 times increase). Comparing with TPAC without electric field effect β_0, the TPAC in SCR increases 130 times! Moreover, using an independent-particle theory, the calculation results of Wahlstrand *et al.*[11] indicated that this electric field effect should be much stronger in a parallel configuration. Thus the TPAC can be enhanced dramatically further by appropriate technical means.

Having demonstrated the strong TPAC enhancement effect induced by the electric field increase, we attempt to explain the observed effects. The significant enhancement of the TPAC could be attributed to the TPA FKE. By a strong electric field assisted tunneling process in SCR, the effective band gap energy E_g will shrink for an electron in the interband transition[12]. Thus, the ratio between the photon energy $\beta(\omega)$ and the effective band gap E_g increases with the electric field. The dispersion dependence of TPAC $\beta(\omega)$ on $\hbar\omega/E_g$ can be written as:

$$\beta(\omega) \propto \frac{(2\hbar\omega/E_g - 1)^{3/2}}{(2\hbar\omega/E_g)^5} \quad . \quad (2)$$

From Eq. (2), one can conclude that as $\hbar\omega/E_g$ increasing, the excited photo-electrons have more probability to be promoted into the conduction band state within the photon energy range used in our experiments. Therefore, the TPAC within the SCR of pn junction increase obviously with the electric field increasing.

There is little doubt that the huge change in photovoltaic response is due to other aspects of TPA FKE (such as field-induced OPA). We recognize that no photo-response signal is observable for the infrared photon wavelength larger than 5.2 μm. The response has not been observed at the incident wavelength (7.92 μm) in the PD. Thus the photo-response induced by OPA can be excluded. Moreover, an important corroboration of the interpretation can be made from the analysis of the relationship between the photovoltaic peak amplitude versus the incident light intensity at different electric field. Fig 2 shows the photovoltaic peak amplitude of PD illuminated with tungsten halogen lamp and laser pulse at different reverse bias. In this weak light illumination experiment, where only OPA occurs, as one can see that in the reverse bias range of $0\ V < V_D < 1\ V$, the photovoltage does not significantly change, meaning that the increase of the bias (hence the built-in field) does not notably change the OPA process. When the bias exceeds 1 V, the photovoltage increases considerably, indicating an electrical breakdown of the photodiode. On the contrast, the photo-response signal from the TPA drastically increases with the reserves bias in the range of $0\ V < V_D < 1\ V$, supporting our analysis and conclusion about the effect of built-in field in the depletion region on the TPA processes.

Since the width of SCR is very thin, a remaining question is whether the TPA in SCR will contribute to the photo-response increasing so obviously with the electric field. A rigorous analysis of the question will be undertaken as part of this work. For photovoltaic structures, the photovoltage (PV) signal from the flat-band region will not be enhanced by increasing the built-in electric field. Only the TPAC in the depletion layer

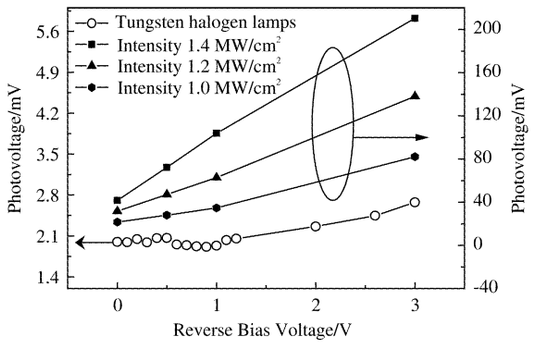

Fig. 2　Photovoltaic peak amplitude of HgCdTe photodiode illuminated with tungsten halogen lamp and laser pulse at different reverse bias

图 2　不同反向偏压下，卤钨灯和脉冲激光照射 HgCdTe 光电二极管的光伏峰值

will be enhanced by the built-in field. The width of the depletion region is estimated to be $l \sim 1$ μm ($l = \sqrt{2\varepsilon_r\varepsilon_0(V_D - V)/(qN_A)}$) in our sample, while the width of absorption layer is $L \sim 10$ μm. If we presume the same TPAC inside and outside the SCR, the portion of the two-photon excited carriers from the depletion layer should be only 2% $\left(N_{SCR}/N_{Total} = \frac{\beta_0 l}{2\hbar\omega_0} I^2 A / \left[\frac{\beta_0 (L-l) + \beta_0 l}{2\hbar\omega_0} I^2 A \right] \right)$. However, due to the FKE enhancement of the TPAC in SCR, from the theoretical model, one can expect that on the condition of built-in field 13 kV/cm(0 V), the percentage of the two-photon excited carriers from the depletion layer will be increased up to 14% $\left(N_{SCR}/N_{Total} = \frac{\beta_1 l}{2\hbar\omega_0} I^2 A / \left[\frac{\beta_0 (L-l) + \beta_1 l}{2\hbar\omega_0} I^2 A \right] \right)$. Furthermore, with the increase of built-in field up to 30 kV/cm(− 1 V), the ratio between two-photon excited carriers from the depletion layer and the whole MCT layer will be increased to be larger than 86%! Although there are contributions of the two-photon excited carriers from the flat band material, this signal will not be increased with the increasing of the built-in field. Meanwhile, this contribution has been considered and subtracted in our data analysis. So that the strong enhancement of the two-photon response signal with the built-in field could not come from the flat band region, and it would be a good attribution for this enhancement of the two-photon response to the depletion layer.

3　Conclusion

In summary, the experiment results show a strong dependence of TPAC on the electric field of MCT PD illuminated with picosecond laser pulses. The TPAC enhances obviously, by two orders of magnitude, which we attribute to the dc field induced FKE. By analyzing the relationship between the photovoltaic peak amplitude of OPA and TPA versus the incident light intensity at different electric field, it is concluded that the photovoltage increasing is caused by TPAC enhancement. Despite that the width of the flat band region is thicker than SCR, the amount of photo carriers generated by TPA in SCR are higher than that in flat band region. Therefore, in the strong electric field, the TPA in SCR will even dominate the photovoltage signal generation. Since the TPA is an important mechanism in semiconductors, our primary result on the electric field induced tunability of TPA and its influence on the photo-response can be very useful for the nonlinear optical device.

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well with that of transmittance spectra.

As shown in Fig. 6, it should be noted that the growth rate first increases substantially when the temperature increases to 150 ℃. Even worse, when the substrate temperature is higher than 200 ℃, e.g. 250 ℃, the growth rate of CdS films is negligible. The reason for this change can be described as follows. When the substrate temperature firstly increase from the room temperature, the sputtered particles have high kinetic energy and move fast at the growth surface, and then they may have much more chance to move to the local position with the energy minimum. Therefore, these particles are strongly bound in the energy minimum and thus it is more difficult for them to desorb than those particles located in other positions at lower temperatures. So, the growth rate increases with the temperature. With further increasing the temperature, all the particles have enough kinetic energy to climb over the energy barrier to move to the positions of the local energy minimum. However, now, the temperature seems so high that the particles are easy to desorb even if they are in the position of energy minimum, and therefore the growth rate decreases substantially. In conclusion, if we take both the growth rate and the crystalline quality of CdS films into consideration, the best growth temperature of CdS films is from 150 ℃ to 200 ℃.

3 Conclusions

In this paper, CdS thin films have been deposited on TCO-coated glass substrates at different temperatures of 30 ℃, 100 ℃, 150 ℃ and 200 ℃. All CdS films show clearly preferential (002) orientation in XRD. From the measurement of SEM, Raman, transmittance and PL spectrum, it can be concluded that the crystalline quality of films becomes much better with increase of growth temperature. The best growth temperature ranges from 150 ℃ to 200 ℃ with the compromise of the growth rate and crystalline quality of films.

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