Electric field dependence of output intensity of TPA in pn junction optoelectronic device

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***Abstract*—We analyze the electrical modulation properties of the output intensity of two-photon absorption (TPA) pumping. The frequency dispersion dependence of TPA and the electric field dependence of TPA are calculated using Wherrett theory model and Gacia theory model, respectively. Both predict a dramatic change of TPA coefficient which can be attributed into the increasing of the transition rate. The prior advantage of electrical modulation is the TPA can be varied extremely continuously, thus adjusting the output intensity in a wide range. This large change provides a manipulate method to control steady output intensity of TPA by adjusting electric field.**

Keywords- Non-linear optical absorption, electric field, Franz-keldysh Effect, output intensity

I. INTRODUCTION

Two-photon absorption (TPA) is a third-order nonlinear absorption process which is closely related to the imaginary part of nonlinear susceptibility of the material [1]. Because TPA has different selection rules than one-photon absorption (OPA), it is widely used in the spectroscopy analyzing of semiconductor. Moreover, Two-photon absorption (TPA) is an effective process to fulfill the nonlinear optical devices owing to its high transparency at low incident intensity while blocking the transmission at high intensities. Although a lot of theoretical calculations and experimental measurements [6] have been reported early, the effects of constant electric fields on the transpiration intensity have not received much attention, which is surprising considering that strong fields are often present in semiconductor-based photonic devices, such as pn junction photovoltaic device. This lack of research is detrimental to the application of nonlinear optical devices.

In this paper, the frequency dispersion dependence of two-photon absorption is calculated using second-order perturbation theory. Then, the electric modulation effect of two-photon absorption coefficient in pn junction photodiode is simulated from a two-band model. It indicates that the two-photon absorption coefficient (TPAC) in space charge region (SCR) is enhanced greatly by the build-in electric field. A two-photon absorption Franz-Keldysh Effect (FKE) mentioned by Gacia is adapted to interpret this phenomenon. On this basis, the dependence of output intensity on electric field is calculated using the TPA modulation relationship. It shows that the output intensity can be manipulated continuously by adjusting the bias voltage.

II. THEORY MODEL

2.1 Frequency dispersion dependence of TPAC

The two-photon process where the two-photon transition occurs from an initial state |*i*> to a final state |*f*> involving simultaneous absorption of two photons was theoretically predicted by Goppert-Mayer et al. in 1931. Since the transition probability is proportional to $\delta(E_f - E_i - \hbar\omega_1 - \hbar\omega_2)$, it may be obtained from Fermi golden rule:

$$W^{(2)} = \frac{2\pi}{\hbar}\sum\left|M_{cv}^{(2)}\right|^2 \delta\left(E_c\left(\vec{k}_c\right) - E_v\left(\vec{k}_v\right) - 2\hbar\omega\right) \quad (1)$$

where $\vec{k}$ is the wave vector of the internal motion of the exciting, $M_{cv}^{(2)}$ is the transition matrix element, respectively. In order to solve Eq. (1), the energy band, momentum matrix element, and the intermediate state should be approximated to simplify the calculation. However, the approximations and simplifying assumptions involves in a direct error between the calculation and experiment results of TPAC. In the computing models presented in the literatures, Wherrett model has been generally recognized. From the second-order perturbation theory, the interaction matrix element H'_{fi} between initial state $|i\rangle$ and final state $|f\rangle$ associated with the absorption of one photon can be obtained as:

$$M_{cv}^{(2)} = \frac{\sum_i H'_{ci}H'_{iv}}{E_{iv}\left(\vec{k}\right) - \hbar\omega} \quad (2)$$

$$H'_{fi} = \frac{q}{im\omega}\left(\frac{2\pi I}{nc}\right)^{1/2} \varepsilon \cdot \mathrm{p}_{fi} \quad (3)$$

where n, p_{fi} and ε are refractive index, momentum matrix element, and radiation polarization, respectively. For the spin degeneracy for the bands, the TPA transition rate $W^{(2)}$ can be written as:

$$\begin{aligned} W^{(2)} &= \frac{1}{\pi\hbar}\left[\left(\frac{2m_{cv}}{\hbar^2}\right)^{3/2}(2\hbar\omega - E_c - E_v)^{1/2}\right] \\ &\times\left[\left(\frac{q}{mw}\right)^4\left(\frac{2\pi I}{nc}\right)^2\left\langle\left|S_{cv}^{(2)}\left(\frac{(2m_{cv})^{1/2}(2\hbar\omega - E_c - E_v)^{1/2}}{\hbar}\right)\right|^2\right\rangle\right] \end{aligned} \quad (4)$$

where $S_{cv}^{(2)} = \sum_i p_{ci}p_{iv}\left[E_{iv}\frac{(2m_{cv})^{1/2}(2\hbar\omega - E_c - E_v)^{1/2}}{\hbar} - \hbar\omega\right]^{-1}$, p repents $\varepsilon \cdot \mathrm{p}$. Retaining the matrix element corresponding to the direct contribution, TPAC can be expressed as:

$$\begin{aligned} \beta(\omega) &= 2^9\sqrt{2}\pi\left(\frac{q^2}{\hbar c}\right)^2 \frac{f_2}{f}\frac{\hbar P}{n_2 E_g^3}\frac{(2\hbar\omega/E_g - 1)^{3/2}}{(2\hbar\omega/E_g)^5} \\ &= A\frac{(2\hbar\omega/E_g - 1)^{3/2}}{(2\hbar\omega/E_g)^5} \end{aligned} \quad (5)$$

where c, q, E_g, $\hbar\omega$ are speed of sound, electron charge, energy gap, and incident photon energy, respectively. $P \propto p_{cv}\hbar/m$ is Kane momentum parameters. f is defined as the numerical factor. Equation (5) shows that the TPAC is almost equal to zero for an incident photon energy less than half energy gap， this shows that no transition occur between energy band. The TPAC will continuously increasing with the photon energy when the photon energy larger than half energy gap. Then, the TPAC will show a decreasing tendency if the photon energy increasing more. This indicates that there is a maximum value in the TPAC. The effects of the external electric field on TPAC has been more complicated, in the electric field, the problem is further complicated and will be discussed below.

2.2 Electric field dependence of TPAC

A two-band model consisting of heavy-hole and light-hole bands mentioned by Garcia is used to discuss the dependence of TPAC on electric field here. Using a non-parabolic approximation of the state's density, the impact of electric field intensity on the TPA transition probabilities can be derived from the Fermi golden rule [2]:

$$W_2 = \frac{1}{(2\pi)^2}\sum_n \sum_{n'} \int dk W^{(2)}(k) \quad (6)$$

$$W^{(2)}(k) = \frac{|P_{vc}|^2}{2\pi\hbar}\left(\frac{2\pi m_c \omega N}{mk\cdot\hat{z}}\right)^2 \left(\frac{\hbar^2}{2MFe}\right)^{2/3} \times \left| I_N\left(\frac{ek\cdot\hat{z}A_0}{m_c\omega c}\right)\right|^2 \left[Ai(\delta_2)a_n^c a_{n'}^v\right]^2 \times \delta\left(E_{k\perp}^c + E_{k'\perp}^v + E_e - E_h + E_g - 2\hbar\omega\right) \quad (7)$$

where P_{vc}, F, $Ai(z)$, m_c, m_v, and m_u are interband momentum matrix element, electric field, Airy function, effective mass of electron and hole, and the reduced mass, respectively. In the whole excitation process, principle of energy conservation is satisfied by δ function, while momentum conservation is satisfied by $\Delta k = k_c - k_v = 0$, thus the TPAC can be derived as:

$$\beta^{(2)}(\omega, F) = \left(\frac{5\pi}{2\sqrt{3}}\right)\frac{K\left(E_p E_g E_\mu\right)^{1/2}}{n^2(2\hbar\omega)^5} \times \left\{2\left[\varepsilon_0^2 Ai^2(\varsigma_0) - \varsigma_0\left|Ai'(\varsigma_0)\right|^2\right] - Ai(\varsigma_0)Ai'(\varsigma_0)\right\} \quad (8)$$

where $\varsigma_0 = (2\hbar\omega - E_g)/E_\mu$, $E_\mu = \left(\hbar^2 e^2 F^2 / 2m_\mu\right)^{1/3}$ is the characteristic energy of the dc electric field. Because of the introduction of this parameter, the TPAC will change with the electric field strength. E_p is the transition matrix. K= 1940 cm/GW (eV) is a material independent constant.

Using the expression in Eq. (8), the TPAC at different electric field is simulated. We compared the simulation results with the experimental results [6]. As one can see, the calculated and the experimental data have a similar dependence on the electric field at 0<F<30 kV/cm. As F>30 kV/cm, the calculation data increase still while the experimental TPAC shows saturation. This can be attributed to the pn junction in this range has been breakdown, and the electric field strength in the SCR will not increase anymore. The TPAC at 0 V (β_1 =10.5 cm/MW) has been enhanced by about seven times comparing to zero electric field (β_0 =1.5 cm/MW). When the built-in electric field varies from 13.4 kV/cm to 30 kV/cm, TPAC will be enhanced into 198 cm/MW, about 19 times increasing. This significant enhancement is attributed to the FEK of the TPAC in SCR. The absorption coefficient is increased in the strong electric field of SCR by increasing the coupling intensity of electron and hole wave functions. FKE occurs because the electric field assisted tunneling process in SCR makes the effective energy gap shrink for an electron in the interband transition. The band gap shrinkage is proportional to the electric field as $\Delta E_g \sim F$. Consequently, the electrons exited from valance band have more probability to transmit into the conduction band. This mechanism has made the TPAC within the SCR increase.

2.3. Electric field dependence of output intensity

Based on the analysis given above, it can be known that the TPAC can be adjusted effectively by varying the electric field applied, thus, changing the output light intensity. Undoubtedly, this TPAC manipulating effect is very attractive for the non-linear optical devices such optical limiter. In the following, we will simulate the effects of TPAC manipulation on the output intensity. The output intensity of pn junction can be solved using function-transfer method [3]:

$$I_{n+1} \approx I_n - \beta I_n^2 \Delta x / \left(1 + \beta I_n \Delta x\right) \quad (9)$$

where Δx is the cell thickness of absorption layer, and I_n is the incident intensity of n layer. As a result of back-illuminated, the incident light passes through the flat band of p region first, and then into the SCR. Comparing with the thick base region, the thickness of the heavy doped emitter can be neglected. Therefore, only the optical loss in flat belt layer and SCR are considered here. Using the conclusion of TPAC modulation mentioned above, the effects of TPAC manipulation on the output intensity can be simulated, which is shown in Fig. 1.

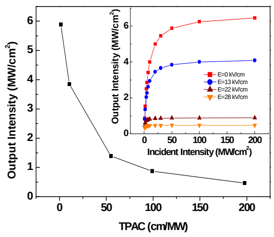

Fig. 1 The dependence of output intensity on TPAC when the incident intensity is 50MW/cm^2. The insert is the dependence of output intensity on incident intensity at different electric field.

It can be seen from Fig. 1, with the TPAC increasing, the output intensity will decrease dramatically. This can be attributed the enhancement of TPA in SCR, resulting in more carriers are excited by the photons, and the output intensity transmitted from material is weakened continually. The inset of Fig 1 shows the output intensity increase non-linearly with increasing intensity of incident light, and eventually reaches saturation. The output saturation intensity depends on the electric field strength, the greater the electric field, the smaller the output intensity is. This shows that the clamped saturation intensity can be controlled by the electric field.

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