The dispersion dependence of nonlinear optical absorption transition in Silicon PIN photodiode

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***Abstract*—This paper presents an experimental study on the dispersion dependence of two-photon absorption (TPA) between 0.689~0.912 eV in a Si-base PIN photodiode. The obvious TPA process is clearly observed as the nonlinear enhancement of peak photoresponse on the incident light intensity in the power of 2. The tendency of the TPA coefficient increases with the incident photon energy increasing. The maximum enhancement factor of the TPA coefficient has been achieved as high as 4 times. This dispersion dependence of TPA has been qualitatively interpreted as when the photon energy increases, the electrons of valance band excited by TPA find an increasing availability states of conduction band by phonon assistance.**

Keywords- two-photon absorption; PIN photodiode; photoresponse

I. INTRODUCTION

Optical absorption transition in semiconductor is one of the most important issues in microelectronics and optoelectronics devices. As a typical nonlinear optical (NLO) absorption effect, Two-photon absorption (TPA) has long been recognized as a powerful tool to study the optical properties and electronic band structure of solids because it has different selection rules and need not suffering the surface effects [1]. But it is undesired in some all-optical devices, such as optical waveguides. The main disadvantage is that the TPA transition will cause the propagation optical losses in the waveguide and generate the photon frequency upconversion that induce crosstalk between different wavelength channels in dense wavelength division multiplexing (DWDM) owing its small mode areas and long interacting lengths, thus limits the performance of the devices. Especially, in the background of future all-optical devices applications, it is desirable to use the materials of large nonlinearities with ultrafast laser exciting. Considering there is much commercial interest in Si-based device applications in optical communications because of the mature processing technology of Si and the suitability of silicon-on-insulator (SOI) material [2], the knowledge of the TPA dispersion dependence of Si is significant interest for device optimization and design. Comparing to a number of studies have been previously carried out to understand the mechanism of TPA for various materials, experimental data have performed on Si are still scare. This is due to the difficulty in obtaining the light source of low-energy side as well as the observing the TPA of silicon.

In this paper, the indirect TPA optical absorption transition is measured using a wavelength tunable and high power pulsed laser source in Si PIN photodiode at room-temperature. Consequently, the dispersion dependence of TPA is studied at transparent wavelength region (1.36~1.80 μm). The TPA coefficient spectrum of Si is related to the energy band structure and such an energy dependence of the TPA coefficient has been interpreted by a theory model.

II. EXPERIMENT

The Si PIN photodiode was formed by boron ion implantation into n-type Si layer, resulting in an abrupt p^+n structure between the Al and the Au electrode. The acceptor and donor concentration were 3×10^{18} cm^{-3} and 1×10^{14} cm^{-3}, respectively. The active area of the photodiode was 3×3 mm^2. The energy gap of Si was determined to 1.12 eV from the linear absorption photo current spectra using a FTIR spectroscopy. The equivalent junction capacitance C_T can be determined to be 288 pF by *C-V* characteristics measurement (HP 4194A impedance analyzer) at the device responding frequency (~20 kHz) at room temperature. The laser pulse can be tuned from 0.7 to 2.3 μm continually which was provided by a commercial picosecond Nd:YAG (EKSPLA PG401/DFG, pulse duration was 30 ps and the repetition rate was 10 Hz). An aperture was placed symmetrically to the axis of the beam, thus the irradiation area was limited by the aperture diameter. The output laser beam (diameter 1 cm) passed through the aperture (diameter 2.1 mm). The incident intensity was monitored by an energy detector (COHERENT J4-09). The pulsed photo-response of the photodiode was measured from the voltage drop across a 10 kΩ load resistance. Both signals were put into an Agilent Infiniium 54832B Oscilloscope for recording. Comparing to the shortest rising time of 200 ns in the pulsed response profile of the photodiode, the laser pulse can be approximated as a δ function in the experiment. The intensity fluctuation between the pulses was less than 1%, in order to minimize the influence of pulse-to-pulse fluctuation on TPA test, an average of 500 pulsed profiles was recorded. The incident laser wavelength were ranging from 1.36 μm (E_{photon}=0.912 eV) to 1.8 μm (E_{photon}=0.689 eV), and the photon energy is lower than 1.12 eV.

III. RESULTS AND DISCUSSION

The laser wavelength were ranging from 1.36 to 1.8 μm, corresponding to the photon energy of 0.689~0.912 eV, about was 60~80% of the band gap of silicon at 300 K. The photoresponse of the Si photodiode excited at different laser intensities show a similar rapid increase and slow decay process due to the relative large value of capacitance and resistance of *pn* junction [3]. The peak amplitude increases with the increase of exciting beam intensity. Because the incident intensity is about 10^6 W/cm^2, at this intensity the three- and higher order multi-photon absorption could be neglected comparing to the photo-assistant two-photon absorption [4]. The free carrier absorption is about 10^{-6} magnitude smaller than TPA in the top contact layer under the irradiation intensity over the wavelengths studied, thus the influence of free carrier absorption on TPA could be neglected. Furthermore, quantification dependence of the peak amplitude 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

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quadratic power dependence on the incident intensity, suggesting a typical two photon absorption process [5]. For the case of electric field dependence of TPA, Garcia [6] has shown that in the presence of a strong dc-electric field (10^6 V/cm), the TPA coefficient of silicon will be influenced because of the Franze-Keldysh effect (FKE). However, in our experiment, the electric field is smaller than 10^4 V/cm due to the thick n layer, so the FKE can be neglected.

We describe the photo-response profile with a charging and discharging process to the effective capacitor of the pn junction: photo-carrier will be separated by the build-in electric field. The photo-carrier will accumulate at the correspond region. This process is consistent with the charging of the pn junction equivalent capacitance and the rapid increase. The photo carrier will annihilate through the circuit including loading resistance and junction equivalent capacitance. This is the discharging process of the pn junction, and corresponds with the slow decay process. Using the transient photovoltage technique, the dissociated charge carrier lifetime are also measured in this work. By fitting the decay phase of the photoresponse with bi-exponential decay components for Si photodiode as done in previous work, we can extract out the carrier lifetime both at electrode/Si interface (0.1 μs) and inside the bulk Si (5 μs). In the exciting range of photon energies, no appreciable change in the photo voltage decay time constant of the pulsed response is observed.

Using the equivalent *RC* circuit model described above, a relationship between the peak photo voltage and incident intensity is derived as: $\Delta V_p = Q/C_T$, where Q is the photogeneration charge, C_T is the equivalent capacitance of pn junction. The photo-induced population of electrons and holes are assumed equal, with contributions from TPA processes:

$$\Delta n = \Delta p = 1/2\beta_{\mathrm{TPA}}(1-R)^2 I^2 \Delta t(\hbar\omega)^{-1} \quad (1)$$

where Δt, β_{TPA} and $\hbar\omega$ are the pulse duration, TPA coefficient and photo energy respectively. R is the Fresnel reflection rate (about 30%) at the surface of the photodiode and I is the incident intensity. The function form relationship between incident intensity and the peak photovoltage is obtained as:

$$\Delta V_p = q/2\beta_{\mathrm{TPA}}(1-R)^2 I^2 \Delta t A L (C_{\mathrm{T}}\hbar\omega)^{-1} \quad (2)$$

where q is the elementary charge, and A_{Area} is the irradiated area in the photodiode, 3.46×10^{-2} cm^2 (2.1 mm beam diameter). L is the width of Si layer. TPA coefficient at different wavelength can be extracted by fitting the peak photovoltage versus incident intensity using Eq (2). The tendency of the TPA coefficient increase with the incident photon energy increasing. This can be qualitatively interpreted as the photon energy increases from $E_{\mathrm{ig}}/2$ to nearly E_{ig}, the electrons excited from the valance band find an increasing availability of conduction band states. A similar tendency is observed in directed band semiconductor TPA, such as GaN and GaInN [7].

In order to understand the mechanism of indirect TPA transition, we perform the theory calculation here. In the earlier theoretical calculations, the final expression can be expressed as [8]:

$$\beta_{\mathrm{TPA}}(\omega) = \mathrm{C}_2 F_2(2\hbar\omega/E_{\mathrm{g}}) \quad (3)$$

$$F_2(2\hbar\omega/E_{\mathrm{g}}) = \left[(2\hbar\omega \mp E_{\mathrm{ph}})/E_{\mathrm{g}} - 1\right]^4 / (2\hbar\omega/E_{\mathrm{g}})^7 \quad (4)$$

where C_2 is constant term associated with effective mass, $\pm E_{\mathrm{ph}}$ takes into account the absorption/emission of phonon. Experiment results are fitted to the expression in Eq. (3) allowing the value of C_2 to be an adjustable parameter. It was found that the calculated and experimental data had a similar dependence upon the photon energy and show the same order of magnitude in values when $\hbar\omega$ is smaller than 0.855 eV. When $\hbar\omega$ exceeds about 0.855 eV, the experimental TPA coefficient shows a saturation while the calculation results expects a further increment. This might be attributed to the saturation of photovoltage in the studied photodiode. The magnitude of C_2 is 314 which is in good agreement with the result found by Rieger [2] and Dinu [8] while is 3 times bigger than the theory calculation value reported by [9]. There are many reasons for the discrepancy of experiment and theory calculation, one is the drastic approximations made in the Dinu model [9] and uncertainties in the values of physical parameters used in the model. Improvements to the derivation shown here would take into account the nonparabolicity of the *X*-valleys in silicon as well as the inclusion of the *K*-valleys, and explicit phonon dispersion curves.

In this study, we also have compared our measurement β_{TPA} values with other relevant measurement in high-energy side of silicon. The ten times bigger value of β_{TPA} (4.7~39.5 cm/GW) in 1.975 eV (0.63 μm) ~ 2.312 eV (0.54 μm) were obtained measured by Reitze [10] using a femtosecond pump and probe experiment. The much smaller value of the TPA coefficient in our measurement can be understood as: there are no direct two-photon transitions at the wavelengths used in the present study whereas there are perpendicularly transitions in ***k***-space Brillouin zone at the high-energy side where others have reported TPA.

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