Extremely Nondegenerate Two-photon Absorption Enhancement in Quantum Well (QW) Semiconductors

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Abstract: We present a theoretical study of extremely nondegenerate two-photon absorption in direct-gap quantum well semiconductors. We predict large enhancement in nondegenerate two-photon absorption for TM-TM polarized light over bulk semiconductors.
OCIS codes: (190.0190) Nonlinear optics; (190.5970) Semiconductor nonlinear optics including MQW

1. Introduction

It has been shown theoretically [1] and experimentally [2] that for direct-gap semiconductors, in the case of extremely nondegenerate (END) photon pairs, the two-photon absorption (2PA) is enhanced by orders of magnitude over the degenerate two-photon absorption (D-2PA). These enhancements have been used in such applications as mid-IR detection [3] and imaging [4] in uncooled GaN p-i-n photodiodes. Based on [5] it is expected that END-2PA will be even enhanced more in quantum well (QW) structures due to their large density of states near the band edge. Furthermore, QWs being inherently anisotropic one should expect this anisotropy to manifest itself in END 2PA which should show a significant difference depending upon whether the incident radiation is polarized in the plane of the QW (TE) or perpendicular to it (TM). In this work a theory for ND-2PA in QWs using second-order perturbation theory is developed for the first time and analytical expressions for the ND-2PA coefficient are derived for all possible polarization combinations, i.e. TE-TE, TM-TM, and TE-TM. Furthermore, it is demonstrated that in the limit of weak confinement, the 2PA in QWs becomes polarization independent and identical to that of the bulk.

2. Theoretical Analysis and results and discussion

2PA in QWs is governed by the selection rules that are different from the bulk. Figure 1(a) shows a sketch of E vs. k of a QW (xy is the plane of the QW and z is the growth direction). In QWs the selection rule for 2PA for TE-TE obeys the condition $\Delta n = 0$ and for TM-TM obeys the condition $\Delta n = odd$, where n represents the index for valence subband or conduction subband. It has been predicted [5] and observed [6] that in the TE-TE case both heavy-holes and light-holes contribute to 2PA and in the TM-TM case only light-holes contribute. In direct-gap semiconductors it has been predicted and verified that interband-intraband transitions dominate 2PA.

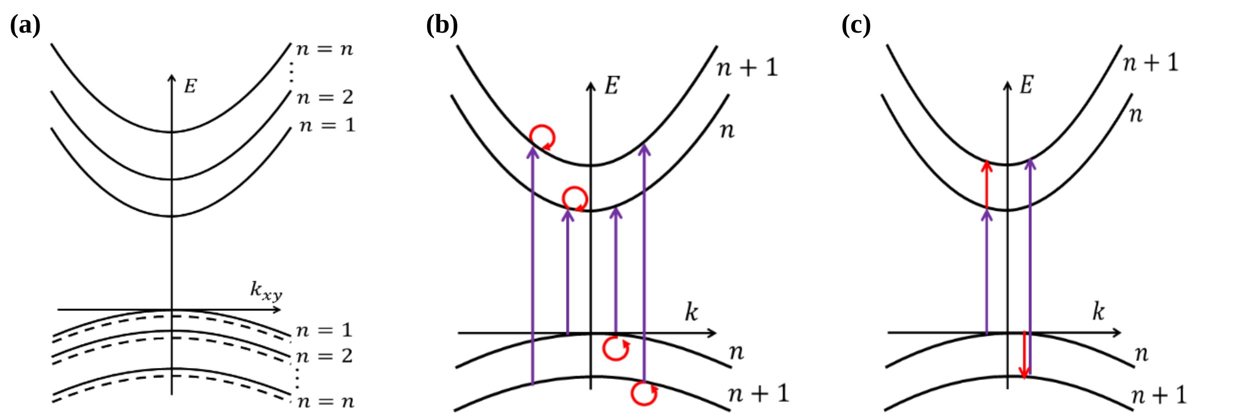

Figure 1: (a) E ~ k diagram for a QW showing conduction and valence subbands. The solid lines in the valence subband represent heavy-holes and the dashed lines represent light-holes, (b) Transition paths shown for ND-2PA in TE-TE case correspond to interband transitions (line) from valence subbands to conduction subbands and hole (or electron) intrasubband transitions, (c) Transition paths shown for ND-2PA in TM-TM case correspond to interband transitions from valence subbands to conduction subbands and hole (or electron) intersubband transitions.

In END-2PA, there are two resonances, the small energy photon can become near resonant to the intraband resonance while the large energy photon can be nearly resonant to the interband transition. The possible transition paths for 2PA in QWs for TE-TE and TM-TM are shown in Figure 1 (b) and (c). The ND-2PA coefficient for TE-TE

($\alpha_2^{ND}(\omega_1,\omega_2)|_\parallel$), TM-TM ($\alpha_2^{ND}(\omega_1,\omega_2)|_\perp$), and TE-TM ($\alpha_2^{ND}(\omega_1,\omega_2)|_{mixed}$) polarized light is derived from the 2PA rate using second-order perturbation theory. ω_1 and ω_2 optical frequencies. The expressions for ND-2PA are too long to be included here, but some key results for $\alpha_2^{ND}(\omega_1,\omega_2)$, using infinitely high barrier GaAs QW's as an example, are plotted in Figure 2.

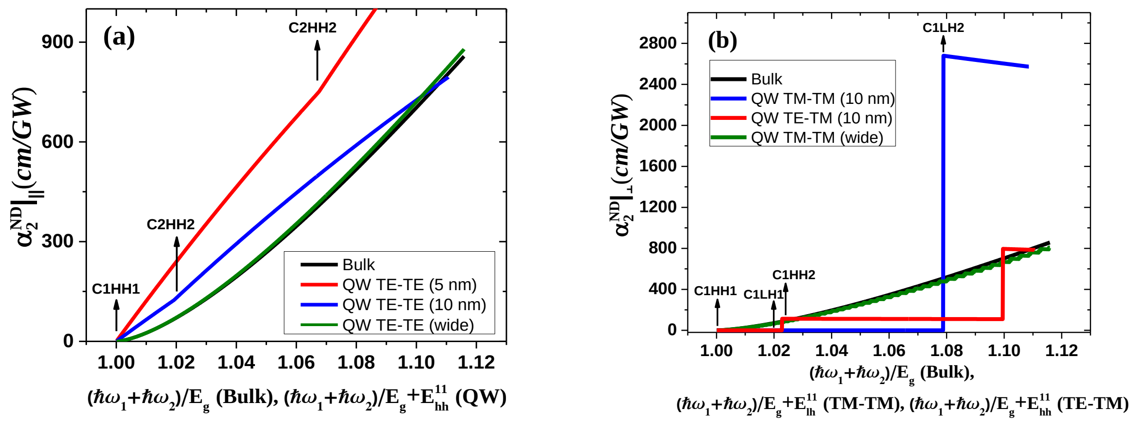

Figure 2: ND-2PA coefficient in bulk GaAs and GaAs QW's of different widths: (a) TE-TE case and (b) TM-TM case.

Figure 2 shows ND-2PA for $\hbar\omega_2 \approx 0.12E_g$, corresponding to a wavelength of 7.5 μm and varying the photon energy $\hbar\omega_1$ for $\alpha_2^{ND}(\omega_1,\omega_2)$. Comparing α_2^{ND} for bulk at $(\hbar\omega_1+\hbar\omega_2)/E_g = 1.02$ and $\alpha_2^{ND}|_\parallel$ for TE-TE at $(\hbar\omega_1+\hbar\omega_2)/E_g + E_{hh}^{11} = 1.02$, we see $\alpha_2^{ND}|_\parallel$ for a QW of width of 10 nm is ≈ 2 times the bulk α_2^{ND} and for QW of width of 5 nm $\alpha_2^{ND}|_\parallel$ is ≈ 3.4 times the bulk α_2^{ND}.

For ND-2PA in the TM-TM case (Figure 2 (b)) the $\alpha_2^{ND}|_\perp(\omega_1,\omega_2)$ shows more structured features due to selection rules and transition paths that allow intersubband transitions [5]. For $(\hbar\omega_1+\hbar\omega_2)/E_g = 1.02$ in the bulk, $\alpha_2^{ND}(\omega_1,\omega_2) \approx 75\ cm/GW$ and for $(\hbar\omega_1+\hbar\omega_2)/E_g + E_{lh}^{11} = 1.02$, in a QW of width 10 nm, $\alpha_2^{ND}|_\perp(\omega_1,\omega_2) \approx 2600\ cm/GW$. In Figure 2 the plots for the 2PA coefficients are plotted against photon energies which are shown scaled to the respective one-photon transition energies. This allows comparing the ND-2PA coefficient for the bulk and QW semiconductors on the same scale. The continuous increase of $\alpha_2^{ND}|_\parallel(\omega_1,\omega_2)$ from n^{th} valence subband to n^{th} conduction subband is attributed to the linear dependence of the intraband transition matrix elements on the in plane electron wave vector, $\boldsymbol{k}_{xy}$ and the step-like features of QWs are not observed. For a QW of width 10 nm in the TM-TM case there is an order of magnitude increase in $\alpha_2^{ND}|_\perp(\omega_1,\omega_2)$ over the bulk $\alpha_2^{ND}(\omega_1,\omega_2)$. The ND-2PA in the TE-TM case is also structured similar to the TM case and both heavy-holes and light-holes contribute to the 2PA. Considering the selection rules here, the 1st 2PA transition starts when the sum of two-photon energies becomes greater than $E_g + E_{hh}^{11}$. The calculated values of ND-2PA in the QW for the TE-TM case and bulk cases are almost equal and is not significantly enhanced over the bulk. Both for increased nondegeneracy and for larger confinements, the enhancement of $\alpha_2^{ND}|_\perp$ over bulk α_2^{ND} increases. These predicted high values of $\alpha_2^{ND}|_\perp(\omega_1,\omega_2)$ for TM-TM, can be used, e.g., mid-IR detection [3], imaging [4], and nondegenerate all-optical switching [7]. Although coupling of TM radiation into a detector is more challenging than TE methods for doing this routinely used in quantum well infrared photodetectors (QWIPs) [8].

Acknowledgments: We gratefully acknowledge support of the National Science Foundation award number ECCS 12022471.

3. References

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