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The role of permanent dipoles on the intensity-dependent nonlinear optical properties in asymmetric coupled quantum wells under a static electric field

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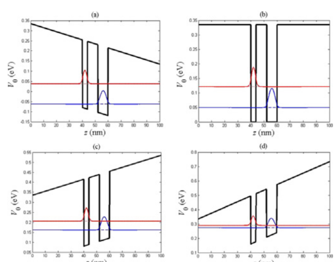
HIGHLIGHTS

- Our results reveal that in contrast to previous studies in which the effects of the permanent dipole moments were ignored they can play an important role in the nonlinear optical response.
- Our results show that the effects of the permanent dipoles on the corresponding optical processes depend crucially on the direction and strength of the static electric field, especially for large optical intensities.
- in contrast to previous studies, our results do not show the misleading effects of bleaching, negative absorption or positive dispersion near or at resonance.

GRAPHICAL ABSTRACT



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ABSTRACT

We study theoretically the intensity-dependent nonlinear optical properties of an asymmetric coupled quantum well under a static electric field. Effects such as nonlinear absorption, optical rectification and refractive index are investigated theoretically by using the density matrix equations including the permanent dipole terms. Our results show that the effects of the permanent dipoles on the corresponding optical processes depend crucially on the direction and strength of the static electric field, especially for large optical intensities. Another interesting result of this work is that the nonlinear optical spectra studied here saturate with an increasing optical intensity and specifically the optical spectra in the case that the permanent dipoles are considered reach saturation for lower intensities than when the permanent dipoles are not considered.

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1. Introduction

Quantum wells (QWs) are layered semiconductor structures in which the motion of charges (electrons and holes) is confined in one direction and in other two directions the charges are essentially free. The quantum confinement in one dimension generates subbands. Transitions between the subbands within the conduction band of a quantum well are known as the intersubband transitions and the nonlinear optical properties based on intersubband transitions in semiconductor QWs are still an active field of research mainly due to their relevance in several device applications, such as for example the quantum cascade laser and infrared photodetectors [1,2].

Among the QWs, there is a special interest in asymmetric quantum wells (AQWs) [3]. The ongoing strong interest in AQWs stems from their large nonlinearities and fast response times which are important for nonlinear optics applications. A major difference between symmetric QWs and AQWs is the existence of permanent electric dipole moments in AQWs. In AQWs the asymmetry of the potential profile leads to nonzero difference between the excited and ground electric permanent dipole moments and it is expected that this difference may take a large value [4,5].

Several theoretical works have studied the nonlinear optical response of asymmetric semiconductor quantum structures coupled with a strong probe field, for recent papers see for example [6–15], with emphasis given to the total (intensity-dependent) absorption coefficient and the total (intensity-dependent) index of refraction. In these studies the total absorption coefficient and the total index of refraction were derived from density matrix equations using perturbation theory and consist of the sum of first-order (linear) term that dependents only on the induced electric dipole matrix element and a third-order (nonlinear) term that depends both on induced and permanent electric dipole matrix elements. This method gives correct results only for small electromagnetic field intensities. For larger intensities it leads to non-physical results such as the creation of a strong dip in the absorption spectrum near or at resonance (the so-called bleaching effect), negative absorption near or at resonance that leads to optical gain and the change of the slope of the total index of refraction near or at resonance from negative to positive that changes the behavior of the system from fast to slow light.

Recently, Paspalakis et al. have studied the nonlinear intensity-dependent absorption and optical rectification in an asymmetric quantum dot by taking into account the effect of the permanent dipole matrix elements [16]. In that work they extended the work of Zaluzny [17] for the calculation of the total nonlinear absorption coefficient and the intensity-dependent nonlinear optical rectification coefficient, in order to include important contributions from the permanent dipoles. The main result of this study is that significant differences between the corresponding nonlinear optical processes of the asymmetric quantum system with and without

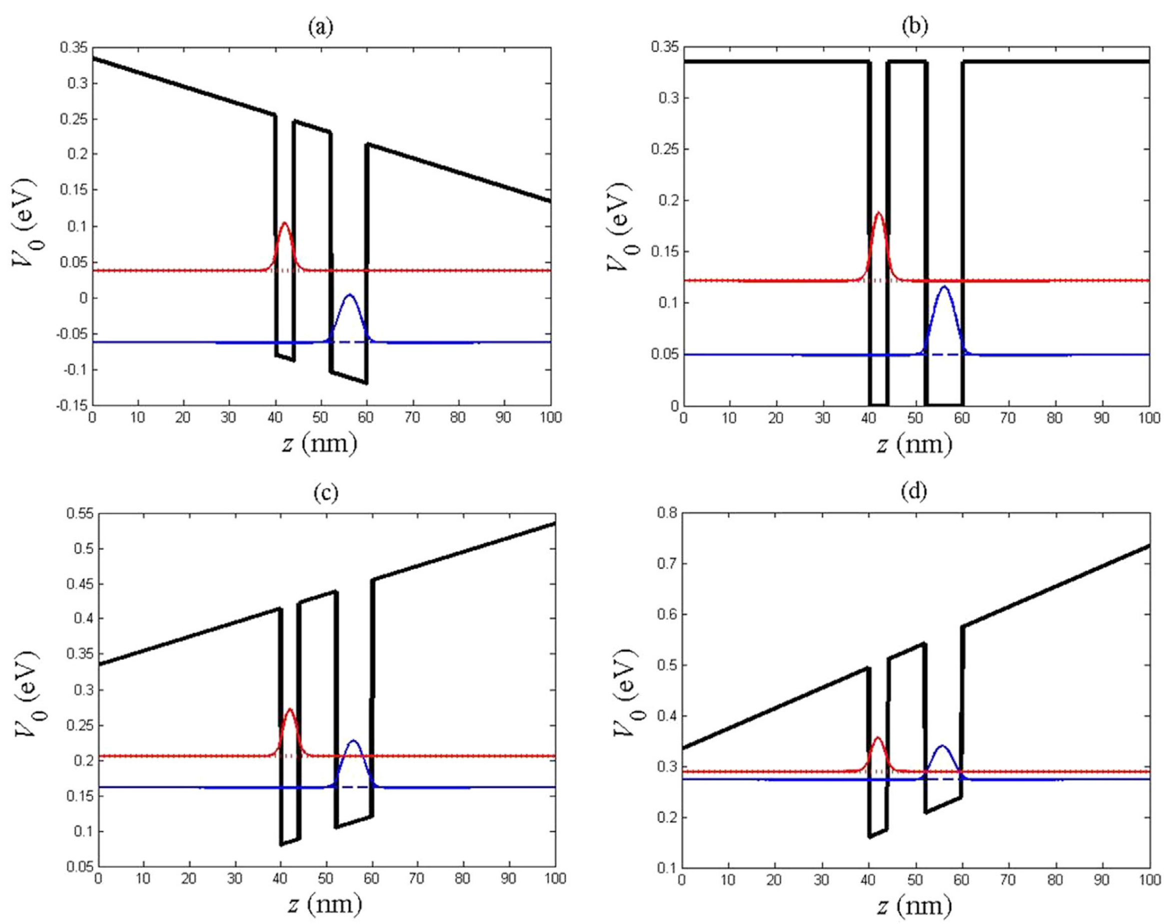

Fig. 1. The potential profile, energies and probability densities of coupled GaAs/$Al_{0.4}Ga_{0.6}As$ quantum wells, with dimensions 4 nm/8 nm/8 nm for four different static electric field values: (a) $F = -20$ kV/cm, (b) $F = 0$ kV/cm, (c) $F = 20$ kV/cm, and (d) $F = 40$ kV/cm.