Superlattices and Microstructures 87 (2015) 97–102

Contents lists available at ScienceDirect

Superlattices and Microstructures

journal homepage: www.elsevier.com/locate/superlattices

Enhanced terahertz emission by Landau quantization in semiconductor superlattices

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ARTICLE INFO

Article history:
Received 13 March 2015
Accepted 30 April 2015
Available online 11 June 2015

Keywords:
Terahertz emission
Semiconductor superlattices
Landau quantization
Bloch oscillations
Wannier–Stark states

ABSTRACT

We present a theoretical description of the process of therahertz emission in biased semiconductor superlattices that follows an ultra-fast interband excitation. The results show that the average current performs Bloch oscillations whose amplitude depends on the intrinsic characteristic of the superlattice as well as on the light pulse parameters. In these calculations we use a fully three-dimensional picture and include the excitonic effects. We also studied the terahertz intensity when the sample is subjected to a magnetic field parallel to its axis. We considered in detail the high magnetic field regime, where the in-plane motion is frozen in Landau orbits spectrally well separated. In this regime, a set of quasi one-dimensional Bloch oscillators can be ideally generated (oscillators with decoupled vertical and lateral electron motions), making the terahertz emission more intense and more coherent.

1. Introduction

The terahertz (THz) frequency range (wavelengths from 3 mm to 30 μm approximately) presents numerous applications in different fields, like medical applications, communications, and quality control [1,2]. However, the field of THz has not been widely studied due to the lack of efficient solid state devices capable of emitting and detecting such range of frequencies [3]. There exist different techniques for the THz generation, which are, in general, techniques already used in other regions of the electromagnetic spectrum, but modified to tune the operating frequency to the THz [4]. However, the efficiency of these techniques decreases as they approach the THz regime, producing only low power light.

A promising alternative for the THz generation are charge oscillations in biased semiconductor superlattices (BSLs). This phenomena, known as Bloch oscillations [5,6], occurs in periodic systems in the presence of a constant external electric field (F) and has been probed in different systems [7–9]. In BSLs, thanks to their long spatial periodicity (d) of typically 10 nm, the Bloch oscillation frequency ($\omega_B = eFd/\hbar$) corresponds to the THz range of the electromagnetic spectrum.

First experimental evidence of Bloch oscillations in superlattices dates back to the late 80's. Through current–voltage (I × V) measurements, it was observed a negative differential resistance in BSLs [10–13]. Few years later, the same results were demonstrated with I × V measurements and the application of continuous THz light on the BSLs [14,15]. Optically,

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http://dx.doi.org/10.1016/j.spmi.2015.04.042
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the four-wave-mixing technique has been used to observe THz light emitted by BSLs after an interband excitation [16,17]. Finally, the time-domain THz spectroscopy allows for more direct measurement of the amplitude and phase of the electric field emitted by the samples optically excited [18–21].

From the theoretical point of view, different approaches have been reported describing the current dynamics in a BSL under transient optical interband excitations and the THz emission associated with the engendered current [18,22–24]. The Coulomb coupling may considerably affect the frequency and amplitude of the THz radiation through the formation of excitons, but this is often disregarded and, besides, the BSLs are sometimes considered as a unidimensional system. In this work we present a fully three-dimensional (3D) modeling of Bloch oscillations in BSLs that follows an ultra-fast interband optical excitation. In our approach, we consider the excitonic effects and describe the interplay between the emissions of the dissociated and bound electron–hole pairs. Our model has been compared, in other reports [18,19], very accurately to experimental results. We extend our work by including the effects of a magnetic field parallel to the bias field. In this final part, we show that the originally 3D system is transformed, because of the Landau quantization, into an array of one-dimensional (1D) Bloch oscillators, that leads to a more intense and coherent THz emission [25].

2. Theory

2.1. Bloch oscillations

In semiconductor superlattices, the tunneling effect produces a hybridization of the wavefunctions and, in the same way than in solid, the discreet eigenstates merge to form mini-bands that allow for the free motion of electrons along the structure. The superposition of an external electric field parallel to the axis of the superlattice ($F \| \hat{z}$) suppresses the resonant tunneling and the mini-bands are substituted by an array of discreet states uniformly distributed along the sample, with a separation of $\hbar\omega_B = eFd$, where d is the periodicity of the SL (Fig. 1a and b). This distribution of states is known as the Wannier–Stark ladder [26].

The in-plane movement ($\hat{x}$, $\hat{y}$) is totally decoupled from the $\hat{z}$ direction, the 3D energy dependence can, therefore, be found by the addition of the dispersion relation of free electrons for the in-plane direction and the Wannier–Stark ladder of states for the vertical direction. The conduction (ε_n^c) and valence (ε_m^v) energy states in a fully 3D picture are then written:

$$\varepsilon^c_{n,k_\perp} = \varepsilon^c_0 + neFd + \frac{\hbar^2 k_\perp^2}{2m_c^*}; \quad \varepsilon^v_{m,k_\perp} = \varepsilon^v_0 + meFd - \frac{\hbar^2 k_\perp^2}{2m_v^*}, \tag{1}$$

where m_c^* (m_v^*) is the electron (hole) effective mass and n (m) is the index of each state along the Wannier–Stark conduction (valence) ladder of states. The Wannier–Stark wavefunctions ψ_n are written in terms of the solution $\varphi_{loc}(z - \nu d)$ of an isolated quantum well for each state ν along the superlattice [26]: $\psi_n = 1/\sqrt{N}\sum_\nu c_{n\nu}\varphi_{loc}(z - \nu d)$, where N is the dimension of the SL in terms of the number of periods d, $c_{n\nu} = J_{n-\nu}(-\Delta/2eFd)$; J being the Bessel functions and Δ the mini-band width.

Before any optical excitation, we consider that the conduction (valence) band is full (empty). This situation corresponds to the ground state $|0\rangle$ of the system. This assumption is valid since all related experiments are performed at low temperature. After the optical excitation, several inter-band transitions take place. Each transition is associated arbitrarily to a site m in the

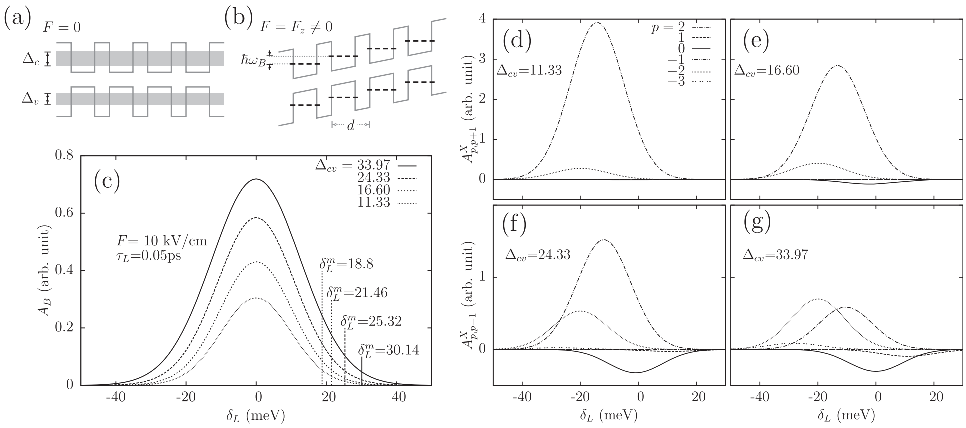

Fig. 1. (a) Conduction (Δ_c) and valence (Δ_v) mini-bands at zero electric field. (b) Formation of the Wannier–Stark ladder (dashed lines) of states in the conduction and valence bands as a result of the application of an electric field parallel to the axis of the superlattice ($F = F_z \neq 0$), where the difference in energy of $\hbar\omega_B = eFd$ between every two consecutive levels is noted. (c) Bloch current amplitude as a function of the excitation energy measured through δ_L. (d)–(g) Current amplitude of the excitonic contributions for the different SL samples, they all have F = 10 kV/cm and τ_L = 0.05 ps. All the calculations have been done up to the same multiplicative constant A_0 to be directly compared.