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Control of a resonant tunneling structure by intense laser fields

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ABSTRACT

The intense laser field effects on a resonant tunneling structure were studied using computational methods. The considered structure was a $GaAs/In_xGa_{1-x}As/Al_{0.3}Ga_{0.7}As/In_yGa_{1-y}As/AlAs/GaAs$ well-barrier system. In the presence of intense laser fields, the transmission coefficient and the dwell time of the structure were calculated depending on the depth and the width of InGaAs wells. It was shown that an intense laser field provides full control on the performance of the device as the geometrical restrictions on the resonant tunneling conditions overcome. Also, the choice of the resonant energy value becomes possible depending on the field strength.

1. Introduction

The resonant tunneling effect in multiple quantum well/barrier heterostructure is of interest because of their importance in designation and production of new-age electronic devices [1–9]. The resonant tunneling diodes (RTD) and the resonant-tunneling hot electron transistors are such structures investigated in the electronic applications. For instance, RTDs have been proven to improve the balance of the hot-carrier solar cell operation [10] as they have been also tested in terahertz imaging systems [11].

A resonant tunneling structure (RTS) is characterized by the potentials of the member barriers and wells as well as their number used in the structural combination [12–16]. In this respect, the device manufacturability of RTSs for sub-millimeter and terahertz applications has been investigated by numerical simulation methods [17]. Also the size effect on the vertical transport in GaN based RTDs has been explored in the framework of the non-equilibrium Green functions formalism [18] and self-consistent solutions of the coupled Schrödinger and Poisson equations [19].

As another RTS characterizing parameter, the dwell time can be described as the quantum mechanical analogue of the time spent by a classical particle in a region of space. It is a measure for the fast switching in RTSs. The dwell time is calculated using the real part of the quantum mechanical wave impedance [20], and can be expressed as a function of the electron velocity, the well and the barrier widths in a symmetrical rectangular RTS made of GaAs/AlGaAs [21]. The asymmetrical rectangular triple-barrier RTSs were similar examples for which the dwell times were calculated [22,23]. Although the RTSs have been fabricated with smooth semiconductor layers [24], a common property of the latter calculations is that the resonant tunneling event and a short dwell time strongly depend on the well-defined geometries of the member potentials

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and the smooth interfaces between the wells and the barriers. Otherwise, the device works in off-resonance conditions within the control accuracy of the layer thicknesses [25].

The laser fields can be used in external control mechanism of electronic devices. It has been established that an intense laser field is suitable for tuning electronic and optical properties of a GaAs/GaAlAs multibarrier structure [26]. In addition, the transmission coefficient of double barrier structures made of GaAs/GaAlAs was calculated through the potential profile change under the laser fields [27]. Dai et al. have investigated the time-dependent dynamical behavior of electron transport in AlGaAs/GaAs double-barrier structures under a high-frequency radiation field [28]. It was shown that the resonant tunneling through multi-barrier structures could be controlled by the laser fields in the presence of a constant electric field [29,30]. The application of an intense laser field can provide an efficacious usage of an RTS as the resonant tunneling currents through a heterostructure, which composed of a pair of barriers separated by a well, have shown to be tuned by the long-wavelength radiations [31].

The effects of an intense high-frequency laser fields on the physical properties of an spesific RTS is the subject of the presented study. The considered structure is an asymmetric well/barrier/well/barrier system, which was previously investigated for the resonance conditions. Hamaguchi et al. in their study varied the barrier widths and the well widths to keep the resonant energy constant and the transmission at maximum conditions [25]. They named the front well in the considered structure as the accelerating well, because the absent of the well causes longer dwell time in the resonance conditions. The same RTS has recently been studied to obtain the dwell time and the transmission coefficient by varying single parameter instead of changing the all geometrical parameters to keep the resonance conditions. It was found that the resonant energy, the transmission coefficient and the dwell time oscillate with the variation of the width of the front well [32]. We investigate the laser effect on the same RTS to find how the resonance conditions affected.

2. Theory

The time dependent equation of motion of an electron in the presence of an intense laser field represented by a plane wave polarized along the crystal growth direction-x is

$$\left[\frac{(\mathbf{p}+e\mathbf{A})^2}{2m^*}+V(x)\right]\psi(\boldsymbol{x},t)=i\hbar\frac{\partial\psi(\boldsymbol{x},t)}{\partial t}, \tag{1}$$

where $V(x)$ is the potential profile of the RTS. The vector potential $\boldsymbol{A}$ in Eq. (1) is created by the laser field parallel to growth direction and given by $\boldsymbol{A}=A_0\sin(\omega t)\hat{\boldsymbol{x}}$. Under a unitary transformation $\psi(\boldsymbol{x},t)\xrightarrow{U}\Phi(\boldsymbol{x},t)$ [33–41], Eq. (1) can be recast into form of

$$\left[-\frac{\hbar^2}{2m^*}\nabla^2+V[\boldsymbol{x}+\boldsymbol{\alpha}(t)]\right]\Phi(\boldsymbol{x},t)=i\hbar\frac{\partial\Phi(\boldsymbol{x},t)}{\partial t}. \tag{2}$$

In Eq. (2), $\boldsymbol{\alpha}(t)=\alpha_0\cos(\omega t)\hat{\boldsymbol{x}}$ describes the effect of the laser field on the electron with an amplitude $\alpha_0=\frac{eA_0}{m^*\omega}$, and is called the laser dressing parameter.

In high frequency limit [38–42], the Hamiltonian can be reduced to time-independent form of

$$\left[-\frac{\hbar^2}{2m^*}\nabla^2+V_D(x,\alpha_0)\right]\Phi(x)=E\Phi(x), \tag{3}$$

where $V_D(x,\alpha_0)$ is the laser-dressed potential given by

$$V_D(x,\alpha_0)=\frac{\omega}{2\pi}\int_0^{2\pi/\omega}V(x+\alpha(t))dt. \tag{4}$$

To obtain transmission coefficient T of an electron for the potential given in Fig. 1(a), the structure was divided into N parts along the growth direction. Eq. (3) is solved for each part, using the standard boundary conditions. This process can be formulated as follows. The Hamiltonian in part j is

$$\left[-\frac{\hbar^2}{2m_j^*}\nabla^2+V_{Dj}(x,\alpha_0)\right]\Phi_j(x)=E\Phi_j(x)\quad (\mathrm{j}=1,\ldots,\mathrm{N}). \tag{5}$$

where m_j^* is the effective mass in $[x_j,x_{j+1}]$ region. The wave function $\Phi_j(x)$ is given by

$$\Phi_j(x)=A_j\exp(k_jx)+B_j\exp(-k_jx), \tag{6}$$

where k_j is the wave number expressed as