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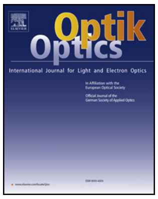

Original research article

Quantum resonant tunneling in semiconductor double-barrier structure

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ABSTRACT

Using Schrodinger equation, we have theoretically studied the quantum transport in double-barrier potential resonant tunneling diodes. To obtain higher peak in transmission coefficient in twofold barrier quantum well system require to reducing the barrier height and increasing the width of the quantum well which causes the electrons to turn unbounded. In addition, the potential energies should be below the height of the barrier. This occurs because on resonance with unity transmission requires exact cancellation in amplitude and phase of a coherent superposition of all contributions to the back-scattered particle-waves. At a certain height, width and potential energy, the resonances sit-down between barriers giving rise to peaks in transmission. Our model can be extended for several barriers to increasing the resonance peaks of transmission.

1. Introduction

Quantum resonant-tunneling diode (QRTD) is a diode in which particle can tunnel through some resonant states at specific energy levels. The current-voltage features a negative differential resistance region. This negative differential resistance property enable the possible use the QRTD in many potential applications, such as high frequency oscillators, ultra-fast logic devices and multi-functional memory devices [1–3].

Diodes are used extensively in analogue device and electronics, and have become increasingly important with enhancement in their performance. Quite recently, tunneling diodes have been considered an integrated and capable approach for ultra-high-speed operation because the effective quantum tunneling through the very thin layers and fast process. For several years, substantial effort has been dedicated to study the fabrication of oscillators and switching devices that can operate at terahertz frequencies [4,5]. Additionally, quantum tunneling dynamics can be potentially applied to tunneling through double-barrier in optical Fabry-Perot interferometer [6].

A resonant-tunneling diode gives rise to a barrier for electron tunneling. Addition of another barrier to this barrier can enhance the performance of the device, giving rise to architecture known as the double-barrier resonant tunneling diode [7], which prevents the flow of electrons during the device but also counters it intuitively, making it transparent to the tunneling of electrons at certain resonant energy levels [8,9].

Quantum resonant-tunneling diode can be fabricated using many types of materials such as III–V, type IV, II—VI semiconductor, as well as many kinds of resonant tunneling architecture [3,10,11], e.g., a highly doped p-n junction in Esaki diodes [12], double barrier, triple barrier, quantum well [13–15], or quantum wire. The fabrication treatment of Si/SiGe resonant inter-band tunneling

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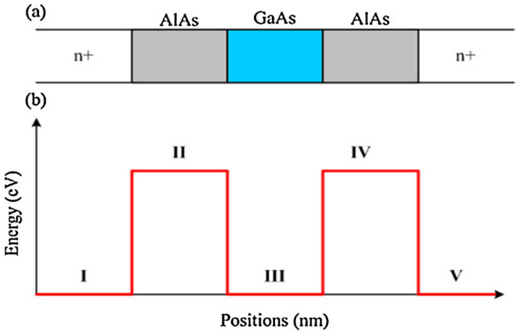

Fig. 1. (a) the structure of the QRTD. The quantum well consists of the undoped GaAs (6, 8, 9 nm), the barriers consist of undoped AlAs (2.5, 5 nm) larger band gapand the contact regions consist of emitter or collector heavily doped GaAs (with a doped concentration of 2 × 1018 cm^{-3}), small band gap. (b) The structure of the conduction band edge. The height of the potential barriers is (2.5–5 nm).

diodes is compatible with complementary modern Si metal-oxide-semiconductor and Si/Si Ge heterojunction bipolar technology [16,17].

One type of QRTDs is formed as a single quantum well-structured surrounded by extremely thin layer barriers. Based on the approach presented in Ref. [12], our potential structure is called a double barrier structure. The energy levels of the carrier electrons and holes are discrete energy values inside the quantum well. When a voltage is applied through a QRTD, a terahertz wave is emitted, and the energy level separation within the quantum well is equal to that of emitted wave. As voltage is increased, the terahertz wave vanishes due to the energy in the quantum well is becoming larger than frequency of the wave.

In recent years, there has been intense research on QRTD structures, and their application in the several devices has become extremely common. The most important advantage of the quantum tunneling structures is the use of partial negative resistance as seen in the image created from link to nanoHuB tools [18,19]. Our method is an effective way to improve the quantum tunneling simulation during a double barrier, so that the transmission probability is consistently below unity for potential barriers height greater than incoming particle energy [20–22]. Considering the fact that a potential profile contains two barriers that are placed close to each other, one can obtain the transmission coefficient as a function of the incoming particle energy using the standard matrix transfer methods [12].

In present work, we focus on the QRTD design and application in AlAs-GaAs-AlAs double barriers system [23–25]. The considered structure is shown in Fig. 1 where the QRTD consists of double barriers AlAs semiconductor. Between two barriers, the wave function of the GaAs well can tunnel into each other [26–30]. We will see that this AlAs/GaAs/AlAs tunnelling can induce more than one unity transmission peaks. Each barrier mode couples with the quantum well system offered by the GaAs semiconductor materials embedded between the barriers.

Even though the double barrier potential is considered as the QRTD, the main conclusion of the present work is suitable in the case of quantum transport. The calculation is implemented using Piece-Wise constant potential barriers tool from nanoHuB tools [18]. Our approach can simulate quantum tunneling through more than two barriers to increase the resonance peaks of transmission. The QRTD transmission is described by the time-independent Schrodinger equation [31–33].

The remainder of this paper is organized as follows. In Sec. II, we give the time-independent Schrodinger equation and propagation matrix methods of two types of transmission probabilities for a single- and double barriers derivations. In Sec. III, we addressed the specific problem of the double-barriers potential, giving results for transmission through either symmetric or asymmetric barriers. We also compared the band structures of our model i.e., open system structure to the particle in a box is a closed system energies. Finally, in Sec. IV, we summarized our conclusions, and outline some suggestions for future work.

2. Model framework

We started by considering a particle impinging on a step change as potential between two regions in which the wave vector changes form k_1 to k_2 due to the potential step-up. The corresponding wave function changes form ψ_1 to ψ_2. The time-independent Schrodinger equation for the wave function $\psi_j(x)$ is given as follows [6,22].

$$\mathscr{H}\psi_j(x, t) = i\hbar\frac{\partial}{\partial t}\psi_j(x, t) \tag{1}$$

$$\psi_j(x) = \mathrm{A_j e^{ik_jx} + B_j e^{-ik_jx}} \tag{2}$$

$$\mathscr{H} = -\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + V(x) \tag{3}$$

$$j = -\frac{ie\hbar}{2m}(\psi^*\nabla\psi - \psi\nabla\psi^*) \tag{4}$$