Intersubband transitions in coupled triple-graded quantum wells under an electric field

E. Kasapoglu*,†, H. Sari‡, and I. Sokmen†

† Department of Physics, Cumhuriyet University, 58140 Sivas, Turkey
‡ Department of Physics, Dokuz Eylul University, Izmir, Turkey

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The intersubband transitions were calculated in three different shaped triple-graded quantum wells. The investigation involved changing the depth of the central well potential under an electric field applied parallel to the growth direction. By changing the depth of the central well potential, one can tune the resonance photon energy. This tunability gives a possibility for the realization of near-infrared electro-absorption modulators and detectors. In addition, the absorption coefficient as a function of the incident photon energy was obtained for the 1–2 transition in a triple square quantum well structure having the same physical parameters as the triple-graded quantum well structure.

1 Introduction

Due to a large variety of technological applications, single and multiple semiconductor quantum well (QW) structures have been extensively studied in different situations including external perturbations, such as magnetic and electric fields, and distinct doping processes. Semiconducting devices are now designed based on the photodetector and electro-optical modulation properties of QW systems, such as the optical modulators based on the QW confined Stark effect. In designing a tunable detector based on the Stark effect one normally aims at getting the maximum tuning range when the bias field changes in a prescribed range. Similar to double-barrier and double-well systems, triple quantum well (TQW) heterostructures have also been shown to have many interesting physical properties. In particular, these TQW systems have been shown to be superior to double QWs with respect to the optical non-linearity induced by resonant coupling [1–4]. Radovanovic et al. have discussed two different approaches for QW optimization with respect to both the Stark effect and the magnitude of the absorption [5, 6]. They concluded that the optimization is described in terms of step and continuously graded QWs to get the best performance as tunable infrared photodetectors. Another interesting application is the fabrication of a three-colour infrared photodetector, operating at a fixed bias and composed of TQW structures, as reported by Huang and Manasreh [7]. The electronic states in multi-QW structures [8] are known to be easily modified by applying an external electric field, resulting in coupling and decoupling of the wave functions. These effects cause a significant change in the optical properties. These effects are known to provide optical non-linearity and allow the production of optical devices.

In this paper, we calculated the intersubband transitions in triple-graded QWs under an electric field applied parallel to the growth direction. As is known, the graded potential profile is obtained by changing the aluminium concentration \(x\) in the Ga\(_{1-x}\)Al\(_x\)As layer.

* Corresponding author: e-mail: ekasap@cumhuriyet.edu.tr
2 Theory

The triple-graded quantum well (TGQW) heterostructure is formed by a central GaAs quantum well coupled through thin barriers to graded wells on both sides. The central well potentials $V_0$ are taken equal to zero (TGQW1), 50 meV (TGQW2) and 100 meV (TGQW3) for each heterostructure, which are shown schematically in Fig. 1. The ground state wave functions for the three TGQW systems are also depicted in order to show the differences between the different confinement cases.

The Schrödinger equation for an electron under an electric field is

$$-\frac{\hbar^2}{2m^*} \frac{d^2 \Phi(z)}{dz^2} + V(z) \Phi(z) + eFz \Phi(z) = E \Phi(z)$$  \hspace{1cm} (1)

where $m^*$ and $F$ denote the effective mass of an electron and the electric field, respectively, and the confinement potential $V(z)$ is given by

$$V(z) = \begin{cases} 
V_{c}, & z < -c \\
-\frac{10V}{2L}(z+b), & -c < z < -b \\
V_{b}, & -b < z < -a \\
-V_{0}, & -a < z < a \\
V_{a}, & a < z < b \\
-\frac{10V}{2L}(z-b), & b < z < c \\
V_{a}, & z > c 
\end{cases}$$  \hspace{1cm} (2)

where $|a| = L_a/2$, $|b| = (L_0/2) + L_b$, $|c| = (L_0/2) + L_b + L$ ($L$ is the graded quantum well width, $L_b$ is the barrier’s width, $L_a$ is the central quantum well width), and $V_b = V$ is the barrier height. After the subband energies and their corresponding wave functions were obtained, we also calculated the absorption coeffi-
cient for the intersubband transitions. The absorption coefficient for the intersubband transitions is given by [9, 10]

\[
\alpha = \sum_i \sum_f \frac{\mu c m_i k e T c^2}{\hbar^2 m_0^2 N_i \omega} (\cos^2 \theta) |M_{fi}|^2 \\
\times \ln \left[ 1 + \exp \left( \frac{E_i - E_f}{k_B T} \right) / 1 + \exp \left( \frac{E_f - E_i}{k_B T} \right) \right] \left( \frac{(\Gamma/2)^2}{(\hbar \omega - E_f)^2 + (\Gamma/2)^2} \right)
\]

(3)

with the matrix element

\[
M_{fi} = \frac{m_0 (E_i^{(f)} - E_i^{(i)})}{i \hbar} \int \Phi_i^*(z) z \Phi_f(z) \, dz
\]

(4)

where \( E_i^{(f)} - E_i^{(i)} \) denote the quantized energy levels for the initial and final states, respectively, \( E_i \) and \( E_f \) are the Fermi energy which depends on the density of electrons in the well, and \( \Gamma \) is the linewidth. For the refractive index we use the first-order Sellmeier equation [11]:

\[
n^2 = A + B \left( \frac{\lambda^2}{\lambda^2 - C^2} \right)
\]

(5)

with \( A = 8.950, B = 2.054, C^2 = 0.390 \) for \( T = 298 \, \text{K} \) [12], \( E_F = 6.49 \, \text{meV} \) which corresponds to about \( n_e = 1.6 \times 10^{17} \, \text{cm}^{-3} \) electrons in the well, \( \theta = 0 \), and \( \Gamma = 10 \, \text{meV} \) from the experimental results [13].

3 Results and discussion

In the numerical calculation we have chosen the following parameters: \( L = 100 \, \text{Å}, L_0 = 40 \, \text{Å}, L_b = 20 \, \text{Å}, V_b = 200 \, \text{meV} \). The variation of the absorption coefficient for the 1–2 transition as a function of the incident photon energy for the TGQW1, TGQW2, and TGQW3 structures for electric fields \( F = 0 \) and 30 kV/cm is shown in Fig. 2. As can be seen, for \( F = 0 \), as the depth of the central well potential \( (V_0) \)
increases both the magnitude of the absorption coefficient and the resonance photon energy increase. By changing the depth of the central well potential, we can tune the resonance photon energy for the 1–2 transition since the resonance photon energy difference between the TGQW1 and TGQW3 structures is approximately 55 meV. This tunability gives a possibility for near-infrared electro-absorption modulators and detectors. When the electric field is applied, the absorption peak position for TGQW1 ($V_0 = 0$) shifts to higher photon energies, while those for TGQW2 ($V_0 = 50$ meV) and TGQW3 ($V_0 = 100$ meV) shift to lower photon energies.

In Fig. 3, for the 2–3 transition, the variation of the absorption coefficient is given as a function of the incident photon energy for the three TGQW structures in the cases $F = 0$ and 30 kV/cm. As the depth of the central well potential increases, both the magnitude of the absorption coefficient and the resonance photon energy decrease, since the overlap decreases between the second and third subbands. The absorption peak position for the TGQW1 structure shifts to lower photon energies while those for the TGQW2 and TGQW3 structures shift to higher photon energies with the application of the electric field. The TGQW2 and TGQW3 structures are very sensitive to the electric field compared to the TGQW1 structure.

The variation of the absorption coefficient for the 1–3 transition as a function of the incident photon energy for all TGQW structures under an electric field ($F = 30$ kV/cm) is shown in Fig. 4. The 1–3 transition is forbidden for $F = 0$, but becomes allowed when $F \neq 0$. The absorption peak position for the 1–3 transition is at a higher photon energy for TGQW3 than those for TGQW2 and TGQW1, due to the geometric confinement.

In order to see the difference between the TGQW structure and a triple square quantum well (TSQW), the variation of the absorption coefficient for the 1–2 transition as a function of the incident photon energy for a TSQW structure having the same physical parameters as the TGQW structure for $F = 0$ and 30 kV/cm is shown in Fig. 5. It can be seen that with zero field the 1–2 transition peak is observed only for TSQW3 ($V_0 = 100$ meV) while it is not observed for TSQW1 ($V_0 = 0$) and TSQW2 ($V_0 = 50$ meV), in contrast to the three TGQW systems. When the electric field is applied, the 1–2 transition peak is observed for all the TSQW structures, and as the depth of the central well potential increases the resonance photon energy decreases and the magnitude of the absorption coefficient increases. For the TGQW3 structure, the resonance photon energy difference between the $F = 0$ and 30 kV/cm electric field values is
approximately 20 meV (curves 3 in Fig. 2); this difference for the TSQW3 structure having the same physical parameters as TGQW3 is approximately 10 meV (curves 3 in Fig. 5). As a result, we can say that the conventional square QW has a large dipole moment but shows too small a Stark effect to be of practical interest.

Fig. 4  Variation of the absorption coefficient for the 1–3 transition as a function of the incident photon energy for the TGQW1, TGQW2, and TGQW3 structures for $F = 30 \text{kV/cm}$.

Fig. 5  Variation of the absorption coefficient for the 1–2 transition as a function of the incident photon energy for a triple square QW structure for $F = 0$ and 30 kV/cm.
4 Summary

We have investigated the intersubband absorption coefficient of TGQW structures as a function of the incident photon energy by changing the depth of the central well potential and by applying an electric field parallel to the growth direction. In addition, in order to see the difference between the TGQW and TSQW structures, we obtained the intersubband absorption coefficient for the 1–2 transition for a TSQW structure having the same physical parameters as the TGQW structure. It is concluded that TGQW structures have more advantages for near-infrared electro-absorption modulator and detector applications than the TSQW structures. To the best of our knowledge, this is the first study of intersubband transition in TGQW structures and the results obtained are in good agreement with those of Ref. [5]. We believe that such an analysis may provide a helpful guide for the engineering of new optoelectronic devices.

References