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Electron transmission through non-tunneling regime of GaAs-AlGaAs Coupled Quantum Well

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We have investigated electron transmission through non-tunneling regime of a semiconductor nanostructure called Coupled Quantum Well (CQW). Oscillatory transmission coefficient as a function of energy is found to show spectacular waxing and waning in amplitude. Corresponding features are expected to be observed in optical (Physical Review B **54** (1996) 1541) and quantum transport (Physical Review Letters **58** (1987) 816) experiments and hence the results besides verifying the Physics will have impact on future devices based on CQW.

I. Introduction

With development of molecular beam epitaxy, two-dimensional systems similar to Quantum Wells (QWs) have been intensely studied in the past two decades and the results are about confined states in QWs. In recent years, however, people have investigated unbound states[3-23] in a series of semiconductor heterostructures including QWs. G Bastard[3] presented theoretical study of continuum states of QW of "separate confinement heterostructures". G. Bastard et al.[4] studied bound and virtual bound (resonant) levels of GaAs-AlGaAs CQWs and showed parametric variation of energy levels. G. Bastard[5] presented results of calculations of bound and virtual bound states of QWs, "separate confinement heterostructures" and superlattices. M. Heiblum et al.[6] reported theoretical and experimental study of electrons transmission through non-tunneling regime of QW structures and ventured to relate transmission coefficient with I-V characteristics. W. Trzeciakowski et al.[7] presented a simple method of calculating global density of states in resonant tunneling structures. S. Fafard[8] have studied transmission coefficient in non-tunneling regime of QWs. Jian-Ping Peng et al.[9] have studied transmission coefficient in non-tunneling regime of double barrier structures; they presented analytical results of life-time for both quasi-bound and extended resonant states. W. Trzeciakowski et al.[10] have studied change in density of states in above barrier states of symmetric and asymmetric QWs introduced by some localised potential. W. Trzeciakowski et al.[11] have derived dispersion relations connecting transmission amplitude and change of density of states introduced by scattering potential. Marcello Colocci et al.[12] have demonstrated existence of above-barrier states in double barrier QW structures. C. D. Lee et al[13] have reported direct observations of numerous above barrier states in QW structures. W. Lu et al.[14] have demonstrated existence of above-quantum-step quasi-bound states in QW heterostructures. R. Ferreira and G. Bastard[15] have presented an excellent review of unbound states in quantum heterostructures.

Bandgap engineering provides possibility of controlling electronic and optical properties of semiconductor QW heterostructures by varying layer thickness and material compositions. Several non-conventional structures have been proposed and realized for both investigating peculiar aspects of carrier physics and improving performances of QW devices. Two quantities have been frequently used to characterize the properties: transmission coefficient and density of states. Now-a-days people are more interested about QW applications in next generation applications in nanoscale. C. S. Liu[16] investigated exciton dynamics in CQW. Wei Wei et al.[17] conducted a study on TMD QWs and the results indicate that QWs hold promise in wide range of applications. More recent work can be found in reference[18, 19].

S. Chowdhury and C. C. Sarker[20] investigated electron transmission through non-tunneling regime of isolated QW and found oscillations in transmission coefficient versus energy curves monotonic in amplitude. S. Chowdhury and M. Hasan[21] investigated electron transmission through non-tunneling regime of single rectangular tunnel barrier and also found oscillations in transmission coefficient versus energy curves monotonic in amplitude. P. Sutradhar and S. Chowdhury[22] investigated electron transmission through non-tunneling regime of symmetric rectangular double barrier and found spectacular waxing and waning in amplitude of oscillatory transmission coefficient versus energy curves. S. Chowdhury and A. Rahman[23] obtained parametric variations of energy of transmission peaks of symmetric rectangular double barrier in non-tunneling regime and found to their surprise that one of the 3 parametric variations in non-tunneling regime is completely different from that in tunneling regime.

This paper presents a theoretical study of transmission of electron through non-tunneling regime of GaAs-AlGaAs CQW. The paper is organized as follows. In sec. II, we present analytical results on transmission coefficient of CQW. A discussion of the results is reported in sec. III and the concluding remarks are given in Sec. IV.

II. Transmission coefficient of Coupled Quantum Well for non-tunneling regime

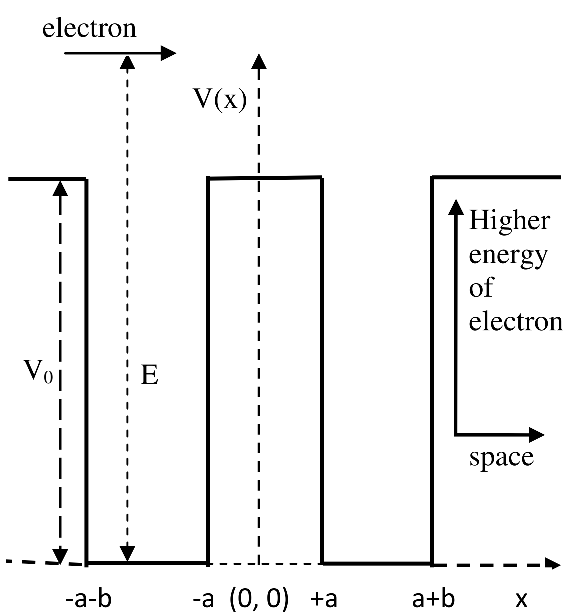


FIG. 1. Band model of GaAs-AlGaAs Coupled Quantum Well in conduction band. V_0 is taken as conduction band offset 773x meV where x is Al content of $Al_xGa_{1-x}As$.

Using the potential energy profile of Fig 1, we have calculated transmission coefficient T(E) of Coupled Quuantum Well for E > V_0 i.e. for non-tunneling regime and obtained

$$T = \frac{T_1^2}{T_1^2 + 4(1-T_1)\cos^2[\beta(2a+b)-\theta]} \quad \text{------(1)}$$

where $T_1 = \dfrac{1}{1 + \dfrac{1}{4}\dfrac{V_0{}^2}{E(E-V_0)}\sin^2\left(b\sqrt{\dfrac{2mE}{\hbar^2}}\right)}$,

$$\theta = -\tan^{-1}[\frac{1}{2}(\frac{\alpha}{\beta}+\frac{\beta}{\alpha})\tan\alpha b] + b\beta ,$$

$$\alpha^2 = \frac{2mE}{\hbar^2} ,$$

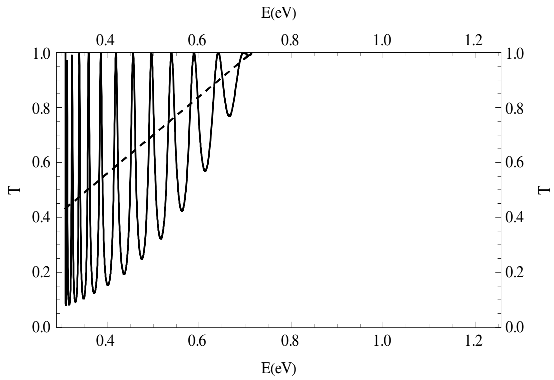
$$\beta^2 = \frac{2m(E-V_0)}{\hbar^2}$$

Here T_1 is transmission coefficient of single Quantum Well.

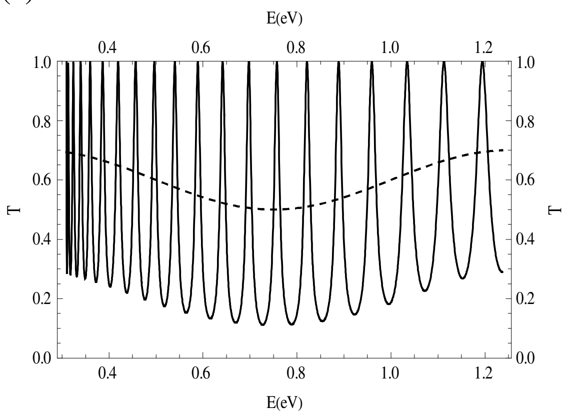
III. Results and discussions

We have used the equations of section II in the form of programs written in Mathematica and have plotted T as function of E and investigated characteristic features of the T versus E curves. Typical T versus E curve is shown by undashed curves in Fig. 2(c) and (d); looking at these curves, we find striking amplitude modulated oscillatory behaviour of T versus E curve of Coupled Quantum Well for non-tunneling regime. Amplitude of the oscillations show spectacular waxing and waning as a function of energy E.

Key to understanding the oscillations and the waxing and waning of amplitude of oscillations is equation (1) in which we find that for a given value of T_1, the oscillations result from oscillatory $\cos^2[\beta(2a+b)-\theta]$ term which oscillates between 0 and 1. As such T oscillates between 1 and $\dfrac{T_1^2}{T_1^2 + 4(1-T_1)}$. Maxima of T are always 1 but minima are $T_{min} = \dfrac{T_1^2}{T_1^2 + 4(1-T_1)}$ which is lower or smaller if T_1 is lower. Thus oscillatory T_1 as function of E causes waxing and waning of amplitude of oscillations of T versus E curve.



(a)

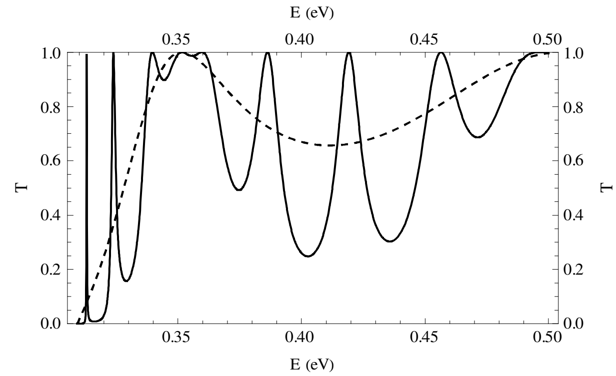


(b)

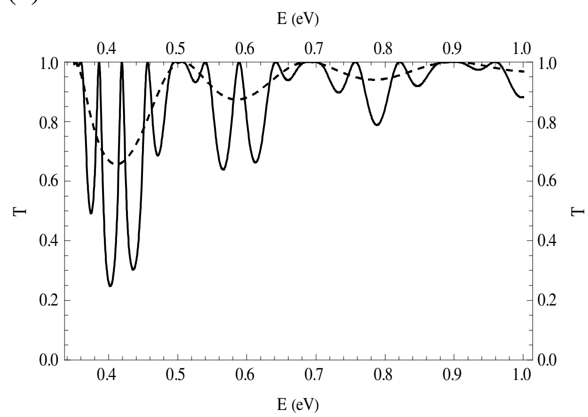
We now demonstrate this using model variations of T_1 as function of E: $T_1 = 1.4$ E for Fig 2(a), and $T_1 = 0.6+ 0.1\sin(2\pi E/1)$ for Fig 2(b). In Figure 2(a), dashed curve shows T_1 rising linearly as a function of E; as such, amplitude of oscillations in undashed T vs E curve wanes rapidly as E rises.

In Figure 2(b), dashed curve shows T_1 reducing from 0.7 to 0.5 before rising again to 0.7 as E rises; as such, amplitude of oscillations in undashed T vs E curve waxes before waning.

We now demonstrate variation of amplitude of oscillations of T versus E curves for actual variations of T_1 as function of E. See Fig 2(c) and (d). In Fig 2(c), as E rises from V_0 to 0.35 eV, dashed curve shows T_1 rising rapidly from 0 to 1; as such undashed curve shows rapid waning in amplitude of T vs E curve in this energy range; compare with Fig 2(a). Between E = 0.35 eV and 0.5 eV in Figure 2(c), T_1 reduces from 1 to 0.65 before rising to 1. As such, as undashed curve in Fig 2(c) shows, oscillations in T vs E curve wax in amplitude before waning; Fig 2(d) shows a series of such waxing and waning in amplitude of T vs E curve.



(c)



(d)

FIG. 2. Undashed: T versus E curve of Coupled Quantum well for non-tunneling regime. Dashed: T_1 versus E curve of single QW. For QW width b = 20 nm, Tunnel barrier width 2a = 36 nm, Al content of $Al_xGa_{1-x}As$ x = 0.4. Dashed curves in (a) and (b) show T_1 as function of E for model variation of T_1 given by (a) $T_1 = 1.4$ E, (b) $T_1 = 0.6+ 0.1\sin(2\pi E /1)$ and dashed curves in (c) and (d) show actual variation of T_1 as a function of E.

IV. Conclusions

To conclude, we have found spectacular waxing and waning in transmission coefficient versus energy curves of Coupled Quantum Well for non-tunneling regime. It provides the possibility of controlling the electronic and optical properties of semiconductor Quantum Well heterostructures by varying the layer thickness and material compositions. We believe that the observed waxing and waning in amplitude might be of some relevance towards the realization of novel Quantum Well devices. Corresponding features are expected to be observed in optical[13] and quantum transport[6] experiments and hence the results will have impact on future devices based on Coupled Quantum Well.

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