

FIELD INDUCED OPTICAL TRANSITIONS IN SEMICONDUCTOR QUANTUM WELLS

Z. Ikonić¹⁾, V. Milanović^{1,2)}

1) Faculty of Electrical Engineering, Bulevar Revolucije 73,
11000 Beograd, Yugoslavia

2) High PTT School, Zdravka Čelara 16, 11000 Beograd, Yugoslavia

Abstract

Optical transition matrix elements between various virtual levels in a semiconductor quantum well in electric field are analyzed in this paper. We found that, contrary to lowest levels, transition matrix element which monotonically decrease with increasing field, those connecting higher levels have qualitatively different behaviour. Specifically, for even-odd transitions being forbidden at zero field, the corresponding matrix elements first increase, pass through a maximum and then decrease with increasing field. At maximums they may reach rather high values and therefore may constitute a major part of quantum well absorption.

1. INTRODUCTION

Recently great attention has been attracted to the problem of light absorption of a semiconductor quantum well (QW) in perpendicular electric field¹⁾. While most papers deal only with lowest electron and hole levels transitions, it is also of some interest to examine transitions between higher levels of the well.

In this paper we shall analyze dependence of envelope transitions matrix elements between various virtual levels of electrons and heavy holes on electric field, taking into account the effective mass discontinuity at the well/bulk boundaries.

2. THEORETICAL CONSIDERATIONS

It is well known that upon application of electric field K the energy spectrum of a quantum well with finite barrier, strictly speaking, becomes continuous. — the former-

ly discrete levels turn to virtual levels (resonances). As shown in our paper²⁾, the resonances energies are determined from expression (for electrons and similarly for holes):

$$[Ai(\xi_{10})Bi'(\xi_{20}) - R_e Ai'(\xi_{10})Bi(\xi_{20})] [Ai(\xi_{2d})Bi'(\xi_{1d}) - \frac{Ai'(\xi_{2d})Bi(\xi_{1d})}{R_e}] + \quad (1)$$

$$[R_e Ai(\xi_{20})Ai'(\xi_{10}) - Ai(\xi_{10})Ai'(\xi_{20})] [Bi(\xi_{2d})Bi'(\xi_{1d}) - \frac{Bi'(\xi_{2d})Bi(\xi_{1d})}{R_e}] = 0,$$

$$R_e = (m_2/m_1)^{2/3}; \xi_{10} = \xi_1 (z=0), \xi_{2d} = \xi_2 (z=d) \text{ etc.} \quad (2)$$

$$\xi_1(z) = -\left(\frac{2m_1 eK}{\hbar^2}\right)^{1/3} \left(z + \frac{E_0 - U_0}{eK}\right); \xi_2(z) = -\left(\frac{2m_2 eK}{\hbar^2}\right)^{1/3} \left(z + \frac{E_0 + E_{tR}}{eK}\right). \quad (3)$$

where z – axis is perpendicular to QW plane and colinear with field. In the above expressions m_1 and m_2 are the electron effective masses in the bulk and the well, V_0 is the conduction band discontinuity, E_0 is difference between the total electron energy and the transversal energy in bulk, E_{tR} is difference between bulk and well transversal energy, Ai and Bi are the two linearly independent solutions of Airy equation³⁾. Depending on the well and the bulk parameters eq. (1) may have one or more (N) solutions $E_0 = E_{Ri}$ ($i = 1, 2, \dots, N$), giving energies of resonances arising from bound levels of the well.

Although, the energy spectrum in the case of finite field is strictly continuous, one can, as shown in²⁾ make very good approximation in treating the well absorption in not too high fields, by using the quasi-discrete spectrum model. This approximation, valid for narrow resonances, consists in using only the wave functions calculated at exact resonances in evaluation of transition matrix elements, instead of using the whole set of continuous spectrum of wavefunctions.

When evaluating the matrix element, we take the electron and hole wavefunctions ψ_e and ψ_h at resonances in the region around the well (and exclude their asymptotic parts far from the well) and normalize them to unity in this region. Within this approximation, the envelope matrix element for transition between i -th electron and j -th hole virtual level is given by:

$$M_{ij} = \int_{-\infty}^{+\infty} \psi_{ei}^* \psi_{hj} dz. \quad (4)$$

Upon irradiation of QW structure with photons with energy $\hbar\omega$, the absorption on (i, j) transitions will appear if $\hbar\omega > \hbar\omega_0(i, j) = E_g + E_{Ri} + E_{Rj}$ (E_g is the QW semiconductor band gap). Both E_{Ri} and E_{Rj} depend on electric field K and so does $\hbar\omega_0(i, j)$.

3. DISCUSSION AND NUMERICAL RESULTS

At zero field the bound level envelope wavefunctions in the well have definite parity (even for odd-numbered, and odd for even-numbered levels). Therefore, as pointed in⁴⁾ the transitions between opposite parity electron and hole levels are forbidden becau-

se of zero transition matrix elements connecting them. On the other hand, the even-even and odd-odd transitions are allowed, where large values of matrix elements correspond to transitions between same indices levels, and generally small ones to different indices⁴⁾.

Upon application of electric field two effects appear that influence the transition matrix elements. First, the well potential ceases to be symmetric and therefore the wavefunctions loose their definite-parity properties, implying disappearance of odd-even transition forbiddness. Second, the envelope wavefunctions deform, with hole wavefunctions „moving” in the field direction and electron ones in the opposite sense. Therefore, with increasing field the even-odd transition matrix elements will, after the starting increase, begin to decrease because of lowered overlapp of electron and hole wavefunctions. For transition between same indices levels, however both these effects induce the matrix elements decrease with increasing field. Finally for same-parity-different-indices transitions, which are only slightly allowed in the absence of the field⁴⁾, we can roughly guess that the matrix elements will increase with increasing field, at least for not too high fields.

It is known that the difference between the lowest virtual levels or between one lowest and one higher level decreases with increasing field⁵⁾, while that between between both higher levels increases for smaller fields and decreases for higher. Therefore, making an appropriate choice of photon energy, say $\hbar\omega < \hbar\omega_0(i, j)$ at $K = 0$, where at least one of (i, j) is equal to one, one can switch on the absorption on (i, j) transitions by increasing the field. With further field increase, of course, the absorption will change in the same way as does the corresponding envelope matrix element squared. On the other hand the absorption on transitions between both higher virtual levels can as well be switched off by increasing the electric field.

We did numerical calculations for $d = 10$ nm thick GaAs QW in $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ bulk. In Fig. 1 the $\hbar\omega_0(i, j)$ vs. K dependence is given. As one can see, from this figure, for not too high fields (up to 10^7 V/m), energies for (2,2) and (2,3) transitions increase

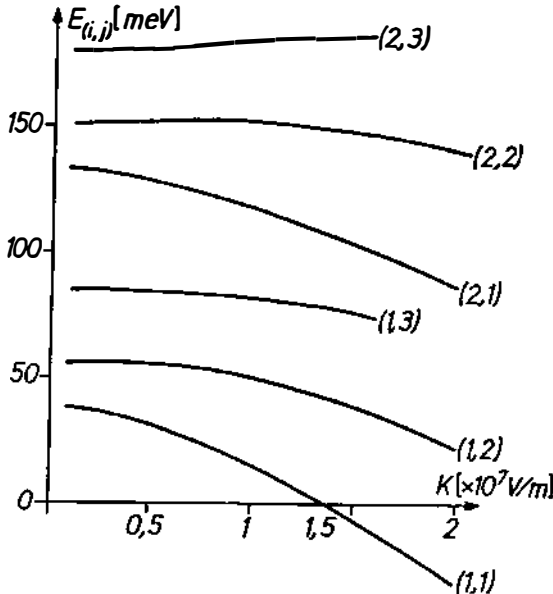


Fig. 1. $\hbar\omega_0(i, j) - E_g$ vs. K dependence for $d=10$ nm thick GaAs QW in $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ bulk, for the first two electron and first three heavy hole virtual levels.

and others, including lowest levels decrease with field. However, beyond 10^7 V/m $\hbar\omega_0$ (2,2) begins to decrease, as well. The dependence envelope matrix elements squared for various transitions is given in Fig. 2. Inspection of this Figure reveals that same indices transition matrix elements decrease considerably with increasing field (that for (2,2) being more sensitive than for (1,1)). Furthermore, the even-odd transition matrix elements may reach high values in the range of the „middle fields” ($\sim 1.5 \cdot 10^7$ V/m in this example), implying that these field induced (and previously forbidden) transitions may give a major part of the fall QW absorption for appropriate photon energies.

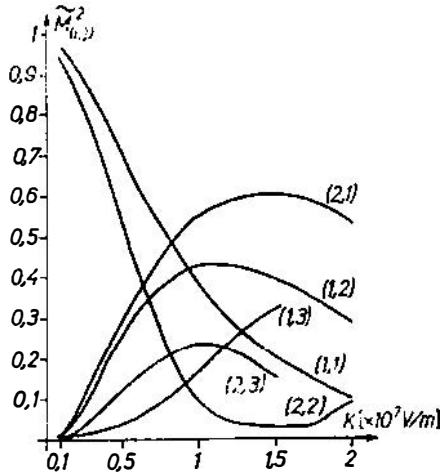


Fig. 2. The transition envelope matrix elements squared vs. field dependence for QW with parameters as in Fig. 1.

4. CONCLUSION

In this paper we analysed the influence of electric field perpendicular to the QW layer plane on interband optical transition matrix elements. We gave the expression (1) from which all energies of virtual levels (resonances) in QW in electric field may be determined. The envelope transition matrix elements are evaluated within the quasi-discrete spectrum model (narrow resonances limit), being valid for not excessively high field. Matrix elements between same index levels monotonically decrease with increasing field, that for (2,2) transition being more sensitive than for (1,1) one. For even-odd transitions, being parity-forbidden at zero field, the corresponding matrix elements first increase for lower fields and decrease for higher fields (Fig. 2). In the „middle” field range they get high values, i.e. these transitions become highly allowed, and may play a major role in light of absorption of QW if the photon energy is large enough. Thus, this effect is far more enhanced in QW's than in isolated atoms, where field induced metastable-ground level transitions may become only slightly allowed for practical field values.

Acknowledgements

The authors would like to express their sincere thanks to Prof. D. Tjapkin for valuable discussions and for important suggestions. The authors also wish to express thanks to Lj. Radoja and G. Andjelković for technical presentation.

REFERENCES

1. M. Glick et al. *Helv. Phys. Acta*, **58** (1985) 403;
2. Z. Ikonić, V. Milanović, D. Tjapkin, *J. of Phys. C* (in print);
3. M. Abramowitz, I. A. Stegun, *Handbook of Mathematical Functions*, N. Y. Dover Publ., 1964;
4. A. Ya. Schik, *Pisma v ZhTF*, **5** (1979) 869;
5. G. Bastard et al. *Phys. Rev.* **B31** (1983) 3241.