Proceedings of the XXV International School of Semiconducting Compounds, Jaszowiec 1996

PHOTON ASSISTED TUNNELING IN ZnSe–ZnTe DOUBLE BARRIER HETEROSTRUCTURES

P. BAŁA

Institute of Physics, N. Copernicus University, Grudziądzka 5, 87-100 Toruń, Poland

The tunneling phenomena in double barrier heterostructures can be affected by various effects. In this paper the effect of the intense THz radiation on the electron dynamics in the double barrier heterostructure is investigated. For the low frequency radiation the shift in the energy scale of the resonant tunneling peak together with its broadening is observed. For the high radiation frequency the multipeak structure is obtained. The interaction with radiation quanta leads to sequential tunneling and the transmitted wave function consists of single separated wave packets.

PACS numbers: 03.65.-w, 73.40.Gk

Resonant tunneling through double barrier structures makes these systems very promising candidates for new generation of ultra high speed electronic devices [1]. The operating frequency of such devices allows for their applications as the integrated microwave generators. Moreover, the device interaction with the electromagnetic radiation is considered to have very interesting applications. High frequency electromagnetic field influences significantly carrier dynamics in low-dimensional structures and the time-dependent methods are required for the proper description of such phenomena.

Recently the experimental evidence of splitting of the resonant tunneling peak of the heterostructure placed in the intensive THz field has been reported [2–4]. The signs of photon assisted tunneling have been also reported in semiconductor superlattices [5] and quantum dots [6].

The interaction of the carriers with the photons can be described, in the first approximation, as the dipole interaction with the oscillating electric field of frequency corresponding to the photon energy $\hbar\omega$. The photon assisted tunneling can be investigated in the two main regimes. For small photon energies the device acts as a classical energy detector, while for higher photon energies absorption of the single photon can lead to the tunneling of the additional electron. Additionally, for the high field strength, multiphoton processes may become important. The absorption and emission of the radiation quanta will lead to the splitting of the resonant tunneling peak. With the increase in the photon energy the multiphoton emission and absorption can take place and multiple satellite peaks should occur.

The standard description of the system interacting with the radiation field is based on the stationary or quasi-stationary (Flequet) approach and gives no information about the tunneling dynamics. The adiabatic change of the electron energy in the high frequency electric field is assumed and the tunneling current in presence of the ac field can be expressed in terms of the current without irradiation shifted by the photon energy. Interesting features are expected to appear in the irradiated structure at the voltages shifted by $\pm n\hbar\omega/e$ compared to the original resonant peak of the tunneling characteristics. The relative replica size depends on the strength of the radiation field. This effect becomes important when the voltage drop across the barrier due to the ac field becomes comparable to the photon energy.

In this paper we introduce, for the first time, interaction of the carriers with the photons to the time-dependent description of the tunneling phenomena [7, 8]. This allows us to obtain proper analysis of the photon assisted tunneling in the limit of both high and low frequencies.

The double barrier resonant tunneling structure is formed by n-type ZnSe layer of width $d_W = 47.6$ Å (quantum well) surrounded by p-type ZnTe layers of width $d_B = 26.4$ Å (barrier region). The height of the barrier is $V_0 = 0.59$ eV which results in the presence of one discrete energy level in the well ($E_0 = 0.38$ eV). The structure is placed between wide n-type ZnSe layers (with length greater than 1000 Å). The system is investigated under constant voltage V applied along the growth direction. The linear potential changes only in the barrier regions are assumed [8]. Within electrical dipole approximation the electron photon coupling is described in the Hamiltonian by the oscillating electric field added to the double barrier potential

$$V_{ac}(x,t) = \mathcal{E}_x x \cos(\omega t). \tag{1}$$

As a result, the electron is placed in the time-dependent potential. The electron dynamics is obtained by solving, within effective mass approximation [9], the time-dependent Schrödinger equation

$$i\hbar \frac{\partial \Psi(x,t)}{\partial t} = \left(-\frac{\hbar^2}{2m^*}\frac{\partial^2}{\partial x^2} + V_B(x) + V_{ac}(x,t) \right) \Psi(x,t), \tag{2}$$

where m^* is the electron effective mass and depends on the layer type ($m^*_{ZnSe} = 0.16 m_e$, $m^*_{ZnTe} = 0.32 m_e$). and $V_B(x)$ denotes static double barrier potential with external voltage applied to the structure. The time-dependent Schrödinger equation (2) is solved using discrete grid methods as it was reported previously [10, 11]. The initial wave function is of the Gaussian shape, and its parameters, time step and the grid size are the same as in the previous papers [7, 12]. The intensity of the electromagnetic field $E_x = 102.85$ kV/cm is chosen in the high intensity limit to emphasize the multiphoton effects.

The tunneling probability calculated with the absence of the electromagnetic radiation exhibits single resonant peak at the applied voltage $V_p = 0.77$ V. The oscillating electric field applied across the structure changes significantly the tunneling probability characteristics. As is presented in Fig. 1 the tunneling probability shows different behavior for the low ($\hbar\omega < 0.01$ eV) and high ($\hbar\omega > 0.01$ eV) frequencies of the ac field.

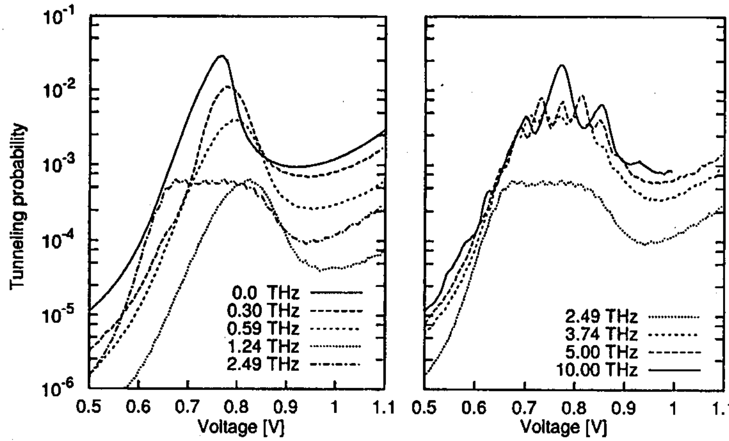

Fig. 1. Tunneling probability for the double barrier ZnTe/ZnSe/ZnTe structure for the different frequency of electromagnetic radiation.

For the low frequencies ω one tunneling peak is observed. However, the resonant tunneling peak is broadened and shifted to the higher energies. The maximal tunneling probability is lowered. With the increase in the photon energy the tunneling peak becomes wider and multipeak structure appears. Further increase in the ac field frequency leads to the better resolution of the multipeak structure. The peak amplitude and peak separation in the energy scale increase with the photon energy. For the highest investigated photon energy $\hbar\omega = 0.0414$ eV (10 THz) the amplitude of the central resonant peak is similar to that in the absence of the electromagnetic radiation. This shows that tunneling is not significantly suppressed, however, the width of the resonant tunneling peak is smaller compared to the one with absence of the electromagnetic field. The amplitudes of the satellite peaks decrease with the photon energy and are lower than that of the main peak. The energy position of the satellite peaks changes almost linearly with the increase in the photon energy.

The obtained results are consistent with the stationary or quasi-stationary approach. In the low frequency limit the oscillating field $V_{\mathrm{ac}}(x,t)$ varies slowly compared to the time scale of the tunneling process. As a result, the electron effectively feels almost constant double barrier potential modified by the slowly varying linear term. In consequence, the shift of the position of the discrete energy level in the quantum well is obtained, which is observed as the shift of the resonant tunneling peak position. In turn, the presence of the multipeak structure in the high photon frequency limit can be viewed as tunneling to photon side bands of a state in the quantum well. The energy of side bands $E_0 \pm n\hbar\omega$ is in good agreement with the observed peak positions.

The presented simple picture cannot be applied in the region of moderate photon energies close to 0.01 eV. The time-dependent tunneling characteristics presented in Fig. 2 show that initially, for the time up to 0.2 ps, only one broadened

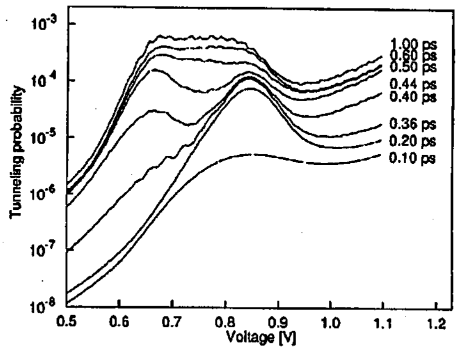

Fig. 2. The tunneling probability characteristics at the different times in the electromagnetic field of frequency 2.49 THz.

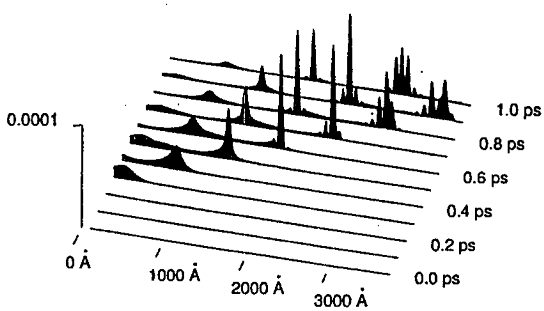

Fig. 3. The transmitted wavefunction in the region right to the double barrier structure at the different times. The voltage applied across the structure is 0.775 V and the frequency of the electromagnetic radiation $\omega/2\pi = 5.00$ THz.

and shifted resonant tunneling peak is observed. After that the second peak at the voltage 0.66 V develops. Finally, at the time 0.6 ps the multipeak structure develops. In the THz field the tunneling process is stepwise except for the low frequency limit. The transmitted wave function, as presented in Fig. 3, splits to the nearly Gaussian wave packets separated by 0.2 ps. The width of transmitted wave packets is smaller than when electromagnetic radiation is absent [8, 12] and reflects the energetic width of the photonic quasi-levels. The interaction with the electromagnetic radiation splits transmitted wave packets into smaller packets.

In conclusion, the detailed time-dependent picture of the photon assisted resonant tunneling phenomena in the double barrier structure is presented. The obtained results allow for understanding of the process and better interpretation of the experimental data.

This work is supported in part by the Committee for Scientific Research under grant No. P03B 156 10. The calculations were partially performed on CRAY YMP in the Interdisciplinary Centre for Mathematical and Computational Modelling at Warsaw University.

References

[1] T.C.L.G. Sollner, W.D. Goodhue, P.E. Tannewald, C.D. Parker, D.D. Peck, *Appl. Phys. Lett.* **43**, 588 (1983).

[2] S. Zeuner, B.J. Keay, S.J. Allen, K.D. Maranowski, A.C. Gossard, U. Bhattacharya, M.J. Rodwell, *Phys. Rev. B* **53**, R1717 (1996).

[3] H. Drexler, A.J.S. Scott, S.J. Allen, K.L. Campman, A.C. Gossard, *Appl. Phys. Lett.* **67**, 2816 (1995).

[4] B.J. Keay, S. Zeuner, S.J. Allen, K.D. Maranowski, A.C. Gossard, U. Bhattacharya, M.J.W. Rodwell, *Phys. Rev. Lett.* **75**, 4102 (1995).

[5] P.S.S. Guimaraes, B.J. Keay, J.P. Kaminiski, S.J. Allen, P.F. Hopkins, A.C. Gossard, L.T. Folrez, J.P. Harbison, *Phys. Rev. Lett.* **70**, 3792 (1993).

[6] L.P. Kouwenhoven, S. Jauhar, J. Orenstein, P.L. McEuen, Y. Nagamune, J. Motohisa, H. Sakai, *Phys. Rev. Lett.* **73**, 3443 (1994).

[7] P. Bała, R. Ryszewski, W. Bała, *Acta Phys. Pol. A* **84**, 685 (1993).

[8] P. Bała, W. Bała, *Appl. Phys. A, Solids Surf.* **60**, 293 (1995).

[9] R. Tsu, L. Esaki, *Appl. Phys. Lett.* **2**, 562 (1973).

[10] P. Bała, J.S. Kwiatkowski, W. Bała, *Acta Phys. Pol. A* **82**, 649 (1992).

[11] H. Tel-Ezer, R. Kosloff, *J. Chem. Phys.* **81**, 3967 (1984).

[12] P. Bała, R. Ryszewski, W. Bała, *Acta Phys. Pol. A* **87**, 341 (1995).