A peculiarity of quantum hot-electron real space transfer in dual-channel GaAs-based heterostructures

V V Vainberg, O G Sarbey, A S Pylypchuk, V N Poroshin and N V Baidus

1 Institute of Physics, National Academy of Sciences of Ukraine, 46 prospekt Nauki, Kiev 03028, Ukraine
2 Physical-Technical Research Institute, N.I. Lobachevsky State University, 603950 Nizhny Novgorod, Russia
E-mail: vainberg@iop.kiev.ua

Keywords: coupled quantum wells, hot electrons, real-space transfer, selective doping, superlattice

Abstract

The model has been proposed for calculation of the electron transport via the double conducting channels formed in heterostructures with the tunnel-coupled quantum wells with the essentially different mobility of electrons. Experiments to test the dependences of the transport characteristics on the temperature and electric field were carried out on the heterostructures based on GaAs. The well with a high electron mobility was formed as an AlGaAs–GaAs–AlGaAs undoped quantum well. The tunnel-coupled well was formed either by a delta layer of impurity or a short-period superlattice (SPSL) fragment. Based on comparison of the experimental and calculated data, it is established that the electron temperatures in such coupled channels in the course of heating them by the electric field strongly differ from each other; their dependences in both wells on the electric field are found. This difference leads to a considerable redistribution of electrons between wells. For the structure with the SPSL fragment at fields more than 450 V cm⁻¹ an inversion of the electron population between the two lower size-quantization energy subbands takes place.

Introduction

First in 1972, Gribnikov [1] put forward the suggestion that a spatial redistribution of electrons heated by the electric field in the structures with potential wells and barriers could bring the negative differential conductivity (NDC) if the mobility of charge carriers in both regions differs essentially. His model supposed the redistribution to be due to thermionic emission of electrons from the wide wells to the barriers with no quantum effects involved. In 1979 Hess et al [2], independently, have come to the same conclusion. Based on this idea, a lot of different structures were used later in investigations and for applications [3].

Kirchoefer et al [4] obtained NDC by heating the electrons in the structure with two thin quantum wells having different quantum levels and separated by a thin barrier. The NDC was interpreted as a result of the spatial transfer of electrons by tunnelling from the deeper subband in one well to the shallower subband in another one, i.e., the quantum real-space transfer. Studies of the properties of such type structures attract attention up to now [5–8].

We have to point out that in the most of published papers devoted to this topic the electron temperatures in both quantum wells were supposed equal. However, from the physical point of view, such suggestion in the case of heating electrons by electric field in the quantum wells, in which the electron mobility significantly differs, draws big doubts. The matter lies in the fact that a strong enough energy exchange between the electrons in both coupled wells is needed in order to equalize the temperatures. The most efficient in such exchange are close collisions of electrons which commonly do not take place for the electrons in different wells. Therefore, the temperatures of electrons in them under heating in the electric field cannot be considerably coupled.

This issue takes on great significance in connection with the other intriguing effect—the inverse distribution of electrons in a system of two different tunnel—coupled quantum wells and the accompanying infrared radiation. It was proposed in [9, 10] and was a subject of investigations for some research teams [11] in a recent decade.
The goal of the present paper is to study the mentioned above issue and especially to show how big could be the difference in the electron temperatures and electron redistribution. It is based on comparison between the measured and calculated dependences of the electron transport characteristics on the temperature and electric field. These characteristics strongly depend on the redistribution of electrons between coupled wells that, in turn, strongly depends on the temperatures of electrons in them.

**Experimental details and results of measurements**

The samples chosen for investigations were the $\text{Al}_x\text{Ga}_{1-x}\text{As/GaAs/Al}_x\text{Ga}_{1-x}\text{As}$ heterostructures with $x = 0.15$. The corresponding offset in the conduction band bottom is 118 meV. The samples were grown by the MOVPE method on the (100)-plane of semi-insulating GaAs substrates. They consisted of 10 identical periods containing double-well units separated by the opaque for electrons barriers. Therefore, these units may be treated as independent conduction channels assembled together with the cyclic boundary conditions only. We consider the following two kinds of structures.

Each period of the first kind contained an 8 nm wide quantum well (QW1). At one side at the distance of 10 nm of it a delta-layer of the Si donor impurity with concentration of $5.4 \times 10^{11}$ cm$^{-2}$ was inserted. The impurity layer forms a potential well with 2D levels (QW2). The both wells are combined into a tunnel-coupled pair QW+ impurity well. The barrier width between the pairs of QW+ impurity delta layer is about 80 nm. The much lower electron mobility in the impurity well is ensured due to a strong impurity scattering. The shortcoming of this method to reduce the electron mobility consists in that it decreases the mobility in the neighbour quantum well (QW1) too.

The quantum well in the second type structures was 14 nm wide (QW1). At one side of it at the distance of 4 nm a SPSL fragment was grown. It was 28.5 nm wide and consisted of 10 periods of the 1.5 nm wide wells separated by the 1.5 nm wide barriers. We denote this sample as QW+SPSL. The structures were doped by Si into the 80 nm wide barriers separating the pairs QW-SPSL. The impurity was uniformly distributed in their central parts being 30 nm wide. $N_S = 1.4 \times 10^{13}$ cm$^{-2}$ per period.

A sufficiently strong scattering of electrons in SPSL is provided by the roughness of a large number of interfaces. The advantage in this case consists in that, unlike the impurity scattering, it does not spoil the electron mobility in the other coupled quantum well (QW1). The mobility in SPSL may be controlled independently.

The background donor impurity concentration, according to technological data, for both kinds of the samples used in experiment was $2 \times 10^{15}$ cm$^{-3}$.

The energy spectra for both structure types at 4.2 K calculated by self-consistent solution of the Schrodinger and Poisson equations are shown in figures 1(a) and (b). Note that the spectrum in SPSL is similar to the energy spectrum in a usual quantum well but with the lifted energy levels and slightly corrugated envelope wave functions. Consequently, we treat it as a one quantum well (QW2).

The experimental investigations included measurements of the temperature (in the range from 4.2 to 200 K) and electric field dependences of the Hall field and conductivity with the bridge-shaped four-probe samples. The measurements at strong electric fields were carried out at 4.2 K in the range of the lateral (i.e., parallel to the quantum well plane) electric field from 0 to 800 V cm$^{-1}$ in the pulse regime to avoid the Joule heating. The pulse duration was 1 $\mu$s, the repetition period was no less than 1 s. As the waveforms both of the voltage and current pulses with such duration were practically rectangular we concluded on absence of the Joule heating and other possible sources of measurements distortions. The bridge-shaped samples allow avoiding the distortion of results by the voltage drop at the current contacts and by the near-contact domains formed under strong lateral fields $[12]$.

In addition, the measurements of magnetoresistivity of the samples at 4.2 K and magnetic fields from 0 to 4.5 T were used with a view to determine the electron concentration in both wells from the FFT spectra of the Shubnikov–de-Haas oscillations. Figure 2 depicts, as an example, the FFT-spectrum for the sample with the delta-doping potential well $[13]$. It is seen that nearly all electrons in this sample at 4.2 K are in the QW1. The same conclusion is true for the sample with SPSL.

Figure 3 demonstrates the temperature dependence of the Hall mobility $\mu_{H}$ and figure 4 shows the current–voltage characteristics for both kinds of samples. We would like to note that here $\mu_{H}$ is determined as $\mu_{H} = \frac{e B}{E_{H}}$, where $B$ is the magnetic field induction, $E_{H}$ and $E_{L}$ are the Hall field and lateral electric field created by the external voltage source, respectively (see inset in figure 3). The magnitude of $E_{L}$ is derived from the voltage drop between the side potential contacts. Thus, the value of $\mu_{H}$ represents the electron mobility averaged over two wells.
Figure 1. The energy spectra of electrons in the samples QW + impurity well (a) and QW + SPSL (b). 1—the conduction band bottom profile; 2—the size-quantization levels and squared envelope wave functions. The dashed lines—the Fermi level. Impurity concentration, $N_S$, in $10^{11}$ cm$^{-2}$ per period: a—$N_S = 5.4$, b—$N_S = 1.4$.

Figure 2. The FFT spectrum for the sample QW + impurity well. The first peak is due to a restricted range of the used magnetic field strength.

Figure 3. The dependences of the Hall mobility on the temperature. The filled symbols—experiment, the empty symbols—calculation results. The squares—QW + impurity well, the circles—QW + SPSL. Inset: the bridge-shaped sample with directions of the measured fields.
Basic assumptions and calculations of conductivity

Our calculations used for fitting of the experimental data are based on the assumptions discussed below briefly.

Firstly, we take into account only one energy subband in each quantum well of the structures shown in figure 1. One may easily estimate that at the temperatures up to 200 K no less than 90% of the total amount of electrons is contained in these subbands. As will be seen below, the electron temperatures at the heating electric field in our experiments are not higher.

Further, the crucial value for redistribution of the electrons along with the temperatures of electrons in both wells is the gap between two levels in them. The gap varies with redistribution of the electrons due to the change of the transverse electric field and, consequently, potential drop between the wells. The latter can be described as a change of the potential difference between two infinite plates, $\Delta V$, as

$$\Delta V = \frac{4\pi \delta N \epsilon d}{\epsilon},$$

where $\epsilon$ is the electron charge, $\varepsilon$ is the dielectric permittivity, $\delta N$ is the change of the charge carriers concentration in the wells and $d$ is some mean distance between charges in the wells. We evaluated $d$ by calculating the energy spectra similar to those shown in figure 1 for a few temperatures and extrapolated $\Delta V$ for the larger redistribution in the strong electric fields. For example, in the structure QW+impurity well the gap grows up to 30 meV instead of 22.8 meV at the zero electric field.

Next, we assume that the transfer of electrons from one well to another goes by tunnelling through the barrier between them. For the tunnelling probability we use the well known expression obtained in the semiclassical WKB Ansatz. In the ideal case, when no scattering by phonons or defects mixes moving of electrons in the QW plane and $z$ direction perpendicular to this plane, the tunnelling probability is described as

$$D(E) = D_0 \exp \left( -\frac{2}{\hbar} \int_{z_1}^{z_2} \sqrt{2m(U(z) - E_{lev})} \, dz \right),$$

where $D_0 \sim 1$ (its expression depending on the barrier shape), $E_{lev}$ is the energy of the corresponding quantum level, $z_2 - z_1$ is the barrier width at the energy level $E_{lev}$, $m$ is the effective mass of electrons, $\hbar$ is the Plank constant, $U(z)$ is the $z$-dependence of the barrier height.

Meshkov in [14] has shown that taking into account phonons and various defects, which mix the lateral and transversal moving of electrons, may change drastically the tunnelling probability. The energy $E_{lev}$ in this case is

![Figure 4. The current–voltage characteristics of the studied samples at $T = 4.2$ K. a—QW+ impurity well, b—QW+ SPSL. The solid symbols—experiment, the empty symbols—calculation results. The empty squares—fitting with different electron temperatures in the coupled wells, the empty triangles—fitting with equal temperatures in both wells.](image)
replaced by the total energy of electrons $E$ and $D_0$ depends on the type of defects. We reason that the acoustic phonons play the main role and set $D_0$ proportional $T_{el}$.

Finally, in all calculations we use the Fermi function with electron temperature for the electron energy distribution in the wells. It is a good approximation for the deeper well (QW1) where the electron concentration is high in the whole range of electric field. However, it is rather poor for the other coupled well. Nevertheless, we used it with the following arguments. On the one hand, the distribution function appears in calculations only in the integrand, and, on the other hand, the contribution of the electrons in the higher well into the total conductivity (i.e., the sum over both wells) is only several percent. Consequently, if we choose the electron temperature in this well as a free fitting parameter the error may be negligible.

In calculation of the electron mobility it is important to take into account screening of scattering. The general formula for the dielectric function can be written as

$$\varepsilon(q) = 1 + \frac{2}{q} H(q) \Pi(q),$$

where $H(q)$ is the form-factor and $\Pi(q)$ is the dimensionless polarization operator. The expressions for $q_i$ and $\Pi(q)$ depend on the degree of degeneration of the electron gas. At the strong degeneration $\frac{E_F}{k_B T_{el}} \gg 1 \quad q_i = \frac{2 \pi n e^2}{k_B T_{el}}, \quad \Pi(q) = \int_0^1 \exp \left( - \frac{E_F}{k_B T_{el}} (1 - x) \right) \, dx.$

In the non-degenerate case $\frac{E_F}{k_B T_{el}} \ll 1 \quad q_i = \frac{2 \pi n e^2}{k_B T_{el}}, \quad \Pi(q) = 1.$

We would like to stress that the dielectric function depends on the electron concentration in the appropriate well and due to redistribution of the electrons has to be calculated at each temperature and electric field. For the intermediate case we used a suitable combination of both cases.

The electron mobility was calculated with the relaxation time defined as

$$\frac{1}{\tau} = -\frac{2\pi}{k_B^2} \int_0^1 \frac{\partial \mu(E_k + \varphi \cos \theta (E_k - E_k^0))}{\partial \varphi} \frac{d\varphi}{(2\pi)^2},$$

where $k$ and $q$ are the wave vector of an electron before scattering and value transferred in the scattering, $E$ is the electron energy with the corresponding wave vector, $M_k$ is the scattering matrix element, $\varphi$ is the angle between $k$ and $q$. We took into account scattering by the ionized impurities and phonons of the acoustic and optical branches in the phonon spectrum (polar scattering) as well as the rough scattering for the SPSL. At that we used for calculation the well-known expressions described in detail, for instance, in [15–17].

The temperature of electrons in the well with a larger mobility was calculated from the balance between the electron energy gain from the electric field and the energy losses due to scattering by phonons

$$\mu(T, E_k) e E_k^2 = \left( \frac{\partial \varepsilon}{\partial n} \right)_{ac} + \left( \frac{\partial \varepsilon}{\partial n} \right)_{pol},$$

whereas in the other well it was prescribed through the expression

$$T_{el} = T_{el1} + k_1 E_k^2 + k_2 E_k^4,$$

with $k_1$ and $k_2$ chosen so that to achieve the best fitting of the current–voltage characteristics. In the case of the QW+SPSL-structure only $k_1$ was used and the last term was omitted. The electron concentrations in the wells were obtained through the balance of the electron fluxes between wells

$$n_1 \tau_{12} = n_2 \tau_{21},$$

where $\tau_{ij}$ is the tunnelling times in both directions, which are inversely proportional to the tunnelling probability averaged over the distribution function.

**Discussion**

As a criterion of precision in the mobility calculation there may serve comparison of the measured and calculated dependences of the electron mobility on the temperature. In this case the distribution functions and concentrations of electrons in both wells are known and one need not make any assumption for them. The empty symbols in figure 3 show the corresponding calculated dependences. It is seen that for both structures the discrepancy does not exceed several percent. We emphasize that in these calculations no fitting parameters were used.

Figure 4 shows the measured and calculated current–voltage characteristics for both kinds of the structures. The calculated characteristics were obtained with the different assumptions for the electron temperatures in the coupled wells. As it is seen, they sufficiently well describe the measured results in the assumption of the different temperatures of electrons in the wells. And they agree neither qualitatively nor quantitatively in the case of the equal temperatures.

Figures 5 and 6 show the dependences of the calculated electron temperatures and concentrations in the wells on the electric field. As follows from figure 5(a), the dependence of the electron temperature on the electric
Figure 5. The calculated dependences of the electron temperature versus electric field. a—in QW, b—in the impurity well and SPSL. The filled symbols—QW + SPSL, the empty symbols—QW + impurity well.

Figure 6. Redistribution of the electron concentration in the coupled wells with the growing lateral electric field (numerical calculations). a—QW + impurity well, b—QW + SPSL. Squares—concentration in QW, circles—concentration in the impurity well and SPSL. Solid symbols—different temperatures in coupled wells, empty symbols—equal temperatures in coupled wells.
field in the well with the higher electron mobility consists of two intervals. It shows first a rapid (due to the high electron mobility) temperature increase up to ~50 K at the field of ~20 V cm\(^{-1}\) and then an essentially slower growth up to ~150 K at about 700 V cm\(^{-1}\). Such behaviour is typical for the III–V–compound-based heterostructures. The inflection in it corresponds to changing the prevailing mechanism of the energy loses from scattering by the acoustic phonons to the scattering by the optic phonons at temperature ~50 K [e.g. 18]. Since the hot electron mobility in both structures in QW1 depends mainly on the scattering by phonons and much weaker on the impurity scattering the electron temperature versus the electric field dependences in both cases nearly coincide. In contrast, the electron temperature in QW2 increases much weaker and only up to ~30 K at 700 V cm\(^{-1}\) (due to a much lower mobility as compared to QW1). It grows monotonously (because the mechanism of energy loses does not change in the whole range) and with a different rate in these structures. The latter is connected with different dependences of the mobility in them on the electron temperature. A large difference in temperatures in QW1 and QW2 leads consequently to a larger redistribution of electrons between wells. For the structure with the SPSL fragment at fields more than 450 V cm\(^{-1}\), even an inversion of electron population between the two low size-quantization subbands takes place.

Now, we would like to make one note. As described above, in the range of electron temperatures and concentrations, where neither classical nor quantum statistics may be used properly, we applied some combination of both to calculate the impurity screening. The changes in this combination simultaneously with small changes of other essential parameters, for instance, the coefficient \(k_1\) or \(k_2\), enable also to achieve satisfactory coincidence with experimental data. At that the conclusion on a large difference in the electron temperatures in the wells and character of electron redistribution in both structures remains unchanged.

Conclusion

The spatial separation of charge carriers in the coupled quantum wells weakens energy exchange between them and causes different heating them under acceleration by the common lateral electric field. This is expressed in a different distribution of electrons by energy levels which may be presented in terms of the electron temperatures by introducing the different electron temperatures for two wells. In order the difference in electron temperatures to be enough pronounced one need to use a special configuration of the coupled wells the examples of which are considered above. The non-equilibrium current–voltage characteristics and the electron mobility versus the applied electric field dependences in this case may be satisfactorily described within the frames of a simple model. The model is based on the conception that the dynamic redistribution of electrons is determined by the electron tunnelling through the barrier between wells. Along with the barrier transparency the tunnelling probability is determined by the full energy of the electrons on each energy level which includes the component accounting for acceleration by the applied lateral electric field.

Finally, we have to make following remark. The initial motivation for our investigation was to create the structure with a clearly expressed NDC. This goal has not been achieved yet. However, the obtained in this work results may be useful for future investigations, particularly, for development of new UHF electronic and terahertz-range optoelectronic devices based on the use of the real-space-transfer effect.

Acknowledgments

The work was supported by the complex program 'Fundamental problems of creation of new nanomaterials and nanotechnologies' of the National Academy of Sciences of Ukraine (Project #10/17-H-18).

ORCID iDs

V V Vainberg  https://orcid.org/0000-0002-9840-8033

References

[1] Gribnikov Z S 1972 Negative differential conduction in the multilayer heterostructures Fiz. Tekh. Poluprovodn. 6 1380–2
[2] Hess K, Morkoc H, Shichijo H and Streetman G B 1979 Negative differential resistance through real-space transfer Appl. Phys. Lett. 35 469–71
[3] Gribnikov Z S, Hess K and Kozinovsky G A 1995 Nonlocal and nonlinear transport in semiconductors: real-space transfer effects J. Appl. Phys. 77 1337–75
[4] Kirchoefer S W, Magno R and Comas J 1984 Negative differential resistance at 300 K in a superlattice quantum state transfer device Appl. Phys. Lett. 44 1054–56
[5] Rui Q Y 1998 Quantum real-space transfer in semiconductor heterostructures Appl. Phys. Lett. 73 3265–7
[6] Šermukšnis E, Liberis J, Matulionis A, Avrutin V, Ferreyra R, Özgür Ü and Morkoç H 2015 Hot-electron real-space transfer and longitudinal transport in dual AlGaN/AlN/(AlGaN/GaN) channels Semicond. Sci. Technol. 30 035003

[7] Chuan J, Zhenqiang C and Jianxin C 2012 Novel quantum real-space transfer in semiconductor heterostructures Proc. SPIE 8419 84191Y

[8] Takeyoshi S, Kazuhiro K, Takashi Y, Souichirou H and Kenji Y 2006 InGaAs dual channel transistors with negative differential resistance Appl. Phys. Lett. 88 142107

[9] Aleshkin V Y et al 2001 Toward far and mid IR intraband lasers based on hot carrier intervalley/real space transfer in multiple quantum well systems Proc. SPIE 4318 192–203

[10] Aleshkin V Y and Andronov A A 1998 Giant inversion of population of hot electrons in heterostructures of the GaAs/AlAs type with quantum wells IETP Lett. 68 73–7

[11] Belevskii P A, Vainberg V V, Vinoslavskii M N, Kravchenko A V, Poroshin V N and Sarbay O G 2009 Real-space transfer and far-infrared emission of hot electrons in InGaAs/GaAs heterostructures with tunnel-coupled quantum wells Ukr. J. Phys. 54 117–22

[12] Vainberg V V, Gudenko Y N, Belevskii P A, Vinoslavskii M N, Poroshin V N and Vasetskii V M. 2006 Current oscillation and high-field domains in the InGaAs/GaAs heterostructures with a δ-doped quantum well Nanomater., Nanotechnol. 4 41–50

[13] Vainberg V V, Pylypchuk A S, Poroshin V N, Sarbay O G, Baidus N V and Biryukov A A 2014 Influence of conduction via a channel of an impurity δ-layer on the magneto-quantum effects in AlGaAs/GaAs/AlGaAs heterostructures Physica E 68 31–6

[14] Meshkov S V 1990 Tunneling of electrons from the two-dimensional channel into the bulk AIP Conf. Proc. 213 185–91

[15] Ando T, Fowler A B and Stern F 1982 Electronic properties of two-dimensional systems Rev. Mod. Phys. 54 437–672

[16] Laikhtman B and Kiehl R A 1993 Theoretical hole mobility in a narrow Si/SiGe quantum well Phys. Rev. B 47 10315–27

[17] Vainberg V V, Pylypchuk A S, Baidus N V and Zvonkov B N 2013 Electron mobility in the GaAs/InGaAs/GaAs quantum wells Semicond. Phys., Quantum Electron. Optoelectron. 16 152–61

[18] Guta R, Balkan N and Ridley B K 1992 Hot-electron transport in GaAs/Ga1−xAlxAs quantum well structures Phys. Rev. B 46 7745–54