REAL-SPACE TRANSFER AND FAR-INFRARED EMISSION OF HOT ELECTRONS IN InGaAs/GaAs HETEROSTRUCTURES WITH TUNNEL-COUPLED QUANTUM WELLS

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The transport of electrons and light emission under the influence of a lateral electric field in InGaAs/GaAs heterostructures with double tunnel-coupled quantum wells has been studied. For the selectively doped structures at 4.2 K and electric fields ∼1 kV/cm, we have found that the rate of current growth diminishes with increasing field, and simultaneously a sharp increase of the IR emission intensity is observed. The effect is related to the real-space transfer of electrons from the undoped quantum well to the higher energy states in the doped well where they are accumulated.

1. Introduction

The real-space transfer of electrons in the semiconductor structures with quantum wells under a strong lateral electric field has been investigated intensively in the 1980-1990s with the purpose to generate high-frequency oscillations of the electric current [1–3]. The electrons heated up to the energy of barriers can be transferred into barriers, where their mobility is lower as compared with that in wells due to the additional scattering by ionized impurities. Therefore, the differential conductivity can become negative, the homogeneous state of the electric field being unstable, and the moving high field domains arise leading to current oscillations. Their period depends on the incubation time and the time of drift through the sample similarly to the Gunn effect in the III-V semiconductors.

The authors of some recent publications proposed to use the real-space transfer of hot electrons for lasers in the middle and far infrared regions. However, in order to obtain an inverse distribution of electrons between quantum levels, the electrons have to be transferred between two quantum wells with different energy spectra and mobilities rather than between a well and a barrier [4–6]. In the weak-field region, the carriers populate the lower level in the wide well with a high mobility. With increasing the field, they become heated and, due to a tunnel transition, occur at the higher level in the narrow well characterized by a lower mobility and a weaker heating, consequently. The population of the latter states increases with a growing field if the probability of the electron scattering between wells increases with the kinetic energy (for example, in the case of the scattering by polar optical modes of the phonon spectrum). The difference of the mobilities in both quantum wells mentioned above can be caused by the additional scattering in a narrow well due to the delta-shape doping or the interface roughness.

This paper presents the results of measurements and the interpretation of electrical transport properties for such structures. The dependence of the emission of far infrared light on the carrier heating is investigated as well.

2. Experiments

The n-In$_x$Ga$_{1-x}$As/GaAs ($x = 0.08$) heterostructures with double tunnel-coupled quantum wells have been

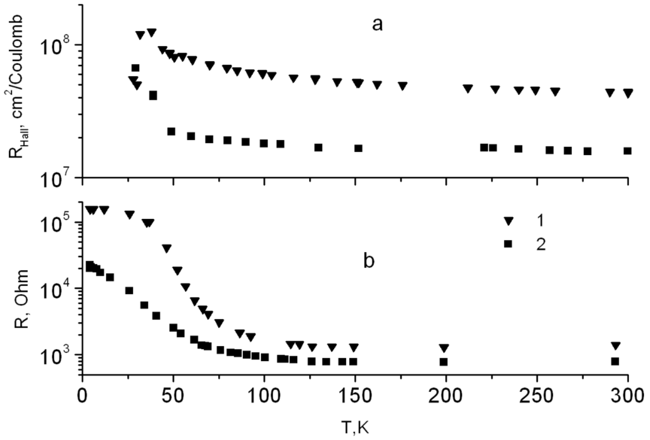

Fig. 1. Temperature dependences of the Hall coefficient (*a*) and resistance (*b*) for selectively (*1*) and uniformly (*2*) doped heterostructures

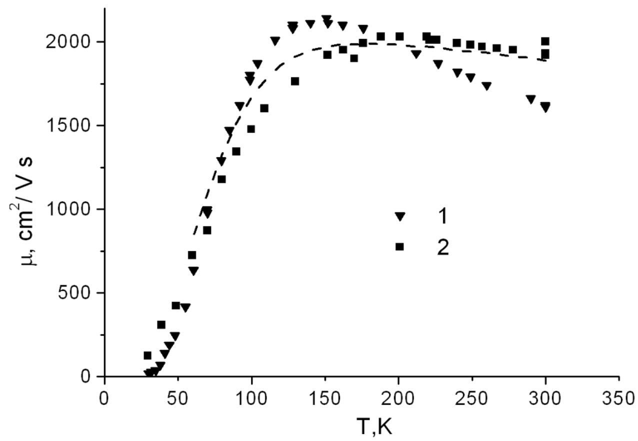

Fig. 2. Temperature dependence of the electron mobility in selectively (*1*) and uniformly (*2*) doped heterostructures. The dash line: calculated dependence for the uniformly doped structure

studied. They were grown[1] on the semiinsulating GaAs (001) substrates by the MOVPE method. The structures consist of 20 periods, each period containing a pair of 200 and 100 Å thick quantum wells (InGaAs) separated by the 50 Å thick GaAs barrier. The pairs are separated by the 780 Å-thick barriers. One set of samples was on-center delta-doped in the narrow quantum well by Si ($N_d \sim 1.2_* 10^{11}$ cm^{-2} per period). In the other set, both quantum wells in a period were uniformly doped ($N_d \sim 3.9_* 10^{11}$ cm^{-2} per period). The rectangular samples were cleaved along the $\langle 110 \rangle$ axis and had dimensions of 10×3 or 5×3 mm. The Ge+Au ohmic contacts were made in the form of transverse strips for current leads and of a small circle for measurements of the Hall voltage. The distance between current contacts was 8 and 3 mm.

The temperature dependences of the resistance and Hall coefficient were measured in the temperature range from 4.2 to 300 K in the dc regime with a drift electric field no more than 10 V/cm. The magnetic field was 0.2 T. The investigation of the hot carriers transport was carried out under pulsed electric fields at temperatures of 100 and 4.2 K. In order to avoid the acoustoelectric domains arising in such structures at electric fields higher than ∼800 V/cm and resulting in a non-uniform distribution of the electric field [7–9], the duration of voltage pulses applied to a sample was chosen less than the incubation period and was equal to ∼ 400 ns. The repetition frequency was 1 Hz. The integral intensity of light emitted by hot electrons in the 50 to 120 μm spectral range was measured by a Ge:Ga detector at 4.2 K. The total response time of the photodetector and the recording circuit was no more than 50 ns. The spectral range was determined by the transmission coefficient of a black polyethylene filter placed between a sample and the detector. The samples were mounted in a helium cryostat. The temperature was controlled with the accuracy down to 0.01 K.

The waveforms of voltage and current pulses through the sample were measured by a digital oscilloscope PCS500 (Velleman Instruments) with a 50-MHz bandwidth connected to the computer for the data acquisition.

3. Results and Discussion

The typical temperature dependence of the resistivity for two samples with different doping profiles are shown in Fig. 1,*b*. It is seen that, for both kinds of samples in the region between 300 and ∼ 100 K, the resistance weakly changes. But, from 100 down to ∼ 30 K, it grows by 1.5 to 2 orders of magnitude and then saturates, by remaining practically constant.

At first sight, such a behavior between 100 and 30 K could be caused by a decrease of the current carrier concentration, for instance, due to the "freezing out" onto doping centers. However, the measurements of the Hall effect contradict such an interpretation. As seen in Fig. 1,*a*, the Hall coefficients for both kinds of structures change no more than by three times over all the range from 300 down to 30 K. Therefore, we prefer another explanation and conclude that, in this temperature

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[1] The structures were grown at the Physical-Technical institute of the Nizhni Novgorod State University, Russia.

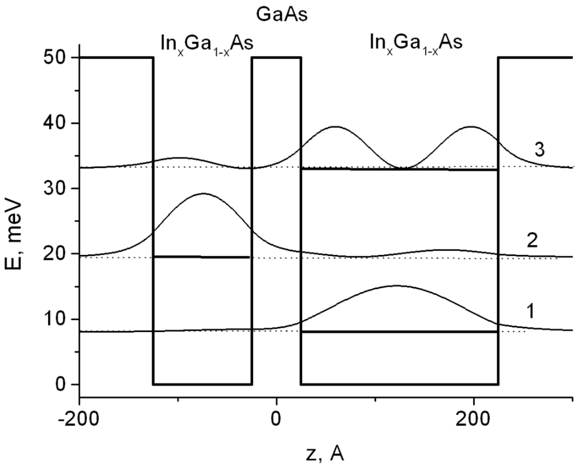

Fig. 3. Size quantization subbands and the squares of the wave functions of electrons in the double tunnel-coupled quantum wells under study

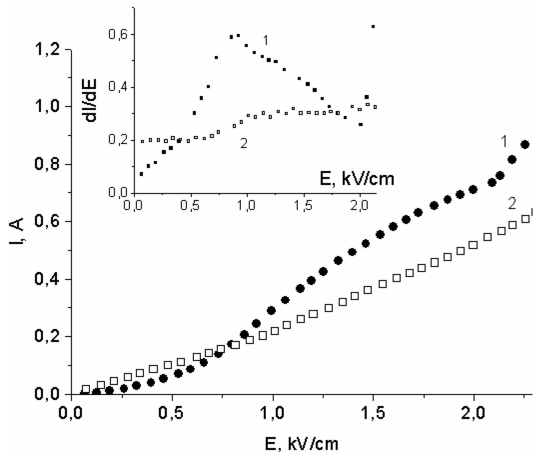

Fig. 4. Current-voltage characteristics of the selectively doped heterostructures at 4.2 K (*1*) and 100 K (*2*). Inset: the derivative of the current with respect to the field

region, a redistribution of electrons between conducting states with different (high and low) mobilities takes place rather than the “freezing out” of carriers. The low-mobility states can belong to the impurity band with a zero or small gap below the conduction band. The existence of the impurity band is evidenced by a maximum in the Hall coefficient vs temperature dependence, which is clearly seen for the selectively doped structures at the lower temperature end (Fig. 1,*a*). In the case of uniformly doped structures, the Hall maximum seems to be shifted to a still lower temperature.

The temperature dependence of the Hall mobility calculated formally as a product of the Hall coefficient and the conductivity is presented in Fig. 2. For all investigated structures, the mobility at first slightly grows with decreasing temperature and afterwards strongly falls. For the selectively doped samples, the initial growth of the mobility is stronger, and its maximum occurs at a lower temperature as compared to that for the uniformly doped sample. From our point of view, such a behavior is caused both by the real dependence of the mobility on the temperature in the conduction and impurity bands and by a redistribution of electrons between them.

In order to examine this suggestion, we calculated the temperature dependence of the mobility supposing that, in the impurity band, it is independent of the temperature, as it is evidenced by the saturation of the resistance as a function of the temperature in the liquid-helium temperature range. In these calculations, we also took the electron distribution over different energy subbands and all possible scattering mechanisms (by acoustic and optical phonons, impurity, roughness of quantum well walls, alloy composition fluctuations) into account. In order to determine the energy levels of the size quantized subbands and the corresponding wave functions of carriers, we solved the steady-state Schrödinger equation in the approximation of a simple parabolic conduction band. The quantum well depth for the In content of 0.08 in $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ was taken equal to 50 meV [4]. The effective masses of electrons in the plane of quantum wells for all subbands are assumed to be the same and equal to 0.06 m_0. The calculated results are depicted in Fig. 3. It is seen that the quantum wells under consideration contain 3 subbands. It is important to emphasize that the wave functions of electrons for the first (lower) and third subbands are localized mainly in the wide quantum well, while the wave functions for the second subband have a large magnitude in the narrow well.

In the calculations of the mobility, we used the known expressions for the time of momentum relaxation given in [9,10]. The electron-phonon coupling constants, optical phonon frequency, density, sound velocity, and dielectric permittivity for $\mathrm{In}_{0.08}\mathrm{Ga}_{0.92}\mathrm{As}$ were determined by interpolation between the corresponding values for GaAs and InAs from [11]. The typical magnitude and the correlation length of the interface roughness equal to 10 and 38 Å, respectively, for the structures under consideration were taken from [5].

We have found that the temperature dependences of the electron mobility calculated by this method are in a good agreement with experiment. It can be seen from

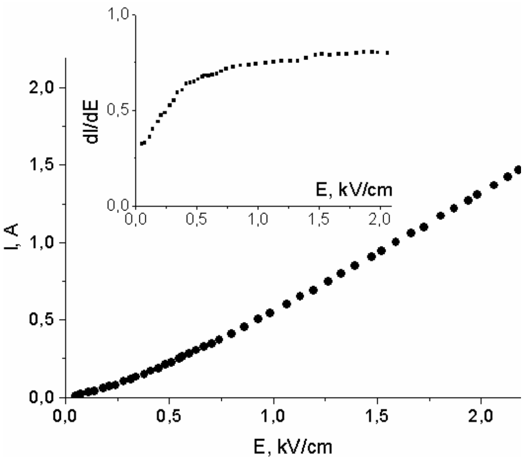

Fig. 5. Current-voltage characteristic of the uniformly doped heterostructure at 4.2 K. Inset: the derivative of the current with respect to the field

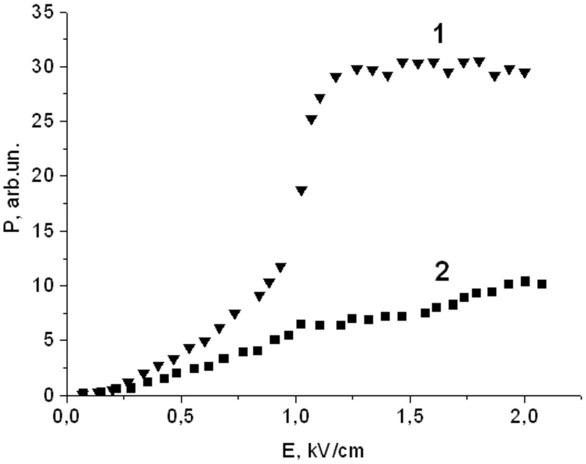

Fig. 6. Dependence of the integral intensity of the light emission by electrons in the selectively (*1*) and uniformly (*2*) doped heterostructures at 4.2 K

Fig. 2, where the calculated results along with experimental data are shown for the uniformly doped sample.

We now consider the results for the transport of carriers under strong electric fields. They are shown in Figs. 4 and 5. The most interesting feature of these results is that, for the delta-doped structures in the field range between 0.9 and 1.5 kV/cm at 4.2 K, the current increases with the field slower as compared with both the lower and higher fields (Fig. 4). This peculiarity of the current-voltage characteristic is absent at 100 K and higher temperatures. It is absent for the uniformly doped structures at all temperatures, too (Fig. 5). We note that, both at temperatures higher than 100 K and at lower temperatures under electric fields higher than a certain value (approximately 0.1–0.3 kV/cm for different samples), the concentration of electrons in the conduction band remains constant, and all the peculiarities of the current-voltage characteristics are related to the behavior of the mobility in the conduction band only.

Moreover, we could observe the far infrared light emission at low temperatures from all the samples studied, if the current through them was high enough. The pulses of emission followed the current waveforms within the accuracy of the response time of the system. This fact gives evidence that the recorded emission has the electron nature. The integral intensity of light emission as a function of the electric field differs for the structures with different doping profiles (see Fig. 6). For the uniformly doped samples, it monotonously increases with the growing field that is characteristic of the light emission by hot electrons. A similar dependence was observed for the delta-doped structures only at fields below about 1 kV/cm. However, at E >1 kV/cm, the light intensity at first sharply increases and then tends to saturation. This sharp increase occurs approximately at the field corresponding to the inflection point in the current-voltage characteristic before its part with tendency to saturation.

We connect both effects with the real-space transfer of electrons from the undoped wide quantum well to the higher energy states in the doped narrow well leading to an additional carrier accumulation as compared with the case of one quantum well. Such additional accumulation occurs due to the different heating of carriers in the different wells due to the different mobilities. To elucidate this suggestion, we calculated the dependences of the electron temperatures in both wells on the electric field. The electron temperatures were calculated, as usual, from the balance of powers obtained by electrons from the electric field $\mu_i(T_i)E^2$ and transferred to the lattice via the interaction with phonons. The expressions for the average rate of energy losses by carriers due to their scattering by acoustic and polar optical phonons are taken from [12]. The Maxwell distribution function of electrons with different electron temperatures in the wide and narrow wells was used in these calculations. It looks reasonable for the free carrier concentrations under consideration and at the not too strong heating of them. The results for the delta-doped case are depicted in Fig. 7.

It is seen that, at any value of the electric field, the electron temperature in the wide well is higher than that in the narrow one. For example, the electron temperature in the wide well at 1 kV/cm is 180 K which is about 3 times as high as compared to that in the narrow well. The electron mobility at this field in the narrow well occurs to be less by 70 times than that in the wide one. As a result, the transition of electrons into the narrow well is accompanied by a slowing increase of the total electric current with the field. The subsequent faster current increase observed experimentally at still higher fields can be related to the transfer of carriers back from the narrow quantum wells to the wider ones. The latter was not taken into account in the calculations.

The calculations in the case of uniformly doped structures have shown that the electron mobilities and the magnitude of their heating by the electric field in the narrow and wide wells are also different. This is caused by the dependence of the electron scattering probability on the well thickness and especially on the interface roughness. However, this difference in the uniformly doped structures is much less than that in the selectively doped structures. Therefore, the effects caused here by the real-space transfer of electrons are weaker and were not observed.

The carriers transferred into the narrow well and accumulated there can emit light both via indirect intrasubband transitions (similar to that in the wide well under a weak field) and quasidirect transitions into the states of the first size quantization subband. The latter transitions are possible due to the overlapping of the wave functions of carriers in these two subbands (Fig. 3). The energy of such transitions is 12.4 meV that corresponds to the spectral sensitivity of our recording system. The probability of quasidirect transitions is higher than that of indirect ones. Therefore, their addition to the indirect optical intrasubband transitions causes a sharp increase of the recorded infrared emission intensity.

The redistribution of hot carriers between two wells described above can be illustrated by a simplified model considering electrons in both connected wells as ideal gases. In this case, the pressure of gases which should be the same in both wells is determined by the temperature and particle concentrations. Taking into account that a redistribution of electrons between wells occurs at energies above the bottom of the second subband, we obtained the following relationship between the ratios of the 2D concentrations in wells (size quantization subbands, respectively) and electron temperatures.

$$\frac{n_2}{n_1} = \frac{T_1 L_1}{T_2 L_2} \exp\left(-\frac{E}{kT_1}\right),$$

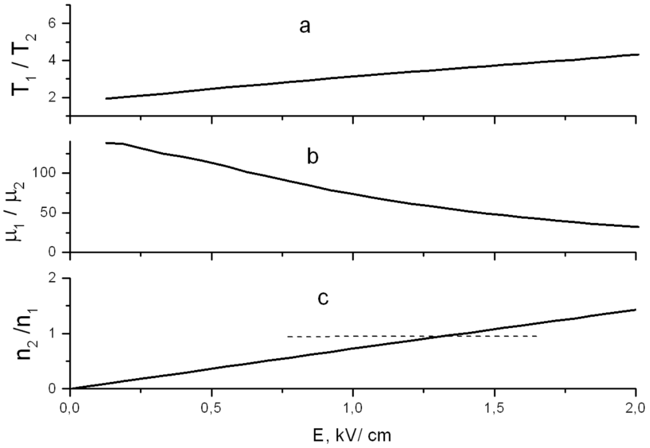

Fig. 7. Calculated field dependences of the ratios of electron temperatures (*a*) as well as electron mobilities (*b*) in the wide and narrow quantum wells, and the ratio of the electron concentrations in the 2^{nd} and 1^{st} size quantized subbands (c)

where E is the energy gap between subbands, and L_1, L_2 are the well widths. Index 1 corresponds to the wide well.

The dependence of this relationship on the electric field is depicted in Fig. 7,*c*. It is seen that the concentration in the second subband at fields above 1.3 kV/cm exceeds that in the first subband. The variation of the concentration in the second subband qualitatively explains the observed behavior of the electric current and the intensity of light emitted by hot electrons.

Finally, we note that the increase of the light intensity caused by quasidirect optical transitions is relatively small. In our opinion, it is related to a comparatively small cross-section of these transitions due to a small overlapping of the electron wave functions of the first and second subbands in the narrow well. The effect might be considerably increased by decreasing the barrier width between the tunnel-coupled wells, which leads to higher values of the wave function in the first subband of the narrow well. However, a thinner barrier may result in the increased scattering of carriers in the wide quantum well by the doping centers in the narrow well. In consequence, a higher electric field may be needed for achieving the accumulation of electrons in the second subband.

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ПРОСТОРОВИЙ ПЕРЕНОС ТА ДАЛЕКЕ ІНФРАЧЕРВОНЕ ВИПРОМІНЮВАННЯ “ГАРЯЧИХ” ЕЛЕКТРОНІВ В ГЕТЕРОСТРУКТУРАХ InGaAs/GaAs З ТУНЕЛЬНО-ЗВ’ЯЗАНИМИ КВАНТОВИМИ ЯМАМИ

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Резюме

Досліджено транспорт електронів в латеральному електричному полі та випромінювання ними світла в InGaAs/GaAs гетероструктурах з подвійними тунельно-зв’язаними квантовими ямами. В селективно легованих структурах при температурі 4,2 К в полях $\sim$ 1 кВ/см виявлені уповільнення росту електричного струму з полем та різке збільшення інтенсивності випромінювання. Ефекти пов’язуються з просторовим переносом електронів з нелегованих квантових ям в стани з більшою енергією в легованих ямах і з їх накопиченням.