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Interband and intraband radiation from the n-InGaAs/GaAs heterostructures with quantum wells under the conditions of injection in high lateral electric fields

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HIGHLIGHTS

- We study the n-InGaAs/GaAs quantum wells with presence of hole injection.
- A strong increase of the lifetime of the injected holes (up to 10^{-6} s) was found.
- The steep rise of the interband and terahertz infrared radiation was revealed.

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ABSTRACT

The interband and intraband radiation from the n-InGaAs/GaAs heterostructures with the double and triple tunnel coupled and selectively doped quantum wells (QWs), which is appeared under the lateral electric field and in the presence of hole injection from the anode contact, has been investigated. A steep increase of the interband radiation intensity was found at the fields of $E \geq 1.7$ kV/cm. This effect should be related to the big lifetime of the injected charge carriers ($\sim 10^{-6}$ s) which exceeds by three orders of magnitude the lifetime in the similar bulk direct-band semiconductor. Its reason lies in spatial separation of the injected holes and electrons between coupled wells, firstly, by the built-in transverse electric field between wells and, secondly, due to the real-space transfer of carriers heated by the lateral electric field from the wide well to the narrow δ-doped one. Furthermore, an increase of the carrier concentration due to injection leads to an increase of that transition intensity and, consequently, to an intensity increase of the radiative intersubband transitions of carriers in QWs which results in a steep intensity increase of the far (50–120 μm) infrared radiation.

1. Introduction

Contemporary studies of the terahertz (THz) radiation mechanisms based on the heterostructures with quantum wells (QWs) are caused by the need to develop new sources of such radiation. The mostly proposed sources are unipolar [1–4]. Also the schemes based on injection lasers with bipolar conductivity [5] were proposed, in which the THz radiation accompanies the interband radiation. In this case one usually makes use of the transverse electric field directed perpendicular to the heterolayers. It is caused by short lifetimes ($\sim 10^{-9}$ s) of the injected carriers and small filling lengths (~μm) of filling the structure based on the direct-band semiconductors.

We investigated earlier the THz radiation from the n-InGaAs/GaAs heterostructures with double tunnel-coupled quantum wells under the lateral (directed along heterolayers) electric field both in the monopolar mode [6,7], and with injection of the minority carriers [8]. The mechanism of THz radiation generation in such heterostructures was proposed in [9]. It is based on real-space transfer of electrons from the first level in the wide QW to the second level in the narrower δ-doped QW in result of heating by the lateral electric field. In this case the envelop wave function of electrons at the first level is maximal in the wide QW, while at the second level it is maximal in the narrow one. The direct THz transition occurs between the second level in the narrow QW and the first level in the wide QW. As shown in [8] we found a sharp increase of the far (40–120 μm) infrared radiation intensity in such heterostructures at a high lateral electric field under the conditions of the real-space transfer of carriers between coupled QWs

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and with the minority carrier injection from a contact. These contacts are ohmic at small and moderate fields.

In the present work the basic attention is given to investigations of the interband and intraband radiations of hot carriers under strong lateral electric fields in heterostructures with the double tunnel coupled QWs (like studied in [8]), and also with the triple QWs under the conditions of the carrier injection from contacts.

2. Structures under study and measurements details

The multilayer n-InGaAs/GaAs heterostructures were investigated. They contained the 20 double or 40 triple tunnel-coupled quantum wells (TCQWs) δ-doped by Si into the center of the narrower QW. The barrier width between TCQWs was 30–40 A. The In composition, x, in the $In_xGa_{1-x}As$ layers forming the quantum wells for electrons was from 0.1 to 0.15. The widths of quantum wells and concentrations of the doping impurity for the structures under study are listed in Table 1. The heterostructures were grown by metalorganic vapor-phase epitaxy on the semi-insulating GaAs (001) substrates.

Calculations of the conduction band profile, energy spectrum of electrons in QWs and envelop wave functions [10] have shown that in double and triple TCQW there are two or three electronic size-quantized subbands. The bottom subband is connected with a wide quantum well. The second subband is located above the first one (for triple TCQW-No 6294-approximately by 15 meV, Fig. 1) and is connected with a narrow well. The Fermi level is located several meV above the first quantum level. Therefore at the liquid helium temperature the most part of free electrons is concentrated in the wide (undoped) wells.

The strip electric contacts, In or GeAu alloy, were deposited and alloyed into samples of the rectangular shape at the distance of 1–5 mm from each other. The single rectangular voltage pulses with duration of $\tau \leq 400$ ns were applied to the contacts. It enabled to avoid formation of the acoustoelectric domains [11], which incubation time in the investigated structures at fields $E \leq 3$ kV/cm is longer or equal to τ [12,13]. The dependences of the radiation intensities and current through a sample on the applied field were measured at T=4.2 K. Also the photoluminescence spectra were measured with excitation by the red laser with the power $P \approx 50$ mW and the electroluminescence spectra were measured at the fields up to 3.5 kV/cm.

The radiation was measured in the direction normal to the surface of structures between the electric contacts. For measurement of the far infrared (FIR) radiation (in the spectral range from 40 to 120 μm the Ge:Ga photodetector was used with the filter of the black polyethylene. The near infrared (NIR) radiation was measured by the photomultiplier or by the Si:B photodetector through the glass filter. It allowed to record radiation with the wave lengths less than 2.5 μm. Besides, the distribution of the NIR radiation intensity along the current direction was measured by means of scanning the sample image increased by the lens and across the monochromator slit. The distribution of the FIR radiation intensity was measured with use of the 0.3 mm wide slit moved along the current direction.

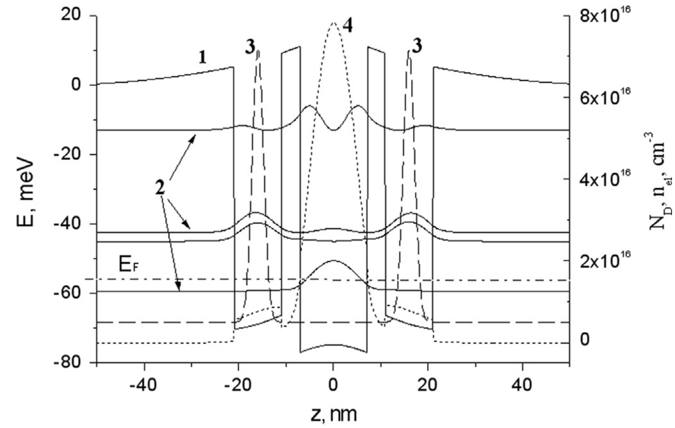

Fig. 1. The energy diagram of the conduction band of the n-InGaAs/GaAs heterostructure with triple quantum wells 100/40/170/40/100 A (#6294). The wide well is in the middle, and two narrow quantum wells δ-doped with Si are located at both sides of it. The envelop wave functions of the first, second and third size-quantized subbands are also shown. The left axis corresponds to: 1 – potential profile of the conduction band of the heterostructure; 2 – size-quantized levels; the right axis: 3 – concentration profile of the impurities; 4 – the profile of the electron density.

3. Experimental results and discussion

The typical current–voltage characteristic (CVC) and field dependence of the interband radiation intensity (NIR) of the heterostructure with the double tunnel-coupled QW (#5975) are shown in Fig. 2. It is seen that at the field less than E=0.5–0.7 kV/cm the current grows approximately proportionally to the field (cr. CVC). At further increase of the field (E=1–2 kV/cm) the CVC slope decreases (the RST1 interval). We connect it with the real-space transfer of electrons in result of heating by the lateral electric field from the first level in the wide QW onto the second level in the adjacent narrow QW where the mobility of electrons decreases because of scattering by the ionized impurities that leads to reduction of the electron temperature [6–8]. The evidence in favor of this suggestion is appearance of the second peak in the electroluminescence spectrum of the double-well structure corresponding to filling the second level in the narrow QW by electrons [8]. This will be also shown further for the spectrum of the three-well structure. Besides, in the case of the homogeneously doped heterostructures with the single QWs and the homogeneous GaAs films a similar CVC slope decrease at such fields was not observed. Also in our experiments there are no conditions for the Gunn effect manifestation for which considerably greater fields ($E > 3$ kV/cm) are required.

At the fields $E > 2$ kV/cm in all structures under study the more sharp growth of the CVC slope is observed (Fig. 2, cr. CVC) which is connected with a carrier concentration increase due to injection of holes. The presence of injected charge carriers is evidenced by

Table 1
Parameters of the investigated n-$In_xGa_{1-x}As$/GaAs structures.

# of the structure	x, 2QW, 3QW	Number of periods	d_{1QW}, A	d_{2QW}, A	d_{3QW}, A	$d_{barrier}$, between coupled wells, A	N_{Si} in nar. QW, 10^{11} cm^{-2} (per period)
5975	0.15, 0.15	20	100	170		30	3.4
5976	0.15, 0.1	20	30	180		30	1.9
5977	0.1, 0.1	20	100	170		30	2.8
6294	0.12	40	100	160	100	40	0.9
	0.14						
	0.12						