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Current and electroluminescence intensity oscillations under bipolar lateral electric transport in the double-GaAs/InGaAs/GaAs quantum wells

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Abstract. The lateral bipolar electric transport has been investigated for multi-period n-$In_{0.08}Ga_{0.92}As$/GaAs heterostructures with tunnel-coupled double-quantum wells for various carrier mobilities at temperatures 4.2…160 K. The presence of two types of charge carriers – electrons and holes – is identified by observation of interband electroluminescence (EL). We found that the current-voltage characteristic has a complex nonlinear shape and changes with current, which is accompanied by modification of the EL intensity and spectrum. We observed oscillations of the current and EL intensity with the frequency of tens MHz, both arise at the electric fields well below the threshold field of the Gunn instability. Oscillations of the EL intensity occur in the opposite phase to the current. The electric and EL measurements have shown that the minority carriers, the holes, are supplied from the anode side of the sample. Spatial separation of electrons and holes in the double-quantum well structures provides abnormally large both electron-hole recombination time and drift length of the holes. Studied behavior of the current and EL can be interpreted as a combined effect of the spatial separation of the electrons and holes and dynamics of their transfer between undoped and doped quantum wells. We suggest that observed real-space transfer effects in high-field bipolar electric transport and, particularly, highly intensive interband electroluminescence from macroscopically large areas may be used in a number of optoelectronic applications.

Keywords: quantum wells, current oscillations, lateral electric transport, negative differential conductivity, real space transfer.

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1. Introduction

The real-space transfer (RST) of charge carriers is one of the hot electron effects giving rise to a nonlinear current-voltage characteristic in the selectively doped heterostructures, including double-quantum well kinds. It was proposed first to implement the negative differential resistance (NDR) in the layered semiconductor heterostructures [1, 2]. The RST and NDR phenomena were extensively investigated [3–13]). They are already applied in a variety of devices, for example, in the negative resistance field-effect transistors [14], tunneling RST and charge-injection transistors [15], light-emitting transistors [16], dual channel transistors [17] (see review [18]).

New phenomena based on RST were observed in heterostructures with tunnel-coupled quantum wells. These are variation of the intersubband light absorption and refraction index in the vicinity of the intersubband resonance [19, 20], variation of the interband photoluminescence spectra [19], inversion of electron population in the size quantization subbands and emission of the far infrared radiation [21, 22], control of carrier scattering in the dual-channel field-effect transistor on the GaN-based heterostructure leading to an increase of the electron drift velocity [23], *etc*.

All these phenomena were observed in heterostructures with a single type of charge carriers: either electrons or holes. Recently, we reported a strong interband electroluminescence (EL) observed in the selectively doped multilayer n-type InGaAs/GaAs heterostructures with tunnel-coupled double-quantum wells in strong lateral electric field [24, 25]. It indicated also appearance of the minority charge carriers (holes) in that kind structures under mentioned conditions.

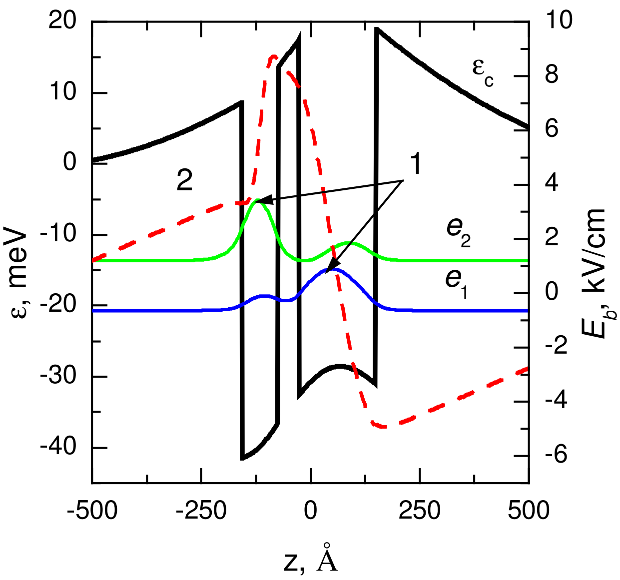

Fig. 1. Potential profile of the conduction band bottom ε_c for the structure (one period); the bottom energies of lowest electron subbands e_i and squared envelope wave functions of electrons (*1*). Dashed line indicates the distribution of the built-in electric-field E_b (*2*). T = 10 K.

The goal of the present paper is to manifest that the monopolar electric lateral transport in such structures under high lateral electric fields at low temperatures becomes bipolar, by its essence. We have ascertained that behavior of current and luminescence in these structures can be defined by the combined effect of spatial separation of electrons and holes, and real-space transfer of hot carriers between the non-doped and doped quantum wells. We report a new effect of simultaneous oscillations of the current and electroluminescence intensity arising in the electric fields considerably less than the threshold field of the Gunn instability.

2. Experiment

Our researches were carried out using the multilayer selectively doped $In_{0.08}Ga_{0.92}As/GaAs$ heterostructures grown by the MOVPE method on the (100)-surface of the semi-insulating GaAs substrates. The structure consisted of 50 identical periods separated by the 800-Å wide barriers being opaque for electrons. Each period contained a pair of 80-Å and 180-Å wide InGaAs quantum wells separated by the 50-Å wide GaAs barrier. The narrow wells were δ-doped by Si with the concentration of $N_i = (1...2)\cdot 10^{11}$ cm^{-2} at the well center. The wide wells were non-doped. The rectangular 5×3 mm^2 samples were cut out of the wafer. The ohmic contacts were made by deposition of the Ge/Au or In layers on the GaAs cap layer and annealing at 480 or 430 °C, respectively. The distance between contacts was between 1.5 to 4.0 mm.

Fig. 1 shows the potential profile of the conduction band bottom in the structure within one period, the bottom energies of two lowest electron subbands and corresponding electron envelope wave functions. This diagram was obtained by self-consistent solving the coupled Schrödinger and Poisson equations at T = 10 K. For the structure studied, the second e_2 subband is above the first e_1 subband by about 20 meV, while the Fermi energy is a few meV above the e_1-subband bottom. So, almost all electrons must occupy the ε_1 subband at this temperature. It is seen also that the e_1- and e_2-electron subbands are 'genetically' associated with the wide and narrow wells, respectively. These calculations also evidence that tunnel coupling of the wells is weak. Spatial separation of the positive ionized donors in the narrow well and electrons in the wide well generate a built-in electric field E_b as depicted in Fig. 1.

Note that, using the quantum mechanics language, relocation of charges between the coupled wells corresponds to transitions between the e_1 and e_2 subbands and is known as a quantum state transition (QST), while in the semi-classical approach one uses the term of RST of charges. For weakly coupled quantum wells both interpretations are adequate. Below, we use the semi-classical approach. In this case, one may introduce the carrier concentrations in each well and the times of interlayer transitions.

The experimental studies of the high-field electric transport were carried out in the pulsed regime. The voltage pulses applied to samples varied up to U = 1000 V by their amplitude with duration close to 1.5…2.0 µs. In order to avoid the Joule heating of samples, the pulse repetition frequency was as low as 1 Hz. Measurement of the voltage and current waveforms in the sample was carried out by the digital oscilloscope Tektronics TDS 1002 with the bandwidth of 60 MHz. Spectral measurements of photo- or electroluminescence were performed using the monochromator with the spectral resolution of 0.2 meV and equipped with the photomultiplier with the rise time approximately 10^{-8} s. The distribution of the voltage drop along the current was measured with use of the 10-probe micro-system with the spatial resolution about 300 µm. The measurements were performed at temperatures 4.2 to 160 K.

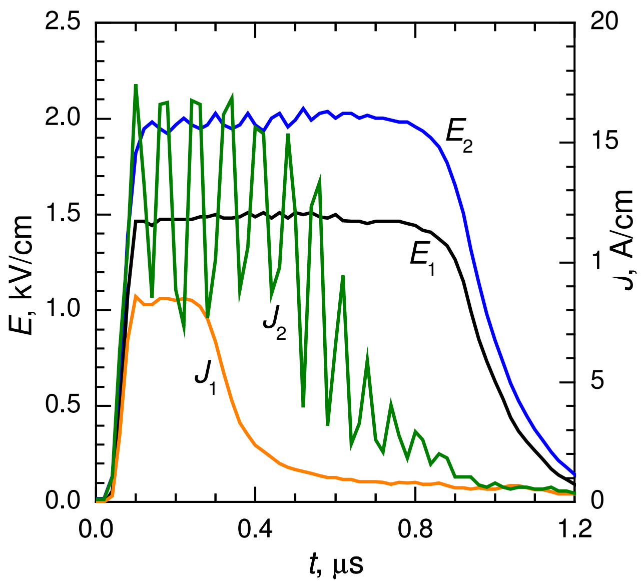

Fig. 2. Waveforms of pulses for the applied field and current. E_1 = 1.45 kV/cm, and E_2 = 1.9 kV/cm. T = 4.2 K.

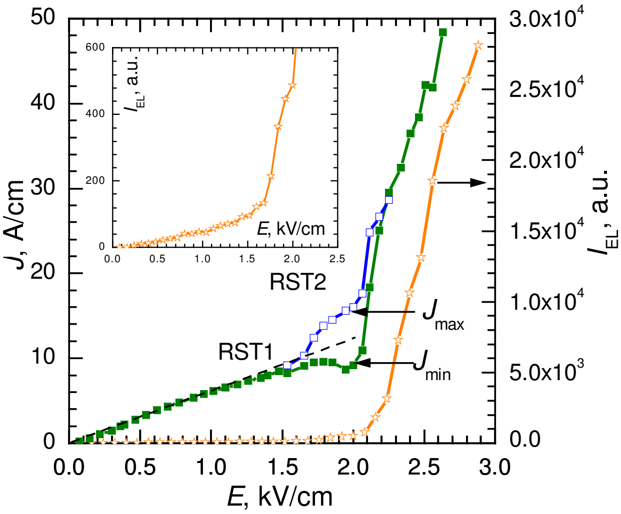

Fig. 3. Field dependence of the current and integrated EL intensity. The maximum (J_{max}) and minimum (J_{min}) current values are shown for the current oscillations. Inset: the field dependence of the integral radiation intensity in the smaller scale. $T = 4.2$ K.

It is known that in long samples at high electric fields, when the carrier drift velocity exceeds the sound velocity, the acoustoelectric domains can appear. In our samples, we observed appearance of the acoustoelectric domains at the average fields' $E \geq 0.4$ kV/cm. The average field is defined as U/L, where U and L are the applied voltage and inter-contact distance, respectively. The domain appears in the middle part of a sample, then moves with increasing amplitude to the anode contact and localises near it. Domain appearance leads to a strong current decrease by more than 10 times. The domain formation takes time, the so-called 'incubation time', τ_i, which in general depends on the field. To illustrate, Fig. 2 presents the pulse waveforms of the average applied field and current at two magnitudes of the field. In these two cases, the incubation time is estimated as 0.2 and 0.4 µs at $E_1 = 1.45$ kV/cm and $E_2 = 1.9$ kV/cm, respectively. In our paper, we focused at the phenomena during times shorter than τ_i, when the acoustoelectric domains are absent yet.

3. Experimental results and discussion

The dependence of the current J vs average field E, $J = f(E)$, referred to as a current vs field characteristic (CFC), measured at times less than τ_i is shown in Fig. 3 for a typical sample.

CFC was practically linear at the fields less than approximately 0.5 kV/cm. However, above this value the CFC slope becomes lower in the range up to $E \sim 1.5$ kV/cm. This part of CFC is labelled as RST1. In the range from 1.5 up to 2.2 kV/cm, the current oscillates. It is illustrated by the current waveform in Fig. 2 at $E = 1.9$ kV/cm. The dependences of the maximum (J_{max}) and minimum (J_{min}) values in the current oscillations on the field E are plotted in Fig. 3. The J_{min} vs E dependence is N-shaped. The value of J_{max} first grows with increasing field, and at $E > 1.5$ kV/cm the growth slows down. This part of CFC is labeled as RST2. Note that appearance of the current oscillations leads to an increase of the incubation time of the acoustoelectric domains, as can be seen in Fig. 2.

The current oscillations weakly depended on the parameters of the electrical circuit. For example, with the load resistor $R = 1$ MΩ the oscillation frequency in different samples varied within the range from 12 to 30 MHz and the amplitude being ~50% of the J_{max} value. The oscillations amplitude with almost the same frequency is reduced down to ~20% of J_{max}, when the load resistor value is decreased down to $R = 50$ Ω in the circuit adjusted for high frequency (HF) measurements. In addition, the current oscillations were observed also at a higher frequency ~80 MHz (Fig. 5b) with the amplitude substantially less than that of the main oscillations in the range 12 to 30 MHz.

With reducing the intercontact distance L, the oscillation frequency remained practically unchanged. The electric field increase from 1.5 up to 2.1 kV/cm resulted in a small (10...20%) decrease of the oscillation frequency. It indicates that these oscillations cannot be associated with formation of the Gunn domains and their motion in the sample. The oscillations frequency slightly grew (approximately by 10%) with temperature increasing from 4.2 up to 160 K. At the same time, the amplitude of oscillations decreases until their full disappearance.

It should be noticed that in similar heterostructures, but with a narrower barrier between quantum wells (30...40 Å), we did not observe current oscillations [24, 25].

In all the studied samples, both with In and Ge/Au electric contacts, electroluminescence (EL) was observed at the fields stronger than ~0.2 kV/cm. Fig. 4 shows the EL spectra at different values of the average electric fields at 4.2 K. A pronounced peak is observed, at the photon energy of 1.434 eV, which is very close to the InGaAs bandgap [26] with the given composition. Observation of the bandgap EL peak provides a very strong evidence of existence of minority carriers – holes that recombine with electrons in the quantum wells.

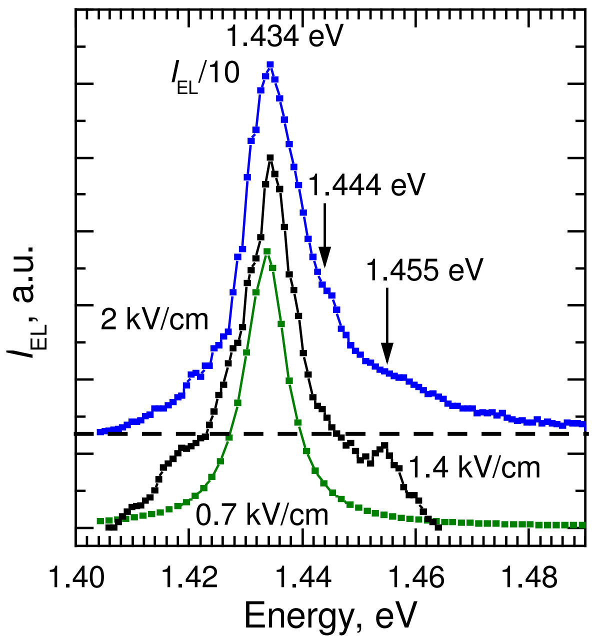

Fig. 4. EL spectra at different electric fields. $T = 4.2$ K.

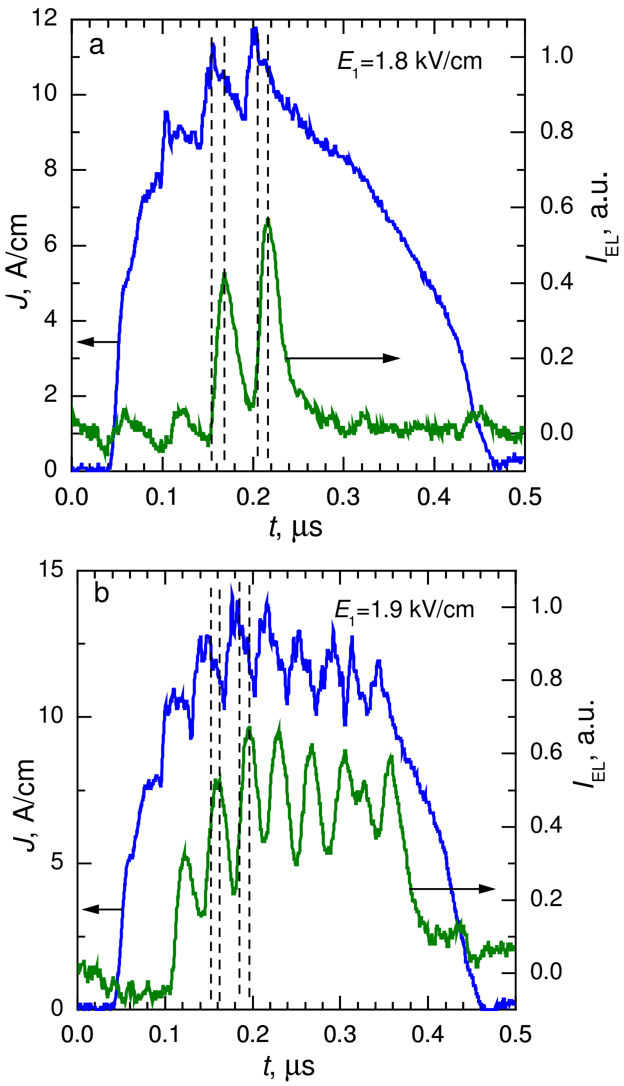

Fig. 5. I_{EL} and current waveforms at two values of the field: a) E_1 = 1.8 kV/cm; b) E_2 = 1.9 kV/cm. T = 4.2 K.

The EL intensity show oscillations in the same field range with the current oscillations. As it follows from simultaneous measurements of the current and EL intensity waveforms, the EL oscillations occur in the opposite phase to those of current. It can be seen from Fig. 5, where the EL intensity integrated in the range from 1.4 to 1.5 eV and current oscillations are shown at different *E* values.

The integral EL intensity measured by collecting the top-surface emission is plotted as a function of the average field *E* in the inset of Fig. 3. It is seen that the EL intensity slightly increases with increasing field up to 1.7 kV/cm. A further field increase from 1.7 to 2.2 kV/cm leads to a strong increase, almost by 2 orders of magnitude, in the EL intensity integrated over duration of the EL oscillations. Along with it, the current increases only by 3 times.

To insight the origin of minority carriers, we measured the distribution of electric field along the current direction in samples. The results are presented in Fig. 6. They show that, at the average fields $E >$ 0.7 kV/cm, a local increase of the electric field E_{loc} takes place near the metallic electric contacts, mainly near the anode. It may be caused by doping inhomogeneity near contacts, probably due to non-uniform intermixing of metals in the course of alloying [27, 28]. The local field strength near these inhomogeneities may be as high as the InGaAs breakdown field (~10^5 V/cm) required for initial impact ionization, which may produce then a cascading avalanche of the electron–hole pairs and band-edge EL via subsequent carrier recombination.

Note that this measurement evidences also the absence of high-field Gunn domains at all investigated average fields. These domains usually propagate from the cathode toward the anode. Impact ionization within these domains results in the band-edge EL that is observed in GaAs/AlGaAs heterostructural planar Gunn diode (see, for example, [28-30]).

We have also investigated the spatial distribution of EL intensity in the samples. At fields $E <$ 1.6 kV/cm, the strongest EL intensity was observed near the anode. It agrees with presence of a locally enhanced electric field near the anode. In addition, we observed an almost exponential decay in the EL intensity in direction to the cathode (Fig. 7). It indicates the holes generated by ionization near the anode to drift in electric field toward the cathode. The drift length obtained for the field values of 1 and 1.5 kV/cm are 0.1 and 0.13 cm, respectively. For a larger electric field ($E >$ 1.6 kV/cm), the electroluminescence distribution over the sample is almost homogeneous. It means that the drift length of holes becomes close or longer than the sample length (up to 0.4 cm) and the holes fill the entire sample during the electric field pulse.

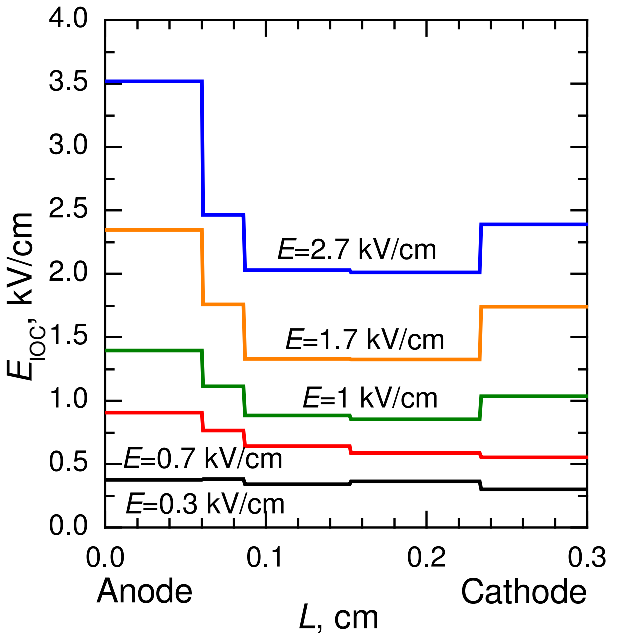

Fig. 6. Distribution of the local electric field E_{loc} along the current direction for different values of the applied average field.

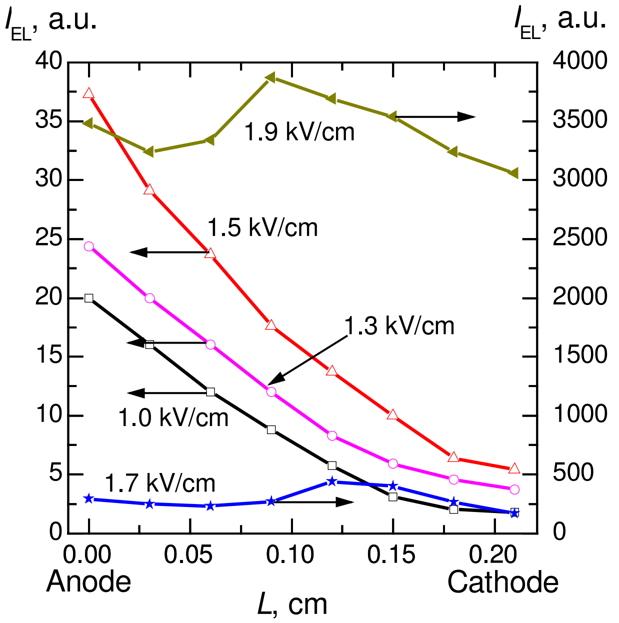

Fig. 7. The spatial distribution of EL intensity along the current direction at different electric fields.

The observed large drift length may be achieved mainly because of the long lifetime of recombining electrons and holes. In the bulk InGaAs, the lifetime of electron-hole pairs is about 10^{-9} s. This lifetime is defined by the radiative recombination process that is direct in the momentum *k*-space. In the double-well heterostructures, the carriers' lifetime may increase, if the recombining electrons and holes are separated in different coupled quantum wells. The spatial separation of generated carriers occurs due to action of the built-in electric field, owing to which the holes fall into the wide quantum wells, while the electrons fall into the narrow wells. Thus, it impedes their recombination and leads to a lifetime increase.

Note that an increase of photogenerated electrons and holes lifetime due to their separation by a built-in electric field of a heterojunction or by an external transverse electric field in heterostructures with coupled quantum wells was observed in [31, 32].

Let us return now again to the current-field characteristic. Note that the presence of two types of carriers renders the character of conductivity bipolar. Remind that in the field range between 0.5 to 1.5 kV/cm the current increases with the field weaker than that at smaller fields (RST1 in Fig. 3). Similar behavior was previously observed for the monopolar electric transport in the *n*-type structures with coupled asymmetrically doped quantum wells. It was associated with the real-space transfer of electrons heated by the electric field from the non-doped wide quantum well to the higher energy states in the doped narrow well [4, 5, 9-11, 22, 24, 25]. As a result, the electron mobility decreases due to additional scattering by the ionized impurities. However, in the studied structures, the electron mobility decrease due to space transfer does not lead to the negative differential conductivity and appearance of current oscillations.

The current oscillations are observed at strong fields, when there occurs also a decrease of the CFC slope in the RST2 part (Fig. 3). We attribute this decrease to the space transfer of holes heated by the electric field from the wide wells to the doped narrow ones. As a result, the hole mobility decreases due to scattering by impurities. In addition, the electrons and holes become spatially unshared. It strongly increases the recombination rate of carriers and, consequently, decreases the concentration of free carriers. As a consequence, the differential conductivity becomes negative, which causes the current oscillations.

Taking into account the absence of current oscillations in the heterostructures with the narrower barriers (30...40 Å) between coupled QWs, it is reasonable to suggest that a sufficient barrier width (≥ 50 Å) is important for oscillation appearance. It causes the tunneling time of holes between the narrow and wide QWs to increase strongly [33] and become comparable or higher than the recombination time of holes in a narrower QW. That is, the recombination is a faster process. This assumption is supported by the experimental fact that the current oscillations decrease with the temperature increase and disappear at $T \geq 160$ K, when the recombination time increases strongly ($\sim T^{3/2}$) [34]. Since the carrier tunneling time depends weakly on temperature [35, 36], such a process becomes predominant over recombination.

Note that an increase of the electron-hole recombination rate is confirmed by a strong increase of the interband EL intensity. Moreover, the carrier heating by the electric field and their spatial transfer from the wide quantum wells into the narrow ones is confirmed by the EL spectrum changes with increasing field (Fig. 4). At $E \geq 1.4$ kV/cm, an exponential decay can be seen on the high energy "tail" of the main peak related with emission from the wide quantum wells. This tail is caused by heating the carriers. In addition, at $E \geq$ 1.4 kV/cm the two new additional lines appear on this tail with photon energy of about 1.444 and 1.455 eV. We associate these lines with optical transitions of the excited electrons and holes, transferred from wide QWs to narrow ones.

4. Conclusion

Thus, we observed oscillations of the current and interband electroluminescence intensity in the range of tens MHz in the multilayer heterostructures with coupled asymmetrically doped quantum wells in the lateral electric fields and in the presence of two types of charge carriers: the majority carriers – electrons and minority carriers – holes. Appearance of these current and EL instabilities is explained by the combined effect of spatial separation of electrons and holes and rate dynamics of their transfer between the non-doped and doped quantum wells. The space transfer leads to a decrease of the carrier mobility and an increase of the radiative recombination rate, which causes a decrease of the carrier concentration.

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