The effect of the external lateral electric field on the luminescence intensity of InAs/GaAs quantum dots

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We report on low-temperature micro-photoluminescence (μ-PL) measurements of InAs/GaAs quantum dots (QDs) exposed to a lateral external electric field. It is demonstrated that the QDs PL signal could be increased several times by altering the external and/or the internal electric field, which could be changed by an additional infra-red laser. A model which accounts for an essentially faster lateral transport of the photo-excited carriers achived in an external electric field is employed to explain the observed effects. The results obtained suggest that the lateral electric fields play a major role for the dot luminescence intensity measured in our experiment — a finding which could be used to tailor the properties of QD-based optoelectronic applications.

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Capture processes of carriers into the quantum dots (QDs) are of great importance for the performance and operation of different QD-based optoelectronic devices [1]. This is due to the fact that in most optical experiments on QDs, electrically injected or photoexcited carriers are primarily created somewhere outside the QDs in the sample (e.g., in the barriers or in the wetting layer (WL) [2]): consequently, excited carriers undergo a transport in the WL/barriers prior to the capture into the QDs.

In the past decade, broad and intensive studies of the carrier capture mechanisms have been performed, e.g., optical phonon-assisted [3], Auger-like [4], and shake-up [5] processes. It was also demonstrated that the lateral carrier transport (i.e. in the plane of the WL) could be affected by carrier hopping between QDs [6], by trapping of migrating particals into localized states of the WL [7], or into non-radiative centers in the surrounding media [8]. An external electric field directed in the growth direction of the sample was shown [9] to play an important role on the carrier capture into and escape out of the QD.

Another novel mechanism for carrier transfer from the WL into the QDs, a built-in electric field (F_{int}) directed in the plane of a WL to facilitate the lateral carrier transport was proposed in our previous study [10]. It was suggested [10] that the existence of this F_{int} is the major factor which determines the size of the collection area of a QD and, consequently, the value of the QDs photoluminescence (PL) signal (L_{QD}).

In the present contribution, a lateral external electric field (F_{ext}) is applied to the sample to directly study the role of the electric field directed in the plane of the WL on the carrier capture efficiency from the WL into the QDs. To the best of our knowledge, there are very few earlier publications in which micro-PL (μ-PL) was employed to study the QDs subjected to a lateral electric field [11,12]. However, in none of the above mentioned studies, the carrier transport could be probed as a function of an external lateral field, since the QDs were excited by the resonant pumping directly into the QD's excited states [11], or as a result of a special sample design, e.g., a mesa containing an individual QD [12].

Our previous results demonstrate that the magnitude of the internal electric field present in the sample at zero external bias is essentially reduced by the illumination of the sample with an additional infra-red laser [10]. The results obtained in the present paper show that the increase of the lateral external electric field can give rise to an increase of the dot luminescence intensity by as much as a factor of 5. These experimental findings are explained in terms of an essentially faster transport of the photo-excited carriers in the plane of the WL, which could be achieved when an external bias has been switched on.

The sample studied was grown by molecular beam epitaxy of a GaAs (100) substrate. The InAn QDs of different density were developed from a single layer of a 1.7 monolayer thich InAn WL deposited by the Stranski-Krastanov growth mode. The WL and the dot layer

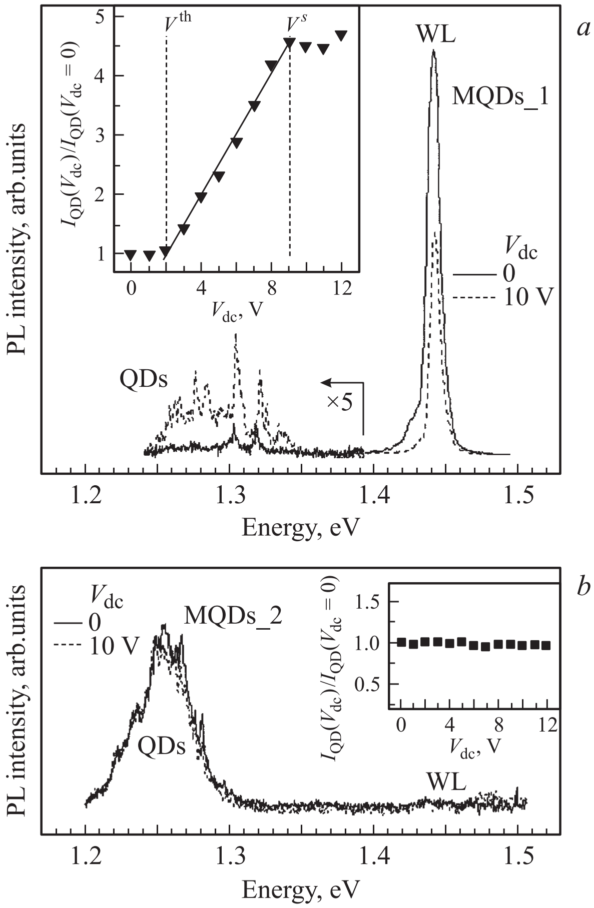

Figure 1. PL spectra at two different spots, (a) MQDs_1 and (b) MQDs_2 measured at $h\nu_{\text{ex}} = 1.675$ eV, $P_0 = 20$ nW and $T = 5$ K shown by solid (dashed) lines for $V_{\text{dc}} = 0$ (10 V), respectively. The insets in (a) and (b) show the dependence of I_{QD} on V_{dc}. The solid line in the inset in (a) shows a liner fit to the data based on the method of least squares.

were sandwiched between two 100 nm thick GaAs barriers. The QDs were studied by means of a diffraction-limited μ-PL setup (a detailed description of the setup and the sample growth procedure is given in Ref. 10).

Two pairs of In gate electrodes with a 25 μm spacing on top of the sample were processed to apply an external electric field across the structure. Two sample spots (denoted as MQDs_1 and MQDs_2) with considerably different QD's densities were investigated in the present study. Since the exact QD's density could not be determined, instead an alternative quantitative method based on the relative PL intensities of the QDs (I_{QD}) and the WL (I_{WL}) was employed to compare the relative QD's densities. The corresponding parameter, defined as $I_{\text{QD}}/(I_{\text{QD}} + I_{\text{WL}})$, equals to 0.06 and 1.0 for the sample spots MQDs_1 and MQDs_2, respectively.

A Ti-Sp laser, which beam was focused on the sample surface down to a spot diameter of 2 μm, was used to excite the sample. The excitation energy of the laser ($h\nu_{\text{ex}}$) was tuned in the range from 1.23 to 1.77 eV with a maximum excitation power (P_0) of 200 μW. For dual laser excitation conditions, a semiconductor laser operating at a fixed excitation energy of 1.589 eV with a maximum power output of 200 nW was used as a principal excitation source, while a Ti-Sp laser was used as an infra-red laser operating at a fixed excitation energy $h\nu_{\text{IR}} = 1.23$ eV. The sample was positioned inside a continuous-flow cryostat operating at a temperature of $T = 5$ K.

The μ-PL spectra of the low density part of the sample (MQDs_1) measured for two different applied voltages ($V_{\text{dc}} = 0$ and 10 V) are shown in Fig. 1, a. Both spectra consist of two emission bands: a narrow band at 1.44 eV originating from the wetting layer and a broad band around 1.30 eV due to the QDs emission. At $V_{\text{dc}} = 0$ (solid line in Fig. 1, a), the WL band dominates the μ-PL spectrum, while for $V_{\text{dc}} = 10$ V (dashed line in Fig. 1, a), the WL PL intensity decreases and the QDs PL signal increases. Special care was taken to measure the QDs PL signal in the absence of optical pumping at $V_{\text{dc}} = 10$ V. No PL signal was recorded from QDs at these experimental conditions, which allows us to exclude the possible origin of the intensity increase of QDs emission as being due to the electric field-induced carrier injection into the sample (the basic operating principle of the QD-based laser [1]).

The dependence of the spectrally integrated PL signal of the QDs (I_{QD}) on the applied voltage V_{dc} is shown in the inset in Fig. 1, a. It is seen that I_{QD} starts to increase for V_{dc} values exceeding a threshold value of V^{th} and can not be further altered as V_{dc} has exceeded a certain value of V^s (inset in Fig. 1, a). Measurements performed (not shown here) reveal that at $V_{\text{dc}} = V^s$ a photo-current is initiated which saturates the voltage drop across the sample under study due to the appearance of an effective screening of the external field by the photo-excited carriers.

The observed effect of the increase (decrease) of $I_{\text{QD}}(I_{\text{WL}})$ registered at $V_{\text{dc}} > 0$ is explained by a model based on the fact that the photo-excited carries subjected to F_{ext} acquire, in addition to the thermal velocity (which carriers possess in the absence of an electric field), a drift velocity (controlled by the value of F_{ext}), which could be considerably higher than the thermal velocity. Consequently, in the presence of F_{ext}, carriers move faster in the plane of the WL, which in turn increases the probability for the carriers to approach the QD and, subsequently become captured instead of recombining in the WL. These processes should lead to a decreace of the I_{WL} and to a corresponding increase of I_{QD}.

The suggested model is justified by the following experimental observations.

a) We were not able to register any changes for I_{QD} measured on the sample spot MQDs_1 in the entire range of $0 < V_{\text{dc}} < V^s$, when exciting the QDs at the excitation energy, $h\nu_{\text{ex}} = 1.40$ eV, i.e. below the OW emission band. At these experimental conditions, carriers are excited directly into the QDs and, consequently, are not subjected to the transport along the WL plane prior to capture into the QDs.

b) The magnitude of the ratio $I_{QD}(V_{dc} = 10\,V)/I_{QD}(V_{dc} = 0)$ measured on sample spot MQDs_1 for excitation with $h\nu_{ex} = 1.460$ eV, i.e. close to the energy of the WL emission band, was found to be ≈ 1.1 (i.e. a change by 10% which is within experimental accuracy). This limited effect could be explained by the fact that at this $h\nu_{ex}$, photo-excited carriers are localized at WL potential fluctuations, which are due to the growth-induced variations of alloy, composition and strain along the plane of the WL [7]. This observation is consistent with the expected disappearance of the effect of F_{ext} on the carrier motion when carriers become localized.

c) No changes in the I_{QD} with increasing V_{dc} were recorded even for excitation with $h\nu_{ex} = 1.675$ eV on the sample spot with high QDs density, MQDs_2 (inset in Fig. 1, *b*). At this sample spot, no WL emission is registered at $V_{dc} = 0$, which is the consequence of essentially higher probability of carrier capture from the WL into the QDs with respect to the case of MQDs_1 (see Fig. 1, *a* and *b*). Consequently, even if the carrier capture probability from the WL into the QDs in further increased with the introduction of F_{ext}, no increase of I_{QD} is expected. This experimental result evidences that the observed increase of I_{QD} (Fig. 1, *a*) can not be explained in terms of an electric field-initiated ionazation of defects or non-radiative recombination centers, which at $V_{dc} = 0$ have captured some part of the photo-excited carriers [13], primarily excited in the WL at $h\nu_{ex} = 1.675$ eV.

The considered model, as explained above, predicts the increase of the capture probability of photo-excited carriers into the QDs as long as the drift velocity of the carriers (proportional to the F_{ext}) increases. Consequently, it is expected that I_{QD} should exhibit a *linear* dependence on the V_{dc}, which is in full agreement with our experimental observations (inset in Fig. 1, *a*). To explain the fact that I_{QD} measured remains unchanged in the range $0 < V_{dc} < V^{th}$ (inset in Fig. 1, *a*), the existence of an internal field F_{int} (due to ionized impurities spatially separated from the QD) inside the structure with a component directed in the plane of the WL has been suggested [10]. The existence of such an internal electric field was reported in studies of QD samples with different material compositions such as InAs/GaAs [9], CdSe/ZnSe [13], and InP/InGaP [14]. The magnitude of F_{int} determines the values of the drift velocities of the carriers (and, hence the value of I_{QD}) at $V_{dc} = 0$. Consequently, to achieve an increase of I_{QD} at $V_{dc} > 0$, F_{ext} should exceed F_{int}, or in other words, V_{dc} should be greater than some threshold value denoted as V^{th} (inset in Fig. 1, *a*).

In order to further test the suggested model on an internal field, we studied the evolution of I_{QD} as a function of V_{dc}, when the sample was excited with an infra-red laser (L_{IR}) with an energy well below any QD related transition, in addition to the principal laser (L_0). The present study reveals that no I_{QD} could be monitored when exciting with only L_{IR}. Accordingly, either no carrier or alternatively only carriers of one sign (electrons or holes) could be excited in the sample. In our previous publication it was demonstrated that free holes were optically created in the sample as a result of the L_{IR} excitation induced ionization of deep levels positioned in the GaAs barriers [10]. It was also suggested that this extra (non-compensated) charge could effectively screen the F_{int}. Consequently, V_{dc} is expected to reach an essentially lower threshold, V^{th}, when excited with both lasers, compared to single laser excitation, in the evolution of I_{QD} as a function of V_{dc}.

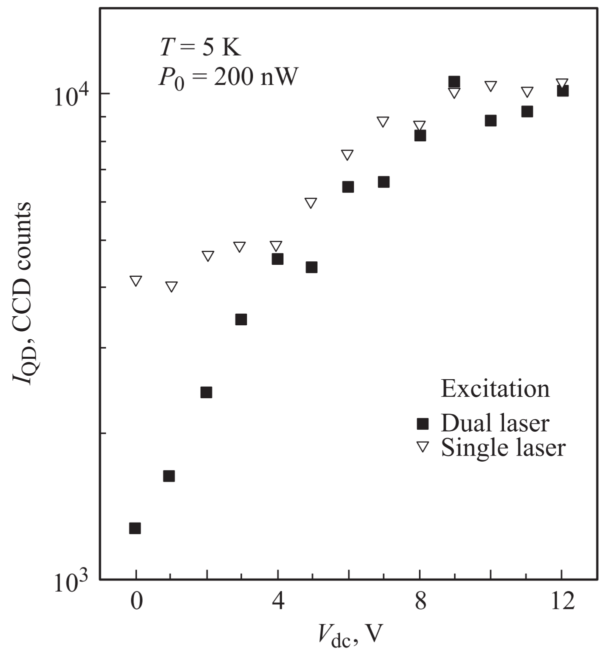

Figure 2. I_{QD} as a function of V_{dc} measured for MQDs_1 at $T = 5$ K, $h\nu_{ex} = 1.589$ eV, $h\nu_{IR} = 1.230$ eV, $P_0 = 200$ nW, $P_{IR} = 100\,\mu$W with single (open symbols) and dual (solid symbols) laser excitation, respectively. The semiconductor laser has been used in these measurements as the principal laser.

Fig. 2 shows the dependence of I_{QD} on V_{dc} for both single and dual laser excitation. For the case of dual laser excitation, no V^{th} could be revealed. In addition, I_{QD} for $V_{dc} = 0$ has an essentially lower value compared to the value of I_{QD} (also for $V_{dc} = 0$), measured for the single laser excitation (compare the solid and open symbols in Fig. 2). These two observations prove that L_{IR} has effectively compensated F_{int} (totally or partially), which was present at $V_{dc} = 0$ with single laser excitation. It should be stressed that the two I_{QD} dependencies on V_{dc} (in Fig. 2) almost coincide for $V_{dc} \geq 4$ B. This behavior is expected since, according to the suggested model, I_{QD} at relatively large V_{dc}'s should be independent on F_{int}. Consequently, the experimental results shown in Fig. 2 support the previously suggested idea that L_{IR} effectively compensates the internal electric field [10], which in turn determines I_{QD} measured in the experiment with the „traditional" single-laser-excitation conditions.

The major role an electric field directed in the plane of the sample on the probability of the carrier capture into the QDs has been demonstrated. The PL intensity from the QDs could be increased several times depending on the strength of the internal electric field (which could be altered by an additional infra-red illumination of the sample) as well as on external electric field applied to the sample. The possibility to effectively control the PL intensity of the QDs by means of an external electric field could be used for a wide range of the QD-based light emitting devices.

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