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Enhancement of the Luminescence Intensity of InAs/GaAs Quantum Dots Induced by an External Electric Field

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ABSTRACT

InAs/GaAs quantum dots have been subjected to a lateral external electric field in low-temperature microphotoluminescence measurements. It is demonstrated that the dot PL signal could be increased several times depending on the magnitude of the external field and the strength of the internal (built-in) electric field, which could be altered by an additional infrared illumination of the sample. The observed effects are explained by a model that accounts for the essentially faster lateral transport of the photoexcited carriers achieved in an electric field.

In most experiments with semiconductor quantum dots (QDs), electrically injected or photoexcited carriers are primarily created somewhere in the sample outside the QDs (e.g., in the barriers or in the wetting layer (WL), on which the QDs normally are grown).[1] Consequently, excited carriers undergo a transport in the WL/barriers prior to the capture into the QDs. This circumstance highlights the crucial role of the carrier transport and capture processes into the QD for the performance and operation of the QD-based devices such as QD lasers,[2] QD infrared detectors,[3] and QD memory devices.[4] The intensive studies of the carrier capture mechanisms reveal optical phonon-assisted,[5,6] Auger-like,[7] shake-up[8] processes and carrier relaxation through the band tail states of the WL with a subsequent emission of localized phonons.[9]

It has also been demonstrated that the lateral (i.e., in the plane of the WL) carrier transport could be affected by carrier hopping between QDs[10] by trapping of migrating particles into localized states of the WL[11] or into nonradiative centers[12] in the surrounding media. A more efficient carrier transfer from the WL into the QDs via radiation-induced defects in the WL has been reported.[13] A magnetic field directed perpendicular to the plane of the structure was observed to limit the lateral transport of carriers.[14] The important role of an external electric field directed in the growth direction of the sample on the carrier capture into and escape out of the QDs has also been demonstrated.[15]

In our previous study, we pointed out another mechanism of significant importance for the carrier transfer from the WL into the QDs, which has not been previously considered: a built-in electric field (F_{int}) directed in the plane of the WL to facilitate the lateral carrier transport.[16] All QDs were supposed to capture carriers from the WL area surrounding each QD, which was referred to as the effective carrier collection area. It was suggested that the strength and space distribution of this F_{int} is the major factor determining the extension of this carrier collection area of a QD and, consequently, the level of the QDs photoluminescence (PL) intensity (I_{QD}) at given experimental conditions.[16]

In the present paper, a lateral external electric field is applied across the sample to 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[17,18] in which the micro-PL (μ-PL) technique was employed as the tool to study the QDs subjected to a lateral electric field. However, in none of the above-mentioned studies, the carrier transport could be probed as a function of an external lateral field because the QDs were excited selectively by either resonant pumping directly into the QD's excited states[17] or into an individual dot as a result of a special sample design in the form of a mesa.[18] As a result, a red-shift of the spectral positions of the QD's μ-PL lines and a decrease of the I_{QD} with an increasing external lateral

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electric field due to the quantum-confined Stark effect, have been revealed.[17,18]

Our present results demonstrate 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. It is also shown that the magnitude of the internal electric field present in the sample at zero external bias could be essentially reduced by illuminating the sample with an additional infrared laser. The results obtained are explained in terms of an essentially faster transport of the photoexcited carriers in the plane of the WL when an external and/or internal electric field is present.

The sample studied was grown by molecular beam epitaxy on a GaAs (100) substrate. The InAs QDs with a height of 4.5 nm and a lateral size of 35 nm were developed from a single layer of a 1.7 monolayer thick InAs WL deposited by the Stranski−Krastanov growth mode. The WL and the dot layer were sandwiched between two 100 nm thick GaAs barriers. The sample was grown without rotation of the substrate, resulting in a gradual variation of the In flux across the wafer and, consequently, a gradient in the QDs density. The QDs were studied by means of a diffraction-limited μ-PL.

To apply an external electric field across the structure, two pairs of In gate electrodes with a 25 μm spacing on top of the sample were processed. Two sample spots (denoted as QD1 and QD2) with considerably different QD's densities were investigated in the present study. The exact QD's density could not be determined at each particular sample spot. Instead an alternative quantitative method based on the relative PL intensities of the QDs (I_{QD}) and the WL (I_{WL}) is introduced to compare the relative QD's densities. The corresponding parameter, defined as $I_{QD}/(I_{QD} + I_{WL})$, equals 0.06 and 1.0 for the sample spots QD1 and QD2, respectively.

To excite the sample, we used a Ti:sapphire laser, where the beam was focused on the sample surface down to a spot diameter of 2 μm. The excitation energy of the laser ($h\nu_{ex}$) 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 the principal excitation source, while a Ti:sapphire laser was used as an infrared laser operating at a fixed excitation energy $h\nu_{IR} = 1.23$ eV. The sample was positioned inside a continuous-flow cryostat operating at a temperature of $T = 5$ K.

Figure 1a shows the low-temperature μ-PL spectra of the low-density part of the sample QD1, measured at the conditions given in the figure caption for two different applied voltages ($V_{dc} = 0$ and 10 V). Both spectra consist of two emission bands: a narrow band at 1.44 eV originating from the WL and a broad band around 1.30 eV due to the QDs emission. At $V_{dc} = 0$ V (solid line in Figure 1a), the WL band dominates the μ-PL spectrum, while for $V_{dc} = 10$ V (dotted line in Figure 1a), the WL PL intensity has decreased and the QDs PL signal has increased. Special care was taken to measure the QDs PL signal in the absence of

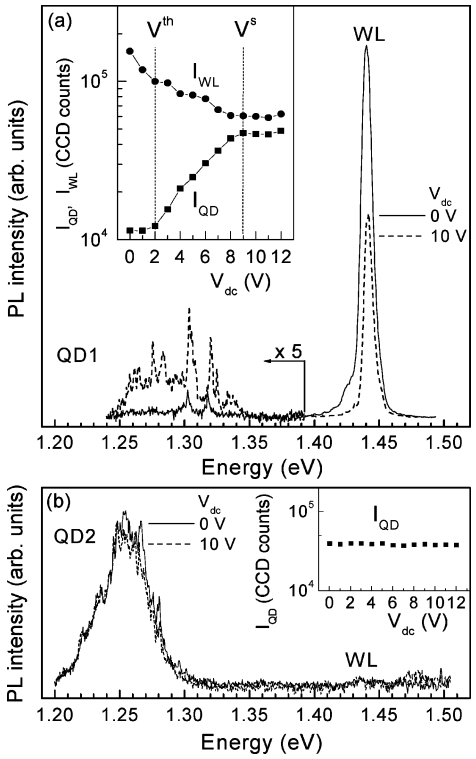

Figure 1. μ-PL spectra for two different spots, (a) QD1 and (b) QD2 measured at $h\nu_{ex} = 1.675$ eV, $P_0 = 20$ nW, and $T = 5$ K, shown by solid (dotted) lines for $V_{dc} = 0$ V (10 V), respectively. The insets in (a) and (b) show the dependence of I_{QD}, I_{WL}, and I_{QD}, respectively, on V_{dc}.

optical pumping at $V_{dc} = 10$ V. No PL signal was recorded from the QDs at these experimental conditions, which allows us to exclude the possible origin of the intensity increase of the QDs emission as being due to the electric field-induced carrier injection into the sample (i.e., the basic operating principle for QD-based lasers[2]).

It should be noted that some additional spectral lines appear in the PL spectrum of QD1 at $V_{dc} = 10$ V (compare solid and dotted lines in Figure 1a). This effect could be explained in terms of carrier filling in the dot, assuming that, at $V_{dc} = 0$ V, some of the individual QDs are empty, alternatively filled with carrier(s) of only one sign (i.e., electron(s) *or* hole(s)). As a result, no emission is expected from these dots. An increase of V_{dc}, according to the model suggested below, initiates an essentially higher capture rate of both electrons and holes into the QDs, opening the possibility to emit light for those individual QDs that initially had a deficit of carriers at $V_{dc} = 0$ V.

The dependencies of the spectrally integrated PL intensities of the WL, I_{WL}, and the QDs, I_{QD}, respectively, on the applied voltage, V_{dc}, are shown in the inset in Figure 1a. Both polarities of V_{dc} exhibit the same influence on the μ-PL spectra: While I_{WL} progressively decreases with increasing V_{dc}, I_{QD} starts to increase for V_{dc} values exceeding a threshold value of V^{th} (as shown in the inset in Figure 1a). It should be noted that neither I_{QD} nor I_{WL} could be further altered as V_{dc} has exceeded a certain saturation voltage, V^s (shown in the inset in Figure 1a). For measurements performed at $V_{dc} \geq V^s$, a photocurrent is initiated that saturates the voltage

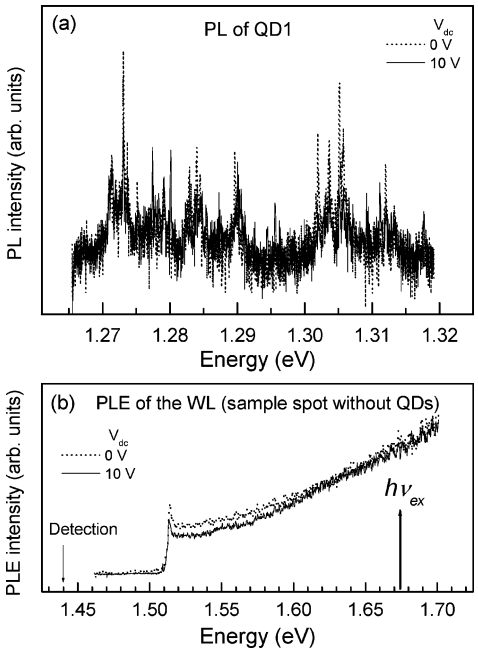

Figure 2. (a) μ-PL spectra for $P_0 = 100$ nW measured at $h\nu_{ex} = 1.40$ eV and $T = 5$ K shown by dotted (solid) lines for $V_{dc} = 0$ V (10 V), respectively. (b) PLE spectra with detection at the WL emission, at $T = 5$ K and $P_0 = 100$ μW, for unbiased (dotted line) and biased (solid line) conditions ($V_{dc} = 0$ and 10 V, respectively).

drop across the structure studied (restricted by the size of the laser spot of 2 μm) due to the appearance of an effective screening of the external field by the photoexcited carriers. Consequently, we can only increase the electric field, F_{ext}, up to the "saturation" value, F_{ext}^{s}, which is, for given experimental conditions (such as crystal temperature and excitation power), controlled by V^{s}.

The simultaneous decrease of I_{WL} and increase of I_{QD} registered at $V_{dc} > 0$ V are explained in terms of a drift velocity achieved by the photoexcited carriers subjected to F_{ext} in addition to the thermal velocity (which carriers possess in the absence of an electric field). Consequently, in the presence of F_{ext}, carriers could move with an enhanced velocity 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 result in a simultaneous decrease of I_{WL} and a corresponding increase of I_{QD}. This model is justified by the following experimental observations: (i) No changes in the I_{QD} could be monitored for measurements on the sample spot QD1 in the entire range of $0 \text{ V} < V_{dc} < V^{s}$ when exciting the QDs with an excitation energy $h\nu_{ex} = 1.40$ eV, i.e., below the WL 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. Figure 2a shows PL spectra, measured for unbiased and biased conditions ($V_{dc} = 0$ and 10 V, respectively). Although some scatter in the intensities of the spectrally resolved PL lines, these spectra demonstrate that the spectrally integrated PL intensity, I_{QD}, remains unchanged. These experimental results will exclude the possible explanation involving a sweep out of the carriers from the QDs for an increasing lateral electric field (cf. the reports by Kowalik et al.[19] and Stavarache et al.[20]). Consequently, we can exclude a possible influence of modifications in the exciton wave functions, induced by the lateral electric field (see ref 19) from our model.

(ii) The strength of the observed effect of an increased I_{QD} measured on sample spot QD1 for the case of $V_{dc} = 10$ V vs I_{QD} measured at $V_{dc} = 0$ V was found to be almost the same, not only for excitations above the band gap energy of the GaAs barriers but also for excitation with $h\nu_{ex} < 1.518$ eV, i.e., in the WL. However, for excitations with $h\nu_{ex} = 1.460$ eV, i.e., close to the energy of the WL emission band, only a small increase of I_{QD} ($\approx$ 10%, which is within the experimental accuracy) was registered. The latter effect could be explained in terms of photoexcited carriers getting localized at WL potential fluctuations, which are due to the growth-induced variations of alloy, composition, and strain along the plane of the WL.[11] Consequently, it is reasonable to expect that the effect of F_{ext} on the carrier motion will disappear as the carriers become localized. This finding could be used as experimental evidence that the observed increase of the I_{QD} should be explained by the increased velocity of free carriers induced by F_{ext} rather than by carrier-hopping processes between localized states in the WL stimulated by F_{ext},[9,11] which could finally lead to the capture of this hopping carrier into the QD.

(iii) The possibility that the observed changes in both I_{WL} and I_{QD} are caused by changes in absorption of the sample caused by a lateral electric field is ruled out (cf. the report on GaAs/AlGaAs quantum wells by Miller et al.[21]). This conclusion is based on a comparative study on the WL PL properties of a sample spot without QDs in the presence of a lateral electric field. The PL excitation (PLE) of the WL (with detection at the maximum of the WL PL band) was recorded for unbiased and biased conditions, $V_{dc} = 0$ and 10 V, respectively (Figure 2b). This comparison exhibits a $\approx$20% change in the absorption for excitation at $h\nu_{ex} \approx 1.515$ eV, which diminishes gradually as the excitation is increased up to $h\nu_{ex} = 1.65$ eV. As obvious from Figure 2b, no detectable change in the absorption can be monitored at $h\nu_{ex} = 1.675$ eV (as used in our experiments and indicated in Figure 2b).

(iv) No change in the I_{QD} for increasing V_{dc} was recorded for excitation with $h\nu_{ex} = 1.675$ eV on the sample spot with the high QDs density, QD2 (Figure 1b). At this sample spot, no WL emission is registered at $V_{dc} = 0$ V, which is the consequence of a probability close to unity for carrier capture from the WL. Consequently, the carriers capture probability from the WL into the QDs cannot be further increased, not even with an applied field. No increase of I_{QD} is then expected, which is in agreement with the experimental observations (inset of Figure 1b). This experimental result demonstrates that the observed increase of I_{QD} (Figure 1a) cannot be explained in terms of an electric field-initiated ionization of defects or nonradiative recombination centers, which at $V_{dc} = 0$ V have captured some part of the

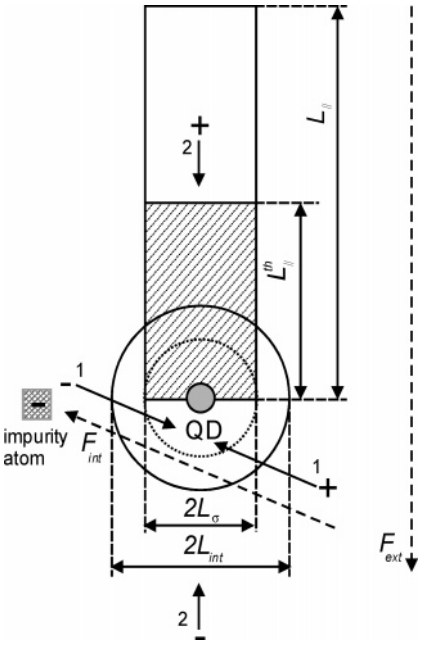

Figure 3. Schematic illustration of the QD's collection areas and the electric field distribution. Numbered arrows indicate the processes explained in the text. The plane of the figure corresponds to the plane of the WL. The effective carrier collection area, σ, is schematically shown as an inner area restricted by a dotted ring. The rectangles shown here correspond to the collection areas for holes. The corresponding collection areas for electrons will have a similar spatial shape just below the QD position (not shown in the figure).

photoexcited carriers,[22] primarily excited in the WL at $h\nu_{ex} = 1.675$ eV.

Next, we will discuss the fact that I_{QD} remains unchanged in the voltage region of $0 < V_{dc} < V^{th}$ (see inset in Figure 1a), although I_{QD}, according to the suggested model, should increase simultaneously with an applied field F_{ext}, already in the low field regime. The unchanged I_{QD} can be understood if a predominant internal field F_{int} exists inside the structure with a component directed in the plane of the WL. The existence of such an internal electric field was reported in studies of QD samples with different material compositions such as InAs/GaAs,[15] CdSe/ZnSSe,[22] CdSe/ZnSe,[23] and InP/InGaP.[24] The origin of F_{int} is suggested to be due to ionized impurities spatially separated from the QD,[22,23,25,26] as schematically shown in Figure 3. The magnitude and direction of this internal field at a given time is determined by the charge distribution and distances between the impurities positioned in the close vicinity of the QD.

In the ideal case, i.e., in the absence of F_{int} (and for $F_{ext} = 0$), the QD is supposed to collect carriers from an area, symmetric in space with respect to the QD's position, which is denoted the effective carrier collection area (σ) of the QD (Figure 3). A carrier will be captured into the QD, and accordingly contributing to its PL intensity (i_{QD}), as soon as it is located within the interior of σ, where the radius L_σ is determined by the thermal diffusion/drift properties of carriers.[27] It should be stressed that, in the following, an analysis of the influence of the electric fields (F_{int} and F_{ext}) only on individual QDs will be presented (as schematically shown in Figure 3). The possibility to use such an approach stems from the fact that carrier collection areas of adjacent QDs in the dot ensemble QD1 do not normally intersect with each other. This is justified by the experimental fact that $I_{QD} \ll I_{WL}$ in the entire range of V_{dc} studied (see inset in Figure 1a). In the opposite case, there should be no possibility to register I_{WL}. This situation is only realized for the case of the denser QDs ensemble QD2 (Figure 1b).

When the carriers, photoexcited at $V_{dc} = 0$ V, are subjected to F_{int}, they will attain a certain drift velocity (illustrated by arrows 1 in Figure 3). This results in the increase of the QD's collection area, which could be characterized by a collection length L_{int}, as schematically shown in Figure 3. The shape of this area is expected to be circular-like (the solid ring in Figure 3) due to the random changes of the direction of F_{int} in time and space. Consequently, the magnitude of i_{QD} and, hence I_{QD} as measured in the experiment, i.e., with F_{int} taken into account but $V_{dc} = 0$ V, will be proportional to πL_{int}^2.

When V_{dc}, i.e., F_{ext}, is switched on, photoexcited holes (electrons), as explained above, will gain a drift velocity in the (opposite) direction of F_{ext}. This leads to two processes: First, the QD collection area will increase (illustrated by arrow 2 in Figure 3) in the direction of F_{ext}, which in turn increases i_{QD}. Second, the carriers can also give rise to a neutralization of the ionized impurities, which in turn causes a decrease of the QD collection area, and consequently also i_{QD}. The balance between these counteracting processes can satisfactorily explain the almost unchanged I_{QD} monitored in the low voltage range, $0 < V_{dc} < V^{th}$ (see inset in Figure 1a).

At $V_{dc} = V^{th}$, the QD collection area is expected to be elongated in the direction of F_{ext} and can, at least in a first approximation, be considered to exhibit a rectangular-like shape (schematically shown in Figure 3). The QD collection area for $V_{dc} = V^{th}$ is given by $(L_{||}^{th} + a) \times 2 \times L_\sigma$ (which is equal to πL_{int}^2 because I_{QD} remains almost unchanged in the voltage range of $0 < V_{dc} < V^{th}$). $L_{||}^{th} = L_{||}(V_{dc} = V^{th})$, where $L_{||}$ is the QD "collection length" (determined by F_{ext}) and parallel to F_{ext} and a (proportional to L_σ) accounts for the possible contribution of thermal diffusion of carriers to the total collection length of the QD ($L_{||} + a$) in the direction of F_{ext}. $L_{||} = v_{dr} \times \tau$, where τ and v_{dr} are the carrier scattering time and carrier drift velocity, respectively. v_{dr} is expressed as $\mu \times F_{ext}$, where μ is the carrier mobility and the value of F_{ext} can be estimated as $\gamma \times V_{dc}/d$, where $d = 25$ μm is the distance between the two metal contacts on top of the sample and γ is the factor that accounts for the field reduction inside the sample relatively the nominal field applied on top of the sample.

Numerical calculations[28] for our sample geometry (where the WL is positioned 100 nm below the sample surface) yield $\gamma \approx 0.65$, which is consistent with the value of $\gamma \approx 0.6$ calculated by others[17] for the field at a distance of 160 nm from the top of a similar GaAs/GaAlAs structure. We estimate $F_{ext}^{s} = F_{ext}$ $(V_{dc} = V^{s}) = 2340$ V cm^{-1} and, consequently, $F_{ext}^{th} = 520$ V cm^{-1}. This value could be regarded as a rough estimate of the space- and time-averaged magnitude of F_{int}, although, as explained above, the exact

space distribution of F_{int} is not known. It should be mentioned that $F_{int} = 520$ V cm^{-1}, estimated for the sample spot QD1 investigated in the present study, is consistent with the estimate of $F_{int} = 400$ V cm^{-1}, which was obtained in our previous study with dual laser excitation conditions for another, but neighboring, spot of the same sample with a very low QD density (1 QD per laser spot).[16]

For $V_{dc} > V^{th}$, i_{QD} (and hence also I_{QD}) will increase because the QD collection area increases. According to the suggested model, the total increase of the QD's collection area ($(L_{||} + a) \times 2 \times L_\sigma$) should be entirely determined by the increase of $L_{||}$ with increasing V_{dc} ($L_{||} = b \times V_{dc}$, where $b = \tau \times \mu \times \gamma/d$). Consequently, the discussed model predicts a linear increase of i_{QD} (I_{QD}) with increasing V_{dc} according to the following equation:

$$\frac{I_{QD}(V_{dc})}{I_{QD}(V^{th})} = \frac{a + b \times V_{dc}}{a + b \times V^{th}}, \qquad V^{th} \le V_{dc} \le V^{s} \qquad (1)$$

To verify the validity of the above prediction, μ-PL spectra of QD1 were measured with a small voltage step (as shown in Figure 4a). The dependence of the parameter $\beta(V_{dc}) = I_{QD}(V_{dc})/I_{QD}(V_{dc} = 0)$ on V_{dc} for different excitation powers is shown in Figure 4b, together with the results of the linear fit to the data (calculated in the range of $V^{th} \le V_{dc} \le V^{s}$ by the least-squares method). The calculated linear curves fit nicely with the experimental data in Figure 4b, which consequently supports the suggested model. In addition, these linear curves are exactly given by an expression of V_{dc}/V^{th} with $V^{th} = 2$ and 3.5 V for $P_0 = 20$ nW and 200 nW, respectively (see Figure 4b). According to the suggested model (eq 1), this can be achieved only in case of $a \ll b \times V^{th}$, or expressed in other words, already at $V_{dc} = V^{th}$, the collection length of a QD in the direction of F_{ext} is almost entirely determined by the carrier drift velocity achieved at this external bias.

It is obvious that the increase of P_0 changes the evolution of β versus V_{dc} (Figure 4b): while V^{s} remains the same (9 V), V^{th} increases and $\beta(V_{dc} = V^{s})$ decreases. From the dependence of $\beta(V_{dc} = 10$ V) on P_0 (Figure 4c), it is seen that $\beta(V_{dc} = 10$ V) remains almost constant in the range of 1 nW $< P_0 <$ 100 nW, but is progressively decreasing to 1 as P_0 is increased from 100 up to 6000 nW. This behavior is explained in terms of screening of F_{ext} with increasing concentration of photoexcited carriers as P_0 increases. In other words, for a given V_{dc} and different values of P_0, F_{ext} could be calculated on the basis of the equation $F_{ext} = \alpha(P_0) \times \gamma \times V_{dc}/d$, where $\alpha(P_0) = 1$ for 1 nW $< P_0 <$ 100 nW and gradually reduces down to 0 with the progressively increasing P_0 in the range of $P_0 >$ 100 nW.

To further test the suggested model, the evolution of I_{QD} is studied as a function of V_{dc}, when the sample is excited with an infrared (IR) laser in addition to the principal laser. The present study reveals that no I_{QD} is registered when exciting with only the IR laser. Consequently, only free carriers of one sign (electrons or holes) could be excited in the sample, if any. In our previous publication,[16] it was

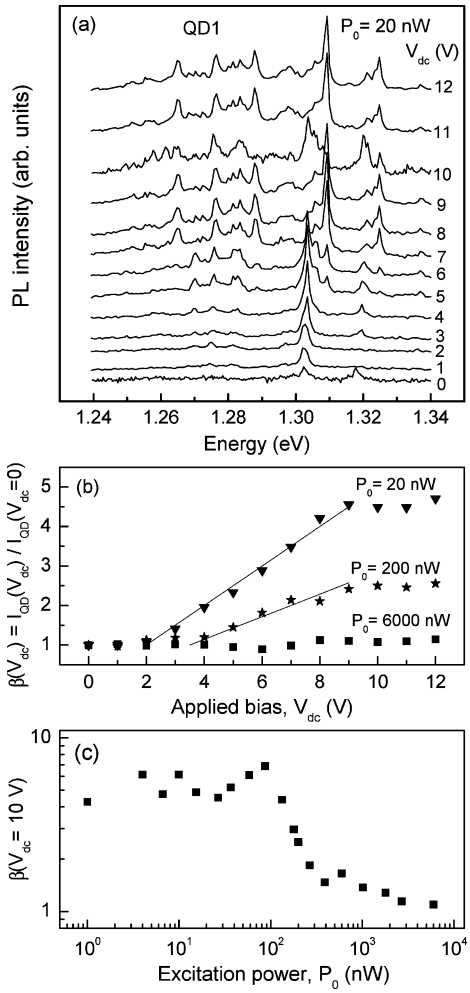

Figure 4. (a) μ-PL spectra and (b) β as a function of V_{dc} measured on the low dot density spot, QD1 at $h\nu_{ex} = 1.675$ eV, $T = 5$ K, and for P_0 levels, as indicated in the figure. The solid lines in (b) correspond to linear fitting curves, as explained in the text. (c) $\beta(V_{dc} = 10$ V) as a function of P_0 measured for QD1 at $h\nu_{ex} = 1.675$ eV and $T = 5$ K.

demonstrated that the free holes were optically created in the sample as a result of the IR excitation induced ionization of the deep levels positioned in the GaAs barriers. It was also suggested that this extra (noncompensated) charge could effectively screen F_{int}.[16] Consequently, with this assumption, the V_{dc} evolution of I_{QD}, with dual laser excitation, should exhibit an essentially lower V^{th} (compared to the case of single laser excitation), if any.

Figure 5a shows a number of μ-PL spectra pairs of the QD1 recorded under single (dotted lines) and dual (solid lines) excitation conditions. It is seen (Figure 5a) that the effect of decreasing I_{QD}, induced by an additional IR laser, gradually disappears with increasing V_{dc}. The dependence of I_{QD} on V_{dc} for principal laser (dual) laser excitation is shown in Figure 5b. For the case of dual laser excitation, no V^{th} could be revealed, and in addition, $I_{QD}(V_{dc} = 0)$ is essentially lower compared to $I_{QD}(V_{dc} = 0)$ measured for the single laser excitation (Figure 5b). These two circumstances prove that L_{IR} has effectively compensated F_{int} (totally or at least partially), which was present at $V_{dc} = 0$ V with single laser excitation. It should be stressed that the two I_{QD}

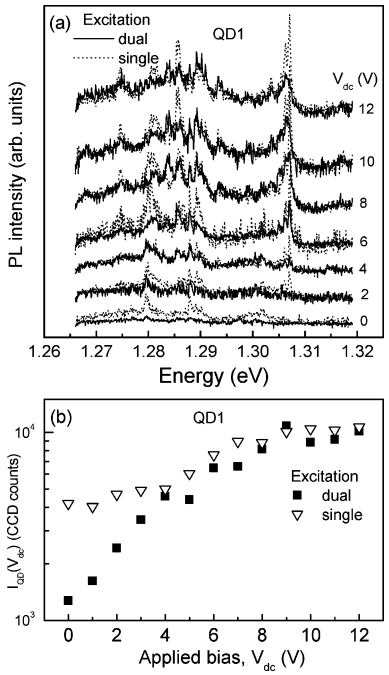

Figure 5. (a) μ-PL spectra and (b) I_{QD} as a function of V_{dc} measured for QD1 at $T = 5$ K, $h\nu_{ex} = 1.589$ eV, $h\nu_{IR} = 1.230$ eV, $P_0 = 200$ nW, and $P_{IR} = 100$ μW with single and dual laser excitation, as indicated in the figure.

dependencies in Figure 5b almost coincide for $V_{dc} \geq 4$ V. This behavior is expected because I_{QD} should be independent of F_{int}, but should be entirely determined by F_{ext} in the region of $V_{dc} \geq V^{th}$ according to the suggested model. Consequently, the experimental results shown in Figure 5b support the previously suggested idea[16] that the IR excitation effectively compensates the internal electric field, which in turn determines I_{QD} (i.e., the QD collection area) measured in the experiment with the "traditional" single-laser excitation.

The major role of the electric field directed in the plane of the sample for carrier transport and, subsequently, 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 infrared illumination of the sample) as well as the external electric field applied across the structure. The possibility to effectively control the PL intensity of the QDs by means of an external electric field could be widely used for a wide range of the QD-based light-emitting devices.

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(26) The existence of the charged impurities in our sample could be inferred from the successive measurement of a series of μ-PL spectra of QD1 directly after the pre-illumination of the sample has been switched off. Indeed, I_{QD} showed a gradual decrease within the first 10 s, but was after that stabilized at this lower I_{QD}. Such an evolution of I_{QD} in real time (of the order of several s) is the signature of fluctuating local electric fields[25] produced by ionized impurities in the close vicinity of QDs.
(27) I_{QD} is related to i_{QD} by performing summation over all individual QDs that are located within the area of the laser spot.
(28) The electric field was computed by solving Maxwell's equations by commercial software relying on methods of finite elements.

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