Carrier screening effects in photoluminescence spectra of InGaAsP/InP multiple quantum well photovoltaic structures

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Room temperature photoluminescence of *p–i–n* InGaAsP/InP multiple quantum well heterostructures was investigated under different excitation intensities. Photoluminescence spectra show the effect of phase space filling in quantum wells with increasing excitation density. Bias dependence of photoluminescence clearly demonstrates field screening that occurs inside the undoped layer. Device simulation is used to explain the observed phenomena. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1386402]

Built-in electric field in a semiconductor *p-i-n* structure is responsible for carrier separation and current generation in photodiodes and solar cells. The magnitude of the built-in electric field is a critical parameter in effective operation of quantum well based solar cells.[1] The field is affected by photogenerated carriers and, as such, it is important to investigate the field screening effect due to photoexcited carriers, especially under high excitation intensities which is relevant to the operation of solar cells in concentrators. In this letter, we report on the effect of carrier screening on the photoluminescence (PL) in a multiple quantum well (MQW) InGaAsP/InP *p–i–n* photodiode.

A MQW sample (J501) used in our experiments was grown by low-pressure metalorganic chemical vapor deposition on *p*-type (100) InP substrates. The sample had the InGaAsP/InP MQW structure embedded inside an undoped *i* layer of an *n–i–p* InP diode: 21 periods of 170 Å of InGaAsP ($E_{gap}=0.928$ eV) separated by 70 Å InP barriers for a total thickness of 0.50 μm. The MQW region was confined by undoped InP 0.1 μm buffer layers. The emitter was formed by 0.1 μm *n*-type InP, which also served as the contact layer.

PL was excited with 1 W 976 nm SDL-5762 MOPA diode laser. Since 976 nm is below the InP band gap, the photoexcitation occurred primarily in the MQW region. Two sets of measurements were performed on the sample. First, a set of photoluminescence spectra was measured at different excitation intensities. Second, the detection wavelength was fixed at the ground-to-ground transition in a quantum well and the PL peak intensity as a function of the bias was measured over two decades of excitation intensities. The excitation intensity was controlled by a neutral density wheel. All measurements were done at room temperature using low duty cycle (25%) chopped laser beam to prevent sample heating.

Figure 1 shows PL spectra at different excitation intensities for sample J501. For convenience, all spectra were normalized at their respective maximum and displaced vertically. Maximum excitation density (I) was 936 W/cm^2. Density of photogenerated carriers is estimated from 1×10^{18} cm^{-3} at I to 1×10^{16} cm^{-3} at 0.01 I.

Several salient features can be observed in Fig. 1. All the spectra are clearly composed of several overlapping peaks. As the excitation density increases the high energy features of the PL spectra become more pronounced and at the highest excitation level the maximum of PL shifts towards higher energy. By fitting an exponential to the high-energy tails of PL spectra one can estimate the effective carrier temperature T_{eff}, which ranged from 320 K for the lowest level of excitation (9 W/cm^2) to 346 K for the highest one (936 W/cm^2).

To explain this PL behavior, the idea of quasi two-dimensional (2D) density of states is used which is shown in the inset of Fig. 1. Each step on this plot is equal to $\rho=(m^*S)/(\pi\hbar^2)^2$ where m^* is the carrier effective mass and S is the sample area. As we start pumping more carriers

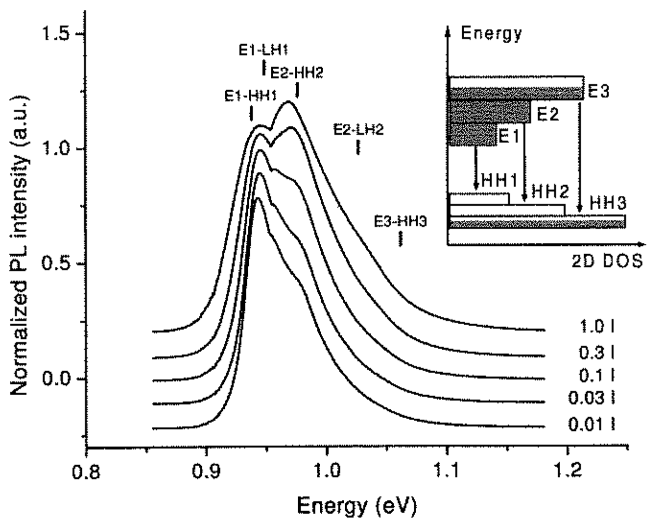

FIG. 1. Photoluminescence spectra of the MQW InGaAsP/InP sample (J501) under different excitation density. $I=936$ W/cm^2. Vertical lines with labels indicate calculated positions of the optical transitions inside the quantum well. The inset shows quasi-2D density-of-states diagram.

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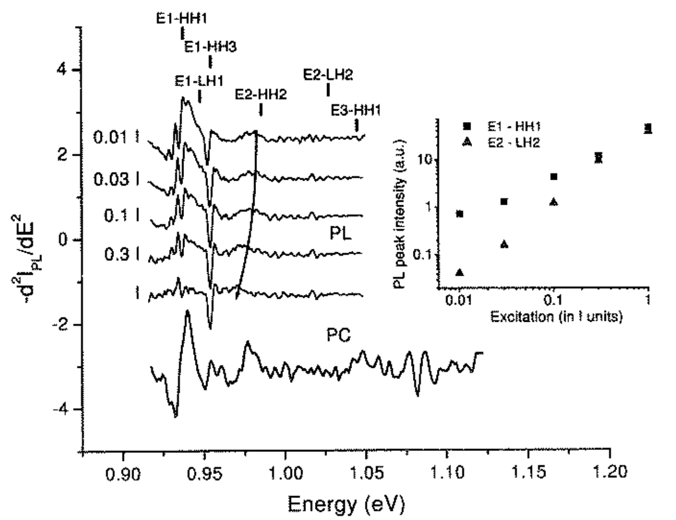

FIG. 2. Second derivative of photoluminescence (thin) and photocurrent (bold) spectra for J501 InGaAsP/InP MQW sample. Vertical lines with labels indicate calculated positions of the optical transitions inside the quantum well.

into the quantum well, these carriers start filling phase space. The result of the phase space filling is the increased emission from upper quantum well states as is seen in Fig. 1. PL spectra clearly show that with increasing pump intensity the amplitude of $E_2 \rightarrow HH_2$ steadily rises. Moreover, PL peaks show not just changes in magnitude but also changes in position and shape.

In a single QW structure the phase space filling would lead to saturation of lower energy optical transitions. We would like to note that in our experiments we did not observe any saturation of low-energy PL features. This is indicative of the multi-quantum well nature of our sample. Because PL spectra represent a sum of emission from all quantum wells, this means that the position of the quasi-Fermi level varies within the MQW layer leaving some QWs filled and others not. This is confirmed by device simulation discussed later.

More detailed information can be obtained from the second derivative of PL spectra as shown in Fig. 2. For comparison, a second derivative of the photocurrent (PC) for the same sample is shown in bold as well as calculated positions of quantum well transitions. Photocurrent was measured at a half resolution of PL spectra to preserve the same signal-to-noise ratio. PL peak positions were calculated using the transfer matrix method with the following material parameters: 0.912 eV for the bulk InGaAsP band gap, 0.170 eV for the conduction band offset, 0.079 m_0 and 0.06 m_0 for the InP and InGaAsP electron, 0.61 m_0 and 0.46 m_0 for the InP and InGaAsP heavy hole, and 0.07 m_0 and 0.12 m_0 for the InP and InGaAsP light hole effective masses, respectively.[3] There is a fairly good overlap of PL, PC and calculated positions of optical transitions.

It can be seen that the increase in the excitation intensity leads to "smoothing" of $E_1 \rightarrow HH_1$ and $E_1 \rightarrow LH_1$ features in the PL spectra. If we assume the excitonic relaxation as a dominating mechanism of radiative recombination then this smoothing can be interpreted as the exciton dissociation due to increased carrier screening. Both $E_1 \rightarrow HH_1$ and $E_1 \rightarrow LH_1$ peaks undergo a blueshift of the order of 1 meV as the intensity changes from $0.01I$ to I. Visible redshift (≈ 10 meV) is observed for the $E_2 \rightarrow HH_2$ feature. We believe that most of these spectral changes are manifestations of many-body effects. The increase of free carrier density inside quantum well leads to a renormalization of the band gap and a redshift of the optical transitions. At the same time, high carrier density screens the Coulomb potential and reduces the exciton binding energy which leads to a blueshift of the optical transitions.[4] The complex nature of our PL spectra does not allow us to unambiguously determine what many-body effects prevail in our experiments. More detailed study is needed and will be the subject of a future work.

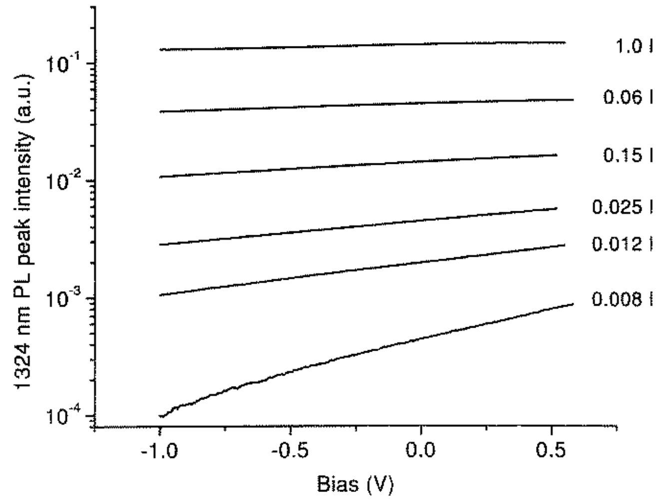

FIG. 3. Bias dependence of 1324 nm PL peak for sample J501.

A high density of photoexcited carriers has manifested itself through screening of the built-in electric field inside the *i* layer. This is observed in bias dependence of PL peak amplitude at different excitation intensities. Bias dependence of

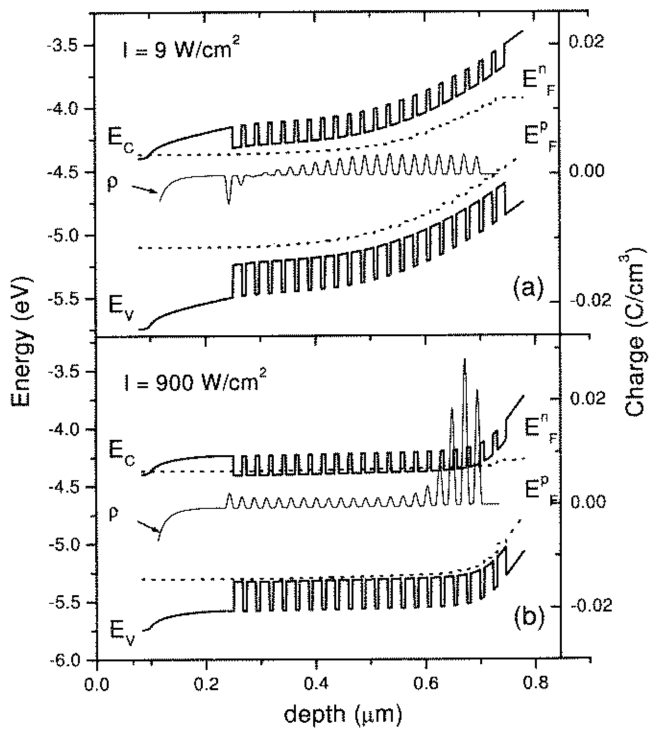

FIG. 4. Band diagram of sample J501 under (a) 9 W/cm^2 and (b) 900 W/cm^2. E_C and E_V are the conduction and valence band edges (bold), E_F^n and E_F^p are the quasi-Fermi levels for electrons and holes (dotted), respectively, and ρ is the total charge density (thin).

PL allows us to distinguish contributions from differently doped parts of the p–i–n structure.[5] Since we detect PL originating in the MQW region then all observed changes can be associated with changing field conditions in this layer. Figure 3 shows bias dependence of 1324 nm PL peak for sample J501. One can observe the following behavior: Monotonous increase towards forward bias and a diminishing rate of increase at higher excitation levels. These trends were observed in the similar sample (2188) with thinner undoped layer $L_i = 0.41\ \mu$m. PL(V) curves for sample 2188, however, were more influenced by bias changes. This results from different thickness of the layer L_i in these samples and, consequently, different values of the built-in electric field $F_{bi} = V_{bi}/L_i$, where V_{bi} is the built-in potential.

These results can be qualitatively explained if one looks closely at the p–i–n diode with MQW layer under illumination. Device simulations were performed using SimWindows32.[6]

Conduction and valence band edges and total charge distribution were calculated for sample J501 under (a) 9 W/cm^2 and (b) 900 W/cm^2 shown in Fig. 4. The latter one clearly shows results of high density excitation—the quasi-Fermi level is positioned *above* the conduction band edge. Both plots show accumulation of positive charge (thin line) inside the MQW layer. This charge accumulation results from very different escape times for holes and electrons for this material combination. Steady state condition requires that the escape rates for both types of carriers were equal: $n/\tau_n = p/\tau_p$, where $n(p)$, $\tau_n(\tau_p)$ are the 2D electron (hole) concentration and escape time, respectively. For InGaAsP/InP we estimate $\tau_n/\tau_p = n/p \approx 1/100$. It is worth noting that at 900 W/cm^2 simulation shows large hole accumulation towards the p side that practically screens the built-in electric field. This is confirmed by PL versus bias behavior at these intensities in Fig. 3. We believe that this charge buildup is caused by a significantly thicker barrier faced by the holes at the MQW/bulk interface. The field screening may have an adverse effect on operation of quantum well solar cells under concentrated light. Reduced field value can lower carrier escape probability and decrease solar cell photocurrent and, thus, must be taken into consideration.

In conclusion, we have investigated excitation intensity and bias dependence of photoluminescence in InGaAsP/InP MQW p–i–n structure. PL spectra demonstrate effects of phase space filling in quantum well as well as the screening of the built-in electric field. Device simulation confirms the observed results.

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[6] The program is freely available on the Internet at http://www-ocs.colorado.edu/SimWindows/simwin.html