Optical investigation of type II GaSb/GaAs self-assembled quantum dots

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We have studied the emission and absorption properties of type II GaSb/GaAs quantum dots embedded in a *p-i-n* photodiode. The excitation power evolution provides clear signatures of the spatially separated confinement of electrons and holes in these nanostructures. We have estimated the confinement potential for the holes to be ~ 500 meV, leading to an intense room temperature emission assisted by recapture processes from the wetting layer. Photocurrent measurements show strong absorption in the wetting layer and in the quantum dots at room temperature which are important for photodetection applications based in this system. © 2007 American Institute of Physics. [DOI: 10.1063/1.2827582]

In recent years, GaSb/GaAs structures have aroused great interest due to their type II band alignment and intrinsically different behavior compared to the well known InAs/GaAs system. Fundamental issues regarding their growth process, energy level structure, and optical properties in addition to their technological applications in photodetection and photovoltaics have been already investigated in different configurations such as quantum dots (QDs),^{1–5} quantum wells⁶ (QWs) or ternary compounds.⁷ In this work, we present various results regarding the GaSb/GaAs QDs system, which extend and complete previous works.

The QDs studied here were grown by solid source molecular beam epitaxy on a *n*-type GaAs(001) substrate after deposition of a *n*-type GaAs buffer layer (Si: $1 \times 10^{18} \text{ cm}^{-2}$). The QDs were nucleated at 480 °C, using a growth rate of 0.1 ML/s. The formation of the GaSb QDs was detected by the change of the reflection high energy electron diffraction pattern after the deposition of 1.3 ML of GaSb. The GaSb layer, with a nominal thickness of 2 ML, was then exposed to Sb flux for 20 s and then annealed for 20 s without an Sb flux to limit the amount of Sb segregated during capping. The GaAs capping was done at 0.4 ML/s in two steps. In the first step, a 10 nm thick GaAs layer was grown at the temperature of QD nucleation to avoid their destabilization. In the second one, a 40 nm thick GaAs layer was deposited at 570 °C. During growth, the As and Sb beam equivalent pressures were 1.0×10^{-5} and 1.9×10^{-6} mbar, respectively. This scheme was repeated six times, with a 3 min growth interruption under an As₄ flux to lower the substrate temperature before the nucleation of the next QD layer. On top, a *p*-type 300 nm thick GaAs layer (Be: $1 \times 10^{18} \text{ cm}^{-2}$) was grown at 580 °C. Finally, standard optical lithography and wet etching techniques were used to define mesas and metal Ohmic contacts.

Figure 1(a) shows the photoluminescence (PL) spectra recorded at 20 K as a function of excitation power at 532 nm. We can clearly identify two bands centered at 1.32 and 1.05 eV. The narrow high energy band corresponds to the wetting layer (WL) recombination and dominates the spectrum at low temperatures. Its peak energy position is compatible with a GaSb WL thickness of 0.7 nm,² which is

larger than the total amount of GaSb deposited (0.57 nm). This suggests that a certain Sb–As exchange has taken place in the GaSb/GaAs interface after the QDs formation and during the subsequent growth interruption. The QD emission is identified with the broader PL band centered at 1.05 eV and shows an inhomogeneous bandwidth of ~ 170 meV. This transition energy is about 50 meV smaller than previous results,^{1,2} whereas the peak width almost doubles that previously reported.

The spectra shown in Fig. 1(a) also reveal a clear blue-shift as the number of photogenerated carriers increases.^{1,2} Such behavior is a characteristic of structures with a type II

FIG. 1. (Color online) (a) Low temperature photoluminescence spectra as a function of excitation power, from 0.5 to 218 mW (spot size of $\sim 80 \mu\text{m}$). (b) The PL peak energy positions lie on a straight line against the third root of the excitation power. (c) Double logarithmic plot of the integrated PL intensity.

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band alignment where nonequilibrium electrons and holes accumulate in separate regions of the semiconductor. In our case, the electrons are accumulated in the GaAs barriers but are also attracted by the holes trapped in the GaSb layers. This small charge separation produces strong internal electric fields that bend the conduction band into a triangular quantum well shape and gives rise to discrete electron energy levels.⁸ The situation can be recognized by the dependence of the PL peak intensity on the cube root of the incoming laser intensity P ,

$$E_{\text{PL}} = E_{\text{PL}}^0 + CP^{1/3}, \quad (1)$$

where E_{PL}^0 is the PL peak position at zero power and $C \propto n_C^{2/3}$ depends on the accumulated carrier density.⁹ Figure 1(b) shows the result of applying Eq. (1) to the WL and QD emission peaks. The emission energies follow the expected behavior, with a blueshifting rate for the QDs three times greater than for the WL. Here, it should be noted that, in the whole investigated range, the linear fit is nearly perfect for the QD emission, with no inflection points that could be attributed to excited states band filling, as noted by other authors.^{2,9} Our result rather indicates that the larger charge density accumulation around the QDs could be related to intrinsic carrier dynamics of the system. However, a definite statement about the role played by the excited states is not possible in our case given the large inhomogeneous broadening of the QD emission band. Figure 1(c) also shows that the emission bands grow approximately linear with the number of photons and, therefore, that electron-hole pairs are rapidly captured in their potential minima.⁹ Above 60 mW, the WL intensity exhibits signatures of saturation, which are not present in the QD band. This behavior has been observed before in GaAsSb/GaAs type II QWs,⁶ and related to accumulation of electrons in the thick (5 nm) GaAsSb regions. Such accumulation is not probable in our system, where we have estimated that the WL is only 0.7 nm thick. Instead, the decrease of the photon emission yield in the WL could be related to a reduction of the oscillator strength caused by screening within the two dimensional electron-hole plasma. A reduction of the electron-hole overlap could also explain why the WL peak energy remains constant above 60 mW [Fig. 1(b)] and is more likely to occur in the WL extended states than in the highly confined QD states.

From Eq. (1) we extract the following transition energies at zero excitation power (conduction band flat): 1.305 eV for the WL and 1.011 eV for the GaSb QDs. Using these transition energies and the GaAs energy gap at 20 K (1.512 eV), we can estimate the heavy hole confinement energies for the QDs (~ 500 meV), and for the WL (~ 207 meV), as shown in Fig. 2. These values are in good agreement with those obtained by Geller *et al.* using a different technique,³ and will be used here to analyze the temperature evolution of the luminescence spectrum. In Fig. 3(a), the WL band is rapidly quenched with increasing temperature, leading to a room temperature spectrum dominated only by the QD emission. We include in Fig. 3(b) an Arrhenius plot of the luminescence intensity as a function of temperature. We obtain an activation energy of 131 meV for the QDs and 223 meV for the WL. The latter is fully compatible with the heavy hole confinement energy determined above, and suggests that thermal escape of holes is responsible for the observed quenching. However, the activation energy found for the QDs is considerably smaller than the hole confinement en-

FIG. 2. (Color online) Band energy diagram deduced from the PL transition energies obtained at 15 mW and 20 K taking into account electron accumulation. The line up of the strained GaSb layers has been taken from Pryor and Pistol (Ref. 11).

ergy. The temperature evolution of the QD emission could be controlled instead by the carrier thermalization processes among the QDs and the WL. In support of this hypothesis, we shall note that in Fig. 3(b), the decay of the WL signal at $KT=11$ meV comes along with an increase of the QD signal at the same temperature. This indicates that holes thermally emitted from the WL can be recaptured into the QDs slowing down the quenching of the QD band.

The absorption properties of our heterostructure have been investigated by means of photocurrent (PC) measurements. Figure 4(a) shows the room temperature PC of the QD sample (solid line) together with the signal from a GaAs reference sample with the same structure and processing (dotted line). At zero bias, the GaSb layers enhance the photogenerated current below the GaAs edge and up to $1.3 \mu\text{m}$. This is important for photovoltaic applications exploiting the intermediate band solar cell concept.^{5,10} The broad shoulder found around 960 nm is attributed to WL absorption whereas the tail at longer wavelengths corresponds to absorption by the QDs. The current-voltage (I - V) characteristic of the device under laser illumination at 808 nm with $20 \text{ mW}/\text{cm}^2$ has been depicted in the inset. We obtain a fill factor of 61.33%, an open circuit voltage (V_{oc}) of 0.52 V, and a short circuit current (I_{sc}) of $2.8 \text{ mA}/\text{cm}^2$. The photocurrent spec-

FIG. 3. (Color online) (a) Temperature dependence of the photoluminescence. (b) Arrhenius plot of the integrated PL intensity. The activation energies for each band are derived from the slope at high temperatures (solid lines).

FIG. 4. (Color online) (a) Comparison of the PC of the GaSb QDs sample and the reference GaAs sample at room temperature. The inset shows the I - V curve of the device under illumination at RT. (b) Bias dependence of the PC. The inset shows the suggested optical transitions.

trum has been measured, also varying the external bias between 0.4 and -4 V, as shown in Fig. 4(b). As it can be seen, for positive voltages (dotted line is 0 V), only the shoulder at 960 nm can be observed. It corresponds to light absorption between the WL heavy hole (HH) level and the fundamental electron level in the triangular well [transition 1 in the inset of Fig. 4(b)]. With increasing negative bias, a second shoulder clearly arises at 918 nm although its origin is not clear. One could possibility be a transition from the WL light hole (LH) level to the fundamental electron level, leaving a HH-LH splitting of ~ 60 meV (labeled as transition 2A).

This would imply, against the expected behavior, that the increase of the negative bias does not enhance the tunneling from deeper confined levels but from shallower ones. Another possibility would be the absorption from the heavy hole level to an excited state of the conduction band triangular well (labeled as transition 2B). In this case, the enhancement at negative voltages results from the larger electron-hole overlap expected for reverse bias in type II heterostructures.

In conclusion, we have investigated the optical properties of type II GaSb QDs embedded in a GaAs based p - i - n diode. At room temperature, emission and absorption from the nanostructures have been demonstrated up to 1.3 μm , which make this material of interest for infrared photodetection and solar cell applications. Spectral signatures of the separate confinement of electrons and holes have been identified and analyzed for both the WL and QD emission bands. Also, the temperature evolution of the QDs luminescence has revealed that the carrier thermalization from WL states to QD states must be included to explain the strong room temperature emission of these nanostructures.

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