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Quantum-dot-induced optical transition enhancement in InAs quantum-dot-embedded $p-i-n$ GaAs solar cells

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Photocurrents (PCs) of three $p-i-n$ GaAs solar cells, sample A with InAs quantum dots (QDs) embedded in the depletion region, B with QDs in the n region, and C without QDs, were studied experimentally and theoretically. Above GaAs bandgap, the PC of A is increased, while B is decreased with respect to C, since in A, the QD-induced reflection of hole wave function increases its overlap with electron wave function so that the optical transition rate is enhanced, while carrier mobility in B is reduced due to QD-induced potential variations. Moreover, A and B have increased PCs in the sub-GaAs-bandgap range due to QD optical absorptions. © 2011 American Institute of Physics. [doi:10.1063/1.3638488]

In(Ga)As/Ga(Al)As nanostructures such as quantum dots (QDs), quantum wells (QWs), and dot-in-wells have been widely used for infrared light emission,¹ absorption,² and solar cell.³ InAs QDs are embedded in GaAs solar cells for increasing photocurrent (PC).^{3–5} PC spectroscopy is commonly used to characterize the optical response of a light-absorbing device as a function of wavelength for information about interband and intraband transitions.^{6–9} In this letter, the PC spectra of three $p-i-n$ GaAs solar cells with and without embedded InAs QDs are measured under xenon and quartz-halogen tungsten lamps for studying QD effects on the light-matter interaction in the devices.

The three GaAs solar cells were all grown on n^+ GaAs (001) substrates with the following growth sequence: a 300 nm thick n^+ -type GaAs buffer layer, a 100 nm thick n^+ $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ back-surface-field layer, a 500 nm n^+ GaAs layer, a 1.86 μm n -type GaAs layer doped at $2 \times 10^{16} \text{ cm}^{-3}$, a 140 nm undoped i region, a 500 nm thick p -type region doped at $2 \times 10^{17} \text{ cm}^{-3}$, a p^+ $\text{Al}_{0.85}\text{Ga}_{0.15}\text{As}$ top-window layer, and finally a 20 nm p^+ GaAs contact layer. This is actually sample C. Samples A and B were grown similarly except that in sample A, five layers of InAs QDs spaced by 20 nm GaAs claddings, which are denoted as one group of QD layers, were embedded in the i region. In sample B, three groups of QD layers were embedded in the n -type region. For more details about sample structures, see Ref. 10.

PC spectra shown in Fig. 1 were first measured by a Keithley multimeter under a xenon lamp with a monochromator. A Si photodiode was used as reference. The external quantum efficiency (EQE) is obtained as $I_{\text{sample}}(\lambda)/I_{\text{Si}}(\lambda) \times \text{EQE}_{\text{Si}}(\lambda)$,¹¹ where I_{sample} and I_{Si} are PC spectra of our sample and Si photodiode, respectively, λ is the photon

wavelength, and EQE_{Si} is the EQE of the Si photodiode. Since EQE_{Si} is almost constant in the range of 500–900 nm,¹² the relative PC intensity $I_{\text{sample}}/I_{\text{Si}}$ becomes a very good measure of the EQE of our samples, which are plotted in the inset of Fig. 1.

PC spectra were further measured by a Bruker Vertex 80v Fourier-transform infrared spectrometer equipped with a quartz-halogen tungsten lamp and a CaF_2 beam splitter. The modulated PC from the sample was amplified by a Keithley 428 current amplifier, and subsequently, Fourier transformed to acquire the spectrally resolved PC signal. Results are shown in Fig. 2(a). A GaAs filter was used to measure the contribution to the PC from QD interband transitions below the GaAs bandgap, with results presented in Fig. 2(b). Note that PC spectra in Fig. 2 have not been calibrated with respect to the photon flux. However, they are consistent with Fig. 1 so that we analyze them directly.

Two main spectral differences are observed between the three samples. The first one is the sub-GaAs-bandgap PC ($\lambda > 900 \text{ nm}$), and the second is the PC enhancement in sample A and reduction in sample B above the GaAs bandgap ($\lambda < 900 \text{ nm}$).

In Fig. 2(a), the PC spectra of the three samples are quite different for $\lambda > 900 \text{ nm}$. QD samples, both A and B, have a clear peak near 920 nm due to the interband absorption in the wetting layer (WL). They also have a wide tail in 950–1300 nm corresponding to the interband absorptions in QDs. Similar features were reported before.^{5,13} Sample C does not have these features. The PC intensity of sample A is almost 30 times higher than B. This is due to the different spatial locations of embedded QDs. In sample A, QDs are embedded in the i region where a strong built-in electric field extracts readily photocarriers in QDs to form the PC signal; In sample B, the average electric field in the n region is relatively low because of the high doping level there as

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FIG. 1. (Color online) PC spectra at 300 K under a xenon lamp. Inset: relative PC intensities. Sample A: InAs QDs in the *i* region; B: QDs in the *n* region; C: without QDs.

compared with the *i* region. Furthermore, the QDs in the *n* region are largely occupied by electrons that cause large potential variations around QDs in the form of potential barriers for electrons and traps for holes which reduce the carrier mobilities, see Fig. 3(a). The reduced carrier mobilities can also be observed in the PC spectral backgrounds (i.e., dark currents) $n_B < n_C$ in Fig. 2(a) as well as the reduced PCs of sample B for $\lambda < 900$ nm in Fig. 1. Moreover, the QDs in sample B are largely filled so that interband transitions will be suppressed. These three factors result in the much small PC in sample B.

The PC spectra of $\lambda > 900$ nm in Fig. 2(b) consist of peaks due to interband absorption in WL and QDs. The wavelengths of QD PC peaks agree with their photoluminescence peaks.¹⁰ The QD PC intensity decreases as the wavelength increases, implying an increasing difficulty to extract photocarriers from a low-energy QD level because of their long tunneling length, high tunneling barrier, and large thermal activation energy, see Fig. 3(b). Similar results have previously been reported.^{6,13,14}

The major difference between the three PC spectra, as shown in Figs. 1 and 2(a), is in the optical range of

FIG. 2. (Color online) (a) PC spectra at 300 K under a quartz-halogen lamp. (b) GaAs-filtered PC spectra. 1–7 mark optical absorptions of QDs.

FIG. 3. (a) Reduced electron mobility by QD induced potential variation. (b) Difficulty to extract photocarriers from low-energy QD level.

500–900 nm above the GaAs bandgap, which predominantly determines the total PC of our samples in the photovoltaic I-V characteristics. In our previous work,¹⁰ the short-circuit current density J_{sc} of sample A was shown to be about 30% higher than sample C. The same 30% enhancement is also obtained here by integrating and comparing the relative PCs in the inset of Fig. 1. Contribution to the observed PC enhancement from sub-GaAs-bandgap WL and QD absorptions is very small, since the PC enhancement in sample A predominantly occurs when $\lambda < 900$ nm. The decrease of sample B's PC can be largely attributed to the reduced carrier mobility in the *n* region, as aforementioned about the PC of $\lambda > 900$ nm in sample B.

One possible reason about the increased PC of $\lambda < 900$ nm in sample A is the multiple exciton generation in QDs. This is, however, not very likely here since the built-in field is not strong enough to accelerate photocarriers generated in GaAs to a kinetic energy as much as twice the ground-state exciton energy in QD.¹⁵

The most possible mechanics of the PC enhancement above the GaAs bandgap in sample A is the increased photon absorption due to QD-induced reflections of the wave functions of an incident conduction-band (CB) electron from one side of the depletion region and an incident valence-band (VB) hole from the other side.¹⁶ Refer to Fig. 4, for simplicity, we model the QD potential variations in the CB and VB as one-dimensional QWs. While the incident CB electron,

FIG. 4. (Color online) Wave functions of CB electron and VB hole with a transition energy $\hbar\omega = 1.593$ eV (above the GaAs bandgap). Also presented are the schematic CB and VB of GaAs embedded with InAs QDs modelled as one-dimensional QWs.

with an energy above the GaAs CB edge, comes to the QD layers in a plane wave form e^{ik_1z} , it is partially reflected $r_1e^{-ik_1z}$ and partially transmitted $t_1e^{ik_1z}$. Similarly, the wave function components for the VB hole are e^{-ik_2z} , $r_2e^{ik_2z}$, and $t_2e^{-ik_2z}$. Note that there are other transmission cases such as both the CB electron and the VB hole incident to the QD regions from the same side but they do not contribute to the PC. Without QDs, $r_1=r_2=0$ and $t_1=t_2=1.0$. The amplitude of such wave functions is shown as dotted lines in Fig. 4. The optical transition matrix element between these two wave functions is proportional to

$$W_C = \langle e^{ik_1z} | e^{-ik_2z} \rangle = \int e^{-i(k_1+k_2)z} dz.$$

The wave functions are modified when QDs are embedded. As shown in Fig. 4, the CB electron transmits relatively well due to the small electron effective mass, while the much heavier VB hole is greatly affected. For the two wave functions presented in Fig. 4, we neglect the transmitted VB hole so that the wave function on the right side of the structure is $e^{-ik_2z} + e^{ik_2z}$. We further approximate the CB electron as a perfect transmission so that its wave function on the right side of the structure is e^{ik_1z} . The optical transition matrix element becomes now

$$W_A = \langle e^{ik_1z} | e^{-ik_2z} + e^{ik_2z} \rangle = W_C + \int e^{-i(k_1-k_2)z} dz.$$

W_C oscillates while the second term in W_A can be very large when $k_1=k_2$. The condition of $k_1=k_2$ can easily be fulfilled which explains the PC enhancement of sample A over the whole optical range above the GaAs bandgap, as clearly shown in Figs. 1 and 2. Note that the W_A enhancement in the above analysis is very large as compared with experimental data due to the approximation of the three-dimensionally confined QD potentials by one-dimensionally confined QW potentials, leading to a strongly exaggerated wave function reflection.

We can apply this mechanism to understand enhanced PCs when n -type dopants were introduced inside QDs (Ref. 14) and close to QDs (Ref. 17) in the i region. As discussed before, the QD potential well is actually three-dimensional, while the transporting photocarrier along the z direction is two dimensionally extended in the xy plane. The scattering of the extended photocarrier wave functions by the three-dimensionally localized QD well is limited. Extra dopants are then expected to further scatter the wave functions of photocarriers. As a result, light absorption above the GaAs bandgap, and therefore the PC, are increased.

In conclusion, interband PC spectroscopy by xenon and quartz halogen tungsten lamps are used to characterize three p - i - n GaAs solar cells with and without InAs QDs. Interband optical absorption of QDs in sample A and B clearly

contributes to the PC in the sub-GaAs-bandgap optical range. The sub-GaAs-bandgap PC of sample A with QDs embedded in the i region is the highest, while it is more than one order of magnitude lower in sample B where QDs are embedded in the n region. Photocarriers generated in QDs in the i region of sample A are easily extracted by the built-in electric field, while the average electric field in the n region of sample B is very small so the photocarrier to PC conversion becomes rather weak. A large PC enhancement in sample A was observed over the optical range above GaAs bandgap as compared to sample C which does not contain any QDs. This enhancement is attributed to the scattering of the electron and hole wave functions by the potential wells of embedded QDs which greatly enhance the optical matrix element, resulting in the observed PC enhancement.

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