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Direct Observation of Carrier Transportation Process in InGaAs/GaAs Multiple Quantum Wells Used for Solar Cells and Photodetectors *

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The resonant excitation is used to generate photo-excited carriers in quantum wells to observe the process of the carriers transportation by comparing the photoluminescence results between quantum wells with and without a p–n junction. It is observed directly in experiment that most of the photo-excited carriers in quantum wells with a p–n junction escape from quantum wells and form photocurrent rather than relax to the ground state of the quantum wells. The photo absorption coefficient of multiple quantum wells is also enhanced by a p–n junction. The results pave a novel way for solar cells and photodetectors making use of low-dimensional structure.

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Light-to-electric conversion is when light converts into electricity by means of a material, which has been used widely for solar cells and photodetection. The p–n junction is a fundamental structure for the light-to-electric conversion devices, which have been used widely in silicon solar cells,[1] nitride-based solar cells,[2,3] GaAs-based solar cells[4,5] and photodetectors.[6−8] GaAs has a great potential in light-to-electric conversion devices such as solar cells and detectors. GaAs-based single-junction solar cells,[9,10] multi-junction solar cells[11,12] and intermediate-band solar cells[13,14] have been investigated widely. Combined with other Ⅲ–V compound semiconductors, GaAs has been used in photodetectors such as quantum well infrared photodetectors,[15,16] and quantum dot infrared photodetectors.[17,18] According to the light-to-electricity theory,[19] photo-excited carriers in quantum wells should be restricted by the barriers and should not generate photocurrent. Recently, it was reported that the range of the spectral response has extended and efficiency has increased in solar cells by the insertion of multiple quantum wells into the depletion region of a p–n junction.[20,21] The photo-excited carrier escaping phenomena in quantum wells are mainly explained by thermionic emission and tunneling processes after the carrier relaxed to the ground state of the quantum wells.[22,23]

The light-to-electricity conversion process includes photon absorption and carrier transport processes. The theory of solar cells and photoelectric detectors utilizes a macro-parameter absorption coefficient to describe the photon absorption process[24,25] and the absorption coefficient is considered to be a constant for a given material. Thus the photon absorption process is the same when the material is with or without a p–n junction and is irrespective of whether the device is under working conditions. The absorption coefficient[26] is proportional to the probability of the transition from an initial state to a final state, to the density of electrons in the initial state, and to the density of available final states. The transition probability is integrated by the initial-state and final-state wavefunctions with the perturbation Hamiltonian of the photon potential, where the conduction band and the valence band are considered as the final states of electrons and holes, respectively. Furthermore, the absorption coefficient is measured by using a thin film without a p–n junction. The quantum well is an appropriate structure to observe the light-to-electricity conversion process, due to the fact that it has the ability to distinguish the restricted carrier from the free carrier. However, the carrier transportation process is difficult to observe directly in experiments. Here we observe directly in experiments that most of the photo-excited carriers escaping from a quantum well to generate photocurrent rather than relax to the ground state of the quantum well in the sample of InGaAs/GaAs multiple quantum wells (MQWs) with a p–n junction when under working conditions.

Samples were grown by molecular beam epitaxy (MBE, VG V80) on insulating GaAs (100) substrates. For the p–i–n structure sample, the active region is sandwiched between a 300 nm Be-GaAs layer with doping density of $3\times10^{17}\,\mathrm{cm}^{-3}$ and a 300 nm Si-GaAs layer with a $7\times10^{17}\,\mathrm{cm}^{-3}$ doping density. The n–i–n

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**Corresponding author. Email: hchen@iphy.ac.cn structure sample was grown under the same condition as the p–i–n sample. The only difference is that the p-contact and p-GaAs were replaced by n-contact and n-GaAs, respectively. The structure includes 10 quantum wells with thickness of 5 nm, and the composition of indium is 0.2. The width of barrier is 20 nm. Device fabrication followed standard p–i–n processing steps including wet chemical etching and metallization for the p- and n-contacts.

A 915 nm laser was used as the excitation source to measure the PL at 260 K. The photon energy of the laser is 1.35 eV, which lies between the bandgaps of InGaAs quantum well and the GaAs barrier, called resonant excitation. The photo-excited carriers are generated only in the InGaAs quantum wells and should be restricted by the GaAs barrier.

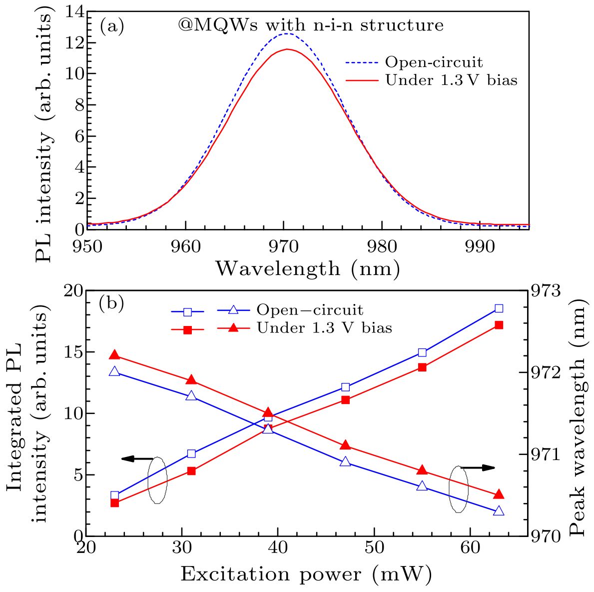

Fig. 1. PL spectra of MQWs without p–n junction under resonant excitation with a wavelength of 915 nm. (a) The PL spectra under the open-circuit and 1.3 V bias conditions with a 63 mW excitation power. Compared with that under the open-circuit condition, the integrated PL intensity under a 1.3 V bias decreases by 9%. (b) The dependence of integrated PL intensities and peak wavelengths on excitation power under the open-circuit and 1.3 V bias conditions. The integrated PL intensity under 1.3 V bias decreases by a few percent for the same excitation power.

PL spectra of MQWs with n–i–n structure shown in Fig. 1(a) were acquired under the open-circuit condition and under 1.3 V bias at the temperature of 260 K. Integrated PL intensity under 1.3 V bias decreases by 9% compared with that under the open-circuit condition, and the position of PL peak is 970.3 nm under the open-circuit condition and red shift to 970.5 nm under 1.3 V bias. This phenomenon also exists under the condition of different excitation powers (Fig. 1(b)). The intensity of PL increases linearly with the excitation power under the open-circuit condition from 23 mW to 63 mW, and decreases by no more than 20% after 1.3 V bias applies. Meanwhile, the position of PL peaks decreases from 972 nm to 970.3 nm under the open-circuit condition, and shifts from 972.2 nm to 970.5 nm under 1.3 V bias. The intensity decrease of PL and peak red shift under external field comes from the quantum confine Stark effect. The PL peak blue shift with excitation power is contributed to the band filling effect. Our results agree with the previous report.[27]

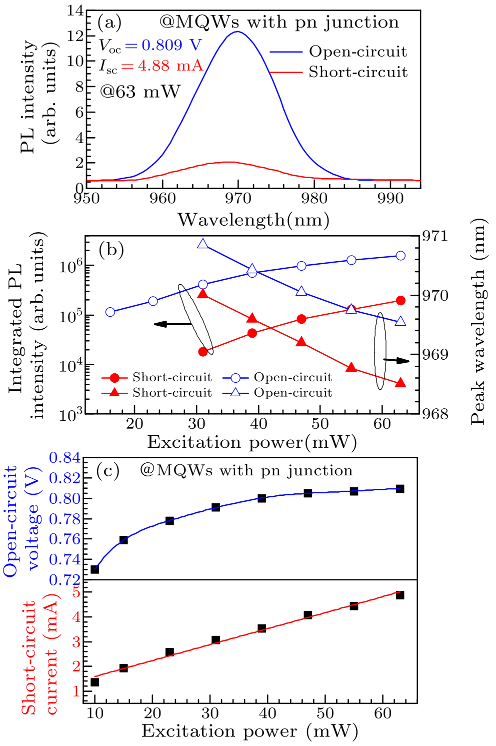

Fig. 2. PL spectra and light-to-electricity conversion results of InGaAs/GaAs MQWs with p–n junction excited by a laser with wavelength of 915 nm. (a) PL spectra under the open-circuit and short-circuit conditions with a 63 mW excitation power. The peak wavelength of the PL spectrum shows a blue shift under the short-circuit condition, and the integrated intensity is reduced to 12.7% of that under the open-circuit condition. The measured open-circuit voltage is 0.809 V and short-circuit current is 4.88 mA. (b) Integrated PL intensity and peak wavelength excited by different excitation powers under the open-circuit and short-circuit conditions. (c) Dependence of open-circuit voltage and short-circuit current upon excitation powers. The short-circuit current increases linearly with the increasing excitation power, whereas the open-circuit voltage increases exponentially with the increasing excitation power.

The PL spectra of MQWs with a p–n junction shown in Fig. 2(a) are measured at the excitation power of 63 mW under the open-circuit and short-circuit conditions, respectively. The peak positions of InGaAs/GaAs MQWs are 969.5 nm and 968.5 nm under the open-circuit and short-circuit conditions, respectively. The integrated intensity under the short-circuit condition decreases to 12.7% of that under the open-circuit condition. The open-circuit photogenerated voltage is 0.809 V and the short-circuit current is 4.88 mA. The results mean that most photo-excited carriers escape from the quantum wells to generate photo-excited current rather than relax to the ground state of quantum wells and recombine to emit light. The dependence of integrated PL intensity and peak wavelength on excitation powers under the open-circuit and short-circuit conditions is shown in Fig. 2(b). As the excitation power increases from 23 mW to 63 mW, the blue shift of the peak wavelength of PL spectrum, a linearly increasing integrated PL intensity, and an exponentially increasing open-circuit photovoltage from 0.778 V to 0.809 V under the open-circuit condition are observed. Under the short-circuit condition, the results present a blue shift of the peak wavelength, a linear increase of the integrated PL intensity and a linear increase of short-circuit photocurrent from 2.56 mA to 4.88 mA. The PL spectrum is not observed when excited by the power less than 30 mW under the short-circuit condition. The results confirm that most photo-excited carriers escape the quantum wells to generate photo-excited current under the short-circuit condition, and the photo-excited voltage generates under the open-circuit condition and illumination. Our finding means that quantum wells is adapted used for solar cells and photodetectors.

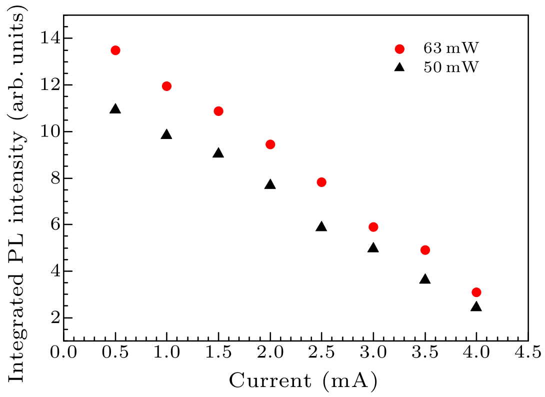

Fig. 3. The inverse linear relationship between the integrated PL intensity and the circuital current with 50 mW and 63 mW excitation powers for the sample with p–n junction. The dependence of integrated PL intensity on circuital currents is acquired by changing the circuit series resistance under a certain excitation power.

The photoluminescence under the short condition has a dramatic decrease compared with that under the open condition for the sample with the p–i–n structure, which is totally different from the photoluminescence under bias compared with that under the open condition for n–i–n structural sample. Thermionic emission is related to band offset in conduction and the tunneling probability is related to width and height of the barrier. Due to the fact that two samples have the same barrier height and thickness, thermionic emission and tunneling processes cannot be used to explain the photo-excited carriers escaping from the quantum well. The photo-excited carriers escaping from the quantum well are induced by p–n junctions.

To verify the competition between recombination and escaping of carriers in quantum wells with a p–n junction, resistors were used to control the current in circuit. A linear decrease of integrated PL intensity with current under two excitation powers is shown in Fig. 3, which implies that escaping of photogenerated carriers rather than recombination dominates in the quantum wells with a p–n junction.

As is well known, an electron in the valence band absorbs a photon with the energy larger than bandgap of the material, then it should be excited to conductance band forming a pair of highly excited free electron and hole left in the valence band. There are two kinds of paths for highly excited carriers to go forward, one path is to relax to the ground state of quantum wells then recombine to emit light, and the other is escape from quantum wells and generate photocurrent. The results present here that the photo-excited electron in quantum wells selects the first path in the sample without a p–n junction structure, while it selects the second path in the p–i–n structure under the close condition. For InGaAs/GaAs quantum wells, the radiative lifetime of photogenerated electron–hole pairs usually is in the range of nanoseconds.[28] However, the escape of carriers from quantum wells is with a time of the order of femtoseconds.[19] The escape time is shorter than radiative lifetime, the process of the free photocarriers escaping the quantum wells predominates. As is well known, the electron mobility of GaAs and InGaAs is larger than the hole one, the distribution of the electric field is almost uniform in the region of InGaAs quantum wells when the bias applies to the quantum well without a p–n junction, thus the drift velocity of electrons is larger than that of holes, the number of electrons flowing out from the QWs is larger than that of holes flowing out from the QWs, a huge positive electric field should be generated in the region of QWs and should stop the carriers' escape from the quantum wells. However, the built-in electric field divides into two slope electric fields for QWs with a p–n junction, which can be adjusted by the concentrations of p or n doping, respectively. The optimizing electric field distribution can balance the hole velocity and can match the electron velocity to maintain the same number of electrons and holes flowing out from the region of QWs and electric neutrality in the region of QWs, thus it is easy for the carriers to escape from the quantum wells.

The total thickness of quantum wells is 50 nm. The photocurrent generated by the incidence light with a power of 63 mW is 5.96 mA. The quantum efficiency is 12.8%, and the absorption coefficient is calculated to be $2.7 \times 10^4\,\mathrm{cm}^{-1}$ at room temperature for the p–i–n structure sample. The reported absorption coefficient of InGaAs/GaAs quantum wells is of the order of $10^3\,\mathrm{cm}^{-1}$.[29] Hence, the ability of light absorption has been enhanced by a p–n junction. The photo absorption coefficient is related to the final state of the carriers, the final state of carriers in quantum wells with a p–n junction is on free state under the short-circuit condition, on the ground state under the open-circuit condition, the photo absorption coefficient should be varied under different conditions.

In summary, we have studied the carriers transportation process of quantum well structure with and without a p–n junction. The photocarriers escape directly from the quantum wells under the short-circuit condition with a p–n junction and the photo absorption coefficient of MQWs is enhanced by a p–n junction. This finding presented here achieves in depth comprehension of the quantum well physical characteristics and provides the basic foundation for the application of quantum wells into solar cells and photodiode detectors.

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