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RAPID COMMUNICATION

Visualizing light-to-electricity conversion process in InGaN/GaN multi-quantum wells with a p–n junction*

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Absorption and carrier transport behavior plays an important role in the light-to-electricity conversion process, which is difficult to characterize. Here we develop a method to visualize such a conversion process in the InGaN/GaN multi-quantum wells embedded in a p–n junction. Under non-resonant absorption conditions, a photocurrent was generated and the photoluminescence intensity decayed by more than 70% when the p–n junction out-circuit was switched from open to short. However, when the excitation photon energy decreased to the resonant absorption edge, the photocurrent dropped drastically and the photoluminescence under open and short circuit conditions showed similar intensity. These results indicate that the escaping of the photo-generated carriers from the quantum wells is closely related to the excitation photon energy.

Keywords: multiple quantum wells, p–n junction, light-to-electricity, photocurrent

PACS: 71.55.Eq, 72.40.+w, 73.21.Fg, 73.63.Hs **DOI:** 10.1088/1674-1056/27/9/097104

1. Introduction

Light-to-electricity conversion is the main process in solar cells and photo-detectors, including crystalline silicon solar cells,[1,2] InAs/GaSb superlattice-based infrared detectors,[3] and GaAs based solar cells[4–6] and detectors.[7–9] According to the well-established theory, when the excitation photon energy is higher than the semiconductor bandgap, high excited state electron and hole pairs will be generated and then relax to the ground state, known as the photon absorption process. These photo-generated carriers will drift under the built-in electric field of a p–n junction, and form a photo-generated voltage or photo-generated current, which is called the carrier transportation process. Most of the existing solar cells and photo-detectors are based upon such mechanisms. It is also known that for low-dimensional quantum systems, i.e., quantum wells and quantum dots, the carriers will be restricted due to the quantum confinement effect.[10] However, the carrier escaping phenomenon is observed experimentally in low dimensional material systems, explained as a result of thermionic electron emission[11–14] or Auger recombination effects.[15,16] Recently, we have reported great enhancement of photon absorption and carrier escaping from quantum structures with a p–n junction.[17–20] Similar observations have also been reported by other research groups.[21–23] Since the absorption coefficient is determined by the density of states and the wave function of the conduction band and valence band, we speculate that the enhancement should be related to the carrier transportation process. An experimental investigation on the photon absorption and carrier transport process is needed.

The photon absorption can be divided into resonant absorption and non-resonant absorption. Resonant absorption occurs when the incident photon energy is equal to the energy bandgap and the photo-generated carriers will be pumped right into the band edge. Non-resonant absorption means the photon energy is higher than the intrinsic bandgap of the semiconductors, and the carriers will be pumped into highly excited states and then relax to the ground state according to the established theory.[24,25] In this paper, we demonstrate an experiment by varying the excitation energy of the incident light to investigate its impact on the photocurrent and photoluminescence (PL) under both open and short circuit conditions. The results show that only in the resonant absorption condition do the carriers stay in the wells and then recombine to emit light, while in the non-resonant absorption condition the carriers are more likely to escape from the quantum wells under the effect of the p–n junction.

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2. Sample fabrication

The sample used here consists of 10-pairs InGaN(2.5 nm)/GaN(12 nm) multi-quantum wells sandwiched within a p–n junction. The active region emission wavelength was designed at $\sim$ 460 nm. All the samples were grown on the (0001)-oriented sapphire substrates via metal-organic chemical vapor deposition in a Aixtron 2400G3 system. The precursors were trimethyl-gallium (TMGa), triethyl-gallium (TEGa), trimethyl-indium (TMIn), and ammonia (NH_3), respectively. The dopant for the n-type GaN was silane (SiH_4), while the p-type GaN doping source was dicyclopentadienyl magnesium (Cp_2Mg). Before GaN growth, the substrate was exposed in hydrogen (H_2) ambient at 1050 °C for 8 min to desorb the surface contaminants. A 1-μm thick undoped and 2.5-μm thick Si-doped GaN layer with a doping intensity of 3×10^{18} cm^{-3} was grown at 1120 °C after the 25-nm thick nucleation layer was deposited on the sapphire substrate at 525 °C. The active regions of GaN (12 nm) /InGaN (2.5 nm) MQWs were grown at 820 °C and 720 °C, respectively. The GaN barriers were slightly Si-doped (3×10^{17} cm^{-3}). After a 10-nm thick undoped GaN space layer was deposited, a 200-nm thick Mg-doped p-GaN layer was grown with the hole concentration of about 5×10^{17} cm^{-3}. The sample was annealed at 700 °C in N_2 ambient for 20 min. Then the samples were made into 1 mm×1 mm size chips with Ni/Au transparent electrode for p-type and Cr/Ti/Al for p- and n-type electrodes. A wire bonding system with Si/Al wire on the electrodes was used for light-to-electricity characterization.

3. Experiments and results

The temperature dependent photoluminescence (TDPL) spectra were acquired by cooling the sample in a closed-loop helium cryostat to 10 K and then gradually heating to 300 K. A 405-nm continuous wave semiconductor laser was selected as the excitation source. The size of the light spot focused on the sample was approximately 0.1 mm. The photoluminescence was dispersed by a triple-grating 100-cm monochromator and detected by a GaAs photomultiplier tube using the conventional lock-in technique. Figure 1(a) shows the temperature dependent resonant excitation photoluminescence results. A clear S-shaped shift behavior of the peak energy is observed for the sample, which indicates the existence of localized states in the InGaN quantum wells.[26,27] The fitted curve shown in Fig. 1 was fitted by the band-tail model.[27,28]

The photoluminescence excitation (PLE) spectra and the photoluminescence curves under open and short circuit conditions are shown in Fig. 1(b). The following Sigmoidal formula[29] was used to determine the bandgap energy by fitting the PLE spectra:

$$y(E) = \frac{\alpha_0}{1 + \exp\left(\dfrac{E_g - E}{\Delta E}\right)}, \tag{1}$$

where α_0 is a constant and E is the excitation photon energy. ΔE is a broadening parameter and E_g represents the bandgap energy. The absorption edge E_g is estimated to be 2.95 eV, exhibiting a 250 meV Stokes shift from the PL peak energy.[29] These results indicate that the quantum well energy band consists of one state of 2.95 eV with many localized-states-induced energy minima which expand to a quasi-continuous sub-band.

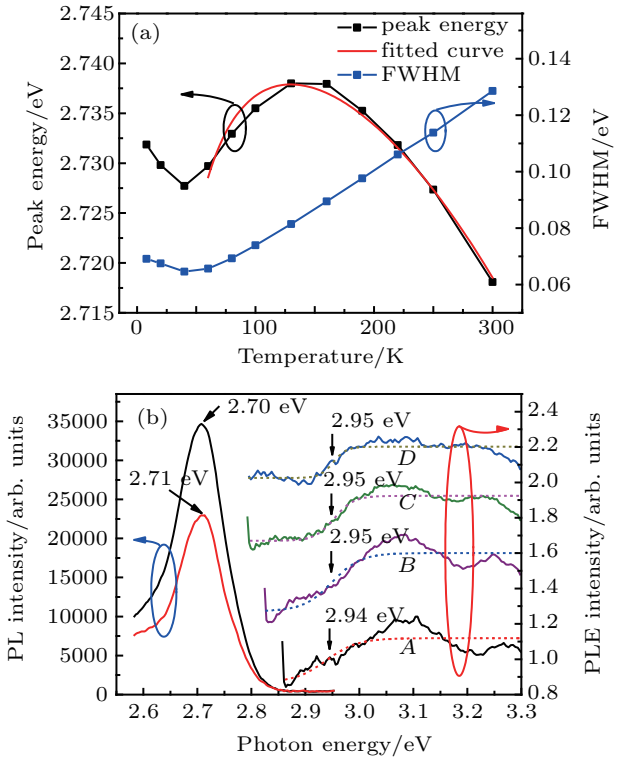


Fig. 1. (color online) (a) PL peak energy and full-width at half-maximum (FWHM) as a function of the temperature. The PL peak energy as a function of temperature exhibits an S-shape curve, which indicates the localized states in the quantum wells.[27,28] The fitted curve obtained from the band-tail model is plotted with a solid line (red) with the fitted σ of 11.62 meV. The U-shaped FWHM curve is also related to the redistribution of carriers in the localized states.[27] (b) The PLE and PL spectra. The PL emission peak locates at $\sim$ 2.70 eV for incident photons with the energy at 2.88 eV. Curves *A*–*D* represent the PLE spectra with detection energy at 2.76 eV, 2.73 eV, 2.70 eV, 2.68 eV, respectively. The dotted lines indicate the fitted curves of the PLE spectra with a Sigmoidal function,[29] which calculates a bandgap energy of about 2.95 eV.

Measurement of the photocurrent was carried out to evaluate the photo-generated carriers with different excitation photon energies. A white light source in conjunction with a 100-cm triple-grating monochromator was used as the excitation source. Meanwhile, the photoluminescence was dispersed by a single-grating 50-cm monochromator and detected by a GaAs photomultiplier tube using the conventional lock-in

technique. The exciting wavelength was changed from 370 nm (3.35 eV) to 453 nm (2.74 eV) by the 100-cm monochromator, and the PL peak position of the MQWs lied at about 460 nm (2.70 eV). The p- and n-electrodes of the chip sample were shortly connected by a copper wire, and the photocurrent was measured by a Keithley 4200 device with excitation photon energy decreasing from 3.18 eV to 2.43 eV, as shown in Fig. 2. The photo-generated current keeps almost constant at a high level of about 40 μA from 3.18 eV to 2.95 eV, corresponding to the non-resonant absorption regime domain. Our previous studies[17,20] showed that the photo-generated carriers mainly escape out of the wells to form a photocurrent, which also leads to a drastically decreased PL intensity. Then it starts to decrease at 2.95 eV, indicating the onset of the resonant absorption, which coincides with the PLE absorption edge. When the excitation photon energy reduces to 2.75 eV, the current shows a sharper decrease to the background signal, which suggests that the excitation photon energy has reached the lower edge of the sub-band introduced by the localized states.

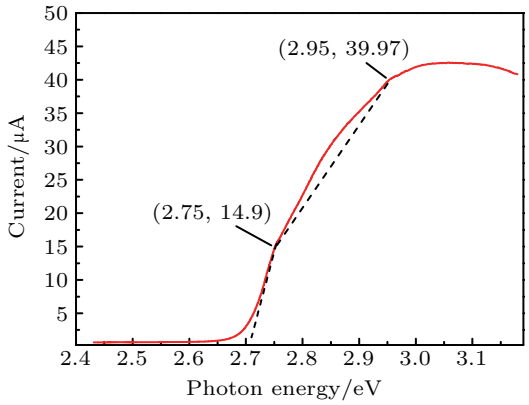


Fig. 2. (color online) (color line) Photo-generated current vs. excitation photon energy. The obvious turning points locate at 2.95 eV and 2.75 eV, representing the uppermost and lowermost bandgaps in the quantum well, respectively. The dashed lines are the guide lines denoting the two decreasing ranges. From 2.95 eV to 2.75 eV, the relatively gently decreasing region is due to the sub-band expansion caused by localized states. While the sheer decreasing after 2.75 eV indicates the cut-off of the absorption regime.

If the photo-generated carriers cannot escape out of the wells, they will recombine to emit light. Hence the photoluminescence intensity reflects the number of photo-generated carriers trapped by the quantum wells. In order to investigate the dependence of the carrier escaping behavior on the excitation photon energy, the photoluminescence was measured under open (p- and n-electrodes unconnected) and short (p- and n-electrodes connected) circuit conditions. Seen from Fig. 3(a), the PL integrated intensity in the open circuit condition is much stronger than that in the short circuit condition, since all the carriers participate in recombination under the open circuit condition while part of the carriers escape out of the wells to form a photo current under the short circuit condition. However, the intensity difference between the two conditions shrinks with decreasing excitation photon energy, and finally the open and short circuit curves are almost coincident. The induced difference of photoluminescence implies that the amount of escaped carriers decreases with lower excitation photon energy. When the photon energy reaches 2.82 eV, only half of the PL curves on the lower energy side are shown in the picture, which is caused by the line width of the incident light mainly due to the sample scattering effect. As the inset in Fig. 3(a) shows, the incident light has a line width of about 121 meV due to the scattering of the sample as well as the resolution limit of the monochromator, therefore it is difficult to distinguish the light signal from the incident light when the excitation energy is close to the photoluminescence peak energy (2.70 eV).

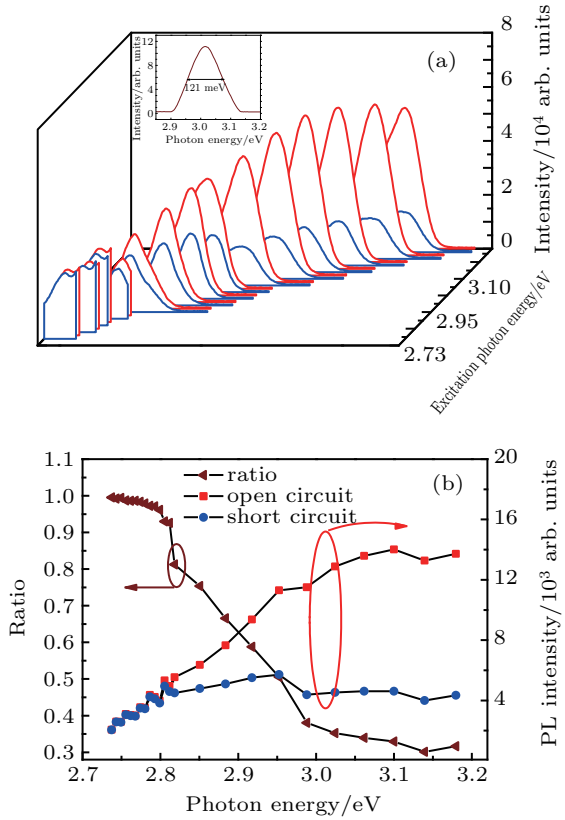


Fig. 3. (color online) (a) PL spectra excited at changing excitation photon energy from 3.18 eV to 2.75 eV. The red and blue curves represent the PL intensities under open and short circuit conditions, respectively. The inset shows the line width of the incident beam due to the sample scattering and limit of the resolution of the monochromator, which is about 121 meV when the incident photon energy is 3.02 eV. (b) The excitation wavelength dependent PL integrated intensities and the ratio of the PL integrated intensity under open circuit condition to short circuit condition.

The PL integrated intensities of open and short circuit conditions and their ratio are shown in Fig. 3(b). The PL integrated intensity in the open circuit condition is much stronger than that in short circuit condition, and the ratio curve also remains constant at $\sim 30\%$ when the excitation energy decreases from 3.18 eV to 2.99 eV where the non-resonant absorption

dominates. According to Fig. 2, the photo-generated current is also very high in this region, implying that most of the carriers escape from the quantum wells and dissipate in the external short circuit, and consequently cause the intensity difference between the open and short circuit conditions. The ratio ramps up to 50.6% when the excitation photon energy reaches 2.95 eV, indicating that when the resonant absorption begins, with lower excitation energy, the carriers tend to be restricted within the quantum wells and recombine to emit light. Then the ratio continues to increase, which reaches 92.1% when the excitation photon energy drops to 2.81 eV. When the excitation photon energy reduces to 2.75 eV, which is the lower edge of the subband due to the localized states, the intensity difference between the open circuit and short circuit conditions becomes extremely small with a ratio of 99.4%. The starting and ending points of the ratio rising phase are 2.95 eV and 2.75 eV, representing the resonant absorption edge of the quantum well and the localized states, respectively, which is consistent with the photo-generated current data.

4. Discussion and conclusion

Based on these experiment results, we are able to get a deeper insight into the light absorption and carrier transport behavior of InGaN/GaN MQWs. The absorption and carrier transportation processes are illustrated in Fig. 4(a). Under the open circuit condition, the excited electrons and holes can only drift inside the material and eventually recombine to emit photons, regardless of the excitation energy. While under the short circuit condition in Fig. 4(b), excited by enough high excitation energy, the carriers can escape from the quantum confinement and form a photo-generated current in the external circuit before the radiative recombination. This is because the carrier transit time is in the order of femtoseconds,[17,30] which is much shorter than the radiative recombination lifetime in the order of picoseconds.[31] However, this escaping behavior is closely connected to the excitation photon energy. As seen in Fig. 4(c), when the excitation photon energy drops from the non-resonant excitation to the resonant excitation, the carriers no longer have enough kinetic energy to get rid of the quantum confinement. As a result, they are restricted in the quantum wells and participate in the radiative recombination.

In our experiment, the photoluminescence and the photocurrent are measured simultaneously, which enables us to clearly locate the carrier transport behavior and visualize the light-to-electricity conversion process in the InGaN/GaN MQWs with a p–n junction. Our method is also applicable to the characterization analysis of other low-dimensional optoelectronic materials for which the light-to-electricity conversion is concerned, such as GaAs and InP based quantum dots and quantum wells. The observation of photocurrent during the non-resonant absorption proves that the carriers directly escaping from the quantum confinement is a novel phenomenon.

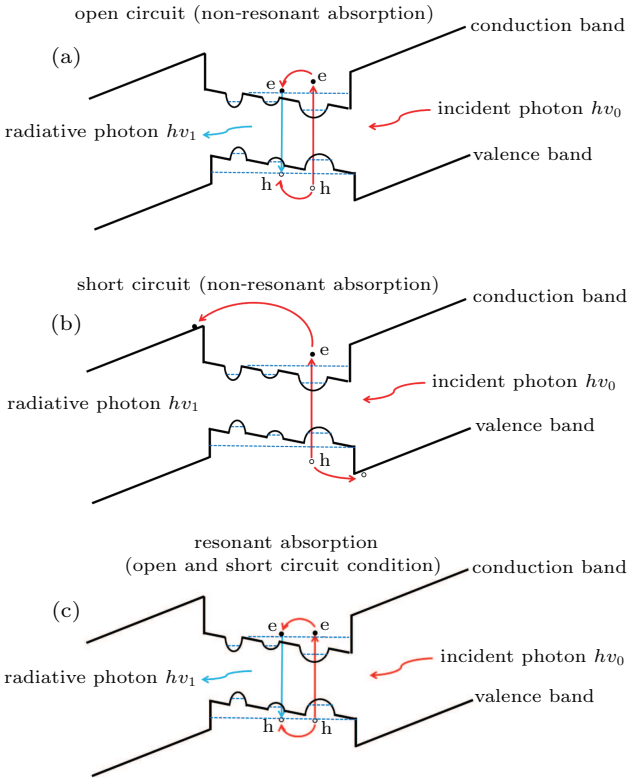


Fig. 4. (color online) Schematic of energy band in the quantum wells considering an expansion caused by localized states. The carriers exhibit different behaviors under (a) open and (b) shortcircuit conditions at non-resonant absorption regime. (c) At resonant absorption edge, the carriers will no longer escape out of the well at either open or short conditions.

With p–n junction, the directly escaping phenomenon of the photo-generated carriers under non-resonant absorption condition in the quantum wells requires the development of a new physical theory of the absorption and light-to-electricity process. Such an absorption and carrier transport process, visualized experimentally in this work, could lead to new techniques for photo-detectors and solar cells that use low dimensional materials as the active region, and gives a new insight for the research of solar cells and photo-detectors with quantum structures.

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