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Electron emission properties of GaAsN/GaAs quantum well containing N-related localized states: the influence of illuminance

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1. Introduction

III–V alloys containing nitrogen (commonly referred to as dilute nitrides), such as $GaAs_{1-x}N_x$ and $In_yGa_{1-y}As_{1-x}N_x$, have received considerable attention experimentally and theoretically in the recent decade. However, the exact nature of N-incorporation in GaAsN/GaAs quantum well (QW) under illumination is still controversial. Hence, understanding the electron emission properties of GaAsN/GaAs QW containing N-related localized states under illumination is particularly worthwhile, from both physics and device design perspectives.

2. Experiments

GaAsN/GaAs QW samples were grown on n^+-GaAs (001) substrates by molecular beam epitaxy (MBE). The growth was started with a 0.3 μm Si-doped GaAs layer of 4×10^{16} cm^{-3} grown at 580 °C, followed by a 80 A-thick GaAsN layer, grown at 480 °C. After the growth of the GaAsN layer, the growth temperature was increased to 580°C for the growth of a 0.3 μm Si-doped GaAs top layer of 4×10^{16} cm^{-3}. The N composition was estimated by the PL peak energy to be about 2.7%.

3. Results and discussions

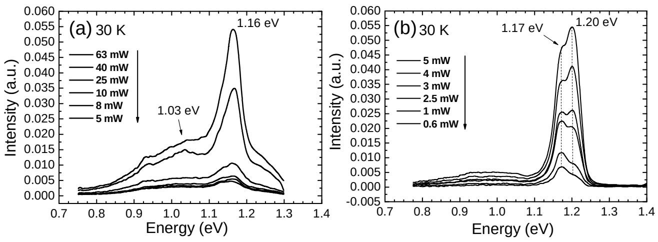

Fig. 1 (a) 30 K power-dependent PL spectra of the 80 A as-grown sample. **(b)** 30 K power-dependent PL spectra of the 80 A sample after RTA at 800℃ for 3 min.

Figure 1 (a) shows the power-dependent PL spectra (at 30 K) of the 80 A as-grown sample. In this figure, two broad emission peaks appear at 1.16 eV and 1.03 eV. Comparing these results with the annealing result (figure 1 (b)) reveals that the broad emission peak appearing at the high-energy side (1.16 eV) is GaAsN QW emission peak. A previous study identified the broad emission peak at 1.03 eV as associated with emission between the GaAsN QW electron states and a deep defect level at about 190 meV above the GaAs valence band. [1] Figure 1 (b) shows the power-dependent PL spectra (at 30 K) of the 80 A sample after RTA at 800℃ for 3 min. According to Figs. 1 (a)-(b), RTA splits the broad as-grown GaAsN QW emission into two peaks, a low energy peak (1.17 eV) and a high energy peak (1.20 eV). Additionally, thermal annealing increases the PL intensity of the GaAsN QW emission and reduces the PL linewidth of the GaAsN QW emission. Thus, the broad emission peak appearing at the high-energy side (1.16 eV) in as-grown sample is identified as GaAsN QW emission peak. Also, the high energy peak (1.20 eV) in RTA samples is also identified as GaAsN QW emission peak. Furthermore, the low energy peak (1.17 eV) exhibits a limited-filling feature relative to GaAsN QW emission peak. According to the limited-filling feature and the relative emission peak position, this low energy emission is the typical emission from N-related localized states. [2]

Figure 2 shows the capacitance-voltage (C-V) depth profiles (at (a) 240 K and (b) 260 K) and the corresponding C-V spectra (as shown on the right side) of the 80 A (a) as-grown and (b) RTA 800℃ samples. In Fig. 2 (a), two concentration peaks appear at 0.344 μm (C-V step at ~ -1.5 V) and 0.357 μm (C-V step at ~ -3.5 V) simultaneously in the as-grown sample. The depth of the shallow peak (0.344 μm) is close to the growth position of the GaAsN QW (~0.3 μm). Notably, increasing the annealing temperature raises the intensity of this peak and reduces its linewidth. These results imply that the thermal annealing improves the carrier-confinement ability of the GaAsN QW electron states. The shallow peak is thus confirmed as the GaAsN QW electron states signal. Based on the Schottky depletion theory,[3] the concentration peak at the left side of the QW peak indicates that the electron trap states of this peak is below the QW electron states. Moreover, increasing the annealing temperature reduces the deep peak intensity and increases the distance between the GaAsN QW peak and the deep peak. Therefore, the electron trap states exhibit the same behaviors as the N-related localized states, suggesting that the deep peak originates from the electron emission of the N-related localized states.

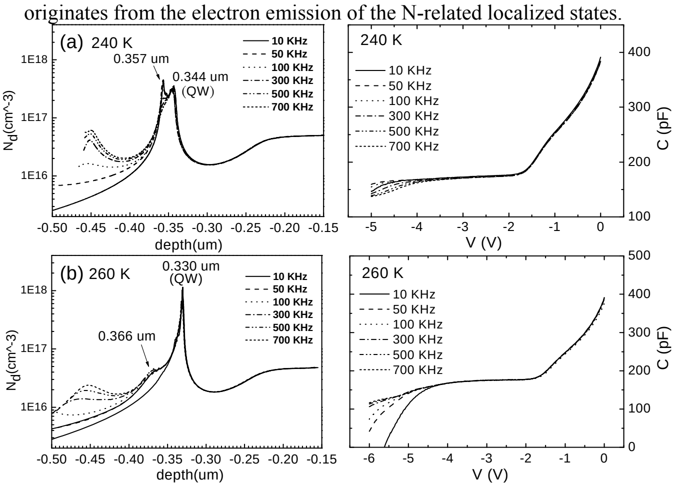

Fig. 2 (a) 240 K C-V depth profiles and the corresponding C-V spectra (as shown on the right side) of the 80 A as-grown sample. **(b)** 260 K C-V depth profiles and the corresponding C-V spectra (as shown on the right side) of the 80 A RTA 800℃ sample.

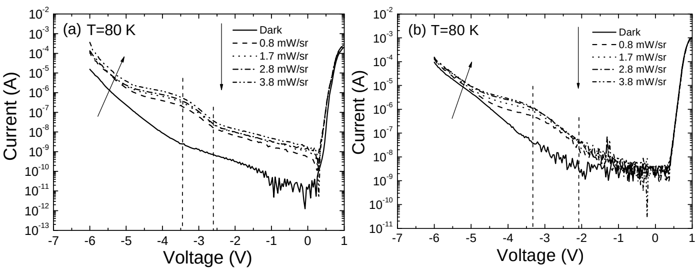

Fig. 3 I-V spectra (at 80 K) of the 80 A **(a)** as-grown and **(b)** RTA 800 ℃ samples under different radiant intensity of λ=940 nm (1.319 eV) LED illumination.

We now turn to examine the influence of illuminance on electron emission properties of GaAsN QW containing N-related localized states. Figure 3 shows the current-voltage (I-V) spectra (at 80 K) of the 80 A (a) as-grown and (b) RTA 800℃ samples under different radiant intensity of λ=940 nm LED illumination. In Fig. 3 (a), two stages of current rise are observed after LED illumination. The bias (at around -2.6 V) of the first current rise corresponds to the bias range of GaAsN QW electron states in above measurement, and the bias (at around -3.5 V) of the second current rise corresponds to the bias range of N-related localized states in above measurement. The similar result is also observed in RTA 800℃ sample, as shown in Fig. 3 (b). Similarly, the biases of the two stages of current rise are also corresponds to the bias ranges of GaAsN QW electron states and N-related localized states. The observation of I-V measurement under illumination suggests that both GaAsN QW electron states and N-related localized states can provide current paths for photo-generated electron-hole pairs.

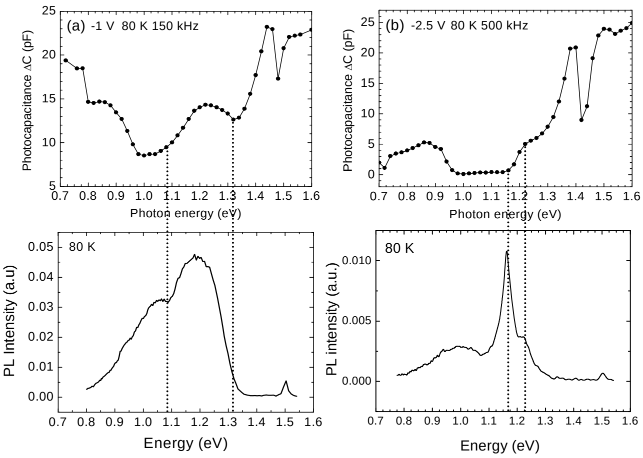

Fig. 4 Photocapacitance spectra (at 80 K) and the corresponding PL spectra (as shown on the below) of the 80 A **(a)** as-grown and **(b)** RTA 800℃ samples.

Figure 4 shows the photocapacitance spectra (at 80 K) and the corresponding PL spectra (as shown on the below) of the 80 A (a) as-grown and (b) RTA 800℃ samples. These photocapacitance measurements were held at (a) -1 V f = 150 KHz for as-grown sample and (b) -2.5 V f = 500 KHz for RTA 800℃ sample. In Fig. 4 (a), as the energy of the incident photon is increased, photocapacitance started falling. This fall in photocapacitance is usual in GaAs layer and is attributed to emission from the hole traps A and B located at energies 0.4 and 0.7 eV, respectively, above the valence band.[4] Further increasing the energy of the incident photon, a obvious rise of photocapacitance start at 1.08 eV which indicates the electron emission from electron states. The end of the photocapacitance rise at 1.08 eV is around 1.32 eV. According to the PL measurement results, this energy range of photocapacitance rise corresponds to the broad emission peak of GaAsN QW which is composed of the emission from GaAsN QW and N-related localized states. Thus, the photocapacitance rise between 1.08 eV and 1.32 eV is attributed to the electron emission from GaAsN QW electron states and N-related localized states. After thermal annealing, as shown in Fig. 4 (b), the photocapacitance features an initial photocapacitance rise at around 0.7 eV which is due to emission from the electron trap in GaAsN layer observed before.[5] Thus, as the energy of the incident photon is increased, the photocapacitance spectrum is dominated by the electron trap in GaAsN layer and the usual hole traps in GaAs layer, resulting in a bump of photo capacitance at initial. Further increasing the energy of the incident photon, two stages of photocapacitance rise are observed at 1.16 and 1.22 eV. The observed energys at 1.16 and 1.22 eV are correspond to the emission energys of GaAsN QW and N-related localized states. Hence, the two stages of photocapacitance rise are attributed to the electron emission from GaAsN QW electron states and N-related localized states. Therefore, the existence of N-related localized states in GaAsN QW can provide more electron states to modify the characteristics of photocurrent and photocapacitance. In GaAsN QW, N-related localized states can extend response range and response sensitivity on photocapacitance, and produce an additional current path for photo-generated electron-hole pairs. Moreover, because the emission rate of electron on GaAsN QW states is faster than hole's on GaAsN QW states, photon-generated electrons on GaAsN QW states are less than photon-generated holes on GaAsN QW states when illumination achieving the steady-state. Therefore, this non-equilibrium carrier distribution of p photon-generated electron-hole pairs can be regarded as a escape of part of photon-generated electrons. The photon-generated electrons escaping into bottom GaAs will cause the change of net charges in the bottom GaAs, resulting in a decrease of depletion region of bottom GaAs. Incidentally, the decrease of depletion region of bottom GaAs also increases the electric field in depletion region of bottom GaAs.

We now turn to examine the influence of illuminance on electron emission rate of GaAsN QW electron state. Fig. 5 (a) shows the photon energy-capacitance spectrum (at 80 K) of the 80 A as-grown sample, held at -3 V 150 Khz. As above-mention, based on the Schottky depletion theory,[3] the depletion width of the bottom GaAs (W_d - W_{QW}) under different incident photon energy can be extracted from Fig. 5 (a), as shown in Fig. 5 (b). In addition, according to this theory, the electric field (F) in depletion region of bottom GaAs under different incident photon energy also can be extracted from Fig. 5 (b), as shown in Fig. 5 (c).

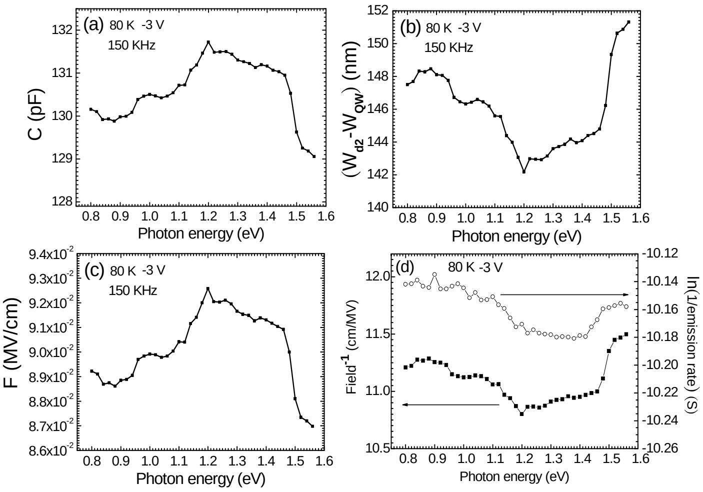

Fig. 5 (a) Photon energy-capacitance spectrum (at 80 K) of the 80 A as-grown sample, held at -3 V 150 KHz. **(b)** Spectrum for depletion width of the bottom GaAs (W_d - W_{QW}) under different incident photon energy. **(c)** Spectrum for the electric field (F) in depletion region of bottom GaAs under different incident photon energy. **(d)** Plots of ln($1/e_n$) vs photon energy (open circle) and ($1/F$) vs photon energy (solid circle) obtained from the C-F measurement and Fig. 5 (c).

Thus, the photon-generated electrons escaping into bottom GaAs will cause the change of net charges in the bottom GaAs, resulting in the change of the electric field in depletion region of bottom GaAs. Next, We utilize the phonon-assisted (field-assisted) tunneling model [6] to analyze the correlation between electron emission rate of GaAsN QW and illuminance. According to this model, the electron emission rate (e_n) is exponentially proportional to the electric field (F) under the large electric field and identical confined energy assumptions, which is given by ln($1/e_n$) ~ ($1/F$). Therefore, the change of the electric field by different incident photon energy will modulate the electron emission rate of GaAsN QW electron state. Capacitance-frequency (C-F) measurement was performed to obtain electron emission rate (e_n) of GaAsN QW electron state under different incident photon energy, and the obtained electron emission rates (e_n) are shown in Fig. 5 (d) (open circle). Fig. 5 (d) plots the ln($1/e_n$) vs photon energy (open circle) and ($1/F$) vs photon energy (solid circle) spectra. According to Fig. 5 (d), the variation of electron emission rates under different incident photon energy exhibits a similar behavior to the variation of electric fields in the bottom GaAs under different incident photon energy, and follows the relation form: ln($1/e_n$) ~ ($1/F$). Thus, the electron emission rate of GaAsN QW electron state can be modulated by different incident photon energy, which is due to the modulation of depletion width of the bottom GaAs.

4. Conclusions

This study elucidates the electron emission properties of GaAsN/GaAs QW containing N-related localized states under illumination. The mechanisms for the responses of I-V measurement under illumination and photocapacitance are investigated. N-related localized states in GaAsN QW can extend response range and response sensitivity on photocapacitance, and produce an additional current path for photo-generated electron-hole pairs. The application of N-related localized states is a feasibility method for device design of opto-electronic devices. Furthermore, exactly how illumination influences the electron emission rate of GaAsN QW electron state is examined. The electron emission rate of GaAsN QW electron state can be modulated by different incident photon energy, which is due to the modulation of depletion width of the bottom GaAs. The variation of electron emission time constant can be utilized to distinguish the incident photon energy.

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