Charge Carrier Heating Mechanism in a Wide Optical Waveguide Structure of Tunnel-Coupled Quantum Wells of GaAs/Al$_x$Ga$_{1-x}$As

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Abstract. Carrier heating in a wide optical waveguide of Tunnel-Coupled Quantum Wells (TCQW) of GaAs/Al$_x$Ga$_{1-x}$As was investigated. To determine hot electron temperature as the function of laser pumping intensity, the high energy tail of Photoluminescence was presented. The experimental result has a good agreement with theoretical result of carrier scatting energy rate with high optical pumping to explain the polar optical phonon scattering dominating carriers scattering mechanism of the system. The experimental result on the charge carrier heating is shown that taking into account non-equilibrium optical phonons accumulation significantly improves agreement between theoretical and experimental results. Compare with another narrower optical waveguide structure, the wider one provides fewer carriers scattering energy rate.

Keywords: Photoluminescence, polar optical phonon, Quantum Wells, waveguide, hot-electron temperature

1. Introduction

The studied nanostructure strongly supported the intersubband population inversion between two excited states of electrons energy levels in QW in the condition of current or optical pumping was presented for instance in [1]. In order to encourage the intersubband population inversion for electrons excited states, the interband laser generation at the fundamental energy levels of electrons-holes ($e_1 - hh_1$) must be generated [2,3]. Then in order to reach a lower either threshold current or pump intensity with the increase of differential efficiency, the supposed structure is Quantum wells with a wide optical waveguide [4, 5]. High optical pumping intensity can induce carriers to have higher kinetic energy, hence it influences on lattice temperature and consequently on carriers' temperature. These high kinetic energy carriers, on the same time to conserve their exceed energy to the whole system, must transfer energy as scattering to other particles or quasi-particles: polar optical phonons, acoustical phonons. The PL study not only provides information about quantum energy emitted from structure, but also can explain special characteristic of the system. Thus, after radiation to structure with high optical source, the distribution function of electrons will be changed, and hence it becomes to be the function of non-equilibrium state. Therefore, it can explain other properties of system parameters and one of the most important parameters is hot-electron temperature, which is higher than lattice (structure) temperature. The high energy tail of PL spectrum can determine hot-electron temperature [6]. The non-equilibrium polar optical phonon accumulation leads to decrease carriers scattering energy rate of the system [7], as a result, it can also lead to the change of non-equilibrium carrier dynamics properties. One of the most important aims of this research is study non-equilibrium phonon accumulation effecting carrier scattering energy rate of a wide optical waveguide of GaAs/Al$_x$Ga$_{1-x}$As.

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2. The design of structure and the high energy tail of PL spectrum

The studied structure fabricated by Molecular Beam Epitaxial method was a nanostructure with 20 periods of Tunnel-Coupled Quantum Wells (TCQW) of GaAs/$Al_{0.36}Ga_{0.64}As$. The size of each structure waveguide is 2.9 μm (compare with other TCQW structures which have 0.1 – 0.5 μm of optical waveguide, for example in [8]) and it is located in the both side of the active region. The active region, located in the center of the $Al_xGa_{1-x}As$ waveguide layers, consists of 20 pairs of the TCQW. The composition of Al atoms was varied from x = 0.36 to x = 0.8. This kind of a wide optical waveguide provides an optical limitation for either near-IR radiation or mid-IR radiation. The high-energy tails of the PL spectra is shown in fig. 1 as a function of the energy of the emitted photon. The spectra were taken at 77 K of temperature. The slopes of high-energy tails can determine hot electron temperature as a function of laser pumping intensity [6]. The selected high-energy tails of PL spectrum as a function of intensity of laser (was selected the first three levels of intensity 1.96, 3.92 and 7.84 kW/cm^2) were presented.
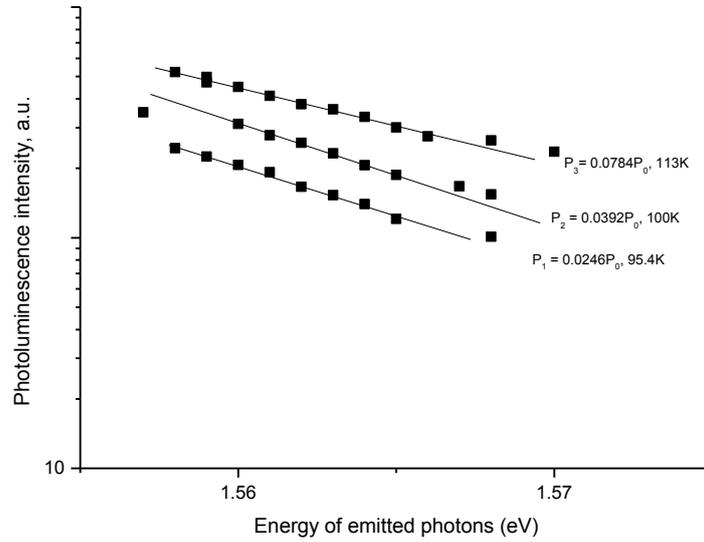

Fig. 1: The high-energy tail of PL spectrum and corresponding carriers' temperature.

3. Carrier heating and scattering process in TCQW

Consequently, hot charge-carriers phenomena influence on optical properties of our TCQW structure, thus in the steady state, the intensity of laser is proportional to the intensity of carrier scattering energy. The high-energy tail of the PL spectrum not only can characterize the carriers' temperature, but also can theoretically define scattering energy rate of carriers (electrons) as the equation below [9]:

$$\left\langle \frac{d\varepsilon}{dt} \right\rangle (T_e) = |e| \cdot E_0 \cdot \left(\frac{2\hbar\omega_{LO}}{\pi m^*} \right)^{0.5} \cdot \frac{\exp(-x_c) - \exp(-x_L)(0.5x_c)^{1/2} \exp(0.5x_c) K_0(0.5x_c)}{1 - \exp(-x_L) \cdot \sqrt{\pi/2}} \qquad (1)$$

Where E_0 – effective electric field, defined by $|e|E_0 = \dfrac{m^*e^2\hbar\omega_{LO}}{\hbar^2}\cdot\left(\dfrac{1}{\varepsilon_\infty}-\dfrac{1}{\varepsilon_0}\right)$, $x_C = \hbar\omega_{LO}/kT_e$,

$x_L = \hbar\omega_{LO}/kT_L$, $T_L = 77$ K – Lattice temperature, $\hbar\omega_{LO}$ – Optical phonon energy, $\varepsilon_0 = 12.9$ – Low-frequency dielectric constant, $\varepsilon_\infty = 10.9$ – High-frequency dielectric constant, T_e is carriers(hot-electron) temperature (K), P_0 is the maximum intensity of laser power absorbed by the sample, and $x_c = \hbar\omega_{LO}/kT_e$, $\hbar\omega_{LO}$ - polar optical phonon energy, m^* - effective mass of electron $= 0.063m_0$, m_0 - mass of free electron charge, e – electron charge.

Refer to equation (1), the dependence of scattering energy rate of carriers (electrons) on the temperature of hot-electrons as a function of laser pumping intensity was presented on fig. 1. Obviously, this function is non-linear, because the scattering energy rate of electrons is different on the different excitation intensity at low pumping intensity levels. The scattering energy rate (fig.2), $\left\langle\dfrac{d\varepsilon}{dt}\right\rangle$ obtained by theoretical calculation (equation 1) shown as dash line gives a good agreement with the experimental result (shown as dark spots) [8, 9], thus this agreement result supports the polar optical mode scattering ($\hbar\omega_{LO}$) dominating energy loss mechanism of the system. Moreover, the polar optical phonon energy can be determined from slope of linear function from semi-logarithm scale and the distribution function of electrons can be explained by Maxwell-Boltzmann distribution function. The calculation result of carrier scattering energy rate with non-equilibrium phonon accumulation model, referred to a model [7], of our wide optical waveguide structure is presented in fig. 3 (dark spots). This calculation based on experimental result of our TCQW structure, thus the structure has a 6 nm width of QW and the surface concentration $n_s = 3\cdot10^{11}cm^{-2}$. Obviously, the experimental calculation gives a good agreement with theoretical calculation of non-equilibrium phonon accumulation effect with $\tau_q = 7\cdot10^{-12}s$ shown as a bold line. The accumulation of non-equilibrium polar optical phonon depends on polar optical phonon life time τ_q and surface concentration n_s . Therefore, compare with the calculation result without the non-equilibrium phonon accumulation effect from the same structure (a dash line), the non-equilibrium phonon accumulation effect provides lower carrier scattering energy rate. Moreover, as the result of lower threshold laser pumping intensity of a wider optical waveguide TCQW, consequently lower polar optical phonon in the system, a wider optical waveguide TCQW structure provides fewer carrier scattering energy rate that the narrower optical waveguide TCQW structure presented as a dash dot line.
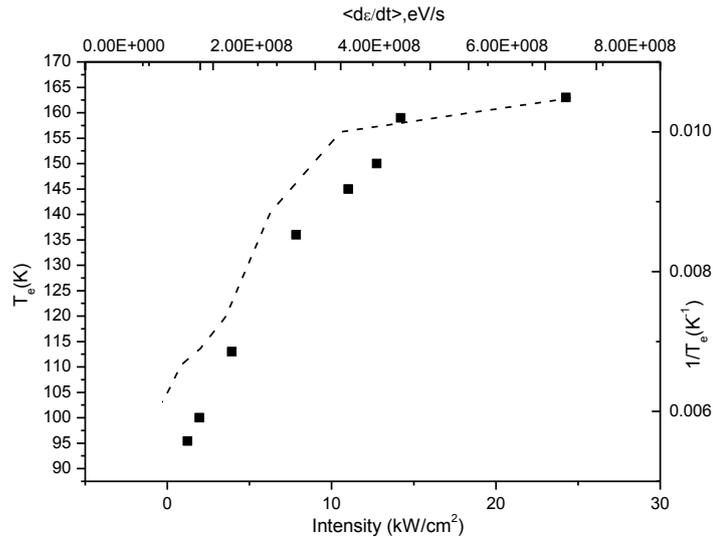

Fig. 2: the experimental dependence of the hot electron temperature T_e on the pumping intensity compared with theoretical calculation.
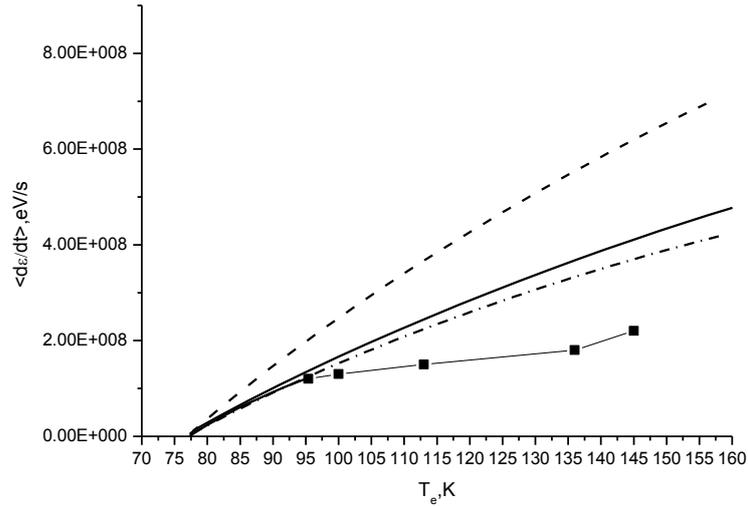
Fig. 3: Carrier scattering energy rate of 2D electrons scattering with polar optical phonon as a function of hot electron temperature of TCQW.

4. Acknowledgements

5. References

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