Numerical modeling of thermionic electrons in abrupt isotype heterojunction for the light emitting transistor

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Abstract

Light can emit from light emitting transistor of III-V materials. The pn^-n^+ structure of light emitting transistor, which has an additional n^-n^+ heterojunction between the base and electron emitter, is suggested. The base voltage can control the light output effectively. The functional principle of light emitting transistor is illuminated. A model about the abrupt isotype heterojunction in the base has been utilized to describe thermionic electron transport, current density and potential barrier in such a device. The model is used to explain the underlying mechanisms of the present devices.

Keywords: pn^-n^+, abrupt isotype heterojunction, Light emitting transistor

1. Introduction

The conventional structure of light-emitting pin hetero-diode includes a central narrow-gap light-emitting quantum well (QW) region (as an active region) and two side wide-gap emitters, that supply the QW region with holes (p-emitter) and electrons (n-emitter) [1,2]. Room-temperature luminescence has been observed from LET, mostly through the real space transfer and npn transistor mechanism process [3,4]. However, according to the newly reported light-emission efficiency, it is still too low for practical applications. Recently, the research has been focused on finding solutions to improve the excitation efficiency and control the excitation intensity.

Pnn structure has been applied on photodiode and diode [5,6]. In this paper, we try to consider a new design pn^-n^+ hetero-diode with the third electrode in the base region. The applied base voltage, which affects barrier of abrupt isotype heterojunction (AIH) between the base and electron emitter, can control device output intensity. We show that such a hetero-diode is actually a hetero-structure light-emitting transistor (LET). This LET can serve as an effective electricity to light transform: it can convert input current into more output light radiation from active region-----usually multiplication quantum wells (MQWs).

2. LET structure and functional mechanism

2.1 Light emitting transistor regime

We consider the pn^-n^+ hetero-structure LET energy band diagram shown in Fig.1. The p-type hole emitter part acts as an effective hole injection region to the active region. The active region captures the holes and electrons in the MQWs. The base control the amount of electrons injected to active region. There is an abrupt isotype heterojunction contact between n^- base region and n^+ electron emitter layer, which results in a big conduction band discontinuity. This conduction band discontinuity forms a potential well in the base region side and a potential

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barrier in the n^+ emitter region. And as a result, AIH has a triangle quantum well (TQW) structure in the base both formally and in essence. The assignment of an additional n^-n^+ heterojunction controls electrons injected from the right n^+ emitter into the complex n^- base. The n-type electron emitter part acts as an effective electron injection region to the base through the AIH.

The band gap of electron emitter is bigger than the base, which is favorable for electron injected to base. The band gap of base is bigger than the band gap of active region, which can form effective photon window for the light emitting from active region. The output light can’t be absorbed in the base and emitter.

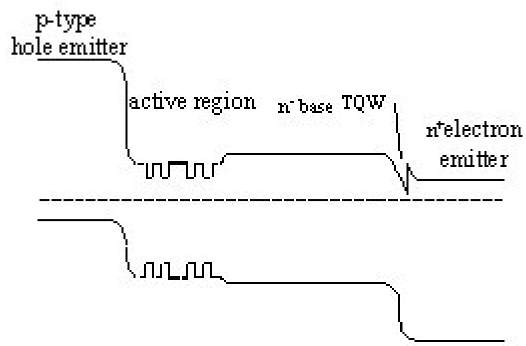

Fig.1 The energy band diagram of LET in thermal equilibrium, a left-side p-type hole emitter region, an active region, an n--type base region and a right-side n+-type electron emitter region

2.2. Functional mechanism of LET

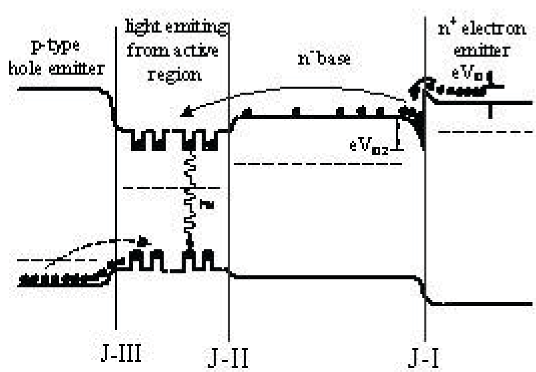

Fig.2 The energy band diagram with U_H=Rated positive voltage, U_E=0V, U_B > 0V. U_H is the hole emitter voltage, U_B is the base voltage V_{D1} is the barrier in the electron emitter region, V_{D2} is the barrier in the TQW. The solid dot “•” stands for electron. The dashed dot “o” stands for hole. The solid arrow stands for the transport orientation of electron. The dashed arrow stands for the

transport orientation of hole. J-I, J-II, and J-III stand for junction-I, junction-II, and junction-III respectively.

Fig.2 shows the light emitting process in the LET. The LET is operating with hole emitter voltage U_H= rated positive voltage, base voltage U_B≥0V, and electron emitter electrodes U_E be grounded.

Current transport across a nn heterojunction is similar to that of a metal–semiconductor junction: diffusion, thermionic emission as well as tunneling of carriers across the barrier can occur. Estimations show that at low temperatures the tunneling mechanism of the current flowing dominates and at high-temperature region (T>270K) the thermionic emission of electrons over the barrier mechanism of the current flowing dominates[7,8]. The LET operating temperature is higher than 300K. That is, in the heterostructure under study the current is due to thermionic emission of electrons over the barrier and flows from electron emitter to the narrow-gap base region.

The electrical characteristics can be explained as follows: for a fixed hole emitter voltage V_H, holes are injected from the hole emitter into the p-type material through junction-III. In a first operation regime, for the base voltage U_B=0, electrons that are injected to TQW can't overcome the barrier V_{D2} in junction-I. In this regime, there is no available electron combining with the holes in the MQWs of active region. Therefore it can't induce the light output.

As soon as $V_B>0$, the device enters the second operation regime. The n^-n^+ AIH is forward-biased, which lowers the TQW barrier V_{D2} and barrier V_{D1} in electron emitter. Electrons in the electron emitter pass over V_{D1} and are injected to the TQW. The electrons in TQW have to overcome the V_{D2} to enter the base through thermion emission effect. Then electrons pass the thin n^- base layer (<100nm) with minimum energy losses and enter the active layer through junction II. Then electrons meet and combine with holes injected from hole emitter through junction III in the active region.

It seems that the strongest of these effects is the heating of electrons by electric field traversed the junction-I. Therefore, it is necessary to provide a sufficient voltage range in the base for the LET regime, which is favorable to increase the electrons for light emitting. This requires a wide band gap in electron emitter region and a high conductive band discontinuity. At the same time, in order to provide more electrons to the active region with lower energy loss to traverse the junction-II, we need to decrease band gap of active region and to keep a certain positive discontinuity.

3. Current-voltage characteristics for the heterojunction interface

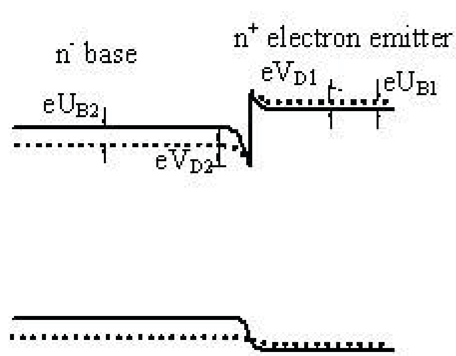

Fig.3 The isotype heterojunction energy band diagram with U_H=Rated positive voltage, U_E=0V, U_B = 0V. The dotted line is the energy band with $U_B = U_{B1} + U_{B2}$.

3.1 The barrier distribution of AIH

The total barrier V_D of junction-I in the AIH is[9]:

$$V_D = V_{D1} + V_{D2} \tag{1}$$

and

$$\frac{V_{D1}}{V_{D2}} = \frac{\varepsilon_2 N_{D2}}{\varepsilon_1 N_{D1}} \tag{2}$$

where V_{D1} is the barrier in the electron emitter region, V_{D2} is the barrier in the TQW, ε_1 and ε_2 are the static dielectric constant of n^+ electron emitter region and n^- base region, N_{D1} and N_{D2} are the doped donor concentration. The built-in barrier for AIH is given by the relation [7]:

$$V_D = \frac{k_0 T}{e} \ln(\frac{N_{D1} N_{n1}}{N_{D1} N_{n2}}) + \frac{\Delta E_c}{e} \tag{3}$$

where k_0 is the Boltzmann constant, T is the operating temperature, e is the electronic charge, N_{n1} *and* N_{n2} are the effective densities of states of the electron emitter and base region , $\triangle E_C$ is the conduction band offsets between the electron emitter and base region.

3.2 The electron concentration and current density of the AIH

When the forward voltage U_B applies on the base , U_B distributes in both sides of AIH [9]:

$$U_B = U_{B1} + U_{B2} \tag{4}$$

and

$$\frac{U_{B1}}{U_{B2}} = \frac{\varepsilon_2 N_{D2}}{\varepsilon_1 N_{D1}} \tag{5}$$

U_{B1} and U_{B2} are the forward voltage distributing on the electron emitter and base.

In wide band gap semiconductor, only thermionic electron energy above the V_{D1} can accumulation in the TQW interface, electron concentration n_{20} in the TQW is [9]:

$$n_{20} = n_1 \exp(\frac{-eV_{D1}}{kT}) \exp(\frac{eU_{B1}}{kT}) \tag{6}$$

n_1 is the electron concentration in the n^+ electron emitter. The base electron concentration n_2 which can get over the TQW is:

$$n_2 = n_{20} \exp(\frac{-eV_{D2}}{kT}) \exp(\frac{eU_{B2}}{kT}) \tag{7}$$

The junction current density as a function of applied bias V_B, can be written in the following form [7,10]:

$$J_n = A^* T^2 \exp(-\frac{eV_D}{k_0 T})[\exp(\frac{eV_B}{\beta k_0 T}) - 1] \quad (8)$$

where A^* is the effective Richardson constant. β=1 is in the case of thermionic current.

Table 1. Parameters of LET

Items	Material	Dope concentration
Hole emitter	p-GaN	5×10^{18}
Active region	5 $In_{0.2}Ga_{0.8}N$ / $In_{0.35}Ga_{0.65}N$ QWs	10^{18}
Base	n^--$In_xGa_{1-x}N_{(x=0.15)}$	5×10^{17}
Electron emitter	n^+-GaN	1.8×10^{19}

4. Discussion

We assume GaN-based materials for LET epitaxy in table 1. Results can be got as follows. Fig.4 demonstrates that, with increasing interface forward voltage, the electron concentration increases exponentially on the n^- side. In other words, electrons accumulate according to Boltzmann's law in the n^- base region. When U_B=0.2 V, the electron concentration increases rather quickly with the increasing U_B, indicating a large sensitivity to the energy distribution of injected electrons.

Fig.5 shows the forward current density–voltage characteristics at several temperatures through AIH. Indeed, forward - bias applied to the heterojunction lowers its barriers, as a result carriers passing over the barrier probably. More thermionic electron can pass over the AIH with increasing temperature.

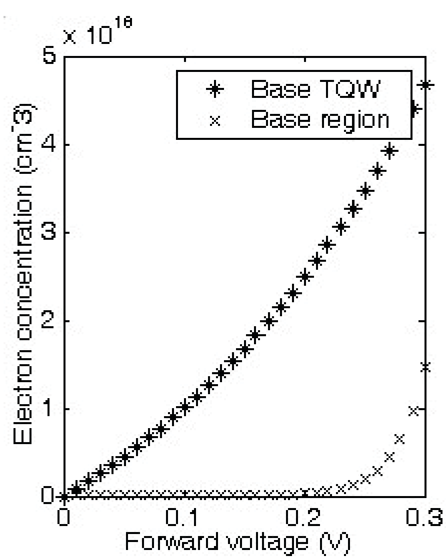

Fig.4 Electron concentration in the base TQW and base region with forward voltage

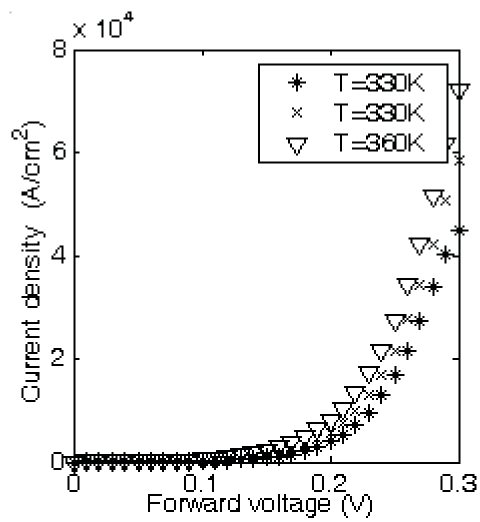

Fig.5 Forward current density–voltage characteristics at several temperatures

Changing x from 0.05 to 0.3 of the base $In_xGa_{1-x}N$ material, we can get the heterojunction barrier magnitude in Fig.6. The well in the base will be deeper when In fraction gets higher. This indicates that along with In fraction getting higher, the control effect will be better.

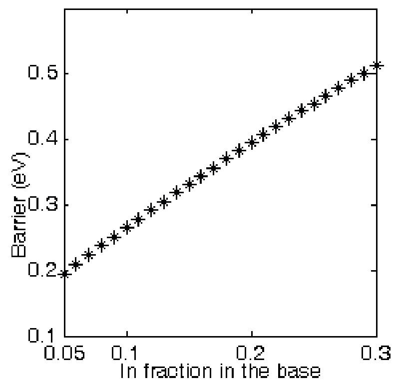

Fig.6 Barrier with different In fraction

5. Conclusion

The transistor is designed to be pn^-n^+ with an n^-n^+ abrupt isotype heterojunction between the base and electron emitter region. The AIH-regime working as a TQW can control electron behavior, which is an additional advantage in comparison with the conventional LED. The functional mechanism of LET is illuminated. A model about the AIH in the base has been utilized to describe current density, electron transport and potential barrier in such a device. The model is used to explain the underlying mechanisms of the devices. It is evident that in order to make the device useful, both device design and process technology need to be further optimized. This LET design would be a possible solution for more efficient light emitting control with a proper material preparation.

6. Acknowledgements

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