Enhancement of Cut-off Frequency and Optical Bandwidth in Light-Emitting Transistors at High Temperature Operation

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Abstract

In this paper, the temperature-dependent electrical and optical characteristics of an InGaP/GaAs light-emitting transistor (LET) with two undoped InGaAs quantum-wells (QWs) embedded in the base are investigated. When the ambient temperature increases from 25℃ to 55℃, the optical modulation bandwidth (f_{3dB}) increases from 0.96 to 1.15 GHz, and the electrical cut-off frequency enhances from 2.13 to 2.78 GHz. The temperature-enhanced electrical and optical characteristics of LETs are attributed to the thermionic emission model in QWs and explained in this paper.

INTRODUCTION

In the age of Big Data and cloud computing, the expanding growth of information and data communication is unprecedented. Traditional electrical interconnects, e.g. copper, experience significant bottleneck due to cross-talk and high power consumption. The light sources with capability of high data transmission rates are expected to replace the electrical interconnect and dominate in future board-to-board, module-to-module, and even chip-to-chip interconnects.

In 2004, M. Feng and N. Holonyak discovered the HBT can be modified and operated as a three-port (one electrical input, one electrical output, and a third port optical output) light-emitting device, resulting in the first light-emitting transistor (LET) [1]. The LET can be further improved by incorporating quantum wells to enhance the minority carrier recombination in the base region and thus optical and electrical properties [2]. The carrier recombination lifetime of the LET is extremely fast and the optical modulation bandwidth of the LET is up to 4.3 GHz in 2009 [3]. The LET inherits the merits of the HBT and the LED as a high-speed light-emitting device, and it can be potentially used for optical communication light source.

Conventionally the optical modulation bandwidth of quantum-well diode lasers will decrease with rising temperature, and it becomes a restraint of the light source for optical communication. In the meanwhile, the effect of temperature on the cut-off frequency of various heterojunction bipolar transistors has been studied. The cut-off frequency is defined as the frequency at which the magnitude of h_{21} drops to unity. The electron saturation velocity in the base-collector junction reduces with increasing temperature, resulting in the increase of the transit time. As a result, the cut-off frequency drops with increasing temperature [4]-[6].

In this paper, the temperature dependent electrical and optical characteristics of an InGaP/GaAs LET are investigated. The device is in common-collector configuration with the emitter and base diameter of 18 µm and 27 µm, respectively. The layer structure and top view are shown in Fig. 1. The optical modulation bandwidth and electrical cut-off frequency are measured through microwave measurement. The results show that the optical modulation bandwidth of the LET increases with temperature, and this unique characteristic may create more potentials in short-range optical communication.

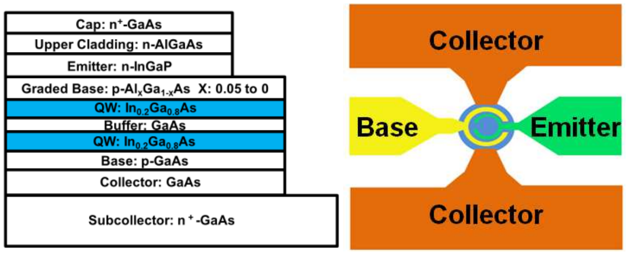

Fig. 1. The device layer structure and top view, respectively.

RESULT AND DISCUSSION

The *S*-parameters of the LET are measured at the bias condition of $V_{BC} = 0$ V and $I_B = 3$ mA from 25℃ to 55℃. Figure 2 shows the optical modulation 3dB bandwidth of the LET from 25℃ to 55℃. The 3dB frequency (f_{3dB}) is 0.96 GHz at 25℃, 1.05 GHz at 35℃, 1.1 GHz at 45℃, and increases to 1.15 GHz at 55℃.

Figure 3 shows the electrical small-signal circuit and the experimental and simulation *S*-parameters, respectively. The elements of the small-signal equivalent circuit at different temperatures can be extracted and used to calculate

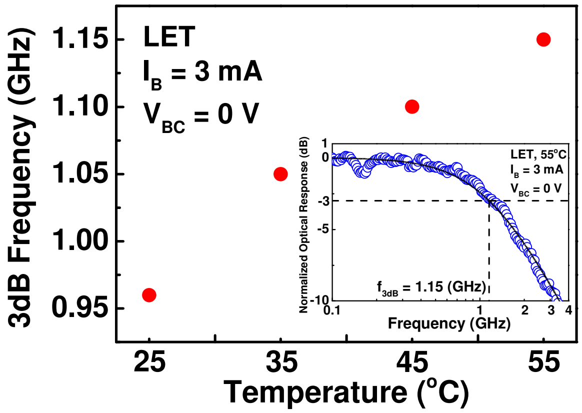

Fig. 2. The optical modulation 3dB bandwidth of the LET at 25°C, 35°C, 45°C, and 55°C.

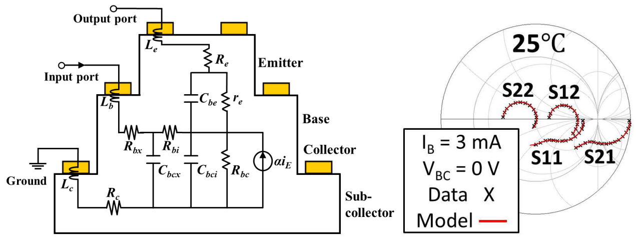

Fig. 3. The electrical small-signal circuit and S-parameters of experiment and model at 25°C, respectively.

different components of the emitter-to-collector transit time [7].

The cut-off frequency (f_T) of the LET can be found from the experimental h_{21} magnitude curve as fig. 4 which can be transferred from the S-parameters. The emitter-to-collector transit time can be expressed in Eq. 1.

$$\tau_{ec} = \frac{1}{2\pi f_T} = \tau_e + \tau_t + \tau_{sc} + \tau_c \tag{1}$$

where τ_{ec} is composed of the emitter charging time (τ_e), the base transit time (τ_t), the space charge transit time (τ_{sc}), and the collector charging time (τ_c). These components can be expressed in Eq. 2(a)-(c) [8].

$$\tau_e = r_e(C_{je} + C_{jc}) \tag{2a}$$

$$\tau_{sc} = \frac{X_{dep}}{2v_{sat}} \tag{2b}$$

$$\tau_c = (R_E + R_C)C_{jc} \tag{2c}$$

where X_{dep} is the depletion thickness in the collector and v_{sat} is the carrier saturation velocity. τ_{ec} can be calculated from transistor cut-off frequency, τ_e and τ_c can be extracted by small signal equivalent circuit, and τ_{sc} can be calculated by physical constants. Thus, τ_t can be calculated by Eq. 1 and the results are summarized in Fig. 5.

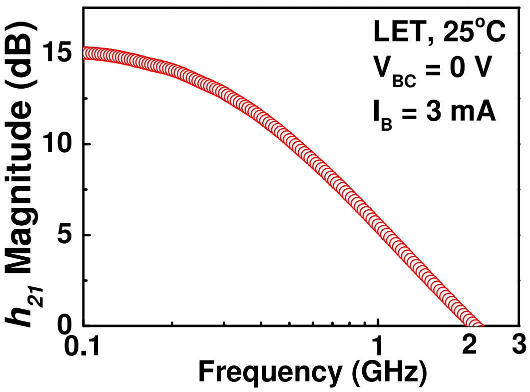

Fig. 4. The experimental h_{21} magnitude of the LET at 25°C.

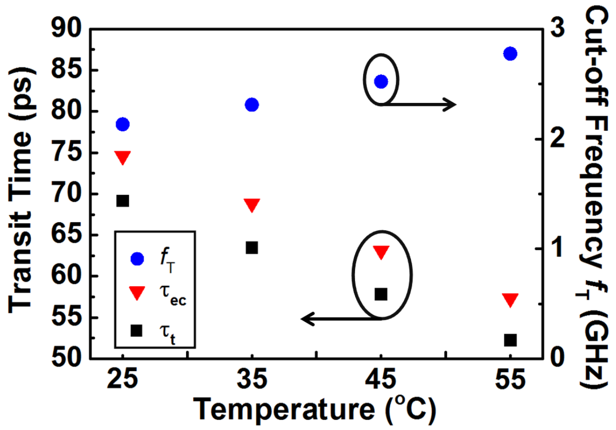

Fig. 5. The cut-off frequency (f_T), emitter-to-collector transit time (τ_{ec}), and base transit time (τ_t) from 25°C to 55°C.

The base transit time of the LET includes the unique process of carriers captured and escaped in the base-embedded quantum well. Therefore, the effective base transit time of the LET can be expressed in Eq. 3 [9]. The effective base transit time will decrease with temperature due to the reduction of thermionic emission lifetime as shown in Eq. 4 [10].

$$\tau_t = \tau_{t0} + C_0(\tau_{cap} + \tau_{esc}) \tag{3}$$

$$\tau_{esc} = \left(\frac{2\pi m^* {L_W}^2}{k_B T}\right)^{1/2} \exp\left(\frac{E_B}{k_B T}\right) \tag{4}$$

where τ_{t0} is the base transit time of the HBT (without quantum wells), τ_{cap} is the quantum-well capture lifetime, C_0 is the coefficient determined by how effective the influence of quantum wells, T is the temperature, m^* is the effective mass, L_W is the quantum well width, k_B is the Boltzmann constant, and E_B is the barrier height for carriers in the quantum wells.

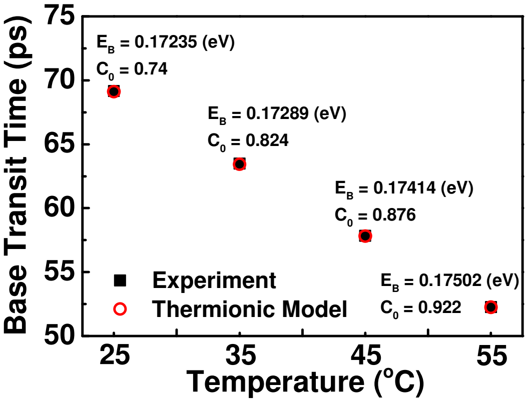

Fig. 6. The base transit time and the coefficient C_0 from 25℃ to 55℃.

The carriers diffusing to the collector are composed of two groups. One group is the carriers diffusing to the collector directly without being affected by QWs, the other group is the carriers diffusing to the collector including the process of carriers captured and escaped in the base-embedded quantum well. The ratio of two groups will affect the value of the coefficient C_0. When all carriers diffuse to the collector directly without being affected by the QWs, C_0 is equal to zero. The coefficient C_0 increases from 0.74 at 25℃ to 0.922 at 55℃ shown in fig. 6. The increase of C_0 implies more carriers diffusing through the base region are affected by QWs.

The number of electrons escaped from the quantum wells through thermionic emission increases because electrons gain more thermal energy at high temperature. The electrons escaped from the quantum well at high temperature will be swept to the collector side due to the reverse BC junction bias under forward-active operation. The reverse bias that sweeps the minority carriers from the base region to collector results in a tilted-charge population distribution in the base region. As a result, the optical light output will decrease at high temperature but the recombination lifetime remains almost constant since the process of removal of slow-recombining (escaped) carriers is still maintained.

CONCLUSIONS

The escaped carriers through thermionic emission in the quantum well at high temperature leads to the increase of current gain and the decrease of the optical power. The reverse bias at base-collector junction sweeps the carriers to the collector resulting in the tilted-charge population distribution in the base region. Therefore, the optical bandwidth is almost the same at different temperature. The escape lifetime decreases with temperature exponentially, which contributes to the reduction of the base transit time. As a result, the cut-off frequency of the LET increases with the temperature.

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ACRONYMS

LET: Light-Emitting Transistor
HBT: Heterojunction Bipolar Transistor
QW: Quantum Well
BC: Base-Collector