# Current Gain Enhancement of Light-Emitting Transistors Under Different Ambient Temperatures

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## Abstract

**The letter reports the different temperature effects on current gain ($\beta$) between InGaP /GaAs light-emitting transistors (LETs) and heterojunction bipolar transistors (HBTs). We demonstrate the enhancement of the current gain of 76.77% from room temperature to 85℃. On the contrary, the conventional HBT shows a decrease of current gain of 7.96% at high temperature.**

## INTRODUCTION

III–V alloys with direct band gaps and carrier injection have made possible the operation of light-emitting diodes (LEDs) and transistors. Due to the temperature sensitivity of their forward bias current-voltage (*I*-*V*) characteristics LEDs have been commercially available for some time as temperature sensors [1-2]. They provide wide range of operating temperatures (1.4 K to 500K), high sensitivity (units-hundreds mV/K), high signal level (from hundreds mV to Volt) at high stability and reproducibility [3].

Heterojunction bipolar transistors (HBTs) are widely used in high speed devices and microwave integrated circuits. For many system applications, the ambient temperature is significantly higher than room temperature due to power dissipation effects. When the HBT is operated at high power condition, thermal phenomenon such as the negative differential resistance (NDR) and collapse of current gain occur [4-5].

Likewise, for light-emitting diodes (LEDs), the ambient temperature also causes some critical problems. For instance, the emission wavelength variation leads to color instability due to temperature change. However, the physical mechanisms dominating the temperature sensitivity are discussed widely. One of the investigations is thermionic emission of carriers. For laser diodes (LDs), the internal quantum efficiency ($\eta_{in}$) is reduced with increasing temperature [6]. Moreover, for quantum-well lasers, thermionic emission of carriers out of the active region cause the nonlinear gain coefficient decreases with increasing temperature [7]. In other words, laser characteristics are very sensitive to temperature, in their threshold current [8]-[10] and modulation characteristics.

In early work a new class of light emitter, a three-port heterojunction bipolar light-emitting transistor (HBLET) [11-13] has been demonstrated by incorporating quantum-wells (QWs) into the base region of a HBT to enhance the base radiative recombination, and hence the optical output. Unlike HBTs, LETs possess a faster recombination lifetime and a GHz spontaneous modulation bandwidth.

In the present letter we investigate the temperature dependent characteristics of an InGaP/GaAs LET (with two undoped InGaAs QWs) and demonstrate the modulation of current gain by varying ambient temperatures. The current gain of conventional InGaP/GaAs HBT was also measured for comparison. Furthermore, we present the high sensitivity of current gain of LET is suitable for temperature sensor.

## EXPERIMENT

The LET and HBT epitaxial structure of the present work [14] are grown by metal-organic chemical-vapor deposition. The LET structure consists of consists of a 3000 Å *n*-type heavily doped GaAs buffer layer, followed by the bottom cladding layers: a 500 Å *n*-type $Al_{0.30}Ga_{0.60}As$ layer, a graded $Al_{0.30}Ga_{0.70}As$ to $Al_{0.90}Ga_{0.10}As$ buffer layer for oxidation, a 600 Å *n*-type $Al_{0.98}Ga_{0.02}As$ oxidizable layer, and then a graded $Al_{0.90}Ga_{0.10}As$ to $Al_{0.30}Ga_{0.70}As$ oxide buffer layer. These layers are followed by a 557 Å *n*-type subcollector layer, a 120 Å $In_{0.49}Ga_{0.51}P$ etch stop layer, and a 2871 Å undoped GaAs collector layer. The active layer design consists of a 1358 Å average *p*-doped $3x10^{19}$ $cm^{-3}$ AlGaAs/GaAs graded base layer with two undoped 112 Å InGaAs QWs (designed for ≈ 980 nm). Finally, the LET epitaxial structure is completed with the growth of a 511 Å *n*-type $In_{0.49}Ga_{0.51}P$ wide-gap emitter layer, the upper cladding layers (the same as the bottom ones), and a 2000 Å heavily doped *n*-type GaAs contact layer. The HBT structure is identical to the LET structure except for the insertion of two QWs in the base region. The devices are fabricated employing standard etching and contact metallization steps. The device schematic is shown in Fig. 1.

In order to maintain the temperature stability, devices are placed in a temperature-controlled stage at least ten minutes before measurement every time. The temperature varies from room temperature and increases in steps of 20℃ to 85℃. Current and bias voltages are provided by AgilentE5270B dc power source.

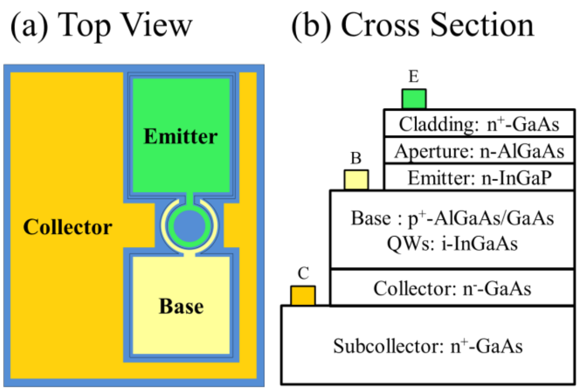

Figure 1. Schematic of the device (a) top view layout and (b) cross section of LET and HBT (without QWs). The emitter area is 74µm x 64µm with aperture widths of 28 µm for both HBT and LET devices.

## RESULT AND DISCUSSION

The *I-V* characteristics are shown in Figure. 2. The base current ($I_B$) is swept from 0 to 3.0 mA in steps of 0.2 mA and collector-to-emitter voltage ($V_{CE}$) is swept from 0 to 2.5 V. The dc current gain ($\beta = \Delta I_C / \Delta I_B$) is ~4.7 for LET and ~15.6 for HBT at room temperature. The result implies that the radiative recombination is effectively enhanced by QWs in LET. Enhanced radiative recombination is a major component of the LET base current and reduces the current gain of the transistors. When $V_{CE}$ is increased from 1.5 to 2.5 V at constant $I_B$, the collector current ($I_C$) remains almost flat for HBT while LET shows a slightly increase of $I_C$. Through the photon-assisted tunneling (Franz–Keldysh absorption) [15], holes are re-supplied to the base region and electrons are injected to the collector region, causing $I_C$ increases with $V_{CE}$ for LET devices.

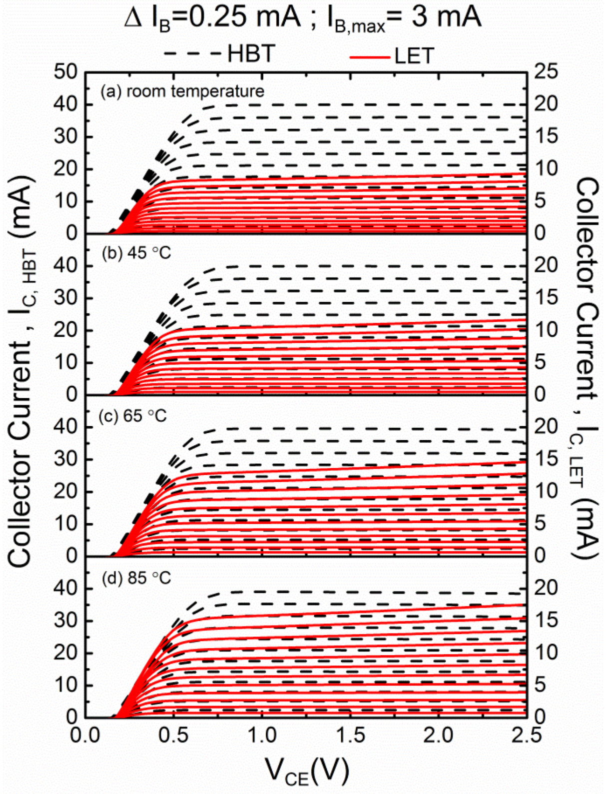

Figure 2. The I-V characteristics of HBT (dashed lines) and LET (solid line) corresponding to stage temperature (a) room temperature (b) 45℃ (c) 65℃ (d) 85℃

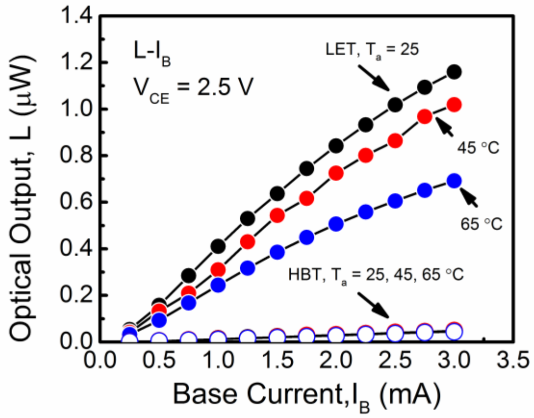

Figure 3. Optical light output *L-$I_B$* characteristics measured at $V_{CE}$=2.5 V from the device top.

The optical output as a function of base current (*L-$I_B$*) is measured from the top of these devices and is coupled through a fiber probe into a power meter (HP8163A Lightwave Multimeter). As shown in Fig. 3, the optical output of the HBT device is extremely weak compared with the LET device. The result can easily be confirmed with electrical measurements. At room temperature, the LET has maximum optical output which is 1.16 µW at $I_B$ = 3 mA. As the LET is heated to 65℃, the light output power decreases to 0.69 µW and $\beta_{LET}$ increases to 7.16, which is related to the enhanced radiative recombination at low temperatures.

Figure 4 shows $\beta$ versus ambient temperature ($T_a$). The current gain of LET increases to 5.124 at 85℃, but HBT shows a decrease to 12.70 at 85℃. The $\beta_{\text{HBT}}$ only decreases slightly with $T_a$ due to the large energy barrier $\Delta E_V$. The $\Delta E_V$

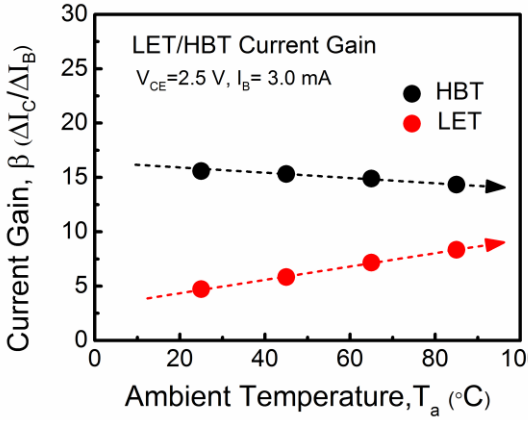

Figure 4. Current gain ($\beta$) versus substrate temperature. The $\beta_{HBT}$ is decreasing with ambient temperature but $\beta_{LET}$ is increasing.

TABLE I

THE RATIO OF CHANGE OF CURRENT GAIN AND OPTICAL OUTPUT FOR BOTH HBT AND LET DEVICES, AS A FUNCTION OF TEMPERATURE.

| | **25°C** | **45°C** | **65°C** | **85°C** |
|---|---|---|---|---|
| $\beta_{HBT}$ | 13.50 | 13.28 | 13.04 | 12.70 |
| Gain enhance of HBT | 0% | -1.67% | -4.36% | -7.96% |
| Optical reduction of HBT | 0% | 12.14% | 40.35% | - |
| $\beta_{LET}$ | 2.574 | 3.214 | 4.272 | 5.124 |
| Gain enhance of LET | 0% | 23.44% | 28.32% | 76.77% |
| Optical reduction of LET | 0% | -3.73% | 7.80% | - |

(= 0.42 *eV*) is effective in blocking the back-injection at elevated temperature. However, for LET, the $\beta_{LET}$ increases evidently with $T_a$. When $T_a$ is higher, electrons gain more thermionic energy and increase the possibility to escape from QWs in the base region. In other words, the thermionic emission lifetime ($\tau_{emi}$) in Eq.1 [15] is reduced and more electrons are tend to escape from the QWs and collected by the collector, resulting in a reduction of base transit time, $\tau_t$.

$$\tau_{emi} = \left(\frac{2\pi m^* L_w{}^2}{k_B T}\right)^{1/2} \exp\left(\frac{E_B}{k_B T}\right) \qquad (1)$$

where $E_B$ is the effective barrier height, m* is the carrier mass, $k_B$ is the Boltzmann constant, and *T* is temperature.

The current gain can be represented in Eq. 2, where $\tau_B$ is carrier recombination lifetime in base region, and $\tau_t$, including thermionic emission lifetime, is carrier transit time from emitter to collector. When ambient temperature increases, $\tau_{emi}$ is reduced, and hence the $\tau_t$. Therefore, the current gain of the LET increases with temperature, which is in contrary to the conventional HBTs.

$$\beta = \frac{\Delta I_C}{\Delta I_B} = \frac{\tau_B}{\tau_t} \qquad (2)$$

Table I. shows the ratio of change of current gain and optical output with ambient temperature. The current gain of the LET increases to 76.77% at 85°C, accompanied with a reduction in optical output. The violent variation is not appearance for HBT. Consequently, for the LET, we can use the apparent change of current gain as a temperature sensor.

## CONCLUSIONS

We have investigated the electrical and optical performance of HBT and LET at different ambient temperatures. By incorporating two InGaP QWs into the base region of an HBT structure, the current gain is sensitive to ambient temperatures. The LET demonstrates the current gain increase of 76.77% from room temperature to 85°C. The positive temperature characteristics of current gain make the LET promising as a sensitive temperature sensor.

## REFERENCES

[1] L. E. Barton, Electronics, 35, 38, 1962.

[2] I. M. Dmitrenko, et al., Cryogenic, 6, 357, 1966.

[3] Lake Shore Cryotronics, Inc. product catalog or website (http://www.lakeshore.com/Pages/Home.aspx)

[4] W. Liu, S. K. Fan, T. Kim, E. Beam and D. Davito, *Current transport mechanism in GaInP/GaAs heterojunction bipolar transistors*, IEEE Trans. Electron Devices, vol. 40, pp. 1378-1383, 1993.

[5] W. Liu and A. Khatibzadeh, *The collapse of current gain in multi-finger heterojunction bipolar transistor: Its substrate temperature dependence, instability criteria, and modeling*, IEEE Trans. Electron Devices, vol. 41, pp. 1698–1707, 1994.

[6] J. I. Pankove, *Temperature dependence of emission efficiency and lasing threshold in laser diodes*, IEEE J. Quantum Electron., vol. QE-4, pp. 119–122, Apr. 1968.

[7] A. Bernussi, H. Temkin, D. Coblentz, and R. Logan, *Gain nonlinearity and its temperature dependence in bulk and quantum-well quaternary lasers*, IEEE Photon. Technol. Lett., vol. 7, pp.348-350 1995.

[8] J. Pan and J. Chyi, *Theoretical study of the temperature dependence of 1.3 mm AlGaInP-InP multiple quantum well lasers*, IEEE J. Quantum Electron., vol. 32, pp. 2133–2138, 1996.

[9] T. Makino, H. Lu, and J. Evans, *Temperature dependence of the threshold current in gain coupled distributed feedback lasers with periodically etched quantum wells: A mechanism for the appearance of an infinite $T_0$*, Appl. Phys. Lett., vol. 68, pp. 1892–1894, 1996.

[10] R. Huang, J. Simmons, P. Jessop, and J. Evans, *A relationship for temperature dependence of threshold current for 1.3 mm compressively strained-layer multiple quantum well lasers*, IEEE Photon. Technol. Lett., vol. 9, pp. 892–894, 1997.

[11] M. Feng, N. Holonyak, Jr., and W. Hafez, *Light-emitting transistor: Light emission from InGaP/GaAs heterojunction bipolar transistors*, Appl. Phys. Lett., vol. 84, pp. 151-153, 2004.

[12] M. Feng, N. Holonyak, Jr., and R. Chan, *Quantum-well-base heterojunction bipolar light-emitting transistor*, Appl. Phys. Lett., vol. 84, pp. 1952-1954, 2004.

[13] C. H. Wu, G. Walter, H. W. Then, M. Feng, and N. Holonyak, Jr., *Scaling of light emitting transistor for multi-GHz optical bandwidth*, Appl. Phys. Lett., vol. 94, pp. 171101-171103, 2009.

[14] C. H. Wu, G. Walter, H. W. Then, M. Feng, and N. Holonyak, Jr., *Scaling of light emitting transistor for multigigahertz optical bandwidth*, Appl. Phys. Lett., 94, 171101, 2009.

[15] A. James, G. Walter, M. Feng, and N. Holonyak, Jr., *Photon-assisted breakdown, negative resistance, and switching in a quantum-well transistor laser*, Appl. Phys. Lett., 90, 152109 (2007).

[16] H. Schneider and K. v. Klitzing, *Thermionic emission and gaussian transport of holes in a GaAs/Al$_x$Ga$_{1-x}$As multiple-quantum-well structure*, Phys. Rev., vol. B 38, pp. 6160-6165, 1988.

## ACRONYMS

HBT: Heterojunction Bipolar Transistor
LED: Light-Emitting Diode
LET: Light-Emitting Transistor