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Extraction of interface states at emitter–base heterojunctions in AlGaAs/GaAs heterostructure bipolar transistors using sub-bandgap photonic excitation

Se Woon Kim [1], Kang Seob Roh, Seung Hwan Seo, Kwan Young Kim, Gu Cheol Kang, Sunyeong Lee, Chang Min Choi, So Ra Park, Jun Hyun Park, Ki Chan Chun, Kwan Jae Song, Dae Hwan Kim, Dong Myong Kim *

School of Electrical Engineering, Kookmin University, 861-1 Jeongneung, Seongbuk, Seoul 136-702, Republic of Korea

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Abstract

Distribution of interface states at the emitter–base heterojunctions in heterostructure bipolar transistors (HBTs) is characterized by using current–voltage characteristics using sub-bandgap photonic excitation. Sub-bandgap photonic source with a photon energy E_{ph} which is less than the energy bandgap E_g ($E_{g,GaAs} = 1.42$, $E_{g,AlGaAs} = 1.76$ eV) of emitter, base, and collector of HBTs, is employed for exclusive excitation of carriers only from the interface states in the photo-responsive energy range at emitter–base heterointerface. The proposed method is applied to an $Al_{0.3}Ga_{0.7}As/GaAs$ HBT ($A_E = W_E \times L_E = 250 \times 100\ \mu m^2$) with $E_{ph} = 0.943$ eV and $P_{opt} = 3$ mW. Extracted interface trap density D_{it} was observed to be $D_{it,max} \sim 4.2 \times 10^{12}\ eV^{-1}\ cm^{-2}$ at emitter–base heterointerface.

1. Introduction

For heterojunction bipolar transistors (HBTs) with inherent high current gain, high cutoff frequency, and high speed operation, interface states at the emitter–base (E–B) heterojunctions are very important for key figures of merits on 1/*f* noise, ideality factor, the current gain, and the base leakage current through the degradation of heterojunction [1–4]. They strongly depend on the quality of the emitter–base heterojunction interface and, therefore, the characterization of traps over the energy bandgap at the E–B heterointerface is one of the most important topics for assessing both the reliability and the robustness of HBTs and their integrated circuits. The density (N_t), trap levels (E_t), and electrical charge states (deep and shallow, donor-and acceptor-like) of traps and interface states in heterojunctions strongly depend on the fabrication process. In addition to lattice mismatch and stresses at the heterojunction during epitaxial growth, surface and bulk traps are generated by device fabrication processes which include etching (wet or dry), deposition, and plasma assisted treatment during device fabrication. There have been enormous efforts on the characterization of interface traps for improved DC and microwave performance, noise characteristics, and the reliability of HBTs and other heterojunction devices [5–7].

Characterization of interface states at the emitter–base heterojunction usually has been performed in a view point of the crystal defects for high quality epitaxial growth. However, it is expected to be very convenient and useful to have electrical characterization for the practical structure of HBT operation in addition to the epitaxial and crystal defect characterization. Especially, it is strongly necessary to investigate the “as is” interface states at E–B heterojunction during/after HBT operation for long-term

* Corresponding author. Tel.: +82 2 910 4719; fax: +82 2 910 4449.
E-mail addresses: dmkim@kookmin.ac.kr, dmkim@ieee.org (D.M. Kim).
[1] S.W. Kim is now with SNS Technology, Daegu, Korea.

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reliability assessment and hot carrier effect investigation. This is because HBTs operate with high current driving and this results in long-term degradation of interface states due to high temperature operation for high current operation. Sub-bandgap photonic technique reported in this work is similar to previously reported sub-bandgap photonic C–V characterization technique developed for MOS capacitors and the optical subthreshold current method for MOSFETs [8,9]. There are significant difference in the effect and characterization methods for interface states between unipolar devices and bipolar devices. This is because carriers in bipolar devices move across the junction interface while they move along the junction in unipolar field effect transistors. The sub-bandgap photonic characterization of traps at heterojunction interface in bipolar devices is the first report. We expect that the proposed sub-bandgap photonic base current method (PBCM) is useful for characterizing energy-dependent traps and interface states in bipolar semiconductor devices including pn diodes, bipolar junction transistors, photo diodes, solar cells, light emitting diodes, laser diodes, phototransistors with heterojunctions which use selective and effective control of electrons and holes across the junctions.

2. Base current in heterojunction bipolar transistors

In this work, a new sub-bandgap ($E_{ph} < E_g$) photonic characterization of the base current (I_B) in HBTs is proposed for extracting the interface states at the emitter–base heterointerfaces comparing base currents under dark and sub-bandgap photonic excitation. Contrary to the conventional optical characterization with a photon energy larger than the bandgaps ($E_{ph} > E_g$, above-bandgap), the photon energy smaller than bandgaps in HBTs is used to exclusively characterize the traps and interface states at E–B heterojunction as shown in Fig. 1. We note that the photon energy ($E_{ph} = 0.943$ eV) is smaller than bandgaps of GaAs and $Al_{0.3}Ga_{0.7}As$ ($E_{g,GaAs} = 1.42$, $E_{g,AlGaAs} = 1.76$ eV). Under sub-bandgap photonic excitation, therefore, there are excess carriers excited only from the traps at the E–B heterointerfaces while suppressing direct excitations from the valence band to the conduction band in N – $Al_{0.3}$-$Ga_{0.7}As$ emitter, p-GaAs base, and n-GaAs collector layers. As schematically shown in Fig. 1, possible energy for electrons at traps to be excited to the conduction band ranges $(E_C - E_{ph}) \leqslant E_t \leqslant E_{Fn}$.

Experimental current–voltage characteristics of an Npn $Al_{0.3}Ga_{0.7}As$/GaAs HBT with the emitter area $A_E = W_E \times L_E = 250 \times 100\ \mu m^2$, as shown in Fig. 2, under dark and photonic excitation are comparatively shown in Fig. 3 for photon energies $E_{ph} = 0.943$ and $E_{ph} = 1.481$ eV. For a photon energy $E_{ph} = 1.481$ eV, which is larger than the bandgap (E_g) of GaAs layer but less than $E_{g,AlGaAs}$, the current–voltage characteristics of $Al_{0.3}Ga_{0.7}As$/GaAs HBTs show considerable changes in the base current (I_B) due to photo-generation of carriers from the valence band to the conduction band in the p-type GaAs base layer at the E–B heterojunction. Although there are photoexcited excess carriers from the interface states and bulk traps, the dominant change is caused by excess carriers excited from the valence band to the conduction band in the p-GaAs base under above-bandgap photons with $E_{ph} > E_g$. Increased base current (ΔI_B) contains photoexcited carriers from band-to-band generation as well as carriers from trap-to-band generation. Therefore, ΔI_B under above-bandgap photons with $E_{ph} > E_g$ cannot be employed for characterizing traps and interface states without any complicated separation procedure.

Under a sub-bandgap photonic excitation with $E_{ph} < E_{g,GaAs}$, on the other hand, we note that a noticeable variation in the base current was also observed at small base-to-emitter voltages (V_{BE}). Contrary to photonic excitations under above-bandgap photons with $E_{ph} > E_g$, there are excess carriers only from the interface states and the bulk traps in the photo-responsive energy band only under sub-bandgap photonic excitation [7]. Comparing the V_{BE}-dependent photonic I–V curves under photonic excitation with that under dark condition, the energy-dependent

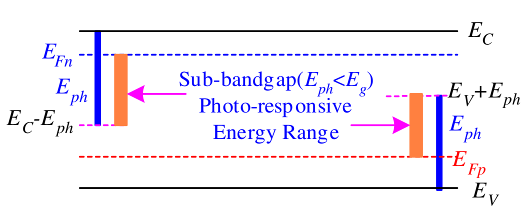

Fig. 1. Schematic diagram of sub-bandgap photonic generation mechanism in semiconductors. For sub-bandgap photon energy with $E_{ph} < E_g$, there is only photonic excitation of electrons from photo-responsive trap levels at $(E_C - E_{ph}) \leqslant E_t \leqslant E_{Fn}$ to the conduction band but excluding electron–hole pair generation from the valence band to the conduction band. Sub-bandgap photo-responsive range in Npn AlGaAs/GaAs HBTs with $N_{DE} << N_{AB}$ can be approximated by $(E_C - E_{ph}) \leqslant E_t \leqslant (E_C - E_{g,GaAs} + qV_{BE})$ this is because $V_{biB}/V_{biE} = V_B/V_E = (V_{biB} - V_B)/(V_{biE} - V_E) = (\varepsilon_{AlGaAs}N_{DE}/\varepsilon_{GaAs}N_{AB}) \sim 0$ and the applied voltage V_{BE} appears across the lightly doped emitter depletion layer.

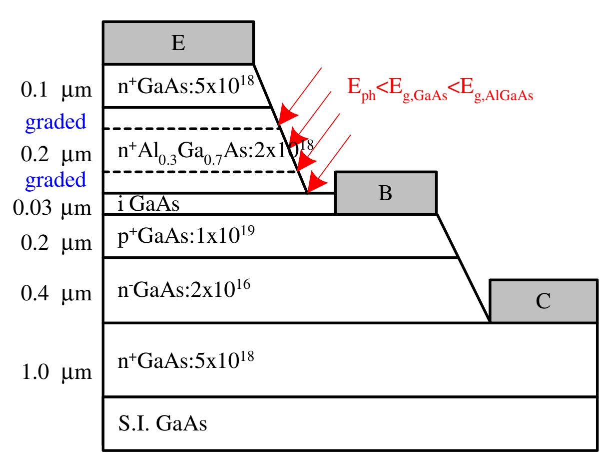

Fig. 2. Schematic cross-sectional device structure of Npn $Al_{0.3}Ga_{0.7}As$/GaAs HBTs employed for sub-bandgap photonic characterization of interface states at emitter–base heterojunction.

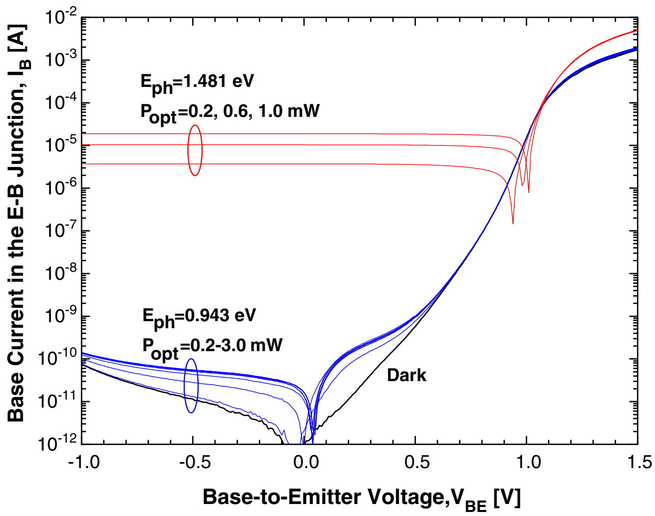

Fig. 3. Photonic I_B–V_{BE} characteristics of an Npn AlGaAs/GaAs HBTs with the emitter area $A_E = W_E \times L_E = 250 \times 100\ \mu m^2$ under dark and photonic excitation with a sub-bandgap photon $E_{ph} = 0.943$ eV ($P_{opt} = 0.2$–3.0 mW) and with a above-bandgap photon $E_{ph} = 1.481$ eV ($P_{opt} = 0.2$–1.0 mW). It is optically saturated over $P_{opt} > 1.8$ mW with a sub-bandgap photon $E_{ph} = 0.943$ eV.

distribution of interface states at the emitter–base heterointerfaces in HBTs can be extracted. We also note that the photonic energy ($E_{ph} = 0.943$ eV) is much larger than the average thermal energy ($kT \sim 0.026$ eV) at room temperature. Therefore, photo-generation of excess carriers and their contribution to the I–V characteristics of HBTs under sub-bandgap photonic excitation are believed to be dominant over the thermal generation at room temperature, especially under high optical power which is utilized for the extraction of the trap density by the sub-bandgap photonic I–V characterization. A schematic energy band diagram of the $Al_{0.3}Ga_{0.7}As$/GaAs emitter-banse heterojunction for Npn AlGaAs/GaAs HBTs under a sub-bandgap photonic excitation with $E_{ph} = 0.943$ eV is shown in Fig. 4. Bias-dependent photo-responsive energy ranges are comparatively illustrated for thermal equilibrium (a) and forward biases (b and c for $0 < V_{BE1} < V_{BE2}$). We note that the electrical characteristics of heterojunctiuon bipolar transistors, including current gain and noise performance, depend strongly on the quality of the emitter–base heterojunctions. The Shockley-Read-Hall (SRH) recombination through the traps at the E–B heterointerface is a dominant performance-limiting factor under low base-emitter voltage. Therefore it is very important to characterize the density and distribution of interface states at the E–B heterointerface in HBTs.

Optically induced base current ($\Delta I_B = I_{B,photo} - I_{B,dark}$) of the emitter–base heterojunction in AlGaAs/GaAs HBTs under dark and sub-bandgap photonic excitation are shown in Fig. 5 under a sub-bandgap phonic excitation for $E_{ph} = 0.943$ eV with $P_{opt} = 0$–3 mW. Under low emitter–base junction voltage, it is well known that the current is dominated by the recombination current and represented by

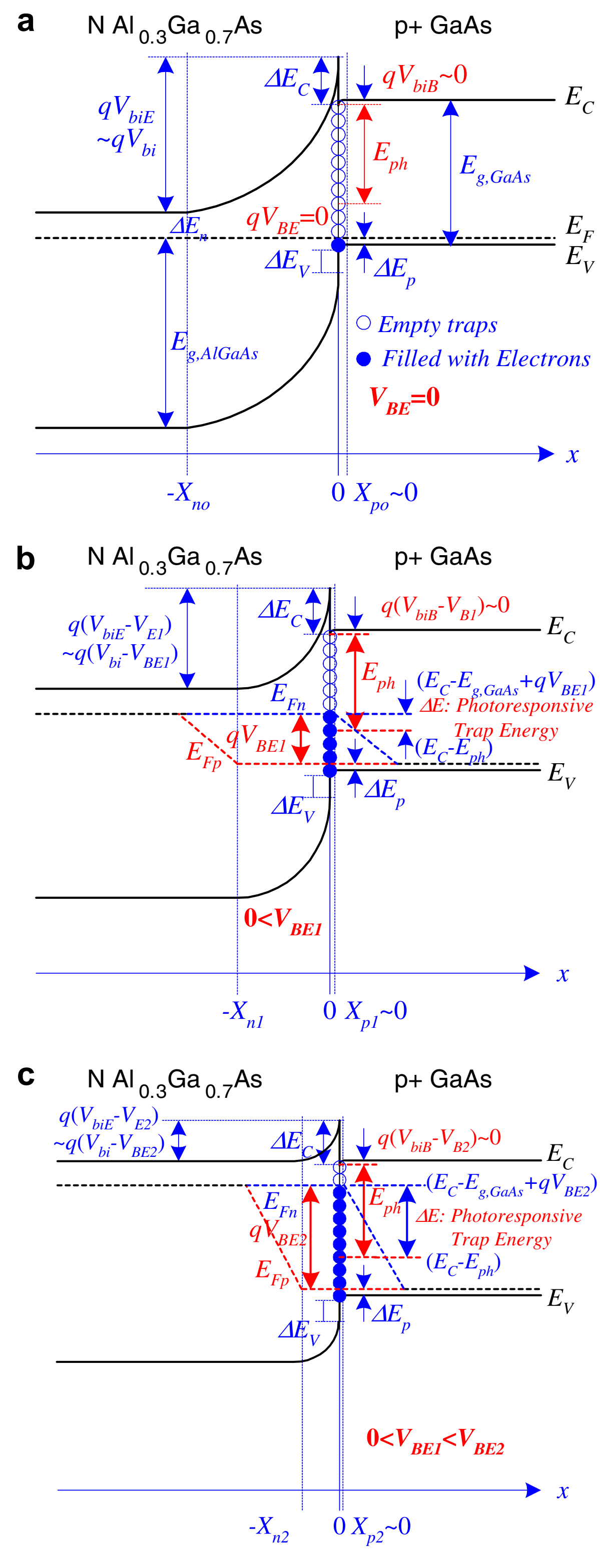

Fig. 4. Energy band diagram of an Npn AlGaAs/GaAs HBTs (emitter–base junction under forward bias) under a sub-bandgap photonic excitation with $E_{ph} < E_g$ which allows a photonic excitation of electrons from traps (E_{it}) to the conduction band ($E > E_C$) while suppressing the direct band-to-band carrier generation. Sub-bandgap photo-responsive range over the energy bandgap in AlGaAs/GaAs HBTs can be described as $(E_C - E_{ph}) < E_t < (E_C - E_{g,GaAs} + qV_{BE})$. (a) Photo-responsive energy band diagram under thermal equilibrium, (b) under medium forward bias $V_{BE} = V_{BE1} > 0$, (c) under large forward bias $V_{BE} = V_{BE2} > V_{BE1}$.

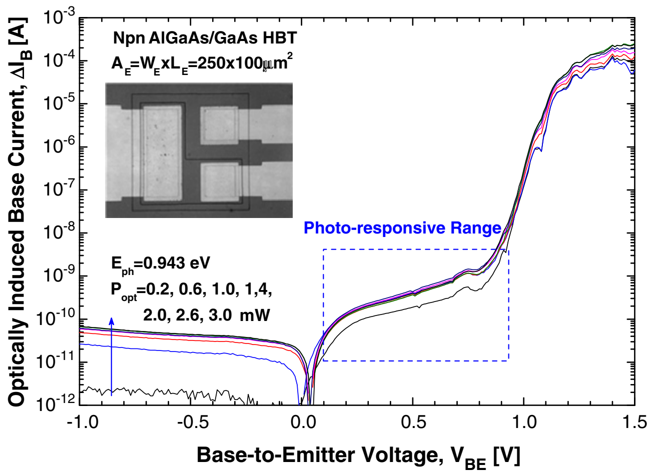

Fig. 5. Optically induced base current ($\Delta I_B = I_{B,photo} - I_{B,dark}$) of the emitter–base heterojunction in AlGaAs/GaAs HBTs under dark and sub-bandgap ($E_{ph} = 0.943$ eV) photonic excitation with $P_{opt} = 0$–3 mW.

$$I_{rec} = I_{ro}(e^{V/\eta V_{th}} - 1) \text{ A} \tag{1}$$

where η = the ideality factor of the junction, I_{ro} = recombination saturation current and they are strongly dependent on the trap distribution.

The carrier recombination mechanism through the interface states in the emitter–base heterostructure space charge region can be described by the Shockley-Read-Hall (SRH) model [10]. The SRH recombination rate $R_{SRH}(E_t)$ for a single trap at the trap level $E=E_t$ can be described by [10,11]

$$R_{SRH}(E_t) = \frac{\sigma v_{th} N_t(E_t)(pn - p_0 n_0)}{(n + p + n' + p')} \text{ s}^{-1} \text{ cm}^{-3} \tag{2}$$

$$pn = n_i^2 e^{V/V_{th}} \text{ cm}^{-6} \tag{3}$$

where V is applied voltage across the junction with $N_t(E_t)$ = trap density per unit volume (cm^{-3}) at $E = E_t$, σ = capture cross section (cm^2), v_{th} = thermal velocity (cm/s), n_i = the intrinsic carrier concentration (cm^{-3}), V_{th} = the thermal voltage (V), and n (n_0) and p (p_0) = the electron and hole concentrations (under thermal equilibrium) per unit volume, respectively. Electron and hole concentrations (n' and p' (cm^{-3})) at trap level $E = E_t$ are described by

$$n'(E_t) = n_i e^{-(E_t - E_i)/kT} \text{ cm}^{-3}, \tag{4}$$

$$p'(E_t) = n_i e^{(E_t - E_i)/kT} \text{ cm}^{-3} \tag{5}$$

with E_t = trap energy level, E_i = intrinsic Fermi level, and n_i = intrinsic carrier concentration.

Under forward bias, the electron concentration (n) is much larger than the hole concentration (p) in the space charge region due to asymmetric energy barriers against electrons ($q\phi_{be} = qV_{bi} - \Delta E_C - qV$) and against holes ($q\phi_{bh} = qV_{bi} + \Delta E_V - qV$) across the N-AlGaAs/p-GaAs heterojunction with V_{bi} and ΔE_C (ΔE_V) as built-in voltage and conduction (valence) band discontinuity, respectively. Therefore, R_{SRH} (E_t) at forward biased heterojunctions in Npn HBTs through a single trap level can be simplified as

$$R_{SRH}(E_t) \cong \frac{\sigma v_{th} N_t(E_t) pn}{(n + p + n' + p')} \cong \sigma v_{th} N_t(E_t) p \text{ cm}^{-3} \text{ s}^{-1}. \tag{6}$$

Hole concentration (p) injected over the energy barrier from the p-GaAs base and crossing the space charge region under forward bias at the base-emitter heterojunction interface can be approximated by

$$p = n_i e^{(E_{Fn} - E_i)/kT} \cong n_i e^{V_{BE}/\alpha V_{th}} \text{ cm}^{-3} \tag{7}$$

and, therefore, $R_{SRH}(E_t)$ can be redescribed as

$$R_{SRH}(E_t) \cong \sigma v_{th} N_t(E_t) n_i e^{qV_{BE}/\alpha kT}. \tag{8}$$

The model parameter α reflects the effectiveness of the barrier lowering for holes in the p-type GaAs base caused by the voltage drop (V_{BE}/α) across the p-type GaAs space charge region. This also models the modulation effects of the quasi-Fermi levels for electrons and holes (E_{Fn} and E_{Fp}) in the junction. If necessary, α can be adaptively adjusted to match the model with the experimental observation and heterojunction structure (doping, epitaxial growth, and Al mole fraction).

The integrated SRH recombination rate ($R_{SRH,m}$) through multiple trap levels distributed over the bandgap ($E_V < E_t < E_C$) can be obtained simply by integrating contribution of each trap level as described by

$$\begin{aligned} R_{SRH,m} &\equiv \int_{E_V}^{E_C} R_{SRH}(E_t)\delta(E_t)\,dE \\ &= \int_{E_V}^{E_C} \sigma v_{th} N_t(E_t) n_i e^{V_{BE}/\alpha V_{th}} \delta(E_t)\,dE \text{ cm}^{-3} \text{ s}^{-1}. \end{aligned} \tag{9}$$

Therefore, the total recombination current (I_R) through the distributed multiple trap levels at the emitter–base heterojunction of AlGaAs/GaAs HBTs under forward bias can be obtained by integrating the SRH recombination rate over the energy bandgap and written as [1,2,11]

$$\begin{aligned} I_R &= qA_E \int_{SCR} R_{SRH,m}\,dx \\ &= qA_E \int_{SCR} \left[\int_{E_V}^{E_C} R_{SRH}(E_t)\delta E(E_t)\,dE \right] dx \\ &= qA_E \int_{SCR} \left[\int_{E_V}^{E_C} \sigma v_{th} N_t(E_t) n_i e^{qV_{BE}/\alpha kT} \delta(E_t)\,dE \right] dx. \end{aligned} \tag{10}$$

We note that the base current under forward bias is mainly composed of (a) recombination current (I_{scr}) in the heterojunction space charge region, (b) thermionically injected hole current (I_p) over the heterojunction energy barrier ($q\phi_{bh} = qV_{bi} + \Delta E_V - qV$), and (c) recombination current (I_{rb}) in the neutral p-GaAs base region.

3. Modeling of base current under sub-bandgap photonic excitation

Photo-generation and resulting contribution of excess carriers, which are only excited from the traps and interface states in the emitter–base space charge region at the AlGaAs/GaAs E–B heterojunction due to sub-bandgap photons ($E_{ph} < E_{g,GaAs}$, $E_{g,AlGaAs}$), generates the photonically induced base current ΔI_B dominated by the recombination of carriers at the emitter–base depletion region. This is summarized as

$$I_B = I_{scr} + I_p + I_{rb} = I_{B,0} + I_{B,ph} \tag{11}$$

$$I_{B,0} = (I_{scr,0} + I_{p,0} + I_{rb,0}) \tag{12}$$

and

$$I_{B,ph} = (I_{scr,ph} + I_{p,ph} + I_{rb,ph}) \tag{13}$$

where $I_{B,0}$ is the base current under dark condition and $I_{B,ph} \equiv \Delta I_B$ is the increased base current due to the sub-bandgap photonic excitation.

We note that there is negligible increase in the hole injection current ($I_{p,ph} \sim 0$) because there is no change in the electrostatic potential energy barrier ($q\phi_{bh} = qV_{bi} + \Delta E_V - qV$) against holes to be injected from the p-GaAs base whatever there is a photonic excitation or not. We also note that the neutral p-GaAs base region (W_B) is designed to be very short compared with the excess carrier diffusion length (L_{nB}) for better diffusion of injected electrons to the collector junction. Therefore, the recombination in the bulk base is also negligible ($I_{rb,0} \sim 0$ and $I_{rb,ph} \sim 0$) both under dark and under sub-bandgap photonic excitation. We obtain the base current approximated by

$$I_B \cong (I_{scr,0} + I_{p,0} + I_{rb,0}) + (I_{scr,ph}). \tag{14}$$

Therefore, the predominant component in the change of I_B is due to photonically generated excess carriers from the interface states rather than those from the bulk traps in the emitter–base depletion region [3,5,7]. The sub-bandgap-photonically induced base current (ΔI_B) of the emitter–base heterojunction in AlGaAs/GaAs HBTs can be modeled as

$$\Delta I_B \triangleq I_{B,photo} - I_{B,dark} \cong (I_{scr,ph} + I_{p,ph}) \cong I_{scr,ph} \tag{15}$$

and can be written using the SRH recombination through multiple traps as

$$\begin{aligned}\Delta I_B &\cong I_{scr,ph} \\ &= qA_E \int_{SCR} \left[\int_{E_C-E_{ph}}^{E_{Fn}} R_{SRH}|_{ph} \delta E(E_t)\,dE \right] dx \\ &= qA_E \int_{SCR} \left[\int_{E_C-E_{ph}}^{E_{Fn}} \sigma v_{th} N_t\,(E_t)|_{ph} n_i\, e^{V_{BE}/\alpha V_{th}} \delta(E_t)\,dE \right] dx\end{aligned} \tag{16}$$

where $I_{B,photo}$ and $I_{B,dark}$: base currents under a sub-bandgap photonic excitation and dark, respectively. Under sub-bandgap photonic excitation, electrons located at traps in the photo-responsive energy range $[(E_C - E_{ph}) \leqslant E_t \leqslant E_{Fn}]$ are excited and contribute to the photonically induced base current. Therefore, ΔI_B is obtained integrating over the photo-responsive energy range. We note that the quasi-Fermi level E_{Fn} and the photo-responsive range contributing to the current are modulated by the voltage V_{BE} across the heterojunction.

We obtain a modified SRH recombination rate through trap levels for photo-responsive energy range as

$$R_{SRH,ph} \cong \int_{SCR} \left[\int_{E_C-E_{ph}}^{E_{Fn}} \sigma v_{th} N_t(E_t)|_{ph} n_i e^{V_{BE}/\alpha V_{th}} \delta(E_t)\,dE \right] dx \ \mathrm{s^{-1}\ cm^{-2}} \tag{17}$$

where $R_{SRH,ph}$ is defined as an effective SRH recombination rate ($\mathrm{s^{-1}\,cm^{-2}}$) at the interface states due to sub-bandgap photonic excitation. With $n >> p$ due to the heterostructure in the $N-Al_{0.3}Ga_{0.7}As$ emitter and p-GaAs base, the optically induced base current of the emitter–base heterojunction in AlGaAs/GaAs HBTs can be re-described as [2,3,11]

$$\begin{aligned}\Delta I_B &\cong qA_E R_{SRH,ph} \\ &\cong \frac{1}{2} qA_E \sigma v_{th} \left[\int_{E_C-E_{ph}}^{E_{Fn}} N_t(E_t)|_{photo} \delta(E_t)\,dE \right] n_{iB} e^{V_{BE}/\alpha V_{th}}.\end{aligned} \tag{18}$$

Defining the energy-dependent two-dimensional interface trap density N_{it} ($\mathrm{cm^{-2}}$) in the photo-responsive energy range as

$$N_{it}(V_{BE}) \equiv \int_{SCR} \left[\int_{E_C-E_{ph}}^{E_{Fn}} N_t(E_t)|_{ph} \delta(E_t)\,dE \right] dx \ \mathrm{cm^{-2}}, \tag{19}$$

we obtain the increased base current as

$$\begin{aligned}\Delta I_B(V_{BE}) &\cong qA_E R_{SRH,ph}(V_{BE}) \\ &= \frac{1}{2} qA_E \sigma v_{th} N_{it}(V_{BE}) n_{iB} e^{V_{BE}/\alpha V_{th}}.\end{aligned} \tag{20}$$

We note that N_{it} depends on ΔI_B through the variation of V_{BE} because the quasi-Fermi level E_{Fn} is modulated by the applied forward bias across the base-emitter heterojunction. This is one of key concepts in this paper for extracting the energy-dependent trap density at the junction interface in bipolar devices including HBTs. In the calculation, the intrinsic carrier concentration n_{iB} is chosen that in the p-type GaAs base because main contribution of generation and recombination comes from smaller bandgap under sub-bandgap photonic excitation. Even though the model parameter α is chosen to be 1/2 for this work, it can be modified and refined for more accurate and better extraction of the traps in the improved sub-bandgap photonic characterization method.

Therefore, the energy-dependent distribution of the interface trap density D_{it} ($\mathrm{cm^{-2}\,eV^{-1}}$) can be finally obtained from

$$D_{it}(E_t) = \frac{\partial N_{it}}{\partial E} = \left(\frac{\partial V_{BE}}{\partial E}\right) \cdot \left(\frac{\partial \Delta I_B}{\partial V_{BE}}\right) \cdot \left(\frac{\partial N_{it}}{\partial \Delta I_B}\right) \tag{21}$$

V_{BE}-dependent variations of energy band ($\partial E/\partial V_{BE}$) and quasi-Fermi levels for electrons and holes can be calculated using the Poisson's equation with the depletion approximation for the heterojunction structure while V_{BE}-dependent base current change ($\partial \Delta I_B/\partial V_{BE}$) under photonic excitation can be obtained from the measured experimental current–voltage characteristic data.

We note that the acceptor doping (N_{AB}) in the GaAs base layer in Npn AlGaAs/GaAs HBTs is much higher than the donor doping (N_{DE}). Therefore, the built-in voltages (V_{biE} and V_{biB}) and the voltage drops across the emitter and base depletion regions (X_n and X_p) in Npn AlGaAs/GaAs HBTs with $N_{DE} << N_{AB}$ can be approximated by

$$\frac{(V_{biB} - V_B)}{(V_{biE} - V_E)} = \frac{V_{biB}}{V_{biE}} = \frac{V_B}{V_E} = \frac{X_p}{X_n} = \frac{\varepsilon_{AlGaAs} N_{DE}}{\varepsilon_{GaAs} N_{AB}} \cong 0. \tag{22}$$

This means that almost all of the built-in voltage and applied voltage appears across the lightly doped emitter depletion layer ($V_{bi} = V_{biE} + V_{biB} \approx V_{biE}$ and $V_{BE} = V_E + V_B \approx V_E$). This allows the photo-responsive trap energy range and applied voltage [$(E_C - E_{ph}) \leqslant E_t \leqslant E_{Fn}$] can be approximated by $(E_C - E_{ph}) \leqslant E_t \leqslant (E_C - E_{g,GaAs} + qV_{BE})$ as comparatively shown in Fig. 4 for (a) under thermal equilibrium and (b,c) under forward bias ($0 < V_{BE1} < V_{BE2}$). This results to the photo-responsive energy range $\Delta E = q\Delta V_{BE}$ and V_{BE}-dependent modulation of the energy band $(\partial E/\partial V_{BE}) = (\partial \Delta E/\partial V_{BE}) \approx 1$. This finally results in

$$\begin{aligned} D_{it}(E_t) &\cong \left(\frac{\partial \Delta I_B}{\partial V_{BE}}\right) \cdot \left(\frac{\partial N_{it}}{\partial \Delta I_B}\right) \\ &= \frac{\partial}{\partial E}\left[\frac{2\Delta I_B}{qA_E \sigma \upsilon_{th} n_{iB}} \exp\left(-\frac{V_{BE}}{2V_{th}}\right)\right] \\ &= \frac{\partial}{\partial V_{BE}}\left[\frac{2\Delta I_B}{qA_E\ \sigma \upsilon_{th} n_{iB}} \exp\left(-\frac{V_{BE}}{2V_{th}}\right)\right]. \end{aligned} \tag{23}$$

4. Experimental results

We applied the proposed PBCM method to GSMBE-grown Npn $Al_{0.3}Ga_{0.7}As$/GaAs HBTs with the emitter area $A_E = W_E \times L_E = 250 \times 100\ \mu m^2$ fabricated by a conventional mesa process (0.2 μm N-$Al_{0.3}Ga_{0.7}As$ emitter with $N_{DE} = 2 \times 10^{18}\ cm^{-3}$, 0.2 μm p-GaAs base with $N_{AB} = 1 \times 10^{19}\ cm^{-3}$, 0.4 μm n-GaAs collector with $N_{DC} = 2 \times 10^{16}\ cm^{-3}$). Capture cross section, saturated thermal velocity, and intrinsic carrier concentration were used $\sigma \sim 10^{-14}\ cm^2$, $v_{th} = 10^7$ cm/s, and $n_{iB} = 1.8 \times 10^6\ cm^{-3}$, respectively. Sub-bandgap photonic I–V characteristics of the emitter–base heterojunction in HBTs were measured using a semiconductor parameter analyzer HP 4156C combining an optical source with $E_{ph} = 0.943$ eV (ILX Lightwave Co.) for the PBCM characterization of traps at the AlGaAs/GaAs heterointerfaces. In order to fully activate the carriers in the traps by the sub-bandgap photonic excitation, we applied maximum available optical power $P_{opt} = 3$ mW ($E_{ph} = 0.943$ eV) that is high enough to obtain optically saturated I–V characteristics.

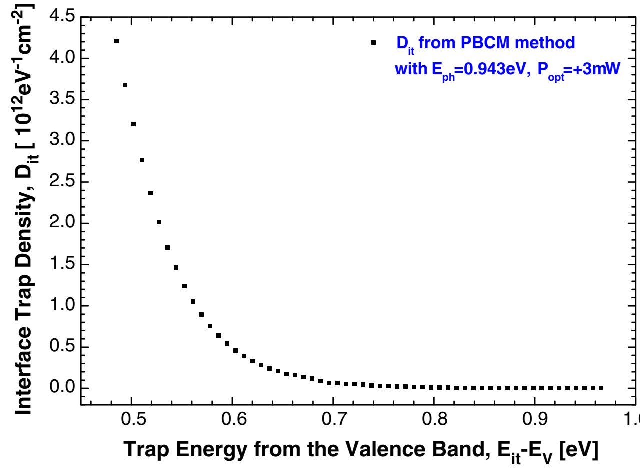

Fig. 6. Extracted distribution of trap density D_{it} in the photo-responsive energy band from the emitter–base heterointerface in AlGaAs/GaAs under a sub-bandgap photonic excitation with $E_{ph} = 0.943$ eV and $P_{opt} = 3$ mW.

Comparing the base current of the emitter–base junction under $E_{ph} < E_g$ with $P_{opt} = 0$ and 3 mW, the energy-dependent distribution of D_{it} over the photo-responsive energy band $(E_C - E_{ph}) < E_t < (qV_{BEn} + qV_{bip} + \Delta E_p)$ (can be approximated by $(E_C - E_{ph}) \leqslant E_t \leqslant (E_C - E_{g,GaAs} + qV_{BE})$) at the emitter–base heterointerfaces in Npn AlGaAs/GaAs HBTs was obtained by combining Eq. (23) and experimental base current change under sub-bandgap photonic excitation. Extracted trap density ranges $D_{it} = 10^8$–$10^{12}\ eV^{-1}\ cm^{-2}$ and is shown in Fig. 6. This experimental result agrees well with previously reported data even though a relatively high density of the interface state rather than previous results [1–3, 5] was observed.

5. Conclusions

An optoelectronic characterization technique, a photonic base current method, has been presented for extracting the interface traps at the emitter–base heterojunction in AlGaAs/GaAs HBTs. An optical source with a sub-bandgap photon energy $E_{ph} = 0.943$ eV ($P_{opt} = 3$ mW) was employed for the photonic I–V characterization of the interface states in the photo-responsive energy band. By comparatively probing the base currents of the emitter–base junction under dark and a sub-bandgap photonic excitation, the interface trap density in the photo-responsive energy band was extracted from the experimental data. The maximum value of the interface state density ($D_{it,max}$) was observed to be $\sim 4.2 \times 10^{12}\ eV^{-1}\ cm^{-2}$ for GSMBE-grown AlGaAs/GaAs HBTs with the emitter area $A_E = W_E \times L_E = 250 \times 100\ \mu m^2$.

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