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Sub-Bandgap Photonic Base Current Method for Characterization of Interface States at Heterointerfaces in Heterojunction Bipolar Transistors

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In this paper, we propose a novel photonic base current analysis method to characterize the interface states in heterojunction bipolar transistors (HBTs) by using the photonic I-V characteristics under sub-bandgap photonic excitation. For the photonic current-voltage characterization of HBTs, an optical source with a photon energy less than the bandgap energy of $Al_{0.3}Ga_{0.7}As$ and GaAs ($E_{ph} = 0.95$ eV $< E_{g,AlGaAs} = 1.79$ eV & $E_{g,GaAs} = 1.45$ eV) is employed for the characterization of the interface states distributed in the photo-responsive energy band (E_C - $0.95 \leq E_{it} \leq E_C$) in emitter-base heterojunction at HBTs. The proposed novel method, which is applied to bipolar junction transistors for the first time, is simple, and an accurate analysis of interface traps in HBTs is possible. By using the photonic base-current and the dark-base-current, we qualitatively analyze the interface trap at the $Al_{0.3}Ga_{0.7}As$/GaAs heterojunction interface in HBTs.

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I. INTRODUCTION

In order to improve speed and high-frequency performance, the device dimensions of HBTs (Heterojunction Bipolar Transistors) are largely scaled down. Due to such fast scaling, the thickness of the base layer is significantly scaled down, and various base heterojunctions are attempted. The base layer is also subject to a high electric field due to built-in electric field caused by composition grading and/or doping grading. Therefore, an ultra-thin base layer needs to have a very high doping and excellent interface properties. The high doping concentrations in the range from 10^{18} to 10^{19} cm^{-3} are already used in the emitter and the base to achieve a better current gain with a higher cut-off frequency.

In addition, with the development of high-speed digital and mixed analog-digital signal processing circuits and low-voltage operations, circuit designers require accurate HBT model parameters for circuit simulations. Reliability and performance degradation are also key concerns in implementing high-performance HBTs and their integrated circuits as monolithic microwave integrated circuits (MMICs) and microwave and millimeter wave monolithic integrated circuits (MIMICs).

The interface traps at AlGaAs/GaAs interface in a HBT structure are well known to play an important role in determining the 1/f noise, the carrier mobility (μ), the ideality factor (η), the current gain (β), and the base leakage current with degradation of device reliability in HBTs [1–6]. Therefore, accurate modeling and characterization of interface traps throughout the bandgap are most important topics for improving the robustness of devices and integrated circuits with HBTs, so enormous efforts have been spent on the accurate characterization of interface traps in HBTs [7]. The characteristics of interface traps are the most important parameters for the DC and the microwave performance, the noise performance, and, especially, the reliability of HBTs [8–10].

Photonic characterizations in the previous works used a photon energy (E_{ph}) larger than the bandgap energy (E_g). In this work, however, a photon energy smaller than the bandgap energy is used to analyze the interface traps at the heterojunctions in HBTs. In this work, a new base current analysis technique, namely, photonic base current analysis (PBCA), is presented for the analysis of HBT interface traps. Based on the photonic current-voltage response of the photodiode and the emitter-base junction in HBT, the base current shows extreme peak characteristics with respect to the optical power in the forward bias. In this way, the difference of the base current in the forward bias directly demonstrates the magnitude of the interface traps. We propose a novel and accurate PBCA using the optical current-voltage (I-V) curve as a means to exploit the above requirement. The basic principle of this method is introduced, and its validity is verified by experiments on npn

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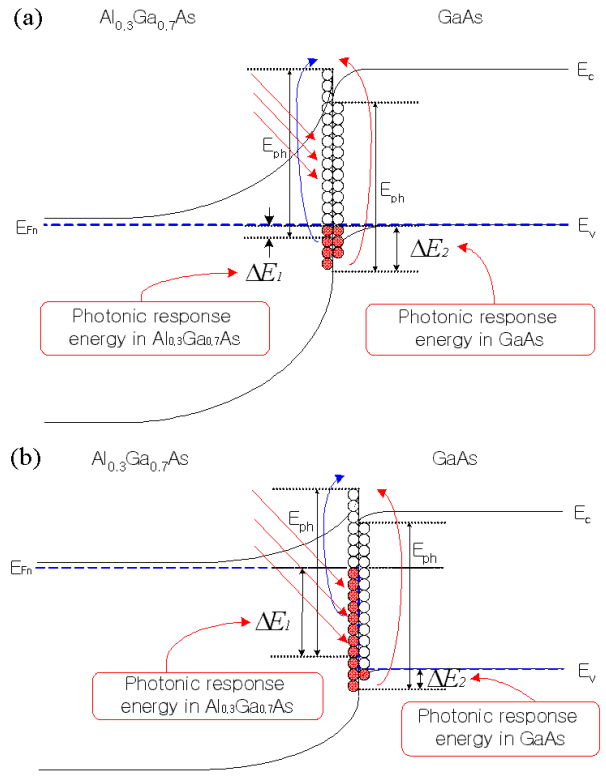

Fig. 1. Schematic energy-band diagram of an emitter-base heterojunction in a HBT with an optical input ($\lambda = 850$ nm; $E_{ph} = 1.45$ eV $> E_{g,GaAs}$): (a) under thermal equilibrium and (b) under a forward bias.

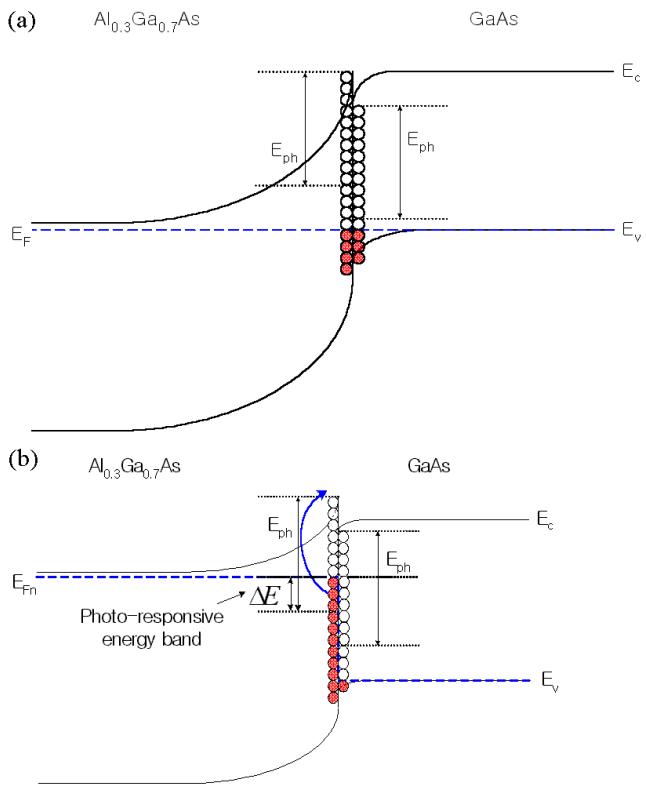

Fig. 2. Energy-band diagram of emitter-base heterojunction in a HBT with a sub-bandgap optical input ($\lambda = 1310$ nm; $E_{ph} = 0.94$ eV $> E_{g,GaAs}$): (a) under thermal equilibrium and (b) under a forward bias.

HBT devices.

II. PHOTONIC I-V CHARACTERISTICS OF AN EMITTER-BASE HETEROJUNCTION

In this section, we describe the photonic current-voltage characteristics of HBTs. Variations of the I-V characteristics of the emitter-base heterojunctions in HBTs are believed to show a large quantity of information on the traps and the interface states under a sub-bandgap photonic excitation. These I-V characteristics strongly depend on the energy band structure caused by the applied bias. In this experiment, we used an optical source with $E_{ph} = 1.45$ eV ($\lambda = 850$ nm), which is larger than the bandgap energy of the GaAs base layer. The band diagrams under thermal equilibrium and forward-bias conditions are illustrated in Figs. 1(a) and (b), respectively.

The photo-generated electrons from the valence band in the base layer [band-to-band generation] contribute to the base leakage current. The photo-generated electrons from the interface traps and the bulk traps at the emitter-base layer [trap-to-band generation] also contribute the base leakage current. Under increasing applied voltage with photonic excitation, the response of the interface traps in the emitter-base heterojunction increases. However, the absolute response is dominated by the excess carriers excited from the band-to-band generation rather than by the interface traps [10,11]. Therefore, the use of an optical source with $\lambda = 850$ nm is not required to analyze the interface traps.

In this section, we use a sub-bandgap optical source with $E_{ph} = 0.95$ eV ($\lambda = 1310$ nm), which is smaller than the bandgap energies of the GaAs base layer and the wide bandgap AlGaAs emitter layer. The energy band diagrams under thermal equilibrium and forward-bias conditions are illustrated in Figs. 2(a) and (b), respectively. Photo-generated excess electrons from band-to-band generation in the AlGaAs layer or the GaAs layer do not exist in this sub-bandgap photonic excitation. Under forward bias condition with sub-bandgap photonic excitation, both bulk traps in the space-charge region and interface traps in the emitter-base heterojunction respond. However, the absolute response is dominated by the excited excess carriers from the interface traps [12].

III. EXPERIMENTAL RESULTS

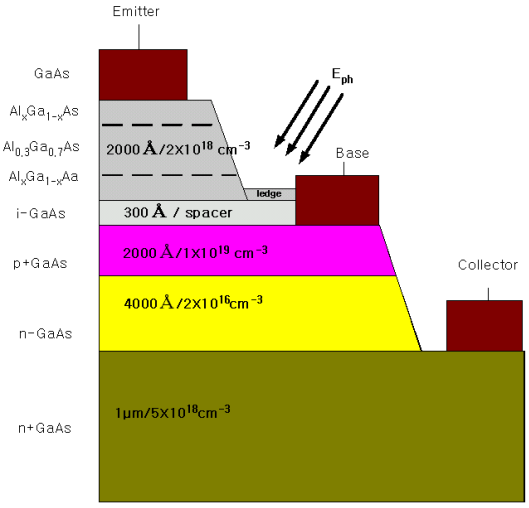

Fig. 3. Cross section of the HBT device structure.

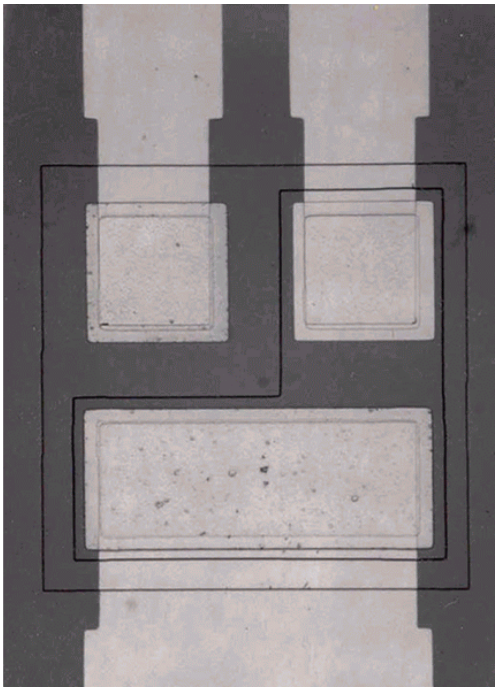

Fig. 4. Photograph of the device pattern and the HBT used in this experiment.

In this section, we describe the device used, the measurement setup, and the experimental observations. A schematic cross-sectional structure of the AlGaAs/GaAs HBT under characterization is shown in Fig. 3. As Fig. 4 below also shows, we applied the proposed PBCA method to HBTs with an emitter area $A_E = W_E \times L_E = 250 \times 100\ \mu\text{m}^2$ and pad sizes $= 100 \times 100\ \mu\text{m}^2$ and $100 \times 250\ \mu\text{m}^2$. The optical characteristics of the emitter-base in the HBT with $W_E \times L_E = 250 \times 100\ \mu\text{m}^2$ were measured with a 1310-nm optical source (ILX Lightwave Co Model 7200), a Cascade probe station and a HP4145B semiconductor parameter analyzer, as shown in Fig. 5.

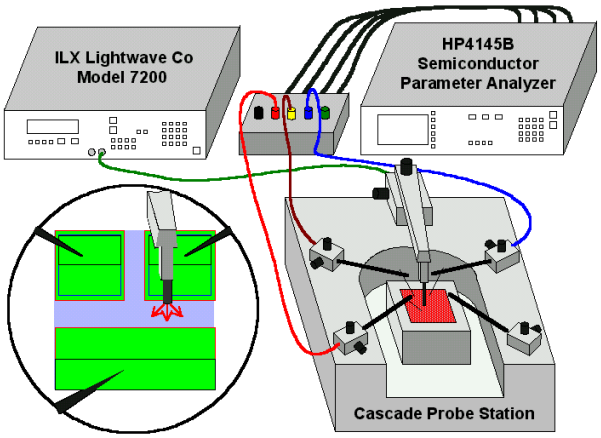

Fig. 5. Experimental setup for the PBCA method.

We investigated variations of the current-voltage characteristics of HBTs and analyzed the interface traps by comparing the dark current with the photonic diode current.

1. Hotonic Base Current Analysis with $\lambda = 850$ nm ($E_{ph} = 1.45$ eV)

We investigated the photonic response characteristics of a base-collector homojunction diode and a base-emitter heterojunction diode in HBTs by using an optical source with $\lambda = 850$ nm (1.45 eV). A laser source with various optical powers ($P_{opt} = 0.2$ mW, 0.6 mW, and 1 mW) was used for the optical excitation of electrons at the interface states in HBTs on-wafer.

Under reverse bias with photonic illumination, the photo-generated electrons from the valence band of the emitter-base and the base-collector junctions [band-to-band generation] contribute to the base leakage current as shown in Fig. 6. However, the number of photo-generated electrons from the interface traps and bulk traps is very small compared with that of the photo-generated electrons from the valence band.

2. Sub-bandgap Photonic Base Current Analysis with $\lambda = 1310$ nm ($E_{ph} = 0.95$ eV)

In this section, we investigate the sub-bandgap photonic current-voltage characteristics of a base-collector junction and a base-emitter heterojunction diode in HBTs with a sub-bandgap optical source with $\lambda = 1310$ nm (0.95 eV). A laser with various optical powers ($P_{opt} = 0.2 \sim 3.0$ mW) was used for the sub-bandgap optical excitation and trap characterization in HBTs on-wafer.

The bulk traps located in the space-charge region of the emitter, base, and collector contribute to the same

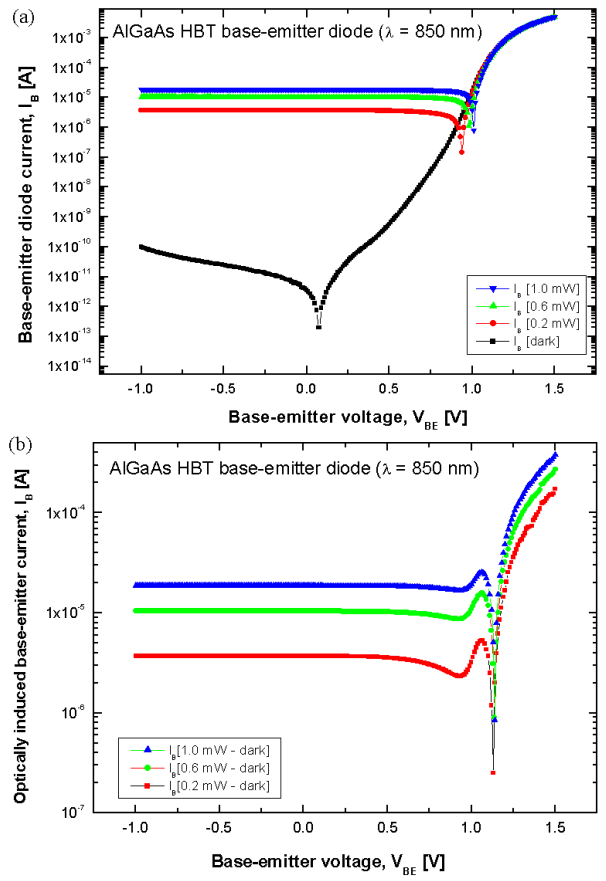

Fig. 6. I-V characteristics of the $Al_{0.3}Ga_{0.7}As/GaAs$ HBT under optical illumination (E_{ph} = 1.45 eV, P_{opt} = 0.2, 0.6, 1.0 mW) [band-to-band generation]:(a) the DC base-emitter current with photonic illumination and (b) the changes in the DC base-emitter current with photonic illumination.

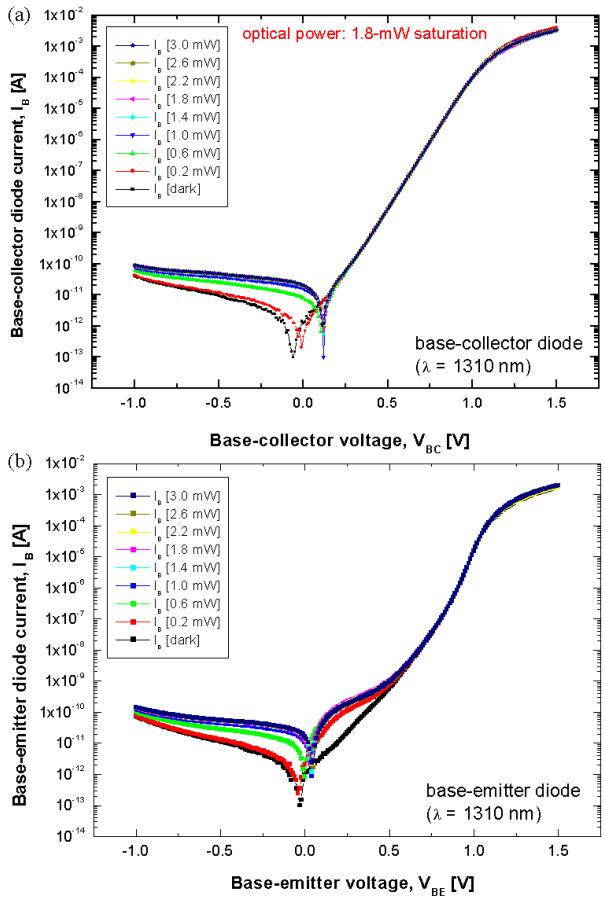

Fig. 7. I-V characteristics of the $Al_{0.3}Ga_{0.7}As/GaAs$ HBT with and without sub-bandgap photonic illumination (E_{ph} = 0.94 eV, P_{opt} = 0.2 ∼ 3 mW) [trap-to-band generation]: (a) the DC base-collector current under photonic illumination and (b) the DC base-emitter current under photonic illumination.

extent to the photonic response of HBTs. On the other hand, the interface traps located at the emitter-base heterointerface may make a major contribution to the change in the photonic current-voltage characteristics in HBTs. Under a forward bias condition with sub-bandgap photonic excitation, bulk traps in the depletion region at the base-collector layer respond to the photonic energy as shown in Fig. 7(a), and both bulk traps and interface traps in the depletion region at the emitter-base heterojunction respond to the optical energy as shown in Fig. 7(b). However, the overall response under sub-bandgap photonic excitation is controlled by the excess carriers generated from the interface traps rather than by those generated from the bulk traps.

The increased forward bias moves the Fermi energy level closer to the conduction band; thus, the number of photo-generated electrons increases. Therefore, the photonic base current under sub-bandgap photonic excitation increases with increasing base-emitter voltage across the heterojunction, as shown in Fig. 8(b). In region I of Fig. 8 with reverse bias under photonic illumination, the photo-generated electrons from the emitter-base and the base-collector are closely associated with bulk traps and cause an increase in the base leakage current. In region II, a considerable difference between the emitter-base and the base-collector currents is observed. This is due to the photo-generated electrons throughout the interface traps in the emitter-base heterojunction rather than to those throughout the interface traps in the base-collector homojunction. In this case, the Shockley-Read-Hall (SRH) recombination rate R_{SRH} is increased because of the excess carriers under sub-bandgap photonic illumination. The total recombination rate due to all three recombination mechanisms is given by [13,14]

$$R_{total} = R_{rad} + R_{SRH} + R_{Auger}, \quad (1)$$

$$R_{rad} = B(np - n_i^2), \quad (2)$$

$$R_{SRH} = \frac{np - n_i^2}{\tau_{po}(n + n') + \tau_{no}(p + p')}, \quad (3)$$

$$R_{Auger} = C(n + p)(np - n_i^2), \quad (4)$$

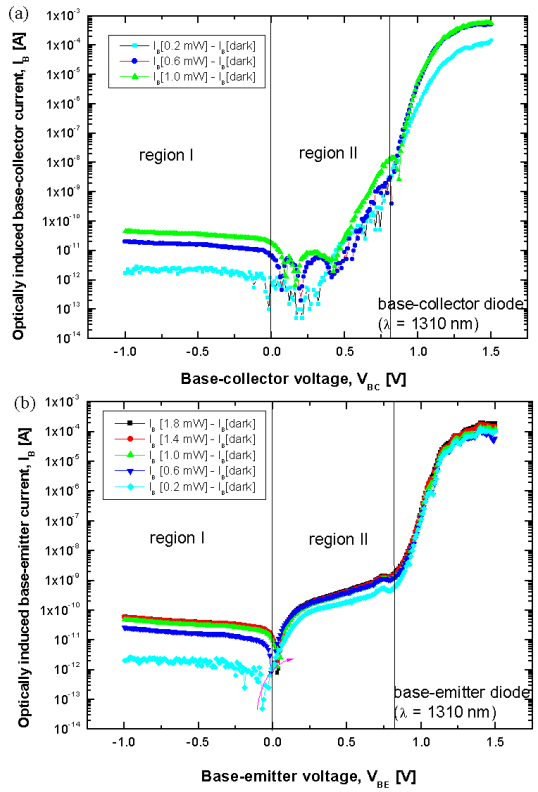

Fig. 8. Optically induced I-V characteristics of the $Al_{0.3}Ga_{0.7}As/GaAs$ HBT ($E_{ph} = 0.94$ eV, $P_{opt} = 0.2 \sim 1.8$ mW) [trap-to-band generation]: (a) base-collector junction and (b) base-emitter junction.

where B is the radiative recombination coefficient, n_i is the intrinsic carrier concentration, $n(p)$ is the electron (hole) concentration, $n'(p')$ is the electron (hole) density in the traps, τ_{no} (τ_{po}) is the electron (hole) lifetime, and C is the Auger recombination coefficient.

When the sub-bandgap optical energy is illuminated, $R_{total,dark}$ is changed into $R_{total,dark} + \Delta R_{total}$ because of trap-to-band generated excess carriers. The number of excess carriers is proportional to the interface trap density. The optically induced total recombination rate (ΔR_{total}) can be expressed as

$$\Delta R_{total} = R_{total,optical} - R_{total,dark}, \tag{5}$$

where $R_{total,optical}$ is the total recombination rate under sub-bandgap photonic illumination, $R_{total,dark}$ is the total recombination rate under dark condition. Also, the optically induced base recombination current, $\Delta I_{B,rec}$, is given by

$$\Delta I_{B,rec} = qA_E \int_{-x_n}^{x_p} \Delta R_{total} dx, \tag{6}$$

where x_p and x_n are the depletion widths of the p-type base and the n-type emitter, respectively. The measured $\Delta I_{B,rec}$ is plotted in region II of Fig. 8(b).

IV. CONCLUSION

A new base current analysis technique, the so-called the sub-bandgap photonic base current analysis (PBCA) method, has been presented for the analysis of interface traps at emitter-base heterojunctions in HBTs. By comparatively probing the base currents with and without sub-bandgap photonic excitation, we analyzed the interface traps based on the experimental data. The validity of the technique has been qualitatively demonstrated by the base-emitter and base-collector leakage currents measured with and without sub-bandgap photonic excitation.

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