Sub-Bandgap Photonic Base Current Method for Extracting the Trap Density at Hetero-Interfaces in Heterojunction Bipolar Transistors

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Abstract

In this paper, we propose a novel photonic base current analysis method to extract the energy-dependent distribution of interface states in heterojunction bipolar transistors (HBTs) using the photonic current-voltage characteristics under sub-bandgap (E_{ph}<E_g) photonic excitation. For the sub-bandgap photonic I-V characterization of HBTs, an optical source with a photon energy less than the bandgaps of $Al_{0.3}Ga_{0.7}As$ and GaAs (E_{ph}=0.95eV< $E_{g,AlGaAs}$=1.79eV & $E_{g,GaAs}$=1.42eV) is employed for the characterization of interface states distributed over the photo-responsive energy band (E_C-0.95≤E_{it}≤E_C) at the emitter-base hetorojunction in HBTs by comparing the base currents under dark and under sub-bandgap photonic excitation. The proposed method is new and simple for accurate extraction of energy-dependent interface trap density in bipolar junction devices including HBTs.

I. Introduction

Heterojunction bipolar transistors (HBT's) have attracted considerable attentions for digital and microwave power applications due to their high speed and high current handling capabilities. In addition, as the development of mixed analog-digital signal processing circuits and the low voltage operation, the circuit designers require the accurate HBT model parameters for circuit simulations. Reliability and performance degradation are also key concerns in implementation of high performance HBTs and their integrated circuits as MMICs and MIMICs. It is well known that the interface traps at AlGaAs/GaAs in HBT structures plays an important role in determining the 1/f noise, carrier mobility (μ), ideality factor (η), the current gain (β), and base leakage current with degradation of device reliability [1-4]. Therefore, the accurate modeling and characterization of interface traps throughout the bandgap, especially in bipolar junction devices, is one of the most important topics for improving the robustness of devices and integrated circuits with HBTs. There have been enormous efforts on the accurate characterization of interface traps for improved DC and microwave performance, noise characteristics, and the reliability of HBTs [5-6].

Contrary to the conventional photonic characterization with a photon energy larger than the bandgap energy, the photon energy smaller than the bandgap energy is used in this work to analyze the interface trap density at heterojunction in HBTs.

II. Modeling of J_{RI} and Experimental Result

Measured electrical collector current (I_C) versus the collector-emitter voltage (V_{CE}) characteristics of $Al_{0.3}Ga_{0.7}As$/GaAs HBTs under dark condition is shown in Fig. 1. Energy band diagrams under thermal equilibrium and forward bias conditions are illustrated in Figs. 2 and 3, respectively. Under forward bias with the sub-bandgap photonic excitation, both bulk traps in the space-charge region and interface traps in the emitter-base heterojunction interface respond. However, the absolute response is dominated by the excited excess carriers from the interface traps in the AlGaAs/GaAs heterojunction under sub-bandgap photonic excitation with E_{ph}<E_g. This mechanism is similar to the sub-bandgap photonic C-V technology developed for MOSFETs [7].

Sub-bandgap photonic current-voltage characteristization is applied to the emitter-base heterojunction in HBTs with the emitter area A_E=W_E×L_E=250×100μm^2 and pad=100×100 & 100×250 μm^2. Optical characteristics of emitter-base in HBT were measured with λ=1310nm optical source (ILX Lightwave Co. Model 7200), Optical Probe (Cascade), and Agilent 4156C semiconductor parameter analyzer. We investigated the variation of the current-voltage characteristics of HBTs and analyzed the interface traps comparing emitter-base currents under dark current with under photonic excitation. Sub-bandgap optical source with λ =1310nm (0.95eV) and with various optical power (P_{opt}=0.2~3.0mW) was used for trap characterization in HBTs on-wafer. However, the amount of traps reacting to sub-bandgap photonic excitation saturates over P_{opt}>1.8mW as shown in Fig. 4. Assuming traps responding to the sub-bandgap photons are completely excited, we extracted D_{it} [eV^{-1}cm^{-2}] from AlGaAs/GaAs emitter-base heterojunction interface.

The carrier recombination mechanism at the heterojunction interface can be modeled by [8]

$$J_{RI} = q\int_{N_{it}} U_{l\max} dx = \frac{1}{2} q\sigma v_{th} N_{it} n_{iE} \exp\left(\frac{V_{BE}}{2V_{th}}\right) \qquad (1)$$

$$D_{it} = \frac{\partial N_{it}}{\partial E} \qquad (2)$$

where U_{lmax} is the SRH recombination rate through the interface states, σ is the capture cross section, v_{th} is the thermal velocity, N_{it} is the number of interface-trap, n_{iE} is the intrinsic concentration at emitter, and V_{th} is the thermal voltage.

The extracted trap density at $Al_{0.3}Ga_{0.7}As$/GaAs emitter-base heterointerface is shown in Fig. 5. D_{it}~10^{12}~10^{13} $eV^{-1}cm^{-2}$ has been obtained over the photoresponsive energy band for AlGaAs/GaAs HBT's under the sub-bandgap photonic excitation.

III. Summary

A new base current analysis technique, so called the sub-bandgap photonic base current method with a sub-bandgap photonic excitation $E_{ph}<E_g$, has been presented for the analysis of interface trap density at emitter-base heterojunction in HBTs for the first time. By comparatively probing of the base currents with and without sub-bandgap photonic excitation, the interface trap density could be extracted from the experimental data. The validity of this technique has been qualitatively explained by the measured data from the base-emitter leakage currents with and without sub-bandgap photonic excitation.

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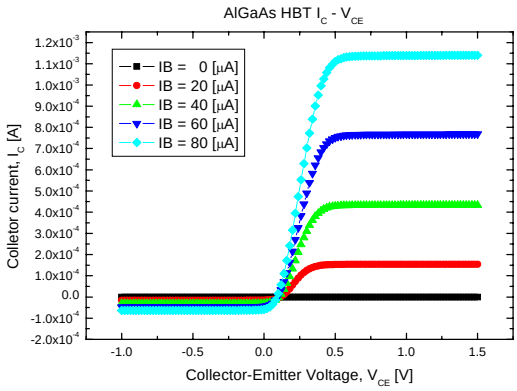

Fig. 1. Measured electrical I_C-V_{CE} characteristics of $Al_{0.3}Ga_{0.7}As$/GaAs HBTs under dark condition.

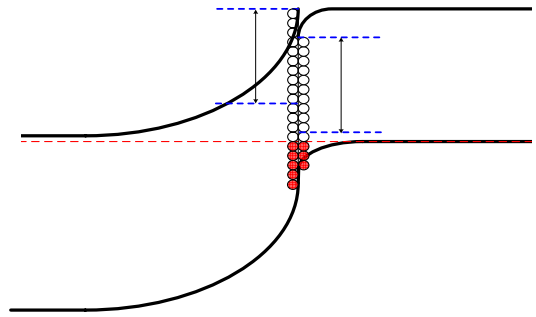

Fig. 2. Traps at E-B heterointerface under thermal equilibrium.

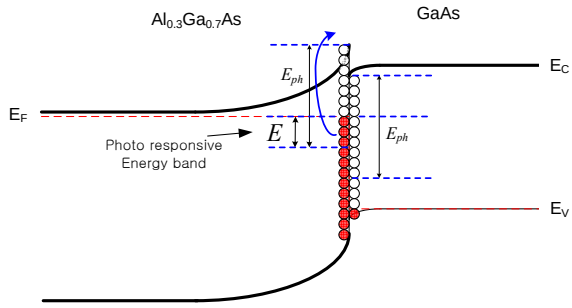

Fig. 3. Traps at E-B heterointerface under forward bias condition.

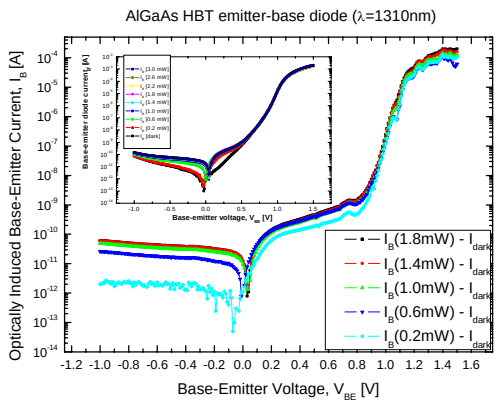

Fig. 4. Base-emitter junction current in AlGaAs/GaAs HBTs is saturated over P_{opt}>1.8mW with sub-bandgap photonic excitation.

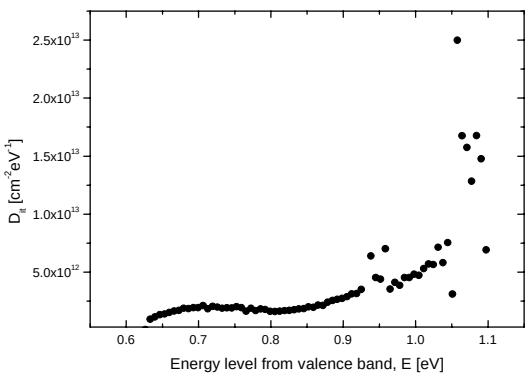

Fig. 5. Extracted D_{it} from AlGaAs/GaAs E-B hetero-interface.