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Surface Photovoltage Spectroscopy and Contactless Electroreflectance Characterization of a GaInP/GaAs Heterojunction Bipolar Transistor Structure

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Abstract. Using surface photovoltage spectroscopy (SPS) and contactless electroreflectance (CER) {including [110] and $[1\bar{1}0]$ polarizations} we have characterized the emitter (CER), collector (CER), and base (SPS) of a GaInP/GaAs (001) heterojunction bipolar transistor, fabricated by metalorganic chemical vapor deposition. CER yields information about the emitter (including ordering) and collector, but produces no signal from the heavily *p*-doped base. However, SPS has been used to evaluate the minority carrier transport properties and related common-emitter gain factor (β) in this section. The SPS spectrum is a function of both the absorption coefficient and minority carrier transport properties in the relevant portions of the sample. The SPS data indicates $190<\beta<290$.

1. Introduction

The GaInP/GaAs heterojunction system is considered as an extremely attractive alternative to the widely used GaAlAs/GaAs couple for several micro- or optoelectronic devices [1] including heterojunction bipolar transistors (HBTs). The use of GaInP as an emitter material rather that GaAlAs, offer several benefits. Among those are its much lower chemical reactivity to oxygen, negligible concentration of deep levels (e.g., the DX centers in GaAlAs). For *npn* HBT devices, the band gap alignment is more favorable with a much lower conduction band offset, so that a composition grating is not necessary at the emitter-base interface. The most interesting is in fabrication: each of the GaInP and GaAs layer can be etched selectively with respect to each other with natural etch stops at the heterointerfaces.

We present a surface photovoltage spectroscopy (SPS) and contactless electroreflectance (CER) [2] investigation of a GaInP/GaAs (001) HBT structure, fabricated by metalorganic chemical vapor deposition, including the dependence of the CER signal on the polarization { [110] and $[1\bar{1}0]$ } of the incident radiation. From the observed Franz-Keldysh oscillations (FKOs) we have evaluated the electric fields at both the collector/base and emitter/base junctions and the corresponding doping levels in the collector and emitter. Under certain conditions GaInP has a strong tendency towards atomic ordering which leads to a band gap reduction (ΔE_{BGR}), valence band splitting (ΔE_{VBS}) and

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related polarization effects [3]. For the [110] and [110] polarizations the signals are primarily for the heavy- and light-hole transitions, respectively. There is good agreement between the ordering parameter ($\eta \approx 0.27$) deduced from both the polarization dependence of the GaInP emitter signals (ΔE_{VBS}) and ΔE_{BGR}.

While CER [4-6] (or the related method of photoreflectance [7]) yields information about the collector and emitter (including ordering), in general these electromodulation methods produce no spectrum from the heavily *p*-doped base. However, SPS does contain a signal from the base (and collector) which can be used to evaluate the minority carrier transport properties in this section and the related common-emitter gain factor (β) [8]. In SPS the contact potential difference between the sample and a reference electrode is measured as a function of photon energy in a capacitive manner. The SPS spectra are dependent on both the absorption coefficient and minority carrier transport properties in the relevant portions of the sample.

2. Experimental Details

The GaInP/GaAs sample was fabricated on semi-insulating GaAs (001) substrate by MOCVD on an EMCORE E400 system. The basic unit of the HBT consisted of the following nominal characteristics: 7000Å of n^--GaAs collector ($\approx 3 \times 10^{16}$ cm^{-3}), 1000Å p^+-GaAs base ($\approx 4 \times 10^{19}$ cm^{-3}), and 400Å n-GaInP emitter ($\approx 3 \times 10^{17}$ cm^{-3}). The CER and SPS measurements were performed on the same experimental arrangement. In CER an *ac* modulating voltage (~ 1 kV) is applied between a front wire grid electrode and a back metal electrode, separated by a distance just slightly greater than the sample thickness. The sample is held in contact with the the latter by means of a vacuum chuck. SPS uses the same grid/back plate configuration except that (a) the incident radiation is chopped and (b) there is no applied high voltage between the grid/back plate but rather the SPS voltage is introduced directly into the lock-in amplifier. Current gain amplification factor $\beta \approx 100$ has been measured on a device with emitter area of 70×70 μm^2 at collector current density of 2 kA/cm^2.

3. Experimental Results

The solid lines in Figs. 1(a) and 1(b) are the 300K CER spectra of the GaInP/GaAs HBT sample for light polarized along [110] and $[1\bar{1}0]$, respectively. The signals starting about 1.4 eV and 1.8 eV are from GaAs collector and GaInP emitter, respectively. Both data exhibit well-defined FKOs with a large number of oscillations, indicating the high quality of the material. From the extrema of the FKOs associated with the GaAs signal we obtained a collector/base field of F^{coll} = 77±5 kV/cm using conduction and heavy-hole masses (in units of the free electron mass) of 0.067 and 0.34, respectively [9]. The GaInP FKOs were fit (dotted lines) to the sum of three electro-optic functions (containing Lorentzian broadening) [6,10], corresponding to transitions from the heavy-and light-hole bands (order induced splitting) as well as the spin-orbit split valence level ($\Delta_0 = 0.1$ eV) [6]. This fit yielded band gaps of 1.878±0.002 eV and 1.888±0.002 eV for the [110] and [110] polarizations, respectively, as indicated by the arrows. We obtained an emitter/base field of F^{emitt} = 230±10 kV/cm using electron, heavy-hole, light-hole, and spin-orbit split masses of 0.09, 0.63, 0.15, and 0.16 [11], in units of the free electron mass.

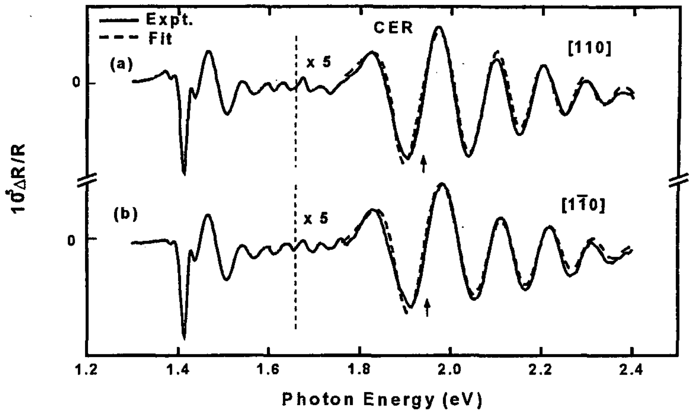

Fig. 1 CER spectra (solid lines) at 300K for light polarized along (a) [110] and (b) $[1\bar{1}0]$. The dashed lines are fits to an electro-optic function yielding the band gaps indicated by the arrows.

The solid line in Fig. 2 is the 300 K SPS spectrum of the same sample. The data exhibit peaks at about 1.39 eV and 1.42 eV, similar to Ref. [8]. The former, related to the base minority carrier properties, is due to the band gap narrowing in the highly *p*-doped portion while the latter is from the collector. In order to understand the SPS signal a numerical simulation of the self-consistent Poisson's-continuity equation (SCPCE) for the electrons and holes [12] has been performed. Using the intended growth parameters of the device and relevant minority carrier transport properties (lifetime, mobility) a simulated spectrum very similar to the experimental result has been obtained and is presented in Fig. 2 by the dashed line. This result will be discussed in more detail below.

4. Discussion of Results

To evaluate the doping densities in the collector and emitter regions, we have performed a numerical SCPCE calculation, including the photovoltaic effect, of the electric fields at the collector/base and emitter/base interfaces [2,4,5] employing minority carrier lifetimes in the collector, emitter, and base of 10^{-9} sec. The doping densities corresponding to the measured build-in interface fields are $2.8\text{x}10^{16}$ cm^{-3} (collector) and $3.0\text{x}10^{17}$ cm^{-3} (emitter). Both results are in good agreement with the nominal intended collector and emitter doping levels. We found that the calculated fields are relatively insensitive to the relevant minority carrier lifetimes in the range 10^{-7} - 10^{-9} sec.

The difference in the band gaps (ΔE_{VBS}) observed in the CER spectra for the two polarizations

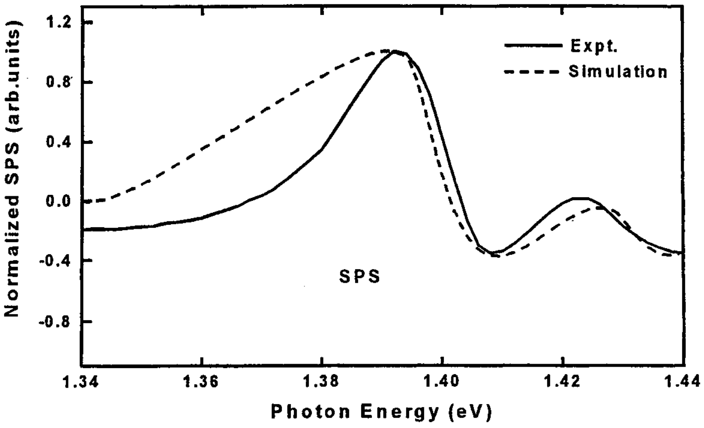

Fig. 2 Normalized experimental (solid line) and simulated (dashed line) SPS spectra from the base and collector of the HBT structure.

(Fig. 1) is due to the ordering in the GaInP material. The "average" degree of ordering η can be estimated from either ΔE_{VBS} or ΔE_{BGR} [3]. From Fig. 1 ΔE_{VBS} = 10±4 meV and ΔE_{BGR} = (1.915-1.878±0.002) = 37±2 meV. Comparison of the former quantity with Table I of Ref. [3] yields η = 0.26±0.05. For the latter:

$$\eta^2 = \frac{\Delta E_{BGR}}{0.471(eV)} \tag{1}$$

producing η = 0.28±05. This agreement for the two determinations of η indicates that the emitter is lattice-matched to GaAs.

From the large number of FKOs observed in both the collector and emitter regions of the CER spectra we can estimate a "coherence" length (L_c) of the electron-hole pair from [13]:

$$L_c = (E_{last\ FKO} - E_g)/qF \tag{2}$$

where $E_{last\,FKO}$ is the energy of the last observable FKO, E_g is the band gap, and F is the electric field measured in the corresponding region of the device. For the GaAs collector E_g =1.422 eV and from Fig. 1 $E_{last\,FKO} \geq 1.766$ eV yielding L_c (collector) ≥ 450Å. In the emitter region $E_{last\ FKO} \geq 2.4$ eV and E_g(GaInP) = 1.878 eV and thus $L_c \geq 190$ Å for the GaInP, which is about half the width of the emitter.

The dashed line in Fig. 2 represents the best fit to the experimental SPS spectrum obtained from the SCPCE calculation. The value of the minority carrier lifetime in the *n*-collector $\tau_{h,C} = 1.2 \times 10^{-8}$ s and the value of the product of minority carrier lifetime and mobility $\tau_{e,B} \times \mu = (4.6 \pm 0.9) \times 10^{-7}$ cm^2/V in the *p*-base have been extracted from the simulation. Note that the collector minority carrier lifetime value is in the range used to obtain the field in this region. The obtained $\tau_{e,B} \times \mu$ product is in reasonable agreement with experimental numbers of $\tau_{e,B} = (2 \pm 1) \times 10^{-10}$ s [14] and $\mu = (1000 \pm 200)$ cm^2/Vs [15]. The β of our HBT was calculated according to $\beta = 2\,kT\mu\tau_{e,B}/eW^2$, where W is the width of the base. Thus we find $190 < \beta < 290$. The difference in the β's evaluated from the SPS data/simulation and the electrical measurements may be due to base-collector interface roughness that degrades transport properties of the minority carriers. This phenomenon was not included in the simulation. However, the SPS technique can be successfully used for the monitoring of relative changes of the β values.

5. Summary

In summary, we have characterized a GaInP/GaAs HBT structure fabricated by MOCVD using SPS and CER, including the dependance of the CER signals on polarization to obtain the degree of ordering in the emitter. From the observed FKOs we have evaluated F^{coll} and F^{emitt}. The related doping levels were determined based on a SCPCE calculation (including the photovoltaic effect). There is good agreement between the calculated and nominal doping values for both emitter and collector regions. In addition, we estimated electron/hole coherence lengths in these portions. The ordering parameter η was deduced from both ΔE_{VBS} and ΔE_{BGR}. The correspondence of η between these determinations is an indication that the emitter is lattice matched to the GaAs. The properties of the base have been evaluated by means of SPS. A comparison of the SPS lineshape with a SCPCE calculation has enabled us to estimate $190 < \beta < 290$. This value is higher than experimentally determined number, an effect that may be due to interface roughness. The large number of FKOs from both the collector and emitter are an indication of the high quality of the GaAs and GaInP materials. This experiment demonstrates that the combination of CER (or photoreflectance) and SPS can be used to nondestructively evaluate important parameters of the collector, emitter, and base of GaInP/GaAs HBTs.

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