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(Citation)
Journal of Applied Physics,94(10):6487-6490

(Issue Date)
2003-11

(Resource Type)
journal article

(Version)
Version of Record

(URL)
https://hdl.handle.net/20.500.14094/90000284

Fourier transformed photoreflectance characterization of interface electric fields in GaAs/GaInP heterojunction bipolar transistor wafers

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(Received 29 May 2003; accepted 9 September 2003)

We performed Fourier transformed photoreflectance (PR) spectroscopy on GaAs/$Ga_{0.5}In_{0.5}P$ heterojunction bipolar transistor wafers. The use of Fourier transformation of the PR spectrum resolves the signals coming from the emitter–base and base–collector interfaces. The evaluated interface electric fields were compared with the capacitance obtained from capacitance–voltage measurements. The result for the base–collector interface is consistent with the Poisson equation. On the other hand, the atomic ordering in the $Ga_{0.5}In_{0.5}P$ emitter plays an important role in determining the characteristics of the emitter–base interface. [DOI: 10.1063/1.1623327]

I. INTRODUCTION

The heterojunction bipolar transistor (HBT) is one of the promising devices to realize both high-power and high-speed operation and high-density integration. Since the device performance depends sensitively on interface electronic structures, precise and selective characterization of each layer and each interface in the heterostructure is prerequisite in designing the HBT. In particular, a contactless method is suitable for an in-line characterization to monitor wafer quality in a mass-production process. Recently, photoreflectance (PR) has attracted much attention as a characterization technique for the interface electric field in HBTs.[1,2] PR is a contactless and nondestructive technique for modulation spectroscopy.[3] As is well known, modulation spectroscopy is an extremely sensitive technique for investigating the electronic band structure, and has actually succeeded in determining the detailed band structures for various compound and alloy semiconductors. PR is suitable for characterization of thin films and microstructures such as HBT wafers, in which chopped pump light modulates the surface electric field and achieves electromodulation. However, a PR spectrum of the HBT consists of signals coming from the emitter–base and base–collector interfaces and gives rise to a complicated structure in the Franz–Keldysh oscillations (FKOs). Accordingly, a conventional PR line-shape analysis (see Sec. III) may not be able to be applicable in a straight forward way. To overcome this problem, we performed a line-shape analysis using Fourier transformation (FT) of the PR spectrum. The FT-PR spectroscopy succeeds in resolving the signals coming from the emitter–base and base–collector interfaces in GaAs/$Ga_{0.5}In_{0.5}P$ HBT wafers. The relationship between the evaluated electric field and the capacitance obtained from the $C-V$ measurement agrees well with the calculations by using the Poisson equation. Furthermore, the atomic ordering effects in $Ga_{0.5}In_{0.5}P$ on the emitter electric field are discussed.

II. EXPERIMENTS AND CALCULATIONS

n^+-GaAs/n-$Ga_{0.5}In_{0.5}P$/p^+-GaAs/n-GaAs HBT structures were grown by metalorganic vapor-phase epitaxy (MOVPE). A typical sample structure is summarized in Table I. In this experiment, the donor concentrations of the GaAs emitter and collector were varied. PR measurements on the samples were carried out at room temperature. A GaInP/AlGaInP laser diode ($\lambda = 635$ nm) was used as an excitation light source. The modulation frequency was 500 Hz. The probe light source in the PR measurements was a tungsten–halogen lamp. The light passed through a monochromator and irradiated the sample surface in near-normal reflection alignment with a reflection angle of less than 10°. The reflected light was detected by a silicon photodiode.

Theoretical calculations were performed on the samples by using the Poisson equation. In order to compare the measured data with the calculated electric field, we calculated a weighted average of the electric field distributed in the depletion layer, in which the FKO signal intensity is a function of the electric field.[5]

III. FAST FOURIER TRANSFORM (FFT) ANALYSIS OF FRANZ–KELDYSH OSCILLATION (FKO)

To evaluate the internal electric field, a PR spectrum can be analyzed by utilizing the well-known FKO analysis method.[4–6] The oscillating behavior of the FKO is described by the electro-optic function, whose asymptotic form can be written as

$$\Delta R/R \propto \cos\left\{\frac{2}{3}\left(\frac{E-E_g}{\hbar\theta}\right)^{3/2}+\frac{\pi}{2}\right\}. \tag{1}$$

Here, $\hbar\theta=(e^2F^2\hbar^2/8\mu)^{1/3}$, where E is the photon energy, E_g is the band-gap energy, F is the internal electric field, and

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TABLE I. Typical HBT structure.

		carrier concentration (cm^{-3})	thickness (nm)
Emitter	n^+-GaAs	4.0×10^{18}	100
	n-GaInP	3.0×10^{17}	50
Base	p^+-GaAs	4.0×10^{19}	110
Collector	n-GaAs	1.5×10^{16}	700

μ is the interband reduced mass. From Eq. (1), the energy position of the jth peak, E_j, in the FKO is given by

$$E_j=\hbar\theta\left\{\frac{3\pi(j-1/2)}{2}\right\}^{2/3}+E_g. \tag{2}$$

According to Eq. (2), the plot E_j vs $[3\pi\{(j-1/2)/2\}]^{2/3}$ shows a linear relationship and its slope yields the internal electric field, F. This method enables us to evaluate a precise value of the internal electric field, when the analysis is performed for a single critical point.[4] On the other hand, the HBT structure including the multiple heterointerfaces causes the FKO's with different periods. The above-mentioned conventional PR line-shape analysis, therefore, is not appropriate to evaluate the internal electric field. To overcome this problem, we performed a line-shape analysis using FT of the PR spectrum. According to Eq. (1), the oscillation frequency $f(\mathrm{eV}^{-3/2})$ of the FKO is given by

$$f=\frac{2(2\mu)^{1/2}}{3\pi e\hbar F}. \tag{3}$$

The relation between f and F indicates that the signals coming from the different interfaces with various electric fields can be resolved in the FT spectrum.[7] Therefore, the FT-PR spectroscopy can be applied to resolve a complicated spectrum consisting of the FKOs coming from the emitter–base and base–collector interfaces of the GaAs/$Ga_{0.5}In_{0.5}P$ HBT wafer.

IV. RESULTS AND DISCUSSION

A typical PR spectrum is shown in Fig. 1. Signals from GaAs and $Ga_{0.5}In_{0.5}P$ can be observed separately. The oscillatory feature, the so-called FKO, indicates a high built-in electric field, which shows a sinusoidal oscillation depending on the electric field. In contrast to the clear FKO from the $Ga_{0.5}In_{0.5}P$ emitter, the signal from GaAs is complicated, because it contains signals from both the emitter–base interface and the base–collector interface. To resolve the FKO's coming from the different interfaces, we performed FT of the PR spectrum. A typical FT spectrum of the GaAs PR signal is shown in Fig. 2. It can be seen that the signals from the emitter–base and base–collector interfaces are clearly resolved.

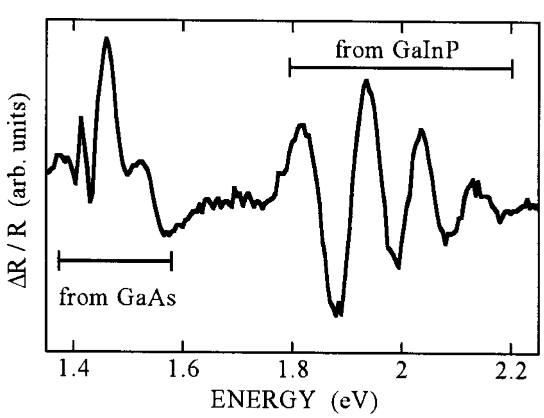

FIG. 1. Typical PR spectrum of the HBT.

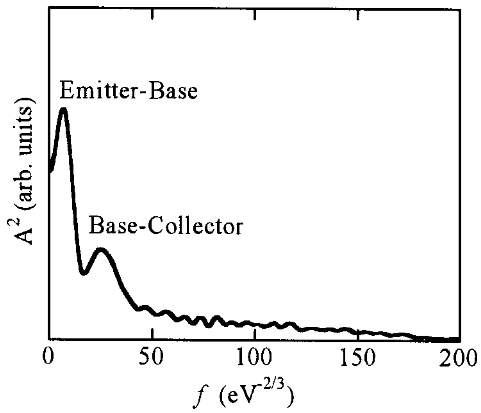

FIG. 2. FT spectrum for GaAs PR of Fig. 1.

A. Base–collector interface

In Fig. 3, the base–collector electric fields (solid circles) evaluated for various samples with different collector doping concentrations are compared with the capacitance values obtained from the $C-V$ measurements. The solid line indicates the theoretically calculated result by using the Poisson equation. In this calculation, the donor concentration of the GaAs collector was varied, and the acceptor concentration of the GaAs base was kept constant at 4.0×10^{19} cm^{-3}. As can be seen from Fig. 3, the calculated result plotted by a solid line agrees well with the experimental results. Furthermore, the measured data are consistent with the calculated data for the donor concentrations in the range from 7.0×10^{15} to 2.0×10^{16} cm^{-3}. This suggests that the base–collector interface

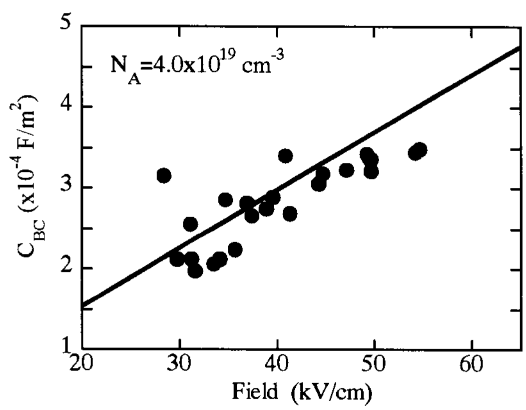

FIG. 3. Capacitance (base–collector) values obtained from the $C-V$ measurement vs the evaluated electric fields at the base–collector interface. Solid line indicates the theoretically calculated results.

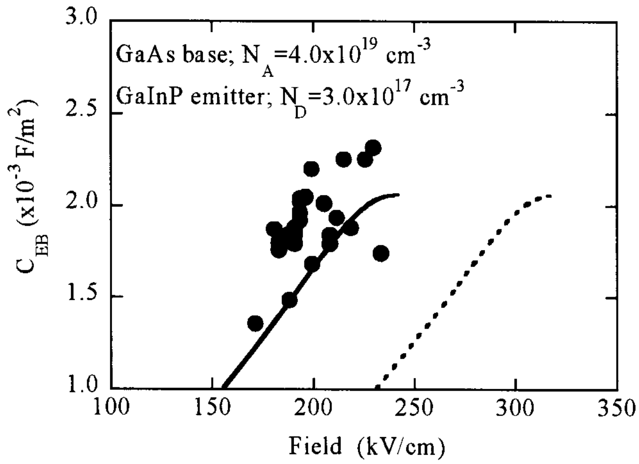

FIG. 4. Capacitance (emitter–base) values obtained from the $C-V$ measurement vs the evaluated electric fields in the GaInP emitter. Solid and dashed lines indicate the theoretically calculated results with and without atomic ordering effects, respectively.

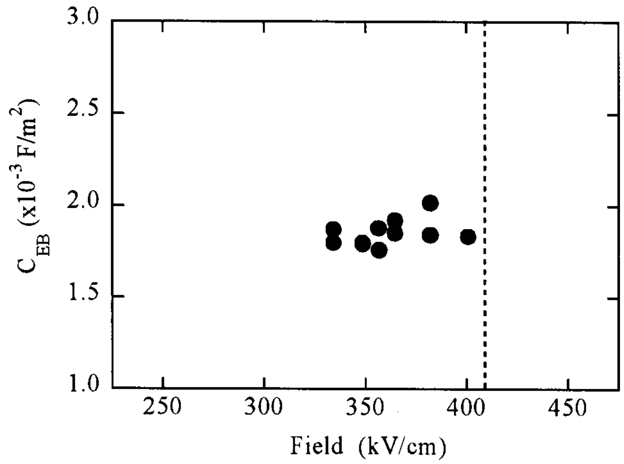

FIG. 5. Capacitance (emitter–base) values obtained from the $C-V$ measurement vs the evaluated electric fields in the GaAs base.

is explained by the single homojunction model and the capacitance can be estimated from the FT-PR technique.

B. GaInP emitter and emitter–base interface

Figure 4 shows results of the $Ga_{0.5}In_{0.5}P$ emitter. It is observed that the measured data show scattering in the electric field. The dashed line indicates the theoretically calculated result. Here, the donor concentration of the GaAs emitter was varied, and the acceptor concentration of the GaAs base and the donor concentration of the GaInP emitter were kept at 4.0×10^{19} and 3.0×10^{17} cm^{-3}, respectively. It is observed that the calculated result, as indicated by the dashed line, is not consistent with the measured data. To explain the disagreement, we take into account a long-range atomic ordering in $Ga_{0.5}In_{0.5}P$. The long-range ordering of the column III sublattices is observed in $Ga_{0.5}In_{0.5}P$ epitaxial films grown on GaAs(001) by MOVPE.[8] The ordered alloy consists of two ordered phases showing the CuPt-like ordering along the [-111] and [1-11]. This corresponds to monolayer superlattices along the ordering directions. As a result, macroscopic polarization, i.e., internal electric field, is then generated by the microscopic polarization. Since the ordering induced electric field is parallel to the ordering vector, the sum of the ordering-induced electric fields is oriented to the [001] direction, i.e., the growth direction. Thus, the internal electric field reduces the electric field in the GaInP emitter. The solid line in Fig. 4 shows the calculated result upon the ordering-induced electric field of ~80 kV/cm. The calculated result agrees with the measured data. The measured data are consistent with the calculated data for the donor concentrations of the order of 10^{18} cm^{-3}. The estimated internal electric field corresponds to the order parameter of ~0.3, according to a relationship $F=-900\eta^2$ kV/cm, given by Froyen *et al.*[9] The order parameter can also be estimated by using the band-gap energy. The reduction of the band-gap ΔE is given by $-430\eta^2$ meV.[10] In this work, we performed a self-consistent FKO analysis between Eqs. (2) and (3) for the GaInP-PR signal in Fig. 1 to determine the band-gap energy. The estimated typical band-gap energy is 1.821 eV, which gives η ~0.4. This value is consistent with the parameter given by the electric field. The data scattering in the electric field indicate a slight variation in the order parameter. Thus, the selective characterization of the $Ga_{0.5}In_{0.5}P$ emitter reveals the ordering effects that play an important role to build up the electric field distributed at the emitter–base interface. Once we take into account the order parameter of $Ga_{0.5}In_{0.5}P$, the relationship between the capacitance and $Ga_{0.5}In_{0.5}P$ electric field can be explained by the theoretical relation. In other words, the electric field estimated by the self-consistent fast Fourier transform (FFT) analysis of the $Ga_{0.5}In_{0.5}P$-FKO signal enables us to evaluate the capacitance at the emitter–base interface.

The low-frequency FT-PR signal of the GaAs PR, as shown in Fig. 2, can be attributed to the emitter–base interface or the GaAs(emitter)/GaInP(emitter) interface. The electric field estimated from the low-frequency FT-PR signal is much larger than the theoretically calculated electric field (250 kV/cm) for the GaAs(emitter)/GaInP(emitter) interface and is close to the calculated field for the emitter–base interface. Therefore, we ascribed the low-frequency FT-PR signal to the emitter–base interface. As shown in Fig. 5, the evaluated electric field values of GaAs at the emitter–base (EB) interface are scattered near 350 kV/cm, however, the change in C_{EB} is small. The calculated maximum electric field at the GaInP(emitter)/GaAs(base) heterointerface is to be 410 kV/cm as indicated by the dotted line in Fig. 5. It is observed that the measured data are scattered below the dotted line. This result indicates a slight change in the thin depletion layer thickness of the GaAs base. Although the reason of the scattered data is not clear yet, we infer that the charge (electron) accumulation[11–14] can reduce the field. The scattering in the observed data might be due to variation in the amount of the charge caused by the slight variation in the order parameter. In the case of the charge accumulation, holes are trapped at the opposite side, i.e., the GaAs(emitter)/GaInP(emitter) interface. The charge trapping will also reduce the electric field at this interface.

V. SUMMARY

We have performed a contactless characterization for $GaAs/Ga_{0.5}In_{0.5}P$ HBT wafers using PR spectroscopy. The use of FT of the PR spectrum has enabled us to discriminate the signals coming from the emitter–base and base–collector interfaces. The evaluated interface electric fields were compared with the capacitance values obtained from the $C-V$ measurements. The relation between the electric field and the capacitance for the base–collector interface agrees well with the calculated results obtained from the Poisson equation. The relation for the $Ga_{0.5}In_{0.5}P$ emitter can be explained by considering atomic ordering effects in $Ga_{0.5}In_{0.5}P$. On the other hand, the capacitance of the emitter–base interface is almost independent of the electric field, which indicates a slight change in the thin depletion layer thickness in the GaAs base. These results have demonstrated that the FT-PR is a powerful, contactless technique for the selective characterization of the interface electric fields in HBT wafers.

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