STUDY OF ELECTRICAL PROPERTIES OF ISOTYPE GaAs(In,Ga)P/GaAs HETEROINTERFACES GROWN BY MOVPE BY CAPACITANCE-VOLTAGE AND DLTFS TECHNIQUES.

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Abstract: Capacitance-voltage measurements and deep level transient Fourier spectroscopy are used to examine the depth resolved electrical characteristics of Si-doped GaAs/(In,Ga)P/GaAs heterojunctions grown by metal-organic-vapor-phase epitaxy. The depth profiles of the carrier concentration are compared with calculations based on self-consistent solutions of the Poisson equation. It is shown that the depth profiles of GaAs/(In,Ga)P interfaces depend strongly on the growth conditions. For interfaces with disordered (In,Ga)P, the conduction band offset is determined to be 0.20 eV. The estimated carrier deficits at the various heterointerfaces are within the range $10^{12} - 10^{11}$ cm$^{-2}$. The apparent loss of carriers at the typical interface is related to the interfacial levels.

Keywords: DLTFS, electrical characteristics, InGaP/GaAs heterojunction, MOVPE.

INTRODUCTION

Aluminum free (In, Ga)P/GaAs heterojunctions are considered to be an attractive alternative to the (Al, Ga)As/GaAs material system for electronic devices. As an example the electronic devices such as heterojunction bipolar transistors (HBTs), high-electron-mobility transistors (HEMTs), light-emitting and laser diodes (LEDs and LDs) and solar cells are being frequently realized by using lattice-matched (In, Ga)P/GaAs layers. The electronic properties of the (In, Ga)P/GaAs interfaces are therefore of vital importance for potential applications of the aforesaid devices. Despite a larger number of investigations, the electrical characteristics of (In,Ga)P/GaAs heterointerfaces are still controversially discussed. The values for the conduction band offset $\Delta E_c$ obtained from the various measurement techniques range from 0.03 to 0.25 eV [Lee \textit{et al}. 1992, Feng \textit{et al}. 1993, Kim \textit{et al}. 1996, O’Shea \textit{et al}. 1996, Cai \textit{et al}. 1999]. For the valence band offset $\Delta E_v$, values between 0.24 and 0.40 eV have been reported in literature [Rao \textit{et al}. 1987, Biswas \textit{et al}. 1990, Chen \textit{et al}. 1991]. Although it is known that (In, Ga)P exhibits a tendency to decompose and order, yet it is not clear, how this affects the electronic properties of lattice-matched (In, Ga)P/GaAs heterointerfaces grown by metal-organic-vapor-phase epitaxy (MOVPE).

Keeping in view the fact that the interfacial levels have drastic effects on the characteristics of the devices [Zhang \textit{et al}. 1987, Krispin \textit{et al}. 1998],
our investigations therefore, focus on Si-doped GaAs/(In, Ga)P/GaAs isotype heterointerfaces grown by MOVPE under different conditions. The electrical properties of the heterojunctions are examined by the capacitance-voltage (C-V) method [Blood and Orton 1992] and deep level transient Fourier spectroscopy (DLTFS) [Weiss and Kassing 1988]. The conduction band offset $\Delta E_c$ has been determined by one-dimensional simulation technique based on self-consistent solution of the Poisson equation [Tan et al. 1990]. It is shown that the free electron distribution at n-type GaAs(In, Ga)P interfaces strongly depends on the growth conditions. Secondly, the carrier deficit observed at the interface by C-V method is actually related to the interfacial and/or deep levels as seen by DLTFS measurements.

MATERIALS AND METHODS

The investigated GaAs(In, Ga)P/GaAs heterojunctions were grown by MOVPE under different conditions. The details of the growth conditions can be seen in our earlier communication [Krispin et al. 2000]. Briefly, the random (In,Ga)P alloys were grown at 580°C on (001)-oriented GaAs. Double- and single-variant ordered (In, Ga)P layers were realized at a growth temperature of 650°C on single and vicinal (001) substrates with a miscut of 2° towards (111)B, respectively. V/III input ratios of 70 or 140 and growth rates of 2.5 $\mu$m h$^{-1}$ were used. The lattice mismatch of the layers in all cases, was smaller than $5 \times 10^{-4}$. The interface regions were realized by growth interruptions of about 5s. For electrical measurements, vacuum-deposited Ti/Au dots sizing $4.11 \times 10^{-4}$ cm$^2$ and $1.58 \times 10^{-3}$ cm$^2$, were formed as metal-semiconductor (MS) contacts and the ohmic contacts of Au-Ge alloy were provided on the backside of the substrate. The depth profile of the apparent free carrier concentration $N_{C-V}$ was measured using the conventional method [Blood and Orton 1992]. The concentration $N_{C-V}$ was obtained from the expression:

$$N_{C-V}(W)=2 / A^2 q \varepsilon \varepsilon_o \left[\frac{d}{dV} \left[\frac{1}{C^2}\right]\right]$$

Where $W$ denotes the thickness of the space-charge layer below the MS contact, $A$ the contact area, $q$ the elementary charge, and $\varepsilon \varepsilon_o$ the dielectric constant. The depth $W$ was calculated from the capacitance $C$ using $W(V) = \varepsilon \varepsilon_o A/C(V)$. Deep levels were investigated by the DLTFS technique [Weiss and Kassing 1988], where the time transients of the capacitance $C$ are digitized and the discrete Fourier coefficients are calculated at each temperature. The interface-state density $N_{SS}$ was calculated by incorporating the DLTFS peak height $\Delta C/C$ in the expression given by Tan et al. [1990]:

$$N_{SS}(E)=\left[\tau N_{C-V} \varepsilon \varepsilon_o / (T_w C k T)\right] \Delta C / C$$
where $E$ represents the activation energy of the interface state, $\tau$ the time constant $T_W$ the pulse width, $k$ the Boltzmann constant ($8.862 \times 10^{-5} \text{ eVK}^{-1}$), and $T$ the temperature position of the DLTFS peak associated with the interface state.

Capacitance-voltage (C-V) measurements were performed using HP4275 LCR meter at 1 MHz. The DLTFS measurements were carried out by PC-controlled DL8000 BioRad system.

**RESULTS AND DISCUSSION**

For various Si-doped Ga-As-on-(In,Ga)P interfaces, the associated depth profiles of the apparent electron concentration $N_{C-V}$ are shown in Fig. 1. It is observed that the characteristics strongly depend on the growth temperature, the V/III ratio, and the substrate orientation. Accumulation of the carrier in the low band-gap material GaAs and depletion valley in the InGaP layer are only achieved for samples grown on the singular (001) surface. For such samples, the conduction band offset $\Delta E_C$ is found to be
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0.20 eV. From the curves 1, 2, 3 and 4 in Fig. 1, we calculate carrier deficits at the interface of about $1 \times 10^{12}$ cm$^{-2}$, $2.5 \times 10^{11}$ cm$^{-2}$, $8 \times 10^{11}$ cm$^{-2}$ and less than $1 \times 10^{11}$ cm$^{-2}$ respectively. The electron deficit can be minimized by growth at 580$°$C and higher V/III ratio (curve 4 in Fig. 1). In contrast, there is no accumulation of the carriers and a drastically enhanced carrier deficit at the interface with single-variant ordered (In,Ga)P (curve 1 in Fig. 1). For this interface, it is therefore not possible to determine the conduction band offset $\Delta E_C$. The position of the heterointerface is estimated at about 160 nm from the Schottky contact and the doping level of GaAs-on-InGaP layer as calculated from each end of the profile curve is nearly $1.1 \times 10^{17}$ cm$^{-3}$ [Blood and Orton 1992]. The lower electron concentration for GaAs in curve 1 is due to the lower doping efficiency during GaAs growth on the misoriented substrate.

In order to verify, whether the carrier deficit at the GaAs-on-(InGa)P interface originates from the deep interfacial levels, we performed DLTFS measurements close to the interface. Fig. 2 shows a series of deep-level spectra for the typical Si-doped GaAs/InGaP/GaAs isotype heterointerface under different bias conditions. The figure exhibits a sequence of distinct DLTFS peaks labeled $E_1$-$E_6$, due to the electron emission from the traps. The peak heights of the levels $E_1$-$E_5$ are decreasing with the increasing depth until all the peaks disappear at reverse bias -3V, which practically exposes the InGaP layer. This clearly indicates that the electron levels $E_1$-$E_5$ originate from GaAs side. The activation energies associated with these levels are $E_C$ - 0.20, $E_C$ - 0.27, $E_C$ - 0.4, $E_C$ - 0.5 and $E_C$ - 0.73 eV respectively. Peak $E_5$ is related to the well-known bulk level EL2 in MOVPE grown GaAs [Krispin et al. 2000] and $E_6$ appearing at higher reverse bias is typically observed in (In,Ga)P layers and is linked with the residual impurities in the MOVPE precursors [Hashizume et al. 1984]. However, we cannot compare the signatures of the peaks $E_1$-$E_4$ with the reported levels in the literature. It is, therefore, likely that these peaks may originate from the interfacial levels, which are responsible for the carrier deficit at the interface. Consequently, we estimated the total surface density $N_{SS}$ by summing up the calculated values for each of the levels $E_1$-$E_4$, given by $1 \times 10^{10}$ cm$^{-2}$, $3.5 \times 10^{10}$ cm$^{-2}$, $1.4 \times 10^{10}$ cm$^{-2}$ and $3.5 \times 10^{10}$ cm$^{-2}$. In this way we found that the total density ($1.2 \times 10^{11}$ cm$^{-2}$) of these so-called interfacial levels happens to be nearly one half of the estimated carrier deficit at the GaAs/InGaP interface (i.e. $2.50 \times 10^{11}$ cm$^{-2}$) by C-V method. Accordingly, we are of the opinion that the large carrier deficit observed at the investigated interface could also be related to the interfacial levels in the lower half of the bandgap and/or to intrinsic electric field at the interface. Further work is therefore required to determine the origin of the large and growth-dependent carrier deficit at the Si-doped GaAs-on-InGaP interface.
CONCLUSIONS

The electrical properties of Si-doped GaAs/(In,Ga)P/GaAs isotype heterointerfaces grown by MOVPE under different conditions have been carried out by using C-V and DLTFS measurement techniques. The salient features of our investigations are as what follows:

a) The characteristics strongly depend on the growth temperature, the V/III ratio, and the substrate orientation.
b) Observation of an accumulation of the carrier in the low bandgap material GaAs and depletion valley in InGaP layer clearly indicates the existence of well-defined heterointerface.

c) The conduction band discontinuity $\Delta E_C$ for the investigated layers is typically found to be 0.20 eV, which confirms the offset values reported in the literature [Biswas et al. 1990].

d) The carrier deficits at the various interfaces are estimated as $1 \times 10^{12}$ cm$^{-2}$, $2.5 \times 10^{11}$ cm$^{-2}$, $8 \times 10^{11}$ cm$^{-2}$ and less than $1 \times 10^{11}$ cm$^{-2}$ respectively.

e) The DLTS study shows six electron levels at energy positions $E_C$ - 0.20 eV, $E_C$ - 0.27 eV, $E_C$ - 0.40 eV, $E_C$ - 0.50 eV, $E_C$ - 0.73 eV and $E_C$ - 0.34 eV respectively. Levels $E_1$-$E_5$ originate from GaAs side and the broad peak $E_6$ comes from the disordered InGaP layer.

f) Peak $E_5$ is related to the well-known EL2 level frequently observed in MOVPE grown GaAs material while a deep level having signatures similar to those of $E_6$ level has also been typically observed in (In,Ga)P layers and is linked with the residual impurities in the MOVPE precursors.

g) Levels $E_1$-$E_4$ are carefully attributed to the interfacial levels so as to justify the apparent carrier deficit found in the C-V measurements. But the total interfacial carrier density due to these levels happens to be half of the estimated carrier deficit.

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References