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# Admittance spectroscopy of InAlAs/InGaAs single-quantum-well structure with high concentration of electron traps in InAlAs layers

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Results are presented of admittance spectroscopy measurements on the lattice-matched $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ single-quantum-well structures. It has been found that the perpendicular conductivity of the structure is controlled by the strong temperature dependence of the space-charge region width around the quantum-well layer. This process is governed by a high density of deep electron traps present in the layers adjacent to the quantum well. Therefore, the energy activation of perpendicular conductivity is determined by the deep-level defects rather than the thermionic emission of electrons from the quantum well. Because of this, it is impossible to extract the magnitude of the band offset between the quantum well and barrier layers from the admittance measurements performed in this study. © *1995 American Institute of Physics.*

## I. INTRODUCTION

Nowadays, semiconductor heterojunctions are widely used to design a rich variety of devices for microelectronics. The most important physical parameters of heterojunctions are the conduction- and valence-band offsets, which determine the electronic properties of such structures. Various electrical techniques have been developed to measure band offsets in semiconductor heterostructures, such as capacitance-voltage ($C$-$V$) or current-voltage ($I$-$V$) characteristics[1-3] and deep-level transient spectroscopy (DLTS) measurements.[4] In the last few years, admittance spectroscopy has been extensively used to obtain information about band offsets of quantum-well (QW) and multiquantum-well (MQW) heterostructures.[5-11] Originally, this method was proposed by Losee[12] for investigations of deep-level defects in the space-charge region (SCR) of $p$-$n$ junction or Schottky barrier. The admittance spectroscopy experiment consists of measuring the ac capacitance and conductance as a function of temperature. The ac perpendicular conductivity of the structure is controlled by deep-level defects. If the thermal emission rate of trapped carriers is equal to the angular measurement frequency, the step of capacitance and the peak of conductance will be observed.[12] Recently this technique has been applied by Lang *et al.*[5] for determination of band offset in semiconductor MQW. It is believed that the band offset is related to the activation energy of the perpendicular conductivity of MQW and single QW structures determined by a thermionic emission of electrons over the barrier between the quantum well and wide-band-gap layers;[5-11] however, we present here results of an investigation of single QW structure showing that a conductance peak (capacitance step) may be caused by the thermal activation of electrons trapped on deep-level defects present in the layers adjacent to the quantum well.

## II. EXPERIMENTAL DETAILS

The two types of samples used in this work were grown by molecular-beam epitaxy (MBE) on $n^+$-InP substrates. The single QW structure consists of 0.5 $\mu$m $In_{0.52}Al_{0.48}As$ buffer layer, 5 nm $In_{0.53}Ga_{0.47}As$ QW layer, and 0.35 $\mu$m $In_{0.52}Al_{0.48}As$ cap layer. The second structure involves only a 0.5 $\mu$m $In_{0.52}Al_{0.48}As$ buffer layer on $n^+$-InP substrate. The free-carrier concentration $N_d - N_a$ in buffer and cap layers was about $5.5\times10^{16}$ cm$^{-3}$ at $T=300$ K. Schottky diodes were made by deposition of Ti and Au consecutively through a photolithography mask (500 $\mu$m diam). Finally, an ohmic contact was formed by AuGe/Ni/Au metallization and alloying in a forming gas on the back of the $n^+$-InP substrate.

The admittance measurements have been performed with a HP4194A impedance/gain phase analyzer controlled by computer. Both capacitance $C$ and conductance $G$ were recorded simultaneously. There are two types of admittance measurements. The first is carried out at fixed reverse bias versus temperature, and the second is carried out at fixed temperature versus reverse bias (the so-called $C$-$V$ measurement). The amplitude of the modulation signal was equal to 0.020 V (peak to peak) and the frequency ranged from 5 to 100 kHz. DLTS measurements were made using a SULA spectrometer, operating at 1 MHz. The sample was mounted in a cryostat, which permitted measurements from 77 to 350 K.

## III. RESULTS AND DISCUSSION

Figures 1(a) and 1(b) show the admittance spectra versus temperature measured at different reverse biases on the QW structure. The amplitudes of conductance peak and capacitance step fall to zero as the value of reverse bias $V_{rev}$ de-

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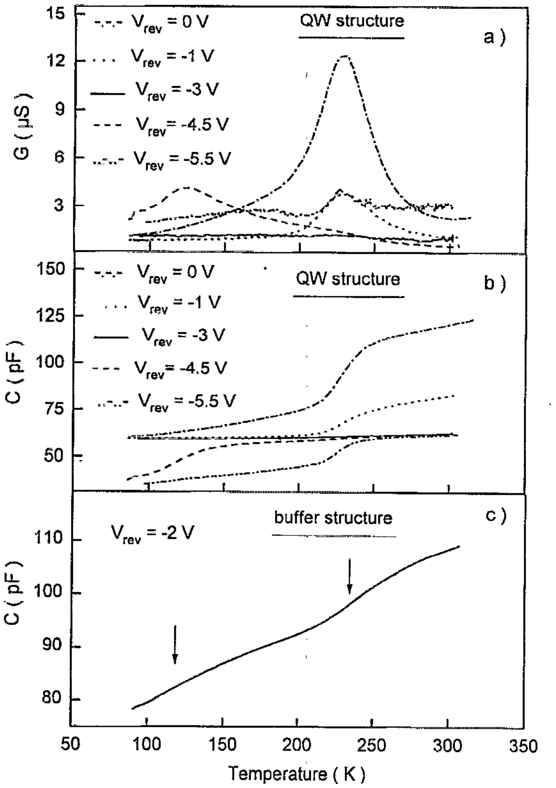

FIG. 1. Admittance spectra of (a), (b) QW structure, and (c) a buffer structure; $f=100$ kHz.

creases from 0 to $-3$ V. Further increasing of reverse bias $V_{\text{rev}}$ from $-4.5$ to $-5.5$ V results in the appearance of a new conductance peak and capacitance step, the temperature position of which is strongly dependent on the value of reverse bias. When the admittance spectra of the QW structures are compared with that of the buffer layer structure [Fig. 1(c)], it is apparent that the nonmonotonical dependence on reverse bias is due to the presence of the QW layer. It should be noted that the temperature position of the capacitance steps on the QW structure spectra coincide with that of the admittance spectra of deep-level defects spectrum measured on the buffer structure [Figs. 1(b) and 1(c)]. Therefore, the most likely explanation is that the admittance spectra of the QW structure are due to the presence of deep-level defects in the barrier layers.

In order to clear up the origin of such unusual behavior in the admittance spectra of the QW structure, $C$-$V$ and $G$-$V$ measurements have been made at different temperatures [Figs. 2(a) and 2(b)]. Figure 3 shows the apparent concentration profiles $N_{C\text{-}V}$ derived from experimental $C$-$V$ data using the following well-known relations:

$$N_{C\text{-}V}(w)=\frac{2}{q\epsilon A^2(dC^{-2}/dV)},\quad w=\frac{\epsilon A}{C},\tag{1}$$

where $w$ is the depth, $\epsilon$ is the dielectric constant, and $A$ is the area of the Schottky barrier. The dielectric constant is assumed to be equal for both the QW and the layers adjacent to the QW.

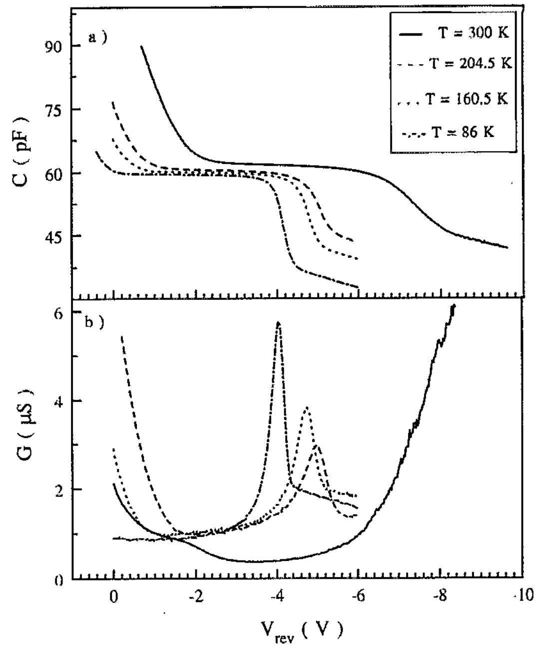

FIG. 2. (a) $C$-$V$ and (b) $G$-$V$ measurements of the QW structure at different temperatures; $f=100$ kHz.

The profiles show accumulation of electrons within, and depletion around, the QW. At room temperature the peak of the apparent profile is positioned at the geometric location of the QW (about 0.36 $\mu$m). The change of capacitance versus voltage due to the sweep out of electrons from QW looks like a step [Fig. 2(a)]. From the theoretical treatment of $C$-$V$ characteristics of QW structures[13–15] it follows that the near-constant value of capacitance [about 60 pF in Fig. 2(a)] corresponds to the position of the edge of the Schottky barrier SCR inside of the QW and the sharp capacitance step is associated with the movement of the edge of the Schottky barrier SCR away from QW. The latter process is accompanied by the peak of conductance, the amplitude of which increases when the temperature goes down [Fig. 2(b)]. The

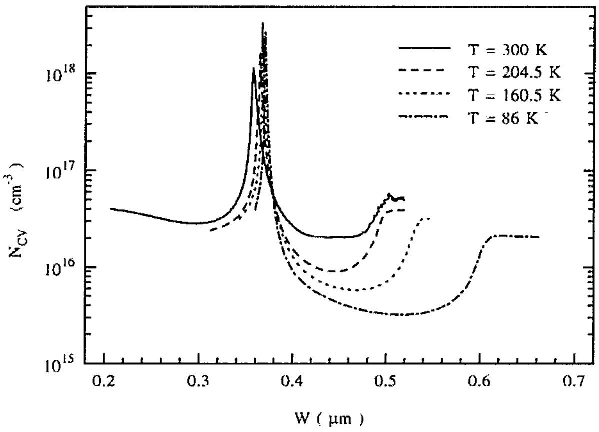

FIG. 3. Apparent electron concentration profiles of the QW structure at different temperatures.

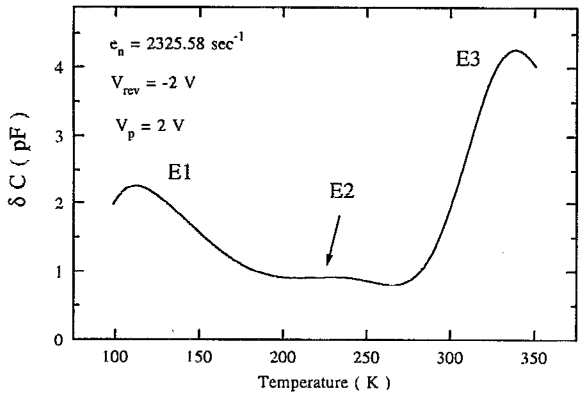

FIG. 4. DLTS spectrum of a buffer structure.

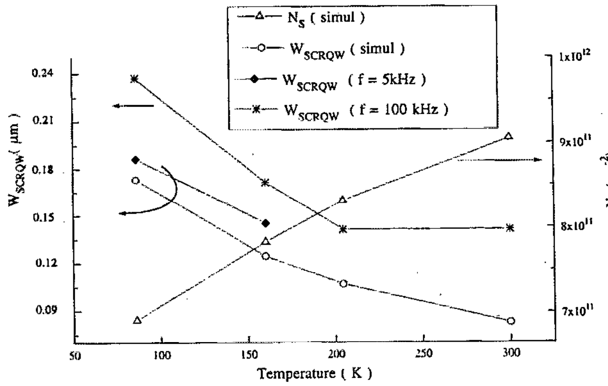

FIG. 5. Simulated the sheet concentration $N_s$ of electrons in the QW and experimental and simulated the width $W_{\text{SCRQW}}$ at different temperatures.

absence of conductance peak at temperature $T=300$ K is due to the strong increasing of the leakage current at high reverse bias.

As can be seen from temperature dependence of $C$-$V$ and $G$-$V$ characteristics in the range from $T=86$ to 300 K [Figs. 2(a) and 2(b)], the capacitance and the conductance depend only slightly on temperature provided that $V_{\text{rev}}$ ranges from $-2$ to $-3.6$ V, since the edge of the Schottky barrier SCR is located inside the quantum well. The $C$-$T$ curve measured at $V_{\text{rev}}=-3$ V is quasiconstant around 60 pF [Fig. 1(b)], which corresponds to the geometrical position of the QW, whereas, if $V_{\text{rev}}$ lies outside of the range described above, the $C$-$V$ and $G$-$V$ characteristics vary drastically with temperature. This results from the fact that the edge of Schottky barrier SCR lies outside of the QW and the width of SCR around the QW ($W_{\text{SCRQW}}$) is strongly temperature dependent (Fig. 3). This means that the peak on $G$-$T$ and the step on $C$-$T$ graphs [Figs. 1(a) and 1(b)] are associated with the movement of the edge of Schottky barrier SCR caused by the decrease of $W_{\text{SCRQW}}$ with increasing temperature.

From the temperature dependence of the apparent concentration profile (Fig. 3) we found that the net concentration of free carriers $N_d-N_a$ in buffer layers is reduced from $5.5\times10^{16}$ cm$^{-3}$ at $T=300$ K to $2.0\times10^{16}$ cm$^{-3}$ at $T=86$ K. To investigate the origin of this, DLTS measurements have been performed on the buffer layer structure. Three electron traps E1, E2, and E3 have been detected (Fig. 4). The deep-level parameters are presented in Table I. All these defects are typical of AlInAs grown by MBE.[16,17] Their concentrations were estimated using the following relation, which takes into account the λ effect:[18]

$$N_T=2(N_d-N_a)\,\frac{\delta C}{C_\infty}\,\frac{W_1^2}{(W_1-\lambda_1)^2-(W_0-\lambda_0)^2},\qquad(2)$$

TABLE I. Parameters of deep-level defects.

| | E1 | E2 | E3 |
|---|---|---|---|
| $E_T$ (eV) | 0.21 | 0.37 | 0.64 |
| $\sigma_\infty$ (cm$^2$) | $2.7\times10^{-12}$ | $4.0\times10^{-14}$ | $5.3\times10^{-13}$ |
| $N_T$ (cm$^{-3}$) | $6.6\times10^{15}$ | $1.0\times10^{15}$ | $2.6\times10^{16}$ |

where $\delta C$ is the DLTS peak height, $C_\infty$ is the steady-state capacitance under reverse bias at DLTS peak temperature, $W_0$ and $W_1$ are the widths of the SCR under low and high reverse bias, respectively, and $\lambda_0$ and $\lambda_1$ are the distances between the edge of the SCR and the point where the quasi-Fermi level crosses the trap level in the space-charge region.

The concentrations of electron traps E1 and E3 exceed the concentration of E2 trap and were found to be equal to $6.6\times10^{15}$ and $2.6\times10^{16}$ cm$^{-3}$, respectively. The sum of these concentrations coincides with the difference of free-carrier concentration in the buffer layer at high and low temperature. Hence, the electron traps E1 and E3 are responsible for the decrease of the free-carrier concentration in the buffer layers with decreasing temperature.

The influence of the free-carrier concentration in buffer layers on the magnitude of $W_{\text{SCRQW}}$, may be evaluated using the neutrality equation,

$$N_S=2(N_d-N_a)W_{\text{SCRQW}},\qquad(3)$$

where the sheet concentration $N_s$ of electrons in the QW is obtained from numerical solution of coupled Poisson's and Schrödinger's equations.[19] The simulations have been performed for different $N_d-N_a$ values from the flat part of the apparent concentration profile (Fig. 3) to take into account the presence of the deep-level defects. The experimental data and results of calculations are shown on Fig. 5. The experimental values of the width $W_{\text{SCRQW}}$ were determined as the distance between the peak and the start of flat part on the right-hand side of the apparent concentration profile (Fig. 3).

The present model correctly describes the tendency of the dependence of the width of $W_{\text{SCRQW}}$ on temperature, since the ratio between the room temperature and the 86 K width of $W_{\text{SCRQW}}$ is about two both for measurements and for calculations (Fig. 5); however, the width $W_{\text{SCRQW}}$ derived from the simulations is lower than the experimental one. In our opinion, this is due to the fact that capacitance is measured by means of superimposing a small oscillation signal $dV$ at frequency $f$ on the applied reverse bias $V_{\text{rev}}$, while calculations have been made for steady-state conditions. Considering that the deep electron traps control the sheet concentration $N_s$ of electrons in the QW through the free-carrier concentration in the buffer layers, we have to lower the measurement frequency to reach equilibrium in this system. The width $W_{\mathrm{SCRQW}}$, obtained from $C$-$V$ measurements at $f=5$ kHz, coincides more closely with our calculations. Unfortunately, it was impossible to carry out the latter measurements at $T>200$ K because of the high level of noise at this low frequency due to the leakage current.

## IV. CONCLUSION

It has been shown that a high concentration of deep electron traps present in InAlAs buffer layers is found to have significant effect on admittance spectroscopy of $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ single QW structures. The deep traps E1 and E3 with concentrations $6.6\times10^{15}$ and $2.6\times10^{16}$ $cm^{-3}$, respectively, control the sheet concentration $N_s$ of electrons in QW through the free-carrier concentration in buffer layers. This results in the fact that the thermal activation of the perpendicular conductivity of QW structure is governed by the deep-level defects rather than thermionic emission of electrons from QW. Therefore, the analysis of admittance measurements proposed earlier[5] to determine the band offset is valid no more because of the high density of deep-level defects present in the layers adjacent to the QW.

A comparison of the admittance spectra with and without a QW layer has shown that the presence of a QW layer gives rise to a number of characteristic pecularities:

(i) if the edge of the Schottky barrier SCR lies inside of QW layer, the capacitance and conductance of the structure are independent of temperature,

(ii) if the edge of the Schottky barrier SCR lies outside of the QW layer, the capacitance and conductance of the structure are controlled by the thermal activation ofelectrons trapped on the deep-level defects in the buffer layers.

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