

Frequency resolved admittance spectroscopy measurements on $\text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{In}_x\text{Ga}_{1-x}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ single quantum well structures

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In this work a new admittance spectroscopy technique is proposed to determine the conduction band offset in single quantum well structures (SQW). The proposed technique is based on the study of the capacitance derivative versus the frequency logarithm. This method is found to be less sensitive to parasitic effects, such as leakage current and series resistance, than the classical conductance analysis. Using this technique, we have determined the conduction band offset in $\text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{In}_x\text{Ga}_{1-x}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ SQW structures. Two different well compositions, $x=0.53$, which corresponds to the lattice-matched case and $x=0.60$, which corresponds to a strained case, and two well widths (5 and 25 nm) have been considered. The average results are $\Delta E_c=0.49\pm0.04$ eV for $x=0.53$ and $\Delta E_c=0.51\pm0.04$ eV for $x=0.6$, which are in good agreement with previous reported data.

INTRODUCTION

The understanding of interface phenomena in semiconductor heterojunctions is the key word for the design of new electronic devices. For instance, the band alignment (conduction and valence band offsets) is one important parameter which determines the transport and optoelectronic properties of these devices. Different experimental techniques have been used to determine band discontinuities, including capacitance-voltage technique on single heterojunctions,¹ current-voltage characteristics on semiconductor/insulator/semiconductor capacitors,² admittance spectroscopy measurements on multi-quantum well,³ photoluminescence on single quantum well (SQW),⁴ or photoemission spectroscopy.^{5,6} Among these techniques admittance spectroscopy measurements are widely used to characterize quantum well structures electrically. However, this technique is not useful when high leakage current or series resistance effects are present. In the work we propose a modification of the admittance spectroscopy technique which is less sensitive to these parasitic effects. Instead of the conductance analysis versus frequency and temperature, we propose the analysis of the capacitance derivative versus the frequency logarithm.

ADMITTANCE OF A SINGLE QUANTUM WELL STRUCTURE

Figure 1 shows the conduction band diagram of a SQW structure with a Schottky contact. The depletion region width is W , L being the location of the well from the Schottky contact and a being the width of the depletion region around the well due to the stored charge. Let us consider the case $W < L - a$, which corresponds to the well located outside the depletion region. The case $W > L - a$ has already been analyzed.⁷

The conduction band bending at the well position ψ_w is a barrier which can be passed above by thermionic emission or

passed through by tunnel. Under our measurement conditions we have neglected the tunnel mechanism. So, only the carriers with energy higher than $E_c + \psi_w$ will be able to pass above the barrier.

The electrical behavior of the structure can be modeled by the circuit in Fig. 1, where capacitance C_1 is the space charge capacitance and C_2 and g are the well capacitance and conductance, respectively.

According to this electrical model the measured capacitance and conductance over frequency of the SQW structure are given by

$$C_{id} = \frac{C_1 G^2 + \omega^2 C_1 C_2 (C_1 + C_2)}{G^2 + \omega^2 (C_1 + C_2)^2} \quad (1)$$

and

$$\frac{G_{id}}{\omega} = \frac{\omega G C_1^2}{G^2 + \omega^2 (C_1 + C_2)^2} \quad (2)$$

The analysis of these dependencies indicate that the resonant frequency of the SQW structure is given by

$$\omega_{\max} = \frac{g}{C_1 + C_2} \quad (3)$$

At this frequency the measured conductance over frequency and the capacitance derivative versus the frequency logarithm of the SQW structure show maxima, whose values are equal and given by

$$\left. \frac{dC}{d \ln \omega} \right|_{\omega_{\max}} = \omega \left. \frac{dC}{d \omega} \right|_{\omega_{\max}} = \frac{G}{\omega} \Big|_{\omega_{\max}} = \frac{C_1^2}{2(C_1 + C_2)} \quad (4)$$

By combining Eqs. (3) and (4) and taking into account that C_1 is the low frequency capacitance, we can obtain the

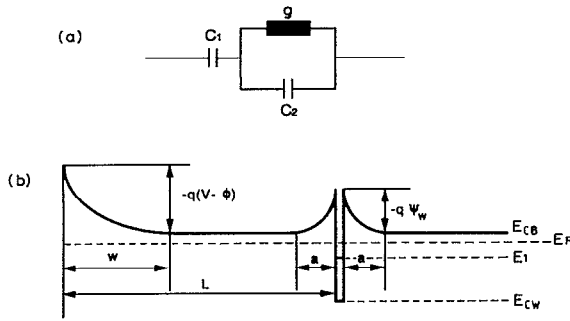


FIG. 1. (a) Equivalent circuit of SQW structure. (b) Conduction band diagram of a SQW structure with a Schottky contact. The depletion region width is W , L is the location of the well from the Schottky contact, a is the depletion layer width around the well, V is the bias voltage, ϕ is the Schottky barrier height, and $q\psi_w$ is the conduction band bending at the well.

value of the well conductance g either from the conductance over frequency curve or from the capacitance derivative versus the frequency logarithm curve.

The above discussion does not include parasitic effects, such as series resistance and leakage current, which can distort the measured values of the capacitance and conductance. In order to analyze these effects we have considered the electric model of the SQW structure shown in Fig. 2, which includes a series resistance R_s and a parallel resistance R_{off} . In this case the measured capacitance and conductance over frequency of the SQW structure are given by

$$C_m = \frac{C_{id}}{(1 + R_s G_{id})^2 + (R_s C_{id} \omega)^2}, \quad (5)$$

$$G_m = \frac{1}{R_{off}} + \frac{G_{id}(1 + R_s G_{id}) + R_s C_{id}^2 \omega^2}{(1 + R_s G_{id})^2 + (R_s C_{id} \omega)^2}. \quad (6)$$

Figure 3 shows the computed curves of the capacitance and conductance over frequency for both the ideal case and when parasitics are taken into account. In addition to the capacitance and conductance, the capacitance derivative with the frequency logarithm is also plotted. In the ideal case the curve corresponding to the capacitance derivative shows a maximum at the same position and of the same value as the conductance. However, when parasitic effects are taken into account we can see that the conductance is much more affected than the capacitance derivative. As a consequence, in order to minimize the error in determining the resonant frequency and then conductance g , it is better to use the capacitance and its derivative instead of the conductance.

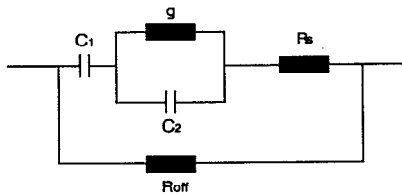


FIG. 2. Equivalent circuit of a SQW structure including parasitic effects, series resistance, R_s , and leakage current R_{off} .

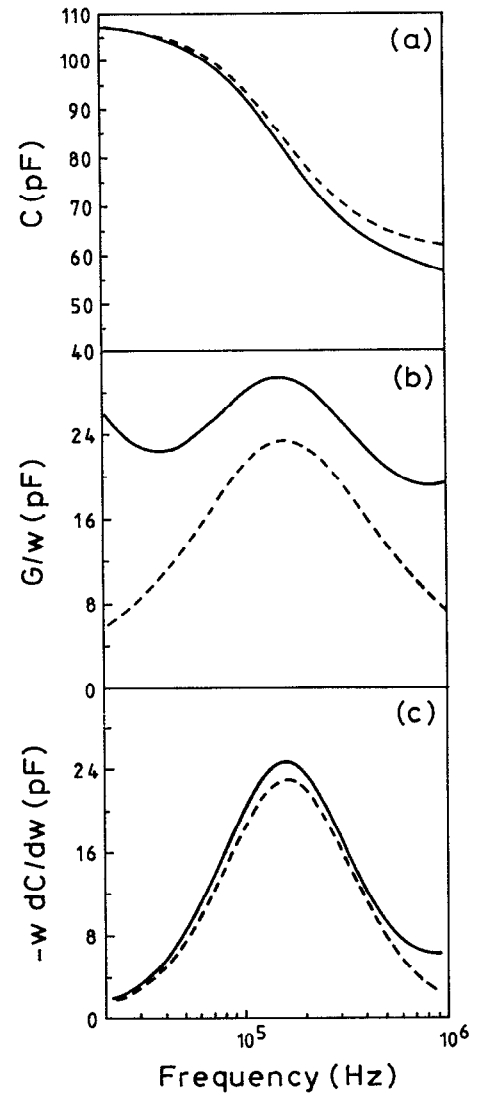


FIG. 3. Admittance computed curves of a SQW structure; solid curve with parasitic effects and dashed curve without parasitic effects: (a) capacitance, (b) conductance, and (c) capacitance derivative.

Once the g parameter is determined from the experimental curves it can be used to obtain the band bending at the well position ψ_w . Let us consider the inverse of g which is equal to the resistance related to the well. This resistance can be calculated as

$$\frac{1}{g} = \frac{1}{A} \int_{D-a}^{D+a} \rho(x) dx, \quad (7)$$

where A is the area of the Schottky contact and $\rho(x)$ is the resistivity at the x position inside the depletion region around the well, which is given by

$$\rho(x) = \frac{1}{q \mu_n n(x)}, \quad (8)$$

q being the electron charge, μ_n the electron mobility, and $n(x)$ the electron concentration at the x position, which is

related with the conduction band bending around the well, $\psi(x)$, and the doping concentration, N_D , according to

$$n(x) = N_D \exp\left(-\frac{q\psi(x)}{kT}\right). \quad (9)$$

The combination of Eqs. (7)–(9) gives

$$\frac{1}{g} = \frac{1}{q\mu AN_D} \int_{D-a}^{D+a} \exp\left(-\frac{q\psi(x)}{kT}\right) dx. \quad (10)$$

In order to obtain an approximate expression of integral (10), let us consider that the band bending at the well position ranges between $10 < -q\psi_w/kT < 20$, which implies $250 \text{ mV} < \psi_w < 500 \text{ mV}$ at room temperature. In this assumption, which must be verified later, the conductance g can be expressed as

$$g = \frac{qAN_D\mu}{2ax} \exp\left[-(1-y)\frac{q\psi_w}{kT} - z\left(\frac{q\psi_w}{kT}\right)^2\right], \quad (11)$$

where $x = 0.1806$, $y = 0.1481$, and $z = 2.58 \times 10^{-3}$. According to Eq. (11) using an Arrhenius plot of the experimental g values, we can determine the conduction band bending at the well position ψ_w without introducing a significant error over the experimental one.

In order to determine the conduction band offset the following relationship has been used (see Fig. 1):

$$\Delta E_C = (E_{CB} - E_F) + (E_F - E_1) + (E_1 - E_{CW}), \quad (12)$$

where E_{CB} is the bottom of the conduction band, E_F is the Fermi level, E_1 is the energy of the first bond state in the well, and E_{CW} is the minimum energy of the conduction band in the well. The value of $E_{CB} - E_F$ depends on the doping N_D , temperature T , and the conduction band bending at the well position ψ_w .

$$E_{CB} - E_F = q\psi_w + kT \ln\left(\frac{M_C}{N_D}\right). \quad (13)$$

The second term $E_F - E_1$ is obtained solving the following systems:

$$n_w = kT \sum_i \sigma_i [\ln(1 + e^{u_i} - u_i)], \quad (14)$$

$$\psi_w = -\frac{qN_D}{2\epsilon} a^2, \quad (15)$$

$$n_w = 2aN_D, \quad (16)$$

where $u_i = (E_i - E_{FW})/kT$, E_i is the energy of the i labeled bond state in the well, E_{FW} is the Fermi level in the well, ϵ is the dielectric constant, a is the depletion region round the well, M_c is the density of states in the conduction band minimum, q is the electron charge, and σ_i is the energy density of states of the i subband in the well, which is given by

$$\sigma_i = \frac{m_i^*}{\pi\hbar^2}, \quad (17)$$

m_i^* being the effective mass of the i subband and \hbar the Planck constant.

Equation (14) is the expression of the carriers density in the well obtained by integrating the two-dimensional density of occupied states.³ Equation (15) has been obtained solving the Poisson equation around the well and gives the relationship between the conduction band bending and a . Finally expression (16) is the neutrality charge equation.

The values of $E_1 - E_{CW}$ have been calculated in a self-consistent manner solving the Schrödinger equation in the effective mass approximation. To do this calculation the non-parabolicity of the conduction band for both barrier and well material has been taken into account according to the Kane model.^{7,8} Our calculations yield: $E_1 - E_{CW} = 0.14, 0.15 \text{ eV}$ for the thin wells and $E_1 - E_{CW} = 0.012, 0.013 \text{ eV}$ for the thick wells. For each well width, the first value corresponds to the lattice-matched case whereas the second one corresponds to the strained case. High resolution electron microscopy indicates that the error in the well width is about 0.5 nm. This well width error implies an error in $E_1 - E_{CW}$ which is about 0.02 eV for the thin wells and 0.001 eV for the thick wells.

EXPERIMENTAL RESULTS

The above method has been used to study $\text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{In}_x\text{Ga}_{1-x}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ SQW structures grown by molecular beam epitaxy over a n^+ -InP substrate. First a $1 \mu\text{m}$ $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ layer doped at $N_D = 2.5 \times 10^{16} \text{ cm}^{-3}$ was grown followed by the $\text{In}_x\text{Ga}_{1-x}\text{As}$ well layer of 5 nm width. The InAs fraction was $x = 0.53$ (matched case) or $x = 0.60$ (strained case). The SQW structure was completed with a $0.35 \mu\text{m}$ $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ layer also doped at $N_D = 2.5 \times 10^{16} \text{ cm}^{-3}$. Schottky diodes were made first by the deposition of 10 nm of Ti through a photolithography mask (500 μm diam) and then by the deposition of 40 nm Ti/100 nm Au through a small area mask (100 μm diam). This provides a Schottky contact allowing phototransmission. Finally, on the backsurface of the n^+ -InP substrate an ohmic contact was formed by an AuGe/Ni/Au metallization.

The admittance measurements have been performed with a HP4192 low frequency (from 5 Hz to 13 MHz) impedance analyzer controlled by a microcomputer. The samples were located in a low temperature microprobe attached to a programmable temperature controller which allows us to perform measurements from 77 to 400 K.

The experimental (G/ω) and $(-\omega dC/d\omega)$ curves as a function of frequency for different temperatures are plotted on Fig. 4. In both cases the parasitic effects, which should be associated with the series resistance and leakage current, are observed. However, the plot of (G/ω) is more disturbed than the plot of $(-\omega dC/d\omega)$ as expected. From the analysis of these curves the values of g as a function of the measurement temperature have been obtained. An Arrhenius plot of the data gives the values of the conduction band bending at the well position ($q\psi_w$) listed in Table I. The same values are listed in eV and, between brackets, in kT units. As we can see, the obtained conduction band bending is always in the range of 10–20 kT , as assumed by integrate expression (10).

The values of the conduction band offset obtained according to expression (12) are listed on the last column of Table I. In addition to the well width error, other error

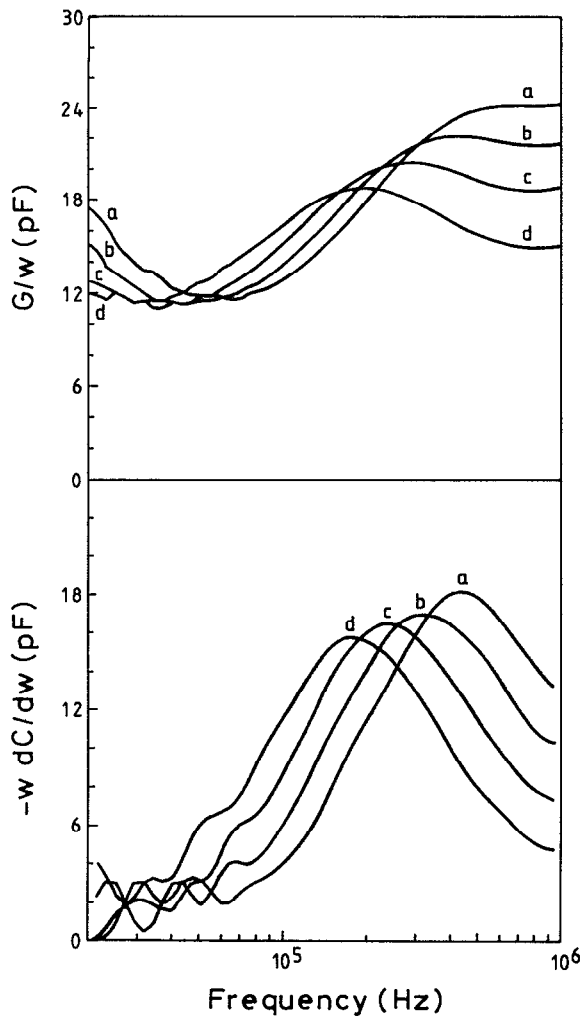


FIG. 4. Experimental G/ω and $-\omega dC/d\omega$ curves as a function of frequency for different temperatures: (a) 312 K, (b) 305 K, (c) 298 K, and (d) 291 K. The well width is 25 nm and the well composition $x=0.6$.

sources are the experimental determination of the conduction band bending from the Arrhenius plots, which contributes with about 20 meV, and the error in the doping concentration N_D and temperature effects, which contribute with about 10

TABLE I. Values of the conduction band bending $q\psi_w$ and conduction band offset ΔE_c for the different samples. The values between brackets are in kT units.

Sample	X	L_w (nm)	$q\psi_w$ (eV)	ΔE_c (eV)
795	0.53	25	0.35 ± 0.01 [14.8]	0.48 ± 0.02
800	0.60	25	0.37 ± 0.02 [15.5]	0.50 ± 0.03
801	0.53	5	0.27 ± 0.03 [14.0]	0.50 ± 0.06
797	0.60	5	0.28 ± 0.02 [13.4]	0.52 ± 0.04

meV. The average results are $\Delta E_c = 0.49 \pm 0.04$ eV for the lattice-matched case ($x=0.53$) and $\Delta E_c = 0.51 \pm 0.04$ eV for the strained case ($x=0.6$), which seems to indicate a dependence of the conduction band offset on the well composition. These results are in good agreement with our previously reported data,⁷ as well as with the data reported by other authors. For instance, in the lattice-matched case thermionic emission gave $\Delta E_c = 0.51 \pm 0.04$ eV;² $C(V)$ profiling at room temperature yielded $\Delta E_c = 0.50 \pm 0.05$ eV;⁹ photoreflectance and photoluminescence excitation in SQWs implied $\Delta E_c = 0.50 \pm 0.05$ eV;¹⁰ low temperature photoluminescence excitation in approximately parabolic wells implied $\Delta E_c = 0.51 \pm 0.02$ eV,¹¹ and x-ray photoemission spectroscopy gave $\Delta E_c = 0.48 \pm 0.03$ eV.⁵ In the strained case photoreflectance and photoluminescence excitation in SQWs yielded $\Delta E_c = 0.55 \pm 0.05$ eV¹⁰ and assuming transitivity and using the band offset data of the $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{InP}$ ¹² and $\text{In}_{0.52}\text{Ga}_{0.48}\text{As}/\text{InP}$ system¹³ gave $\Delta E_c = 0.55 \pm 0.04$ eV.

CONCLUSIONS

We have presented a new admittance spectroscopy technique to determine the conduction band offset in SQW structures. This technique is based on the analysis of the capacitance derivative versus frequency logarithm instead of the classical conductance analysis. The proposed method can be used when parasitic effects are present, such as series resistance and leakage current, and the use of the classical conductance analysis is not suitable. Using this technique we have determined the conduction band offset in $\text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{In}_x\text{Ga}_{1-x}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ SQW structures. The obtained results are in good agreement with previously reported data and seem to corroborate a dependence of the conduction band offset on the well composition.

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