AIP Journal of Applied Physics

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Citation: Journal of Applied Physics **109**, 056102 (2011); doi: 10.1063/1.3554673
View online: http://dx.doi.org/10.1063/1.3554673
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/109/5?ver=pdfcov
Published by the AIP Publishing

Inconsistent temperature dependence in capacitance-voltage profiling of quantum wells

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(Received 11 October 2010; accepted 17 January 2010; published online 10 March 2011)

Carrier profiles of quantum wells, obtained from experimental capacitance-voltage (*C-V*) measurements match the theoretically simulated carrier profile quite closely but these are much different from the actual carrier profile. It is observed that the peaks of the experimental and simulated carrier profiles move in the opposite direction and at low temperature there nature changes drastically. These observations have been explained taking into account the two dimensional carrier confinement and its temperature dependence through self-consistent solutions of the Schrödinger and Poisson equations. The effect of the series resistance seems to be highly pronounced in experimental *C-V* measurements. © *2011 American Institute of Physics*. [doi:10.1063/1.3554673]

INTRODUCTION

The nondestructive capacitance-voltage (*C-V*) technique is widely used for the determination of various parameters of bulk semiconductors and semiconductor quantum structures.[1–7] In the *C-V* profiling of a quantum well (QW) structure there are certain important observations which call for proper explanations. The typical structure used for *C-V* measurements is discussed in Ref. 8. Usually the apparent carrier profile, obtained from experimental *C-V* measurements, is matched with the apparent carrier profiles obtained from theoretical simulations. Both of these are widely different from the actual carrier profile of the QW.[4,9] At room temperature the apparent concentration peaks, obtained from both experimental observations and theoretical simulations, are much smaller than the peak of the actual carrier distribution whereas at low temperature those are very sharp and higher.[9] Moreover, in experimental measurements the apparent carrier peak shifts away from the Schottky as the temperature decreases[6,9] but in the simulated carrier profile the peak moves in the opposite direction.[5,6] These observations are not well explained.

According to the assumption of the conventional *C-V* technique there is an abrupt space charge region with a well defined depletion width.[1] For an increment of the reverse bias ΔV if the depletion width W increases ΔW, it can be written that[1]

$$\Delta V = qN(W)W\Delta W/\varepsilon \tag{1}$$

and

$$\Delta Q = AqN(W)\Delta W, \tag{2}$$

where ΔQ is the charge depleted by ΔV, $N(W)$ is the carrier concentration at W, A is the area of the Schottky, ε is the dielectric constant and q is the electron charge. The capacitance of the structure is given by

$$C = \frac{\Delta Q}{\Delta V} = \frac{A\varepsilon}{W}, \tag{3}$$

and $N(W)$ is expressed as

$$N(W) = -\frac{2}{q\varepsilon A^2 \frac{d}{dV}\left(\frac{1}{C^2}\right)}. \tag{4}$$

In the case of QWs, Eqs. (1) and (2) may lead to serious errors because neither the properties of two dimensional (2D) carriers, confined in the QW, nor the effect of temperature is included in these expressions.

In this paper, we have explained the mechanism of the ambiguous temperature dependence of the *C-V* profiles of a single QW structure through simulated results, obtained by solving the Schrödinger and Poisson equations self-consistently. It emerges from these studies that the series resistance has a significant role in the temperature dependence of the carrier profiles.

The experimental data was obtained by *C-V* measurements on an $In_{0.24}Ga_{0.76}As/GaAs$ single QW structure at different temperatures. The details of the growth condition and the structure are discussed in Ref. 7.

To determine the actual carrier distribution of the structure the one dimensional Schrödinger and Poisson equations are solved self-consistently using finite difference method.[8] Parameters, related to the structure of $In_{0.24}Ga_{0.76}As/GaAs$ QW, are listed in the Table 1. The donor ionization energy is taken as 5 meV[4] for Si doping to calculate ionized donor concentration. To construct the theoretical apparent profile the capacitance C is calculated using Eq. (3) where ΔQ is computed by the change of the electric field across the surface according to the Gauss theorem.[4]

The *C-V* characteristics and the apparent carrier profiles of the structure, obtained from experiments for three different temperatures are shown in Fig. 1. The actual carrier profiles for these three temperatures are determined by the simulation as depicted in Fig. 2. It is seen from Figs. 1 and 2,

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TABLE 1. Parameters used for the simulation on $In_{0.24}Ga_{0.76}As$/GaAs QW. (m^*, m_0, ϵ_0 and ΔE_c are the effective mass of electron, the rest mass of electron, the permittivity of free space and the conduction band offset respectively.)

Well width (nm)	ΔE_c [a] (eV)	m^*/m_0 Well[b]	m^*/m_0 Barrier[c]	ϵ/ϵ_0 Well[d]	ϵ/ϵ_0 Barrier[c]
8	0.175	0.054	0.067	13.52	13.18

[a] From Ref. 4.
[b] From Ref. 12.
[c] From Ref. 13.
[d] From Ref. 14.

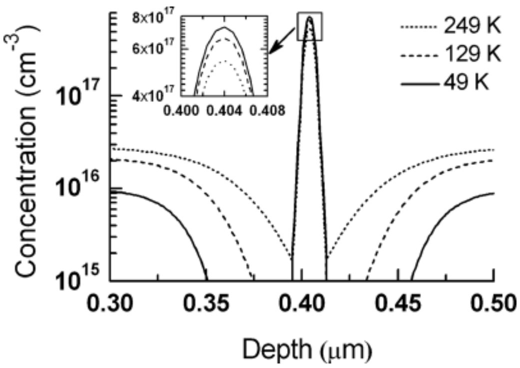

FIG. 2. Actual carrier profiles of the structure at different temperatures.

that at 249 K the apparent peak height is smaller than the actual peak. With decrease of temperature the height of the experimental peak increases at a very high rate. At 49 K it is nearly three times larger than the actual peak height. It is also observed that the full width at half maximum (FWHM) of the experimental carrier peak decreases rapidly with temperature whereas the FWHM of the actual carrier peak has negligible change with temperature. To understand the basic difference between the apparent carrier profile and the actual carrier profile, the apparent profiles are evaluated theoretically as shown in Fig. 3. At 249 K the simulated apparent profile is almost similar to that derived experimentally but at lower temperature it has an opposite shift.

In the QW structure the distribution of the two-dimensional (2D) carriers is determined by the normalized wave function. With the change in the applied reverse bias the change of this distribution is quite different from that of the bulk structure. For this reason the advancement of the depletion edge in and around the QW with increment of the reverse bias, as mentioned earlier, causes significant errors in the interpretation of the *C-V* profile. To make it more clear, the change of the 2D carrier concentration (n_{2D}) with the external reverse bias is illustrated in Fig. 4. It is seen that as the temperature decreases the slop of the n_{2D} versus V_r curves tends to become constant which corresponds to a plateau in the C versus V_r curve as well as an extremely large peak height in the carrier profile.

Figures 1 and 3 illustrate how the carrier peaks move with temperature. With the decrease of the temperature from 249 K to 49 K the position of the experimental peak shifts by 5 nm toward the substrate whereas the simulated peak moves 6 nm toward the Schottky. Since the shift of the carrier peaks at 249 K is negligible, the total shift of the peak at 49 K is about 11 nm. The reason behind the shift of the simulated peak seems to arise from the Debye smearing out between 2D and three-dimensional (3D) electrons at higher temperatures.[9] This leads to a lower value of the capacitance at the peak position as shown in Fig. 4, because of the decrease in the 2D carrier confinement which in turn produces the higher depth of the peak.

The opposite shift of the carrier peak in the experimental profile can be explained by the existence of the temperature dependent series resistance (R_s) across the structure.[5,10] At low temperature R_s increases due to low current conduction across the heterojunction,[11] the increase in the contact

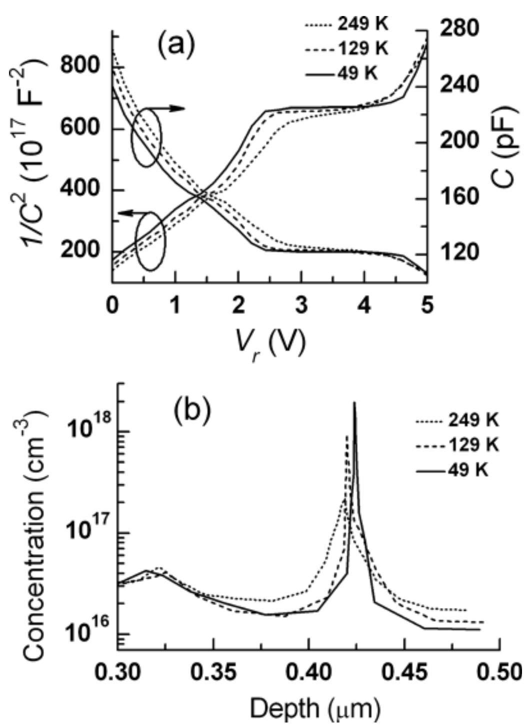

FIG. 1. Experimental results: (a) *C-V* characteristics of the structure at different temperatures and (b) apparent carrier profiles at different temperatures.

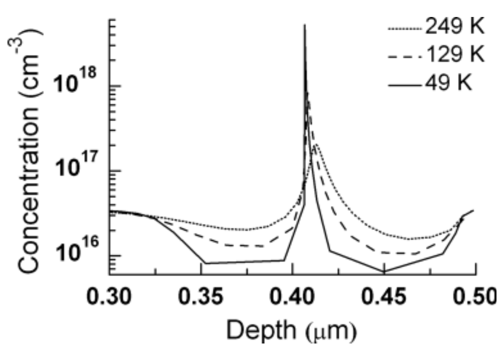

FIG. 3. Simulated apparent carrier profiles of the structure at different temperatures.

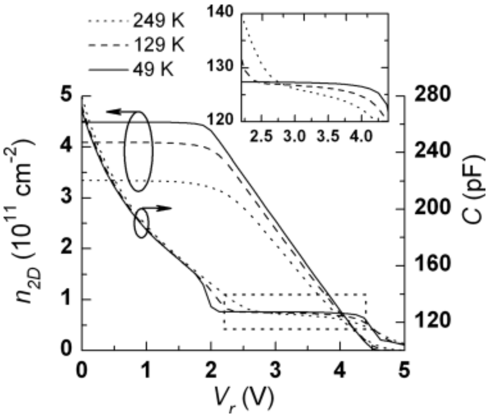

FIG. 4. n_{2D} and the simulated capacitance of the structure as a function of reverse bias V_r at different temperatures. The selected portion of the capacitance plots is enlarged in the inset.

resistance, the decrease of ionization of carriers in the bulk or due to a front diffused back contact. In presence of R_s, the relationship between the actual capacitance C and the measured capacitance C_m is[5]

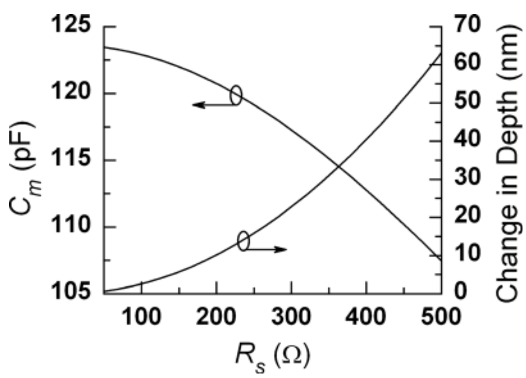

FIG. 5. The measured capacitance C_m and the change in the depth as a function of the series resistance R_s. The variation is shown with respect to the experimental peak capacitance at 249 K.

$$C_m = \frac{C}{1 + (2\pi f R_s C)^2}, \tag{5}$$

where f is the frequency of the ac signal. With respect to the experimental capacitance at 249 K the variation of C_m and the depth with R_s at 1 MHz is shown in Fig. 5. It is evident from Fig. 5 why at low temperature the carrier peak in C-V measurements recedes from the Schottky instead of moving to the Schottky as predicted theoretically.

It may be concluded that for a QW structure the exclusion of the attributes of the 2D carriers and the temperature dependence in the formulations of the C-V profiling are the main reasons behind the deviation of the apparent profile from the actual profile. The series resistance has a major role in the shift of the experimental carrier peak at low temperature.

One of the authors (S.P.) acknowledges the financial support from University Grants Commission, Govt. of India under the RFSMS scheme.

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