Experimental Determination of Quantum and Centroid Capacitance in Arsenide–Antimonide Quantum-Well MOSFETs Incorporating Nonparabolicity Effect

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Abstract—Experimental gate capacitance \( (C_g) \) versus gate voltage data for \( \text{InAs}_y\text{Sb}_{1-y} \) quantum-well MOSFET (QW-MOSFET) is analyzed using a physics-based analytical model to obtain the quantum capacitance \( (C_Q) \) and centroid capacitance \( (C_{\text{cent}}) \). The nonparabolic electronic band structure of the \( \text{InAs}_y\text{Sb}_{1-y} \) QW is incorporated in the model. The effective mass extracted from Shubnikov–de Haas magnetotransport measurements is in excellent agreement with that extracted from capacitance measurements. Our analysis confirms that in the operational range of \( \text{InAs}_y\text{Sb}_{1-y} \) QW-MOSFETs, quantization and nonparabolicity in the QW enhance \( C_Q \) and \( C_{\text{cent}} \). Our quantitative model also provides an accurate estimate of the various contributing factors toward \( C_g \) scaling in future arsenide–antimonide MOSFETs.

Index Terms—Effective mass, high-\( \kappa \) dielectric, \( \text{InAsSb} \), interface states, nonparabolicity, quantum capacitance, split capacitance–voltage.

I. INTRODUCTION

MIXED-ANION \( \text{InAs}_y\text{Sb}_{1-y} \) quantum wells (QWs) with high electron mobility are candidates for direct integration with high hole mobility \( \text{In}_{1-x}\text{Ga}_x\text{Sb} \) QW for ultra-low-power complementary applications [1], [2]. However, as a direct consequence of the low effective mass for electrons in the \( \Gamma \)-valley, \( \text{InAs}_y\text{Sb}_{1-y} \) QW-MOSFETs can suffer from the so-called density of states (DOS) bottleneck that may limit the effective ON-current and adversely affect switching in fixed load capacitance dominated digital circuits [3]. The capacitance associated with the QW in \( \text{InAs}_y\text{Sb}_{1-y} \) QW-MOSFET depends on the 2-D DOS (quantum capacitance \( C_Q \)) as well as the electron wave function distribution (centroid capacitance \( C_{\text{cent}} \)) in the QW [4]. Even though the low effective mass limits the \( C_Q \) quantization and nonparabolicity enhance the \( C_Q \) and the \( C_{\text{cent}} \) of the \( \text{InAs}_y\text{Sb}_{1-y} \) QW [5]. Incorporation of a gate dielectric within the \( \text{InAs}_y\text{Sb}_{1-y} \) QW-MOSFET, together with finite capacitance \( C_{\text{barrier}} \) arising from the upper semiconductor barrier layer, further increases the equivalent oxide thickness (EOT) in a QW-MOSFET. Hence, it is imperative to understand how the different components of capacitance \( (C_Q, C_{\text{cent}}, C_{\text{barrier}}, \text{and} C_{\text{ox}}) \) affect the overall gate capacitance and scalability of this device.

In this paper, we present a physics-based analytical model to analyze the experimental gate capacitance \( (C_g) \) versus gate voltage \( (V_g) \) data for an \( \text{InAs}_y\text{Sb}_{1-y} \) QW-MOSFET with a composite high-\( \kappa \) gate stack (5.5 nm Al\(_2\)O\(_3\)-1 nm GaSb) and to systematically extract the quantum capacitance of the channel including the nonparabolicity effect, as well as the centroid capacitance associated with the spread of the electron wave function in the QW. The significance of this work lies in the fact that accurate quantification of the quantum capacitance in high mobility channel MOSFETs is critical to future device scaling. A small-signal equivalent circuit model is utilized to correct the measured gate capacitance data from the impact of the interface state density \( D_{\text{it}} \). In a previous work done by Jin et al. [6], the quantum capacitance of a Schottky-gated \( \text{InAs QWFET} \) was analyzed, but without considering the effect of nonparabolicity in the band structure and the impact of interface states. Jin et al. used a single effective mass higher than the \( \Gamma \)-valley mass of bulk \( \text{InAs} \) to account for the increase in \( C_Q \) due to quantization and nonparabolicity. In this paper, we incorporate the nonparabolicity in the \( \text{InAs}_y\text{Sb}_{1-y} \) band structure using the nonparabolicity factor \( \alpha \), which captures the energy dependence of both the 2-D DOS and the effective mass. The effective mass obtained from the capacitance modeling was further verified using Shubnikov–de Haas (SdH) magnetotransport measurements at a low temperature (2–15 K) and a high magnetic field (0–9 T). We also present an EOT scalability study that shows that for \( \text{InAs}_y\text{Sb}_{1-y} \) QW-MOSFET with thin
dielectric (0.7 nm EOT) and barrier (0.45 nm EOT), the oxide and barrier capacitance has similar contribution to the gate capacitance (53% of $1/C_g$), as that from the quantum capacitance $C_Q$ (39% of $1/C_g$) and the centroid capacitance $C_{\text{cent}}$ (8% of $1/C_g$) for a gate overdrive of 0.35 V (approximately two-thirds of $V_{\text{DD}} = 0.5$ V).

II. EXPERIMENTAL $C_g$–$V_g$ MEASUREMENTS AND CORRECTING FOR $D_{\text{it}}$

Fig. 1 shows the schematic of the fabricated InAs$_{0.8}$Sb$_{0.2}$ QW-MOSFET with 1 nm GaSb and 5.5 nm Al$_2$O$_3$ dielectric that forms a composite gate stack on top of the barrier. The fabrication details of the transistor are reported elsewhere [7]. A thin layer of GaSb (1 nm) is used as an interfacial layer with the high-$\kappa$ dielectric to reduce the interface state density [8].

Fig. 2 (a) and (b) shows the measured and modeled split $C_g$–$V_g$ and $G$–$V_g$ characteristics of InAs$_{0.8}$Sb$_{0.2}$ QW-MOSFET at 77 K and the frequency dispersion characteristics due to the interface states. Similar analysis was done at 150 and 300 K (not shown here). The $C_g$–$V_g$ and $G$–$V_g$ data were self-consistently modeled using an equivalent circuit model that accounts for the admittance contribution from the interface states at the Al$_2$O$_3$–GaSb interface. The conductance response of the traps ($G_0/\omega$) versus frequency [7] shows positive slope with $V_g$, indicating electron capture/emission process. The technique for extracting the interface state density ($D_{\text{it}}$), trap response time ($\tau$), and the frequency-independent semiconductor capacitance using the equivalent circuit model is explained in detail in [9]. Fig. 3 shows the $C_g$–$V_g$ curves corrected for $D_{\text{it}}$ along with the measured $C_g$–$V_g$ characteristics for 77 and 150 K.

III. ANALYTICAL MODELING OF GATE CAPACITANCE OF QW-MOSFET INCLUDING NONPARABOLICITY

The capacitance of the InAs$_{0.8}$Sb$_{0.2}$ QW ($C_S$) can be expressed as a series combination of the quantum capacitance ($C_Q$), which is related to the 2-D DOS in the QW, and the centroid capacitance ($C_{\text{cent}}$), which is related to the change in the subband energy levels in the QW due to the sheet charge density in the QW, as given by

$$C_S = \frac{\partial(-Q_S)}{\partial \psi_{S,\text{QW}}} = \sum_i \frac{\partial N_{S,i}}{\partial \psi_{S,\text{QW}}} \tag{1}$$

$$N_S = \sum_i N_{S,i} = \sum_i \int_{E_i}^{\infty} \text{DOS}_{2D}(E) f(E) dE \tag{2}$$

$$q \frac{\partial \psi_{S,\text{QW}}}{\partial E} = \partial(E_F - E_C) = \partial(E_F - E_i) + \partial(E_i - E_C) \tag{3}$$

$$C_S = \sum_i \frac{\partial^2}{\partial(E_F - E_i)} \frac{\partial N_{S,i}}{\partial(E_F - E_i)} + \frac{\partial(N_{S,i})}{\partial(E_i - E_C)} \tag{4}$$

$$C_S = \sum_i \frac{\partial^2}{\partial(E_F - E_i)} \frac{\partial N_{S,i}}{\partial(E_F - E_i)} \frac{\partial(E_F - E_i)}{\partial(E_F - E_i) + \partial(E_i - E_C)} \tag{5}$$

$$C_S = \sum_i C_{S,i} \tag{6}$$

$$\frac{1}{C_{S,i}} = \frac{1}{C_{Q,i}} + \frac{1}{C_{\text{cent},i}} \frac{\partial(E_i - E_C)}{\partial(E_i - E_C)} = \frac{1}{C_{Q,i}} + \frac{1}{C_{\text{cent},i}} \tag{7}$$

$$C_{Q,i} = q^2 \frac{\partial N_{S,i}}{\partial(E_F - E_i)}; \quad C_{\text{cent},i} = C_{Q,i} \frac{\partial(E_F - E_i)}{\partial(E_i - E_C)} \tag{8}$$
where, $N_{S,i}$ stands for charge density in the $i$th subband, $\Psi_{S,QW}$ stands for the QW potential, $C_{Q,i}$ stands for quantum capacitance of the $i$th subband, $C_{cent,i}$ stands for centroid capacitance of the $i$th subband, $C_{ox}$ stands for the series combination of oxide and barrier capacitance, and $\Psi_{S,QW}$ stands for the quantum well potential. Only two subbands are considered in the model.

The nonparabolicity of the InAs$_{0.8}$Sb$_{0.2}$ QW band structure is included in the model by modifying the effective mass and 2-D DOS using the nonparabolicity factor $\alpha$ as follows:

$$m^* = \frac{\hbar^2 k}{\partial E/\partial k} = m_T(1 + 2\alpha E)$$

$$\text{DOS}_{2-D} = \frac{m^*}{\pi \hbar^2} = \frac{m_T(1 + 2\alpha E)}{\pi \hbar^2}$$

The gate capacitance obtained in (11) is a function of the $\Psi_{S,QW}$ in the QW. The applied gate potential is taken to be $0.018 m_0$ for InAs$_{0.8}$Sb$_{0.2}$ [12]. The analytical model shows excellent agreement with the numerical simulations (Nextnano). This validation was first done for a parabolic band structure case ($\alpha = 0$). The subband positions for evaluating the centroid capacitance were numerically obtained as a function of the Fermi level from Nextnano simulations for all the cases considered in this paper. Now, we incorporate the nonparabolicity of the band structure in our analytical calculations to model and analyze the experimental $C_g-V_g$ data obtained from the InAs$_{0.8}$Sb$_{0.2}$ QW-MOSFET after $D_{it}$ correction. Fig. 6(a) shows the experimental $C_g-V_g$ data corrected for $D_{it}$ at 77 K along with the analytical model. The effect of varying $\alpha$ on the different components of gate capacitance is also shown in Fig. 6. For single effective mass approximation ($\alpha = 0$), the quantum capacitance will not change with gate bias as the Fermi level moves above the first subband in the QW. This is due to the constant DOS in the QW, and $C_Q$ reaches the quantum capacitance limit. Increasing $\alpha$ gives rise to increasing $C_Q$, even after the Fermi level moves above the first subband. Hence, the $C_Q$ and $C_{cent}$ will keep increasing with gate bias. The best fit to the experimental data was obtained with $\alpha = 2.5 \text{ eV}^{-1}$. Fig. 7 shows the different components of the gate capacitance for InAs$_{0.8}$Sb$_{0.2}$ QW-MOSFET at both 77 and 150 K. Fig. 7(a) and (b) shows the different components of the gate capacitance for the 77 and 150 K data obtained from the InAs$_{0.8}$Sb$_{0.2}$ QW-MOSFET after $D_{it}$ correction. Fig. 6(a) shows the experimental $C_g-V_g$ data corrected for $D_{it}$ at 77 K along with the analytical model. The effect of varying $\alpha$ on the different components of gate capacitance is also shown in Fig. 6. For single effective mass approximation ($\alpha = 0$), the quantum capacitance will not change with gate bias as the Fermi level moves above the first subband in the QW. This is due to the constant DOS in the QW, and $C_Q$ reaches the quantum capacitance limit. Increasing $\alpha$ gives rise to increasing $C_Q$, even after the Fermi level moves above the first subband. Hence, the $C_Q$ and $C_{cent}$ will keep increasing with gate bias. The best fit to the experimental data was obtained with $\alpha = 2.5 \text{ eV}^{-1}$ at both 77 and 150 K. Fig. 7(a) and (b) shows the different components of the gate capacitance for the 77 and 300 K $C_g-V_g$ data. There is additional voltage stretch-out in the 300 K $C_g-V_g$ data, even after correcting for $D_{it}$, most likely due to hole accumulation in the GaSb barrier layer. Hence, we modeled only a portion of the 300 K $C_g-V_g$ data in Fig. 7(b).
Fig. 7. Components of the gate capacitance for (a) the 77 K, and (b) the 300 K $C_g-V_g$ data. Additional voltage stretch-out in the 300 K $C_g-V_g$ data, even after correcting for $D_{ox}$, is most likely due to accumulation of holes in the Al$_{0.8}$In$_{0.2}$Sb barrier layer.

Fig. 8. Effective mass extracted from the $C_g-V_g$ analysis as a function of charge density in the QW.

Fig. 8 shows the effective mass extracted from the $C_g-V_g$ analysis as a function of charge density in the QW. For a charge density of $2.0 \times 10^{12}$ cm$^{-2}$, the extracted effective mass is $0.042m_0$, which is 2.33 times higher than $m_1$ ($0.018m_0$) due to quantization and nonparabolicity. The nonparabolicity factor extracted from $C_g-V_g$ analysis ($\alpha = 2.5$ eV$^{-1}$) is similar to that for the InAs/AlSb QW heterostructure ($\alpha = 2.5$ eV$^{-1}$) reported from cyclotron resonance measurements [13].

IV. SdH ANALYSIS FOR EFFECTIVE MASS EXTRACTION

The effective mass obtained from the capacitance modeling was verified using SdH magnetotransport measurements on an InAs$_{0.8}$Sb$_{0.2}$ QW heterostructure (without dielectric) at low temperatures (2–15 K) and high magnetic fields (0–9 T). The magnetotransport measurements, in standard four-probe DC configuration, were carried out using Quantum Design Model 6000 Physical Property Measurement System, with a base temperature of 1.8 K and magnetic field in the range of 0–9 T. Fig. 9(a) and (b) shows the measured sheet resistance ($R_{XX}$) and Hall resistance ($R_{XY}$) of the device from 0 to 9 T. The insets in the figures show the configurations to measure $R_{XX}$ and $R_{XY}$. SdH oscillations are observed in $R_{XX}$ at magnetic fields below 8 T. At fields above 8 T, the quantum Hall plateaus appear in $R_{XY}$, and $R_{XX}$ tends to zero resistance. The magnetic field and temperature dependence of sheet resistance can be expressed as [14]–[16]

$$\frac{\Delta \rho_{XX}}{\rho_0} = R_S \frac{4\chi}{\sinh \chi} \exp \left( \frac{-\pi}{\omega_c \tau_q} \right) \cos \left( 2\pi \frac{E_F}{\hbar \omega_c} + \phi \right) \tag{12}$$

where $\rho_0$ is the sheet resistance at zero B, $\tau_q$ is the quantum lifetime, $\chi = 2\pi^2 kT/\hbar \omega_c$, and $\omega_c = eB/m^*$. The prefactor $R_S$ is associated with Zeeman splitting and is assumed to be independent of the magnetic field in the following analysis [14]. While extracting the effective mass from SdH oscillations, the background magnetoresistance was corrected as follows. The envelope of maxima (minima) of the $\rho_{XX}$ oscillations was evaluated from the peak (valley) in the $\rho_{XX}$ as a function of $B$. The average of the two envelopes gave the background magnetoresistance that was subtracted from the measured $\rho_{XX}$. Fig. 10 shows the periodic SdH oscillations in $\Delta \rho_{XX}/\rho_0$ (after removing the background contribution) as a function of $1/B$. FFT of $\Delta \rho_{XX}/\rho_0$ versus $1/B$ is shown in Fig. 10 (inset). There is a well resolved peak at the fundamental oscillation period $B_0 = 42.2$ T. From the period of oscillation, $\Delta(1/1B) = 0.024$ T$^{-1}$, the sheet carrier density can be obtained as $N_S = 2q/\hbar \Delta(1/1B) = 2.01 \times 10^{12}$ cm$^{-2}$. The carrier density obtained from period of SdH oscillations is independent of the device dimensions or QW thickness.

The analytical procedure to extract the effective mass is as follows. From (12), a plot of $\ln(\Delta \rho_{XX}/\rho_0)$ versus $\ln(\chi/\sinh \chi)$ gives a straight line with slope $= 1$. $\ln(\Delta \rho_{XX}/\rho_0)$ is from the experimentally measured magnetoresistance data as a function of temperature, and $\ln(\chi/\sinh \chi)$ is calculated as a function of temperature using $m^*$ as an
adjustable parameter. The correct value of \( m^* \) gives a slope of 1 for the graph. Fig. 11 shows the extraction procedure at \( B = 2.54 \) T and \( B = 3.01 \) T. The extracted effective mass from the analysis is 0.043 \( m_0 \), which gives a universal straight line for all temperatures, as given by (12). The slope of the line is \( -\pi m^*/q\tau_q \), which yields a quantum lifetime of \( \tau_q = 0.065 \) ps.

The assumption that \( R_s \) is independent of the magnetic field is justified from Figs. 11 and 12, which give good straight lines as expected from (12). The ratio of transport time \( \tau = 0.5 \) ps obtained from QW electron mobility at 2 K to the quantum scattering time is \( \sim 7.5 \). This indicates that the dominant scattering mechanism in the \( \text{InAs}_{0.8}\text{Sb}_{0.2} \) QW heterostructure (without a dielectric) at low temperatures is due to the ionized impurities in the \( \text{In}_{0.2}\text{Al}_{0.8}\)Sb barrier or interface charge at the barrier–QW interface, as observed in the case of the GaAs/\( \text{Al}_x\text{Ga}_{1-x}\text{As} \) QW heterostructure [18].

V. QW-MOSFET GATE CAPACITANCE SCALING PROJECTION

In this section, we provide a quantitative estimate of the various factors determining gate capacitance scaling in future arsenide–antimonide QW-MOSFETs. As shown in the previous sections, both the quantization and the nonparabolicity increase the effective mass in the QW, which increases the quantum capacitance \( C_Q \) and the centroid capacitance \( C_{\text{cent}} \). As we scale the gate length of future generation QW-MOSFETs, we need to scale the thickness of the semiconductor barrier and the QW. Thinner QWs will exhibit higher \( C_{\text{cent}} \) due to less change in the subband energy levels with Fermi level position [19], and higher \( C_Q \) as well due to increased DOS at higher energy, for a given sheet carrier density \( N_s \) in the QW. For a gate overdrive of 0.35 V (approximately two-thirds of \( V_{DD} = 0.5 \) V), the oxide and barrier capacitance together contribute to about half (53%) of \( 1/C_g \), whereas the quantum and centroid capacitance contribute to the remaining half, with \( C_Q \) (39% of \( 1/C_g \)) being a more limiting factor than \( C_{\text{cent}} \) (8% of \( 1/C_g \)). The charge density in the QW for 0.35 V gate overdrive is \( \sim 3.5 \times 10^{12} \) cm\(^{-2} \) (Fig. 14). This implies that the oxide and barrier capacitance are as significant as quantum
capacity for gate capacitance scaling in MOS-QWFETs in the arsenide–antimonide material system.

VI. CONCLUSION

In this paper, we have presented a physics-based analytical model to extract the quantum capacitance and nonparabolicity factor in InAs$_{0.8}$Sb$_{0.2}$ QW-MOSFET. The effective mass extracted from $C_g$–$V_g$ analysis is validated through SdH measurements at low temperature (2–15 K) and high magnetic field (0–9 T). The effective mass of 0.043 $m_0$ was obtained at $N_s = 2.0 \times 10^{12}$ cm$^{-2}$ (from SdH as well as $C_g$–$V_g$ analysis), which is 2.3 times higher than the $\Gamma$-valley mass of bulk InAs$_{0.8}$Sb$_{0.2}$. A nonparabolicity factor of 2.5 eV$^{-1}$ was obtained from $C_g$–$V_g$ modeling. Gate capacitance scaling study of InAs$_{0.8}$Sb$_{0.2}$ QW-MOSFET, with a 5-nm-thick QW, a 1.5-nm-thick In$_{0.2}$Al$_{0.8}$Sb barrier (0.45 nm EOT), and a thin high-$\kappa$ oxide (0.7 nm EOT) shows that the oxide and barrier capacitance limit the gate capacitance (53% of $1/C_g$) more than the $C_Q$ ($39\%$ of $1/C_g$) and the $C_{cent}$ ($8\%$ of $1/C_g$) for a gate overdrive of 0.35 V (approximately two-thirds of $V_{DD} = 0.5$ V).

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