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Electronic transport in InGaAs/Al₂O₃ nFinFETs

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Abstract

Based on the multiple subbands quasi-ballistic transport theory, we investigate the electronic transport of nano size In₀.₅₃Ga₀.₄₇As nFinFETs with Al₂O₃ gate dielectric, emphasizing the saturation current region. 1D mobile charge density and gate capacitance density are introduced for the first time to describe the nano-FinFET transport property under volume inversion. With the extracted effective channel mobility of electrons in the linear region from our experiments, the electron mean free path \( \lambda \) in the channel with the value of 5–9 nm is obtained. With only one fitting parameter \( \alpha = 0.31 \) for the critical length \( L_c \) in the quasi-ballistic transport theory, the calculated drain current can fit all experimental data for various gate voltage \( V_g \), source–drain voltage \( V_d \), and temperature (240–332 K) in overall very good agreement. The backscattering coefficient \( r \) in the saturation region is larger than 0.8, indicating a large room for improvement for the present InGaAs FinFET technology and performance.

Keywords: In₀.₅₃Ga₀.₄₇As nFinFET, quasi ballistic transport, quantum capacitance, backscattering coefficient, critical length

(Some figures may appear in colour only in the online journal)

1. Introduction

InGaAs compound semiconductor as a promising candidate to replace silicon as channel material in n-MOSFETs has attracted great attention recently due to its high electron mobility [1–8]. The new FinFET structure demonstrates its excellent gate control capability which suppresses the short channel effect effectively [9]. However, only few works have been reported on the electrical characteristics of InGaAs FinFET [2, 7, 8, 10].

This paper is an extension of [10] to investigate the transport property of In₀.₅₃Ga₀.₄₇As nFinFET with fin width \( W_{\text{Fin}} = 40 \) nm, fin height \( H_{\text{Fin}} = 40 \) nm, channel length \( L = 100 \) nm, Al₂O₃ gate dielectric thickness of 5 nm, in the high \( V_g \) (saturation) region. Based on the quasi-ballistic transport theory [11, 12] and the extracted electron channel mobility from our experimental data in the linear region, the electron mean free path, the backscattering coefficient, and the critical length of the InGaAs nFinFETs are discussed. The calculated drain currents are in good overall agreement with the experimental results for various \( V_g \) and \( V_d \), and at different temperatures (240–332 K). The details on the device structure and fabrication process can be found in [7].

2. The characterization methodology

2.1. General considerations

The following points should be considered for our specific InGaAs nFinFET devices. (1) The conventional drift-diffusive transport model is not a rational starting point to characterize high mobility short channel InGaAs FETs. The quasi-
ballistic transport theory developed by Lundstrom et al is a good starting point [11, 12] to be used in this work. (2) For Fin body of W_{Fin} = 40 nm, H_{Fin} = 40 nm, and electron effective mass of In_{0.53}Ga_{0.47}As, m^* = 0.043 m_0 [13], electron quantum confinement effect should be considered. However, the quantized energy splitting is small and multiple subbands rather than one subband should be considered in the model. (3) The gate capacitance C_G cannot be measured accurately due to the high density of interface traps [14] and very small gate area of the FinFET. The C_G consisting of the oxide capacitance C_OX and quantum capacitance C_G is estimated by careful simulation. (4) For nano FinFET under volume inversion, 1D line densities of mobile charge Q_n and gate capacitance C_G along the channel direction are introduced [10]. They are more appropriate than the 2D surface density of mobile charge and gate capacitance used in the conventional MOSFET modeling to describe nano InGaAs FinFET devices.

2.2. Electron quantization, volume versus surface inversion

Two methods have been used for the electron quantization calculations.

(1) Flat bottom well (FBW) with infinitely high barrier approximation, the quantized energies E_i can be expressed by [15]:

\[
E_i = \frac{i^2 \pi^2 \hbar^2}{2m^*L^2}, \quad i = 1,2,3... \tag{1}
\]

(2) Numerical solution of Schrödinger equation with the bent bottom of conduction band (BBB) obtained by Synopsys Sentaurus Device simulation tool for the FinFET structure. This method is denoted by BBB method.

Figure 1(a) shows the geometry of the FinFET with 40 nm fin width, 40 nm fin height and 100 nm fin length. Figure 1(b) shows the bottom of the conduction band E_c(Z) profile in the FinFET channel. Using this E_c(Z) with infinitely high barrier approximation at two interface sites Z = 0 and 40 nm, the quantized energies E_i and the wave functions \psi_i(Z) can be obtained by numerical solution of the Schrödinger equation. The wave functions shown in figure 1(c) indicate volume inversion in the channel. The quantized energies obtained by BBB method are quite close to the E_i obtained by the FBW approximation as shown in figure 2. Both methods obtain very close results of calculations in the following sections.

2.3. The cyclic coupled equations loop

Denote Q(0) as the 1D line density of mobile charge along the channel length at the top of the source–channel barrier. Modifying the equation of Q(0) in [12] for one subband 2D surface mobile charge density to multiple subbands 1D line mobile charge density, Q(0) can be expressed by:

\[
Q(0) = \sum_{i=1}^{\infty} Q_i(0)
\]

\[
= \frac{1}{2} qH_{Fin} N_{2D}
\]

\[
\times \sum_{i=1}^{\infty} \left( (1 + r_i) J_0(\eta_i) + (1 - r_i) J_0(\eta_i - \frac{qV}{k_BT}) \right)
\]

\[
N_{2D} = \frac{m^*k_BT}{\pi\hbar^2} \tag{2a}
\]

here \(\eta_i = (E_i - E_F)/k_BT\), \(E_F\) is the Fermi level, \(E_i\) is the bottom energy of the \(i\)th subband. \(J_0(\eta_i)\) is the \(i\)th Fermi--Dirac integral [16]. The drain current \(I_d\) in [12] can be modified to:

\[
I_d = \langle v_{thermal} \rangle \left( \frac{1 - r}{1 + r} \right)
\]

\[
\times \sum_{i=1}^{\infty} \left[ Q_i(0) \times \frac{J_{1/2}(\eta_i')}{J_0(\eta_i')} \right]
\]

\[
\times \left[ 1 - \frac{J_{1/2}(\eta_i' - qV/k_BT)}{J_{1/2}(\eta_i')} \frac{J_0(\eta_i' - qV/k_BT)}{J_0(\eta_i')} \right]
\]

\[
= \frac{2k_BT}{\pi m^*_e} \tag{3}
\]

where \(\langle v_{thermal} \rangle\) is the electron thermal velocity \(r\) is the back scattering coefficient which is defined as [11, 12]

\[
r = \frac{l}{l + \lambda} \tag{4}
\]

with \(l\) the critical length:

\[
l = \text{Min} \left[ L, L \left( \frac{k_BT/q}{V_d} \right)^{\alpha} \right] \tag{5}
\]

\(\alpha\) is a fitting parameter related to the potential variation profile along the channel direction [12], and \(\lambda\) is the electron mean free path [10]:

\[
\lambda = \frac{\langle 2k_BT/q \rangle}{\langle v_{thermal} \rangle} \sum_{i=1}^{m} \frac{J_0(\eta_i)}{\langle v_{thermal} \rangle \sum_{i=1}^{m} J_{-1/2}(\eta_i)} \tag{6}
\]
In the saturation region $I_{\text{d, saturation}}$ in (3) is reduced to

$$I_{\text{d, saturation}} \approx \left( v_{\text{thermal}} \right) \left( \frac{1 - r}{1 + r} \right) \sum_{i=1}^{\infty} Q_{i} \left( 0 \right) \frac{\mathcal{J}_{1/2}(\eta'_{F})}{\mathcal{J}_{0}(\eta'_{F})} \right)$$

$$= \left( \frac{1 - r}{2} \right) qN_{2}H_{\text{Fin}} \left( v_{\text{thermal}} \right) \sum_{i=1}^{\infty} \mathcal{J}_{1/2}(\eta'_{F})$$

To compare $I_{\text{d}}$ calculated by (3) with the experimental data of $I_{\text{d}}$ as functions of $V_{g}$ and $V_{d}$, the relationship between $V_{g}$ and $\eta'_{F}$ can be obtained by using the following procedure. Since a change in the gate voltage $dV_{g}$ induces a change in the Fin inversion potential $dV_{\text{Q}}$ by

$$dV_{\text{Q}} = \left( C_{G}/C_{Q} \right) dV_{g}$$

here $C_{G}$ is the line density for the 1D gate capacitance which consists of two components in series:

$$C_{G}(V) = \frac{C_{\text{OX}}C_{Q}}{C_{\text{OX}} + C_{Q}}$$

The line density for the 1D oxide capacitance $C_{\text{OX}}$ with $\text{Al}_{2}\text{O}_{3}$ of thickness $t_{\text{OX}} = 5 \text{ nm}$ and dielectric constant $\varepsilon_{\text{Al}_{2}\text{O}_{3}} = 8$ [17] is

$$C_{\text{OX}} = \frac{\varepsilon_{\text{Al}_{2}\text{O}_{3}}e_{0}(W_{\text{Fin}} + 2H_{\text{Fin}})}{t_{\text{ox}}}$$

$$= \left( 14/\mu \text{F}/\mu \text{m} \right) (W_{\text{Fin}} + 2H_{\text{Fin}}) = 1.70 \mu \text{F}/\mu \text{m}$$

The line density for the 1D quantum capacitance $C_{Q}$ shown in (7) and (8) is the derivative of 1D charge density in the channel with respect to surface potential $V_{\text{Q}}$. By (2), we have

$$C_{Q} = \frac{q^{2} m_{e}^{*}}{2\pi h^{2}} H_{\text{Fin}}$$

$$\times \sum_{i=1}^{\infty} \left( 1 + r \right) \mathcal{J}_{-1}(\eta'_{F}) + \left( 1 - r \right) \mathcal{J}_{1}(\eta'_{F} - \frac{qV_{g}}{k_{B}T})$$

$$= \left( 1.15 \mu \text{F}/\mu \text{m} \right) (W_{\text{Fin}} + 2H_{\text{Fin}}) = 1.70 \mu \text{F}/\mu \text{m}$$

Note that when $V_{d}$ is high, the surface inversion potential $V_{\text{Q}}$ and charge density $Q$ are not uniform along the channel. Therefore in (2) and (10), $Q(0)$ and $V_{\text{Q}}(0)$ represent respectively the 1D charge density and the surface potential at the channel locating at the top of the source-channel barrier. Integrating (7) in both sides, we obtain

$$V_{g}(\eta'_{F}) = V_{\text{th}} + \int_{\eta'_{F}}^{\eta'_{F}} \frac{C_{Q}k_{B}T}{qC_{G}} d\eta'_{F}$$

where $\eta'_{F\text{th}}$ represents the $\eta'_{F}$ when the gate voltage equals the
threshold voltage $V_{th}$ and the electron 2D density in the channel is about $10^{11}$ cm$^{-2}$ [18].

Equations (4), (6), (10), and (11) are cyclic coupled. They can be solved by iteration procedure with the initial condition $r=1$, with very rapid convergence. The converged $r$ and $\eta_F$ values are substituted into (3) to calculate the $I_d$.

Figure 3 shows the calculation flow diagram of the iteration procedure.

3. Calculation results compared with our experiments

Figure 4 shows the 1D charge density $Q(0)$ calculated by traditional method in Si MOSFETs [19],

$$Q(0) = C_{ox} (V_g - V_{th}),$$  \hspace{1cm} (12)

and by our model of equations (2), (8), (9), (10), and (11). The large difference between two methods is due to the small effective mass and therefore small quantum capacitance of the InGaAs channel. Figure 3 indicates a heavy overestimation of the channel mobile charge density and therefore an underestimation of the extracted channel mobility using (12).

3.1. The cyclic coupled equations loop solved by iteration

Figure 5 shows the calculated $\eta_F$ at different gate voltage and temperature using (10) and (11).

3.2. Comparison with the experiments—the DIBL effect

To compare with experimental $I_d-V_d$ curve with fixed $V_g$, DIBL effect must be considered since the threshold voltage
$V_d$ decreases with increasing $V_d$. Figure 7 shows the DIBL as a function of temperature extracted from the measured $I_d$–$V_g$ data with different $V_d$. Consequently, in the conventional $I_d$–$V_g$ plot, each measured $I_d$–$V_g$ curve with fixed $V_g$ has larger $V_g$–$V_{th}$ value when $V_d$ is larger. Correspondingly, $\eta_1^F$ is larger, while $\lambda$ is smaller. On the other hand, parameter $\alpha$ in (5) is adjusted to fit all calculated $I_d$ at different $V_g$, $V_d$, and temperature $T$ to get an overall agreement with experimental data. When $\alpha=0.31$, the calculated $I_d$ using (3) and the measured $I_d$ curves are shown in figures 8(a) and (b). The calculated results show overall good agreement with experimental $I_d$ for various $V_g$, $V_d$, and temperature.

3.3. Back-scattering coefficient in the saturation region

Figure 9 shows the backscattering coefficient $r$ and the critical length in the saturation region. In the present In$_{0.53}$Ga$_{0.47}$As nFinFET with 100 nm channel length, the $r$ is higher than 0.8, indicating a large potential of improvement can be made for the In$_{0.53}$Ga$_{0.47}$As nFinFET technology and performance.

4. Discussion

The short mean free paths and the abnormal phenomenon that $\lambda$ increases with increasing temperature, as indicated in
traps may respond to the charge density induced by \( L = 100 \text{ nm} \). The inset is the critical length versus is actually not be measured, and higher real mobility effect. We would not follow the method in [25] since we have not considered the trap mean free path since we have not considered the trap energy densities in the InGaAs conduction band. (2) The charged traps induce additional Coulomb scattering mobility component \( \mu_{\text{Coulomb}} \), which increases with increasing temperature [19]. It is consistent with our experimental result. Therefore, the method stated in this paper underestimate the real mobility and mean free path since we have not considered the trap effect. We would not follow the method in [25] since we cannot measure the gate capacitance, and higher real mobility is actually not beneficial to higher \( I_d \). We would rather follow the conventional mobility studies [26–28], and ascribe the degraded effective mobility to the existence of high acceptor trap density. The results shown in this work indicate that there is a large room to improve the present InGaAs n-FinFET fabrication technology by improving the InGaAs/dielectric interface to reduce the acceptor like interface trap and border trap energy densities in the InGaAs conduction band.

The agreement between calculated and experimental \( I-V \) curves in figure 8 is not perfect at higher \( V_d \). This may reflect that introducing a critical length with only one parameter \( \alpha \) in (5) is not accurate enough and could be further improved. On the other hand, the DIBL constants shown in figure 7 are sensitive to the slope of the curves at high \( V_d \) range, but may introduce some errors or uncertainty by different methods to extract the \( V_{th} \) from the \( I-V \) curves.

5. Conclusion

The multiple subbands quasi-ballistic transport theory is used to characterize the nano In\(_{0.53}\)Ga\(_{0.47}\)As/Al\(_2\)O\(_3\) nFinFET, emphasizing the saturation region. 1D mobile charge density and gate capacitance density are adopted to describe the electron transport property in the channel under volume inversion. The quantum capacitance, which plays a more important role in estimating the mobile charge density than in Si MOSFET with the same scaling geometry, due to much smaller electron effective mass in InGaAs, is carefully modeled. The electron mean free path in the channel is in the range of 5–9 nm. The critical length, and the backscattering coefficients in the saturation region are evaluated. The calculated drain currents \( I_d \) with only one fitting parameter \( \alpha=0.31 \) for the critical length \( l = L \left( \frac{2e^2}{nq^2} \right)^{1/3} \) are in overall good agreement with all experimental data with various \( V_g \), \( V_{th} \), and temperature. The backscattering coefficient at the saturation region is larger than 0.8, indicating large room for improvement for InGaAs nMOSFETs technology and performance.

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References


Figure 9. The calculated backscattering coefficient \( r \) defined in (4), (5) with \( V_d = 0.6 \text{ V} \), using the experimental mean free path \( \lambda \) in figure 6, the critical length \( l = L \left( \frac{4e^2}{nq^2} \right)^{1/3} \) and channel length \( L = 100 \text{ nm} \). The inset is the critical length versus \( V_d \) and \( T \).

\( V_g \) vs. \( V_{th} \) (V)
[23] Taoka N et al 2011 Int. Electron Device Meeting 27.2.1–4