The Role of Acceptor Density on the High Channel Carrier Density I-V Characteristics of AlGaAs/GaAs MODFETs

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19 October 1990

Prepared for
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This report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract No. F04701-88-C-0089 with the Space Systems Division, P.O. Box 92960, Los Angeles, CA 90009-2960. It was reviewed and approved for The Aerospace Corporation by M. J. Daugherty, Director, Electronics Research Laboratory. Captain Janet Modl was the Air Force project officer for the Mission-Oriented Investigation and Experimentation (MOIE) program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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A triangular-well, one-subband depletion layer model has been developed for the high density region of a modulation-doped field-effect transistor (MODFET). High density operation is defined as operation when the channel carrier density, in the entire channel, is equal to or greater than $n_{th}$, where $n_{th}$ is the channel carrier density at threshold. This high density model has been used to describe the effects of the depletion layer charge on the I-V characteristics. An approximation for the experimentally determined threshold voltage is derived. For small acceptor densities, $10^{11} \text{ cm}^{-2}$, it is shown that the experimentally determined threshold voltage may differ from the strong inversion threshold voltage by $0.25 \text{ V}$. We show that this discrepancy is due to the effect of the depletion layer charge in the high density region. Also, the depletion layer charge is shown to account for the discrepancy in the device capacitance and the AlGaAs layer capacitance. The effective layer thickness $d_{eff}$ is shown to decrease from $90 \text{ Å}$ at an acceptor density of $10^{13} \text{ cm}^{-2}$ to $75 \text{ Å}$ at $10^{11} \text{ cm}^{-2}$. 
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I. INTRODUCTION

The dependence of the threshold voltage, subthreshold I-V characteristics, and radiation response of n-channel AlGaAs/GaAs MODFETs (modulation doped field-effect transistors) on acceptor doping density has been described previously (Refs. 1-4). These analyses have now been extended to describe the dependence of MODFET high channel carrier density I-V characteristics on acceptor doping density. The effect of acceptor doping density on the experimental threshold voltage and device capacitance is explicitly addressed.

The band structure of a typical AlGaAs(n)/GaAs heterojunction with Schottky barrier, \( \phi_m \), at the gate, and a spacer layer at the interface under bias \( V_g \) is shown in Fig. 1. In the depletion layer approximation, the donors and acceptors are assumed to be completely ionized in the doped AlGaAs layer \( d \), the spacer layer \( a \), and in the depletion layer \( W \). The doping densities \( N_D \) and \( N_A \) are assumed constant. The quasi-two-dimensional electron eigenstates at the interface are solved for using a triangular potential well, and only the lowest subband is included in the calculation. A delta-function channel charge distribution at the average channel width is assumed. Band bending from the interface at \((d + a)\) to the edge of the depletion region \((W + d + a)\) is the difference of the position of the conduction band relative to the Fermi level in the GaAs far from the interface \((E_g/2 + \phi_{\text{bulk}})\), and the Fermi level \( E_F \) relative to the bottom of the two-dimensional channel.

Under the restrictions imposed by these assumptions, Poisson's equation may be integrated across the structure to obtain the applied gate voltage as a function of device geometry, doping densities, and channel charge \( n_S \):

\[
V_g = \phi_m - \Delta E_c + E_F + (q/e)[-N_D d^2/2 + (N_A W + n_S)(d + a)]
\]  

(1)
Fig. 1. Band Diagram of a Typical AlGaAs/GaAs MODFET with Schottky Gate, under Bias $V_g$
where

\[ \Delta E_c = \text{conduction band offset} \]

In the one-subband approximation, the Fermi level \( E_F \) may be calculated as

\[ E_F = E_0/q + (kT/q)\ln[\exp(\frac{\hbar^2 n_s^2 m_1}{m_1 kT}) - 1] \]  \hspace{1cm} (2)

where the first quantum level \( E_0 \) may be calculated in the triangular-well approximation and is given by

\[ E_0 = (\frac{9\hbar^2}{8m_1})(4E_{m_1} K^2)^{2/3} \]  \hspace{1cm} (3)

The field \( E_i \) at the interface is

\[ E_i = (q/\epsilon)(n_s + N_A) \]  \hspace{1cm} (4)

Substitution of Eqs. (2-4) into Eq. (1) yields

\[ V_g = V_0 + f(n_s) \]  \hspace{1cm} (5)

where

\[ V_0 = \phi_m - \Delta E_c - (q/\epsilon)N_d a^2/2 \]  \hspace{1cm} (6)

The function \( f(n_s) \) may be written as

\[ f(n_s) = (q/\epsilon)(d + a)(N_A W + n_s) + C_0(N_A W + n_s)^{2/3} \]

\[ + (kT/q)\ln[\exp(n_s/n_c) - 1] \]  \hspace{1cm} (7)
where

\[ C_0 = \left( \frac{9\kappa^2}{8m_1q} \right) \left( \frac{4q^2m_1}{\kappa^2c} \right)^{2/3} \]

\[ = \left( -1.7 \times 10^{-9} \ \text{V} \cdot \text{cm}^{4/3} \right) \]

\[ \hbar = \text{Planck constant divided by } 2\pi \]

\[ m_1 = \text{longitudinal effective mass of the carriers} \]

We have retained terms containing the depletion width \( W \) in the definition of \( f(n_s) \) because the depletion width is implicitly a function of the channel charge \( n_s \).

The quantities \( q, \epsilon, k, \text{ and } T \) are the elemental charge, AlGaAs(GaAs) permittivity (assumed identical), Boltzmann constant, and absolute temperature.

Similarly, charge density \( n_c \) is a function of physical constants and the effective carrier mass:

\[ n_c = \frac{\pi \kappa^2}{m_1 kT} \]

and is equal to \(-8.4 \times 10^{11} \ \text{cm}^{-2}\).

A discussion of the dependence of the depletion width \( W \) on acceptor density has been given elsewhere (Ref. 1). In section II we describe the mathematical properties of the function \( f(n_s) \), in the high channel carrier density region, and exploit the results to describe the characteristics of these devices.
II. HIGH DENSITY REGION

A. DEFINITION

We define the high density region such that $n_s > n_c$ over the whole channel. In this region Eq. (7) may be expanded in a Taylor series in $n_s$ about $n_c$. The results of this approximation to first order are shown in Fig. 2 for two extremes of acceptor doping density. The solid lines are the results of Eq. (7), and the dashed lines are the result of the first order expansion in $n_s$ about $n_c$. Above $n_c$ (8.4 x 10^{11} \text{cm}^{-2})$, the expansion is quite good. Much below $n_c$ (< 3.0 x 10^{11} \text{cm}^{-2})$, the first order expansion departs from the exact result and approaches a constant. Substitution of the first order expansion for $f(n_s)$ in Eq. (5) and inverting to find $n_s$ as a function of $V_g$ yields

$$n_s = n_c + K^{-1}[V_g - V_0 - f(n_c)]/(kT/q)$$  \hspace{1cm} (10)

where $K$ is a constant that depends on the device geometry, doping densities, depletion width, and physical constants. This form for $n_s$ is different than previously assumed (Ref. 5), which ignores the contribution from $n_c$ and from $f(n_c)$ and assumes that the reciprocal of $K$ is the AlGaAs layer capacitance per unit area per unit charge times the absolute temperature in electron volts. In our formulation, near saturation, $K$ is given by:

$$K = (q/kT)(q/\epsilon)(d + a) + (2/3)C_0(q/kT)/(N_AW + n_c)^{1/3} + 1.58/n_c$$  \hspace{1cm} (11)

B. DEVICE CAPACITANCE

The derivative of Eq. (10) with respect to $V_g$ yields the device capacitance per unit area, which may be written in the following form (Ref. 6):

$$C_{\text{area}} = \epsilon/(d + a + \Delta d)$$  \hspace{1cm} (12)
Fig. 2. Function $f(n_s)$ versus Channel Carrier Density for Two Extremes\textsuperscript{\textregistered} of Acceptor Density. The solid curves are the exact results of Eq. (2); the dashed lines are the results of the linear approximation, described in text.
where $\Delta d$ is invoked to account for the discrepancy between the $\text{AlGaAs}$ layer capacitance $c/(d + a)$ and the device capacitance. Taking the derivative of Eq. (10) and using Eq. (12) to solve for $\Delta d$ yields

$$
\Delta d = (2.3q)C_0(N_AW + n_c)^{1.3} + 1.58(kT/q)(e^q) n_c
$$

For low acceptor densities ($\leq 10^{13} \text{ cm}^{-3}$), $\Delta d$ levels off at a value of $-89 \text{ kA}$, which is in good agreement with values cited in the literature (Ref. 5). As the acceptor density increases, $\Delta d$ decreases. At an acceptor density of $10^{17} \text{ cm}^{-3}$, $\Delta d$ decreases to $-74 \text{ kA}$.

C. EXPERIMENTAL THRESHOLD VOLTAGE

MODFET threshold voltages are determined experimentally by extrapolating the saturation current, or square root of the saturation current, versus gate voltage to zero. The gate voltage intercept is the experimentally determined threshold voltage. We may approximate the experimental threshold voltage by solving Eq. (10) for the gate voltage when $n_s$ is equal to zero. This yields a threshold voltage which differs from the strong inversion definition of threshold voltage (Ref. 1). The difference between this approximation for the threshold voltage and the strong inversion threshold voltage is given by

$$
V_{th} = f(n_c) - f(n_{th}) - qn_c C_{area}
$$

where the channel charge at threshold $n_{th}$ is equal to the acceptor density $N_A$, times the average channel width $z_{av}$, which may be calculated in the triangular-well approximation using variational functions (Refs. 7, 8). This definition of threshold has been described elsewhere (Ref. 1).

In Fig. 3 the threshold voltage difference, Eq. (14), is plotted versus acceptor density. Each term in Eq. (14) is plotted separately. At low acceptor densities ($\leq 10^{14} \text{ cm}^{-3}$) the difference may be as much as 0.25 V. This difference decreases as the acceptor density increases. As this difference depends on the acceptor density, a comparison of
Fig. 3. Difference between Experimental and Theoretical Threshold Voltage versus Acceptor Density

\[ \Delta V_{th} = \eta(n_e) - \eta(n_h) - qn_e/C_{area} \]
experimental threshold voltages may not be appropriate if acceptor densities differ by a significant amount.

D. I-V CHARACTERISTICS

In the gradual channel approximation, charge control is determined by the effective potential in the channel:

\[ V(x) = V_g - V_c(x) \]

where \( V_c(x) \) is the channel voltage under the gate at point \( x \). Using Eq. (10) we solve for the carrier density in the channel:

\[ n_s(x) = n_c + K^{-1} \left[ V_g - V_0 - f(n_c) - V_c(x) \right] / (kT/q) \]

The form of Eq. (16) allows the source-drain current to be calculated in the usual way (Ref. 5). The result is

\[ I_{HD} = q(Z/L)u \left[ n_c + \frac{\left( C_{area}/q \right) \left( V_g - V_0 - f(n_c) \right) \left( V_c(L) - V_c(0) \right)}{V_c^2(L) - V_c^2(0)} \right] \]

where \( u \) is the channel mobility and \( Z/L \) is the gate-width to gate-length ratio. For a grounded source, in the limit of zero source-drain resistance, we recover the usual dependence on drain voltage.

In the development of Eq. (17) we have assumed that each point in the channel has a carrier density greater than \( n_c \). This places a limit on the bias conditions for the applicability of Eq. (17). Evaluating Eq. (16) at the drain contact and using the condition that \( n_s(L) \) must be greater than \( n_c \), yields the following limitations on the bias conditions for a grounded source and zero source-drain resistance:

\[ (V_g - V_d) - V_0 + f(n_c) \]

13
where \( V_D \) is the drain voltage. Shown in Fig. 4(a) is \( I_{DS} \) versus \( V_D \) for a grounded source and zero source-drain resistance for various acceptor doping densities and the device parameters shown. The heavy dots indicate the point at which the calculation is no longer valid by virtue of Eq. (18). As the acceptor density increases, the current at a given drain voltage decreases and the limit of the applicability of the calculation decreases, in drain voltage, for a given gate voltage. A similar graph is shown in Fig. 4(b) in which \( I_{DS} \) versus \( V_D \) is shown for a given acceptor density and various gate voltages. As the gate voltage decreases, the current at a given drain voltage decreases, as expected, and the region of applicability of the calculation, in drain voltage, decreases. This result implies that using an equation of the form given in Eq. (17), which results from a linearization of \( f(n_S) \) above \( n_c \), to infer the nature of the saturation characteristics in MODFETs, in which the drain portion of the channel has a channel carrier density much less than \( n_c \), is suspect (Ref. 5).
Fig. 4. Drain-Source Current versus Drain Voltage for Various Acceptor Densities (a), and Various Gate Voltages (b). Heavy dots indicate the limits of the calculation as given by Eq. (11) in the text.
III. SUMMARY

We have developed a triangular-well, one-subband depletion layer model to describe the high channel density operation of MODFETs. The effects of acceptor density on the I-V characteristics in the high channel density region has been investigated. The depletion layer charge, due to ionized acceptors, is shown to account for the discrepancy between the device capacitance and the AlGaAs layer capacitance, as described in the literature (Ref. 6). The depletion layer charge also accounts for the discrepancy between the theoretical threshold voltage, in the strong inversion model (Ref. 1), and the experimental threshold voltage, as determined by extrapolation of the source-drain current. Therefore, comparison of threshold voltage characteristics, particularly for devices with appreciably different acceptor densities, should be based on a consistent description of threshold that accounts for ionized acceptors, i.e., the strong inversion model.
REFERENCES


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