Available online at www.sciencedirect.com
SCIENCE DIRECT®

Solid-State Electronics 49 (2005) 167–174

SOLID-STATE ELECTRONICS

www.elsevier.com/locate/sse

Analytical non-linear charge control model for InAlAs/InGaAs/InAlAs double heterostructure high electron mobility transistor (DH-HEMT)

Ritesh Gupta, Sandeep Kumar Aggarwal, Mridula Gupta, R.S. Gupta *

Semiconductor Device Research Laboratory, Department of Electronic Science, University of Delhi South Campus, New Delhi 110 021, India

Received 1 November 2003; received in revised form 1 February 2004
Available online 28 September 2004

The review of this paper was arranged by Prof. S. Cristoloveanu

Abstract

An analytical charge control model for sheet carrier density is presented for InAlAs/InGaAs/InAlAs double heterostructure high electron mobility transistor (DH-HEMT). The model uses a polynomial dependence of sheet carrier concentration on position of quasi-Fermi energy level to successfully predict the gradual saturation of charge in the device and is valid from subthreshold region to high conduction region for both the channels. The model has been extended to calculate I_d–V_d characteristics, transconductance and cut-off frequency of the device.

Keywords: InAlAs/InGaAs/InAlAs heterojuction; InP based HEMT; Dual-channel; Sheet carrier density; Transconductance; Drain current; Cut-off frequency

1. Introduction

Ever since the introduction of high electron mobility transistors (HEMTs) several heterostructure (AlGaAs/GaAs, AlGaAs/InGaAs, InAlAs/InGaAs etc.) have been studied for high speed and high frequency circuit applications [1–4]. InAlAs/InGaAs heterostructure amongst all was found to be more promising due to its high sheet carrier density, resulted from large conduction band discontinuity [5] between InAlAs and InGaAs layer. The concept of modulating doping allows the conduction electrons to be separated from their present donors enabling very high mobility of the two dimensional electron gas (2-DEG) at the heterointerface due to the reduced impurity scattering. However, to maximize circuit speed, a large drain current is also required for which a higher 2-DEG density is needed.

Recently, interest in double heterojunction high electron mobility transistors (DH-HEMTs) has grown due to larger 2-DEG concentration, greater current derivability and better carrier confinement over single heterojunction device. It also exhibits higher transconductance with less degradation over a wider range of gate voltage as compared to a single channel HEMT [6–15]. These enhanced characteristics lead to improved device performance and demand a more accurate model that is simple and valid over a wide range of device operation. Both numerical and analytical models have been proposed [16–23] with some limitations [24] for AlGaAs/GaAs/AlGaAs DH-HEMT. Inoue et al. [16] proposed a numerical technique to obtain the total channel charge density as a function of gate voltage. Cazaux et al. [17] suggested an analytical approach to derive the channel charge assuming a triangular potential well at each

---

* Corresponding author. Tel.: +91 11 2410 5580; fax: +91 11 2688 6606.
E-mail address: rsgu@bol.net.in (R.S. Gupta).

0038-1101/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.sse.2004.08.002

Nomenclature

Symbols

$d_{i1}(d_{i2})$	thickness of InAlAs undoped Schottky layer (buffer layer)
$d_{a1}(d_{a2})$	thickness of Si-doped InAlAs layer above (below) the InGaAs layer
$d_{s1}(d_{s2})$	thickness of InAlAs spacer layer above (below) the InGaAs layer
d_{w}	thickness of InGaAs layer
$N_{d1}(N_{d2})$	doping concentration of Si-doped InAlAs layer above (below) the InGaAs layer InAlAs;
$\varepsilon_1(\epsilon_2)$	dielectric permittivity of InAlAs layer above (below) the InGaAs layer InAlAs;
$n_{s1}(n_{s2})$	sheet carrier concentration in channel-1 (channel-2)
$V_{th1}(V_{th2})$	threshold voltage of channel-1 (channel-2)
$\Delta E_{c1}(\Delta E_{c2})$	conduction band discontinuity at the (top bottom) heterointerface
$d_1(d_2)$	distance of channel-1 (channel-2) from the gate (substrate)
$E_{f1}(E_{f2})$	position of quasi-Fermi energy level at the top (bottom) heterointerface
$F_1(F_2)$	normalized field at the top (bottom) heterointerface
$n_{so1}(n_{so2})$	maximum Sheet carrier density at the top (bottom) heterointerface
E_{f1e}	relative shift in quasi-Fermi level at the top heterointerface with the variation in sheet carrier density at the bottom heterointerface
n_{s1e}	2-DEG carriers depleted at the bottom heterointerface by the top heterointerface
$I_{d1}(I_{d2})$	drain current flowing through channel-1 (channel-2)
$g_{m1}(g_{m2})$	transconductance due to channel-1 (channel-2)
n_{sT}	total sheet carrier density for DH-HEMT;
g_m	transconductance of DH-HEMT;
f_c	cut-off frequency of DH-HEMT;
$V_{dsat1}(V_{dsat2})$	saturation voltage of channel-1 (channel-2)
$V_g(V_d)$	gate (drain) voltage
q	electronic charge
W	width
$n(x)$	total sheet carrier density
$v(x)$	electron velocity
v_{sat}	saturation velocity of electron in InGaAs region
μ_o	low field mobility of InGaAs
$V(x)$	channel potential at a distance x;
E_c	critical electric field at which electron saturates in InGaAs region
ϕ_b	barrier height of Schottky gate
N_A	Background doping of the undoped InGaAs layer

AlGaAs/GaAs interface and carried out an analysis analogous to that of a conventional HEMT and found it justifiable for GaAs thickness exceeding 210 Å Yu and Abdel-Motaleb [18] proposed analytical model for the current voltage characteristics of AlGaAs/GaAs/AlGaAs DH-HEMT and related the charge in the bottom channel to the Fermi-level in the top well. Also using a relation between the top Fermi-level and the applied gate voltage, a relation between the bottom channel charge and the gate voltage is derived.

In this paper a model has been presented to calculate the total channel charge in the InAlAs/InGaAs/InAlAs DH-HEMT in response to the applied gate voltage. The model uses a polynomial dependence of sheet carrier concentration (n_s) on position of quasi-Fermi energy level (E_f) [25–28] to successfully predict the gradual saturation of charge and validate the model from subthreshold region to high conduction region for both the channels. It is assumed that the InGaAs layer is wide enough to justify the assumption that a triangular potential well is formed at each of the heterointerfaces. The model has been extended to predict the drain current, transconductance and cut-off frequency. The results so obtained for 2-DEG sheet carrier concentration are compared with the results obtained from actual $n_s - E_f$ relationship and are in good agreement, which justifies the validity of the present model.

2. Modeling of the 2-DEG in quantum well for DH-HEMT

Fig. 1 shows the cross-sectional view of pulsed doped InAlAs/InGaAs/InAlAs DH-HEMT along with the conduction band diagram consisting of InAlAs undoped buffer layer of thickness d_{i2}; Si-doped InAlAs layer of thickness d_{a2} to provide 2-DEG sheet charge density at the bottom heterointerface; InAlAs undoped spacer-layer of thickness d_{s2}; undoped InGaAs layer of thickness d_w to form the 2-DEG channel; InAlAs undoped spacer-layer of thickness d_{s1}; Si-doped InAlAs layer of thickness d_{a1} to provide 2-DEG sheet charge density at the top heterointerface; undoped InAlAs Schottky enhancement layer of thickness d_{i1}.