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<p>The superior properties of InP material, e.g., higher peak electron drift velocity, thermal conductivity, and breakdown field, to GaAs have made it an attractive alternative for high-performance applications in microwave and millimeter-wave regimes as well as high-speed digital circuits. Recently, a high-efficiency InP MISFET has demonstrated 4.5 watts output power with 4 dB gain and 46% power-added efficiency at 9.7 GHz by Messick et al. These impressive results clearly confirmed the promising superior performance of InP MISFETs.</p> <p>The main concern in the applications of III-V MISFETs has been the reliability of output characteristics of the devices, which is mainly attributed to the variations of interfacial properties of the gate dielectric layer and the underlying semiconductor active layer. The task of modeling output characteristics of III-V compound-based MISFET devices has become more complex with the possible dominance of the interfacial properties in the devices' performance. Much more attention should be paid to the nonlinear modulation of the surface potential by the external gate voltage due to the presence of an excessive amount of interfacial states, since the accompanying carrier trapping, scattering, and recombination could have altered completely the charge control and transport mechanisms, and consequently the device output characteristics.</p> <p>Because of these factors, we have developed analytical and computer-aided models for depletion-mode and accumulation-mode MISFETs based on a nonlinear charge control model derived from semi-empirical surface potential formulation, which can provide us not only an accurate description of the drain I-V characteristics, but also a comprehensive study of the influence of interfacial properties on the output performance of InP MISFETs. Key aspects of the physics of this device, which relate to charge control, carrier trapping, and field-dependent mobility, are modeled in this study.</p>					
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In order to further verify the calculated results and predict device performance in the submicron gate-length regime, we have developed a general finite-element two-dimensional semiconductor device simulation program, which is able to analyze and simulate various device structures including homo- and hetero-junctions III-V compound semiconductor-based devices with arbitrary geometries. Preliminary simulation results of a  $1 \mu\text{m}$  AlGaAs/GaAs HEMT device are reported. It is planned to extend the two-dimensional model to submicron InP MISFETs.

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# Analytical and Computer-Aided Models of InP-Based MISFETs and Heterojunction Devices\*

A.-J. Shey and W.H. Ku, UCSD and L. Messick, NOSC

## Abstract

The superior properties of InP material, e.g., higher peak electron drift velocity, thermal conductivity, and breakdown field, to GaAs have made it an attractive alternative for high-performance applications in microwave and millimeter-wave regimes as well as high-speed digital circuits. Recently, a high-efficiency InP MISFET has demonstrated 4.5 watts output power with 4 dB gain and 46% power-added efficiency at 9.7 GHz by Messick et al.<sup>[1]</sup> These impressive results clearly confirmed the promising superior performance of InP MISFETs.

The main concern in the applications of III-V MISFETs has been the reliability of output characteristics of the devices, which is mainly attributed to the variations of interfacial properties of the gate dielectric layer and the underlying semiconductor active layer. The task of modeling output characteristics of III-V compound-based MISFET devices has become more complex with the possible dominance of the interfacial properties in the devices' performance. Much more attention should be paid to the nonlinear modulation of the surface potential by the external gate voltage due to the presence of an excessive amount of interfacial states, since the accompanying carrier trapping, scattering, and recombination could have altered completely the charge control and transport mechanisms, and consequently the device output characteristics.

Because of these factors, we have developed analytical and computer-aided models for depletion-mode and accumulation-mode MISFETs based on a nonlinear charge control model derived from semi-empirical surface potential formulation, which can provide us not only an accurate description of the drain I-V characteristics, but also a comprehensive study of the influence of interfacial properties on the output performance of InP MISFETs. Key aspects of the physics of this device, which relate to charge control, carrier trapping, and field-dependent mobility, are modeled in this study.

In order to further verify the calculated results and predict device performance in the sub-micron gate-length regime, we have developed a general finite-element two-dimensional semiconductor device simulation program, which is able to analyze and simulate various device structures including homo- and hetero-junctions III-V compound semiconductor-based devices with arbitrary geometries. Preliminary simulation results of a 1  $\mu\text{m}$  AlGaAs/GaAs HEMT device are reported. It is planned to extend the two-dimensional model to submicron InP MISFETs.

## References

- [1] L. Messick et al., "High-Power High-Efficiency Stable Indium Phosphide MISFETs," *Proc. of the IEDM*, p. 767-770, 1986.

\*This work was supported by NOSC under Contract N66001-85-C-0422.

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# Analytical and Computer-Aided Models of

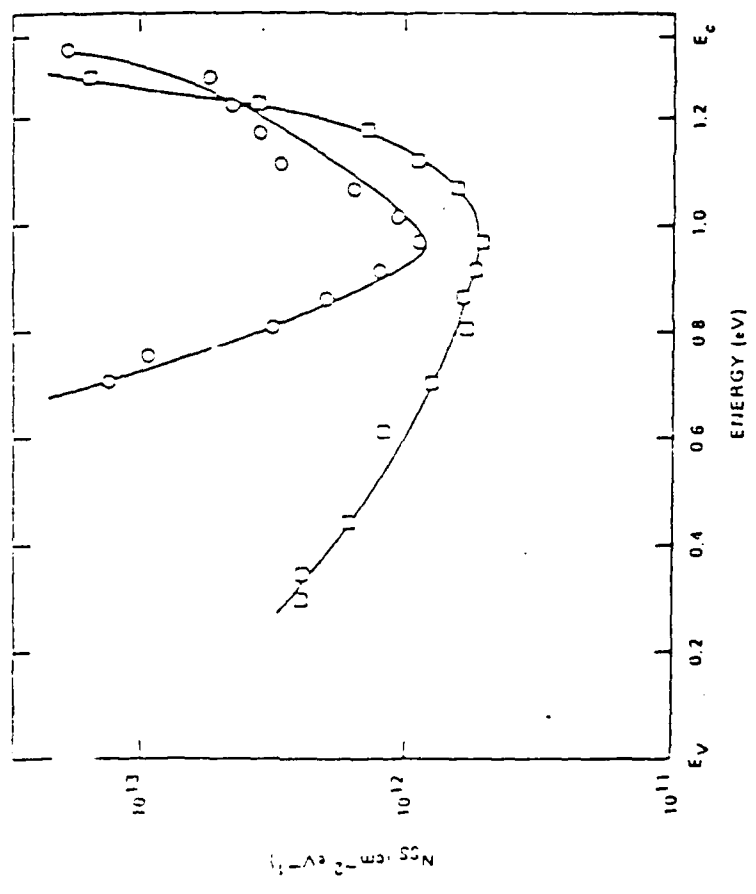
## InP-Based MISFETs<sup>\*</sup> and Heterojunction Devices<sup>\*\*</sup>

A. J. Shey,<sup>†</sup> W. H. Ku,<sup>††</sup> and L. Messick<sup>††</sup>

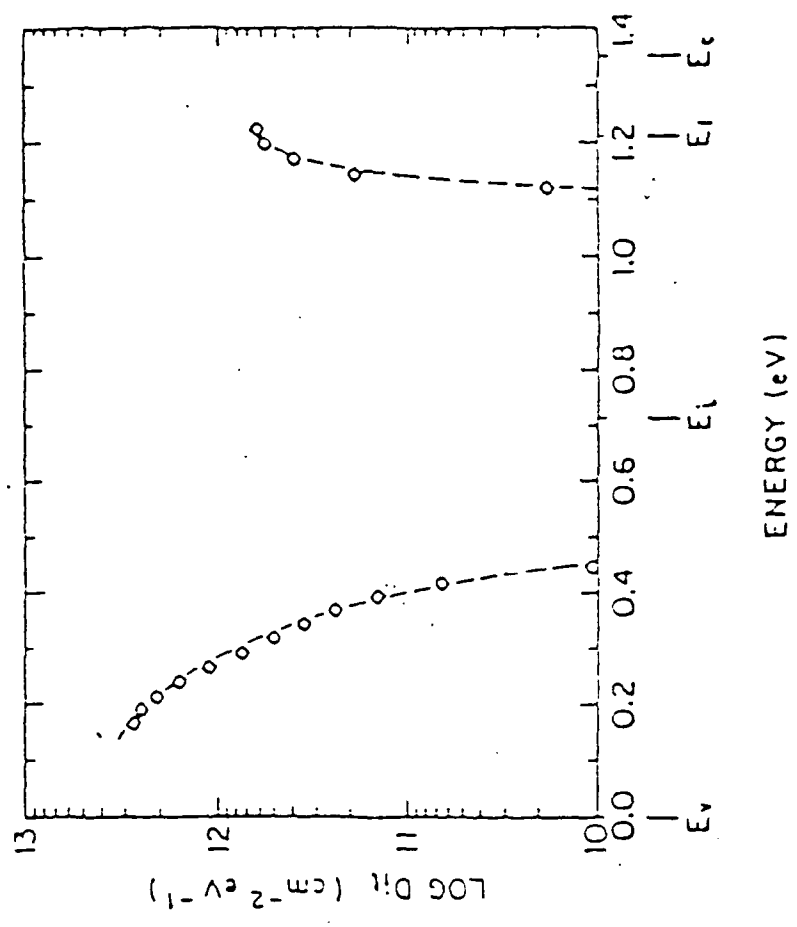
- + Dept. of Electrical and Computer Engineering, University of California, San Diego
- †† Naval Ocean Systems Center, San Diego
- \* Research supported by NOSC under Contract No. N66001-85-C-0422.
- \*\* Research supported by AFOSR under Grant No. AFOSR-86-0339, monitored by Dr. Gerald Witt.

- Introduction
- 1-D MISFET Model<sup>★</sup>
- 2-D HEMT Model<sup>★★</sup>
- Summary

# Typical Distribution of Interface State Density within Energy Band Gap Measured by C - V or Optical Methods

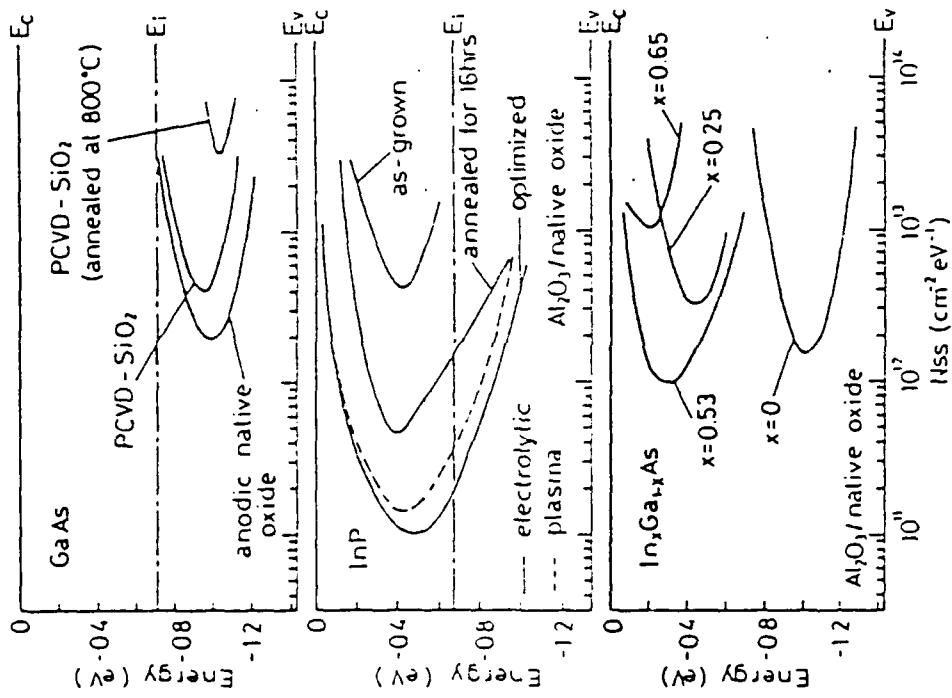


From H. H. Wieder, Surface Science 133 (1983) 390.



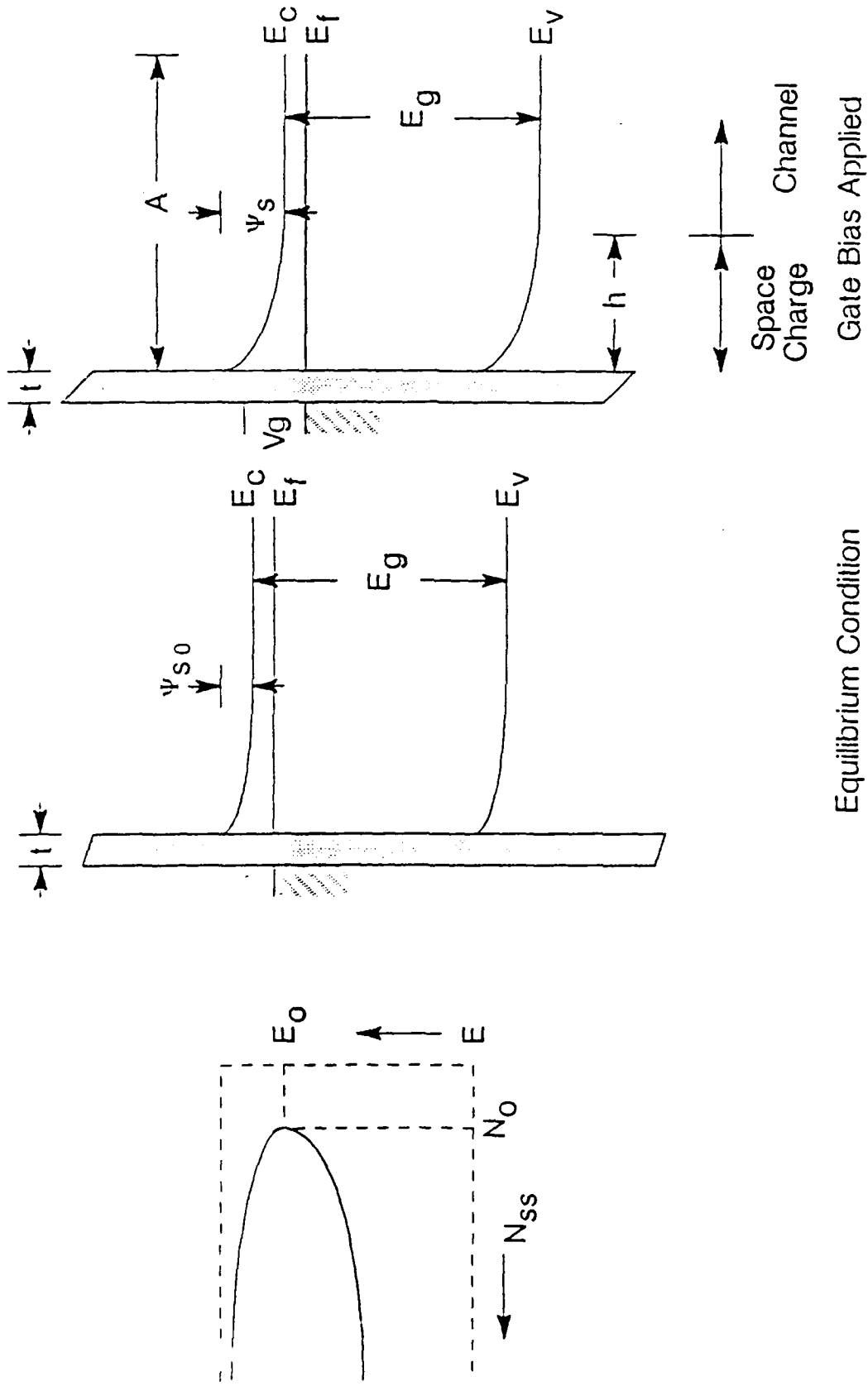
From P. D. Gardner et al. IEEE Electron. Dev. Lett.,

# Typical Distribution of Interface State Density within Energy Band Gap Measured by C - V or Optical Methods



Measured  $N_{ss}$  distribution of the I-S interfaces, using C-V and PCTS methods. Note that no peaks in the  $N_{ss}$  distribution are observed. While minimum  $N_{ss}$  and U-shape curvature depends on processing conditions, the location of  $N_{ss}$  minimum remains constant for each semiconductor.

Energy band diagram of an n-type InP MIS structure



## Charge control model

By Gauss law

Electrical field at the interface of insulator and semiconductor

$$E - E_0 = - \frac{1}{\epsilon_d} \left[ (Q_s - Q_{s0}) + (Q_{ss} - Q_{ss0}) \right]$$

$Q_s$  : space charge

$Q_{ss}$  : interface state charge

subscript 0 : equilibrium state value

$$V_g - V(x) = - \frac{t}{\epsilon_d} \left[ (Q_s - Q_{s0}) + (Q_{ss} - Q_{ss0}) \right] + (\psi_{s0} - \psi_s)$$

$t$  : insulator thickness

$\epsilon_d$  : insulator permittivity

$V(x)$  : channel potential

$\psi_s$  : surface potential

**Distribution of interface states within energy band gap** <sup>\*</sup>  
 Existing model ( uniform interface states distribution model ) :

$$N_{SS} = N_0 : \text{constant}$$

$$\Delta Q_{SS} = qN_0 ( \psi_s - \psi_{s0} )$$

Hasegawa's DIGS model :

$$N_{SS} = \begin{cases} N_0 \exp \left( \frac{E - E_0}{E_{0a}} \right)^{n_a} & E \geq E_0 \\ N_0 \exp \left( \frac{E_0 - E}{E_{0b}} \right)^{n_b} & E \leq E_0 \end{cases}$$

$$\Delta Q_{SS} = -q \left( \int_{\psi_s} N_{SS} f(E) dE \right) - \left( \int_{\psi_{s0}} N_{SS} f(E) dE \right)$$

$f(E)$  : the occupation function

Variable interface states distribution model :

Simplified Hasegawa's model with  $n_a = n_b = 1.0$

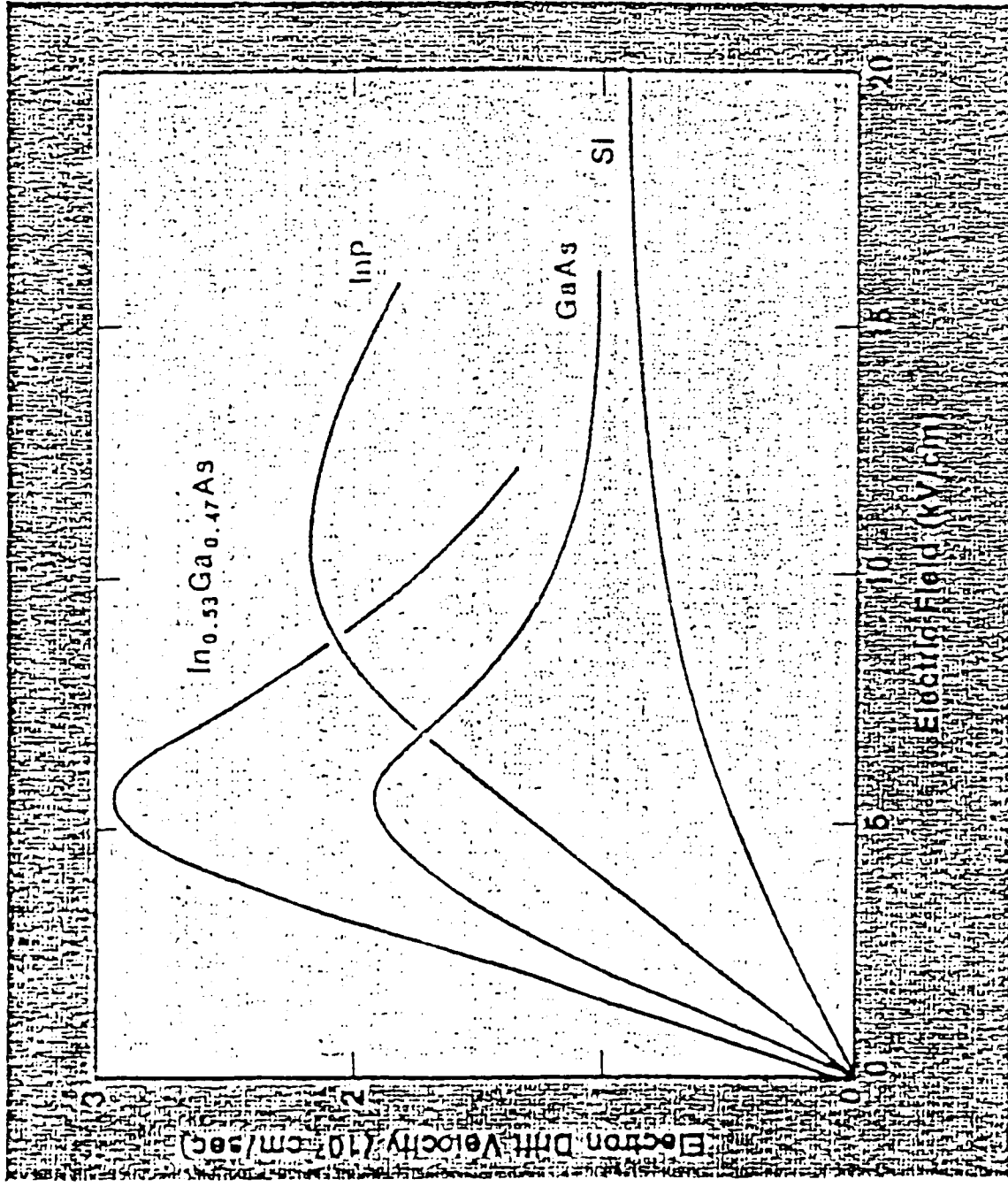
<sup>\*</sup> R. Pucel et al., *Advances in Electronics and electron Devices*, 38 (1975) 195.  
 D. Lile, *Solid-State Electron.*, 21 (1978) 1199.  
 P. Hill, *IEEE Trans. Electron Devices* ED-32 (1985) 2249.

## The empirical velocity versus electrical field model<sup>\*</sup>

$$v = \left\{ \begin{array}{l} \frac{\left( \mu + \frac{v_{\text{sat}}}{E_C} \right) E}{1 + \frac{E}{E_C}} \quad E \leq E_S \\ v_{\text{sat}} \quad E \geq E_S \end{array} \right.$$

where  $v_{\text{sat}} = \mu E_S$

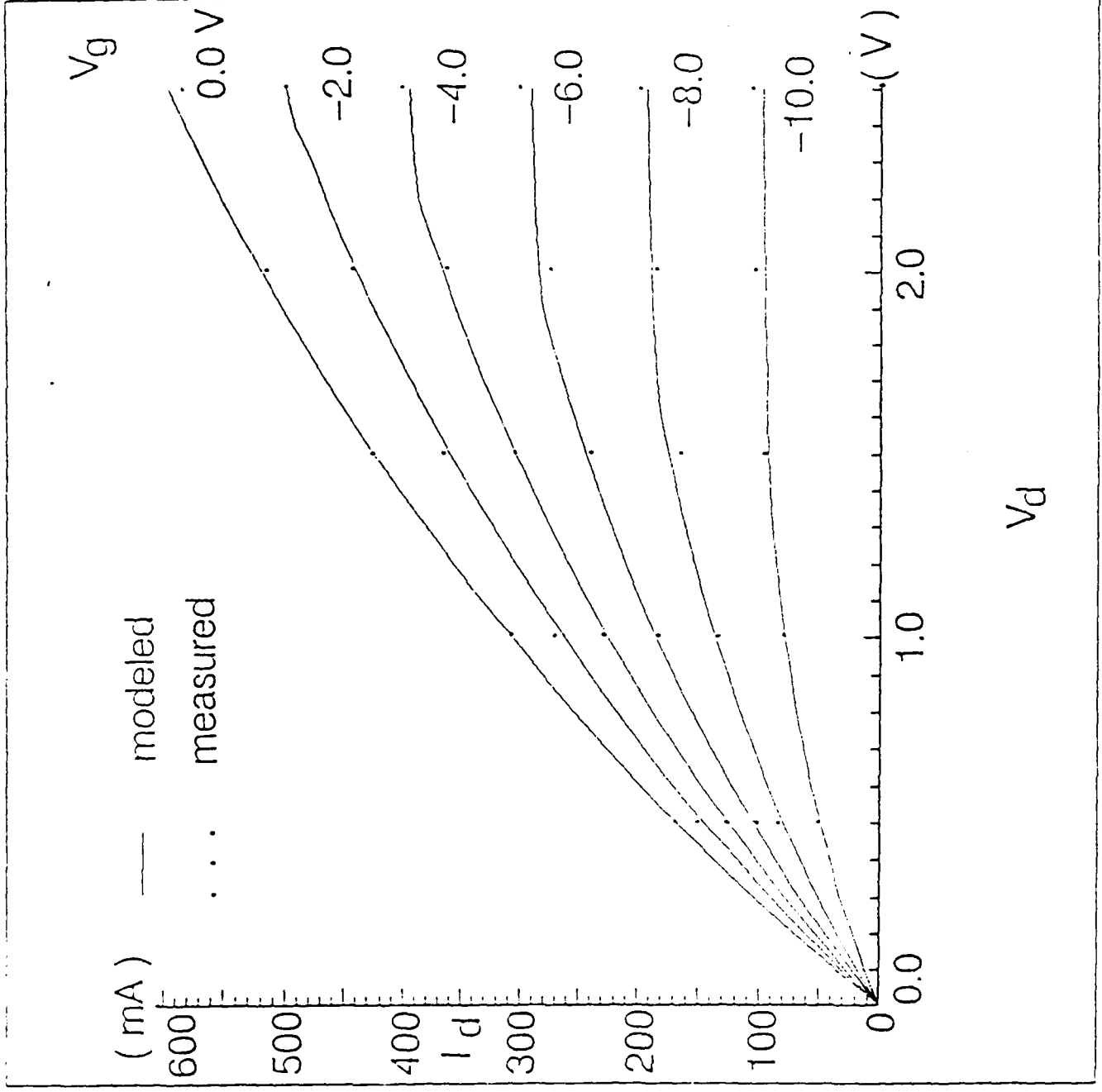
<sup>\*</sup> W. Curtice, *IEEE Trans. Electron Devices*, ED-29 (1982) 1942.



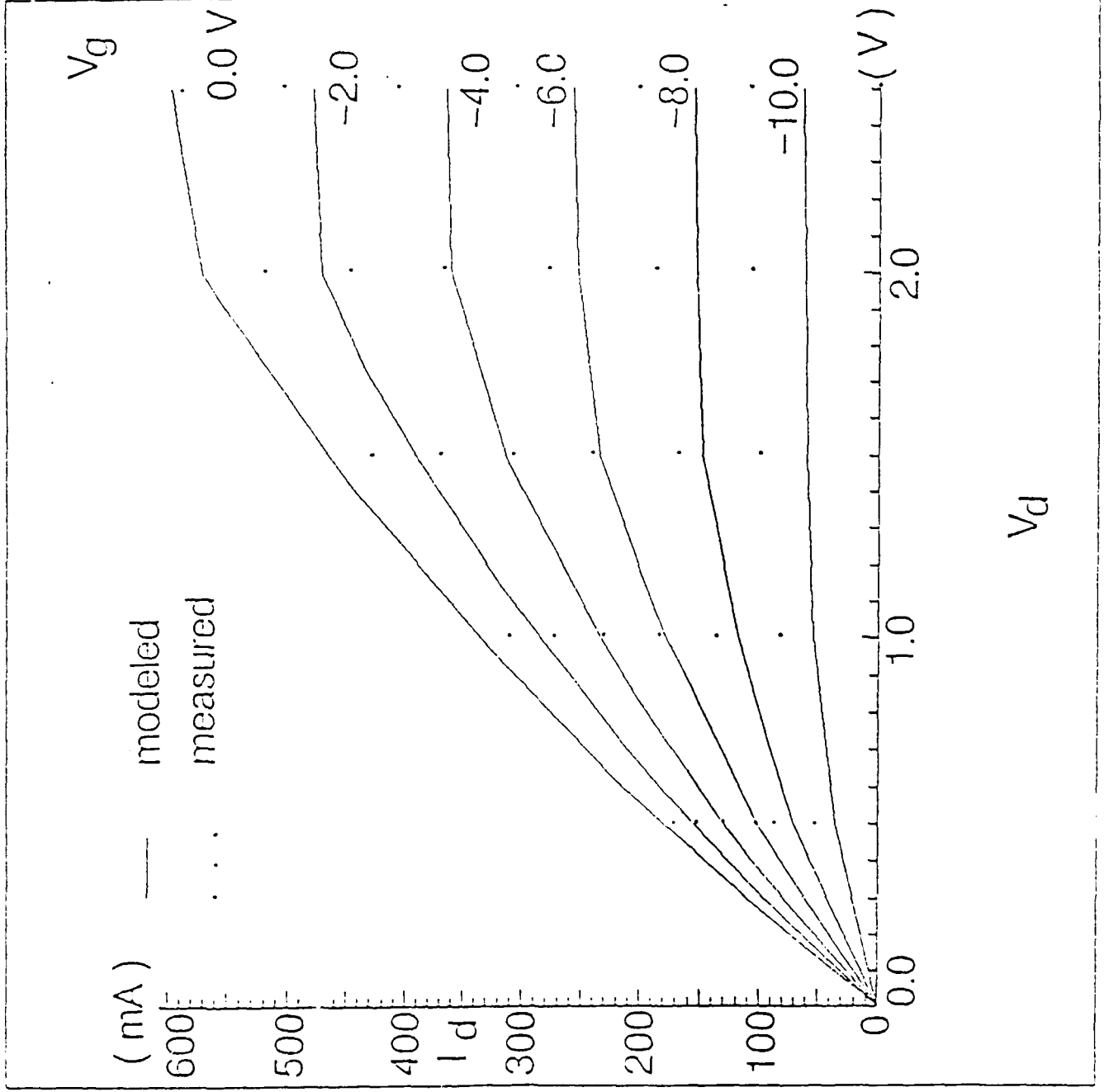
Electric Drift Velocity vs. Electric Field ( 300 K )

From H. Morkoc et al. *Solid State Technology*, 31 (1988), 83.

# Modeled Drain I - V Characteristics by Variable Interface State Distribution Model



# Modeled Drain I - V Characteristics by Uniform Interface State Distribution Model



Device parameters used in MISFET models  
for the best fit to the measured data

	variable density model	uniform density model	unit
L	1.4	1.4	$\mu\text{m}$ *
Z	1000	1000	$\mu\text{m}$ *
A	0.2	0.2	$\mu\text{m}$ *
t	1000	1000	$\text{\AA}$ *
$\mu$	2000	2000	$\text{cm}^2 / \text{Vs}$ *
$E_C$	$2.0 \times 10^4$	$2.0 \times 10^4$	$\text{V} / \text{cm}$ *
$E_S$	$1.15 \times 10^4$	$1.15 \times 10^4$	$\text{V} / \text{cm}$ *
$v_{\text{sat}}$	$2.38 \times 10^7$	$2.38 \times 10^7$	$\text{cm} / \text{s}$ *
$\epsilon_d$	3.9	3.9	$\epsilon_0$ *
$\epsilon_s$	12.4	12.4	$\epsilon_0$ *
$N_D$	$1.4 \times 10^{17}$	$1.4 \times 10^{17}$	$\text{cm}^{-3}$ *
$E_g$	1.34	1.34	$\text{V}$ *
$\psi_{s0}$	0.42	0.98	$\text{V}$
$N_O$	$1.2 \times 10^{11}$	0	$\text{cm}^{-2} \text{eV}^{-1}$
$E_{oa}$	0.11		$\text{V}$
$E_o$	$E_C - 0.34$		$\text{V}$
$R_s$	0.6	0.6	$\Omega$ *
$R_d$	0.6	0.6	$\Omega$ *

## Two-dimensional Simulation of III-V Compound Semiconductor Devices

### Objectives :

- Use two-dimensional simulation to assist in the analysis and modeling of short-channel effects.
- Include momentum balance and energy balance equations to take hot carrier effects into account.

### Features :

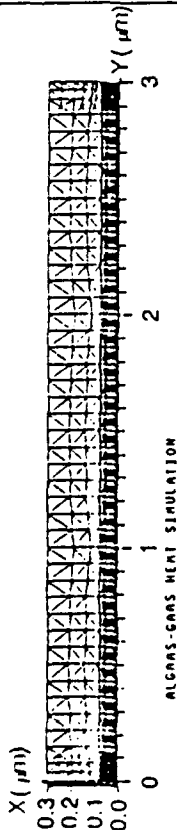
- New finite-element discretization method<sup>\*</sup>
- Fermi-Dirac statistics
- Velocity overshoot effect

\* W. Ku et al. *IEEE Trans. CAD*, to appear in May 1989

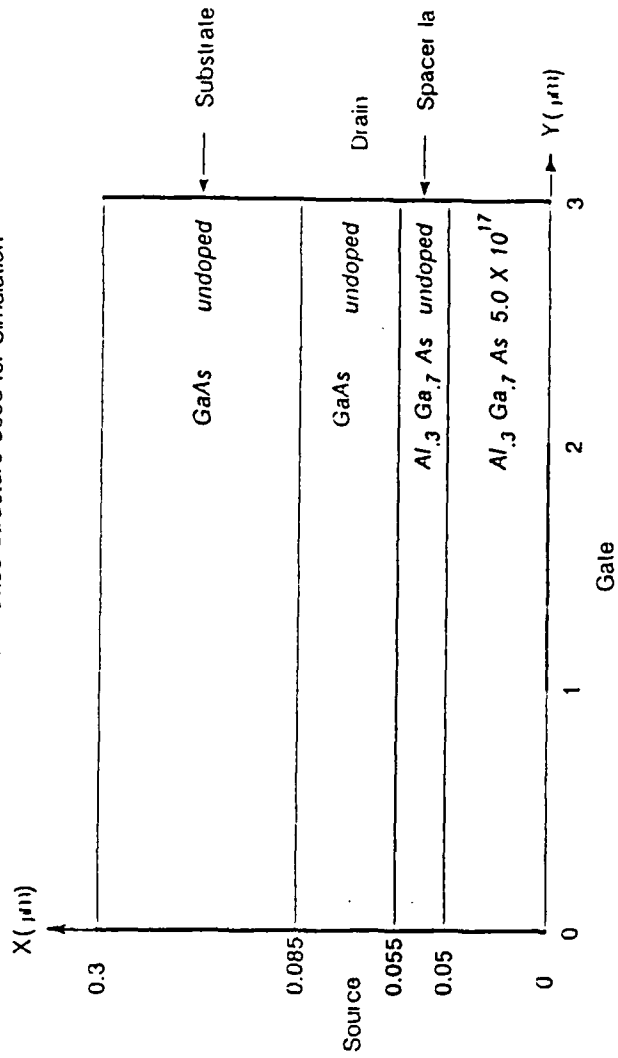
Simulation Mesh

# of points = 1273

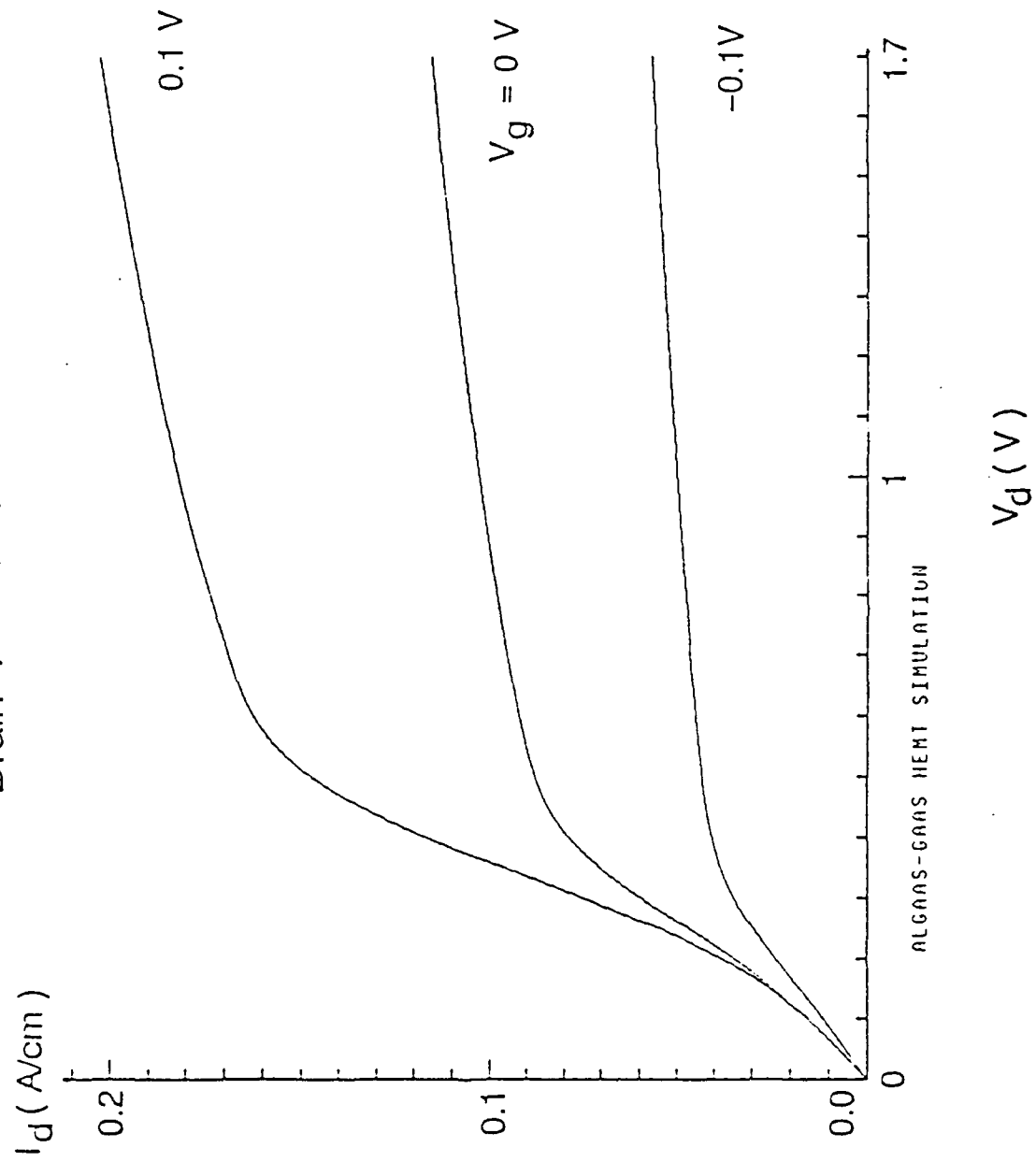
# of elements = 2380

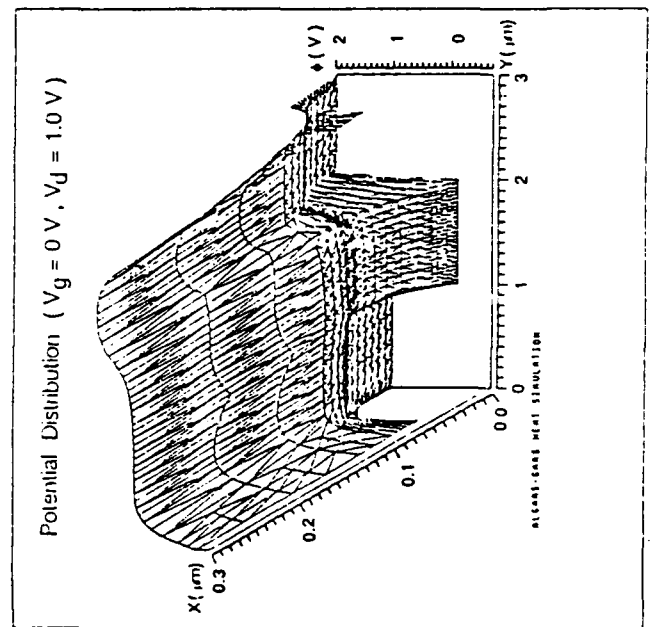
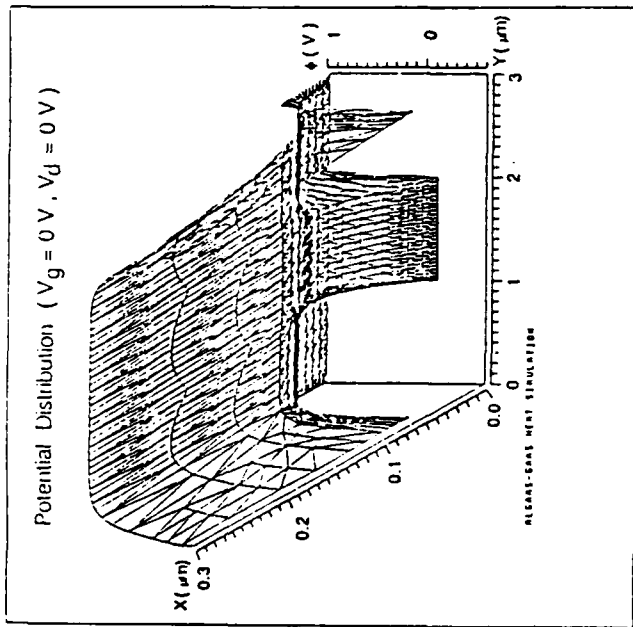
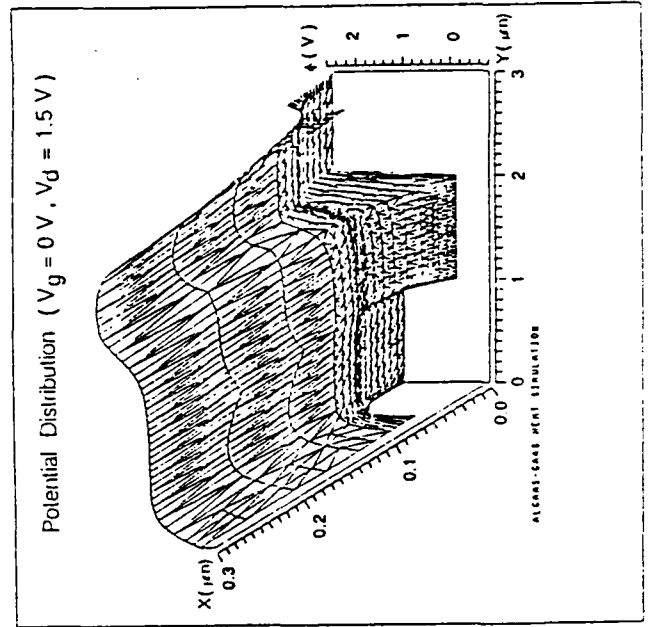
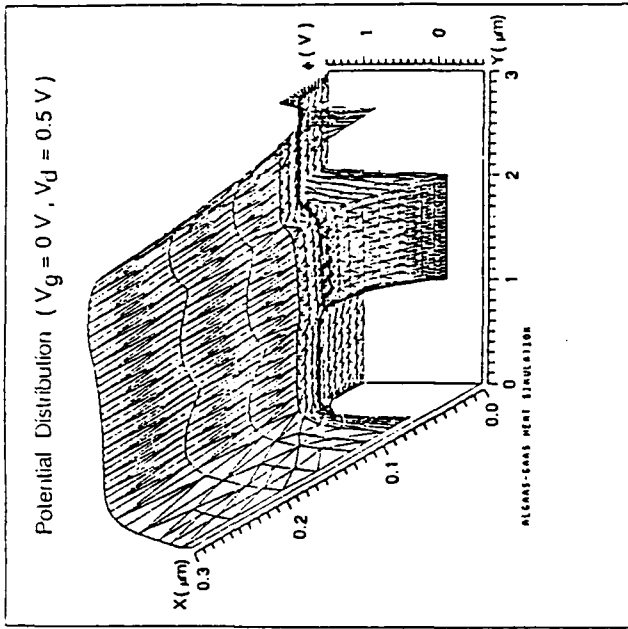


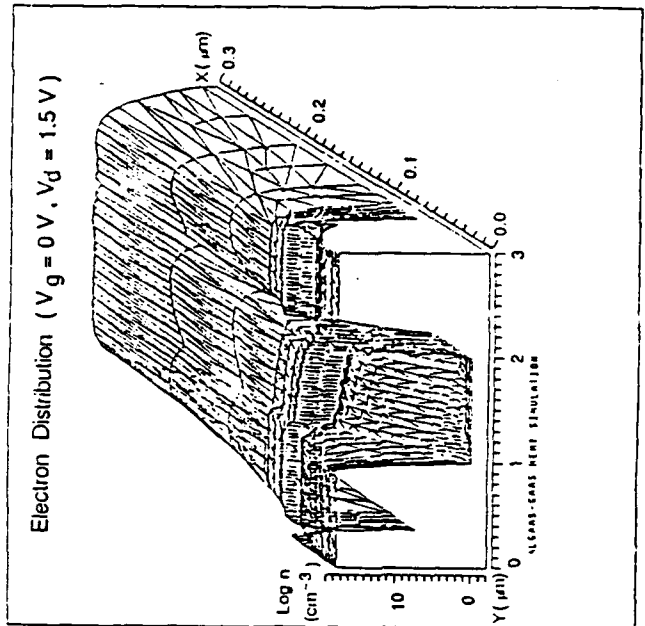
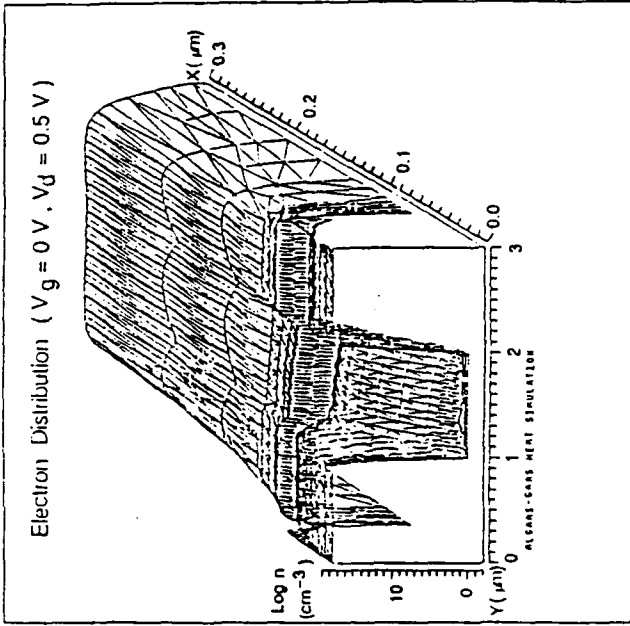
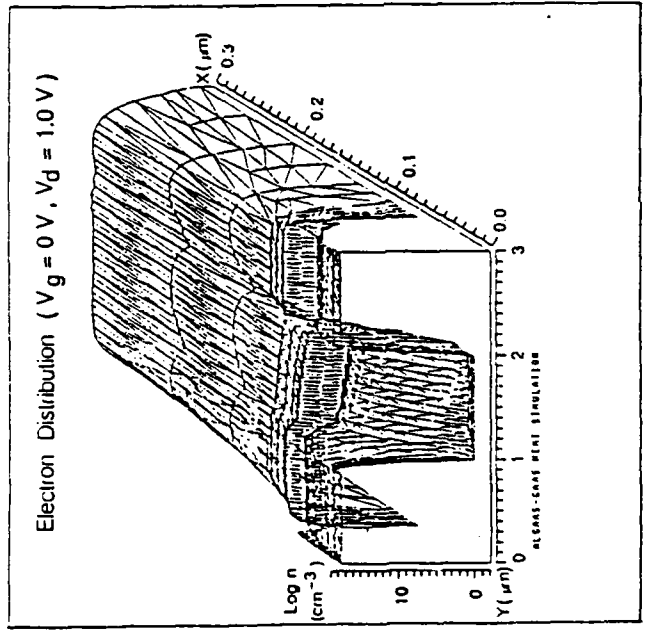
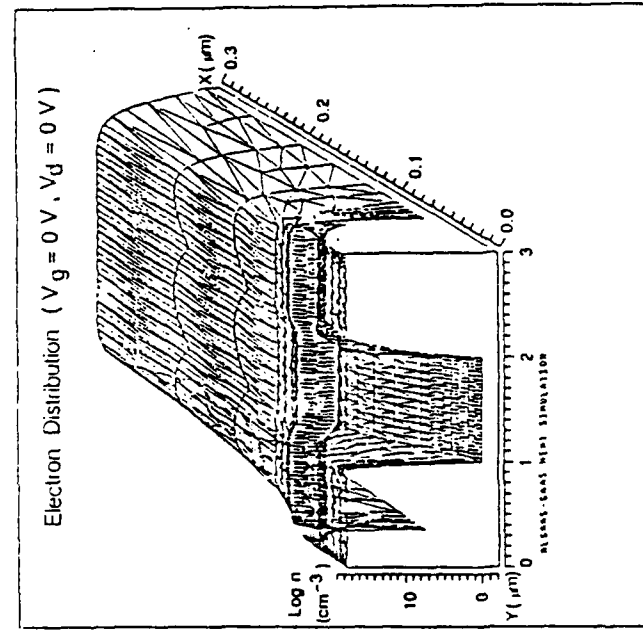
AlGaAs / GaAs HEMT Device Structure Used for Simulation



# Drain I - V Characteristics







## Summary

- The inclusion of interface states distribution profile into drain  $I - V$  characteristics model leading to a more accurate description of output performance of MISFETs
- Successful implementation of a two-dimensional model for HEMT devices based on a new finite-element discretization method
- Plan to apply the two-dimensional numerical model to the modeling of submicron gate length MISFETs and HEMTs