II-5

THEORETICAL COMPARISON OF 0.35 μm GATE LENGTH GaAs and GaInAs HEMTs

Duke H. Park and Kevin F. Brennan

School of Electrical Engineering and Microelectronics Research Center
Georgia Institute of Technology

Atlanta, Georgia 30332

We present a theoretical study of the performance of nearly identical 0.35 μm gate length HEMTs made from three different materials systems, $GaAs/Al_{0.32}Ga_{0.68}As$, $In_{0.15}Ga_{0.85}As/Al_{0.15}Ga_{0.85}As$, and $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$. The calculations are made using an ensemble Monte Carlo simulation which includes the full details of real space transfer, the transport properties of the two-dimensional electron gas, nonstationary transport, and the two-dimensional electric field profile through the self-consistent solution of the Poisson equation. The performance of each device type, measured in terms of the current-voltage characteristic, transconductance, and cutoff frequency is compared. In this way, the effects of the material parameters on the device performance can be completely isolated and as such independently ascertained. It is found that the InGaAs-based devices well outperform the "conventional" GaAs/AlGaAs device, consistent with recent experimental measurements. Of the three devices, the GaInAs/AlInAs structure provides the highest frequency performance and delivers the greatest current.

INTRODUCTION

One of the most important new semiconductor devices for microwave applications is the high electron mobility transistor, HEMT. Advancements in exacting materials growth technologies, such as molecular beam epitaxy and metal organic chemical vapor deposition, have enabled the practical realization of these structures. Though GaAs/AlGaAs is by far the most mature materials technology, the highest frequency performance of HEMTs has been reported in devices made from Indium based alloys. To date, the record HEMT cutoff frequency is ~170 GHz measured for a 0.1 μm gate length, $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As$ device [1]. This is substantially higher than that reported for a 0.1 μm gate length GaAs/AlGaAs device, ~110 GHz [2], and for a 0.2 μm gate length pseudomorphic HEMT, ~120 GHz [3]. Though some attempt has been made to compare the performance of devices made from each of these material compositions [4,5], no systematic study, either by experiment or theory, using identical or nearly identical structures has been made. It is the purpose of this paper to present the first such theoretical comparison of identical conventional, $GaAs/Al_{0.32}Ga_{0.68}As$, pseudomorphic, $Al_{0.15}Ga_{0.85}As/In_{0.15}Ga_{0.85}As$ and lattice matched, $Ga_{0.47}In_{0.53}As/Al_{0.48}In_{0.52}As$ HEMTs.

In essence, we present a "computer experiment" in which the effect on device performance of different material systems, in otherwise identical device structures, is examined. Our model has been carefully tested throughout each stage of its development to experimental data or other independent calculations. Ultimately, the model calculations are compared to a comparable experimental structure. Excellent agreement between the calculated and experimental current-voltage characteristic is found. Thus, our model can then reliably predict the performance of similar structures, forming the basis for a comparison of different materials systems.

MODEL DESCRIPTION

The calculations are made using an ensemble, many particle Monte Carlo simulation coupled with a two-dimensional Poisson solver. The Monte Carlo model includes the complete transport properties of the two-dimensional electron gas, nonstationary transport, i.e. ballistic transport and velocity overshoot, and real space transfer. A three valley, nonparabolic band structure is used for each bulk constitutive material. The material parameters used in the simulation, such as the optical phonon energy, intervalley threshold energies, valley effective masses, and static and high frequency dielectric constants are determined by comparing the calculated values of the bulk drift velocity, threshold electric field, and peak carrier velocity to experimentally measured quantities [6,7]. In this way, a reliable set of material parameters can be determined which leads to an accurate representation of each bulk system. The full details of the model have been reported elsewhere [8,9], but the key ingredients of the simulation can be summarized as follows.

The transport within the two-dimensional system formed at the heterojunction as well as classical real space transfer have been independently studied and compared to experiment [7,10]. Excellent qualitative agreement between our model and previous calculations [11] has been found yielding high confidence in the accuracy of the model.

Transport within the two-dimensional electron gas is modeled as follows. The two-dimensional system for each device type is defined by the triangular quantum well formed at the heterostructure interface between the narrow gap and large gap semiconductors. The well is bordered on

1989 IEEE MTT-S Digest

one side by the conduction band edge discontinuity and on the other side by the band bending. For simplicity, only the first two subbands are included in the simulation. When the electron is confined within the two-dimensional system, its k-vector in the y-direction remains fixed during its flight while the x and z components change in accordance with the action of the applied electric field. The electron's trajectory is subject to various two-dimensional scattering mechanisms, such as polar optical phonon, remote impurity, acoustic phonon, and where appropriate, alloy scattering.

The coupling of the two-dimensional system to the three-dimensional bulk, defined as those states above the band bending energy, is done in two ways. First, the electron can transfer between the two systems via drifting upwards or downwards in energy. At electron energies greater than that corresponding to the band bending, the transport is assumed to be that of the bulk three-dimensional system. Similarly, if an electron drifts to lower energies below the well height, the electrons are assumed to transfer to the two-dimensional states. Though this approach is somewhat artificial, the net result is physically correct; when the electrons are at energies below the top of the well, they are treated as belonging to the two-dimensional system. Alternatively, transfer can occur via polar optical phonon scatterings. At electron energies near the top of the well, the electron can transfer between the two and three-dimensional systems through phonon absorption or emission.

Numerous, ~9000, electrons are simulated in the calculation. The effect of the self-consistent electric field, as well as the gate and drain fields, is included by solving the two-dimensional Poisson equation at various intervals during the simulation. The interval between successive solutions of the Poisson equation is chosen sufficiently short so as to avoid serious error from the failure to update the electric field while as long as possible to save computer time. Nevertheless, all of the calculations are performed on a Cray XMP supercomputer.

CALCULATED RESULTS

The device structures for each material system examined in this work are presented in Figure 1. All of the structures are essentially identical except for the different materials systems employed. The geometry was chosen to closely correspond to the AlGaAs/InGaAs pseudomorphic HEMT analyzed by Nguyen et al. [12]. The doping concentration in each device is taken as 3.0×10^{18} cm^{-3} within the source and drain contacts, as well as in the modulation doped region, and 3.0×10^{15} cm^{-3} within the unintentionally doped layers. Though the doping concentrations are quite high, degeneracy effects are not included in the calculation. These effects will be addressed in a later work.

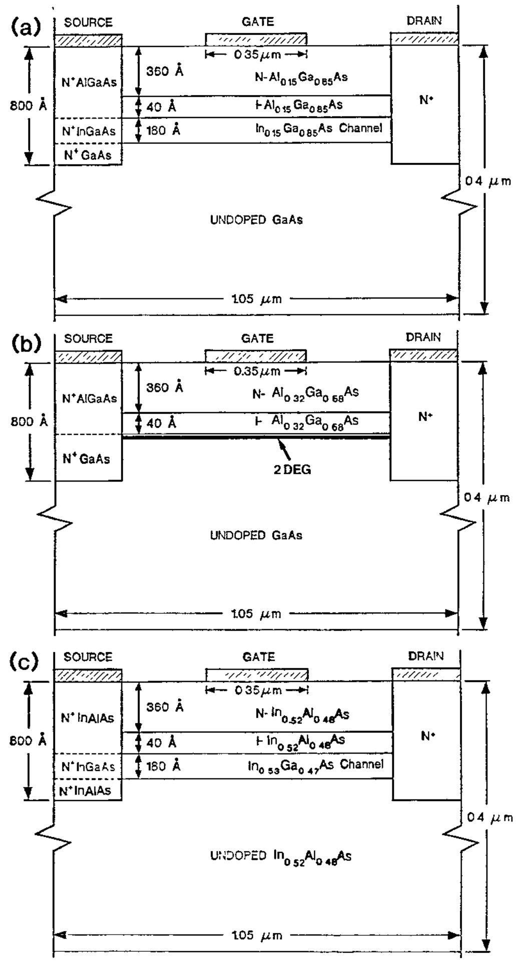

Figure 1: (a) Cross sectional view of the pseudomorphic HEMT used in the simulation.
(b) Cross sectional view of the conventional GaAs/AlGaAs HEMT.
(c) Cross sectional view of the GaInAs/AlInAs HEMT.

The calculated and experimentally measured [12] current-voltage characteristics for the pseudomorphic AlGaAs/InGaAs device are shown in Figure 2. The calculated points are marked as solid dots in the figure. The dashed lines illustrate the family of curves on which the calculated points lie. As can be readily seen from the figure, excellent agreement between theory and experiments is attained. It is important to note that no adjustable "fitting" parameters are used in the calculation. The results are determined from a first principles solution of the electron transport. Therefore, the model can reliably describe the behavior of various other structures.

In order to characterize the performance of these devices for microwave applications, it is necessary to compare their current-voltage characteristics and, more importantly, their transconductances and cutoff frequencies. The calculated current-voltage characteristics for the

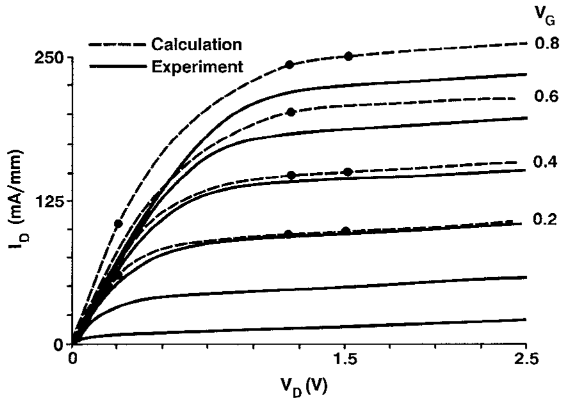

Figure 2: Calculated, marked by solid points, and experimental current-voltage characteristic for a 0.35 μm AlGaas/GaInAs pseudomorphic HEMT. The experimental measurements are from Nguyen et al. [12]. The dashed curves illustrate the family of curves predicted by the calculations.

"conventional" GaAs/AlGaAs and lattice matched, GaInAs/AlInAs devices are shown in Figures 3 and 4, respectively. Comparison of the three characteristics reveals that the current at identical bias is greatest in the GaInAs/AlInAs device. In fact, the current is more than twice as high in the GaInAs/AlInAs device than in the pseudomorphic HEMT and more than four times greater than that in the GaAs HEMT. Since the geometries and doping concentrations are identical among the three device types, the calculated difference in the current arises solely from the different properties of the materials systems employed.

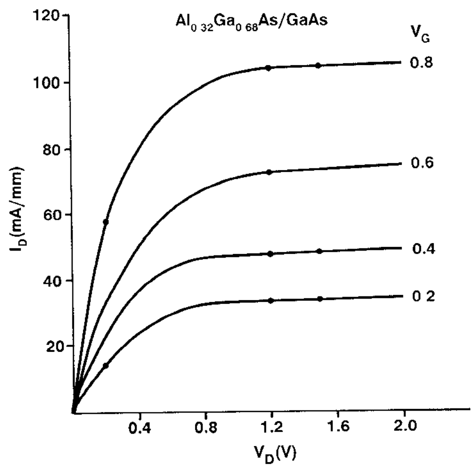

Figure 3: Calculated, marked by solid points, current-voltage characteristic for a 0.35 μm gate length GaAs/AlGaAs conventional HEMT. The lines represent the predicted family of curves for the current-voltage characteristic.

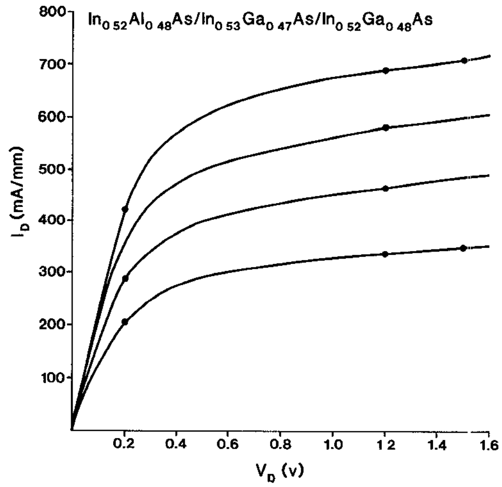

Figure 4: Calculated, marked by solid points, current-voltage characteristic for a 0.35 μm gate length GaInAs/AlInAs HEMT. The lines represent the predicted family of curves for the current-voltage characteristic.

For microwave applications, the transconductance and cutoff frequency of the device are of greater importance. The transconductances of each device are plotted together as a function of gate bias at a fixed drain bias of 1.2 volts in Figure 5. Notice that the peak transconductance is greatest in the GaInAs/AlInAs device. The transconductance of the pseudomorphic HEMT is more constant over a wider range of bias however, than that in either of the other two devices.

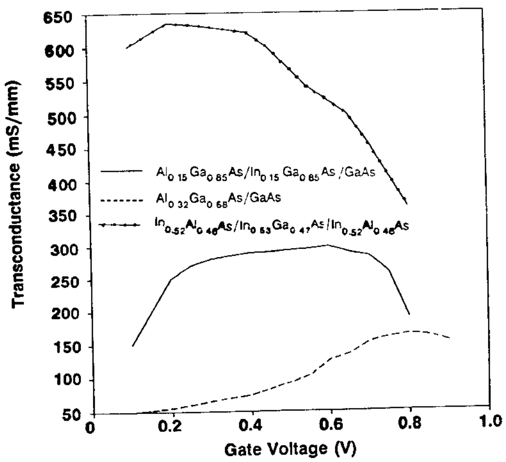

Figure 5: Transconductance in all three device structures plotted as a function of gate voltage at a drain bias of 1.2 volts.

The cutoff frequencies of each device type are plotted as a function of gate voltage at a fixed drain bias of 1.2 volts in Figure 6. Clearly, the GaInAs/AlInAs device exhibits the greatest cutoff frequency. From these calculations, a cutoff frequency as high as 135 GHz is possible. It is important to note however, that no parasitic effects, such as contact resistances and capacitances, have been included. Therefore, the calculated values of the cutoff frequencies should be considered as the most optimistic values possible for each device type. Nevertheless, the calculated cutoff frequencies provide a meaningful way of comparing each structure. The cutoff frequency of the pseudomorphic HEMT, though less than that attainable in the GaInAs/AlInAs device, is apparently less sensitive to the gate bias.

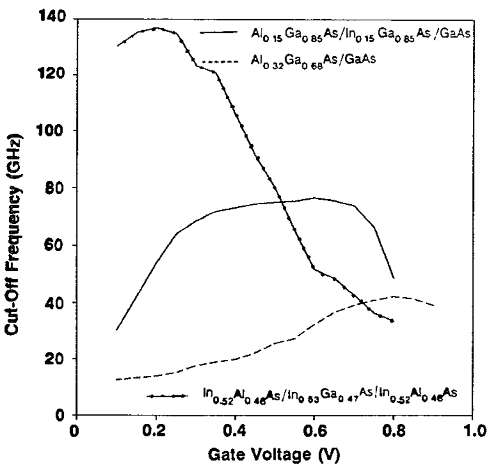

Figure 6: Cutoff frequency in all three device structures plotted as a function of gate voltage at a drain bias of 1.2 volts.

CONCLUSIONS

In this paper, we have presented a "computer experiment" in which the effect of three different material compositions, in otherwise identical HEMTs, is evaluated. The performance of each device in terms of current-voltage characteristic, transconductance, and cutoff frequency is examined. It was found that the lattice matched, GaInAs/AlInAs HEMT device significantly outperformed either the GaInAs/AlInAs pseudomorphic HEMT or the conventional GaAs/AlGaAs HEMT in these criteria. The cutoff frequency of the GaInAs/AlInAs device is predicted to be as high as 135 GHz, well above the peak values of the pseudomorphic, 76 GHz, and GaAs, 42 GHz, devices. The predicted cutoff frequencies are somewhat optimistic since no parasitic effects are included in the analysis. Nevertheless, they serve as an upper limit to possible high frequency performance.

The superior performance of the GaInAs/AlInAs HEMT over the other device structures arises from the much greater electron confinement within the channel region. This is due to the much greater conduction band edge discontinuity formed on either side of the channel. As a consequence, the electrons are more highly confined within the channel region than in either of the other two device types [8,9], resulting in much higher frequency performance.

ACKNOWLEDGEMENTS

The authors would like to thank P. Knight and D. Fouts at the Georgia Institute of Technology for their assistance in the preparation of this manuscript. This work was sponsored in part by a Presidential Young Investigator Award from the National Science Foundation, and by a matching grant from Bell Communications Research. Use of the National Science Foundation Pittsburgh Supercomputer Center is gratefully acknowledged.

REFERENCES

[1] U.K. Mishra, et al., "Microwave performance of AlInAs-GaInAs HEMTs with 0.2 and 0.1-μm gate length," IEEE Electron Dev. Lett., vol. EDL-9, pp. 647-649, 1988.

[2] A. Lepore, et al., "Fabrication and performance of 0.1 μm gate-length AlGaAs/GaAs HEMTs with unity current gain cut-off frequency in excess of 110 GHz," presented at the Device Res. Conf., Boulder, CO, June 1988.

[3] L.D. Nguyen, et al., "0.2 μm gate-length atomic-planar doped pseudomorphic $Al_{0.3}Ga_{0.7}As/In_{0.25}Ga_{0.75}As$ MODFETs with f_t over 120 GHz," IEEE Electron Dev. Lett., vol. EDL-9, pp. 374-376, 1988.

[4] K. Hikosaka, et al., "Current-gain cutoff frequency comparison of InGaAs HEMTs," IEEE Electron Dev. Lett., vol. EDL-9, pp. 241-243, 1988.

[5] A.A. Ketterson, et al., "Characterization of InGaAs/AlGaAs pseudomorphic modulation-doped field-effect transistors," IEEE Trans. Electron Dev., vol. ED-33, pp. 564-571, 1986.

[6] K.F. Brennan, et al., "Theory of the velocity-field relation in AlGaAs," J. Appl. Phys., vol. 63, pp. 5004-5008, 1988.

[7] K.F. Brennan and D.H. Park, "Theoretical comparison of electron real space transfer in classical and quantum two-dimensional heterostructure systems," J. Appl. Phys., vol. 65, pp. 1156-1163, 1989.

[8] D.H. Park and K.F. Brennan, "Theoretical analysis of an $Al_{0.15}Ga_{0.85}As/In_{0.15}Ga_{0.85}As$ pseudomorphic HEMT using an ensemble Monte Carlo simulation," accepted for publication in IEEE Trans. Electron Dev.

[9] D.H. Park and K.F. Brennan, "Monte Carlo simulation of 0.35 μm gate length GaAs and InGaAs HEMTs," submitted to IEEE Trans. Electron Dev.

[10] D.H. Park and K.F. Brennan, "Theory of electronic transport in two-dimensional $Ga_{0.85}In_{0.15}As/Al_{0.15}Ga_{0.85}As$ pseudomorphic structures," J. Appl. Phys., vol. 65, pp. 1615-1620, 1989.

[11] T.H. Glisson, et al., "Monte Carlo simulation of real space electron transfer in GaAs-AlGaAs heterostructures," J. Appl. Phys., vol. 51, pp. 5445-5449, 1980.

[12] L.D. Nguyen, et al. "Charge control, DC, and RF performance of a 0.35 μm pseudomorphic AlGaAs/InGaAs modulation-doped field-effect transistor," IEEE Trans. Electron Dev., vol. ED-35, pp. 139-143, 1988.