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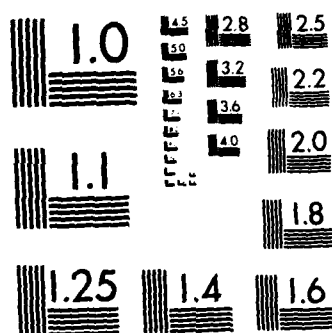
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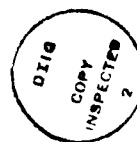
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1983 MINIGRANT FACULTY RESEARCH PROGRAM

Sponsored by the
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

FINAL REPORT

Gallium Arsenide Field-Effect Transistor Magnetic Field Studies

Prepared by: Michael J. Moloney
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Abstract

This Minigrant work followed the author's effort in the 1982 Summer Faculty Research Program at WPAFB developing a prototype GaAs FET computer model. During the Minigrant work, the computer model was developed, tested and run extensively.

Development included using true GaAs velocity overshoot correctly in the model, greatly increasing model speed, evolving an improved way to handle carrier transport, studying conduction through the semi-insulating substrate, handling individual cell doping and mobility, testing the model for valid capacitance calculations, testing the model for Gunn oscillations in a diode configuration (and obtaining good results), and use of rectangular cells rather than the original square ones.

Consultation with Dr. David C. Look of AFWAL/AADR, WPAFB was continuous and highly beneficial, resulting in a joint paper presented at the March 1984 APS meeting and a second collaboration in press.^{1,2}

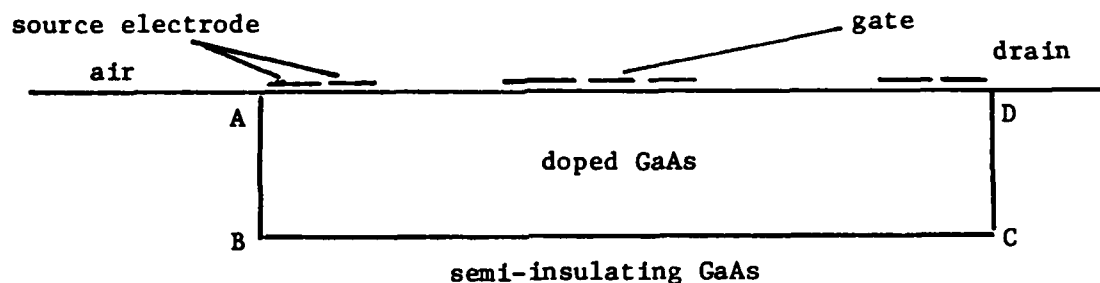
AIR FORCE
WPAFB
1984

DR. DAVID C. LOOK
CHIEF, TECHNICAL STAFF DIVISION

Discussion of Effort

A prototype computer model of GaAs FETs was created during the author's tenure in the 1982 Summer Faculty Research Program (SFRP) at Wright-Patterson AFB, and its general features are now briefly reviewed.

The doped device structure lies in region ABCD of the semi-insulating GaAs half-plane in a large number of cells. Source, gate, and drain electrodes are modelled by uniform sheet charges, and the model evolves in a series of time steps with charge flowing under the influence of diffusion and drift.



Immediate improvements in this model after the summer of 1982 were rectangular cells and not just square ones in region ABCD, greatly increased calculational speed, and use of true velocity overshoot relations for GaAs.

At $t=0$, all cells in the model are neutral, with as many electrons as donors, and the electric field comes from the sheet charges on the source, gate, and drain electrodes. In the first time step, the electrons move due to electric fields only. After that, each cell has a net charge, and then every charge throughout the model

is used to calculate the electric potential at the center of every cell, and charges move due to both drift and diffusion between cells in the region ABCD. The cells directly underneath the source and drain electrodes are maintained electrically neutral, and net flow of charge is into and out of these cells. No charge flow is otherwise permitted through the boundary ABCD.

After some hundreds of time steps, the charge flowing into each cell equals the charge flowing out of that cell. This is the "steady state" for the model, and one may then examine the electron concentration, electric current, electric fields, etc., throughout the model.

The influence of a unit charge in one cell of the model on the electric potential of all other cells, including the effects of the air-GaAs boundary and the electrodes is calculated one time at the beginning of a run, and the "influence coefficients" for potential in one cell due to unit charge in another are then saved for use prior to each time step. The built-in voltage at the gate Schottky barrier is taken into account simply by applying a suitable potential to the gate electrodes, in addition to the externally applied gate voltage.

For a model of N cells, there are $N^2/2$ coefficients which have to be stored and then used in N^2 multiplications and additions prior to each time step. After some major economies very early on, the author tried some half-dozen schemes to help out with the " N^2 " problem, but none offered any real improvement.

For 200 cells in the model, it takes some 5 minutes of VAX 11/780

CPU time to obtain a single data point on an I-V curve. Thus, the largest feasible number of cells in the model is around 500, owing to long execution time and storage requirements for the coefficients.

Gunn oscillations were undertaken as a short study in the development of the model as a test of whether the transport calculations were being done correctly. Since true velocity overshoot in the drift-velocity vs. electric field curve had been implemented, it was felt that Gunn oscillators should "fall out" of the GaAs FET model if all the device physics was correctly in place. The work on Gunn oscillators was successful in modelling devices, in particular reproducing the results of Aishima³ et. al. where a "notch" in concentration would cause Gunn domains to break off and travel down the device. It was also successful in making the author aware that the Einstein relation could not be used at high electric fields and in his employing a high-field diffusion constant.

A limited amount of work was also done right during and after the Gunn oscillators on graphical output: projected views of electron concentration in the model or voltage in the model at selected points in time. This was a very interesting interlude, but time did not permit truly high quality output to be generated.

Several weeks of Minigrant effort were devoted to studying "parasitic" conduction from the doped region via the semi-insulating substrate. There is a definite Fermi level difference between the intentionally doped area of the device and the lightly doped region surrounding it and thus a barrier to electrons moving into the

substrate. The modeling was done by assigning roughly 10^{17} cm^{-3} doping to the "device" area and some 10^{14} cm^{-3} to the surrounding area. This modeling did not reach a definitive conclusion, but it was quite valuable at focusing on the inadequacy of the "straightforward" transport equations for drift and diffusion and at properly modeling the "barrier" between the regions. Some of this inadequacy had been seen earlier in the way depletion occurred under the gate.

Effort was thus directed to find a more suitable form of the transport equations for use with the relatively large cells in the model. This effort was successful and provides a definitely superior method of transport calculation to be briefly described in what follows.

The first versions of the model had used for j_n the electron current density

$$(1) \quad j_{nx} = q(D_n \frac{\partial n}{\partial x} + \mu_n n E_x), \text{ where } n = \text{electron concentration}$$

μ_n = electron mobility

$q = 1.6 \times 10^{-19}$ coulombs

D_n = electron diffusion constant

$E_x = -\frac{\partial V}{\partial x}$ = electric field
x-component

At low fields, the Einstein relation is valid, $D_n = \mu_n kT/q$ and (1) may be rearranged to

$$j_{nx} = qD_n n \frac{\partial}{\partial x} (\ln n - qV/kT).$$

A little more manipulation gives

$$(2) \quad j_{nx} = e^{qV/kT} qD_n \frac{\partial}{\partial x} (n e^{-qV/kT}).$$

This form (modified at high electric fields when the Einstein relation does not hold) has served very well as a basis for transport calculations in the last half of the Minigrant work and is the major tool used in a paper by the author.⁵

For FET gate lengths shorter than one micron, heating of electrons and ballistic effects become important to device operation. These topics were studied during the minigrant work, because of their fundamental importance, and it was found possible to include these effects in the numerical model, mainly following the work of Carnez⁴ et. al. Average energy per electron in each cell of the model is calculated based on increases due to heating by the electric field and energy relaxation via lattice collisions. Linear momentum components were also calculated in each cell due to electric field-time increases and a momentum relaxation time for collisions with the lattice. Carnez et. al. used a one-dimensional Monte Carlo simulation to generate curves of effective mass vs. average cell energy, so that drift velocity components could be evaluated from momentum components.

This author stated in the Minigrant proposal that it might be possible to measure the effect of a magnetic field pointed along the long direction of the gate, forcing moving charge carriers from source to drain toward or away from the gate and acting in a sense like an additional gate voltage. This effect was looked for in several devices, but in all cases there was no observable difference in device current with or without a magnetic field of about 0.85 T present.

A number of successful measurements of "magnetoresistance mobility" were made at Rose-Hulman, providing good experience for this author and his students.

It was also stated in the Minigrant proposal that some of the Wallis-Jay results might have been due to high fields, even with only 50 mV from source to drain, but model results show clearly that no high electric field is present under these conditions.

There were high hopes for capacitance measurements when the Minigrant proposal was written, and a very forceful and successful test was done after that but prior to the formal start of the Minigrant, in which excellent results for capacitance were obtained for the classic one-dimensional situation, as well as showing that precisely as much charge was added to the gate electrodes as was depleted from underneath the gate--a very powerful test of the charge and field calculations within the model.

About half a dozen commercial GaAs FETS were tested at Rose-Hulman, but all had quite small capacitances, such that the capacitance bridge setup at Rose-Hulman could not give precise enough results to be helpful in device modeling.

In addition to their small capacitances, the great disadvantage of commercial GaAs FETs is that their exact construction is not known. The author never solved this problem but was able to use one of the techniques of Fukui⁶ to graphically determine the source-plus-drain resistance of one of his commercial FETs.

I-V curves were taken on the commercial GaAs FETs using the

Keithley voltage and current sources. This was excellent experimental experience, in the course of which we found that the Keithley 610C electrometer does not sink more than around 7 mA of current and so had somewhat limited utility. The author and one of his students spent a significant amount of time attempting to remotely command the Keithley model 220 and model 230 through an IEEE 488 connector driven from a KIM-1 microcomputer. The author had extensive conversations on the phone with Keithley in Cleveland but never had success at this automation attempt.

The heart of the Minigrant work lay in consultation and collaboration with Dr. David C. Look at AFWAL/AADR, Wright-Patterson AFB. Telephone conversations and exchange of items in the mail were fairly continuous from the end of the summer in 1982 through the present, including a visit by the author to AFWAL/AADR at the end of June 1983 to give a presentation and to discuss the progress of the work. Dr. Look motivated the adaptation of the model to include arbitrary doping and arbitrary mobility in each cell of the model, so that implanted structures with experimentally known doping and mobility profiles could be numerically modelled.

Things came together in the modeling and in Dr. Look's experimental work on profiled and implanted GaAs FETs late in 1983, so that the computer model was able to contribute to two studies in this area.^{1,2}

Conclusion

The two-dimensional GaAs FET model from the summer 1982 SFRP at Wright-Patterson AFB has been developed and is currently capable of realistic device modeling. The experimental work carried out at Rose-Hulman was highly beneficial in terms of experience for the author and his students, but it did not play as significant a role in the Minigrant work as had been anticipated.

The author wishes to express his appreciation for the opportunity to study a great many aspects of GaAs FET device physics during the Minigrant. This experience was beneficial to the "device physics" course taught by the author this past winter and is very valuable as the author begins work on analysis of modulation-doped FETs (MODFETS) with Dr. Hadis Morkoç at the University of Illinois.

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