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GaN Modeling & CAD

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14. ABSTRACT

Fundamental contributions to science:
Mobility – the GaN and GaAs mobility curves have previously been modelled as linear and saturated regions. Turns out there is an intermediate region that are in the physics publications but the current models have ignored or “simplified”. This impacts Psat vs PAE load-pull.
Gradual channel approximation – the traditional formulation is incorrect for pHEMTs given the quantum quantisation of the 2DEG. This effects gm slope in saturation which impacts OIP3 in GaN.
Diffusion current – this current traditionally ignored as “small” relative to majority carrier drift current. There is a substantial diffusion near pinch-off which makes a contribution to total charge and shifts the C vs V curve for the device. This has implications for envelope simulation in particular.
Initial work to add nonlinear noise modelling inherent to MQFET 2.0: single model giving linear, nonlinear, & noise
New Technology status – partial implementation of new GaN measurement tehnology
Arbitrary Pulsed Semiconductor Parameter Analyser 2.0 – system assembled & software being coded
1.0 - custom measurement system developed for GaAs by Macquarie with HP
Upgraded for GaN long-time constant trapping

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PI's: Prof. Michael Heimlich and Emeritus Prof. Tony Parker

PO: Dr Jeremy Knopp

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Introduction

The Macquarie HEMT model uses physics inspired descriptions of current, charge, trapping and heating that are extracted as a single-finger core embedded in an arbitrary layout. Significantly, the model scales with device topology and extrapolates to bias and frequency conditions outside the initial extraction domain. The modelling approach is effective but required specialist experience for implementation. Although well proven in a range of GaAs technologies, the model was not widely available nor tested in GaN technologies.

This project addressed the requirements for systematic implementation procedure, application to GaN, and wider dissemination of the capability. A key outcome is the leverage of the capability to support further projects with industry and defence.

Four avenues of work were completed to provide technology transfer to AFRL, to extened the model capability, to demonstrate validation, and to leverage the modelling approach through funding and dissemination.

Technology Transfer

To facilitate technology transfer, the work program commenced with the development of a systematic model extraction procedure. Preliminary work demonstrated successful extraction of a scalable 0.25μm GaN process (WIN Semiconductor) model using basic network parameter measurements at moderate frequencies – a first time application of the model to GaN.

The extraction process was implemented in a CAD environment (AWR Microwave office and latter in Keysight ADS) to carry analysis of small signal model extraction, trapping offsets, thermal effects and final large-signal model PDK generation. Technology challenges solved within the scope of this program include porting to the ADS environment. For the porting, the EM solver was evaluated to determine the required reference plane for extraction of the intrinsic model.

Through a series of site visits and training sessions, the process of extraction of the Macquarie model was transferred. Presentations and document packs delivered detailed description of the modelling methodology.

An extension to the project was an update of pulse testing capability for the model extraction with an implementation of Macquarie University's APSPA system in PXIe format. For this low level drivers and a programming environment have been established and tests with measurements of a real device have been achieved. The system specification and software deliverable were produced. These use text files with parameter lists to setup the measurement and returns tabulated data for further processing. The system is now ready for a second phase where data handling and job parameters can be linked to a user interface.

Model Extension

Extensions to the model include noise, thermal networks, and GaN physics. Publications associated with this project have disseminated the findings.

With support from this project, gate resistance thermometry was applied to separate thermal paths into local channel, finger-to-finger, and bulk regions. Each exhibits their own time constants that are resolved with gate-resistance-thermometry. Device layouts were delivered to facilitate replication of the results.

The thermal work initiated a MTBF/reliability extension to the model. A proposal was developed to model large-signal degradation with a node driven by a long time-constant network that captured stress conditions. As part of this study, channel noise was investigated and a noise model was delivered. This was the first-time implementation of noise in the Macquarie model.

Focus shifted in the latter half of the project from reliability to pulse testing. It became clear that trapping effects have more immediate impact on GaN devices. For this, focus shift to pulse testing.

Extension to GaN physics involved refinement of the model description in several aspects. Channel charge description has been refined with a novel explicit expression [IMS 2017]. Channel current has been expressed with a sophisticated mobility and bulk potential expression [BCICTS 2021]. The latter work has shown that using bulk potential rather than surface-potential expressions greatly combines drift and diffusion into a single potential gradient term. The work has also produced the first and only model that correctly accounts for mobility in GaN. Channel-length modulation was redefined with a first-time ability to fit measured output conductance [APMC 2021].

Validation

The global shut down and staffing issues within Macquarie have delayed completion of the final validation stages of the project. Yet to complete are a demonstrator PA amplifier in a USA sourced process. Notwithstanding this, a PA in GaN has been demonstrated [EUMIC 2020] in the WIN Semiconductor process. This featured an application of gate resistance thermometry in a first-time demonstration of temperature tracking during operation. Further designs in a European process are planned.

Although a validation circuit specific to this project has not been produced, the model has provided good results for other users. Several commercial products have been developed with the model by members of the user group established as a deliverable of this project.

Leverage and Dissemination

The technological advantages of the Macquarie model methodology have been leveraged to attract major investment by Analog Devices Inc. and the Australian Defence Initiative Fund. The model, particularly for GaN processes, has underpinned these ventures.

Analog Devices Inc. sponsors the Macquarie Analog Devices Laboratory (MADLAB) to leverage the University's infrastructure. Commercial circuit design and research training are core activities. Over AU$13,000,000 has been committed to the six-year venture, which is anticipated to be renewed on a continuing basis. MADLAB places circuit design engineers in-situ at Macquarie with its measurement and modelling researchers and transistor characterization capability

The Australian Defence Initiative Fund, which sponsors strategic large-scale projects, has supported a project on radio telemetry systems featuring GaN technology. Macquarie University has leveraged the GaN transistor characterization capability to underpin novel radar and radio front-end development. The project has completed phase one and Macquarie has won a bid to participate in the second phase, with over AU$3,000,000 going directly to the University.

To deliver an expansion of the user base for the model, a user group was established as a direct result of this work program. Several PDKs for both GaAs and GaN processes have been developed and shared. Users include Analog Devices Inc., Altum RF, Microsemi Inc., WIN Semiconductor, TNO (Netherlands), University of Colorado, and Defence Science and Technology Group (Australia).

A series of site visits, workshops, and training sessions, have been conducted for the user group. Several members (Microsemi Corp., Altum RF, and WIN Semicductor) have entered into funding arrangements to support the model extraction and PDK work. These arrangements are developing better model implementation, noise capability, and exploring foundry model implementations.

A medium term aim of the user group is to embed the model, which is current available in Verilog-a format, in commercial CAD tools. Both Cadence and Keysight have been providing support for this.

Follow-on

Further verification with demonstrator PA amplifier will emerge as the Defence project progresses. This will focus on European processes. Exploration of US sourced processes remains problematic.

The model physics development is entering the final stage of a single energy-conserved charge expression. Preliminary results have shown that an elegant expression comes directly from the new channel charge density expression [IMS 2017].

Software development has commenced for both the ASPSPA port and, more significantly, for automating model extraction. The extraction methodology documentation is planned to be completed within a tome describing for full model.

An issue yet to be addressed is the automation of the model extraction procedure. Preliminary software development has taken place for some aspects but the procedure remains a time consuming, specialist activity.

Publications

[EUMIC 2018] B. K. Schwitter, A. E. Parker, S. J. Mahon and M. C. Heimlich, "Characterisation of GaAs pHEMT Transient Thermal Response," 2018 13th European Microwave Integrated Circuits Conference (EuMIC), 2018, pp. 218-221. DOI: 10.23919/EuMIC.2018.8539961.
Abstract: Transient gate resistance thermometry is employed to characterise the time domain response of a GaAs pHEMT under pulsed conditions. Self-heating is observed from hundreds of nanoseconds to hundreds of milliseconds. A TFR-heated test structure is used to develop a 3-D finite-element thermal model that scales with power density and gate periphery. Thermal coupling between gate fingers in a multi-finger device is measured, and then further investigated via simulation. The model's application to thermal optimisation of devices and circuits is discussed.

[IMS 2020] A. E. Parker, "GaN and GaAs HEMT Channel Charge Model for Nonlinear Microwave and RF Applications," *2020 IEEE/MTT-S International Microwave Symposium (IMS)*, 2020, pp. 424-427. DOI: 10.1109/IMS30576.2020.9223994.
Abstract: An explicit energy-based expression for HEMT channel charge is proposed. The expression is a compact formulation that is superior for design and simulation tools. As advancement over existing approaches, the new expression offers the well-behaved high-order linearity that is critical for wireless applications.

[EUMIC 2020] S. J. Mahon et al., "Real-time, In-circuit Temperature Sensing of an X-Band GaN Power Amplifier," *2020 15th European Microwave Integrated Circuits Conference (EuMIC)*, 2021, pp. 37-40.
Abstract: A 10-watt X-band GaN power amplifier has been designed as a testbed to study amplifier temperature under a variety of biases and input drive levels using gate-resistance thermometry. Real-time, in-circuit temperature sensing is demonstrated and discussed for a range of biases and input levels.

[BCICTS 2021] A. E. Parker, "GaN and GaAs HEMT Channel Current Model for Nonlinear Microwave and RF Applications," *2021 IEEE BiCMOS and Compound Semiconductor Integrated Circuits and Technology Symposium (BCICTS)*, 2021, pp. 1-8. DOI: 10.1109/BCICTS50416.2021.9682497.
Abstract: An explicit drain current model accounts for channel charge and electron velocity in GaN and GaAs HEMTs. Saturated current is shown to be dependent on the bulk potential gradient and correct determination of mobility and peak velocity potential. As advancement over existing approaches, the model produces an improved prediction of linearity and temperature dependence in a compact formulation. It offers superior high-order linearity prediction critical for wireless applications.

[APMC 2021] A. E. Parker, "GaN and GaAs HEMT Channel Conductance Model for Nonlinear Microwave and RF Applications," 2021 IEEE Asia-Pacific Microwave Conference (APMC), 2021, pp. 94-96. DOI: 10.1109/APMC52720.2021.9661735.
Abstract: An explicit HEMT channel-length modulation model is developed that describes drain conductance in HEMTs. The model is added to a current description

based on bulk potential gradient and associated velocity saturation potential. Effective channel-length reduction is described in a compact formulation that correctly fits measured drain conductance and describes formation of the drain current knee. This offers superior high-order linearity and power limit prediction critical for wireless applications.