GaN HEMTs Modeling

Pranav Kumar
Under Prof. Shaloo Rakheja
Part I of Internship at NYU, Summers’16

Contents

History and Introduction

History of GaN

- In the early 1990s, GaN was deemed an excellent, next generation, semiconductor material for high power/high frequency transistors based on the material parameters of bandgap, electron mobility, and saturated electron velocity.
- The development of GaN for RF electronics was significantly aided by the intense development that occurred in the race to first production of blue and, eventually, white light-emitting diodes (LEDs).
- The specifics of GaN compared with various other elemental and compound semiconductors are given on the next slide.

Specifics

	Silicon	Gallium Arsenide	Indium Phosphide	Gallium Nitride
Bandgap (eV)	1.1	1.42	1.35	3.49
Electron mobility at 300K (cm^2/V-s)	1500	8500	5400	1000-2000
Saturated Electron Velocity ($x10^7$ cm/s)	1	1.3	1	2.5
Critical Breakdown Field (MV/cm)	0.3	0.4	0.5	3.3
Thermal Conductivity (W/cm-K)	1.5	0.5	0.7	>1.5
Relative Dielectric Constant (ε_r)	11.8	12.8	12.5	9

High Electron Mobility Transistors

- The bandgap engineering corresponding to heterojunctions involving III-V compounds (e.g., GaAs) like in MESFETs is exploited in HEMTs as well.
- In order to maintain high transconductance in a MESFET, the channel conductivity must be as high as possible. Channel conductivity can be increased by doping.
- However, increased doping causes increased scattering by the ionized (donor) impurities, which degrades mobility.
- Thus, a way is needed to create a high electron concentration in the channel of a MESFET by some means other than doping.

HEMTs (contd.)

- A clever solution to this problem is to grow a thin undoped well (e.g. GaAs) bounded by a wider bandgap, doped barriers (e.g., AlGaAs). This configuration is called *Modulation Doping*.
- This results in conductive GaAs when electrons from the doped AlGaAs barriers fall into the well and are trapped. Since the donor ions are in the AlGaAs rather than GaAs, there is *no impurity scattering* of electrons in the well.
- If a MESFET is constructed with the channel along the GaAs well (perpendicular to the slide in Fig. 1), we can take advantage of this reduced scattering and resulting higher mobility. This effect is especially strong at low temperatures when lattice scattering is also low. This device is a HEMT.

Fig.1 Modulation doping, showing only the conduction band (Simplified View)
Fig.2 The thin sheet of charge due to free electrons at the interface forms a 2-dimensional electron gas (2-DEG).

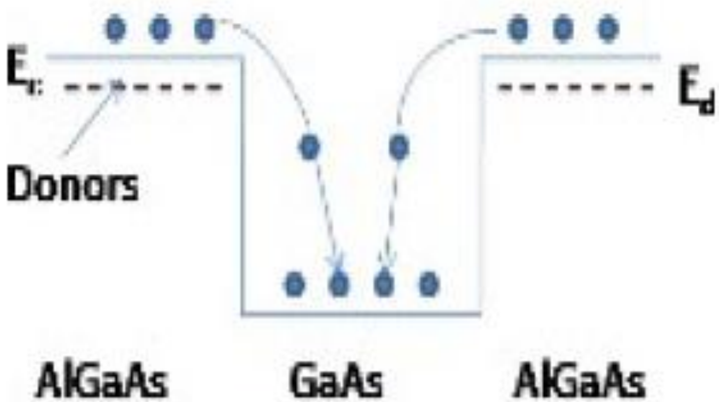


Fig. 1

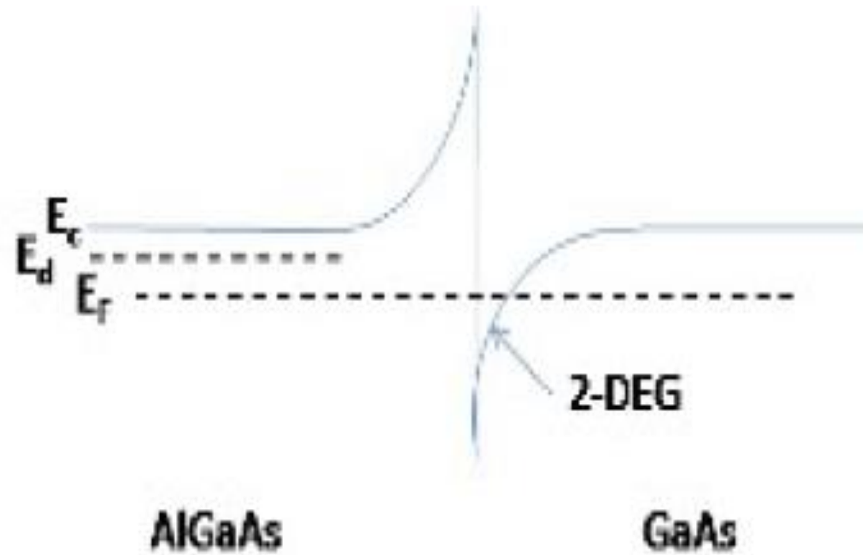


Fig. 2

GaN HEMTs

- GaN HEMTs or heterojunction FETs (HFETs) are currently the most widespread and most advanced electronic nitride devices.
- They make full use of heterostructures and the advantageous breakdown and transport properties of undoped GaN.
- They exhibit high cutoff frequencies and thus are advantageous in RF circuits.
- They are advantageous in power-supply circuits because they exhibit high maximum current, high breakdown strength due to large bandgap and can be operated at high temperatures.

Why AlGaN/GaN heterostructure?

- AlGaN is a wide bandgap material as compared to GaN.
- AlN and GaN have bandgaps of 6.3 and 3.3 eV respectively. Thus bandgap of $Al_xGa_{1-x}N$ can be found by linear interpolation.
- Thus, a thin undoped well of GaN bounded by doped AlGaN will result in the needed *modulation doping* for GaN HEMTs.
- Also due to the large lattice mismatch between AlN and GaN a strain in the AlGaN layer is induced, which generates a piezoelectric field.
- Together with the large conduction band offset and the spontaneous polarization this leads to very high values for the electron sheet charge density as compared to AlGaAs/GaAs structure.

Evolution of GaN HEMTs

- 2001 – An optimization step was the addition of a thin AlN barrier between the GaN channel and the AlGaN layer. It increased the conduction band offset and the two-dimensional electron gas (2DEG) density and decreases the alloy disorder scattering, thereby increasing the mobility.

  L. Shen, S. Heikman, B. Moran, R. Coffie, N. Zhang, D. Buttari, I. Smorchkova, S. Keller, S. DenBaars, and U. Mishra, ``AlGaN/AlN/GaN High-Power Microwave HEMT,'' IEEE Electron Device Lett., vol. 22, no. 10, pp. 457-459, 2001.

Evolution … (Contd.)

- 2001 - An enhancement in the electron gas transport properties through the double-heterojunction structure was proposed. The InGaN layer under the channel introduced a negative polarization charge at the interface, and thereby improved the carrier confinement in the channel.

  N. Maeda, T. Saito, K. Tsubaki, T. Nishida, and N. Kobayashi, ``Two-Dimensional Electron Gas Transport Properties in AlGaN/GaN Single- and Double-Heterostructure Field Effect Transistors,''Mat.Sci.Eng.B, vol. 82, no. 1-3, pp. 232-237, 2001.

Evolution … (Contd.)

- 2004 and 2007 - An approach previously used in high-voltage p-n junctions (1972), the field-plate electrode, significantly improved device performance by reducing the peak values of the electric field in the device. Thus, the breakdown voltage could be further increased. This technique was further refined to T-shaped (1) and subsequently Y-shaped (2) gate electrodes.

(1) R. Thompson, T. Prunty, V. Kaper, and J. Shealy, ``Performance of the AlGaN HEMT Structure With a Gate Extension,'' IEEE Trans.Electron Devices, vol. 51, no. 2, pp. 292-295, 2004.
(2) K. Makiyama, T. Ohki, M. Kanamura, K. Imanishi, N. Hara, and T. Kikkawa, ``High-f GaN HEMT with High Breakdown Voltage over 100 V for Millimeter-Wave Applications,'' Phys.stat.sol.(a), vol. 204, no. 6, pp. 2054-2058, 2007.

Technology Challenges that prevented main stream deployment

- No native substrate of GaN was readily available.
- The breakdown voltage of AlGaN/GaN HEMTs can be evaluated by pulsed ID-VD measurements.
- When BDV is reached, Snapback occurs and the junction can degrade even before BDV.
- Breakdown measured in voltage controlled mode is very abrupt (no sustainable breakdown present in GaN HEMTs).
- While the depletion mode (D-mode) technology has been significantly improved, no comparable progress on the enhancement counterparts can be noted.

Solutions to these problems

- For growing GaN, heteroepitaxy of (0001) GaN typically on sapphire, silicon carbide or silicon was done.
- For the breakdown problem, field-plate optimization was proposed. The usage of field-plate reduced electric field and thus increased breakdown voltage and lowered electron injection into traps.
- Devices featuring very thin AlGaN layers (M. Khan *et al.* 1996) and Fluoride-based plasma treatment (Y. Cai *et al.* 2005) have also been proposed, however certain stability concerns remain.

Solutions… (Contd.)

- Another very promising method is the recess gate structure reported by Kumar *et al.* in 2003.
- Also recently, excellent results have been achieved with InGaN-cap devices (T. Mizutani *et al.* 2007)

Modeling Concerns

Behavioral Nuances of GaN

Behavioral Nuances of GaN

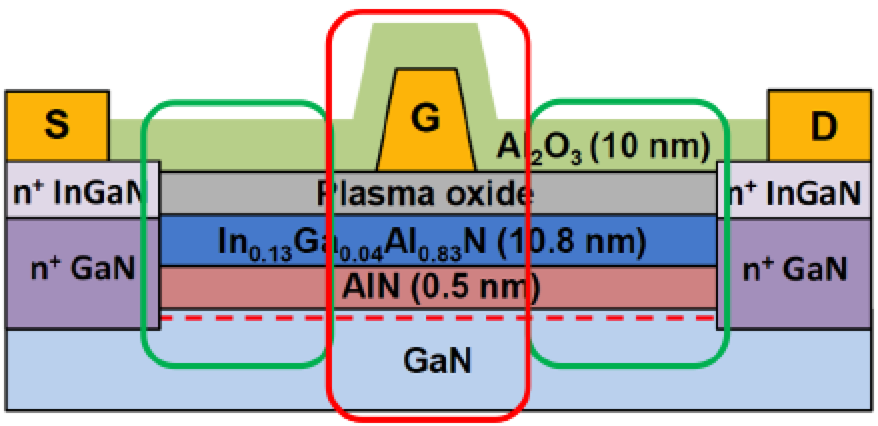
1) Self-Heating
2) Access Regions
3) Charge Trapping

1. Self-Heating

- Although the GaN based devices have the advantage of high electron density and output current, the high current flow generates a lot of heat which is known as self-heating.
- Self-heating is a serious concern in GaN devices. Due to self-heating, channel temperatures can reach several hundred degrees above the ambient base temperature.

2. Access-Regions

- GaN HEMTs usually have Schottky gates and the source and drain are not self-aligned to avoid gate leakage.
- This results in source and drain access regions which are essentially un-gated heterostructure regions, as shown in the schematic below.



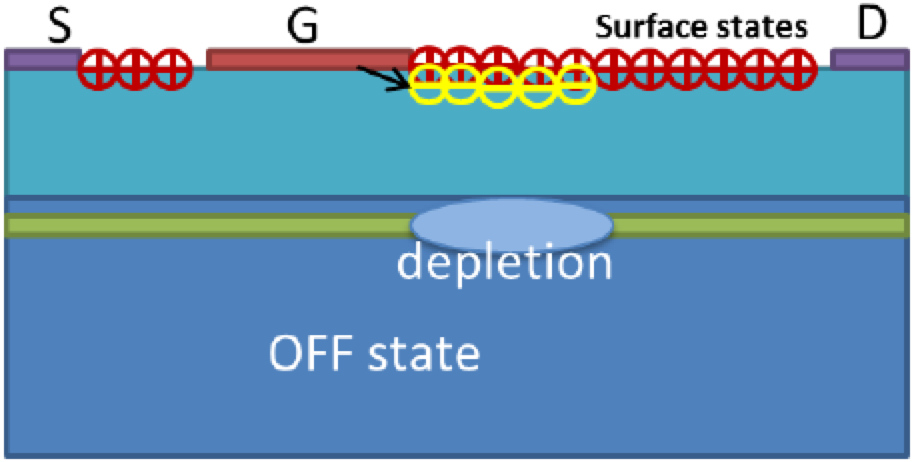
Ref. [4]

- Under low bias conditions, access regions are resistive regions.
- Under high bias conditions, velocity saturation, self-heating and pinch-off in these regions introduce non-linearity in access region behavior.

3. Charge Trapping

- Current collapse is the increase in on-resistance and reduction in on-current during pulsed switching conditions.
- Many theories have been put forward to explain this and one of virtual gate charging appears most convincing.
- Since the 2DEG in the channel of a GaN HEMT is created by donor type surface states, any impact on the surface states reflects in the 2DEG charge density.

- In the virtual gate charging scheme, the electrons from the gate compensate some of the surface states in the drain access region adjacent to the gate electrode.
- This created depletion region is therefore like a virtual gated region which increases the drain access region resistance, causing current collapse



Ref. [4]

Review of current models

Their advantages and disadvantages

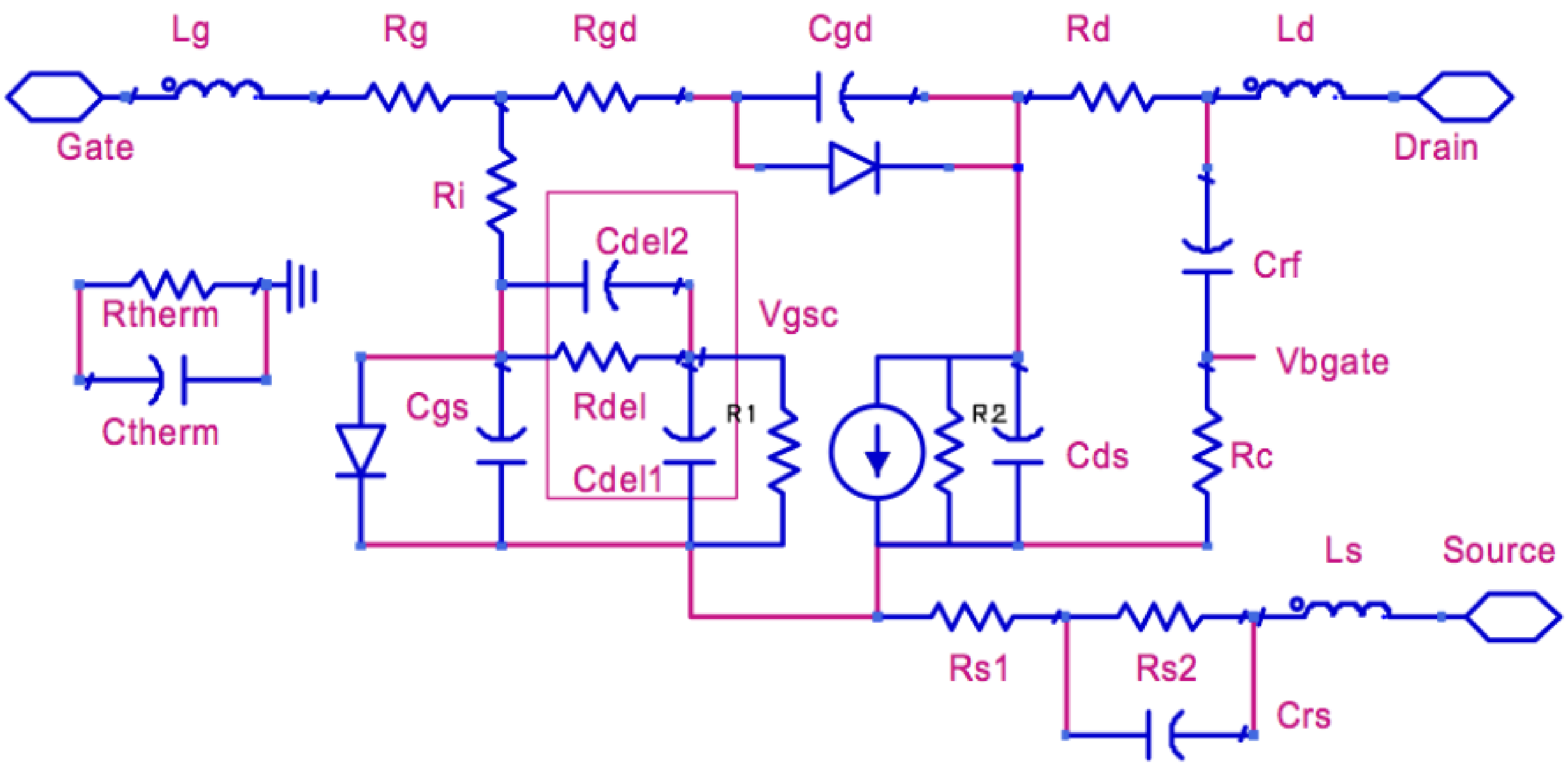
GaN HEMT Models

1) Angelov Model
2) Curtice Model
3) EEHEMT Model
4) MVSG-RF Model

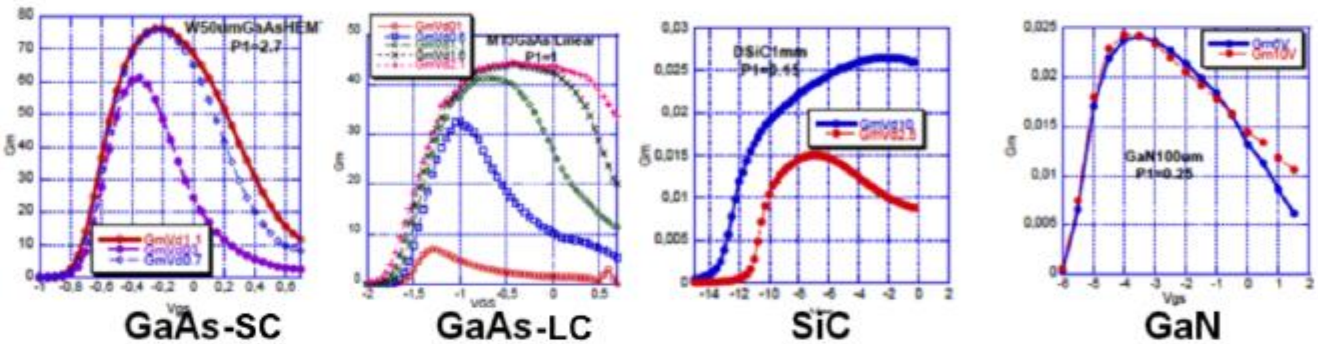
1. Angelov Model

- A popular empirical non-linear IV model.
- The model was first proposed in 1992 by Prof. Iltcho Angelov of Chalmers university, Sweden.
- It is an equivalent circuit type model suitable for GaAs, GaN, SiC and even CMOS technologies.
- The equivalent circuit is shown on the next slide.

Equivalent Circuit of Angelov Model [1]



- Angelov model tries to capture the non-linearity in transconductance (g_m) observed in GaN, GaAs and other material technologies.



Ref. [1]

- As can be seen from the figure, the g_m plots exhibit the so called 'bell shaped' characteristic. Capturing this shape is the key idea around which Angelov model has been built.

Formulations in Angelov Model

- $g_m = g_{mpk}\,(1 - \tanh^2[p_{1m}\,(V_{gs} - V_k)]\,)$
- The current becomes :
  $I_{ds} = I_{pks}\,(1 + \tanh(\psi_p))\,\tanh(\alpha V_{ds})\,(1 + \lambda V_{ds})$
- The non-linearity is captured by :
  $\psi_p = P_{1m}\,(V_{gs} - V_{pk0}) + P_2\,(V_{gs} - V_{pks})^2 + P_3\,(V_{gs} - V_{pksm})^3$
- $C_{gs} = C_{gsp} + C_{gso}\,(1 + \tanh(\psi_1))\,(1 + \tanh(\psi_2))$
- The non-linearity is achieved through :
  $\psi_1 = P_{10} + P_{11}V_{gs} + P_{111}V_{ds}$
  $\psi_2 = P_{20} + P_{21}V_{ds}$
- G_{mpk}, p_{1m}, V_k, I_{pks}, α, λ, P_2, P_3, etc. are fitting parameters.

Advantages

- It includes electro-thermal models for self-heating.
- The access regions are modeled as empirical non-linear elements.
- Angelov model has about 90 parameters. This empirical nature of the model with large fitting parameters increases the model accuracy if the parameters are correctly extracted.
- The model does capture the non-linear behavior and resulting harmonics in power circuits.

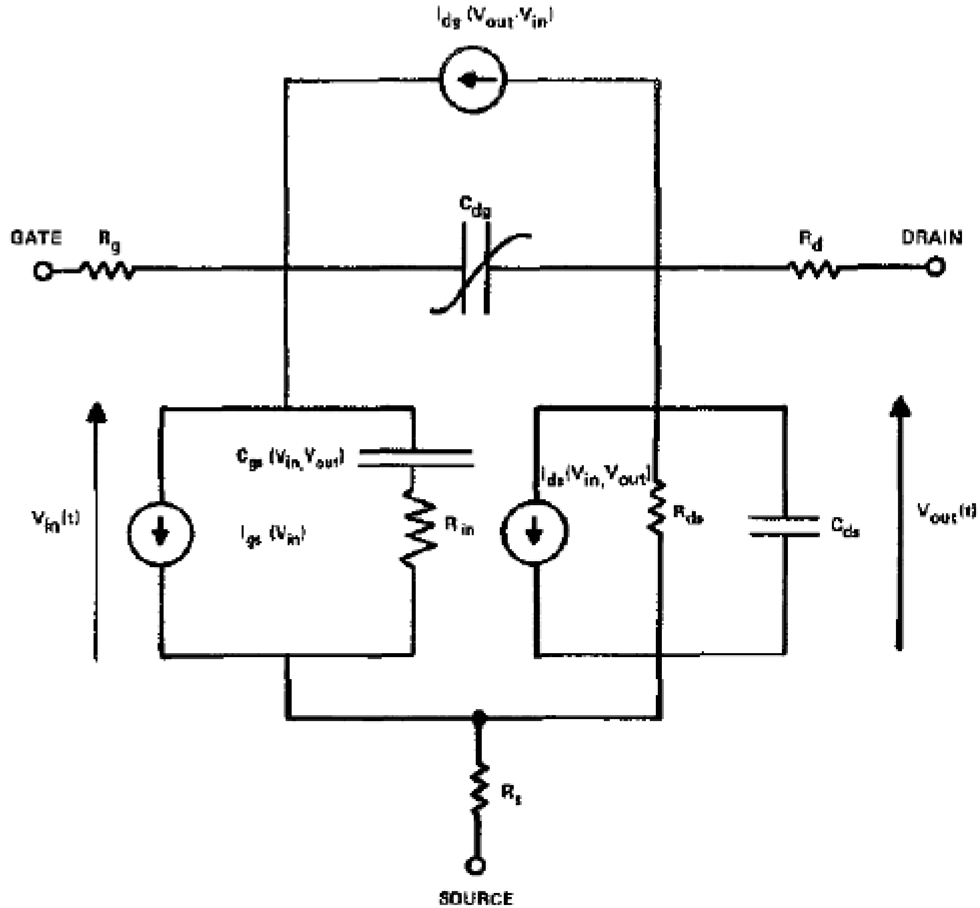
Disadvantages

- The model is not physics-based.
- Any changes to the device or process technology will mean that the model has to re-fitted to the characteristics. This increases optimization time.
- This also makes the model non-scalable with regard to geometry.

2. Curtice Model

- The model was originally proposed in 1985 for GaAs FETs by Prof. Walter Curtice of University of Michigan but has been extended to other material systems including recently to GaN HEMTs.
- There has been considerable expansion on the original model with present model variations called CFET and C_HEMT.
- The equivalent circuit is given on the next slide.

Equivalent Circuit of the original version of the Curtice Model [2]



Formulations of the Curtice Model

- The currents have a polynomial dependance on the input voltage as :
  $I_{ds} = (A_0 + A_1V_1 + A_2V_1^{\,2} + A_3V_1^{\,3})\tanh(\gamma V_{out}(t))$
  $V_1 = V_{in}(t - \tau)[1 + \beta(V^{o}_{out} - V_{out}(t)]$
- Here β is the current factor whereas the rest of the parameters are fitting parameters.

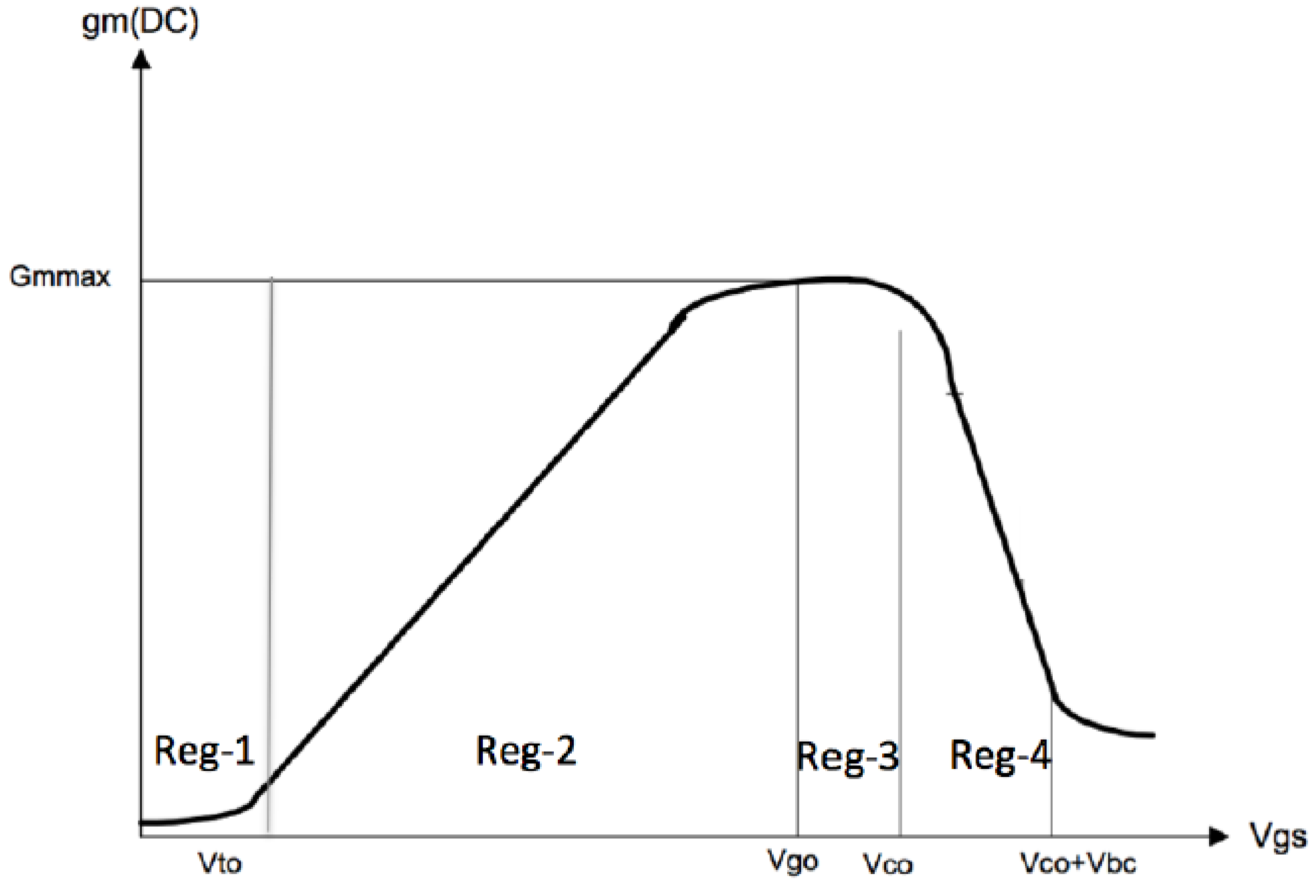
Disadvantages

- The Curtice model in its Curtice3 form is not geometry scalable.
- It also does not model self-heating effects.

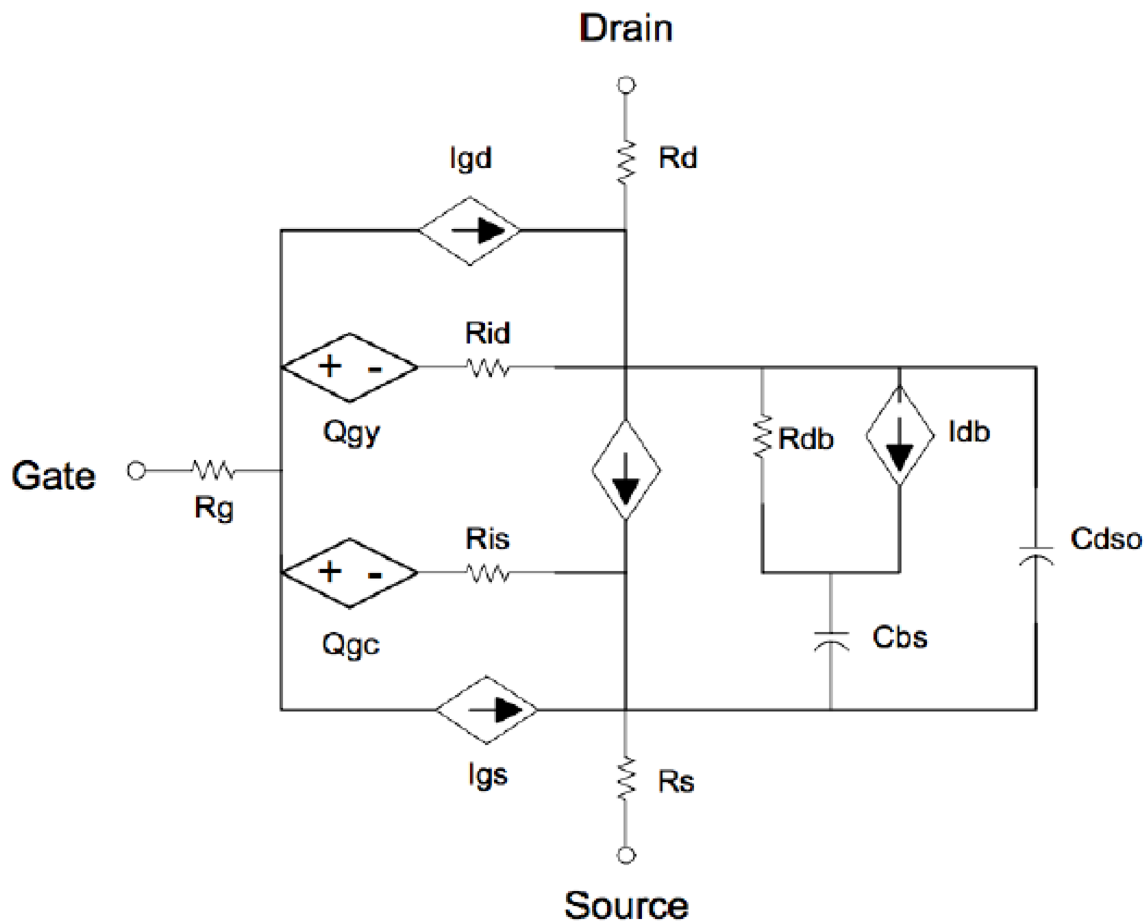
3. EEHEMT Model

- The Eesof HEMT model is an extension of the Curtice Model.
- The EEHEMT model is defined for different regions of device operation based on V_{gs}.
- The different model equations with their own parameters are then 'stitched' together to get the complete model.

The different regions based on g_m plot is shown [3]



Equivalent circuit of EEHEMT model [3]



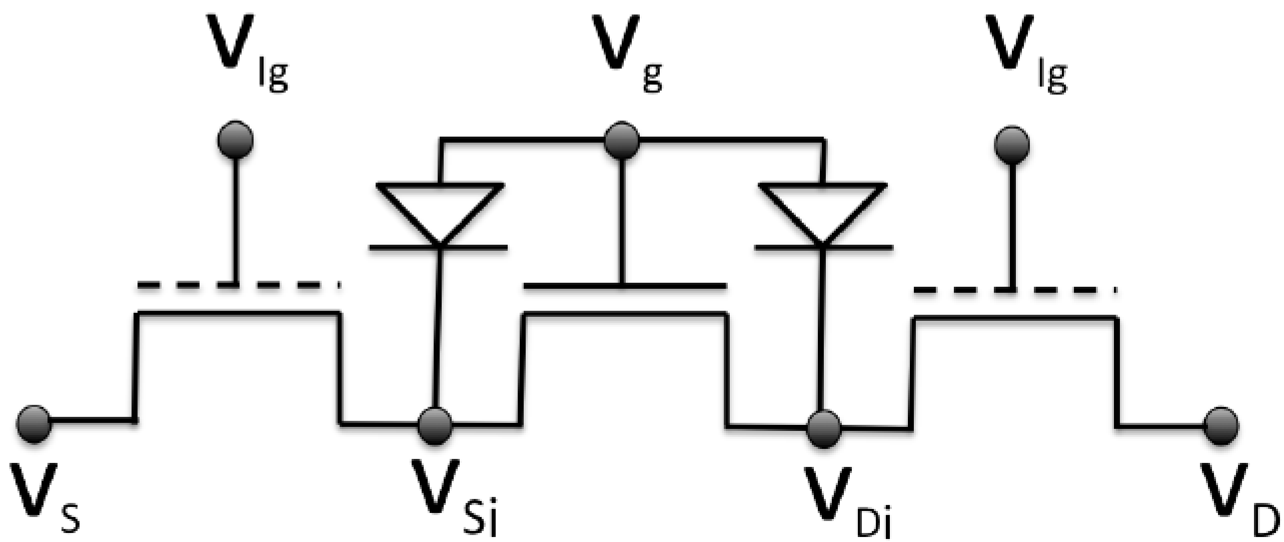
Advantages and Disadvantages

- The EEHEMT model also separates the DC and AC behavior for a simpler model extraction. This brings independence but increases parameter count and model complexity.
- Larger parameter count means longer parameter extraction times.
- Does not capture electrothermal effects.

4. MVSG-RF Model

- In conclusion, the review of GaN models carried out up till now reveals that all the existing models are empirical with large number of non-physical parameters.
- They do not as yet capture all the GaN HEMT behavioral nuances.
- A new MIT Virtual Source GaNFET - Radio Frequency has lesser number of parameters (35), is geometry scalable, includes self-heating effects amd captures the physics of charge transport in access regions.

Sub-circuit model of MVSG-RF Model [4]



A
G

Disadvantages

- Does not account for charge trapping.
- The self-heating model is semi-empirical and is a static model.
- The parasitic terminal capacitances, inductances and resistances must be included in the model to account for the magnitude and phase shifts of input/output signals between the device and terminals.

References

1) I. Angelov, H. Zirath, and N. Rosman, “A new empirical nonlinear model for HEMT and MESFET devices," Microwave Theory and Techniques, IEEE Transactions on, vol. 40, no. 12, pp. 2258-2266, 1992.
2) W. R. Curtice and M. Ettenberg, “A nonlinear gaas fet model for use in the design of output circuits for power ampliers," Microwave Theory and Techniques, IEEE Transactions on, vol. 33, no. 12, pp. 1383-1394, 1985.
3) C. William, Small and large signal modeling of mm-wave HEMT devices. PhD thesis, University of South Florida, 2003.
4) ‘Compact Transport And Charge Model For Gallium Nitride-based HEMTs For radio-Frequency applications’ U. Radhakrishna, MIT, Jun.-2013.