TCAD Simulation Models, Parameters, and Methodologies for β-Ga_2O_3 Power Devices

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Abstract: β-Ga_2O_3 is an emerging material and has the potential to revolutionize power electronics due to its ultra-wide-bandgap (UWBG) and lower native substrate cost compared to Silicon Carbide and Gallium Nitride. Since β-Ga_2O_3 technology is still not mature, experimental study of β-Ga_2O_3 is difficult and expensive. Technology-Computer-Aided Design (TCAD) is thus a cost-effective way to study the potentials and limitations of β-Ga_2O_3 devices. In this paper, TCAD parameters calibrated to experiments are presented. They are used to perform the simulations in heterojunction p-NiO/n-Ga_2O_3 diode, Schottky diode, and normally-off Ga_2O_3 vertical FinFET. Besides the current-voltage (I-V) simulations, breakdown, capacitance-voltage (C-V), and short-circuit ruggedness simulations with robust setups are discussed. TCAD Sentaurus is used in the simulations but the methodologies can be applied in other simulators easily. This paves the road to performing a holistic study of β-Ga_2O_3 devices using TCAD.

Keywords: Gallium Oxide, FinFET, Heterojunction, Power Devices, Short-Circuit Ruggedness, TCAD Simulation

1. Introduction

β-Gallium Oxide (β-Ga_2O_3) is an emerging material with an ultra-wide bandgap that has the potential to realize high breakdown and low loss power switching devices[1]-[3]. Since the Baliga figure of merit (BFOM) scales as the sixth power of the bandgap, its BFOM is expected to be almost 9 times that of GaN[1]. A low-cost substrate can also be obtained through various methodologies, such as the edge-defined film-fed growth (EFG) method[1]. The two fundamental devices in power electronics systems, namely the diode[4] and field-effect transistor (FET) [5][6], have been demonstrated using β-Ga_2O_3.

However, due to the absence of p-type doping in β-Ga_2O_3, forming a p-n diode is not possible and a Schottky diode needs to be used[4]. It is also possible to create a heterojunction p-n diode. For example, in Reference [7], a high voltage heterojunction p-n diode is demonstrated by using p-type NiO and n-type Ga_2O_3. Due to the same reason, it is difficult to form a p-type substrate/body in a β-Ga_2O_3 n-type transistor. Therefore, β-Ga_2O_3 n-type transistors are usually normally ON [5][6] (threshold voltage, V_{TH}, < 0) which is not suitable for fail-safe operation. Innovative ideas have been proposed to form enhancement mode devices (normally off with $V_{TH} > 0$). For example, vertical β-Ga_2O_3 FinFET with a narrow fin is used to achieve normally-off devices by utilizing the difference between the gate workfunction and channel Fermi-level[8]-[10]. Another example is by recessing a part of the channel of a cascode β-Ga_2O_3 MOSFET[11][12].

β-Ga_2O_3 is also known for its low thermal conductivity[3]. Therefore, it is important to understand the effect of self-heating when designing novel β-Ga_2O_3 devices[13].

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Technology Computer-Aided-Design (TCAD)[14] is a very cost-effective tool for investigating novel ideals and structures of β-Ga_2O_3 devices[15][16], while the Ga_2O_3 technology is still expensive and not mature. TCAD can handle multi-physics including thermal effects. However, simulation of β-Ga_2O_3 is difficult due to the following reasons. Firstly, β-Ga_2O_3 is an emerging material and a widely-adopted and standardized set of models and parameters is not available. Secondly, like simulating wide-bandgap materials such as Gallium Nitride[17], simulation convergence in UWBG is even more difficult due to its numerical underflow or overflow. Thirdly, to have useful and accurate simulations for high voltage applications in which self-heating is significant, models such as incomplete ionization, self-heating, and impact ionization which are notorious for causing convergence problems need to be included. Moreover, it is also important to include temperature-dependence parameters in the simulations.

Therefore, in this paper, we summarize a consistent set of models and parameters used for various types of β-Ga_2O_3 device simulations which are calibrated to experimental results. They are used in heterojunction p-NiO/n-Ga_2O_3 diode, Schottky diode, and normally-off Ga_2O_3 vertical FinFET simulations. Besides the IV simulations, breakdown, CV, and short-circuit ruggedness simulations with robust setups are discussed.

2. β-Ga_2O_3 TCAD Models and Parameters

2.1 Bandgap and other basics models

The basic material parameters are shown in Table 1. It includes the dielectric constant, thermal conductivity, and *temperature-dependent* bandgap parameters. The corresponding Sentaurus Device[14] keywords are also shown. It should be noted that the thermal conductivity depends on the crystal orientation[3][18] as β-Ga_2O_3 is anisotropic. While it is possible to perform anisotropic simulation in TCAD[14], it is not recommended unless it is necessary, as this makes convergence more difficult.

For the bandgap parameters, the following models are used[14][19]:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta} \quad (1)$$

$$\chi(T) = \chi_g(0) - \frac{\alpha T^2}{2(T+\beta)} \quad (2)$$

where T, $E_g(T)$, and $\chi(T)$ are the temperature, the bandgap, and electron affinity at temperature T, respectively. α and β are parameters. This gives a room temperature bandgap of 4.85eV. For electron affinity, there is a wide range of values in the literature from 3.5eV[20] to 4eV[21] at 300K. Table 1 shows the parameters that will make $\chi(300K) = 3.7eV$. Electron affinity value is less important in β-Ga_2O_3 as p-type doping is not available. However, for the Schottky device, oxide interface, and heterostructures, it is recommended to calibrate to the experimental value as Fermi-level pinning and interface traps will change the effective electron affinity.

The effective electron mass, m_e, is $0.28m_0$[22], where m_0 is the electron rest mass. In TCAD simulation, what important is the density of state (DOS), N_c, which depends on m_0. The following temperature-dependent equations are used. The parameter $N_c(300K)$ is chosen such that it gives m_e= $0.28m_0$ at 300K.

$$N_c(T) = N_c(300K)\left(\frac{T}{300}\right)^{1.5} \quad (3)$$

$$\frac{m_e}{m_0} = \left(\frac{N_c(300K)}{2.5094\times10^{19}}\right)^{2/3} \quad (4)$$

2.2 Mobility and incomplete ionization models

In TCAD, phonon scattering limited mobility is calculated using the following equation,

$$\mu_L = \mu_{max}\left(\frac{T}{300}\right)^{-\theta} \quad (5)$$

For quick room temperature TCAD simulation, Eq. (5) is simplified to $\mu_L = \mu_{max}$ and one can use the value found in Reference [3] with μ_L= 300 cm^2/(Vs) without considering impurity scattering if the device is undoped. However, in most devices, the channel is doped. Therefore, it is necessary to include the doping-dependent mobility model. To model doping-dependent mobility, Reference [23] uses the Arora model, and Reference [24] uses the Masetti model. The Masetti model is not temperature-dependent and is not suitable for self-heating simulation. Although the Arora model is temperature dependent, the parameters have not been rigorously calibrated[23]. The Philips Unified Mobility Model (PhuMob)[25] is proposed to be used and will be discussed after the incomplete ionization model.

When the impurity scattering (Coulomb scattering) mobility model is used, it is also important to turn on the incomplete ionization model because the most commonly used dopants (such as Silicon and Germanium) in β-Ga_2O_3 are not shallow enough to assume complete ionization and the doping level is not high enough to form an impurity band[26]. The impurity scattering depends on the percentage of ionization as only ionized dopants will contribute to mobility degradation. The following equation is used to model the doping-dependent ionization energy, E_D.

$$E_D = E_{D0} - \alpha N_D^{1/3} \quad (6)$$

For Silicon, the zero doping ionization energy of Si (E_{D0}) is set to 52meV with doping concentration (N_D) dependent ionization energy coefficient, α, being 3.398×10^{-8} eVcm. For Germanium, E_{D0} is set to 17.5meV. N_D is not available for Germanium as doping-dependent experiments are available. The values extracted are consistent with the literature [27][32].

Fig. 1 shows the ionized dopant concentration as a function of temperature and doping in calibrated TCAD simulation and Hall measurement in refs. [27][28]. It shows that the ionization energy parameters are calibrated well.

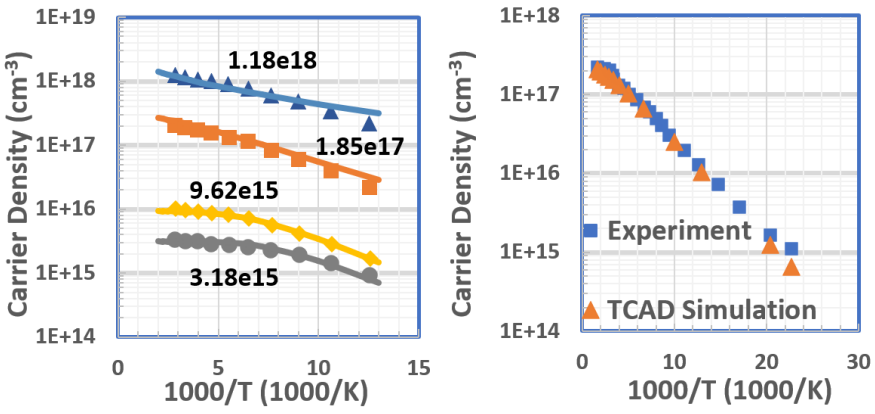

Fig. 1. Comparison of experimental[27][28] and TCAD free carrier concentration data in Si-doped (left) and Ge-doped

(right) Ga_2O_3.

PhuMob model takes the screening of ionized impurities by charge carriers and temperature into account. In Reference [26], it has been demonstrated that it can be extended to cryogenic temperatures in a silicon device. The major PhuMob equations are the following and Table 2 shows the calibrated parameters.

$$\frac{1}{\mu} = \frac{1}{\mu_L} + \frac{1}{\mu_{DA}} \tag{7}$$

$$\mu_{DA} = \mu_N \left(\frac{N_{sc}}{N_{sc,eff}}\right)\left(\frac{N_{ref}}{N_{sc}}\right)^{\alpha} + \mu_c \left(\frac{n+p}{N_{sc,eff}}\right) \tag{8}$$

$$\mu_N = \frac{{\mu_{max}}^2}{\mu_{max}-\mu_{min}}\left(\frac{T}{300}\right)^{3\alpha-1.5} \tag{9}$$

$$\mu_c = \frac{\mu_{max}\mu_{min}}{\mu_{max}-\mu_{min}}\left(\frac{300}{T}\right)^{0.5} \tag{10}$$

The PhuMob model, μ, has two major parts, namely the phonon scattering due to lattice vibration, μ_L, and the impurity scattering part, μ_{DA}. They are combined through the Mathiessen rule in Eq. (7). The phonon scattering is temperature dependent as shown in Eq. (5) and the temperature sensitivity is determined by θ. μ_{DA} is also temperature dependent and determined by α. It also depends on a few parameters, namely, μ_{max}, μ_{min}, and N_{ref}. Note that μ_{max} is the same as the one in Eq. (5). In Eq. (8), n, p, N_{SC}, and $N_{sc,eff}$ are the electron, hole, scattering concentration, and effective scattering concentration with minority and electron-hole scattering effects, respectively. The model is calibrated against the experimental mobility data in refs. [27] and [28] with incomplete ionization turned on in Si and Ge[29] (Table 2).

This calibrated PhuMob model has been used to simulate the Schottky diode[29] and vertical FinFET[30] and agrees with experimental data well after minor adjustments of μ_{max} and μ_{min} due to the difference in crystal qualities. Moreover, in Reference [29], it is demonstrated to match experimental Schottky diode IV with self-heating for Ga_2O_3 at various temperatures. It also shows a smooth trend up to 2000 K as shown in Fig. 2 which can be used for short-circuit simulation.

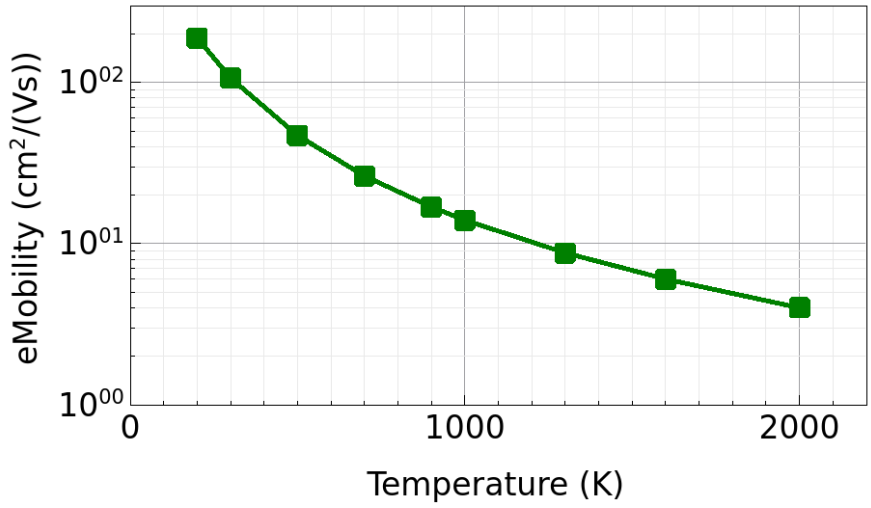

Fig. 2. Electron mobility as a function of temperature when the doping is 1.475×10^{17} cm^{-3}.

Electron saturation velocity is found to be 2×10^7cm/s based on Reference [31]. However, there is no experimental data on its temperature dependency. Therefore, the exponent, $v_{sat,exp}$, in the following equation is set to be 0.

$$v_{sat} = v_{sat,0}\left(\frac{300}{T}\right)^{v_{sat,exp}} \quad (11)$$

2.3 Impact ionization model

Since β-Ga_2O_3 is intended for high-power high-voltage electronics, it is important to include the impact ionization model in the simulation in the breakdown and short-circuit simulations. Although the convergence will be worse, it is also necessary to turn on the self-consistent impact ionization model, in which the generated carriers are included in the Poisson and carrier continuity equations for accurate simulations. The impact ionization coefficient is calculated using the van Overstraeten – de Man model[14]:

$$\alpha = ae^{\frac{-b}{F}} \quad (12)$$

where a and b are fitting parameters and F is the effective driving force in V/m. For good accuracy and convergence, the gradient of the electron quasi-Fermi level is used as the driving force. For the device breaks down in the (100) direction, the corresponding parameters, a and b, are 0.79×10^6 V/cm and 2.92×10^7 V/cm, respectively, based on Reference [33].

It should be noted that due to deep acceptor traps, very often impact ionization is not the cause of initial device breakdown because the hole generated are captured by the deep acceptors [34]. However, when the electric field is high enough, impact ionization of the deep traps will occur [34].

Table 1. Gallium Oxide Material Parameters Used in this Work.

Parameter	Keyword in SDevice	Value (unit)	Source
Dielectric Constant	Epsilon	10.0 (unitless)	[3]
Thermal Conductivity [100]	Kappa	0.11 (WK/cm)	[3]
Thermal Conductivity [010]	Kappa	0.27 (WK/cm)	[3]
Bandgap at 0K, $E_g(0)$	Eg0	5.0234(eV)	[19]
Bandgap parameter α	Alpha	4.45e-3 (eV/K)	[19]
Bandgap parameter β	Beta	2000 (K)	[19]
Electron Affinity at 0K, $\chi_g(0)$	chi0	3.6128(eV)	Within the range of [20] and [21]
Electron Density of State, $N_c(300K)$	Nc300	3.718e18 (cm^{-3})	[22]
Constant Mobility, μ_L	mumax	300 (cm^2/(Vs))	[3]
Silicon Ionization Energy at zero concentration, E_0	E_Si_0	0.052 (eV)	[29]
Silicon Ionization Energy coefficient, α	alpha_Si	3.398e-8 (eV·cm)	[29]
Si dopant degeneracy, g	g_Si	2	[29]

Ge Ionization Energy at zero concentration, E_0	E_Ge_0	0.0172 (eV)	Fig. 1
Ge dopant degeneracy, g	g_Ge	2	Fig. 1
Saturation Velocity, v_{sat}	vsat0	2e7 (m/s)	[31]
Impact ionization pre-exponent, a	a(low), a(high)	7.9e5 (cm^{-1})	[33]
Impact ionization exponent, b	b(low), b(high)	2.92e7 (V/cm)	[33]

Table 2. Philips Unified Mobility Model Parameters for Si and Ge dopants in Ga_2O_3. * is either Si or Ge,

Parameter	Keyword in Sdevice	Si in Ga_2O_3	Ge in Ga_2O_3
μ_{max} ($cm^2/V{\cdot}s$)	mumax_*	150	115
μ_{min} ($cm^2/V{\cdot}s$)	mumin_*	80	0
θ	theta_*	1.8	1.65
N_{ref} (cm^{-3})	n_ref_*	2×10^{17}	5.68×10^{18}
α	alpha_*	0.9	0.68

3. Simulations of β-Ga_2O_3 Devices

3.1. Heterojunction p-NiO/n-Ga_2O_3 diode

Since it is difficult to form p-type Ga_2O_3 and thus a Ga_2O_3 p-n diode, it has been proposed to form a heterojunction p-n diode with p-NiO and n-Ga_2O_3[7]. Such novel structures usually have many non-idealities as the technologies of both materials and their interface are not mature. TCAD is very suitable to help understand its electrical properties. By using the parameters discussed in the earlier section except with $\chi(300K) = 4eV$ to achieve a better fitting to the experiment, it can be seen in Fig. 3 that the discontinuity at the valence band (3.69eV) is much higher than that of the conduction band (2.2eV). Therefore, electron current is expected to be dominating at forward bias.

In Reference [7], TCAD is also used to reverse engineer its properties by simulating its capacitance-voltage (CV) characteristics with various n-doping levels. It is found that when the doping is $4.5\times10^{16}cm^{-3}$, the TCAD CV matches the experimental CV the best (Fig. 3). This value is similar to the expected value based on the experimental design. It should be noted that, for the properties being studied, only 1D or pseudo-1D simulations are required. This will speed up the simulation and also improve the convergence. For the CV simulation, one may also turn off incomplete ionization to further speed up the simulation and improve the convergence as the result is expected to be the same. This is because all dopants are expected to be fully ionized in the depletion region.

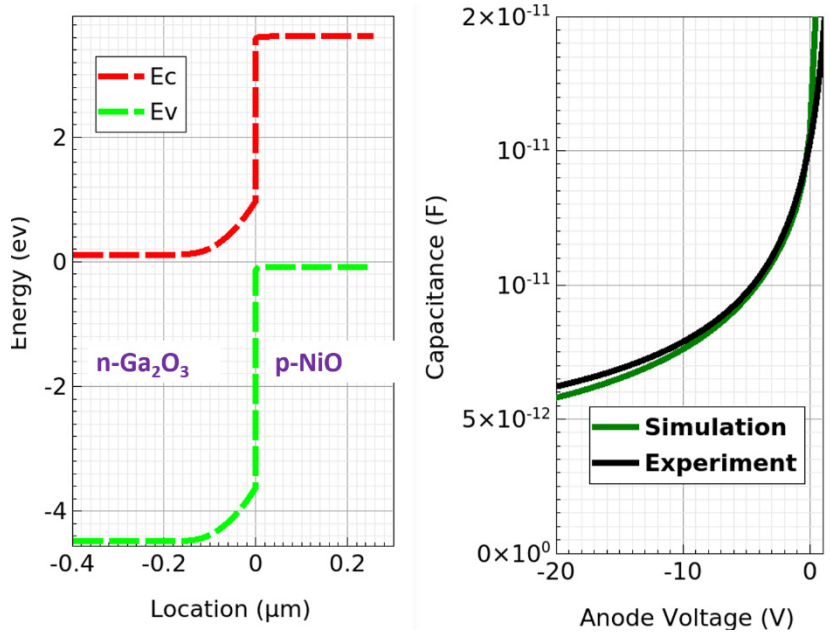

Fig. 3. TCAD simulated band diagram at zero bias (left) and comparison of simulated and experimental CV curves when the n-type doping is 4.5×10^{16}cm^{-3} (right) of a heterojunction p-NiO/n-Ga_2O_3 diode.

3.2. Schottky β-Ga_2O_3 diode simulation

Schottky diode is the natural choice as a two-terminal rectifier in β-Ga_2O_3 technology since p-type β-Ga_2O_3 is not available. In ref [29], TCAD is calibrated by comparing the current-voltage current against experimental data at various temperatures in a Schottky diode (Fig. 4). The models and parameters in Section 1 are used except that μ_{max} is changed to 123cm^2/V·s in Table 3 from 150cm^2/V·s in Table 2. This can be justified by the possibility that the crystal quality in this experiment may be worse than the one in Reference [27].

Since β-Ga_2O_3 has a low thermal conductivity, it is necessary to turn on self-heating for accurate simulation. It is thus also important to include the substrate in the simulation domain to properly account for heat transfer. Usually, to speed up the simulation, one may use an effective thermal resistance. However, this needs careful calibration. Fortunately, power Schottky diodes usually have cylindrical symmetry. Therefore, one can create a 2D slice of the structure and perform a 3D simulation using cylindrical coordinates. By using coarse mesh in the substrate, an IV curve can be obtained in a few minutes with a full domain of 3.3mm (Fig. 4). Indeed, the simulation speed is fast enough to generate tens of thousands of data for machine learning[35][36].

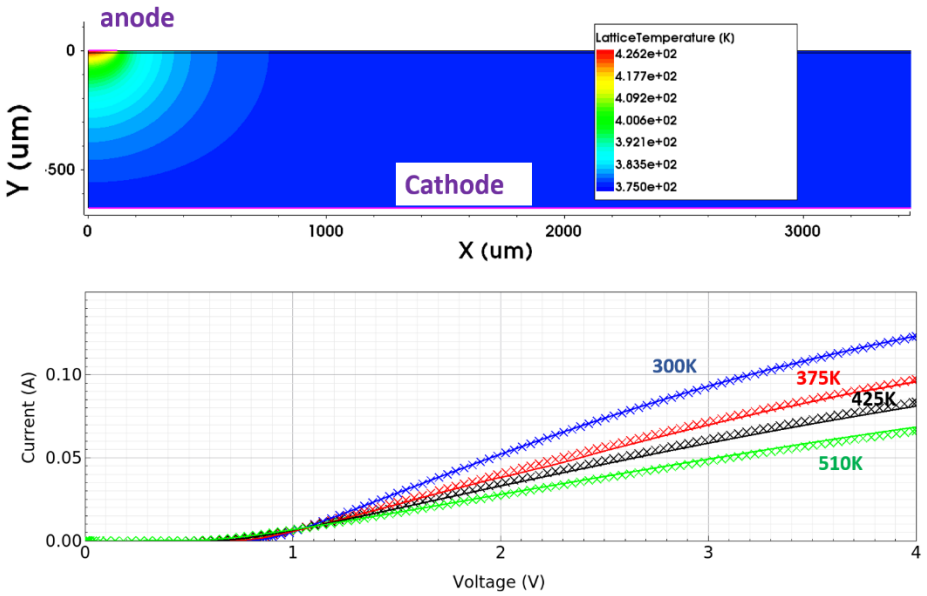

Fig. 4. Temperature distribution when the Schottky diode is under 4V forward bias (top) and TCAD vs. experimental forward IV at various ambient temperatures (bottom). The cylindrical coordinate is used and rotated about X = 0μm.

Table 3. Philips Unified Mobility Model Parameters used in Schottky diode [29]

Parameter	Keyword in Sdevice	Si in Ga_2O_3
μ_{max} ($cm^2/V{\cdot}s$)	mumax_*	123
μ_{min} ($cm^2/V{\cdot}s$)	mumin_*	80
θ	theta_*	1.8
N_{ref} (cm^{-3})	n_ref_*	2×10^{17}
α	alpha_*	0.9

3.3. Vertical β-Ga_2O_3 FinFET simulation

Vertical β-Ga_2O_3 FinFET is a very promising power device that can be normally off for fail-safe operations as long as it has a narrow enough fin and appropriate gate workfunction[8]- [10] [16][30][37]. However, since the fin is narrow and is formed after etching, the effective mobility can be substantially reduced. By using the model presented earlier, it is found that the mobility in the fin needs to be recalibrated. Fig. 5 shows the structure of the FinFET and the TCAD and experimental I_DV_G comparison. To match the I_DV_G, the Fin channel mobility is reduced by changing μ_{max} and μ_{min} of PhuMob model to 18.45$cm^2/V{\cdot}s$ and 12$cm^2/V{\cdot}s$, respectively (Table 4) to account for the degradation of the crystal quality due to etching and the narrow fin.

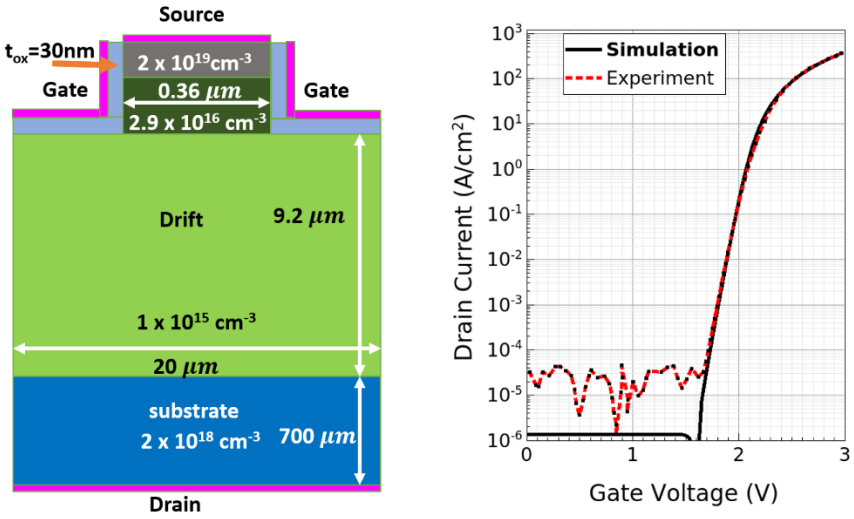

Fig. 5. Illustration of the vertical Ga_2O_3 FinFET structure (left) and TCAD vs. experimental I_DV_G (right)

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Table 4. Philips Unified Mobility Model Parameters used in Ga_2O_3 FinFET [30][37]

Parameter	Keyword in Sdevice	Si in Ga_2O_3
μ_{max} (cm^2/V·s)	mumax_*	123 (bulk)/ 18.45 (Fin)
μ_{min} (cm^2/V·s)	mumin_*	80 (bulk)/ 12 (Fin)
θ	theta_*	1.8
N_{ref} (cm^{-3})	n_ref_*	2×10^{17}
α	alpha_*	0.9

Simulation of β-Ga_2O_3 simulation does not present much more convergence challenges compared to the Schottky diode. However, when performing breakdown and short circuit simulations, it is necessary to turn on background carrier generation to stabilize the numeric to avoid underflow or overflow. As shown in Reference [37], a background carrier generation of 10^5 cm^{-3}s^{-1} to 10^{12} cm^{-3}s^{-1} is required to obtain a correct breakdown value and this will also improve convergence[17].

4. Conclusion

In this paper, we present a comprehensive set of TCAD models and parameters for β-Ga_2O_3 power device simulations. Most of the parameters are temperature-dependent and calibrated to various experiments. We demonstrated their applications in heterojunction p-NiO/n-Ga2O3 diode, Schottky diode, and normally-off β-Ga_2O_3 vertical FinFET simulations. The setup is robust and accurate. It is expected that, with the setup, β-Ga_2O_3 devices can be designed and optimized before the technology is matured.

Acknowledgments

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References

[1] Tsao J Y, Chowdhury S, Hollis M A, et al. Ultrawide-Bandgap Semiconductors: Research Opportunities and Challenges. Adv. Electron. Mater., 2018, 4: 1600501.
[2] Higashiwaki M, and Jessen G H, Guest Editorial: The dawn of gallium oxide microelectronics. Appl. Phys. Lett., 2018, 112(6): 060401
[3] Higashiwaki M, Sasaki K, Murakami H, et al. Recent progress in Ga2O3 power devices. Semicond. Sci. Technol., 2016, 31: 034001.
[4] Wang B, Xiao M, Yan X, et al. High-voltage vertical Ga2O3 power rectifiers operational at high temperatures up to 600 K. Appl. Phys. Lett., 2019, 115: 263503
[5] Higashiwaki M, Sasaki K, Kuramata A, et al. Gallium oxide (Ga2O3) metal-semiconductor field-effect transistors on single-crystal β-Ga2O3 (010) substrates. Appl. Phys. Lett., 2012, 100: 013504.
[6] Moser N, McCandless J, Crespo A, et al. "High pulsed current density β -Ga2O3 MOSFETs verified by an analytical model corrected for interface charge. Appl. Phys. Lett., 2017, 110: 143505.
[7] Shimbori A, Wong H Y and Huang A Q. Fabrication and Analysis of a Novel High Voltage Heterojunction p-NiO/n-Ga2O3 Diode. 32nd International Symposium on Power Semiconductor Devices and ICs (ISPSD), 2020: 218-221.
[8] Hu Z, Nomoto K, Li W, et al. Enhancement-Mode Ga2O3 Vertical Transistors With Breakdown Voltage >1 kV. IEEE Electron Device Letters, 2018, 39(6): 869-872.
[9] Hu Z, Nomoto K, Li W, et al. Breakdown mechanism in 1 kA/cm2 and 960 V E-mode β-Ga2O3 vertical transistors. Applied Physics Letters, 2018, 113: 122103.
[10] Li W, Nomoto K, Hu Z, et al. Single and multi-fin normally-off Ga2O3 vertical transistors with a breakdown voltage over 2.6 kV. 2019 IEEE International Electron Devices Meeting (IEDM), 2019: 12.4.1-12.4.4.
[11] Wong H Y, de Almeida Braga N, Mickevicius R. Normally-off gallium oxide field-effect transistor. USA Patent, US 10644107, 2020.
[12] Wong H Y, Braga N, Mickevicius RV, et al. Normally-OFF dual-gate Ga2O3 planar MOSFET and FinFET with high ION and BV. 2018 IEEE 30th International Symposium on Power Semiconductor Devices and ICs (ISPSD), 2018: 379-382.
[13] Buttaya C, Wong H Y, Wang B, et al. Surge Current Capability of Ultra-Wide-Bandgap Ga_2O_3 Schottky Diodes. Microelectronics Reliability, 2020, 114: 113743.
[14] Sentaurus™ Device User Guide, Synopsys Inc
[15] Saltin J, Tian S, Ding F, et al. Novel Doping Engineering Techniques for Gallium Oxide MOSFET to Achieve High Drive Current and Breakdown Voltage. 2019 IEEE 7th Workshop on Wide Bandgap Power Devices and Applications (WiPDA), 2019: pp. 261-264
[16] Elwailly A, Xiao M, Zhang Y, et al. Design Space of Vertical Ga2O3 Junctionless FinFET and its Enhancement with Gradual Channel Doping. 2020 IEEE Workshop on Wide Bandgap Power Devices and Applications in Asia (WiPDA Asia), 2020: 1-5.
[17] Chatterjee B, Shoemaker D, Wong H-Y, et al. 6 - AlGaN/GaN HEMT device physics and electrothermal modeling, In Woodhead Publishing Series in Electronic and Optical Materials, Thermal Management of Gallium Nitride Electronics, Woodhead Publishing, 2022.
[18] Guo Z, Verma A, Wu X, et al. Anisotropic thermal conductivity in single crystal β-gallium oxide. Appl. Phys. Lett., 2015, 106: 111909.
[19] Rafique S, Han L, Mou S, and Zhao H. Temperature and doping concentration dependence of the energy band gap in β-Ga2O3 thin films grown on sapphire. Opt. Mater. Express, 2017, 7, 3561-3570.
[20] Lopez I, Nogales E, Hidalgo P, et al. Field emission properties of gallium oxide micro- and nanostructures in the scanning electron microscope. Phys. Status Solidi, 2012 A 209, (1): 113–117.
[21] Fares C, Ren F, Pearton S J. Temperature-Dependent Electrical Characteristics of β-Ga2O3 Diodes with W Schottky Contacts up to 500°C. ECS Journal of Solid State Science and Technology, 2019 8 (7): Q3007-

Q3012.
[22] Janowitz C, Scherer V, Mohamed M, et al. Experimental electronic structure of In2O3 and Ga2O3. New J. Phys., 2011, 13: 085014.
[23] Park J and Hong S M. Simulation Study of Enhancement Mode Multi-Gate Vertical Gallium Oxide MOSFETs. ECS Journal of Solid State Science and Technology, 2019, 8 (7): Q3116-Q3121.
[24] Kotecha R, Metzger W, Mather B, et al. Modeling and Analysis of Gallium Oxide Vertical Transistors. ECS Journal of Solid State Science and Technology, 2019, 8 (7): Q3202-Q3205.
[25] Klaassen D B M. A unified mobility model for device simulation-I. Model equations and concentration dependence. Solid-State Electronics, 1992, 35 (7): 953-959.
[26] Wong H Y. Calibrated Si Mobility and Incomplete Ionization Models with Field Dependent Ionization Energy for Cryogenic Simulations. 2020 International Conference on Simulation of Semiconductor Processes and Devices (SISPAD), 2020: pp. 193-196.
[27] Goto K, Konishi K, Murakami H, et al. Halide vapor phase epitaxy of Si doped β -Ga2O3 and its electrical properties. Thin Solid Films, 2018, 666: 182-184.
[28] Moser N, McCandless J, Crespo A, et al. Ge-Doped β -Ga2O3 MOSFETs. IEEE Electron Device Letters, 2017, 38(6): 775-778.
[29] Wong H Y, Xiao M, Wang B, et al. TCAD-Machine Learning Framework for Device Variation and Operating Temperature Analysis With Experimental Demonstration. IEEE Journal of the Electron Devices Society, 2020, 8: pp. 992-100.
[30] Wong H Y and Tenkeu A C F. Advanced TCAD Simulation and Calibration of Gallium Oxide Vertical Transistor, 2020, 9: 035003.
[31] Mastro M A, Kuramata A, Calkins J, et al. Perspective—Opportunities and Future Directions for Ga2O3. ECS J. Solid State Sci. Technol., 2017, 6: P356.
[32] Neal A T, Mou S, Rafique S, et al. Donors and deep acceptors in β-Ga2O3. Appl. Phys. Lett., 2018, 113: 062101.
[33] Ghosh K and Singisetti U. Impact ionization in β-Ga2O3. Journal of Applied Physics, 2018, 124: 085707.
[34] Yakimov E B, et al. Role of hole trapping by deep acceptors in electron-beam-induced current measurements in β-Ga2O3 vertical rectifiers. J. Phys. D: Appl. Phys. 2020, 53: 495108.
[35] Dhillon H, Mehta K, Xiao M, et al. TCAD-Augmented Machine Learning with and without Domain Expertise. IEEE Transactions on Electron Devices, 2021, 68(11): 5498-5503, Nov. 2021.
[36] Raju S S, Wang B, Mehta K, et al. Application of Noise to Avoid Overfitting in TCAD Augmented Machine Learning. International Conference on Simulation of Semiconductor Processes and Devices (SISPAD), 2020: pp. 351-354.
[37] Lu A, Elwailly A, Zhang Y, et al. Study of Vertical Ga2O3 FinFET Short Circuit Ruggedness using Robust TCAD Simulation. ECS J. Solid State Sci. Technol., 2022, 11: 115001.