MOS-AK

Analytical Modeling of double channel GaN HEMTs

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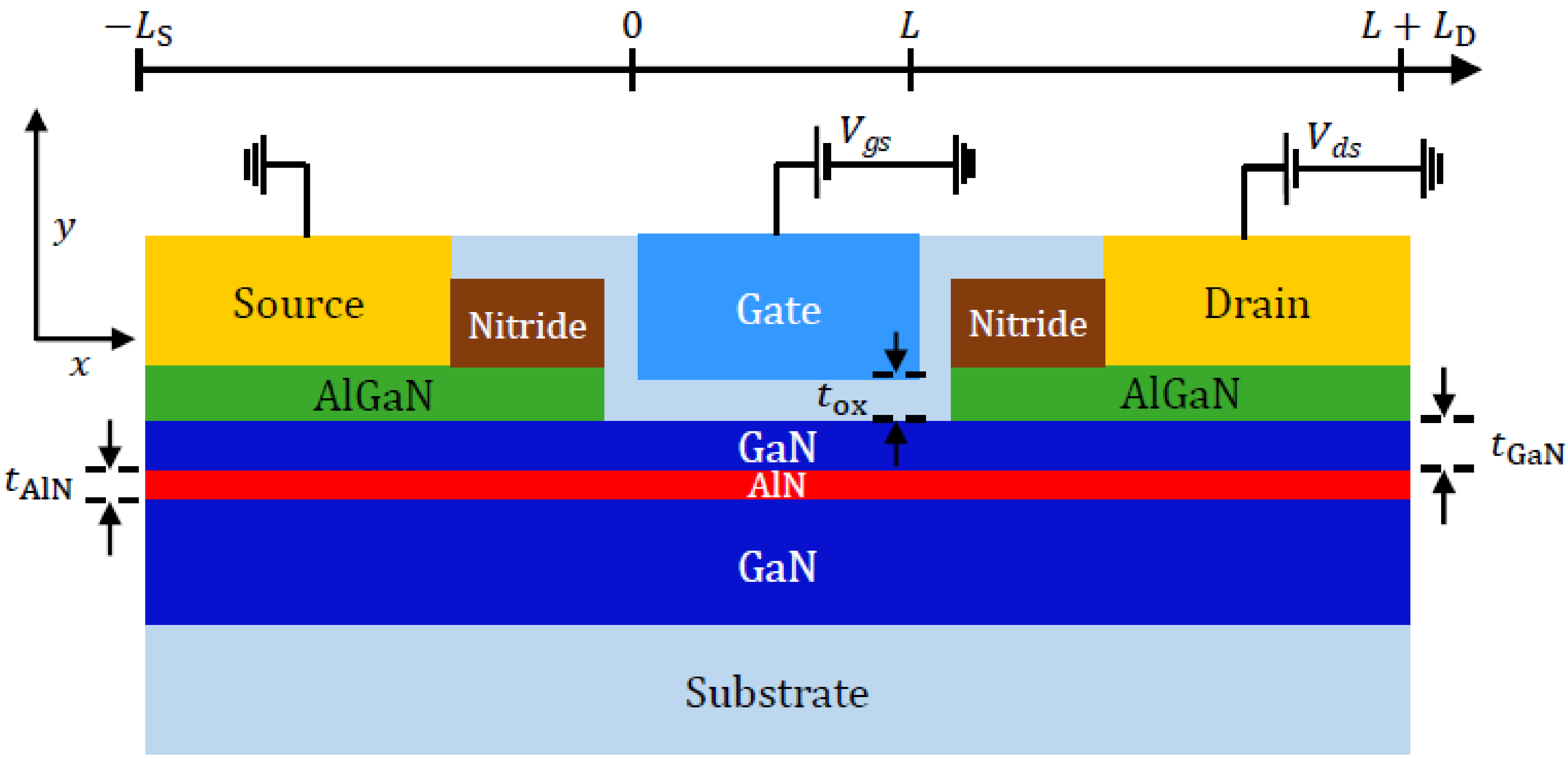
Acknowledgements

Device Schematic



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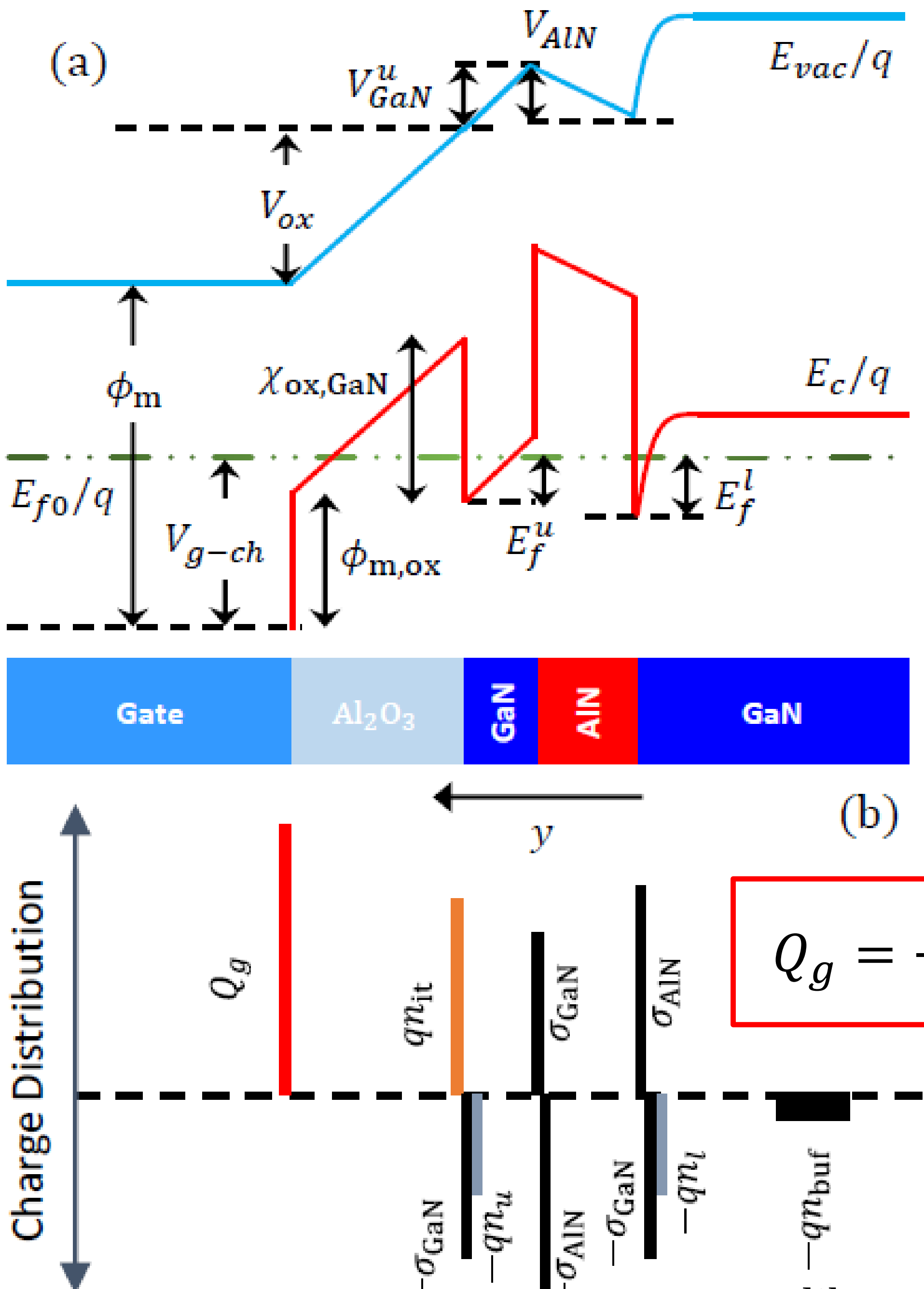
Band diagram



Charge neutrality

$$Q_g = -(qn_{it} - qn_u - \sigma_{\mathrm{GaN}} - qn_l - qn_{\mathrm{buf}})$$

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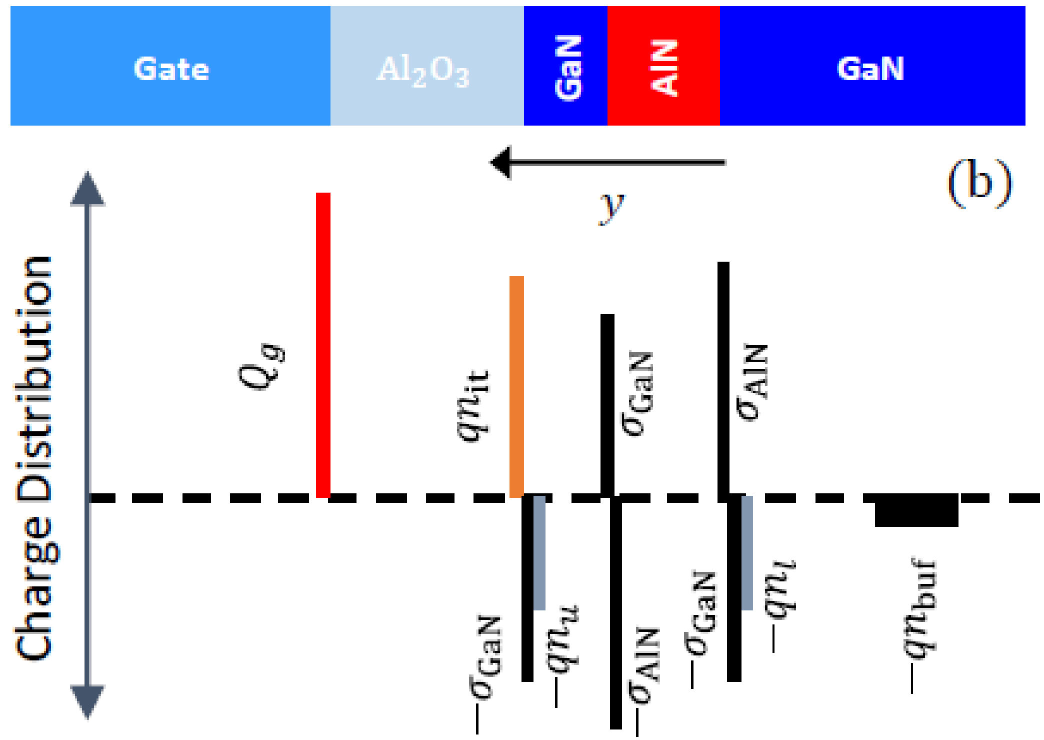
1D Poisson Eq

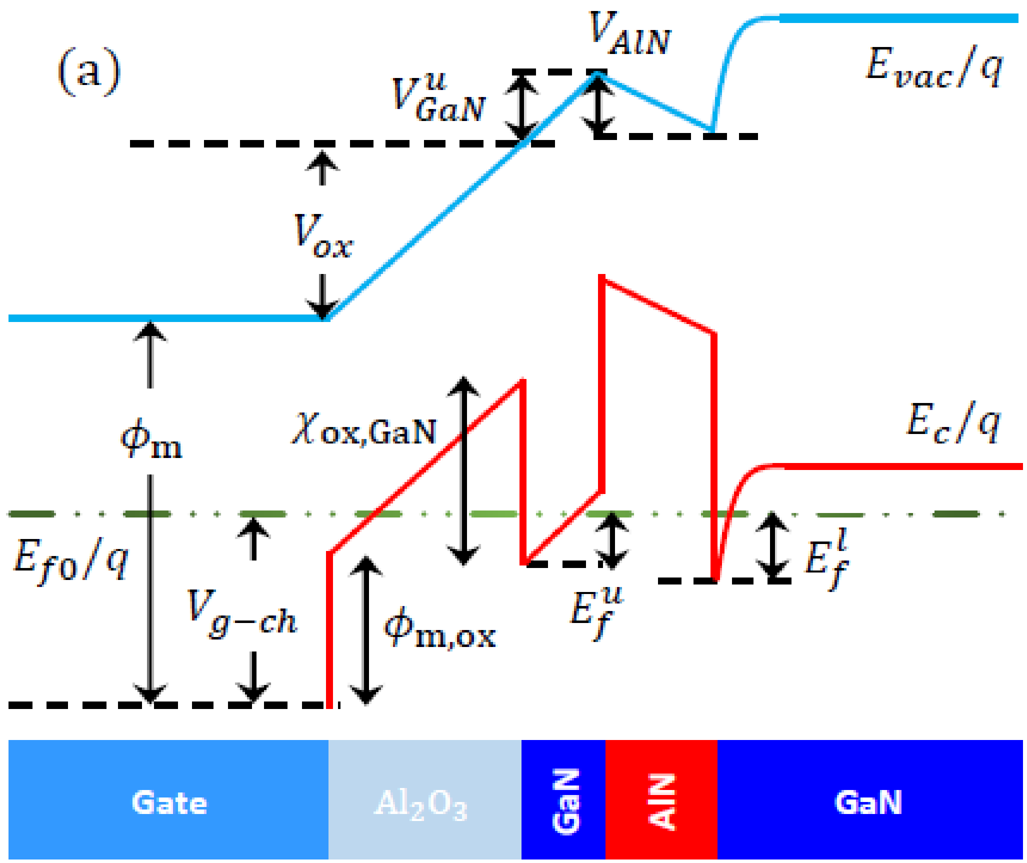


$$V_{ox} = \frac{Q_g}{C_{\mathrm{ox}}} \tag{2}$$

$$V^u_{GaN} = \frac{Q_g + qn_{\mathrm{it}} - \sigma_{\mathrm{GaN}} - qn_u}{C_{\mathrm{GaN}}} \tag{3}$$

$$V_{AlN} = -\frac{Q_g + qn_{\mathrm{it}} - qn_u - \sigma_{\mathrm{AlN}}}{C_{\mathrm{AlN}}} \tag{4}$$

Potential balance – upper channel



$$\phi_{\mathrm{m,ox}} - V_{g-ch} + V_{\mathrm{ox}} - \chi_{\mathrm{GaN,ox}} + \frac{E_f^u}{q} = 0 \qquad (7)$$

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$$\boxed{E_f^u = qV_{gov}^u + \frac{q(qn_{\rm it} - qn_u - \sigma_{\rm GaN} - qn_l - qn_{\rm buf})}{C_{\rm ox}} \quad (8)}$$

where $$V_{gov}^u = V_{g-ch} - \phi_{\rm m,ox} + \chi_{\rm GaN,ox} \quad (9)$$

Redo the potential balance for lower channel

$$\boxed{\begin{aligned} E_f^l = qV_{gov}^l &+ \frac{q(qn_{\rm it} - qn_u - \sigma_{\rm GaN} - qn_l - qn_{\rm buf})}{C_{\rm ox}} \\ &+ q\left(qn_{\rm it} - \sigma_{\rm GaN} - qn_l - qn_{\rm buf}\right)\left(\frac{1}{C_{\rm GaN}} + \frac{1}{C_{\rm AlN}}\right) \quad (10) \end{aligned}}$$

where $$\begin{aligned} V_{gov}^l = V_{g-ch} - \phi_{\rm m,ox} + \chi_{\rm GaN,ox} + \frac{\sigma_{\rm AlN}}{C_{\rm AlN}} \\ + \frac{\sigma_{\rm GaN}}{C_{\rm GaN}} - qn_{\rm it}\left(\frac{1}{C_{\rm GaN}} + \frac{1}{C_{\rm AlN}}\right) \quad (11) \end{aligned}$$

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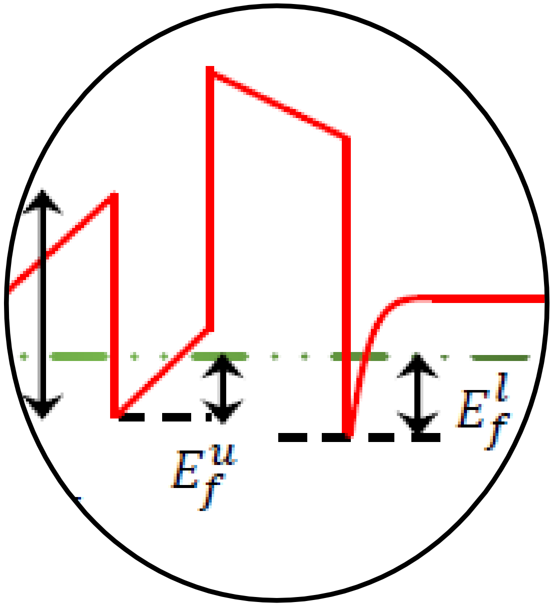
Sub-bands in triangular quantum wells

$$E_j = q\left(\frac{\hbar^2}{2m^*}\right)^{\frac{1}{3}}\left(\frac{3}{2}\pi q\mathcal{E}\right)^{\frac{2}{3}}\left(j+\frac{3}{4}\right)^{\frac{2}{3}} \qquad (12)$$



$$E_{c1}^{u(l)} = \alpha\left(\mathcal{E}_{GaN}^{u(l)}\right)^{\frac{2}{3}} \qquad (13)$$

where

$2.1920\times10^{-25}\ \mathrm{Kg}^{\frac{1}{3}}\mathrm{m}^{\frac{4}{3}}\mathrm{A}^{\frac{2}{3}}$ for GaN effective mass of $0.22m_0$

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Fermi Dirac Statistics

$$n_{u(l)} = D_{\mathrm{n}} kT \ln\left[1 + \exp\left(\frac{E_f^{u(l)} - E_{c1}^{u(l)}}{kT}\right)\right] \qquad (14)$$

where $D_{\mathrm{n}} = m^*/\pi\hbar^2$ is the 2-D DOS

$$n_u = D_{\mathrm{n}} kT \ln\left[1 + \exp\left(\frac{qV_{gov}^{u}}{kT} + \frac{q\left(qn_{\mathrm{it}} - qn_u - \sigma_{\mathrm{GaN}} - qn_l - qn_{\mathrm{buf}}\right)}{C_{\mathrm{ox}} kT} - \frac{\alpha}{kT}\left(\frac{qn_l + qn_{\mathrm{buf}}}{\epsilon_{\mathrm{GaN}}}\right)^{\frac{2}{3}}\right)\right] \qquad (15)$$

$$\begin{aligned} n_l = D_{\mathrm{n}} kT \ln\Bigg[1 + \exp\Bigg(&\frac{qV_{gov}^{l}}{kT} + \frac{q\left(qn_{\mathrm{it}} - qn_u - \sigma_{\mathrm{GaN}} - qn_l - qn_{\mathrm{buf}}\right)}{C_{\mathrm{ox}} kT} \\ &+ \frac{q\left(qn_{\mathrm{it}} - \sigma_{\mathrm{GaN}} - qn_l - qn_{\mathrm{buf}}\right)}{kT}\left(\frac{1}{C_{\mathrm{GaN}}} + \frac{1}{C_{\mathrm{AlN}}}\right) - \frac{\alpha}{kT}\left(\frac{qn_l + qn_{\mathrm{buf}}}{\epsilon_{\mathrm{GaN}}}\right)^{\frac{2}{3}}\Bigg)\Bigg] \qquad (16) \end{aligned}$$

System of two non-linear equations with unknowns n_l and n_u

Drift-diffusion transport

$$\boxed{J = J_u + J_l = -\mu_{\mathrm{nu}} n_u \frac{dE_f}{dn_u}\frac{dn_u}{dx} - \mu_{\mathrm{nl}} n_l \frac{dE_f}{dn_l}\frac{dn_l}{dx} \qquad (20)}$$

Integrate with limits

$$x : 0 \rightarrow L,\ n_u : n_{u,s} \rightarrow n_{u,d} \quad n_l : n_{l,s} \rightarrow n_{l,d},$$

$$I\frac{L}{W} = -\mu_{\mathrm{nu}} \int_{n_{u,s}}^{n_{u,d}} \left(n_u \frac{dE_f}{dn_u} \right) dn_u - \mu_{\mathrm{nl}} \int_{n_{l,s}}^{n_{l,d}} \left(n_l \frac{dE_f}{dn_l} \right) dn_l \qquad (21)$$

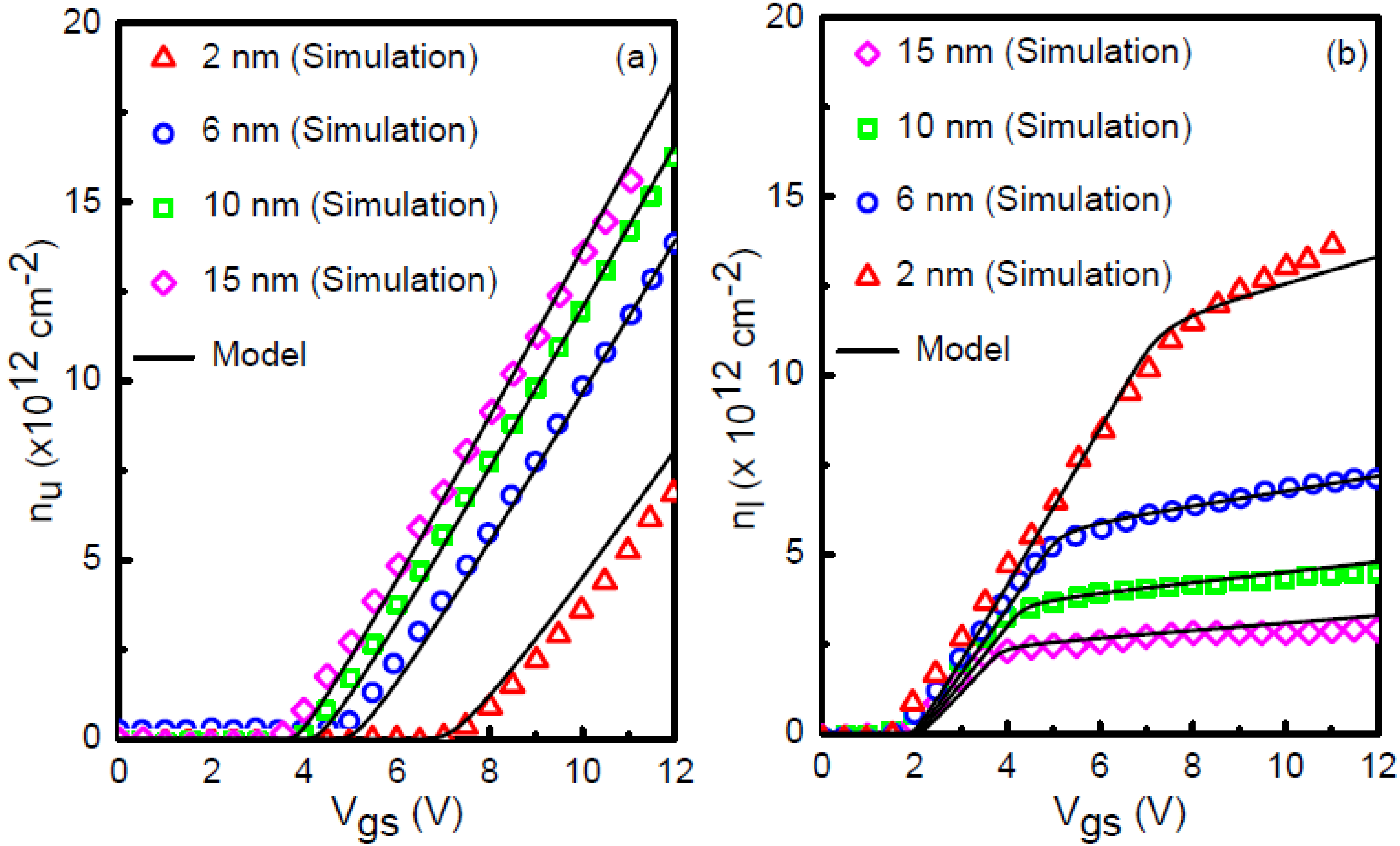
$$\frac{dE_f}{dn_u} = \frac{q^2}{C_{\mathrm{ox}}}\left(1 + \frac{dn_l}{dn_u}\right) + \frac{kT}{n_{\mathrm{q}}}\frac{e^{n_u/n_{\mathrm{q}}}}{e^{n_u/n_{\mathrm{q}}} - 1} + \frac{2q\alpha}{3\epsilon_{\mathrm{GaN}}}\left(\frac{qn_l + qn_{\mathrm{buf}}}{\epsilon_{\mathrm{GaN}}}\right)^{-\frac{1}{3}} \frac{dn_l}{dn_u} \qquad (23)$$

$$\frac{dE_f}{dn_l} = \frac{q^2}{C_{\text{ox}}}\left(1 + \frac{dn_u}{dn_l}\right) + \frac{kT}{n_{\text{q}}}\frac{e^{n_l/n_{\text{q}}}}{e^{n_l/n_{\text{q}}} - 1}$$
$$+ \frac{2q\alpha}{3\epsilon_{\text{GaN}}}\left(\frac{qn_l + qn_{\text{buf}}}{\epsilon_{\text{GaN}}}\right)^{-\frac{1}{3}} + q^2\left(\frac{1}{C_{\text{GaN}}} + \frac{1}{C_{\text{AlN}}}\right) \quad (24)$$

Final drift diffusion current

$$J = -\underbrace{\frac{\mu_{\text{nu}}}{L}\frac{q^2}{C_{\text{ox}}}\int_{n_{u,s}}^{n_{u,d}} n_u dn_u}_{J_{\text{I}}} - \underbrace{\frac{\mu_{\text{nl}}}{L}q^2\left(\frac{1}{C_{\text{ox}}} + \frac{1}{C_{\text{GaN}}} + \frac{1}{C_{\text{AlN}}}\right)\int_{n_{l,s}}^{n_{l,d}} n_l dn_l}_{J_{\text{II}}} - \underbrace{\frac{2\mu_{\text{nl}}q\alpha}{3\epsilon_{\text{GaN}}L}\int_{n_{l,s}}^{n_{l,d}}\left(\frac{qn_l + qn_{\text{buf}}}{\epsilon_{\text{GaN}}}\right)^{-\frac{1}{3}} n_l dn_l}_{J_{\text{III}}}$$
$$-\underbrace{\frac{\mu_{\text{nu}}}{L}\frac{kT}{n_{\text{q}}}\int_{n_{u,s}}^{n_{u,d}}\left(\frac{e^{n_u/n_{\text{q}}}}{e^{n_u/n_{\text{q}}} - 1}\right) n_u dn_u}_{J_{\text{IV}}} - \underbrace{\frac{\mu_{\text{nl}}}{L}\frac{kT}{n_{\text{q}}}\int_{n_{u,s}}^{n_{u,d}}\left(\frac{e^{n_l/n_{\text{q}}}}{e^{n_l/n_{\text{q}}} - 1}\right) n_l dn_l}_{J_{\text{V}}}$$
$$-\underbrace{\frac{\mu_{\text{nl}}}{L}\frac{q^2}{C_{\text{ox}}}\int_{n_{u,s}}^{n_{u,d}} n_l dn_u}_{J_{\text{VI}}} - \underbrace{\frac{\mu_{\text{nu}}}{L}\frac{q^2}{C_{\text{ox}}}\int_{n_{l,s}}^{n_{l,d}} n_u dn_l}_{J_{\text{VII}}} - \underbrace{\frac{2\mu_{\text{nu}}q\alpha}{3\epsilon_{\text{GaN}}L}\int_{n_{l,s}}^{n_{l,d}}\left(\frac{qn_l + qn_{\text{buf}}}{\epsilon_{\text{GaN}}}\right)^{-\frac{1}{3}} n_u dn_l}_{J_{\text{VIII}}} \quad (25)$$

Validation against TCAD



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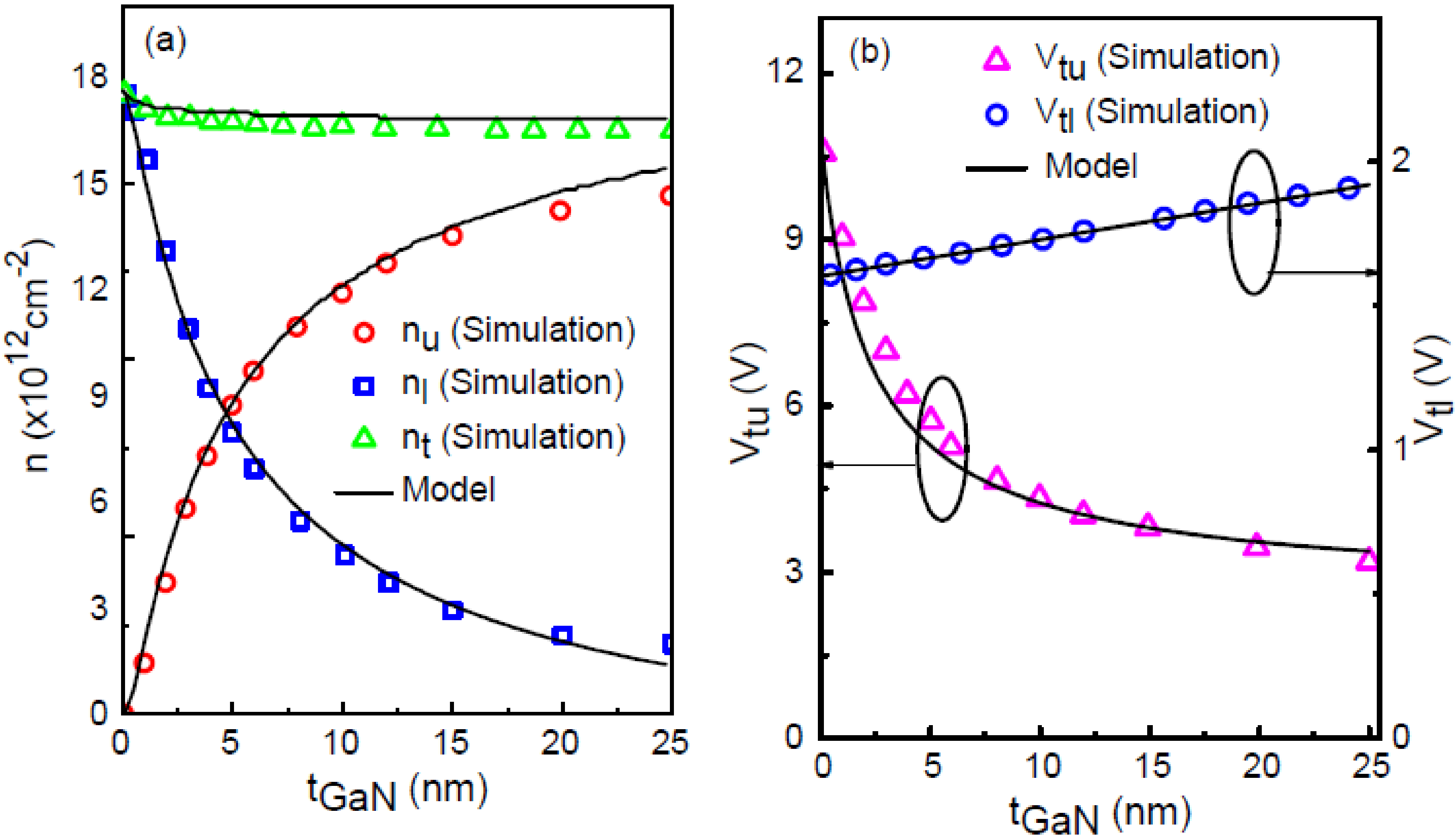
Validation against TCAD



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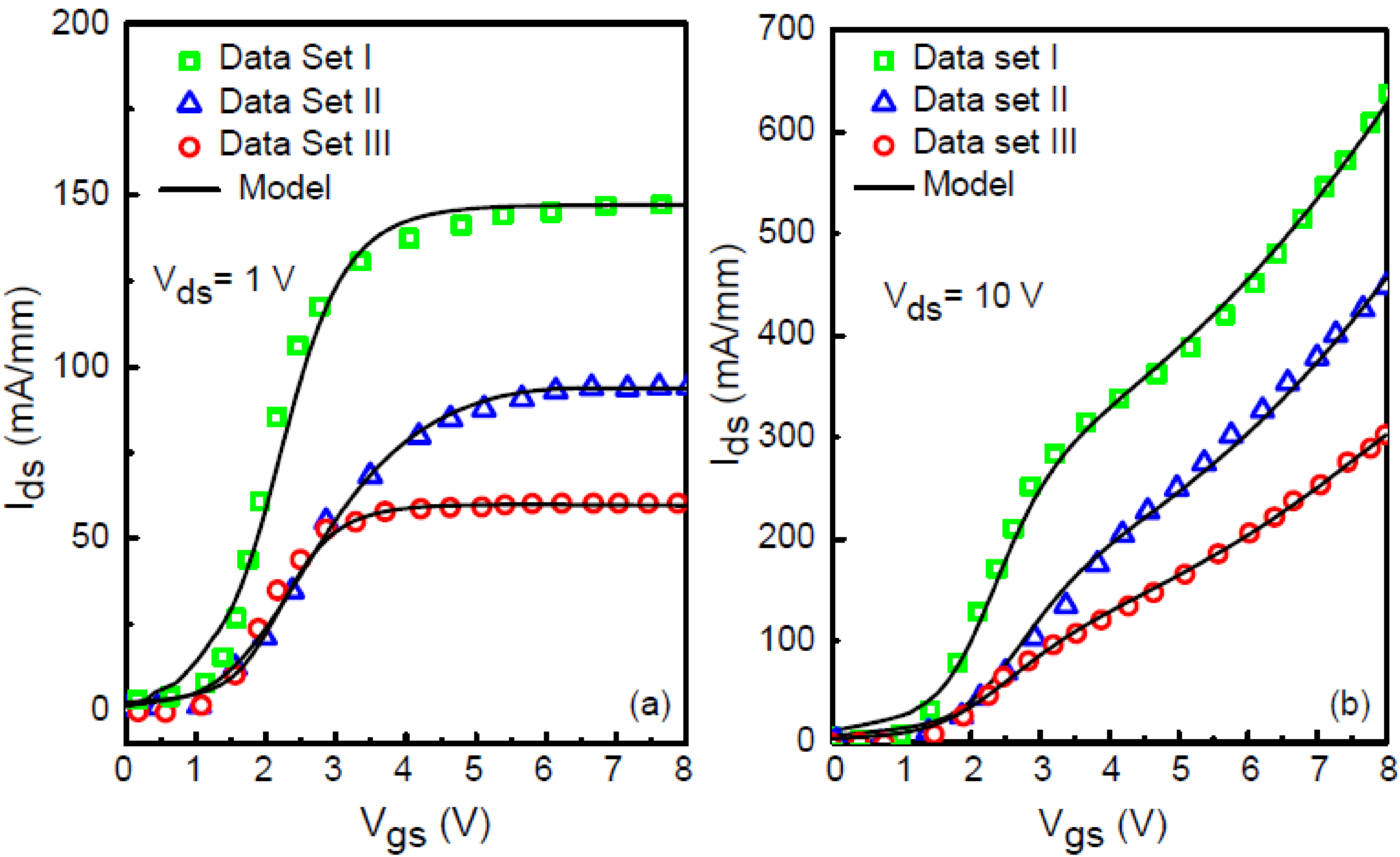
Validation against experimental



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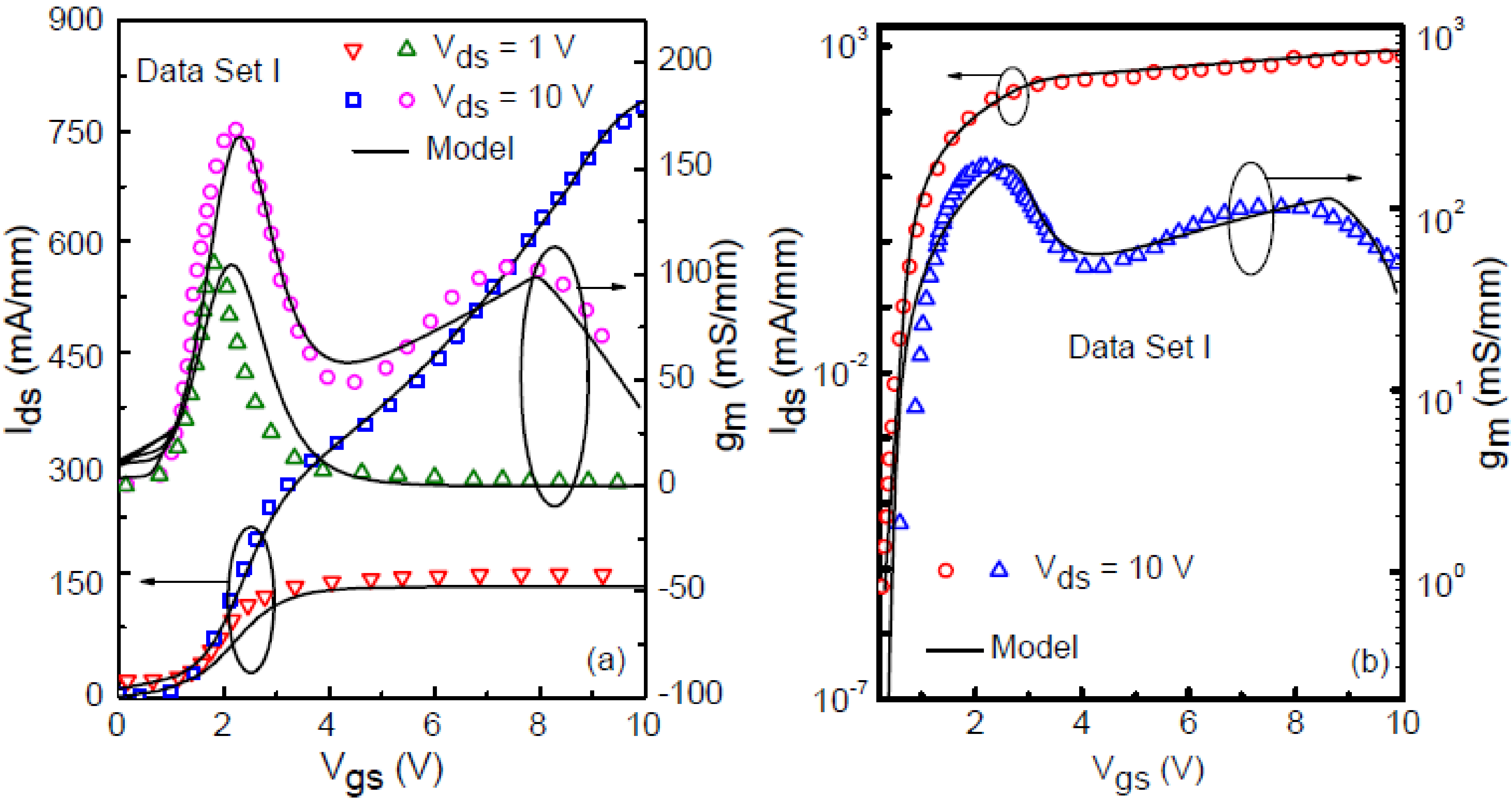
Validation against experimental



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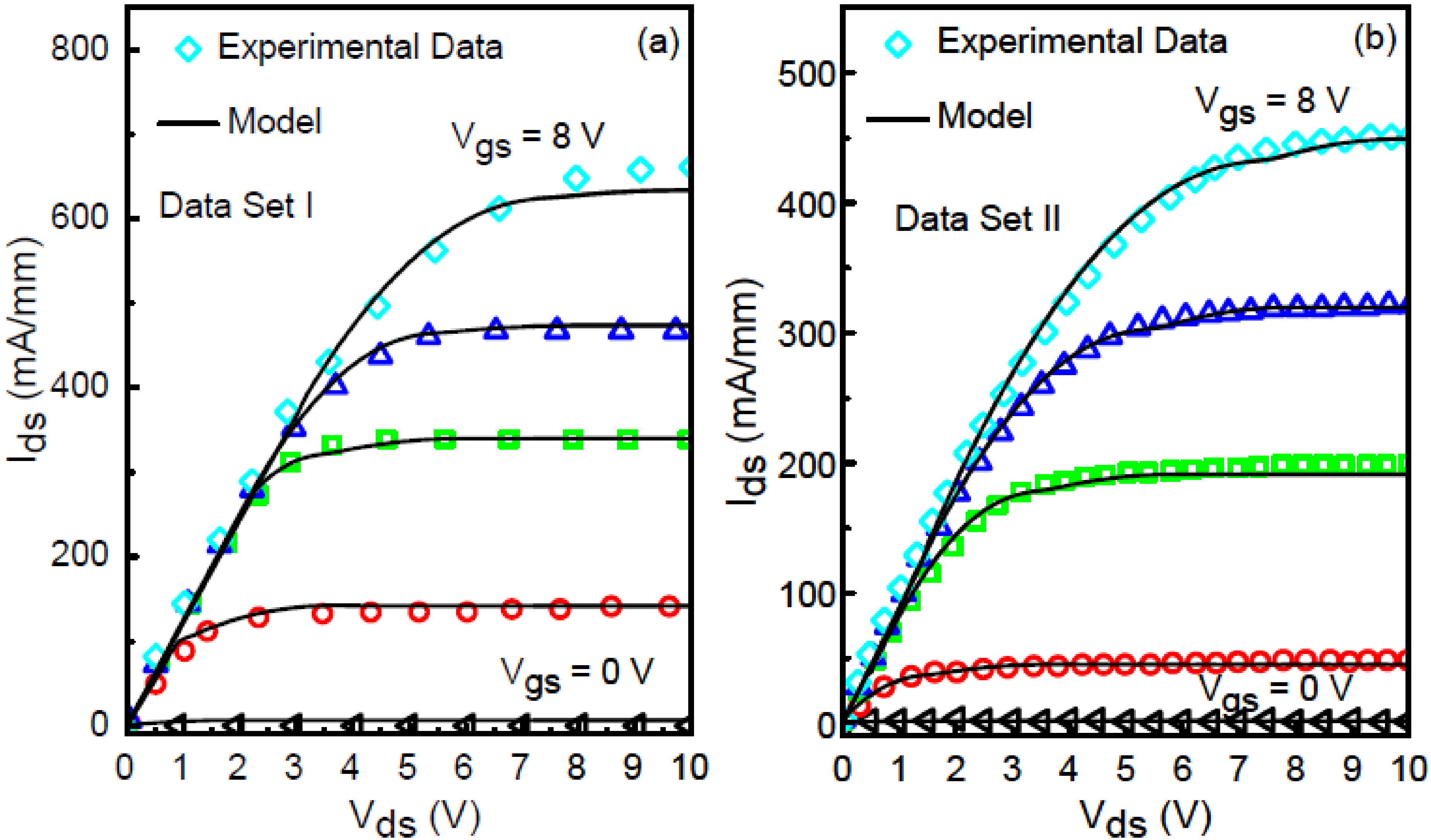
Validation against experimental



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Conclusion

- A physics-based compact model for double channel GaN HEMTs was presented
- The model is analytical
- Includes the essential physics of 2D density of states, double-channel electrostatics
- Fits TCAD and experimental data reported in literature

Thank You!