A Simple, Accurate Capacitance-Voltage Model of Undoped Silicon Nanowire MOSFETs

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Overview

- Motivation
- Model Equation
- Simulation Results & Verification
- Conclusion

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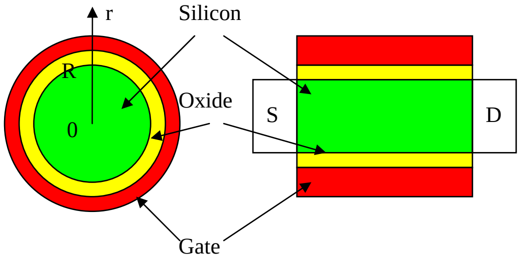
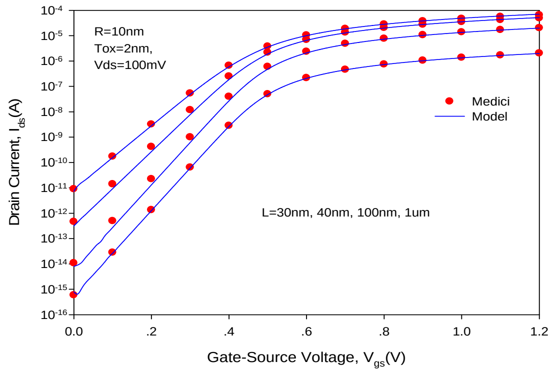
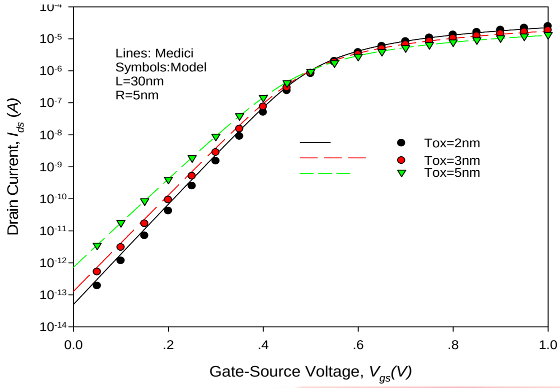
SiNW MOSFETs







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Modeling Capacitances in FET

- Intrinsic Capacitances, Extrinsic Capacitances
- Simple
- Accurate, Valid in all region
- Symmetry

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Surface Potential Solution

$$\frac{d^2\phi}{dr^2}+\frac{1}{r}\frac{d\phi}{dr}=\frac{qn_i}{\varepsilon_{Si}}e^{(\phi-V_C)/v_{th}}$$

$$V_{GF}=\phi_s+\frac{4\varepsilon_{si}v_{th}}{RC_{ox}}\left(\frac{\delta R^2 e^{\frac{\phi_s-V_C}{v_{th}}}}{-4+2\sqrt{4+2\delta R^2 e^{\frac{\phi_s-V_C}{v_{th}}}}}-1\right)$$

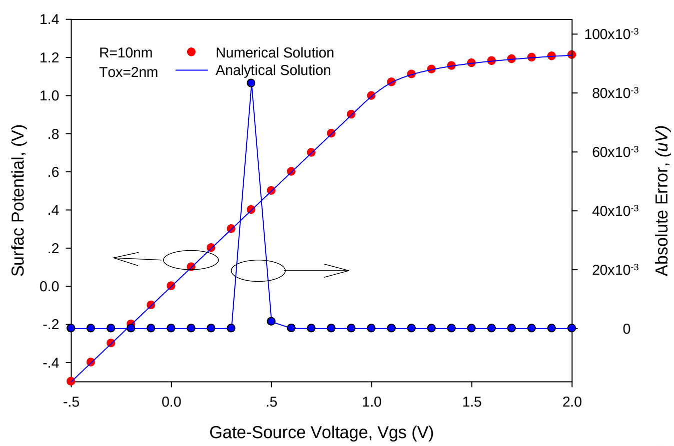
$$\phi_{s1}\approx V_{gf}-\frac{4\varepsilon_{si}v_{th}}{RC_{ox}}\left(\frac{\delta R^2\left(1+\frac{V_{gf}}{v_{th}}\right)}{-4+2\sqrt{4+2\delta R^2\left(1+\frac{V_{gf}}{v_{th}}\right)}}-1\right)$$

$$\phi_{s2}\approx v_{th}\ln\left(\frac{8\cdot\frac{4\varepsilon_{si}v_{th}}{RC_{ox}}\cdot V_{GF}\left(\frac{4\varepsilon_{si}v_{th}}{RC_{ox}}\cdot V_{GF}+1\right)}{\delta R^2}\right)$$

$$\phi_{s3}=\frac{1}{2}\left(\phi_{s2}+\phi_{s1}-\sqrt{\left(\phi_{s2}-\phi_{s1}\right)^2-d}\right)$$

$$\phi_{s4}\approx v_{th}\ln\left(\frac{8\cdot\frac{4\varepsilon_{si}v_{th}}{RC_{ox}}\cdot\left(V_{GF}-\phi_{s3}\right)\left(\frac{4\varepsilon_{si}v_{th}}{RC_{ox}}\cdot\left(V_{GF}-\phi_{s3}\right)+1\right)}{\delta R^2}\right)$$

$$\phi_{s5}=\frac{1}{2}\left(\phi_{s4}+\phi_{s1}-\sqrt{\left(\phi_{s4}-\phi_{s1}\right)^2-d}\right)$$



$$\phi_s=\phi_{s5}+K-\frac{f_2}{2f_1}K^2+\frac{\left(3f_2\right)^2-f_1f_3}{6\left(f_1\right)^2}K^3+\frac{10f_1f_2f_3-\left(f_1\right)^2f_4-15\left(f_2\right)^3}{24\left(f_1\right)^3}K^4$$

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Charge Equation

- Gate Charge

$$Q_G = 2\pi R \int_0^L Q_G(y)dy$$

- Source and Drain Charge (Ward-Dutton method)

$$Q_S = 2\pi R \int_0^L \left(1 - \frac{y}{L}\right) Q_i(y)\,dy$$

$$Q_D = 2\pi R \int_0^L \frac{y}{L} Q_i(y)\,dy$$

- Capacitance

$$C_{ij} = \delta_{ij} \frac{\partial Q_i}{\partial V_j} \qquad \delta_{ij} = \begin{cases} 1, i = j \\ -1, i \neq j \end{cases}$$

Current Expressions

- Current Equation

$$I_{ds} = \mu \frac{2\pi R}{L} \int_{\phi_s(0)}^{\phi_s(L)} (-Q_{sc}) \frac{dV}{d\phi_s} d\phi_s \qquad \frac{dV_C}{d\phi_s} = 1 + v_{th} \cdot \left(\frac{1}{V_{GF} - \phi_s} + \frac{1}{(V_{GF} - \phi_s + C_R)} \right)$$

$$= \mu C_{ox} \frac{2\pi R}{L} \left\{ V_{gf} \Delta\phi - \overline{\phi_s} \Delta\phi + v_{th} \left[2\Delta\phi + C_R \ln\left(\frac{V_{gf} - \phi_s(L) + C_R}{V_{gf} - \phi_s(0) + C_R} \right) \right] \right\}$$

- Approximate Current Equation

$$I_{ds} = 2\pi R \mu Q_{sc}(y) \frac{dV_C}{dy} \qquad \frac{dV_C}{d\phi_s} \approx 1 + v_{th} \cdot \frac{1}{V_{GF} - \phi_s}$$

$$\approx -\mu \frac{2\pi R}{L} \int Q_{sc}(y)\, d\phi_s + \mu v_{th} \frac{2\pi R}{L} \int dQ_{sc}(y)$$

$$= \mu \frac{2\pi R C_{ox}}{L} \left[\left(V_{gf} + v_{th} \right) \cdot \Delta\phi - \Delta\phi \cdot \overline{\phi} \right]$$

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y Expression

- It is derived based upon current

$$y = \frac{2\pi R\mu}{I_{ds}} \int_{V_s}^{V} Q_{sc}(y)\, dV_C$$

$$= \frac{L}{\left[\left(V_{gf} + 2v_{th}\right) - \overline{\phi_s}\right]\Delta\phi} \left[\left(V_{gf} + 2v_{th}\right) - \overline{\phi_s^{'}}\right]\Delta\phi^{'}$$

- Taylor's expansion

$$y \approx \frac{L}{2}\left(1 + \frac{\Delta\phi}{4H}\right) + \frac{L}{\Delta\phi}\left(\phi_s - \overline{\phi_s}\right) + \frac{L}{\Delta\phi H}\frac{\left(\phi_s - \overline{\phi_s}\right)^2}{2}$$

$$= \frac{L}{2}\left(1 + \frac{\Delta\phi}{4H}\right) + \frac{L}{\Delta\phi}\left(u - \frac{u^2}{2H}\right)$$

Terminal Charge

- Gate Charge

$$Q_G = 2\pi R \int_0^L Q_G(y)\, dy$$

$$= 2\pi R C_{ox} L \left[\left(V_{gf} - \overline{\phi_s}\right) + \frac{\Delta\phi^2}{12H}\right]$$

- Drain Charge

$$Q_D = 2\pi R \int_0^L \frac{y}{L} Q_i(y)\, dy$$

$$= \pi R C_{ox} \cdot \left[\begin{array}{l} -\frac{L}{H^2}\frac{\Delta\phi^3}{80} - \frac{-y_m \Delta\phi^2 + \Delta\phi \cdot L\left(V_{gf} - \overline{\phi_s}\right)}{6H} \\ -\frac{\Delta\phi L}{6}\left(1 + \frac{\left(V_{gf} - \overline{\phi_s}\right)}{2H}\right) + 2y_m\left(V_{gf} - \overline{\phi_s}\right) \end{array}\right]$$

- Source

$$Q_S = 2\pi R \int_0^L \left(1 - \frac{y}{L}\right) Q_i(y)\, dy$$

$$= Q_G - Q_D$$

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Short-Channel Effects

- Short-Channel Current

$$I_{ds} \approx \frac{\mu_s 2\pi R C_{ox}\left[\left(V_{gf}+2v_{th}\right)-\overline{\phi_s}\right]\Delta\phi}{L+\frac{\delta_L \Delta\phi}{E_{satn}}+R_{sd}\mu_s 2\pi R C_{ox}\left[\left(V_{gf}+2v_{th}\right)-\overline{\phi_s}\right]}$$

- Terminal Charge

$$y \approx \frac{L}{2}\left(1+\frac{\Delta\phi}{4H^*}\right)+\frac{L}{\Delta\phi}\left(u-\frac{u^2}{2H^*}\right)$$

$$Q_G = 2\pi R C_{ox} L\left[\left(V_{gf}-\overline{\phi_s}\right)+\frac{\Delta\phi^2}{12H^*}\right]$$

$$Q_D = \pi R C_{ox}\left[\begin{array}{l} -\frac{L}{H^{*2}}\frac{\Delta\phi^3}{80}-\frac{-y_m\Delta\phi^2+\Delta\phi\cdot L\left(V_{gf}-\overline{\phi_s}\right)}{6H^*} \\ -\frac{\Delta\phi L}{6}\left(1+\frac{\left(V_{gf}-\overline{\phi_s}\right)}{2H^*}\right)+2y_m\left(V_{gf}-\overline{\phi_s}\right)\end{array}\right]$$

$$Q_S = Q_G - Q_D$$

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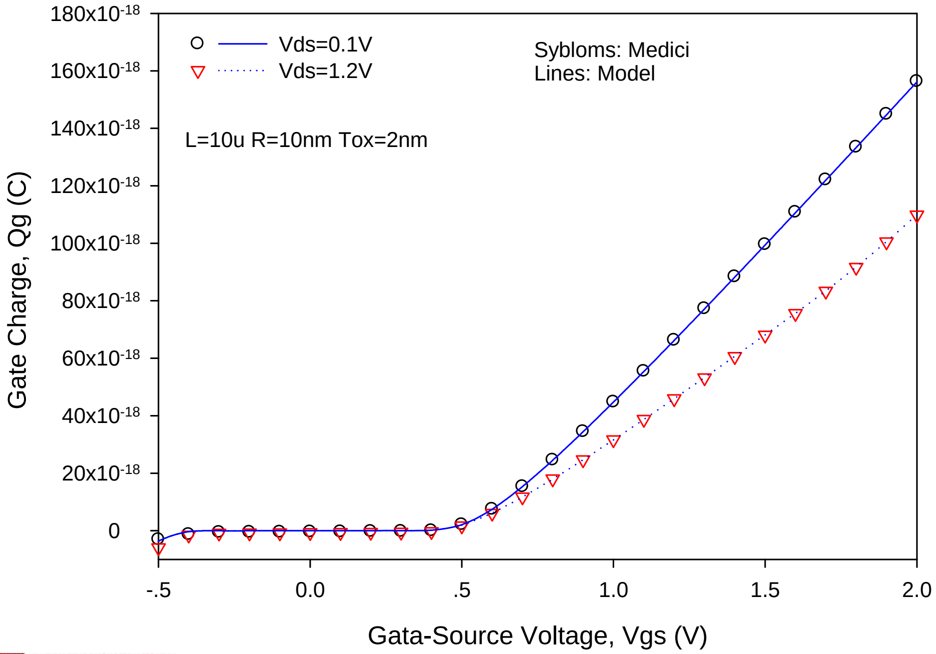
Charge Verification



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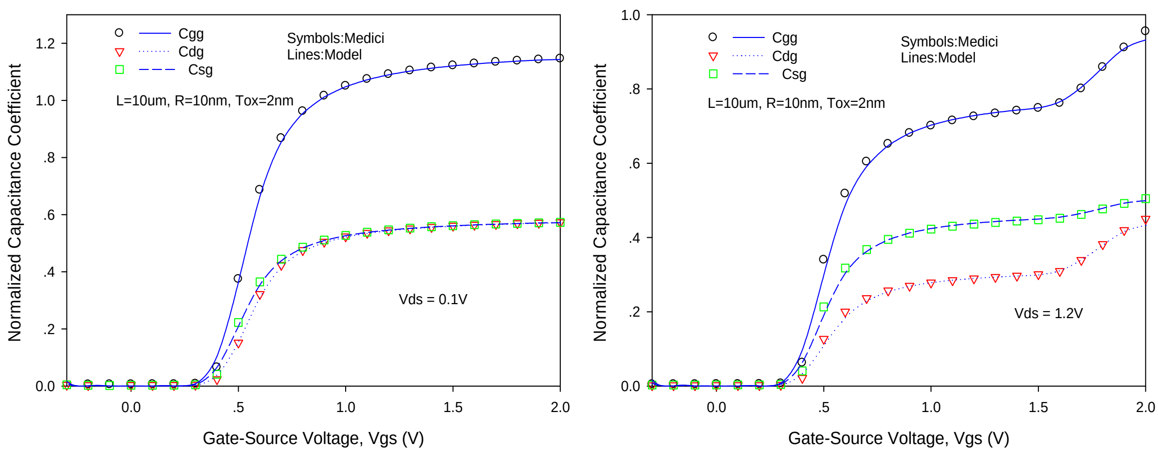
Cxg Verification



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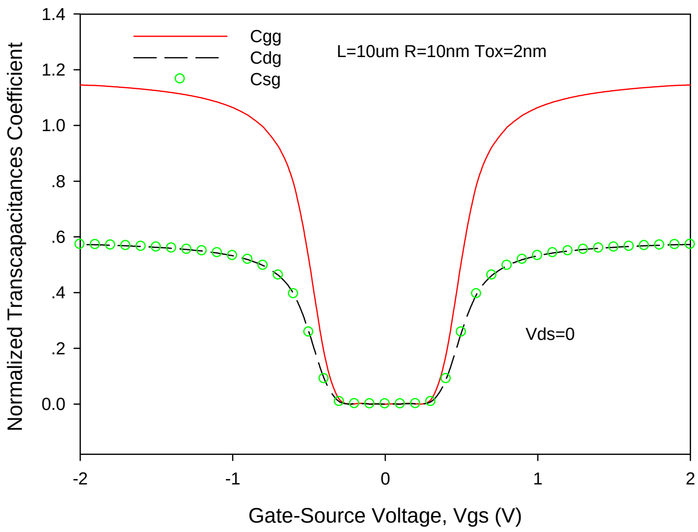
Symmetry of Cxg



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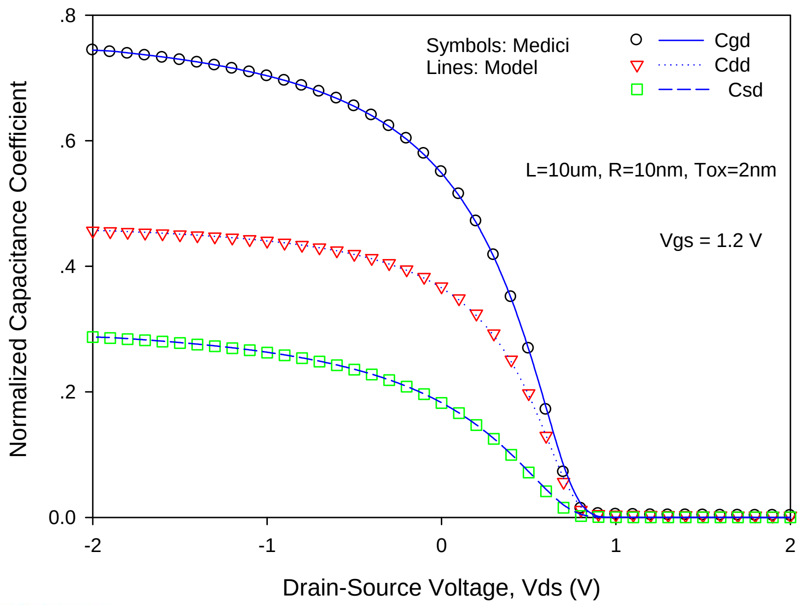
Cxd Verification



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Conclusion

- An approximate current equation is developed
- A simple charge model is derived based upon the approximate current equation
- Accurate and valid in all region

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Thank You!

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