Special Topics on Basic EECS I Design Technology Co-Optimization Lecture 5

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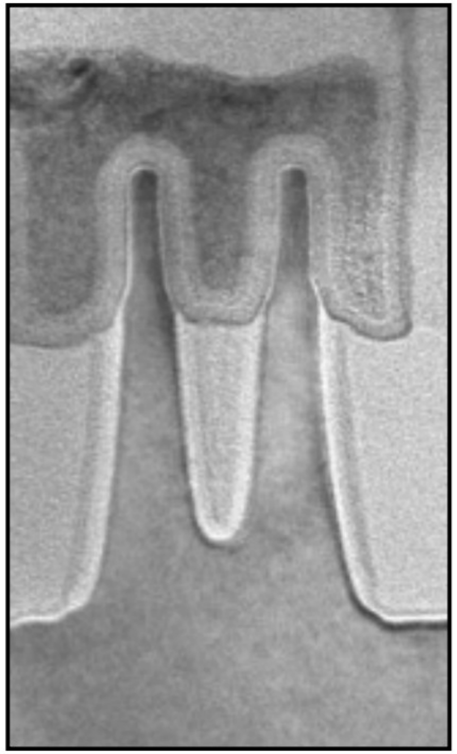
L5

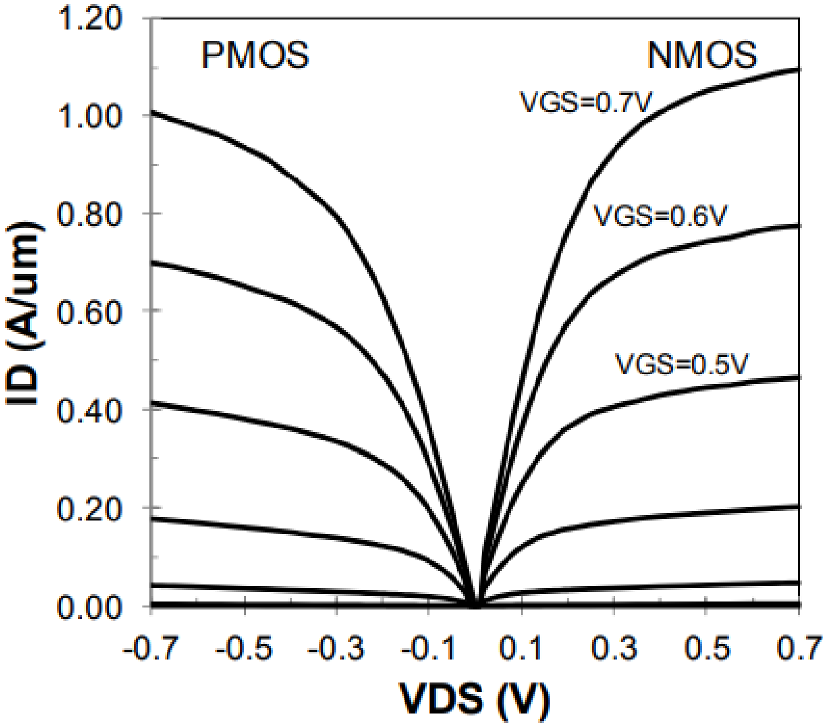
Intel 14 nm @ IEDM 2014

- 16 years later,
  - First of all, it is not a planar MOSFET but a FinFET.
  - Fin pitch is 42 nm. Contacted gate pitch is 70 nm.
  - Gate length is 20 nm. SRAM: 0.0588 μm^2

Transistor fin image (Intel)

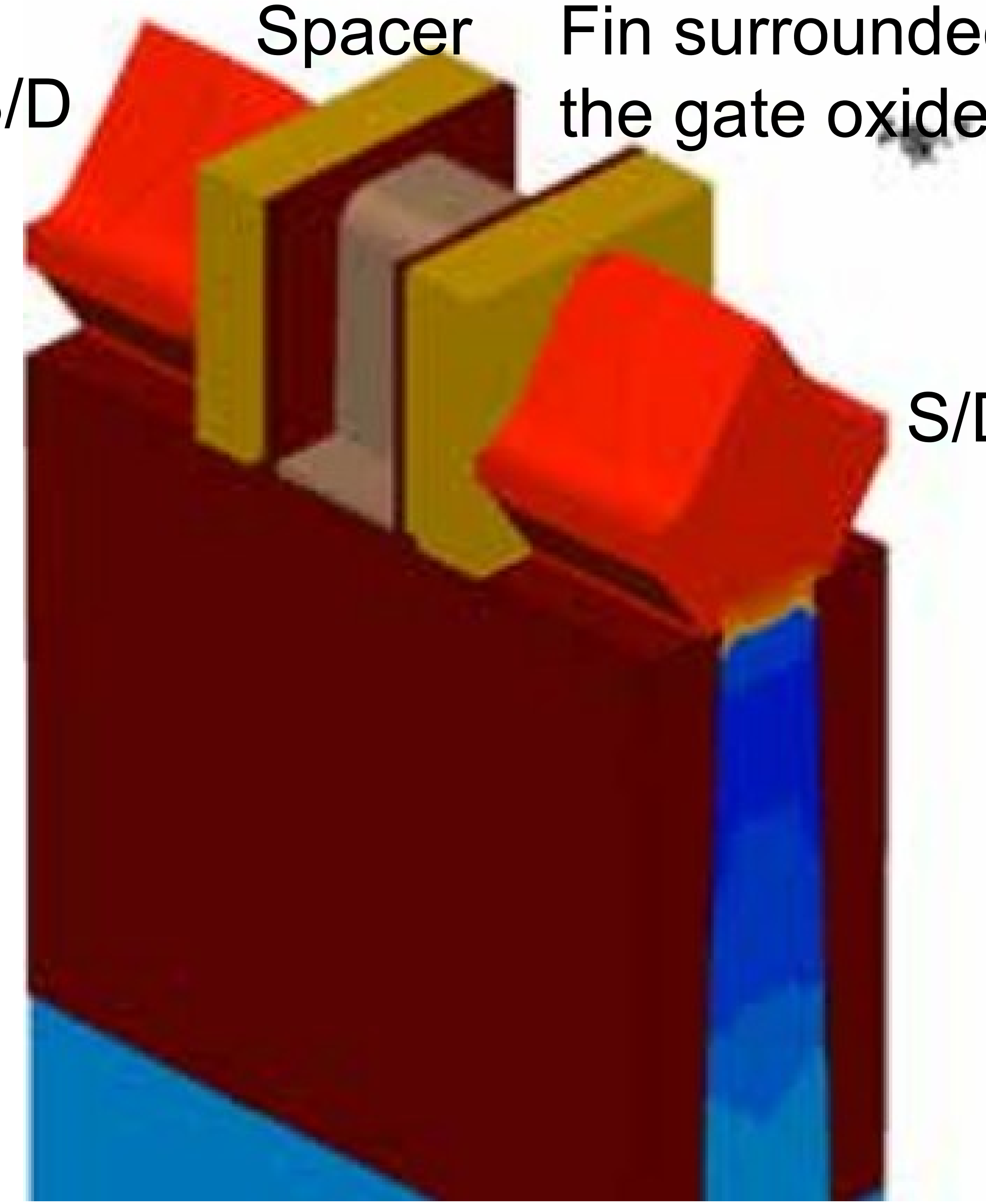


Transistor IV curves (Intel)



FinFET

- A tall fin
  - "Tri-gate" by Intel
  - It's like a double-gate.
- Then, why double-gate?
  - Better gate controllability (We all know it.)



3D structure of a FinFET transistor (Synopsys)

Lesson from "VLSI Devices" (1)

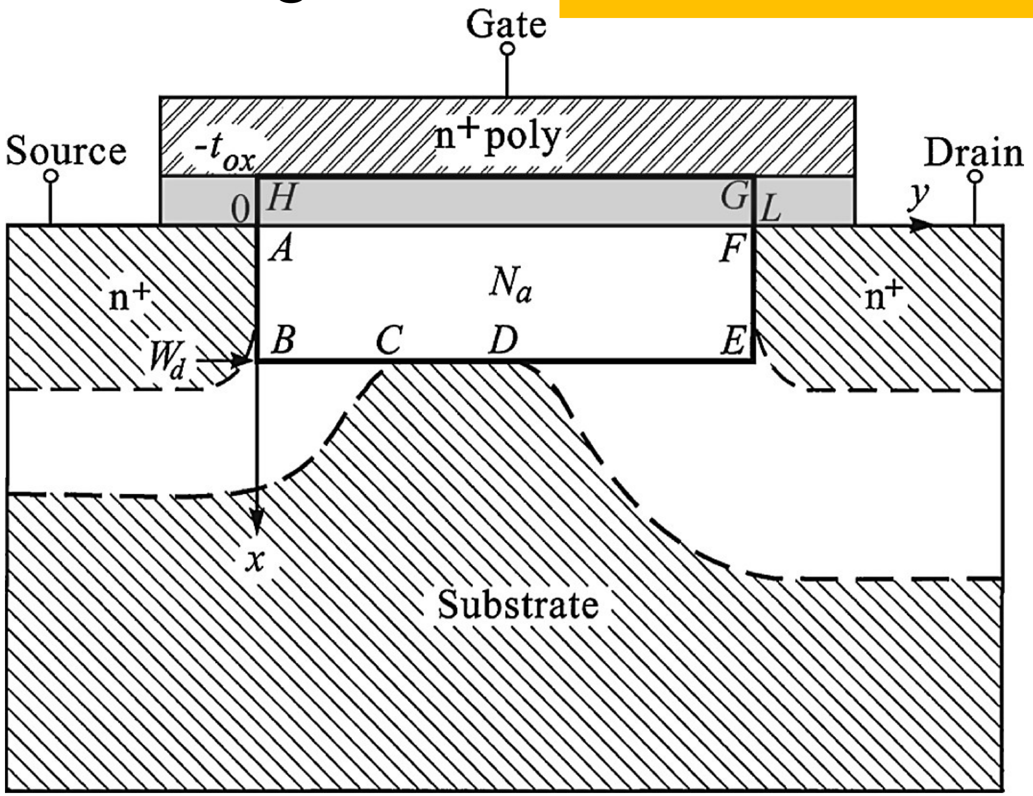
For your interest, watch the video, [Eng][VLSIDevices2025] L16, L17, and L18

- In the subthreshold regime, we may solve
  - The Poisson equation without inversion charges

$$\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}=-\frac{qp(x,y)}{\epsilon_{si}}+\frac{qN_a}{\epsilon_{si}}$$

  - Hole density is a nonlinear function of $\phi(x,y)$.
  - It can be neglected in the depletion region.

$$\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}=\frac{qN_a}{\epsilon_{si}}$$



Planar MOSFET
(Prof. Taur's book)

Lesson from "VLSI Devices" (2)

For your interest, watch the video, [Eng][VLSIDevices2025] L16, L17, and L18

- Boundary conditions by terminal voltages
  - Try the following function:

$$\phi(x,y) = v(x,y) + u_L(x,y) + u_R(x,y) + u_B(x,y)$$

Poisson equation with upper b.c. (Long-channel)

Laplace equation to match left b.c.

Laplace equation to match right b.c.

Laplace equation to match bottom b.c.

  - Then,

$$\frac{\partial^2 u_R}{\partial x^2} + \frac{\partial^2 u_R}{\partial y^2} = 0$$

Lesson from "VLSI Devices" (3)

For your interest, watch the video, [Eng][VLSIDevices2025] L16, L17, and L18

- Solution of Laplace equation
  - Separation of variables

$$u_R(x,y) = X(x)Y(y)$$

  - When $\frac{d^2X}{dx^2} = -\frac{1}{\lambda^2}X$ and $\frac{d^2Y}{dy^2} = \frac{1}{\lambda^2}Y$,

$$\frac{d^2X}{dx^2}Y + X\frac{d^2Y}{dy^2} = 0$$

Exponential functions

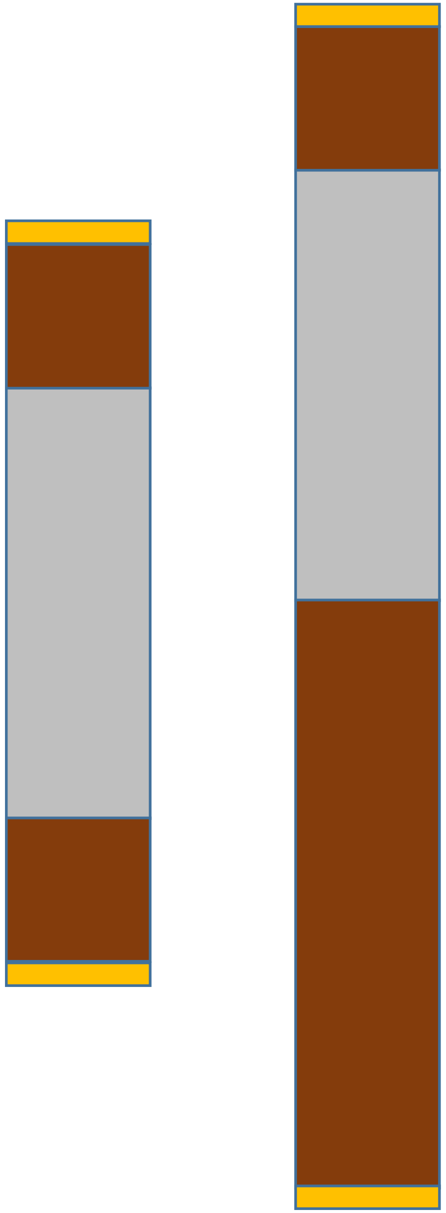
Sinusoidal functions

  - *The vertical variation and the lateral variation are coupled.*

Compare two structures.

- Calculate λ for two structures
  - 1) Double-gate (from $x = -\frac{t_{si}}{2}$ to $x = \frac{t_{si}}{2}$)
  - Top- and bottom-gates
  - Symmetric about $x = 0$

  - 2) (Almost) single-gate (from $x = 0$ to $x = t_{si}$)
  - Only top-gate
  - Vanishing electric field at $x = 0$



Boundary condition

- Continuity of displacement @ Si/SiO_2 interface
  - Assume that u_R is a homogeneous solution induced by the drain voltage.
  - 1) Double-gate

$$\epsilon_{si}\left.\frac{\partial u_R}{\partial x}\right|_{x=\frac{t_{si}}{2},y} = -\epsilon_{ox}\frac{u_R\left(x=\frac{t_{si}}{2},y\right)}{t_{ox}}$$

  - 2) Single-gate

$$\epsilon_{si}\left.\frac{\partial u_R}{\partial x}\right|_{x=t_{si},y} = -\epsilon_{ox}\frac{u_R(x=t_{si},y)}{t_{ox}}$$

Vertical components only

Boundary condition for $X(x)$

- Recall $u_R(x, y) = X(x)Y(y)$.
  - 1) Double-gate

$$\epsilon_{si} \left.\frac{dX}{dx}\right|_{x=\frac{t_{si}}{2}, y} \cancel{Y} = -\epsilon_{ox} \frac{X\left(x = \frac{t_{si}}{2}\right)\cancel{Y}}{t_{ox}}$$

  - 2) Single-gate

$$\epsilon_{si} \left.\frac{dX}{dx}\right|_{x=t_{si}, y} \cancel{Y} = -\epsilon_{ox} \frac{X(x = t_{si})\cancel{Y}}{t_{ox}}$$

  - In both cases, $\frac{dX}{dx} = -\frac{\epsilon_{ox}}{\epsilon_{xi} t_{ox}} X$ at Si/SiO_2 interface.

Double-gate

- Due to symmetry, $X(x) = \cos\frac{x}{\lambda}$. (Sine function is not possible.)

$$-\epsilon_{si}\frac{1}{\lambda}\sin\frac{t_{si}}{2\lambda} = -\epsilon_{ox}\frac{\cos\frac{t_{si}}{2\lambda}}{t_{ox}}$$

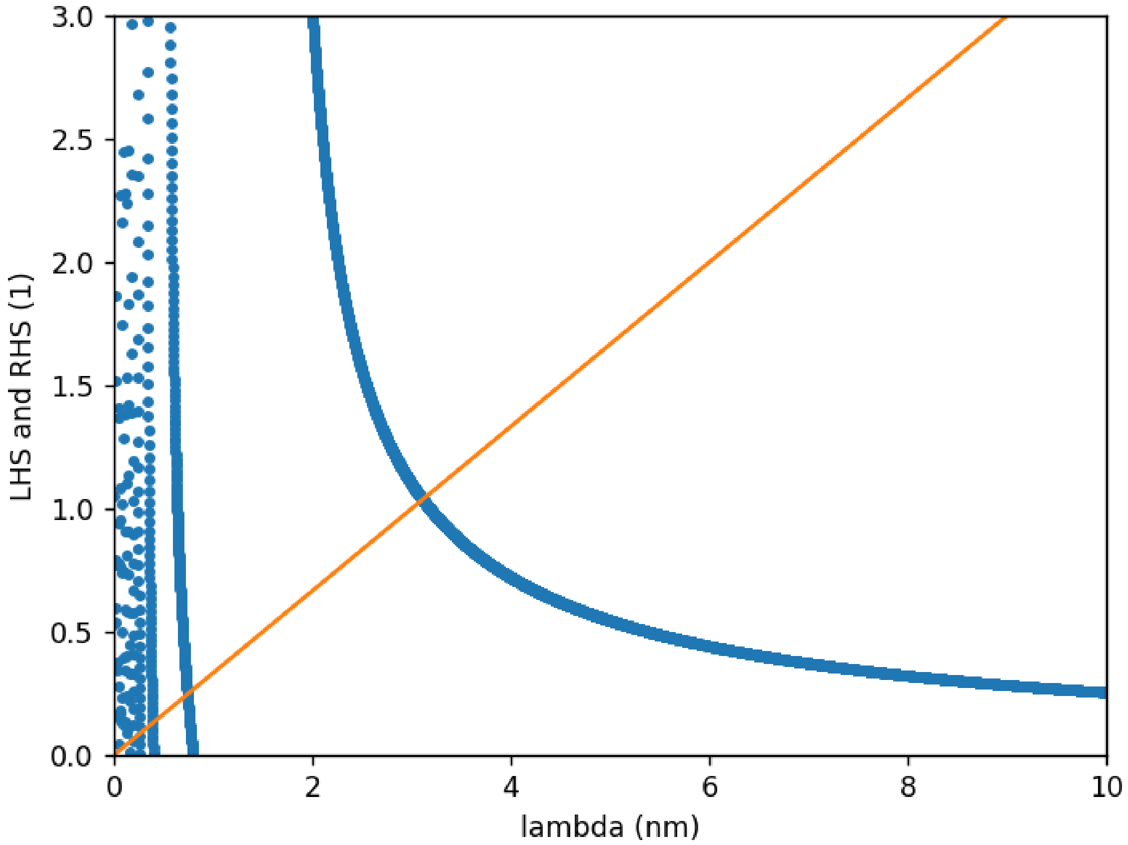
$$\tan\frac{t_{si}}{2\lambda} = \frac{\epsilon_{ox}}{\epsilon_{si}t_{ox}}\lambda$$

– An example)

t_{si} = 5 nm and t_{ox} = 1 nm

ϵ_{si} is three times ϵ_{ox}.

➔ Largest λ is 3.111 nm.



Single-gate

- Again, due to the boundary condition at $x = 0$, $X(x) = \cos\frac{x}{\lambda}$. (Sine function is not possible.)

$$-\epsilon_{si}\frac{1}{\lambda}\sin\frac{t_{si}}{1\lambda} = -\epsilon_{ox}\frac{\cos\frac{t_{si}}{1\lambda}}{t_{ox}}$$

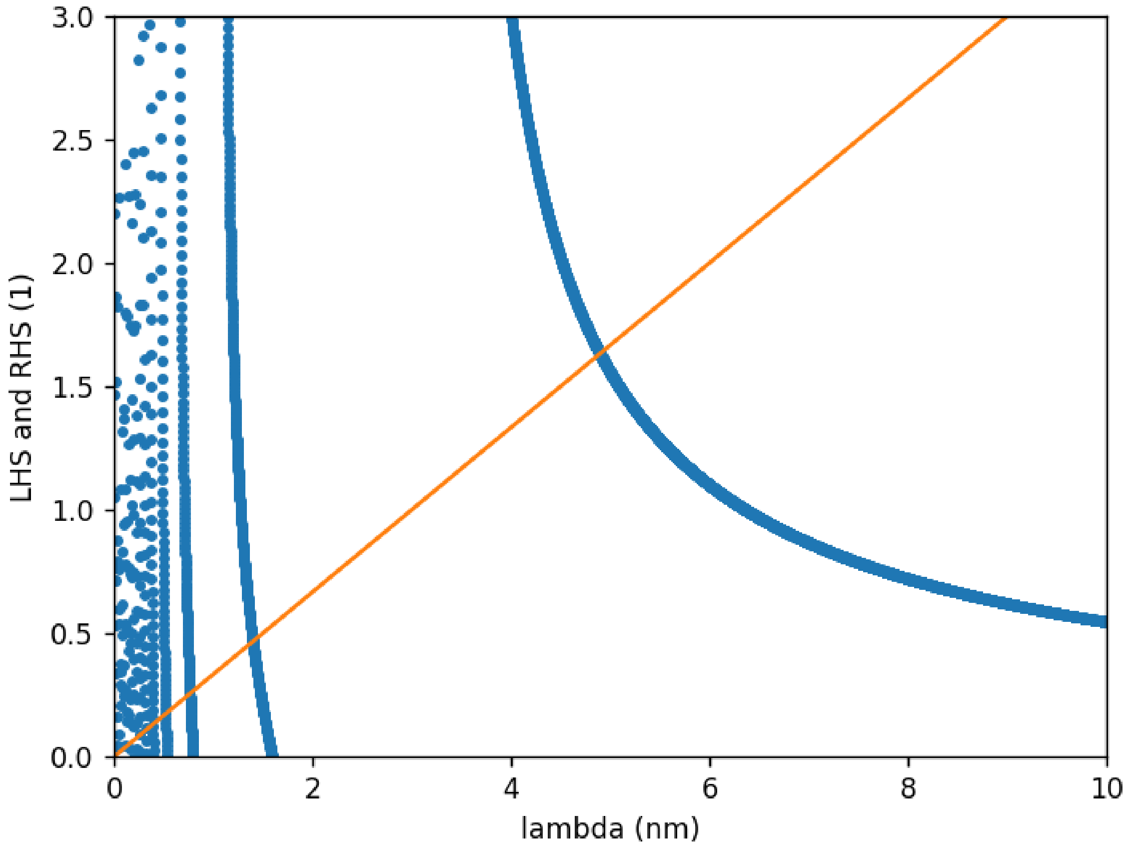
$$\tan\frac{t_{si}}{1\lambda} = \frac{\epsilon_{ox}}{\epsilon_{si}t_{ox}}\lambda$$

– An example)

t_{si} = 5 nm and t_{ox} = 1 nm

ϵ_{si} is three times ϵ_{ox}.

➔ Largest λ is 4.897 nm.



Approximate expressions

- Two structures share the same expression.

$$\tan\frac{t_{si}}{N\lambda} = \frac{\epsilon_{ox}}{\epsilon_{si}t_{ox}}\lambda$$

  - Although not perfect (as shown in our example), it is frequently approximated as

$$\frac{t_{si}}{N\lambda} = \frac{\epsilon_{ox}}{\epsilon_{si}t_{ox}}\lambda$$

$$\lambda = \sqrt{\frac{\epsilon_{si}}{N\epsilon_{ox}}t_{si}t_{ox}}$$

  - This expression yields 2.7 nm (DG) and 3.9 nm (SG), respectively.

Thank you!