Final exam, VLSI Devices, Spring semester, 2025

June 16, 2025

If not stated otherwise, assume 300 K.

1. The threshold voltage of an NMOSFET is expressed as follows:

$$V_t = V_{fb} + 2\phi_B + \frac{\sqrt{2\epsilon_{si} q N_a (2\phi_B - V_{bs})}}{C_{ox}}$$

1) Derive $\frac{dV_t}{d(-V_{bs})}$.

2) Assume that the effective oxide thickness is 20 nm and the substrate doping concentration is 10^{16} cm^{-3}. The vacuum permittivity is 8.854 X 10^{-12} F m^{-1} and the relative permittivity of silicon dioxide is 3.9. The relative permittivity of silicon is 11.7. Of course, q is 1.6X10^{-19} C. You must assume a reasonable value for the intrinsic carrier density. Calculate $\frac{dV_t}{d(-V_{bs})}$ when V_{bs} is –2 V.

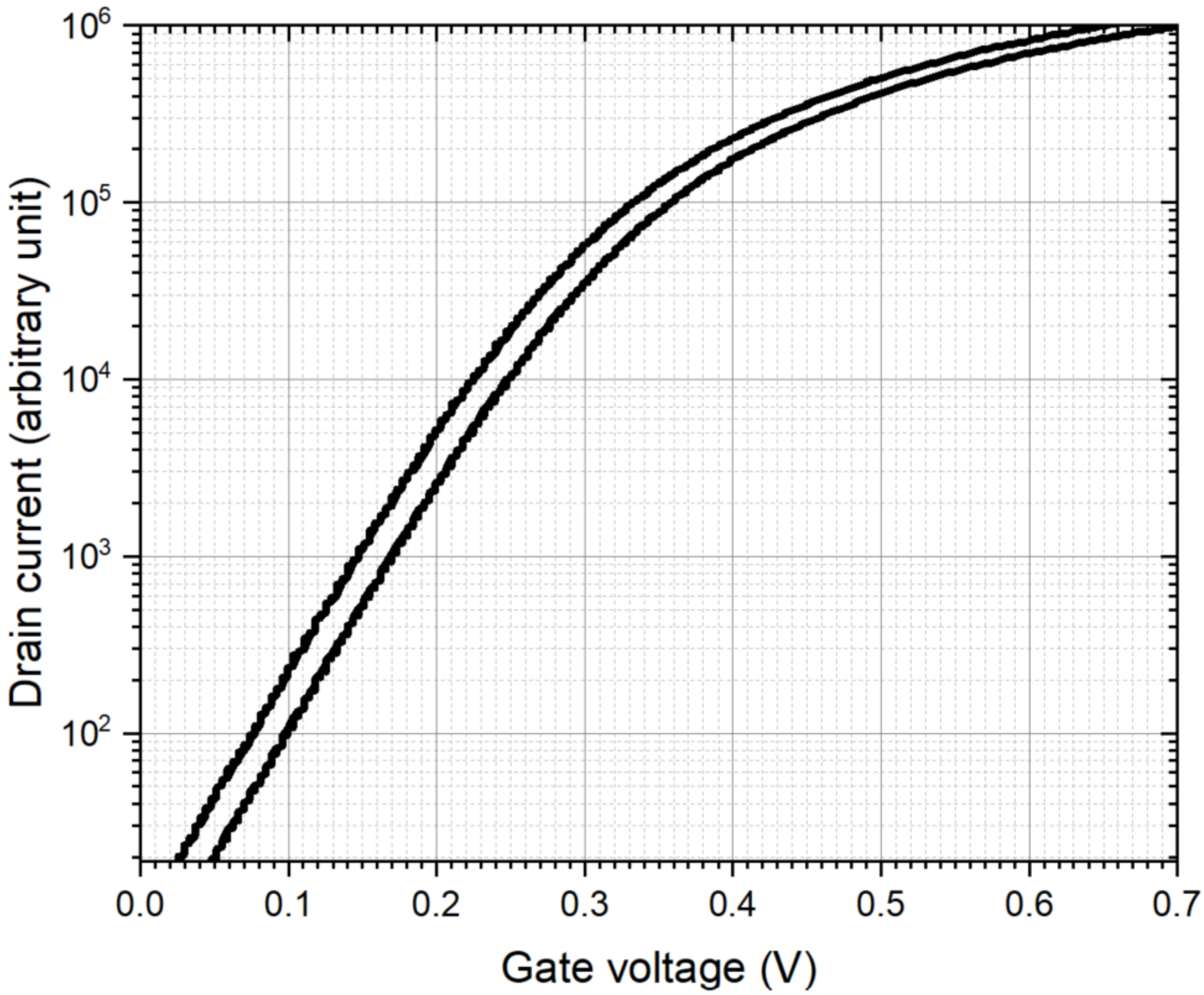
2. The effective mobility can be calculated by

$$\mu_{eff} = \frac{\int_0^{x_i} \mu_n(x) n(x) dx}{\int_0^{x_i} n(x) dx}$$

(The thickness of inversion layer, x_i, can be regarded as ∞.) In this problem, assume that $n(x) = n(0)\exp\left(-\frac{qE_s x}{k_B T}\right)$, where E_s is the magnitude of surface electric field. Also, the mobility is given as $\mu(x) = \mu(\infty) - \big(\mu(\infty) - \mu(0)\big)\exp(-\lambda x)$, where $\mu(\infty) > \mu(0)$. Derive an expression for the effective electron mobility.

3. Even when the drain-to-source voltage is zero, the threshold voltage of a short-channel MOSFET differs from that of a long-channel MOSFET. Explain the underlying reason.

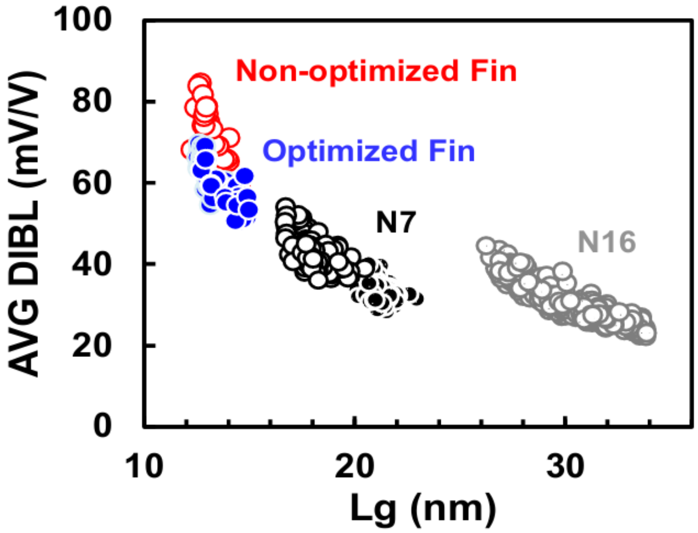
4. The IV graph shown below is taken from an NMOSFET (Intel 18A technology). Two different curves are measured at two drain voltages of 0.05 V (below) and 0.7 V (above), respectively. Although the drain current is normalized, we can clearly identify the subthreshold region.



From the above graph, estimate the DIBL. (mV/V)

5. In our lectures, we study the 2D Poisson equation inside the MOSFET. In this problem, we consider a rectangular domain. Its x value varies from 0 to T. Also its y value varies from 0 to L. (It is not the temperature.) We want to get a solution of the Laplace equation, $u(x,y)$. The boundary conditions are: $u(0,y) = 0$, $u(T,y) = 0$, $u(x,0) = 0$, and $u(x,L) = \sin\left(\frac{\pi}{T}x\right)$. Suggest a form of $u(x,y)$. Explicitly show that your solution satisfies the Laplace equation.

6. In their IEDM 2022 for announcing the 3 nm node, TSMC showed that the recent technologies are superior in terms of the DIBL immunity. Explain the underlying reason, with help of the solution of Problem #5.



7. In the 2D Poisson equation studied in our lectures, the surface potential along the channel direction can be expressed as

$$\phi(0,y) = \phi_s + \frac{b_1 \sinh\left(\frac{\pi(L-y)}{\lambda}\right) + c_1 \sinh\left(\frac{\pi y}{\lambda}\right)}{\sinh\left(\frac{\pi L}{\lambda}\right)} \sin\left(\frac{\pi 3 t_{ox}}{\lambda}\right)$$

, where symbols have been introduced in our lectures. Here, ϕ_s, b_1, c_1, λ, and so on are constant. By taking the derivative with respect to y, find out the position for the minimum potential. In this problem, you may assume that $\cosh z \approx \frac{\exp z}{2}$ for a positive z.

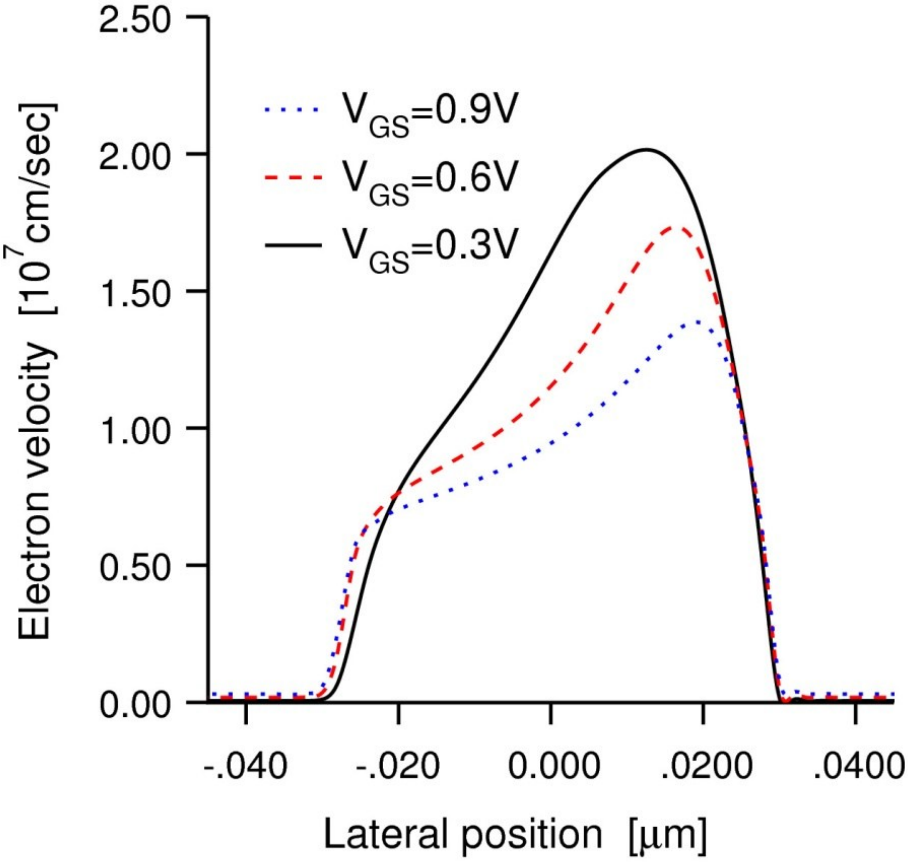
8. The velocity-field relationship is usually expressed as the well-known Caughey-Thomas expression:

$$v = \frac{\mu_{eff}\mathcal{E}}{[1 + (\mathcal{E}/\mathcal{E}_c)^n]^{1/n}}$$

1) Explicitly consider the two extreme cases: $\mathcal{E}$ is much lower than $\mathcal{E}_c$. $\mathcal{E}$ is much higher than $\mathcal{E}_c$. For those cases, derive expressions for the velocity.

2) Consider two cases of $n = 1$ and $n = 2$. Compare two cases.

9. The below curve shows the average electron velocity as a function of position. We can clearly see that the electron velocity exceeds the saturation velocity (~ 10^7 cm sec^{-1}). Explain how electrons obtain such high velocities.

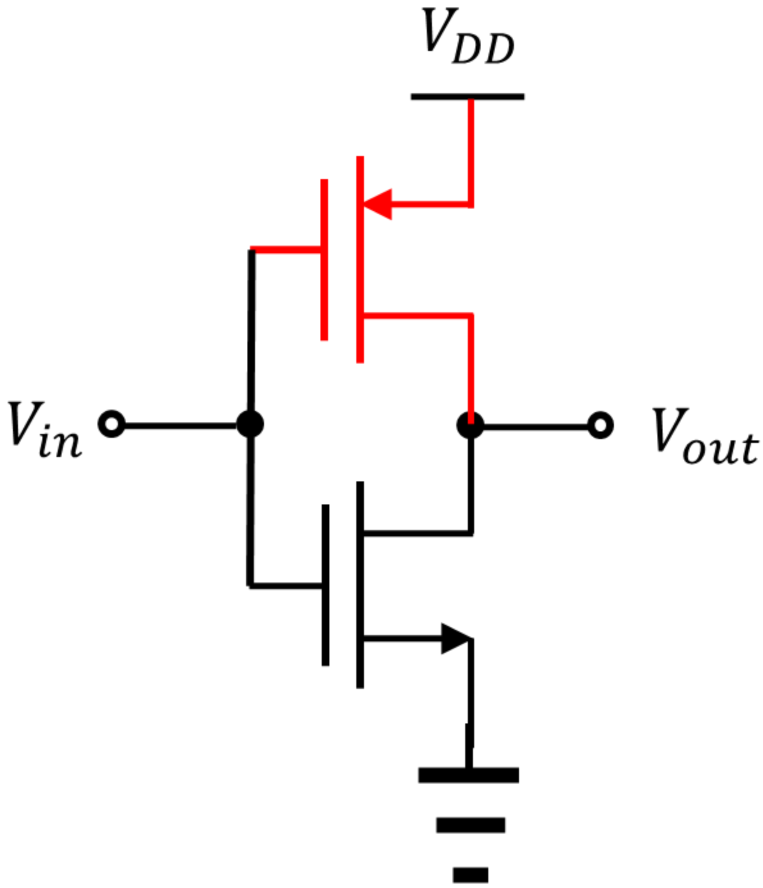


10. In our lecture, we have introduced the energy distribution function, $f(\mathbf{r}, E)$. Discuss Its physical meaning and importance in the hot-carrier modeling.

11. Consider a CMOS inverter, where an NMOSFET and a PMOSFET (red one) are connected. We can have two input cases: The input voltage is low (0 V) or the input voltage is high (V_{DD}).

1) For these two cases, calculate V_{gs} and V_{ds} of two MOSFETs.

2) Discuss important stress bias conditions. (It is assumed that the temperature is elevated.)



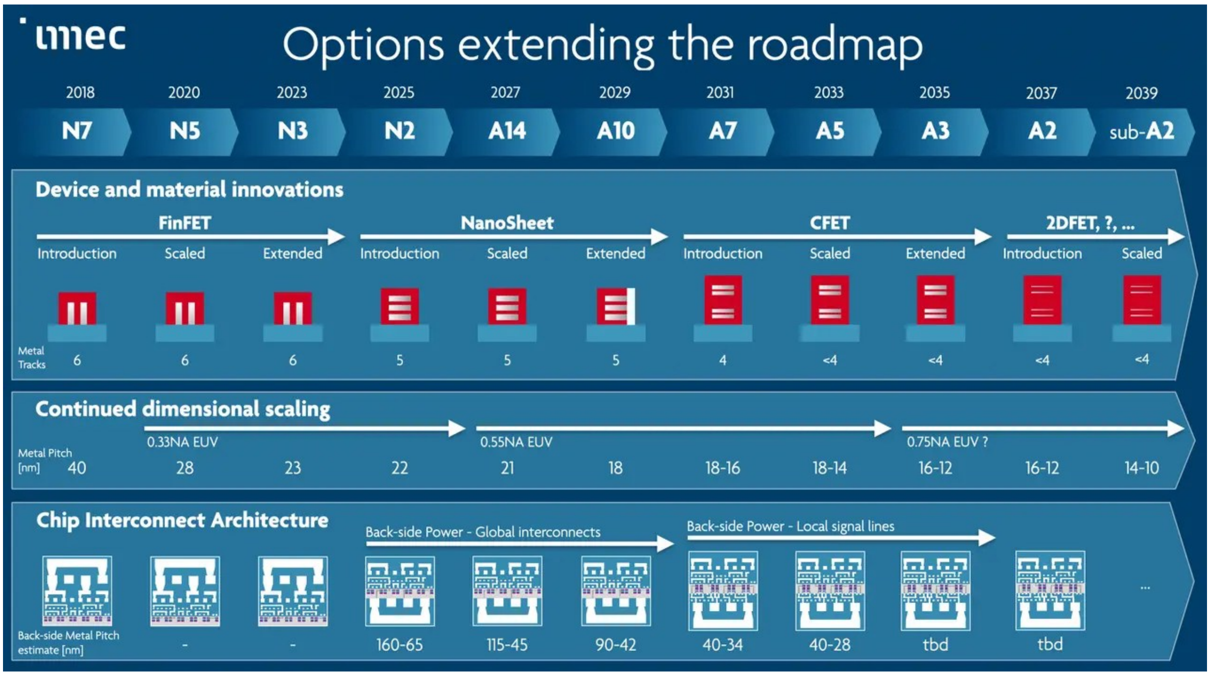
12. In a gate stack, the interlayer (SiO_2) thickness is 0.6 nm. On top of it, the 2-nm-thick HfO_2 layer (whose relative permittivity is 20) is found. Calculate the effective oxide thickness (EOT) of this gate stack.

13. Calculate the Schrödinger equation for a 1D infinite potential well.

$$\left[-\frac{\hbar^2}{2m_{xx}}\frac{d^2}{dx^2}\right]\psi(x) = E\psi(x)$$

Its domain is given as $(0,L)$. Since the potential energy is zero, it does not appear in the equation. At two boundary points, $x = 0$ and $x = L$, the wavefunction vanishes. Calculate $\psi(x)$ and E.

14. The following figure shows the IMEC's latest technology roadmap. As of 2025, the 2 nm node (N2) is under mass production. Industry is currently preparing a new architecture, CFET (Complimentary Field-Effect Transistor), which will be manufactured in the angstrom era. Explain what the CFET technology is. What is the main motivation to introduce the CFET technology?



15. Consider a double-gate MOS structure with an intrinsic substrate. Therefore, the Poisson equation simply reads:

$$\frac{d^2\phi}{dx^2} = \frac{q}{\epsilon_{si}}n_i \exp\left(\frac{q\phi}{k_BT}\right)$$

In our lectures, we have seen that the electric field at any point can be expressed in terms of two potentials, $\phi(x)$ and $\phi(0)$. Derive such an expression by integrating the Poisson equation with a weighting factor, $\frac{d\phi}{dx}$.