Advanced MOSFETs and Novel Devices

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9. Tutorial & Excercise

9.1 Homework CMOS Roadmap

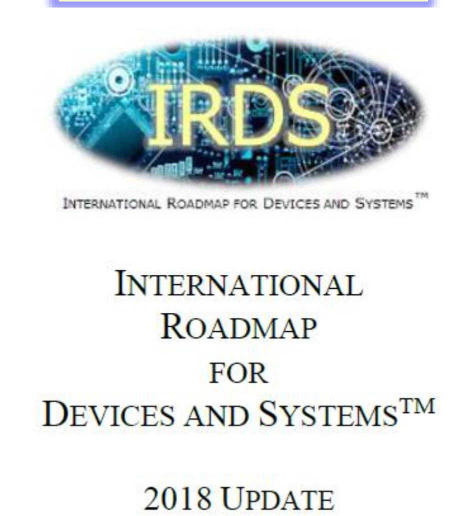
9.2 Exercise TFET

International Roadmap for Devices and Systems

Find out the dates, when the physical gate length (for HP logic) drops below 20 and 14 nm. Relate these values to the according technology nodes and give the device lateral pitch for high performance devices. (IRDS 2018)

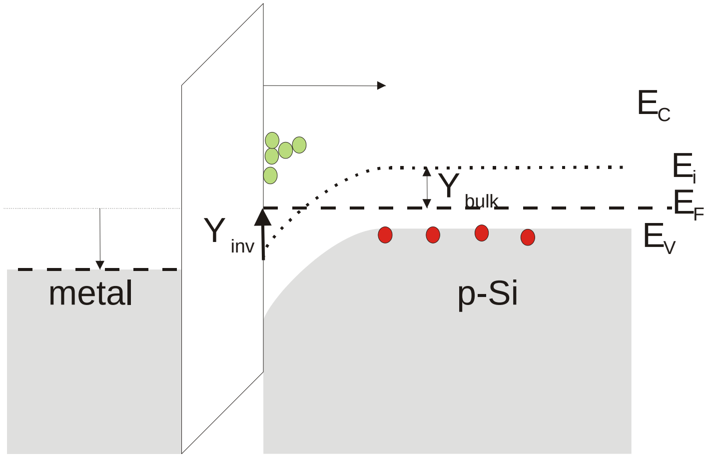
Technology Node		
Year		
Physical Gate Length	< 20 nm	< 14 nm
Device lateral pitch (nm)		

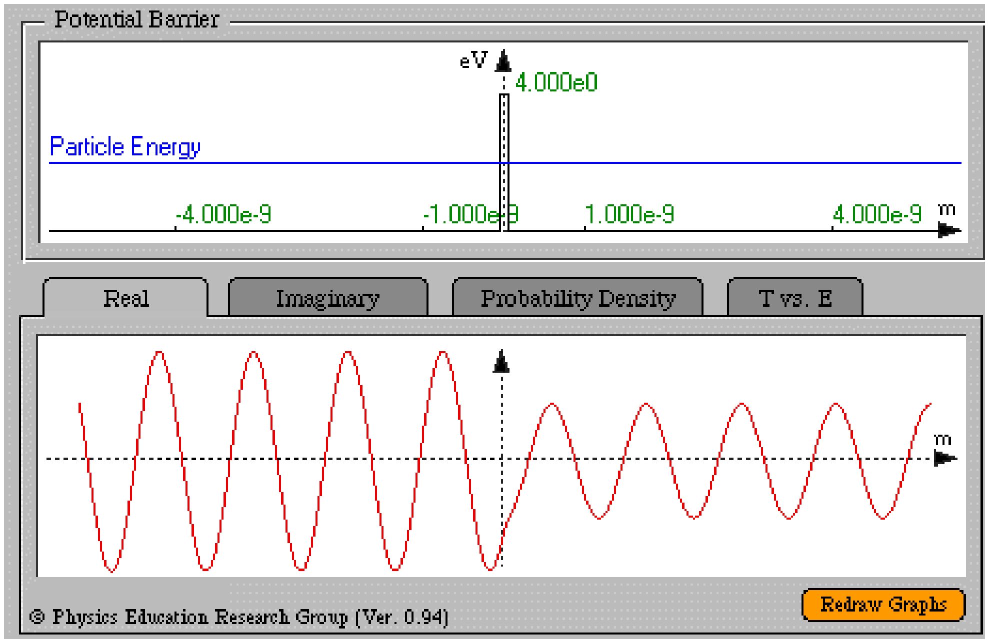
https://irds.ieee.org


INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS™

INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS™

2018 UPDATE





source: http://phys.educ.ksu.edu/vqm/html/qtunneling.html

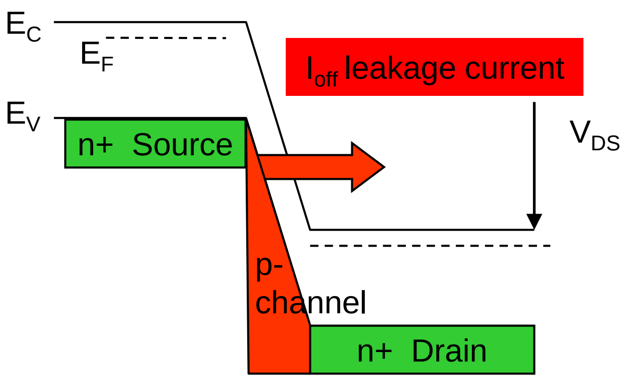
- SiO_2 has a barrier height of 3.1eV
- In classical physics no electron with less energy should pass this barrier
- But leakage current exists

⇒ quantum mechanical tunneling

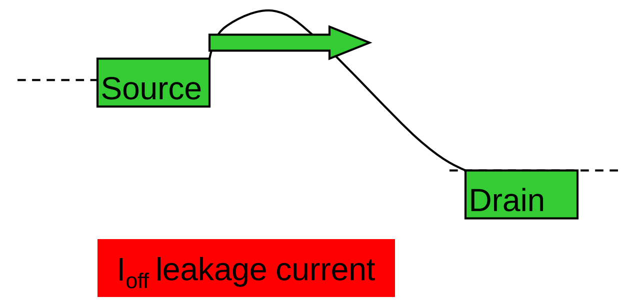
- Electrons have a wavelength of 8 nm
- Electrons can tunnel through Gateoxids less than 3 nm

Tunneling effects in Short-channel MOSFETs:

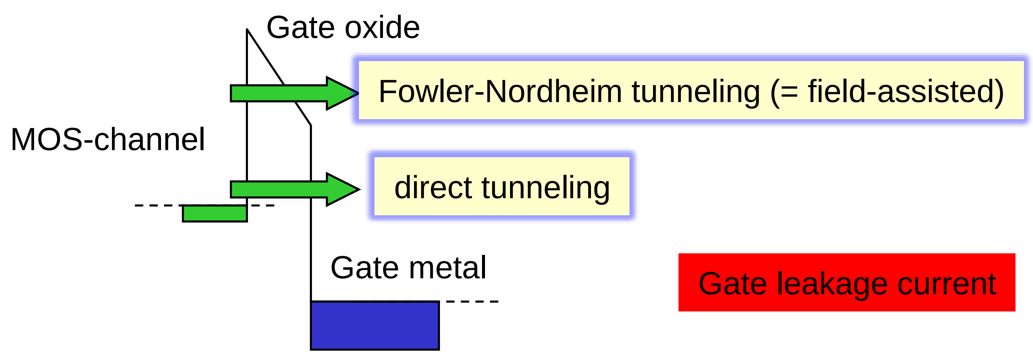
Band-Band Tunneling



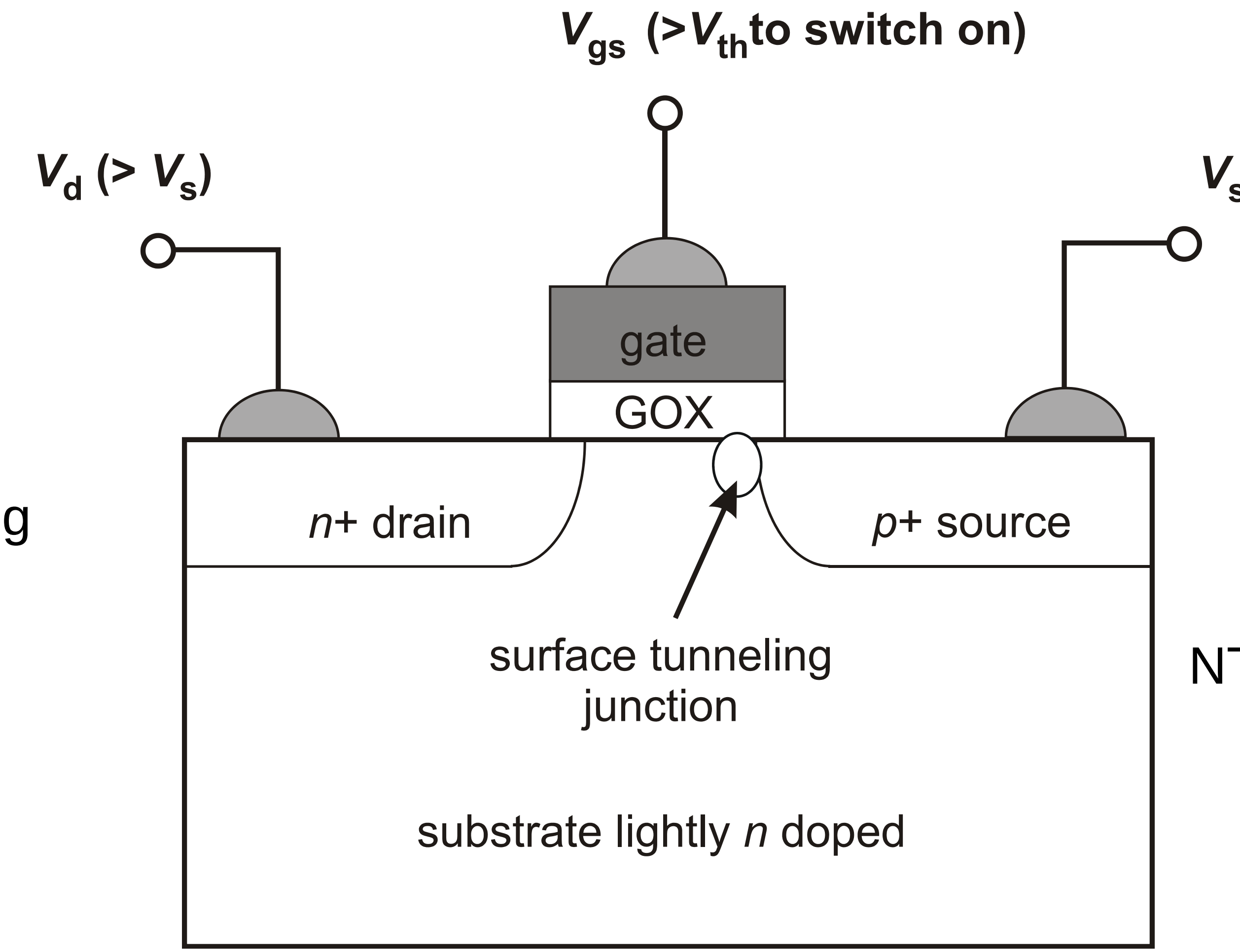
Direct Tunneling



Direct (Heterostructure) Tunneling



- Reverse biased *pin*-diode
- Interband tunneling is controled by a MOS-gate



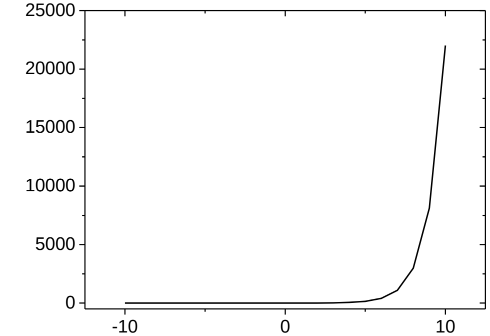
NTFET

Tunneling probability for interband tunneling:

1. Physical model:

$$P_t = \frac{|\Psi(x_2)|^2}{|\Psi(x_1)|^2} \approx \exp\left(-2\int_{x_1}^{x_2} |k(x)|\,dx\right) = \exp\left(-\frac{\pi\sqrt{m^*}\,E_g^{3/2}}{2\sqrt{2}\,eE\hbar}\right) \quad \text{with} \quad k(x) = \sqrt{\frac{2m^*}{\hbar^2}\cdot \Delta E(x)}$$

$\Psi(x)$ = wave function
$|\Psi(x)|^2$ = probability density function



2. Empirical model used by medici simulation

Wentzel-Kramer-Brillouin approximation

Medici User Guide Band-to-Band Tunneling

G^{BB} Generation current by band-band tunneling

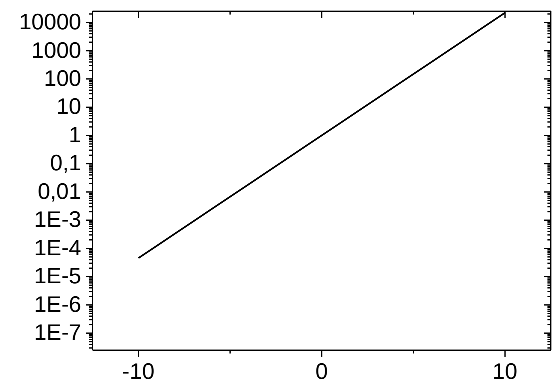
The model used by Medici has the form of Kane's model [56].

$$G^{BB} = \mathrm{A.BTBT}\frac{E^{\mathrm{C.BTBT}}}{E_g^{1/2}}\cdot \exp\left(-\mathrm{B.BTBT}\frac{E_g^{3/2}}{E}\right) \qquad \text{Equation 2-389}$$

In this expression, E is the magnitude of the electric field and E_g is the energy bandgap. A search along the direction opposite to the electric field is performed to determine whether there is an electric potential increase of at least E_g/q for the band-to-band tunneling to occur. The check for sufficient band-banding can be adjusted using the parameters `T.DISTAN` and `V.CHANGE` on the `MODELS` statement.

The parameters `A.BTBT`, `B.BTBT` and `C.BTBT` are user adjustable parameters. Their default values are shown in Table 2-14. These values can be modified using the `MATERIAL` statement.

Table 2-14 Default Values for Band-to-Band Tunneling Parameters



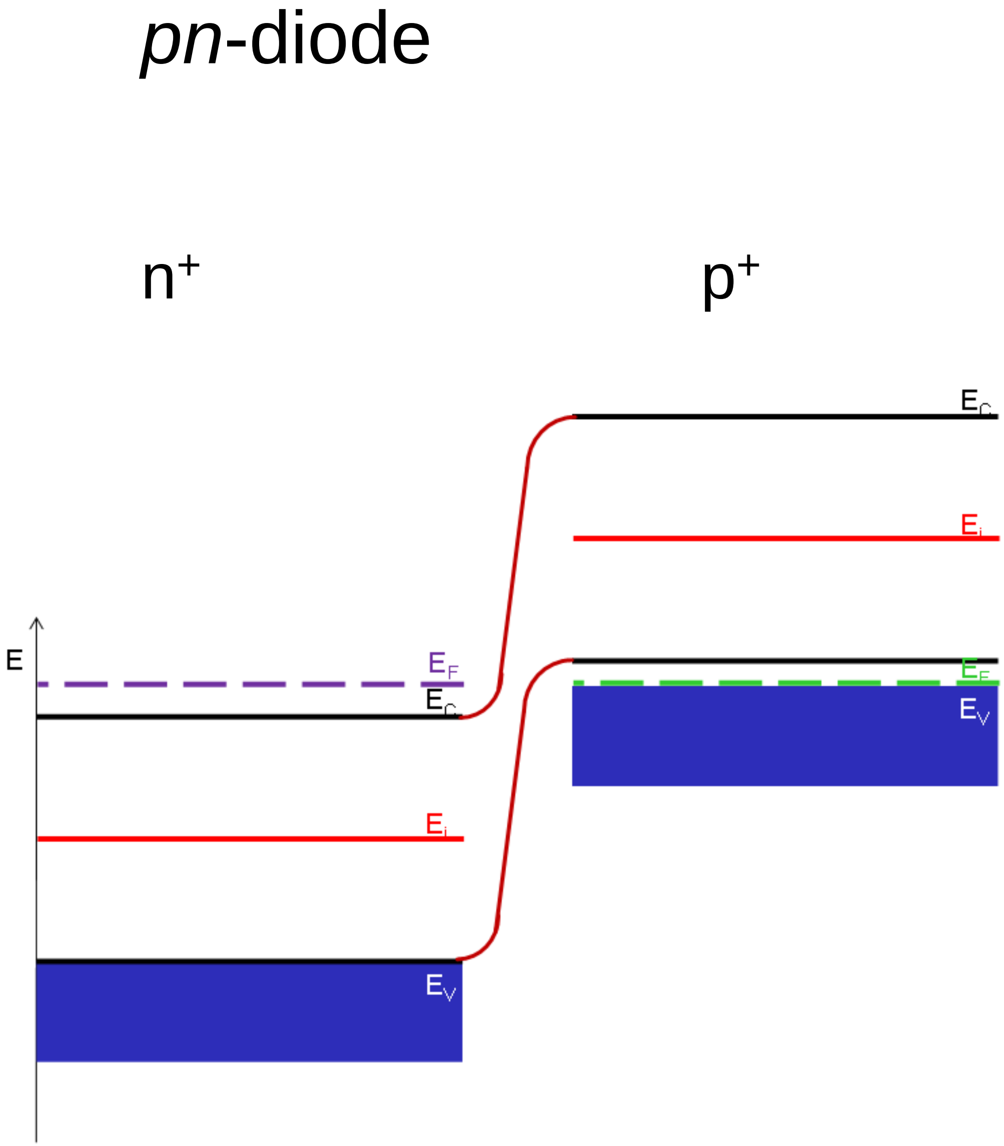
Tunneling current density of a reverse biased *pn*-diode (zener tunneling):

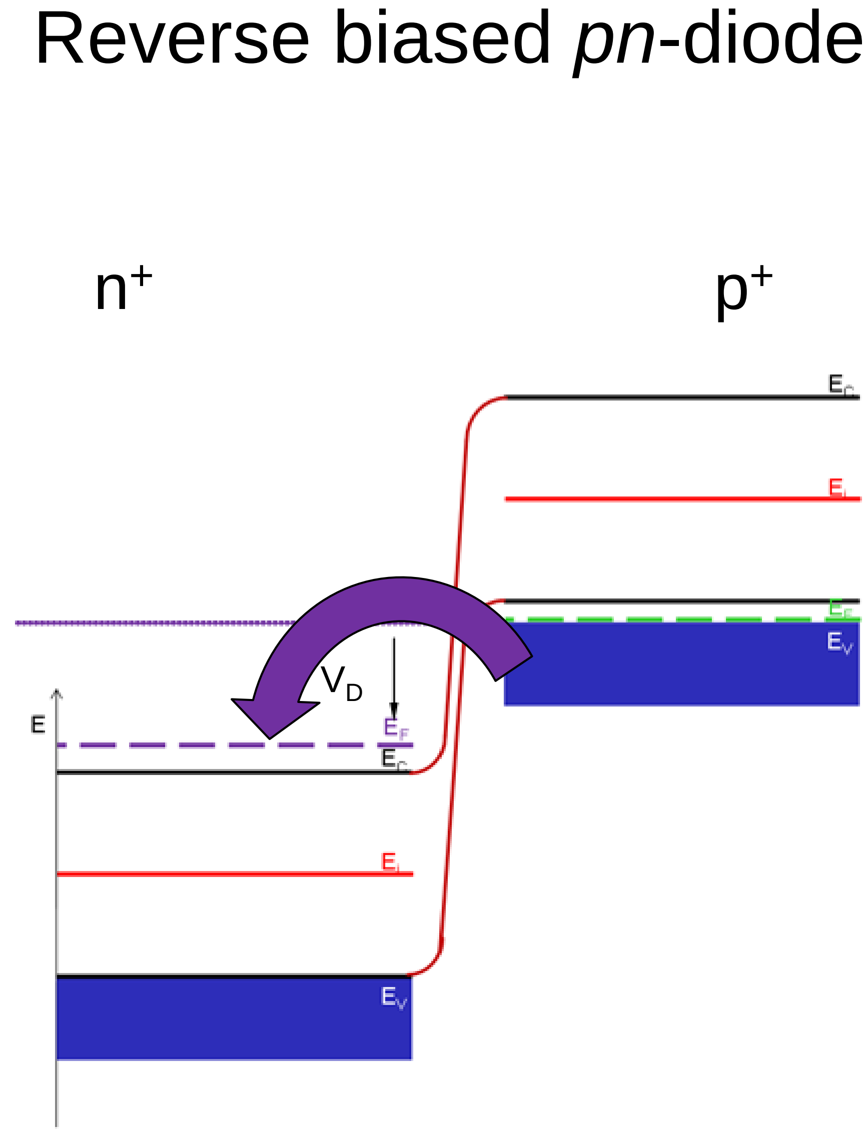
$$j_{\mathrm{t}} = \int_{E_{\mathrm{C}}}^{E_{\mathrm{V}}} \frac{\partial j_{\mathrm{incident}}}{\partial E} P_{\mathrm{t}} \left(f_{\mathrm{V}}(E) - f_{\mathrm{C}}(E) \right) dE$$

Source: S. M. Sze, Physics of Semiconductor Devices

$f(E)$ = Fermi distribution

j_{incident} = incident probability current density


pn-diode
n+
p+
E
E_F
E_C
E_i
E_V
E_C
E_i
E_F
E_V


Reverse biased *pn*-diode
n+
p+
E
V_D
E_F
E_C
E_i
E_V
E_C
E_i
E_F
E_V

Tunneling current density of a reverse biased *pn*-diode:

$$j_{\mathrm{t}} = \frac{\sqrt{2}\cdot e^{3} E \sqrt{m^{*}} V_{\mathrm{bias}}}{4\pi^{3}\hbar^{2}\sqrt{E_{\mathrm{g}}}} \exp\left(-\frac{\pi\sqrt{m^{*}}\, E_{\mathrm{g}}^{3/2}}{2\sqrt{2}\cdot eE\hbar}\right)$$

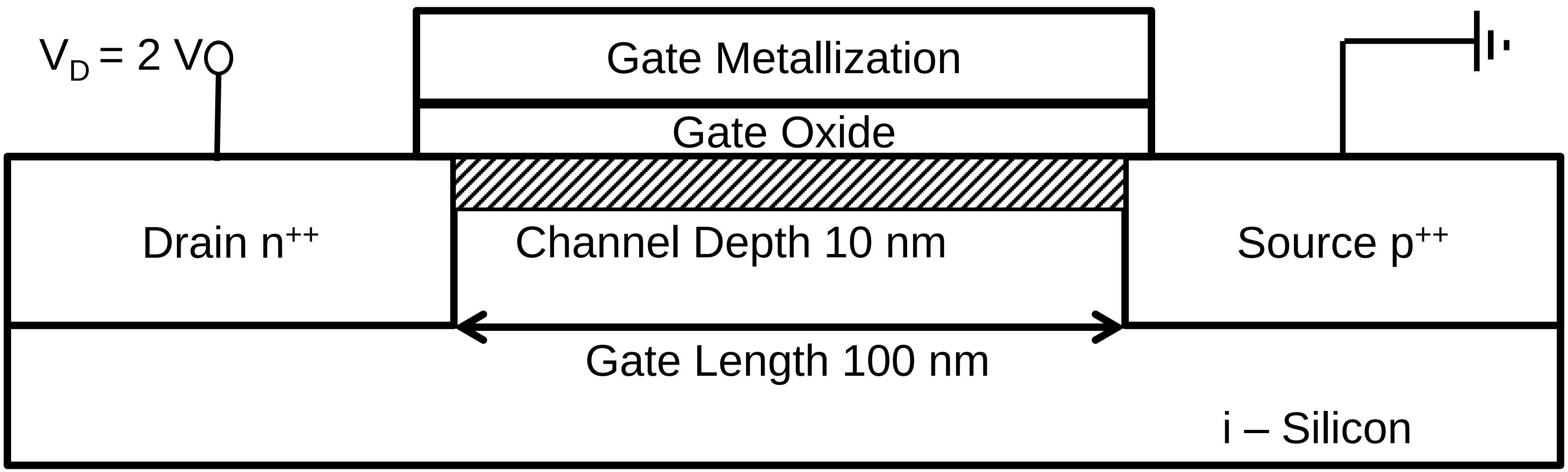
$$E \approx \frac{(E_{\mathrm{g}}/e) + V_{\mathrm{bias}}}{w}$$

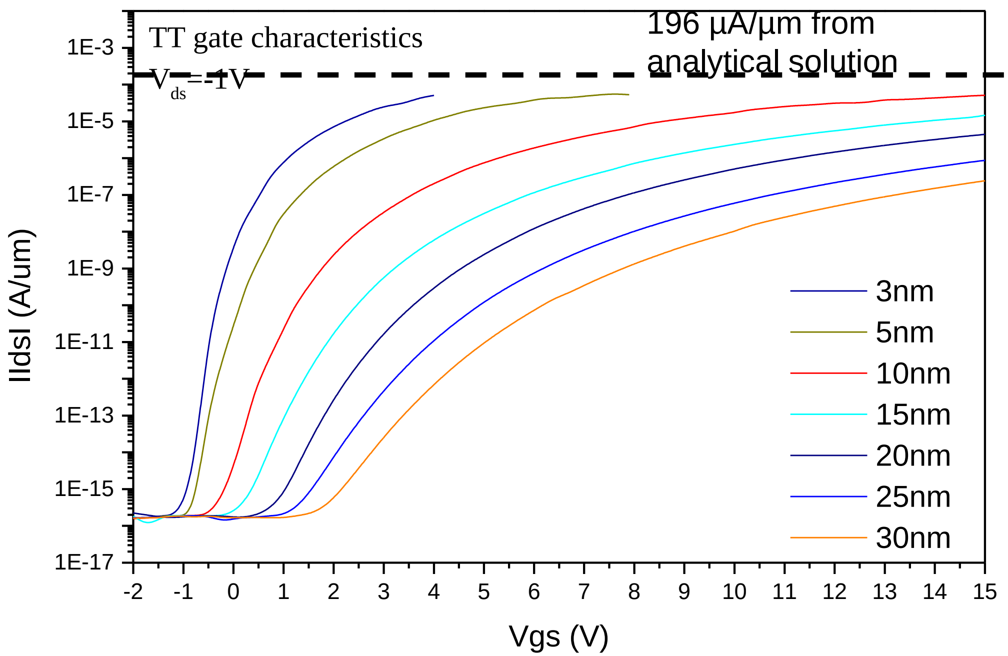
Approximation: Electric field E constant along the whole space charge region w

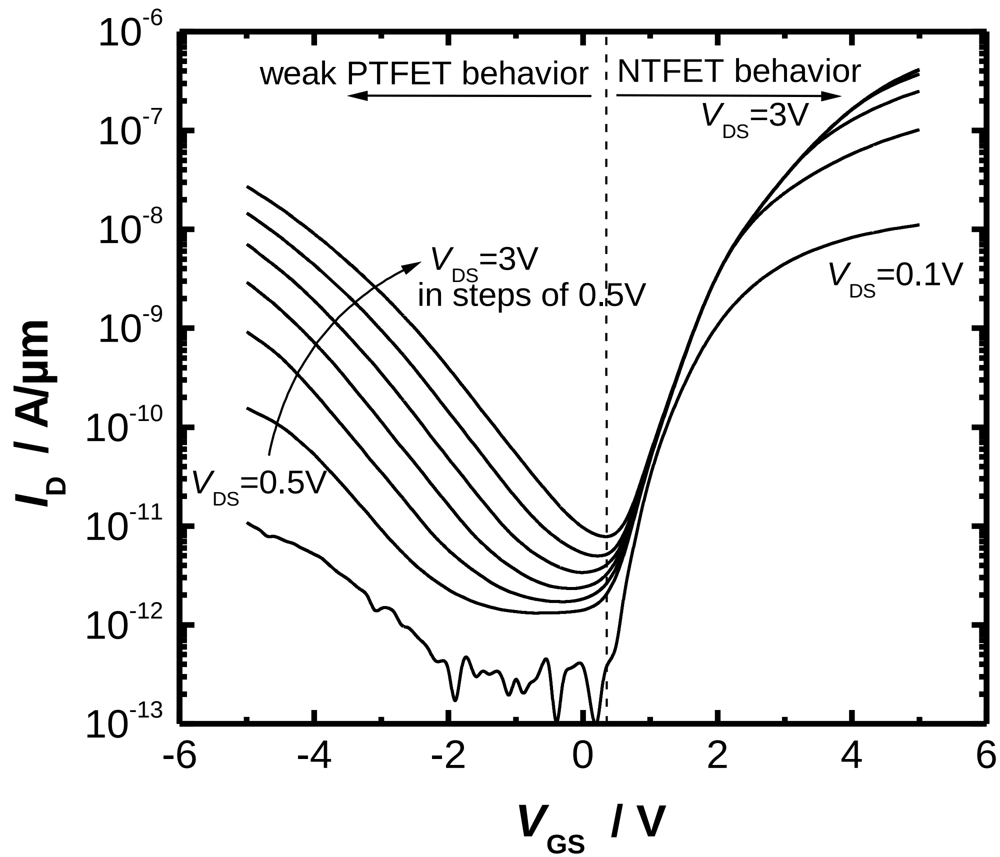
Calculate the band-to-band tunneling current per micrometer channel width of a *n*-channel Tunneling Field Effect Transistor (NTFET) in the „on“ and the „off“ state.

The source and drain regions have a doping concentration of N_A=5*10^{20} cm^{-3} and N_D=5*10^{20} cm^{-3}, respectively. The 100 nm channel can be considered to consist of intrinsic silicon. The applied drain-source voltage V_{DS} is equal to 2.0V.

Assume that the channel depth is 10 nm. Also assume that in the „on“ state the drain doping is extended along the channel to the source, creating an abrupt *pn*-junction at the source-channel interface. The electric field *E* within the space charge region can be regarded constant.







- Even quantum mechanical tunneling currents can be calculated