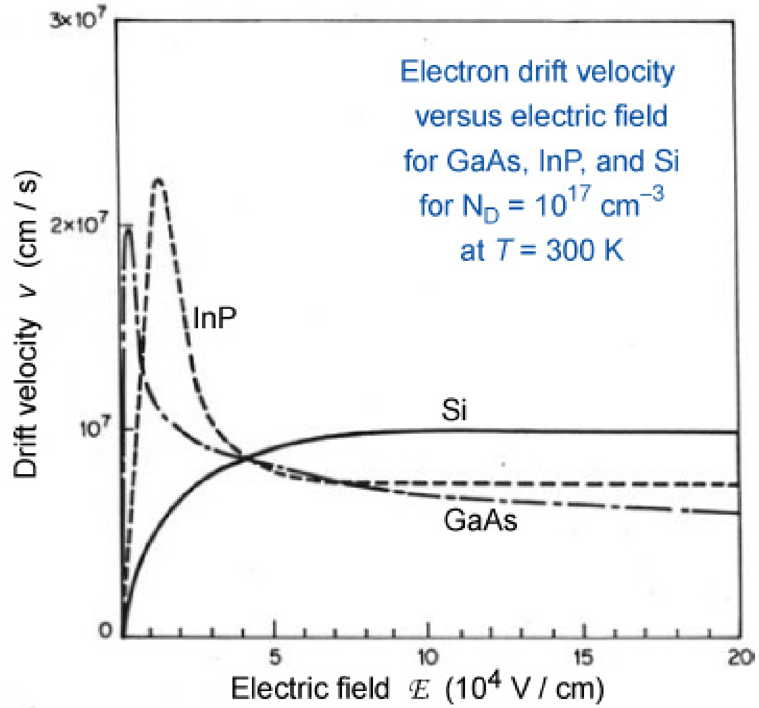
Saturated velocity model

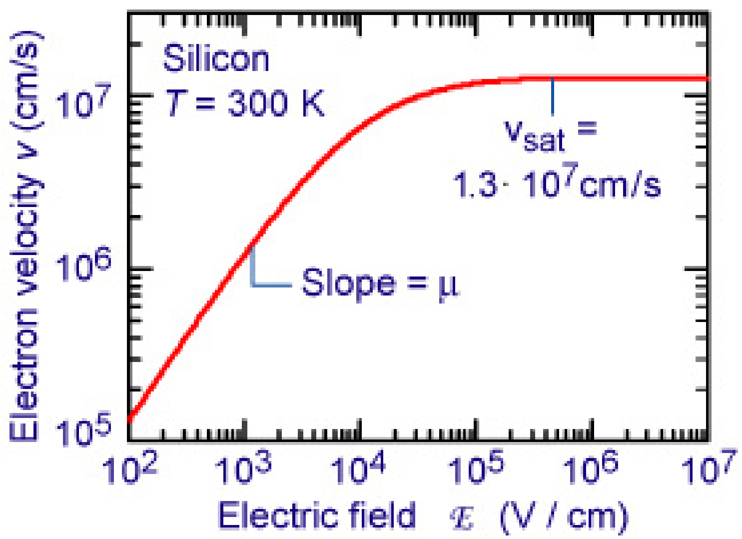
Velocity saturation

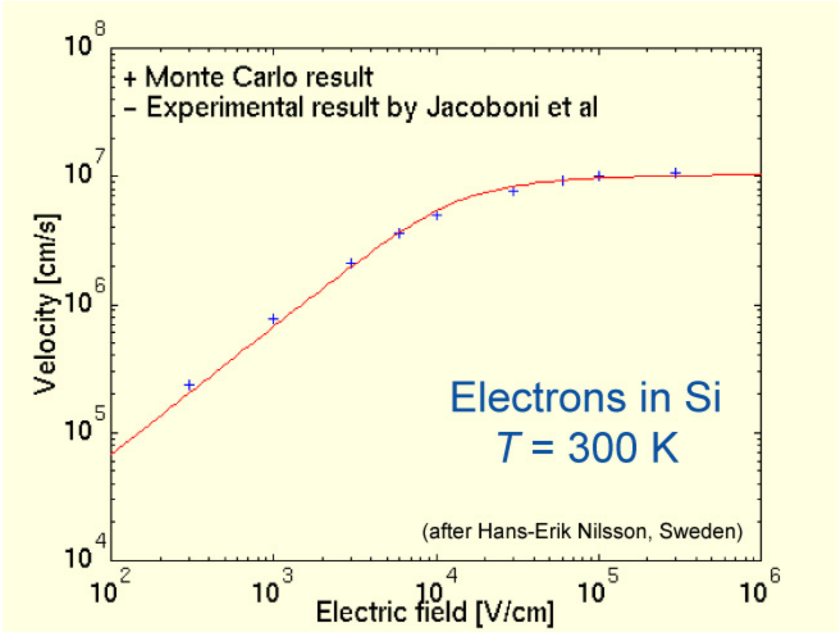
The relation $v = \mu \mathcal{E}$ is valid only at relatively low electric fields. As the electric field increases, LO phonon emission occurs very rapidly as the kinetic carrier energy approaches $h\nu_{LO}$, so that the velocity saturates.



In Si, the velocity versus-field characteristic saturates at high electric fields. At low fields, the electron mobility in Si can be as high as μ_n = 1 500 cm^2 / (Vs). However, at high fields, the velocity saturates due to LO phonon emission. The saturation velocity in Si is 1.3×10^7 cm / s.

Experimental velocity-versus-field curve of Si:





The low-field velocity-versus-field curve can be expressed as

$$v(\mathcal{E}) = \mu \mathcal{E} \qquad (1)$$

In Shockley's gradual-channel approximation, it was assumed that $v = \mu\mathcal{E}$. However, for very short gate lengths, this relation does not hold, because the electric field is so high that velocity saturation occurs.

For high electric fields, the velocity-versus-field curve can be approximated by

$$v(\mathcal{E}) = v_{\text{sat}} \qquad (2)$$

Saturated velocity model

Recall:

$$I_{\mathrm{D}} = Q_{\mathrm{n}}^{\mathrm{2D}}(x)\; v(x)\; Z \tag{3}$$

We assume that the gate is very short and that carriers propagate with saturated velocity under the gate. We no longer assume a gradual change of properties along the channel as in the gradual channel approximation). In this case, the drain current in the saturation regime is given by

$$I_{\mathrm{D,\,sat}} = Q_{\mathrm{n}}^{\mathrm{2D}}\; v_{\mathrm{sat}}\; Z \tag{4}$$

The charge under the gate per unit area is given by:

$$Q_{\mathrm{n}}^{\mathrm{2D}} = -\frac{\varepsilon_{\mathrm{OX}}}{d_{\mathrm{OX}}}\left(V_{\mathrm{GS}} - V_{\mathrm{th}}\right) \tag{5}$$

Thus the drain current is given by

$$I_{\mathrm{D,\,sat}} = -\frac{\varepsilon_{\mathrm{OX}}}{d_{\mathrm{OX}}}\left(V_{\mathrm{GS}} - V_{\mathrm{th}}\right) v_{\mathrm{sat}}\, Z \qquad (6)$$

… current I_D is negative since it flows in the negative x direction

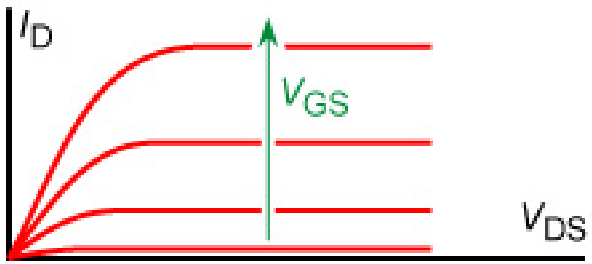
… saturated drain current depends linearly on V_{GS}

The transconductance is given by:

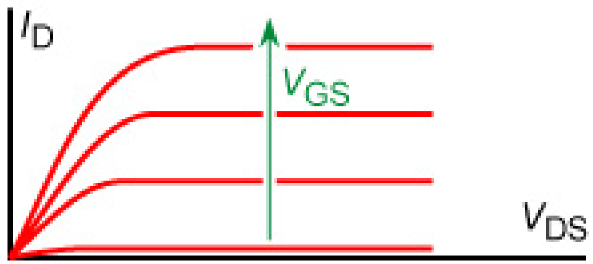
$$g_{\mathrm{m,\,sat}} = \frac{\mathrm{d}I_{\mathrm{D,\,sat}}}{\mathrm{d}V_{\mathrm{GS}}} = -\frac{\varepsilon_{\mathrm{OX}}}{d_{\mathrm{OX}}}\, v_{\mathrm{sat}}\, Z \qquad (7)$$

The transconductance is a constant, that is, independent of V_{GS}.

Output *I*-*V* characteristics for the two models:



Shockley model:
g_m is proportional to V_{GS}



Saturated velocity model:
g_m is independent of V_{GS}

Field-dependent-mobility models

Recall:

The Shockley gradual channel approximation assumed:

$$v(\mathcal{E}) = \mu \mathcal{E} \tag{8}$$

The saturated velocity model assumed:

$$v(\mathcal{E}) = v_{\text{sat}} \tag{9}$$

The **field-dependent-mobility model** assumes:

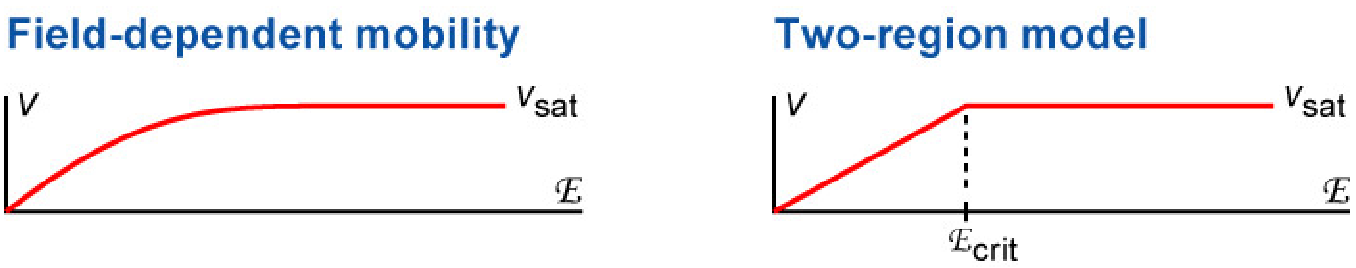
$$v(\mathcal{E}) = \frac{\mu \mathcal{E}}{1 + \dfrac{\mu \mathcal{E}}{v_{\text{sat}}}} \tag{10}$$

Another model, the **two-region model** assumes two regions, a low-field region and a high-field region:

$$v(\mathcal{E}) = \mu \mathcal{E} \qquad \text{(at low fields, } \mathcal{E} < \mathcal{E}_{crit}\text{)} \qquad (11)$$

$$v(\mathcal{E}) = v_{sat} \qquad \text{(at high fields, } \mathcal{E} \geq \mathcal{E}_{crit}\text{)} \qquad (12)$$

Illustration of v vs. $\mathcal{E}$ for the two models:



The results obtained with a field-dependent mobility model are somewhat "in between" the Shockley and the saturated-velocity model.

The field-dependent-mobility model shows that the transconductance is almost independent of the V_{GS} and has a smaller value than the g_m obtained from the Shockley model.