A little more about pinchoff, threshold voltage variation, the body factor and the body effect

When you have a voltage difference between the source and the drain \((V_D > V_S)\), you also must have an electric field pointing from the drain to the source.

\[
E_{ds} = -\nabla V_{ds}
\]

To get an inversion layer, phi at the surface must be larger than or equal to \(2 |\text{phi-b}|\). You have to superpose the effects of the electric field from the gate on the electric field of the drain-to-source. So you need the voltage at the semiconductor-oxide surface to be larger than the voltage due to the drain-source voltage by at least \(2\phi_b\) in order to get an inversion layer. Another way of saying this is that now the gate voltage that marks the point where you get inversion \((V_t)\) has to be higher than it did before by \(V(y)\) due to \(V_{DS}\). \(V(y)\) varies from \(0\) at the source to \(V_{DS}\) at the drain. So since the voltage due to \(V_{DS}\) at the source is \(0\), \(V_t\) at the source is still the same \(V_t\) as we had for a MOScap:

\[
V_t = \frac{2e\phi_b N_A}{2|\phi_b| + 2|\phi_b|}
\]

And at the drain, the threshold voltage is now that old \(V_t + V_{DS}\). And in all the channel in between the drain and source, the threshold voltage is that old \(V_t + V(y)\). And if the gate voltage isn’t large enough to cause inversion at the drain, but it is large enough to cause inversion at the source and along the channel partway from the source to the drain, then we pinched off the channel.

The voltages at which pinchoff occurs depend on both the gate and drain voltages.

Equation 140 in your reader gives you the specific \(V_{DS}\) at which pinchoff begins. Then for every incremental increase in \(V_{DS}\) beyond this pinchoff voltage (called \(V_{DSat}\)) the channel ends closer to the source. Since the voltage at which pinchoff occurs is constant for a given \(V_G\), as you increase \(V_{DS}\) past \(V_{DSat}\), and the channel gets shorter, the voltage drop across the channel stays the same: it’s \(V_{DSat}\). The rest of \(V_{DS}\) drops between the end of the channel and the drain.

Since the voltage across the channel (which is a resistive path, with the resistance set by the charge concentration, length and area of the channel) doesn’t change anymore with increasing \(V_{DS}\), we no longer see the rise in \(I_{DS}\) with \(V_{DS}\) that we saw for a small \(V_{DS}\). We do see *some* small rise in \(I_{DS}\) due to \(V_{DS}\), but this rise is because the channel itself is getting shorter, and the channel resistance shrinks as its length shrinks.

Equation 140 uses a doping-dependent constant \(K\), defined in Equation 141. That \(K\) is called the body factor and is usually represented with a \(\gamma\) rather than a \(K\). It’s a
convenient constant that shows up in a bunch of equations, including calculations of the body effect. But it doesn’t mean there *is* a body effect in the circuit.

Body effect is where you further complicate the set of electric fields in the channel and around the drain and source by having a voltage difference between the source and the substrate bulk. The source in an nFET has to be at a higher voltage than the bulk (otherwise you would be forward-biasing the source-bulk pn junction) so this will be a positive V_{sb} or negative V_{bs}. That means you are reverse biasing the pn junction, so increasing the size of the depletion region between the source and bulk and making it even harder to get 2*phi-bulk higher than the bulk in order to achieve inversion. So this voltage also raises the threshold voltage, or the minimum voltage on the gate necessary to cause inversion. *That* is the body effect, and you can see its effect on $I_{DS}$ in equation 144.

For small signal models, you will find how $V_{DS}$ reacts to small changes at any of the terminals: the gate ($g_m=dI_{DS}/dV_{GS}$), the drain ($g_{ds}=dI_{DS}/dV_{DS}$), and the bulk ($g_{mb}=dI_{DS}/dV_{BS}$). We measure all these voltages relative to the source. You have a bunch of different operating ranges and levels of simplification, so you have a bunch of different equations for $g_m$, $g_{ds}$, and $g_{mb}$. 