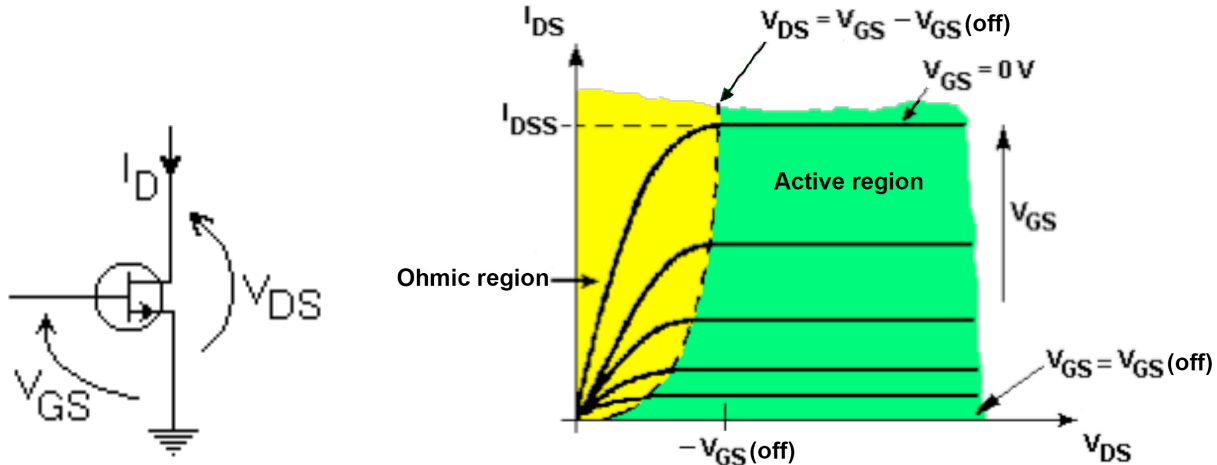


## The field effect transistor as a voltage controlled resistor

We consider the use of a n-channel FET as a voltage controlled resistor where the resistance between the drain and source is controlled by the gate-source voltage.



There are two distinct regions. In the Ohmic region<sup>1</sup>, the drain-to-source current,  $I_{DS}$ , depends on the gate-to-source voltage,  $V_{GS}$ , as well as the drain-to-source voltage  $V_{DS}$ . For small values of drain-to-source voltage,  $I_{DS}$   $V_{DS}$  and the FET functions as a resistor, with a conductance that depends on  $V_{GS}$ . In the active region, to be discussed next, the drain-to-source current is almost entirely independent of the drain-to-source voltage and the FET functions as a current source with the value of the current set by  $V_{GS}$ .

The equation of the curve that separates the two regions is  $V_{DS} = V_{GS} - V_{GS(off)}$ , where  $V_{GS} < 0$  for JFETs and  $V_{GS} > 0$  for MOSFETs.

In the Ohmic region ( $0 < V_{GS} - V_{GS(off)} < V_{DS}$ )

$$V_{GS} - V_{GS(off)} < V_{DS}$$

and

$$I_D = \frac{2I_{DSS}}{V_{GS}^2(off)} \left( [V_{GS} - V_{GS(off)}]V_{DS} - \frac{V_{DS}^2}{2} \right).$$

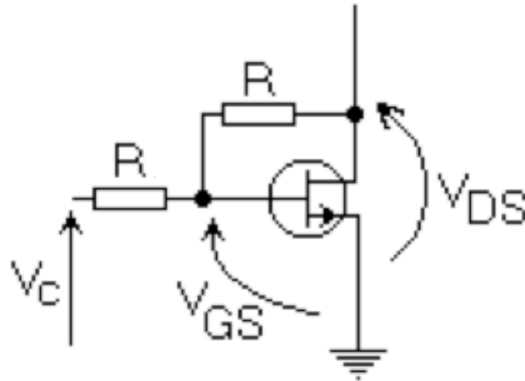
This leads to an equivalent conductance across the FET, denoted  $1/r_{DS}$ , of:

$$\frac{1}{r_{DS}} = \frac{I_D}{V_{DS}} = \frac{2I_{DSS}}{V_{GS}^2(off)} \left( V_{GS} - V_{GS(off)} - \frac{V_{DS}}{2} \right).$$

The source is grounded so that the gate voltage,  $V_G$ , is  $V_G = V_{GS}$  and thus  $V_G$  acts as the control voltage. However, this scheme remains a bit imperfect since the resistance is sub-linear from the presence of the negative  $V_{DS}$  term.

<sup>1</sup> The active region is also known as the "saturation region" and the "pentode region". The Ohmic region is also known as the "linear region", the "inversion region", and the "tetrode region".

The above non-linearity can be removed by adding an amount  $V_{DS}/2$  to the gate voltage. This is achieved using the following circuit:



We replaced  $V_{GS} = V_G$  by the weighted sum of a control voltage, denoted  $V_C$ , and the drop across the transistor,  $V_{DS}$ . Using two equal resistors to form a voltage divider, we use Kirchhoff's current law to write:

$$0 = \frac{V_{GS} - V_C}{R} + \frac{V_{GS} - V_{DS}}{R}$$

or

$$V_{GS} = \frac{V_C + V_{DS}}{2}$$

so that

$$\frac{1}{r_{DS}} = \frac{I_D}{V_{DS}} = \frac{2I_{DSS}}{V_{GS}^2(\text{off})} \left( \frac{V_C + V_{DS}}{2} - V_{GS}(\text{off}) - \frac{V_{DS}}{2} \right) = \frac{2I_{DSS}}{V_{GS}^2(\text{off})} \left( \frac{V_C}{2} - V_{GS}(\text{off}) \right)$$

Therefore  $1/r_{DS}$  is now a linear conductance, with  $2 V_{GS}(\text{off}) < V_C < 0$ , so that

$$0 < \frac{1}{r_{DS}} < \frac{2I_{DSS}}{|V_{GS}(\text{off})|}$$

**Note:**

1. Adding the resistors reduces the control sensitivity by factor of two.
2. R should be large in value since  $2R$  shunts the drain-to source resistance and limits the maximum value of the source-to-drain resistance to  $r_{DS} || 2R$ .
3. One terminal of the resistor must be at a fixed potential, e.g., the source must be grounded. Otherwise the control voltage,  $V_C$ , must be allowed to float.
4. The control voltage should be supplied from a low impedance source.