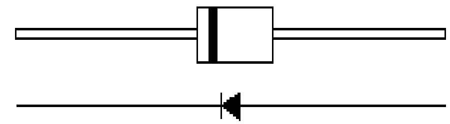
Electronic Circuits Laboratory EE462G Lab #2

Characterizing Nonlinear Elements, Semiconductor Analyzer, Transfer Characteristics

Original slides prepared by Kevin D. Donohue (Spring 2007)
Modified by Zhi David Chen (Fall 2023)

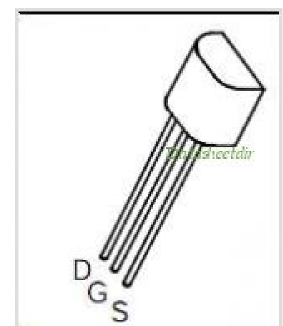
Nonlinear Elements

Diodes



- *pn* junction
- Zener

Transistors

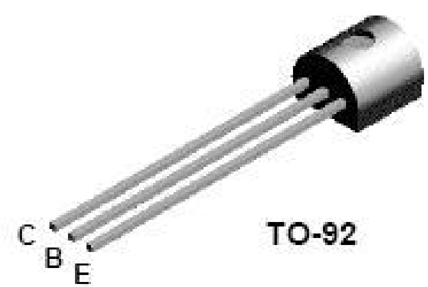


- Field Effect Transistors – (FETs)

  ZVN3306A -NMOSFET
  ZVP3306A -PMOSFET

- Bipolar Junction Transistors – (BJTs)

  PN2222 –NPN BJT

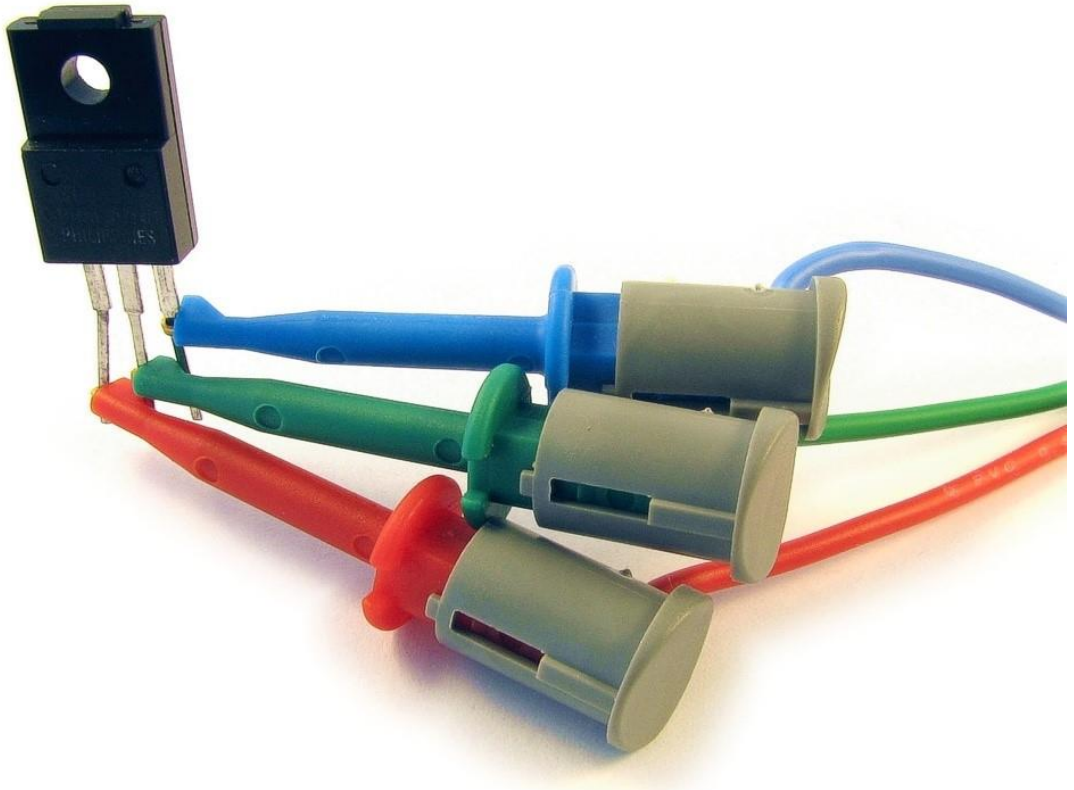


Instrumentation

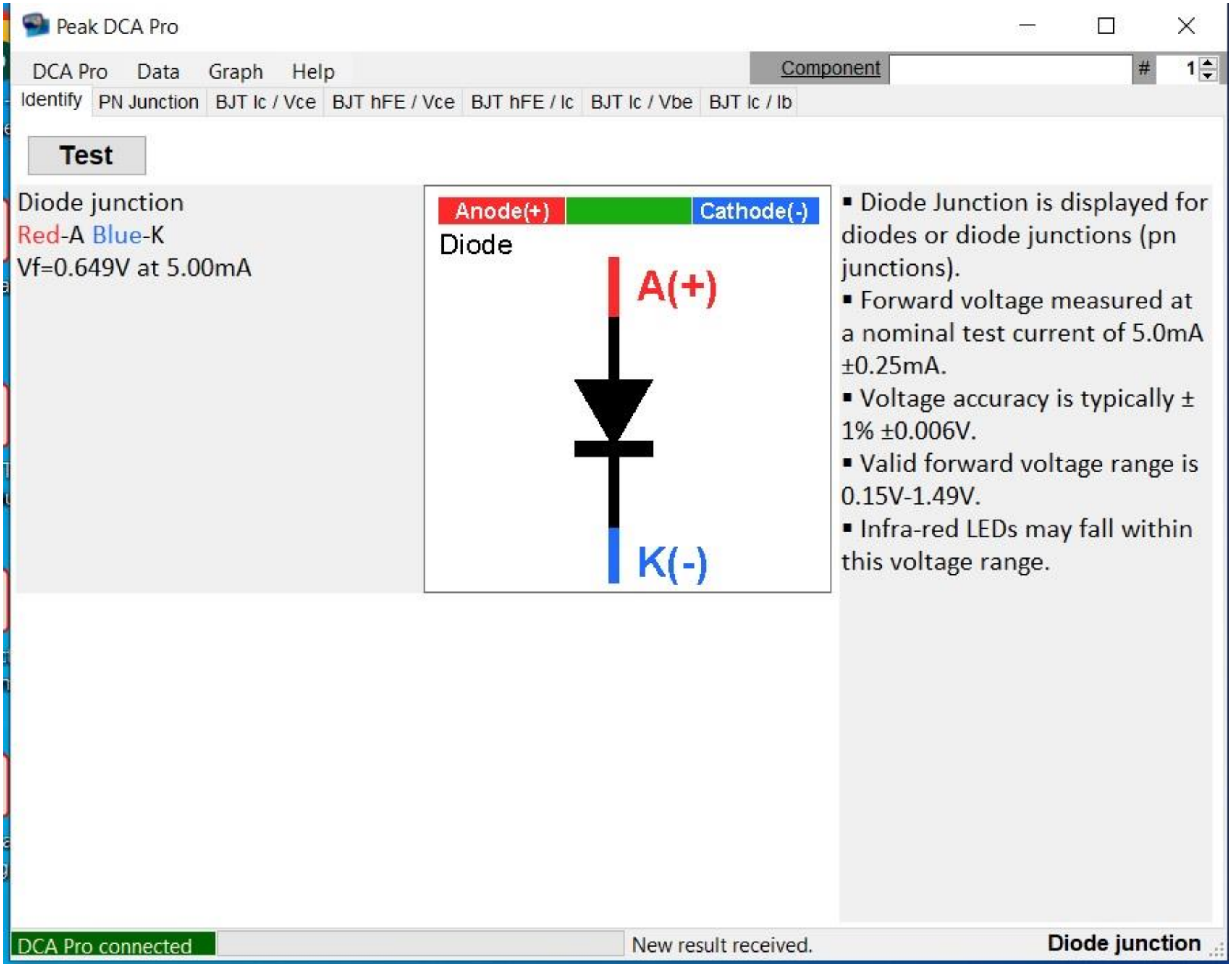
Peak Electronics

DCA75 - Atlas DCA Pro Advanced Semiconductor Analyzer

Instrumentation

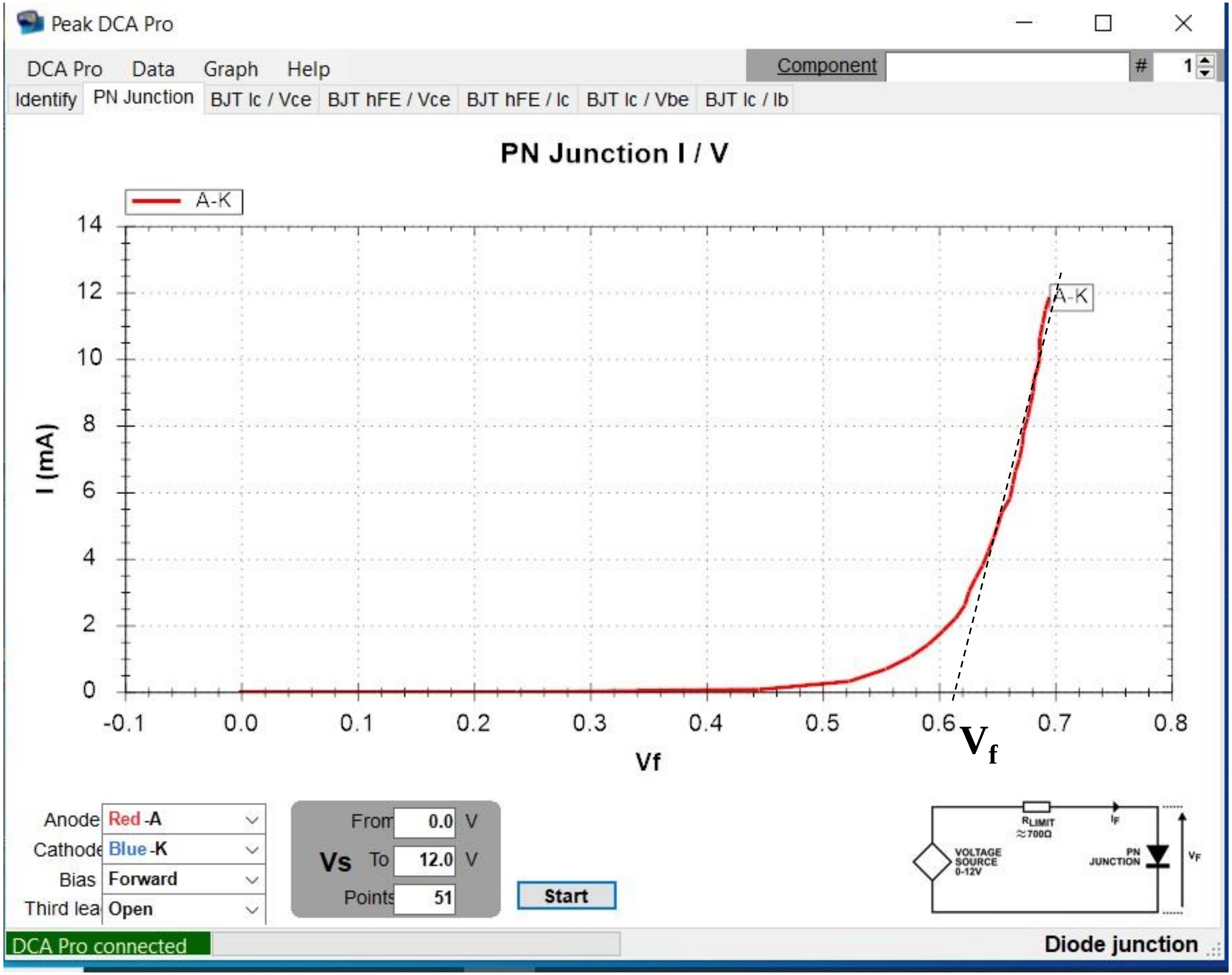


Instrumentation

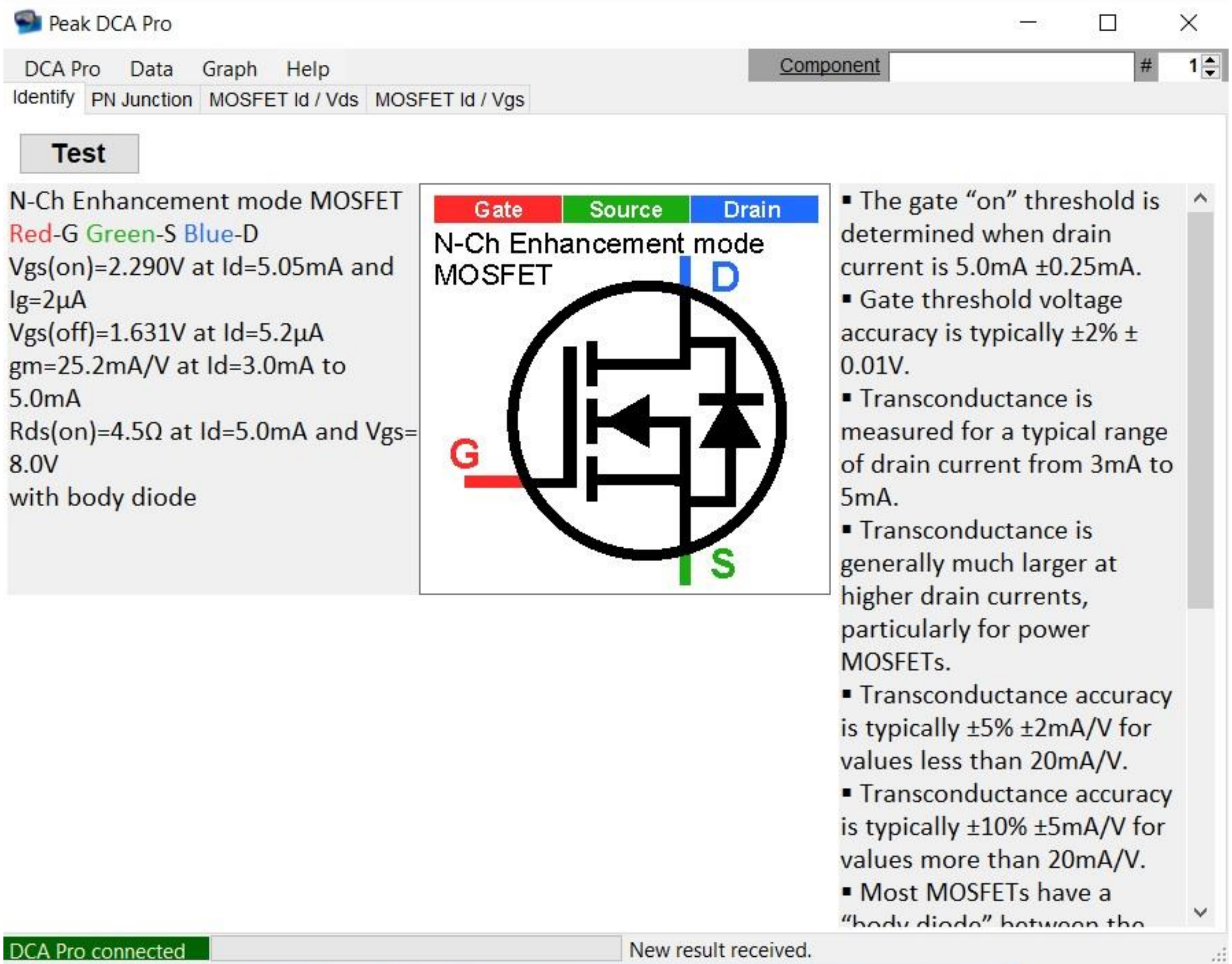


Instrumentation

Find turn-on voltage V_f

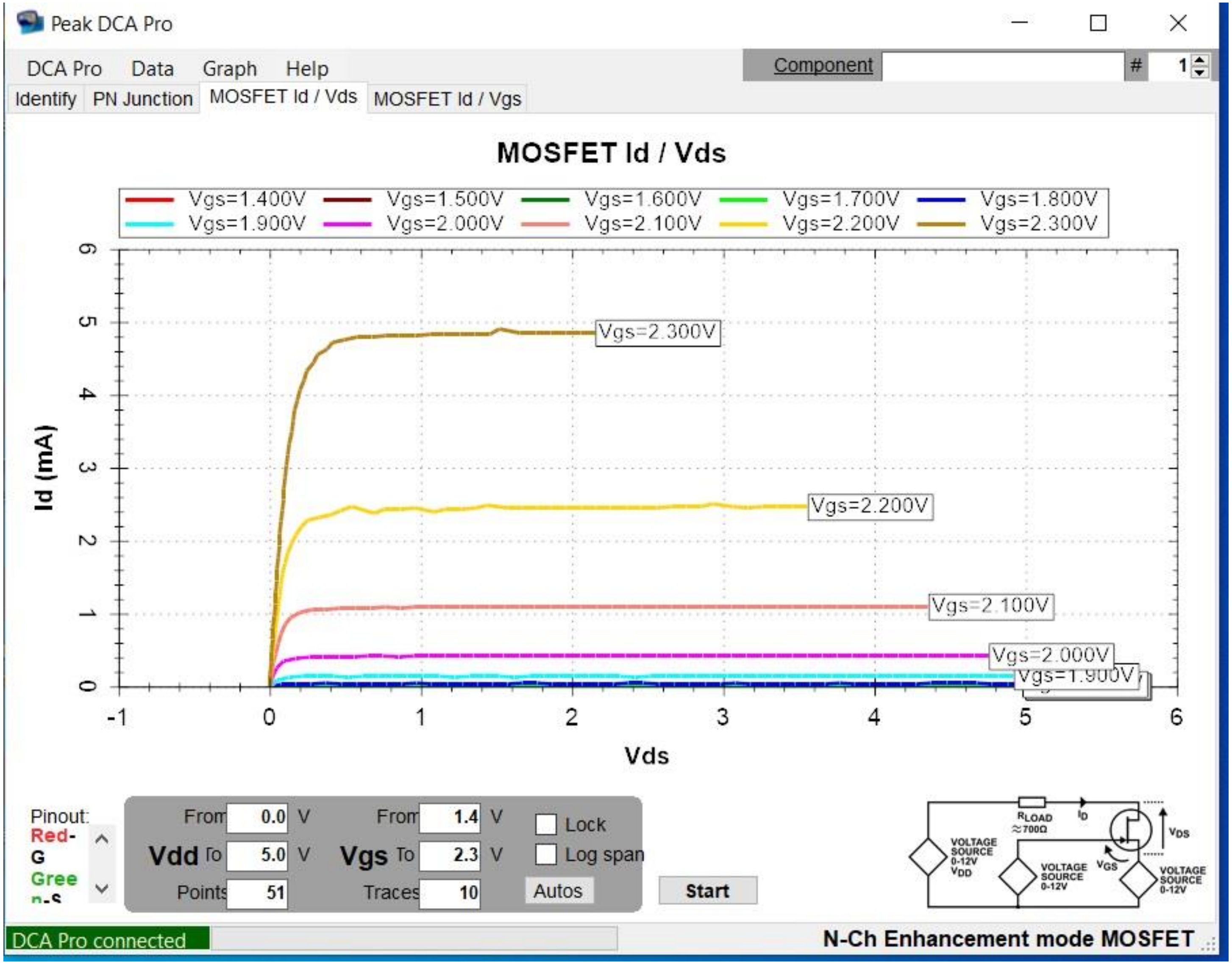


Instrumentation



Instrumentation

Find threshold voltage V_{th}



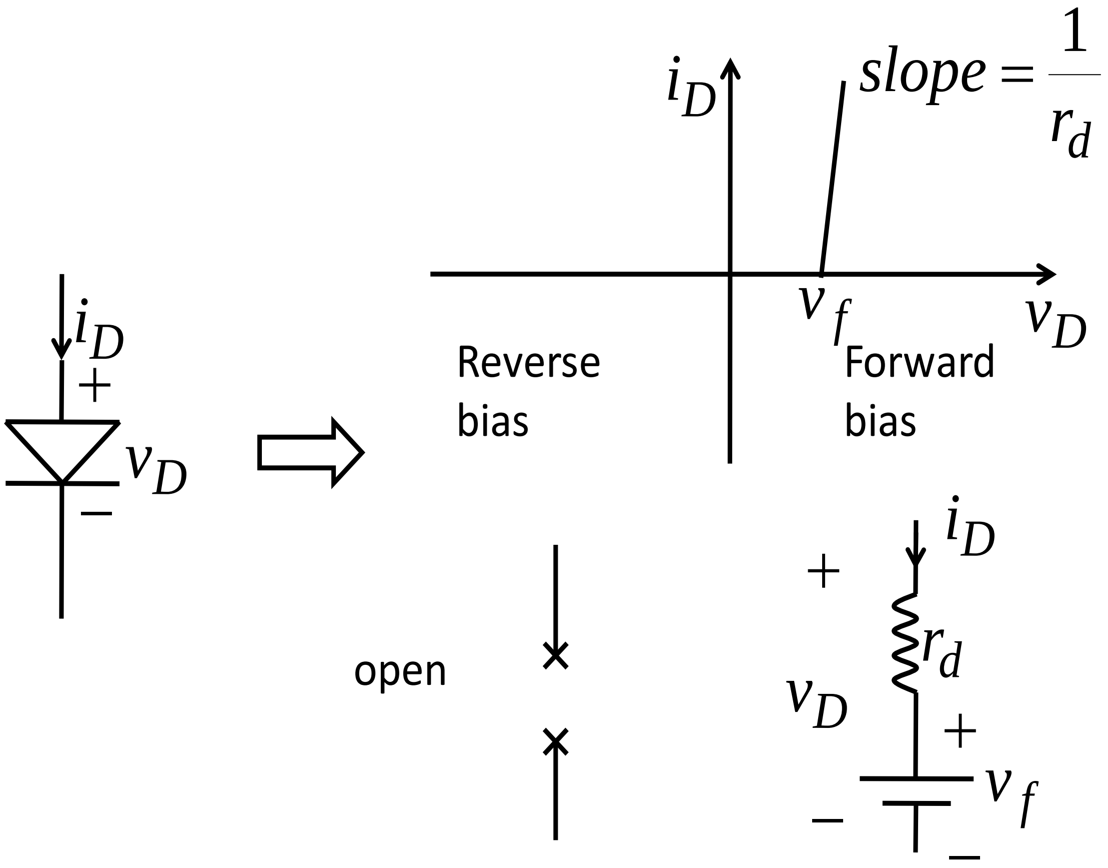
Transfer Characteristics

Transfer Characteristics

- A relation describing the amplitude input-output relationship of a device (I-V curve).

- A sufficient characterization in most engineering problems for instantaneous systems (present output does not depend on future or previous values). These systems are sometimes referred to as memoryless and are typical of systems with no energy storage elements.

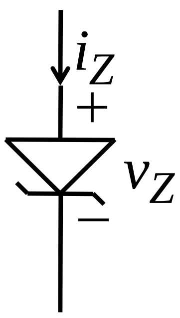
PN junction diode

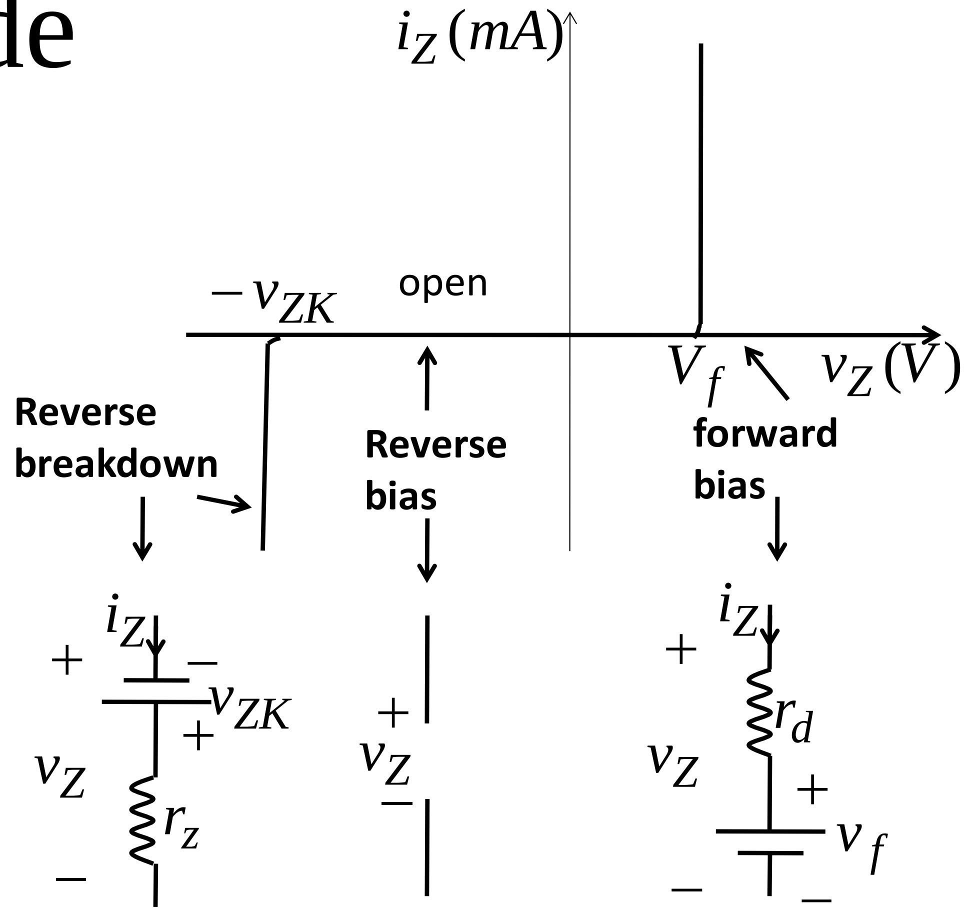


The band on the component usually denotes the cathode terminal

Zener diode

Symbol

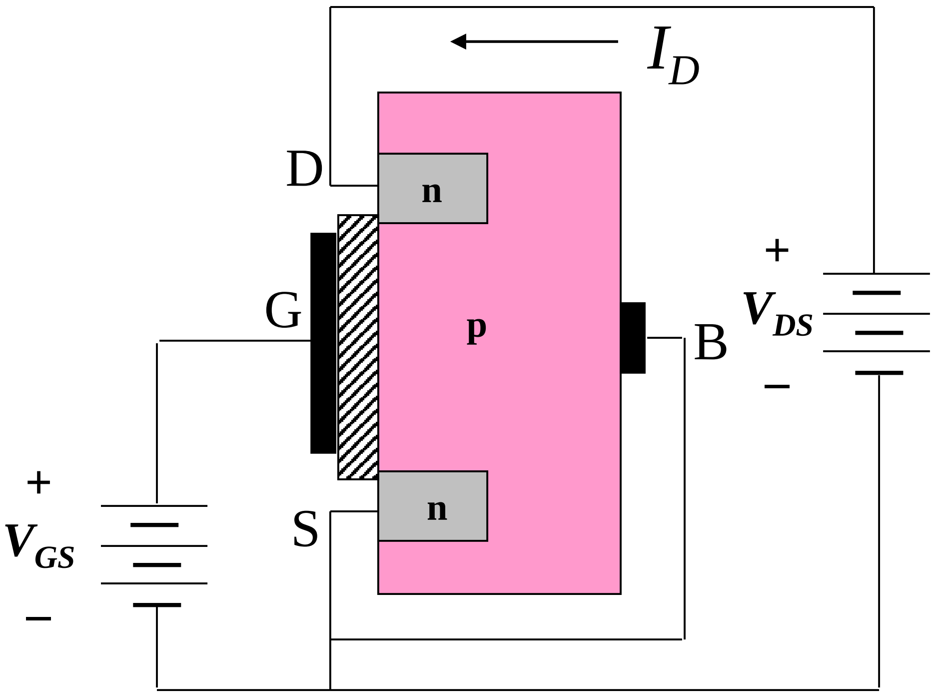


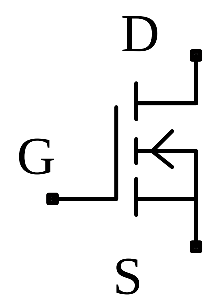


The band on the component usually denotes the cathode terminal

n-Channel MOSFET

A Metal-Oxide-Semiconductor field-effect transistor (MOSFET) is presented for charge flowing in an n-channel:





B – Body or Substrate

D – Drain

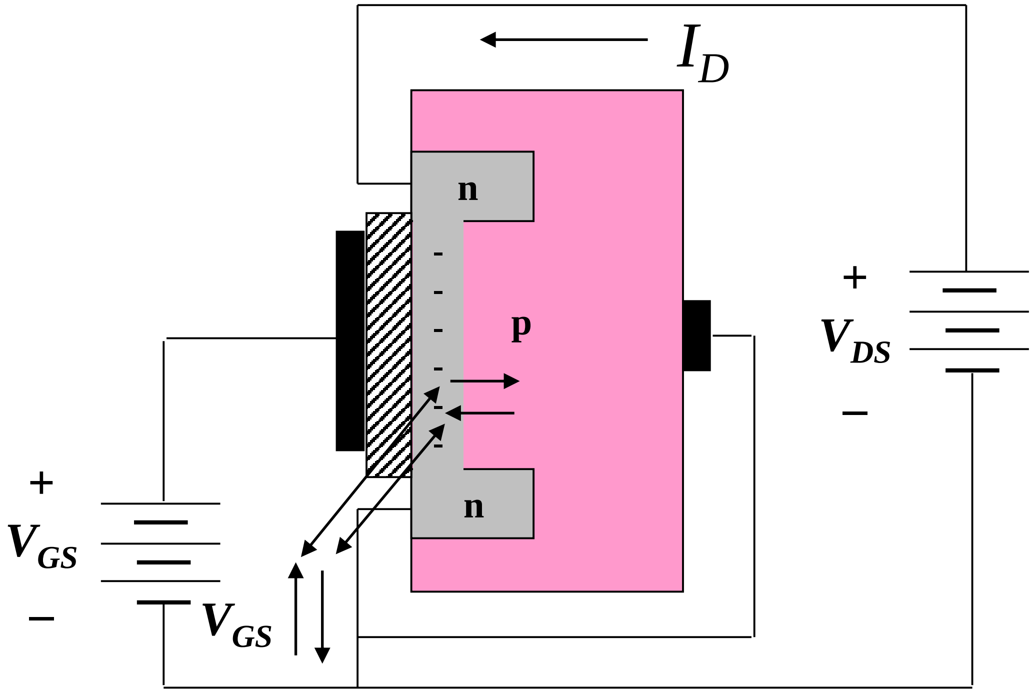
G – Gate

S – Source

For many applications the body is connected to the source and thus most FETs are packaged that way.

FET Operation

The current flow between the drain and the source can be controlled by applying a positive gate voltage:



Three Regions of Operation:

Cutoff region

$(V_{GS} \leq V_{tr})$

Triode region

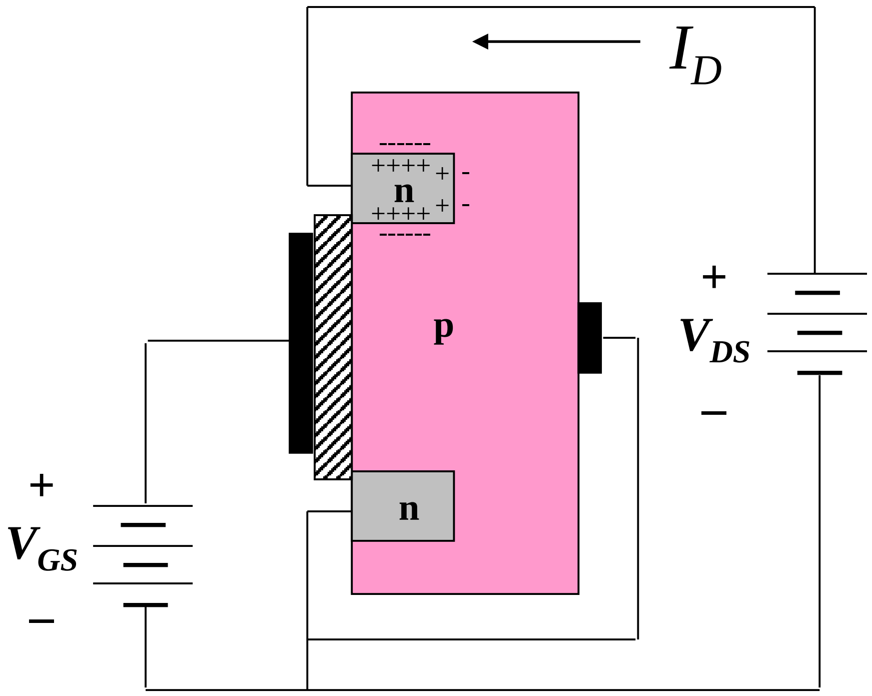
$(V_{GS} \geq V_{tr}\, ,\, V_{DS} \leq V_{GS} - V_{tr})$

Constant current region (CCR) (saturation)

$(V_{GS} \geq V_{tr}\, ,\, V_{DS} \geq V_{GS} - V_{tr})$

Cutoff Region

In this region ($V_{GS} \leq V_{tr}$) the gate voltage is less than the threshold voltage and virtually no current flows through the reversed biased PN interface between the drain and body.

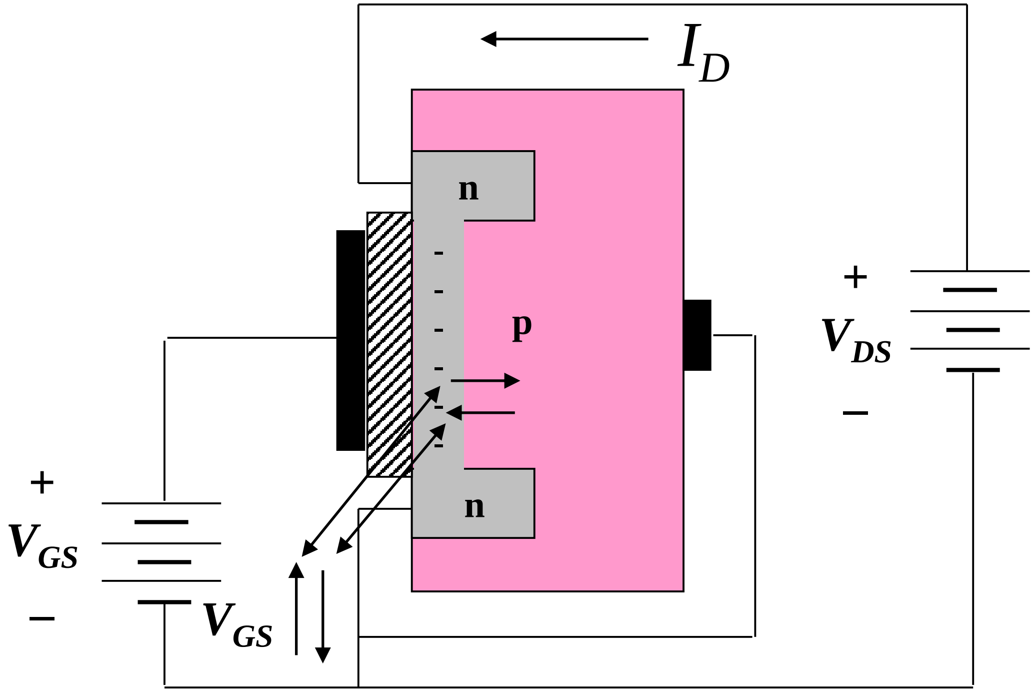


Typical values for V_{tr} (or V_{to}) range from 1 to several volts.

Cutoff region: $I_D = 0$

Triode Region

In this region ($V_{GS} > V_{tr}$ and $V_{DS} \leq V_{GS} - V_{tr}$) the gate voltage exceeds the threshold voltage and pulls negative charges toward the gate. This results is an *n*-Channel whose width controls the current flow I_D between the drain and source.



Triode Region:

($V_{GS} > V_{tr}$, $V_{DS} \leq V_{GS} - V_{tr}$)

$$I_D = \left(\frac{W}{L}\right)\frac{K_p}{2}\left[2(V_{GS} - V_{tr})V_{DS} - V_{DS}^2\right]$$

where: $K_p = \mu_n C_{ox}$

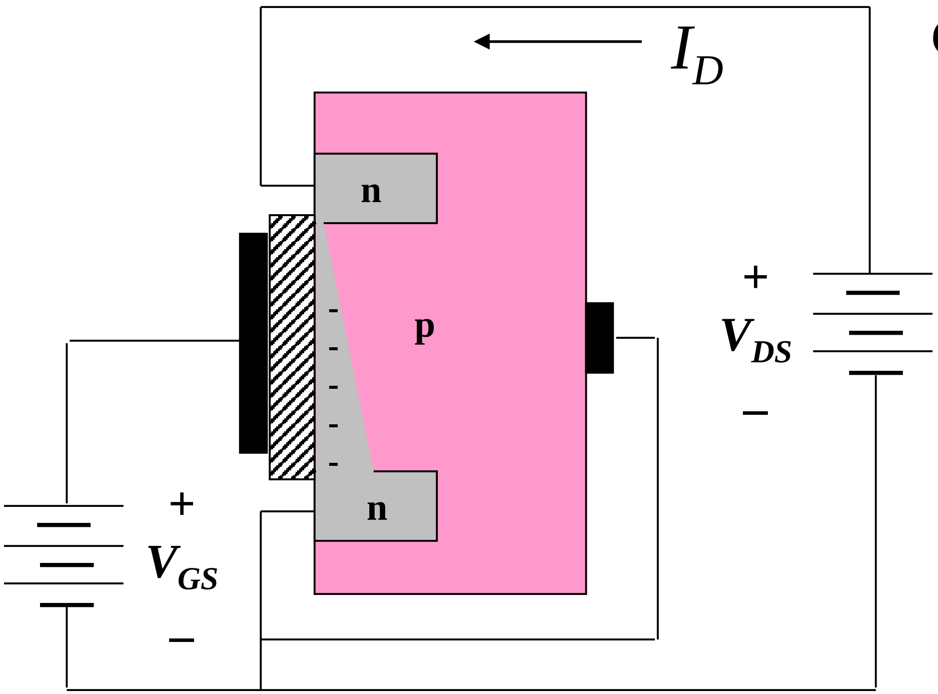
product of surface mobility of channel electrons μ_n and gate capacitance per unit area C_{ox} in units of amps per volts squared,

W is the channel width, and

L is channel length.

Constant Current Region (CCR)

In this region ($V_{GS} > V_{tr}$ and $V_{GS} - V_{tr} \leq V_{DS}$) the drain-source voltage exceeds the excess gate voltage and pulls negative charges toward the drain and reduces the channel area at the drain. This limits the current making it more insensitive/independent to changes in V_{DS}.



CCR: $V_{GS} > V_{tr}$, $V_{DS} \geq V_{GS} - V_{tr}$

$$I_D = \left(\frac{W}{L}\right)\frac{K_p}{2}(V_{GS} - V_{tr})^2$$

The material parameters can be combined into one constant:

$$I_D = K(V_{GS} - V_{tr})^2$$

At the point of beginning of CCR (Saturation), for a given V_{GS}, the following relation holds:

$$I_D = KV_{DS}^2$$

NMOS Transfer Characteristics

The relations between I_D and V_{DS} for the operational regions of the NMOS transistor can be used to generate its transfer characteristic. These can be conveniently coded in a Matlab function

```
function ids = nmos(vds,vgs,KP,W,L,vto)

%  This function generates the drain-source current values "ids" for
%  and NMOS Transistor as a function of the drain-source voltage "vds".
%    ids = nmos(vds ,vgs,KP,W,L,vto)
%    where "vds" is a vector of drain-source values
%              "vgs" is the gate voltage
%              "KP" is the device parameter
%              "W" is the channel width
%              "L" is the channel length
%              "vto" is the threshold voltage
%   and output "ids" is a vector of the same size of "vds"
%   containing the drain-source current values.
```

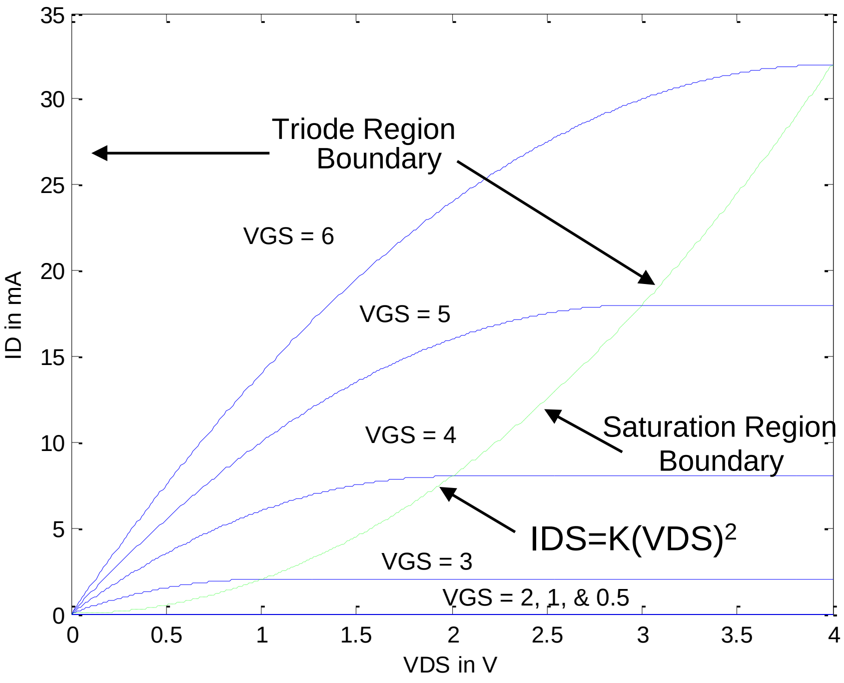
NMOS Transfer Characteristics

```
ids = zeros(size(vds));  %  Initialize output array with all zeros
k = (W/L)*KP/2;   %  Combine devices material parameters
%  For non-cutoff operation:
if vgs >= vto
    %  Find points in vds that are in the triode region
    ktri = find(vds<=(vgs-vto) & vds >= 0);  %  Points less than (gate – threshold voltage)
    %  If points are found in the triode region compute ids with proper formula
    if ~isempty(ktri)
        ids(ktri) = k*(2*(vgs-vto).*vds(ktri)-vds(ktri).^2);
    end
    % Find points in saturation region
    ksat = find(vds>(vgs-vto) & vds >= 0);   % Points greater than the excess voltage
    %  if points are found in the saturation regions compute ids with proper formula
    if ~isempty(ksat)
        ids(ksat) = k*((vgs-vto).^2);
    end
 %  If points of vds are outside these ranges, then the ids values remain zero
end
end
```

NMOS Transfer Characteristics

Plot the transfer characteristics of an NMOS transistor where KP = 50 μA/V^2, W= 160 μm, L= 2 μm, V_{tr}= 2V, and for VGS = [.5, 1, 2, 3, 4, 5, 6] volts

```
vgs = [.5, 1, 2, 3, 4, 5, 6]
vds =[0:.01:4];
for kc = 1:length(vgs)
ids = nmos(vds,vgs(kc),50e-6,160e-6,2e-6,2);
figure(1); plot(vds,ids*1000)
hold on
end
ids = (50e-6/2)*(160e-6/2e-6)*vds.^2;
figure(1); plot(vds,ids*1000,'g:')
hold off
xlabel('VDS in V')
ylabel('ID in mA')
```



Find K from Curves

Recall at the start of CCR the following holds: $I_D = KV_{DS}^2$

From graph: $I_D = KV_{DS}^2$

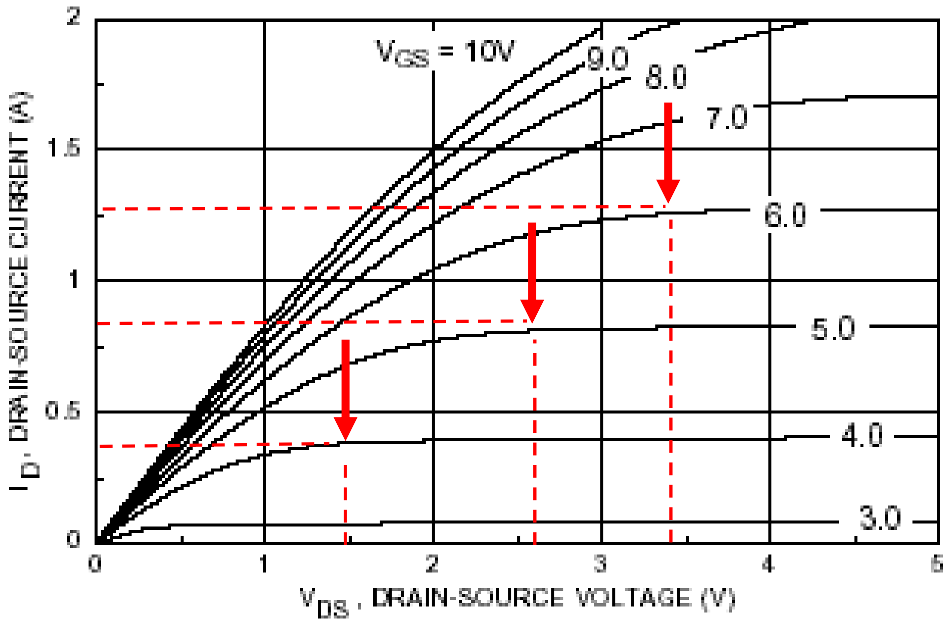
$0.4 = K1.5^2$

$0.7 = K2.6^2$

$1.5 = K3.4^2$

One way to estimate K is to compute it for each equation and take the average. In this case it becomes K=.137 A/V^2, which for W=L=1, implies:

K_p= K*2 = 0.274 A/V^2



Find K from Curves

From graph:

$$I_D = KV_{DS}^2$$

$$0.4 = K1.5^2$$

$$0.7 = K2.6^2$$

$$1.5 = K3.4^2$$

A better approach uses a least-squares solution that gives the error in each equation equal weight. Find K to minimize mean square error for the measured data:

$$\langle E^2 \rangle = \frac{1}{M}\sum_{i=1}^{M}\left(I_{Di} - KV_{DSi}^2\right)^2$$

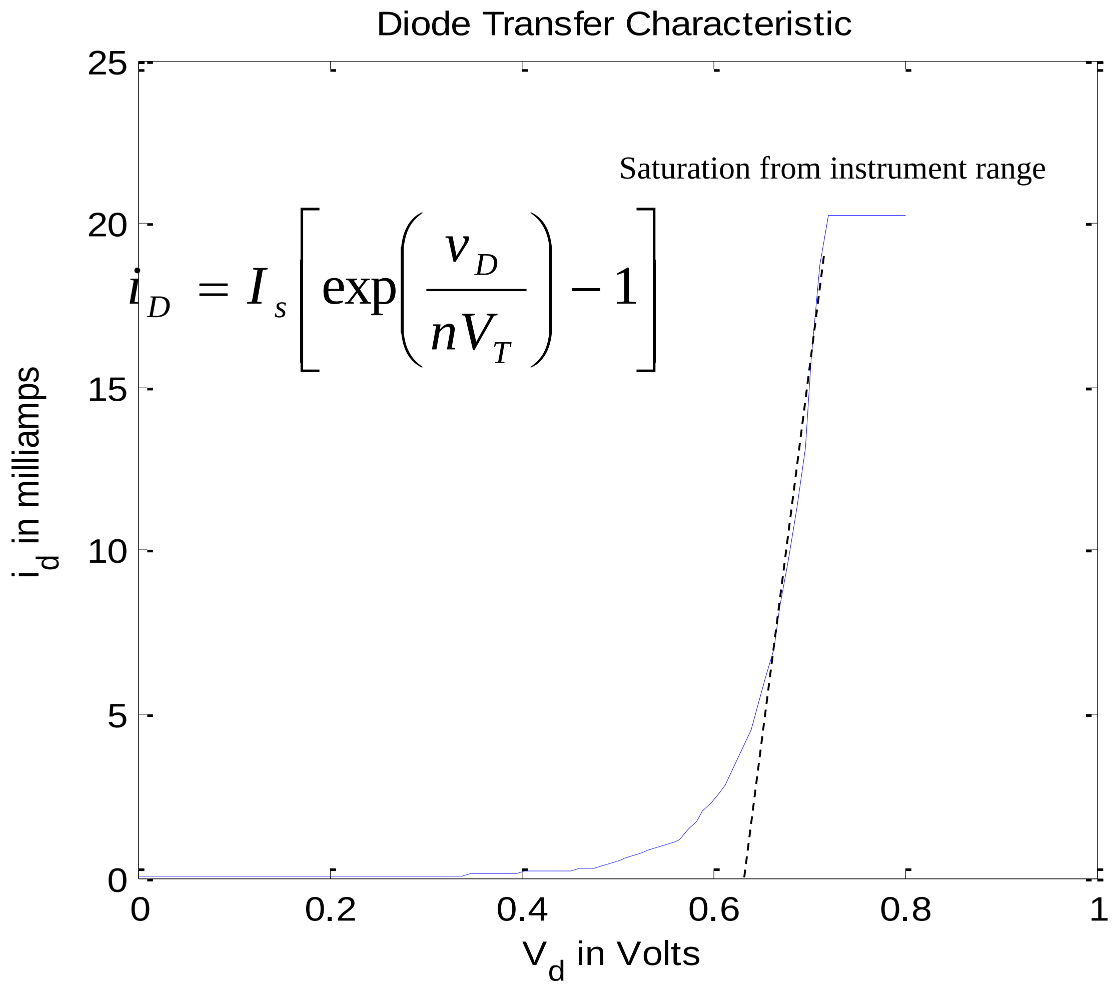
Take derivative with respect to K and set equal to 0 to obtain:

$$K_{LS} = \frac{\sum_{i=1}^{M}\left(V_{DSi}^2 I_{Di}\right)}{\sum_{i=1}^{M}\left(V_{DSi}^2 V_{DSi}^2\right)} \quad K_{LS} = \frac{\left(.4\times1.5^2 + .7\times2.6^2 + 1.5\times3.4^2\right)}{\left(1.5^2\times1.5^2 + 2.6^2\times2.6^2 + 3.4^2\times3.4^2\right)} = .1246 \quad \frac{\mathrm{A}}{\mathrm{V}^2}$$

which for W=L=1, implies: K_p= K_{LS}*2 = 0.2492 A/V^2

Diode TC (I-V curve)

Use Atlas DCA Pro Advanced Semiconductor Analyzer to obtain the diode I-V curve. Find the turn-on voltage V_f.



$$i_D = I_s\left[\exp\left(\frac{v_D}{nV_T}\right) - 1\right]$$

FET TC (I-V curve)

Use Atlas DCA Pro Advanced Semiconductor Analyzer to obtain the FET I-V curves. Find the threshold voltage V_{th}.