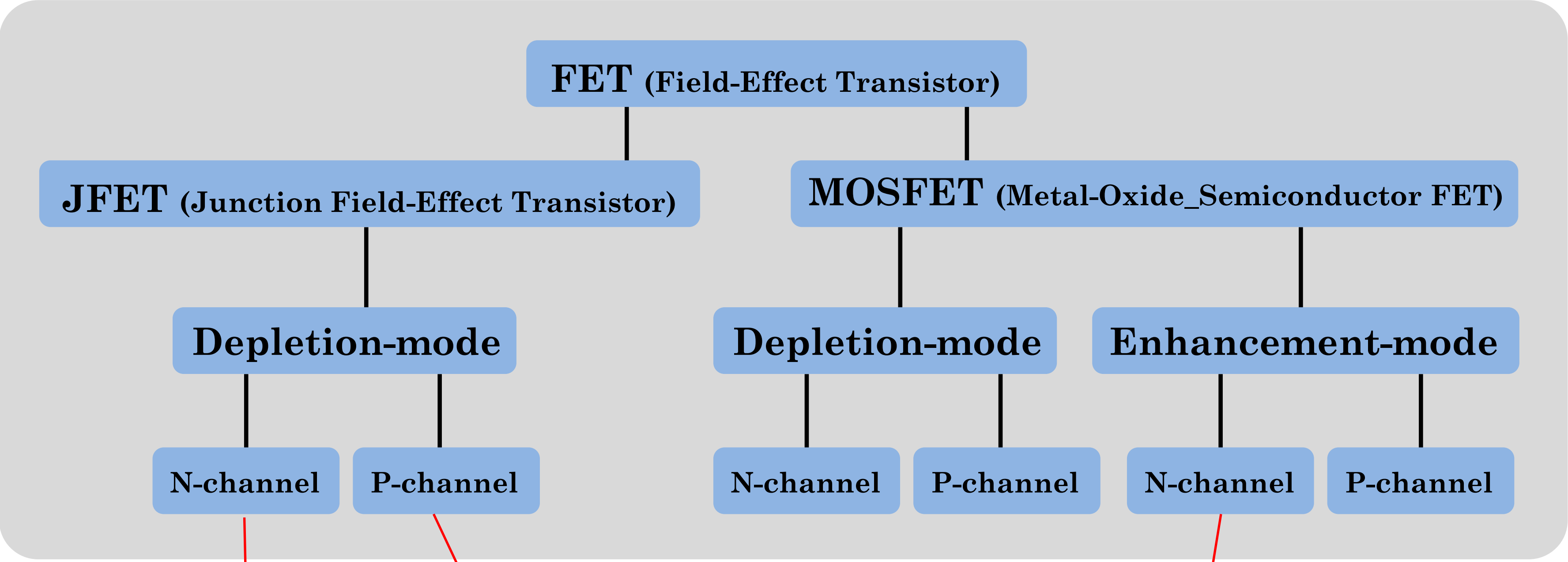
FYSE400 ANALOG ELECTRONICS

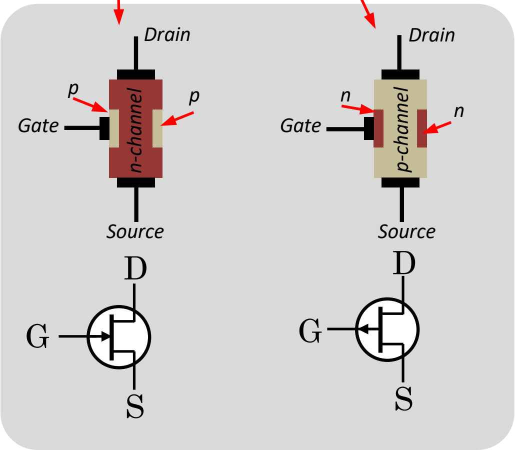
LECTURE 4

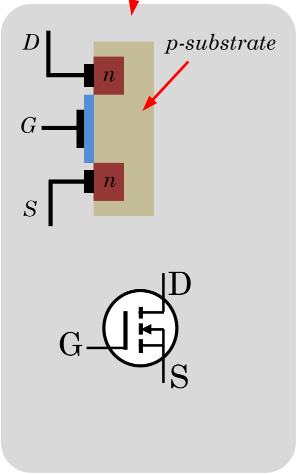
FET Circuits

DISCRETE COMPONENT FET



- **FET** (Field-Effect Transistor)
  - **JFET** (Junction Field-Effect Transistor)
    - Depletion-mode
      - N-channel
      - P-channel
  - **MOSFET** (Metal-Oxide_Semiconductor FET)
    - Depletion-mode
      - N-channel
      - P-channel
    - Enhancement-mode
      - N-channel
      - P-channel





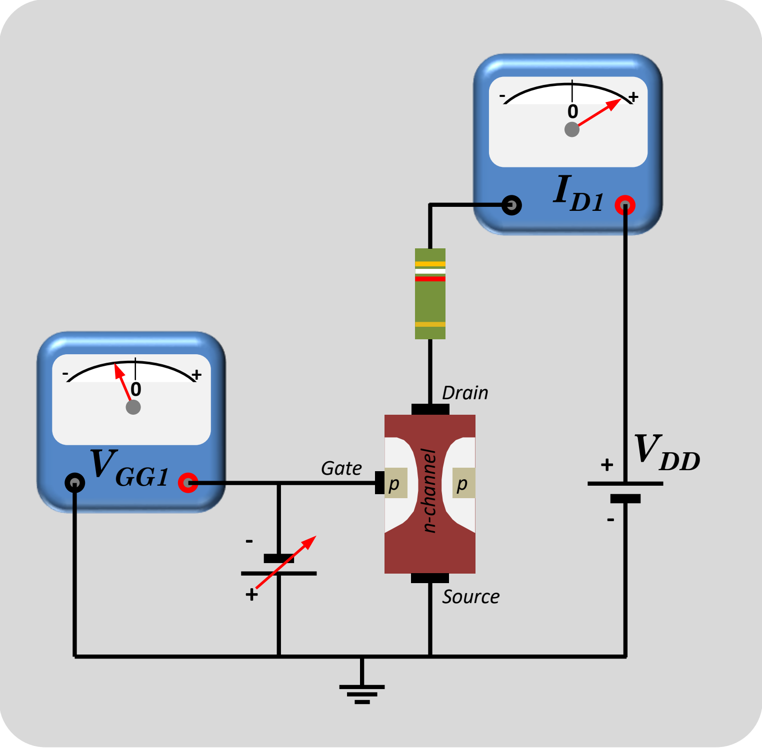
Symbols in FET-amplifiers

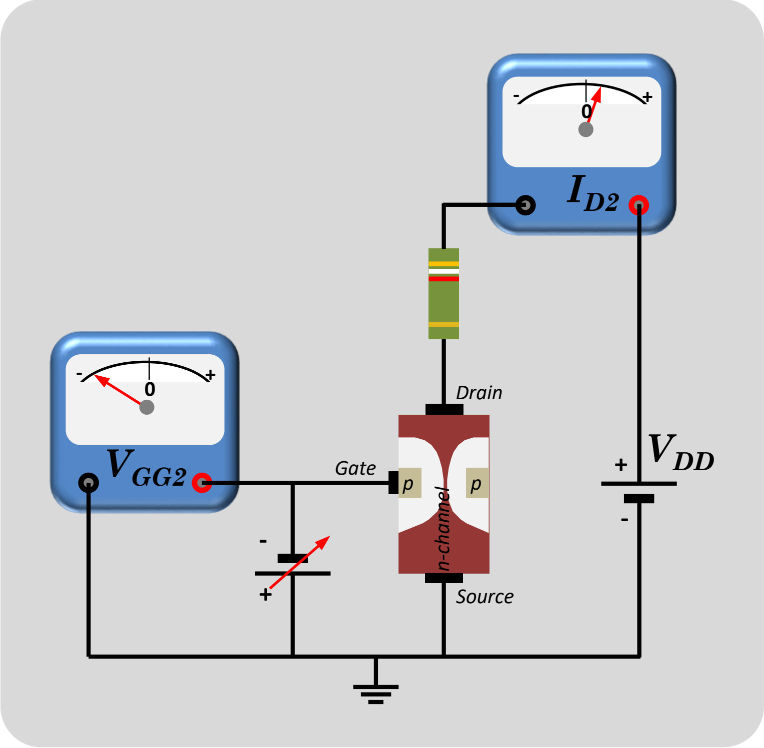
	Supply	Quisent	ac instant	ac rms	ac+dc instant	ac+dc average
Drain voltage	V_{DD}	V_{DQ}	v_d	V_d	v_D	V_D
Drain current	I_{DD}	I_{DQ}	i_d	I_d	i_D	I_D
Gate voltage	V_{GG}	V_{GQ}	v_g	V_g	v_G	V_G
Gate current	I_{GG}	I_{GQ}	i_g	I_g	i_G	I_G
Source voltage	V_{SS}	V_{SQ}	v_s	V_s	v_S	V_S
Source current	I_{SS}	I_{SQ}	i_s	I_s	i_S	I_S

A biased n-channel JFET

Large signal analysis

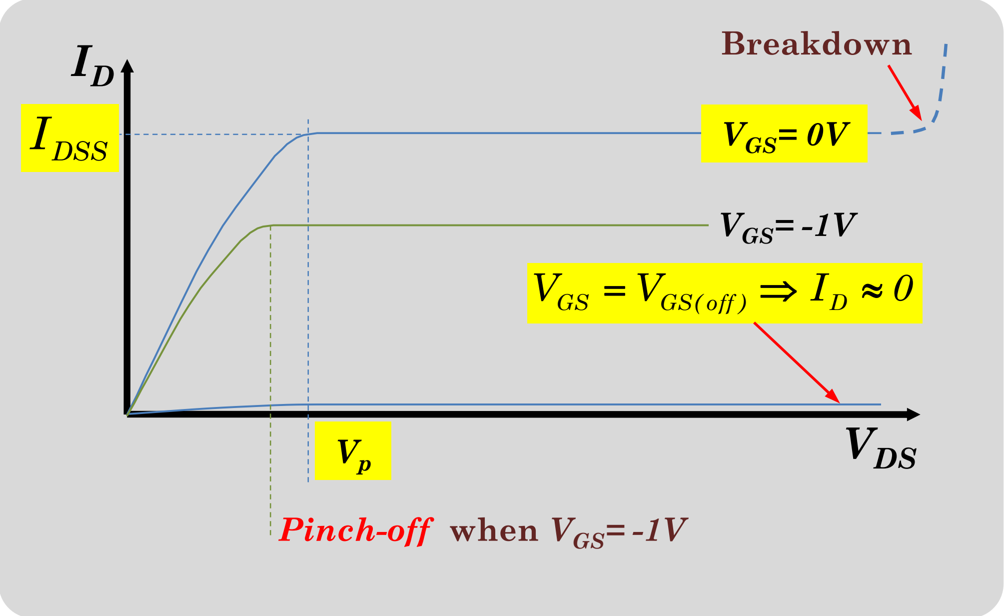
$$|V_{GG2}| > |V_{GG1}| \quad \Rightarrow \quad I_{D2} < I_{D1}$$





A biased n-channel JFET

Large signal analysis



Drain Characteristic Curve

Cutoff voltage $V_{GS(off)}$

Input range for V_{GS} when $V_{DS} > V_p$

$$V_{GS(off)} < V_{GS} < 0 \quad \Rightarrow \quad 0 < I_D < I_{DSS}$$

Pinch-off voltage V_p when V_{GS}=0

$$-\left|V_{GS(off)}\right| = \left|V_p\right|$$

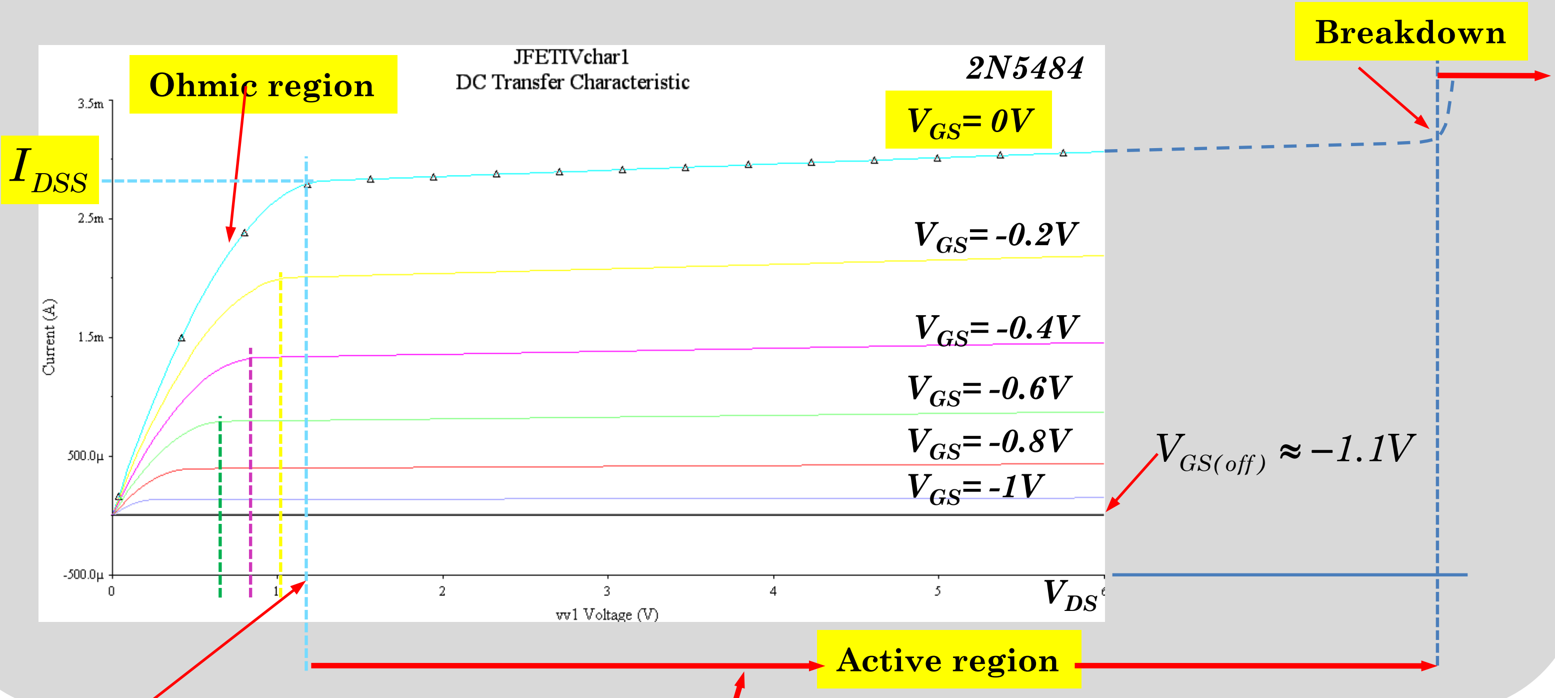
Breakdown

A biased n-channel JFET

Large signal analysis

Example of typical rf JFET *2N5484*

Family of drain characteristic curves for 2N5484



Pinch-off voltage V_p

Assumption: V_{GS}= 0V

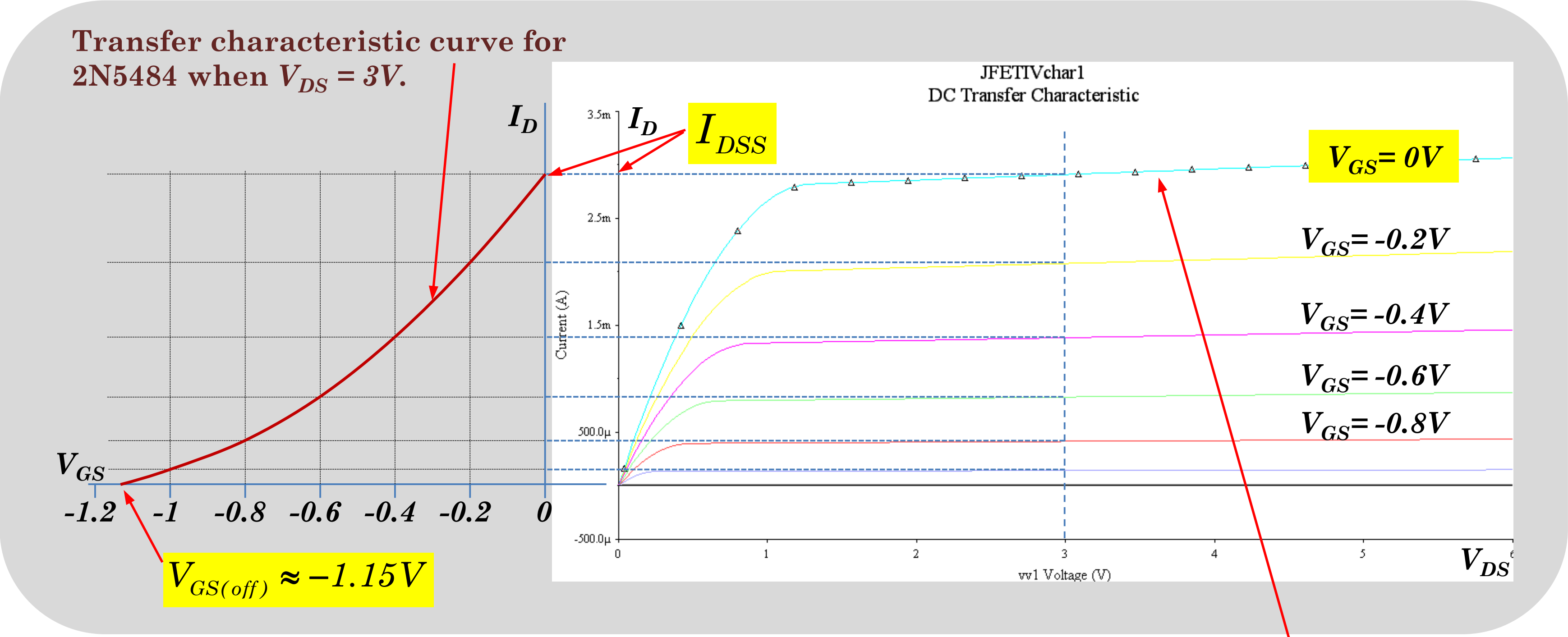
Active operation region

Data sheet of 2N5484

A biased n-channel JFET

Active region Large signal analysis

Example of typical rf JFET *2N5484*



Transfer characteristic curve for 2N5484 when $V_{DS} = 3V$.

$V_{GS(off)} \approx -1.15V$

$$I_D \cong I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$$

Approximation

The slope of drain characteristic in active region is zero.

Example : $V_{GS(off)} = -1.15V$ and $-1V < V_{GS} < 0$

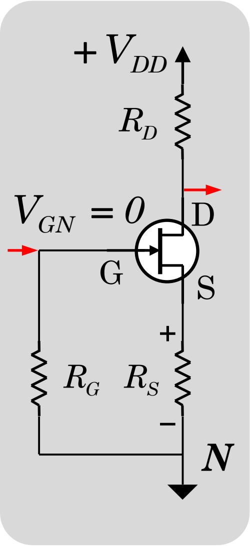
A biased n-channel JFET

Active region

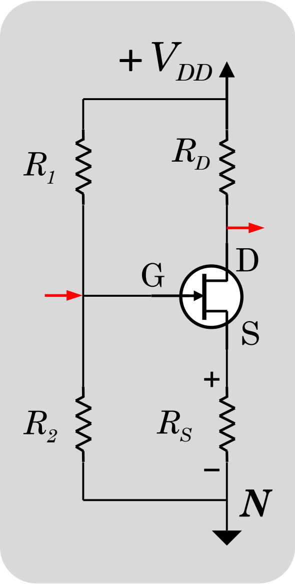
Large signal analysis

The four basic biasing schemes

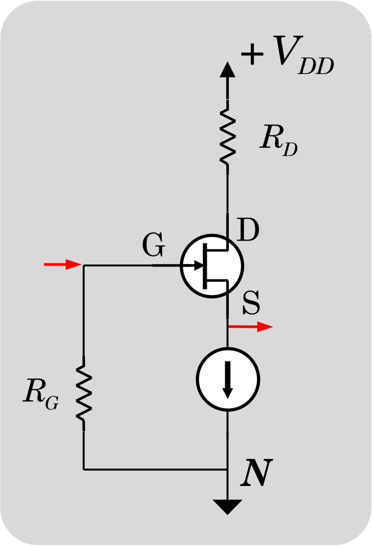
Self bias



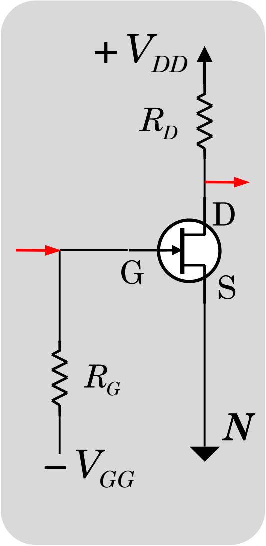
Voltage-divider bias



Constant current-source bias



Constant voltage bias



A biased n-channel JFET

SELF-BIAS

Active region

Large signal analysis

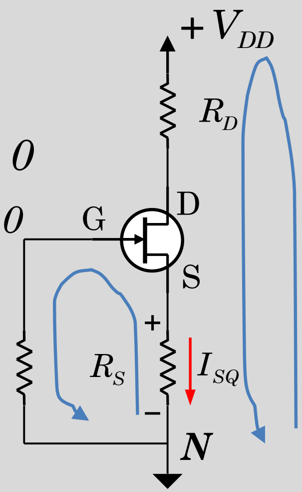
$$I_{SQ}R_S + V_{GSQ} + 0 = 0$$

$$V_{DD} - I_{DQ}R_D - V_{DSQ} - I_{SQ}R_S = 0$$

$$I_{SQ} = I_{DQ}$$

$$I_{GQ} \approx 0$$

$$V_{GN} = 0$$



$$V_{GSQ} = -I_{DQ}R_S$$

$$V_{DSQ} = V_{DD} - I_{DQ}\left(R_D + R_S\right)$$

A biased n-channel JFET

SELF-BIAS

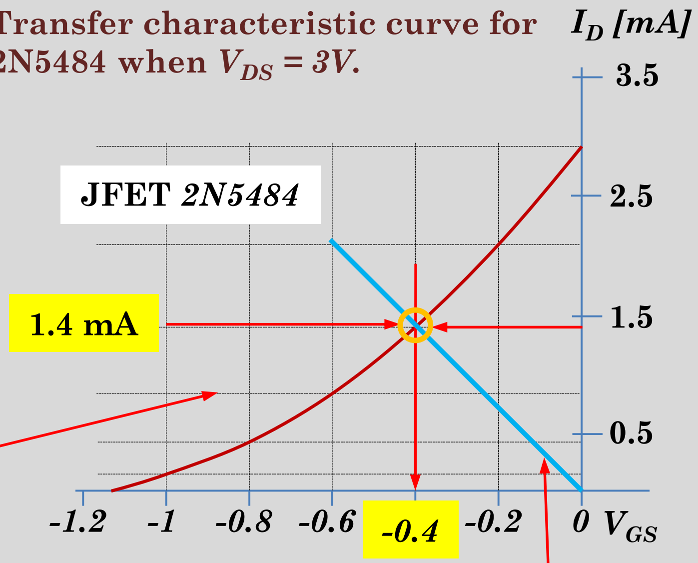
Active region

Large signal analysis

If we know parameters $V_{GS(off)}$ and I_{DSS}, we can solve V_{GSQ} by using the following equation.

$$I_{DQ} \cong I_{DSS}\left(1-\frac{V_{GSQ}}{V_{GS(off)}}\right)^{2}$$

Transfer characteristic curve for 2N5484 when $V_{DS} = 3V$.



Or graphical analysis : We can solve V_{GSQ} by using the transfer characteristic curve.

$$V_{GSQ} = -I_{DQ}R_S \Rightarrow R_S = -V_{GSQ}/I_{DQ}$$

Self-bias dc LOAD LINE

$$I_D = -\frac{1}{R_S}V_{GS}$$

$$R_D = \frac{V_{DD}-V_{DSQ}}{I_{DQ}} - R_S$$

A biased n-channel JFET

SELF-BIAS EXAMPLE

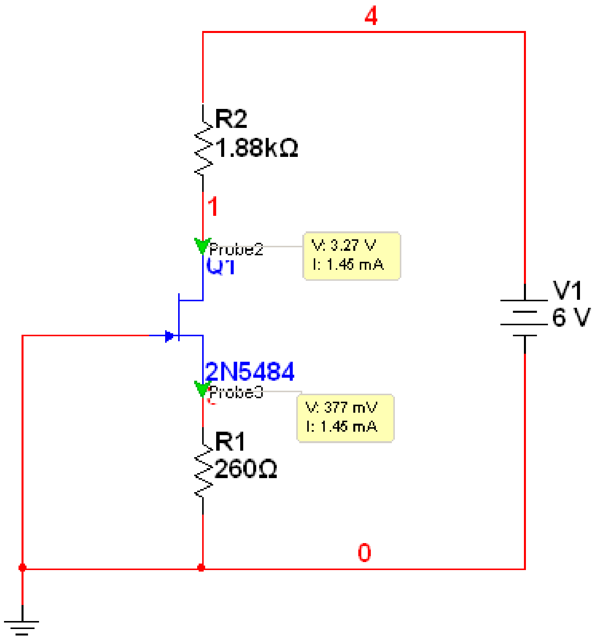
Active region

Large signal analysis

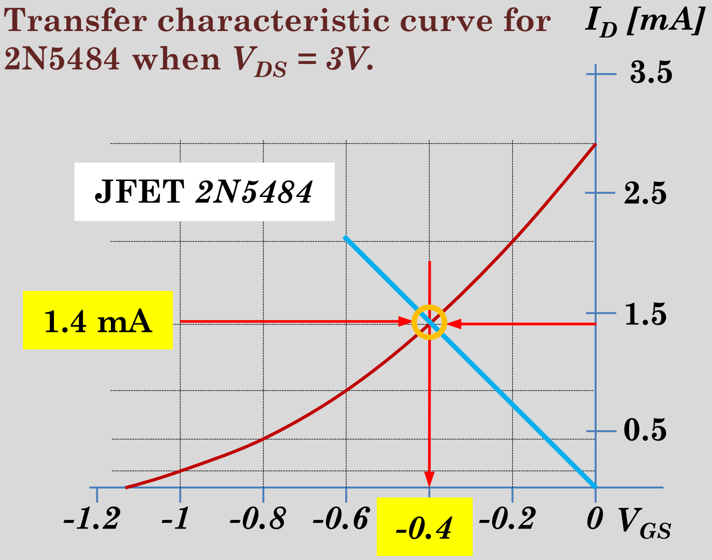
Assumptions : $V_{DSQ} = 3V$

Typically $I_{DQ} \approx \frac{1}{2} I_{DSS} \approx 1.4\ mA$

$V_{GS(off)} \approx -1.15V \quad I_{DSS} \approx 3\ mA$



Transfer characteristic curve for 2N5484 when $V_{DS} = 3V$.



$$V_{GSQ} \approx 1.15V\left(\sqrt{\frac{1.4}{3}} - 1\right) \approx -0.364V$$

$$R_S = -\frac{-0{,}364V}{1.4mA} = 260\Omega$$

$$R_D = \frac{6V - V_{DSQ}}{1.4mA} - 260\Omega = 1.9k\Omega$$

A biased n-channel JFET

VOLTAGE-DIVIDER BIAS

Active region

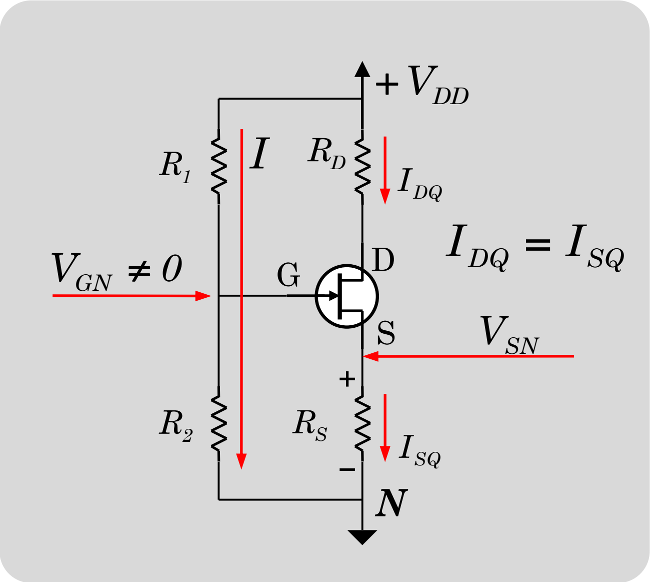
Large signal analysis

$$V_{GN} = \left(\frac{R_2}{R_1 + R_2}\right) V_{DD}$$

$$V_{SN} = V_{GN} - V_{GS}$$

$$I_D = \left(V_{GN} - V_{GS}\right) / R_S$$

$$V_{DD} - V_{DS} - I_D\left(R_D + R_S\right) = 0$$



On biaspoint Q : $$I_{DQ} \cong I_{DSS}\left(1 - \frac{V_{GSQ}}{V_{GS(off)}}\right)^2$$

$$V_{GSQ} = V_{GS(off)}\left(1 - \sqrt{\frac{I_{DQ}}{I_{DSS}}}\right)$$

$$I_D = \frac{1}{R_S} V_{GN} - \frac{1}{R_S} V_{GS}$$

Voltage-divider bias dc LOAD LINE

A biased n-channel JFET

VOLTAGE-DIVIDER BIAS EXAMPLE

Active region

Large signal analysis

Assumptions :

$V_{DSQ}= 3V$

Typically $I_{DQ} \approx \frac{1}{2} I_{DSS} \approx 1.4\ mA$

$V_{GS(off)} \approx -1.15V \quad I_{DSS} \approx 3\ mA$

$R_2 = 1\ M\Omega \quad R_S = 1\ k\Omega$

$$V_{GSQ} = V_{GS(off)}\left(1 - \sqrt{\frac{I_{DQ}}{I_{DSS}}}\right) \approx -0.364V$$

$$I_{DQ} = \left(V_{GNQ} - V_{GSQ}\right)/R_S \Rightarrow V_{GNQ} = I_{DQ}R_S + V_{GSQ} = 1.036V$$

$$V_{SNQ} = I_{DQ}R_S = 1.4V$$

$$V_{GN} = \left(\frac{R_2}{R_1 + R_2}\right)V_{DD} \Rightarrow R_1 = R_2\left(\frac{V_{DD} - V_{GNQ}}{V_{GNQ}}\right) = 1M\Omega\frac{9V - 1.036V}{1.036V} = 7.68\,M\Omega$$

$$V_{DD} - V_{DS} - I_D\left(R_D + R_S\right) = 0 \Rightarrow R_D = \frac{V_{DD} - V_{DSQ}}{I_{DQ}} - R_S = \frac{9V - 3V}{1.4mA} - 1k\Omega = 3.29k\Omega$$

A biased n-channel JFET

VOLTAGE-DIVIDER BIAS EXAMPLE

Active region

Large signal analysis

Assumptions :

$$I_{DQ} = 1.4mA$$

$$V_{DSQ} = 3V$$

$$R_2 = 1\,M\Omega \quad R_S = 1k\Omega$$

Calculated values:

$$V_{GNQ} = 1.036\,V$$

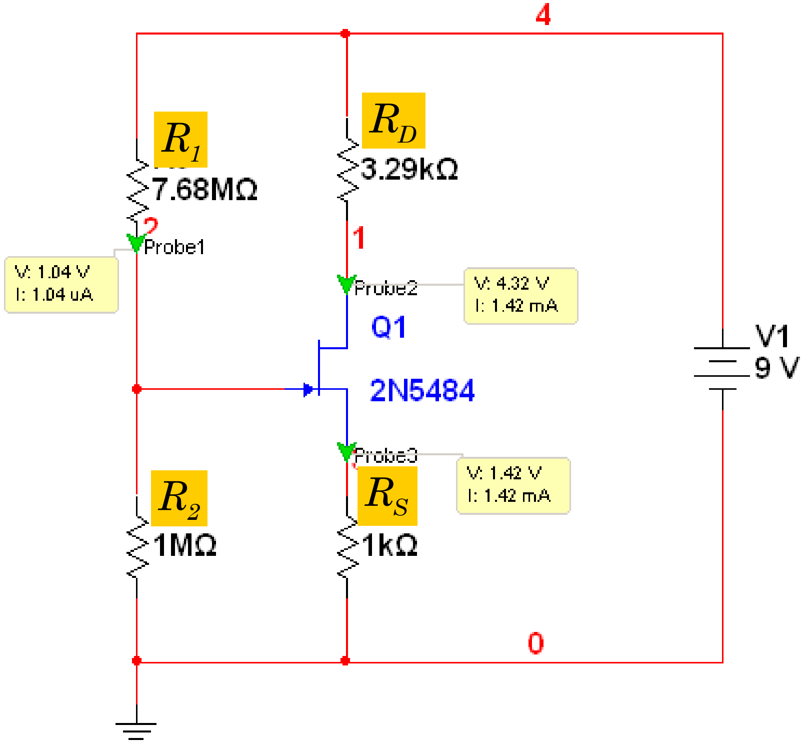
$$V_{SNQ} = 1.4V$$

$$V_{GSQ} = -0.364\,V$$

$$R_D = 3.29k\Omega$$

$$R_1 = 7.68M\Omega$$

Simulated bias point values



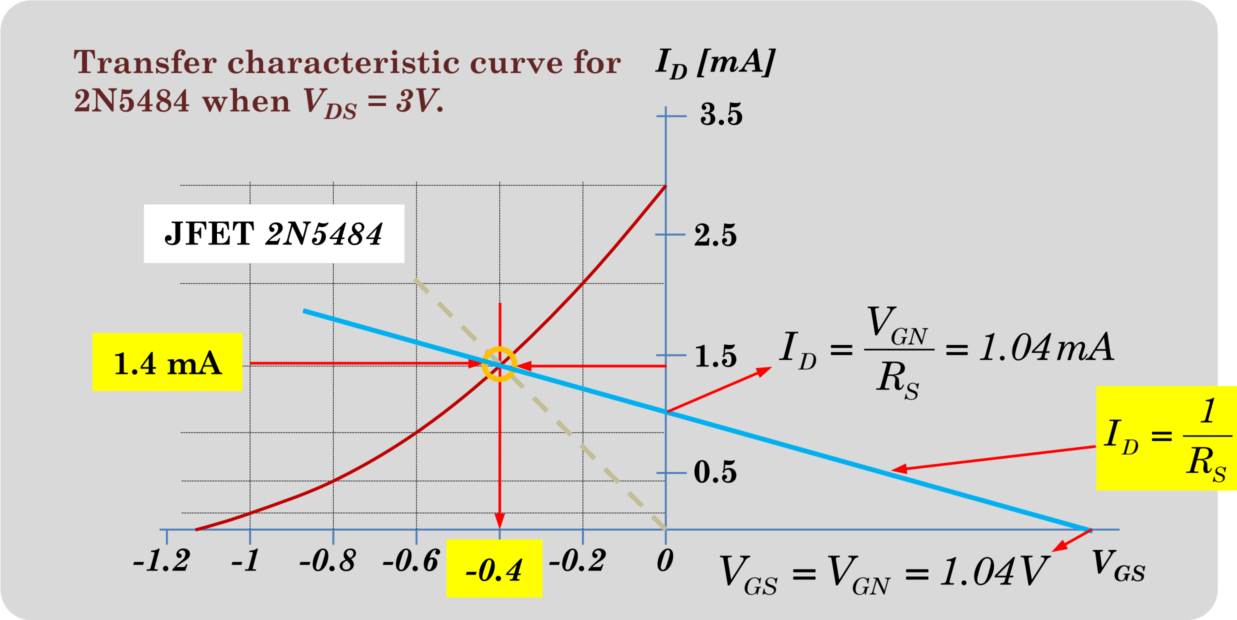
A biased n-channel JFET

VOLTAGE-DIVIDER BIAS EXAMPLE

Active region

Large signal analysis

Graphical analysis

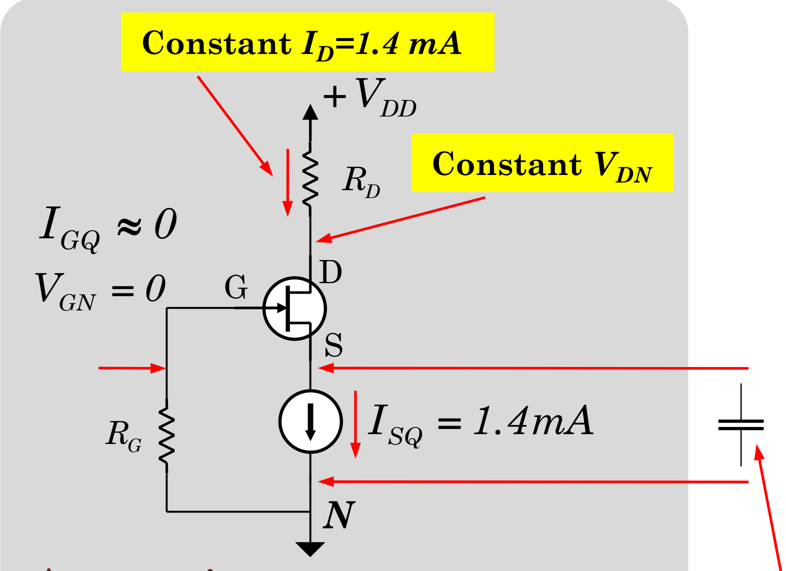


A biased n-channel JFET

CONSTANT CURRENT-SOURCE BIAS

Active region

Large signal analysis



Constant I_D=1.4 mA

Constant V_{DN}

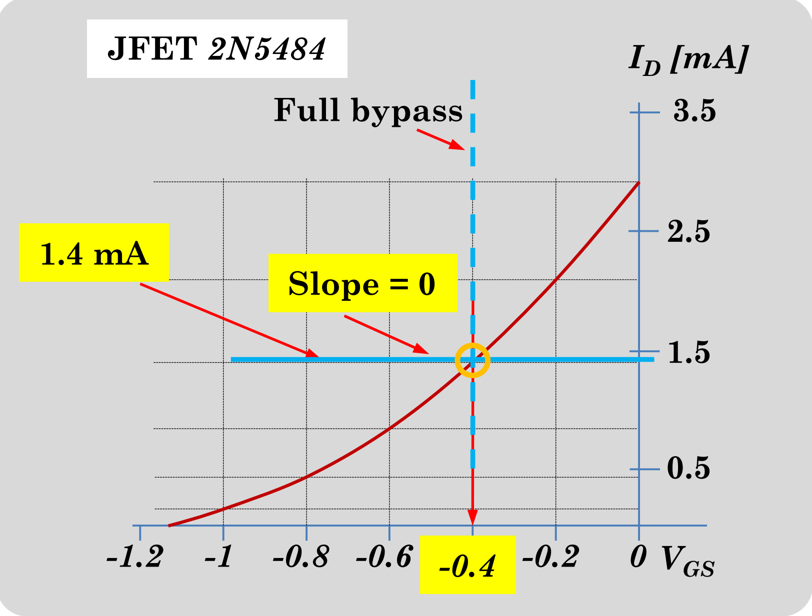
$I_{GQ} \approx 0$

$V_{GN} = 0$

$I_{SQ} = 1.4mA$

Assumption :

Ideal current-source $R_O = \infty$



JFET *2N5484*

Full bypass

1.4 mA

Slope = 0

Limited to source follower type applications

Current-source must be bypassed with capacitor to get drain ac-signal.

A biased n-channel JFET

CONSTANT CURRENT-SOURCE BIAS EXAMPLE

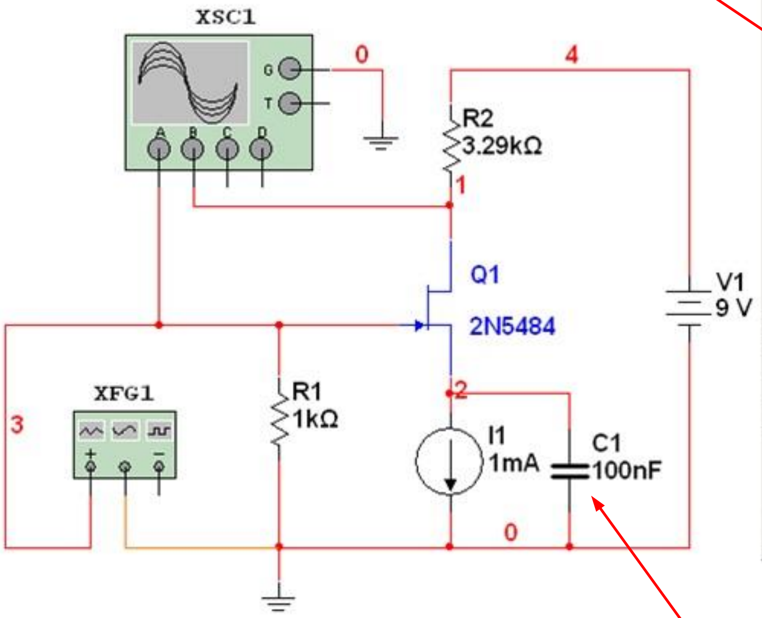
Active region

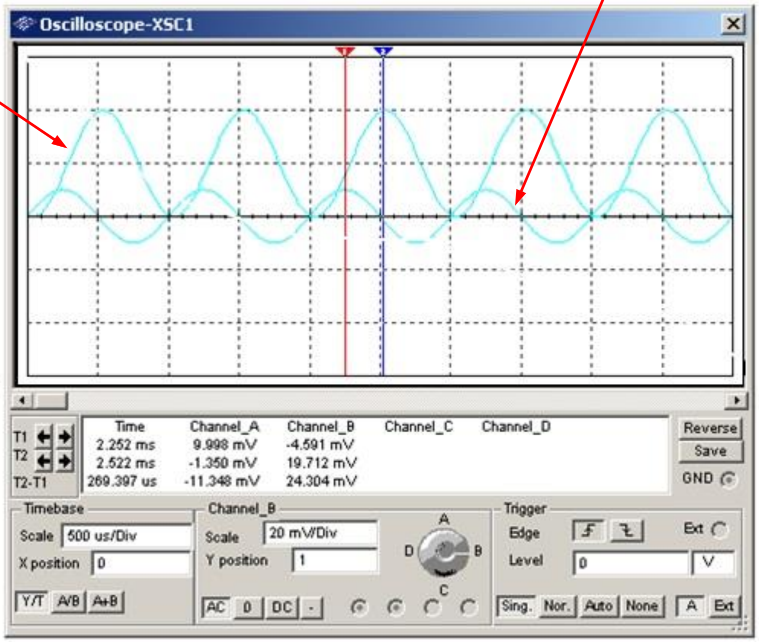
Large signal analysis

Simulation with BYPASS CAPACITOR

Output: DRAIN signal

Input: GATE ac-signal $V_{pp} = 20mV$





Time	Channel_A	Channel_B	Channel_C	Channel_D
2.252 ms	9.998 mV	-4.591 mV		
2.522 ms	-1.350 mV	19.712 mV		
269.397 us	-11.348 mV	24.304 mV		

Timebase
Scale 500 us/Div
X position 0

Channel_B
Scale 20 mV/Div
Y position 1

Trigger
Edge
Ext
Level 0 V

Bypass capacitor

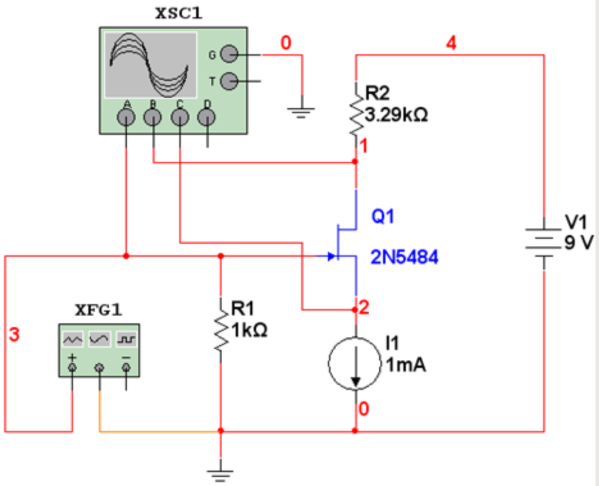
A biased n-channel JFET

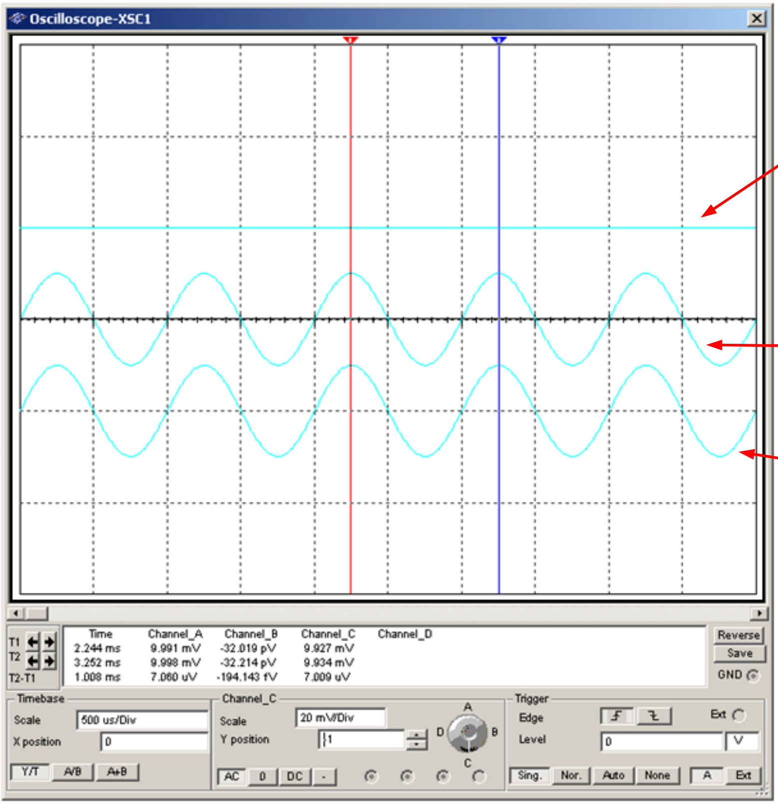
CONSTANT CURRENT-SOURCE BIAS EXAMPLE

Active region

Large signal analysis

Simulation without BYPASS CAPACITOR





```
        Time       Channel_A   Channel_B    Channel_C   Channel_D
T1      2.244 ms   9.991 mV    -32.019 pV   9.927 mV
T2      3.252 ms   9.998 mV    -32.214 pV   9.934 mV
T2-T1   1.008 ms   7.060 uV    -194.143 fV  7.009 uV
```

Timebase
Scale 500 us/Div
X position 0

Channel_C
Scale 20 mV/Div
Y position 1

Trigger
Edge
Level 0 V
Ext

Output: DRAIN
ac-signal $V_{pp}=0$

Input: GATE
ac-signal $V_{pp}= 20mV$

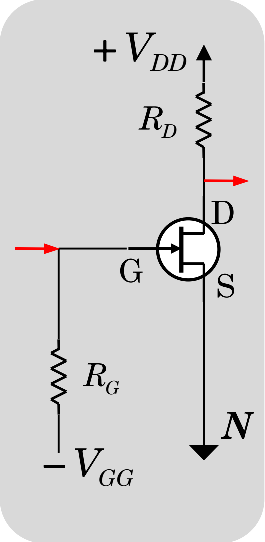
Output: SOURCE
ac-signal $V_{pp}= 20mV$

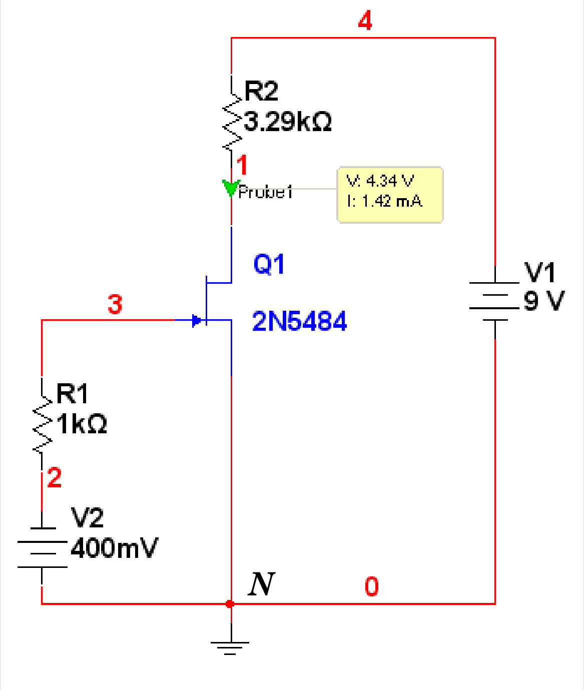
A biased n-channel JFET

CONSTANT VOLTAGE BIAS

Active region

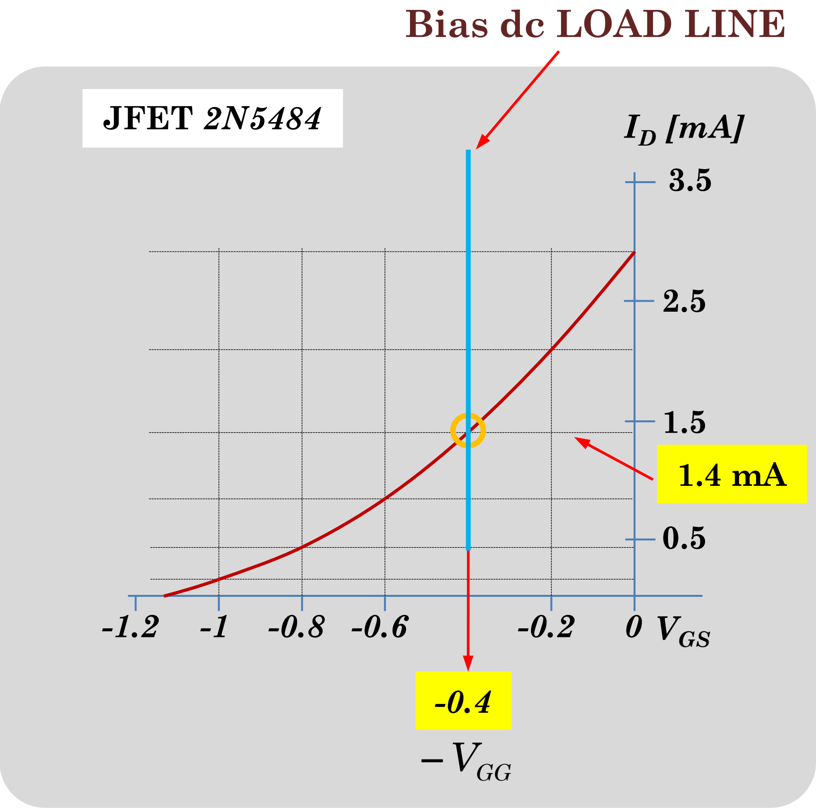
Large signal analysis





DRAIN VOLTAGE $V_{DQN} = 4.34V$

DRAIN CURRENT $I_{DQ} = 1.42mA$

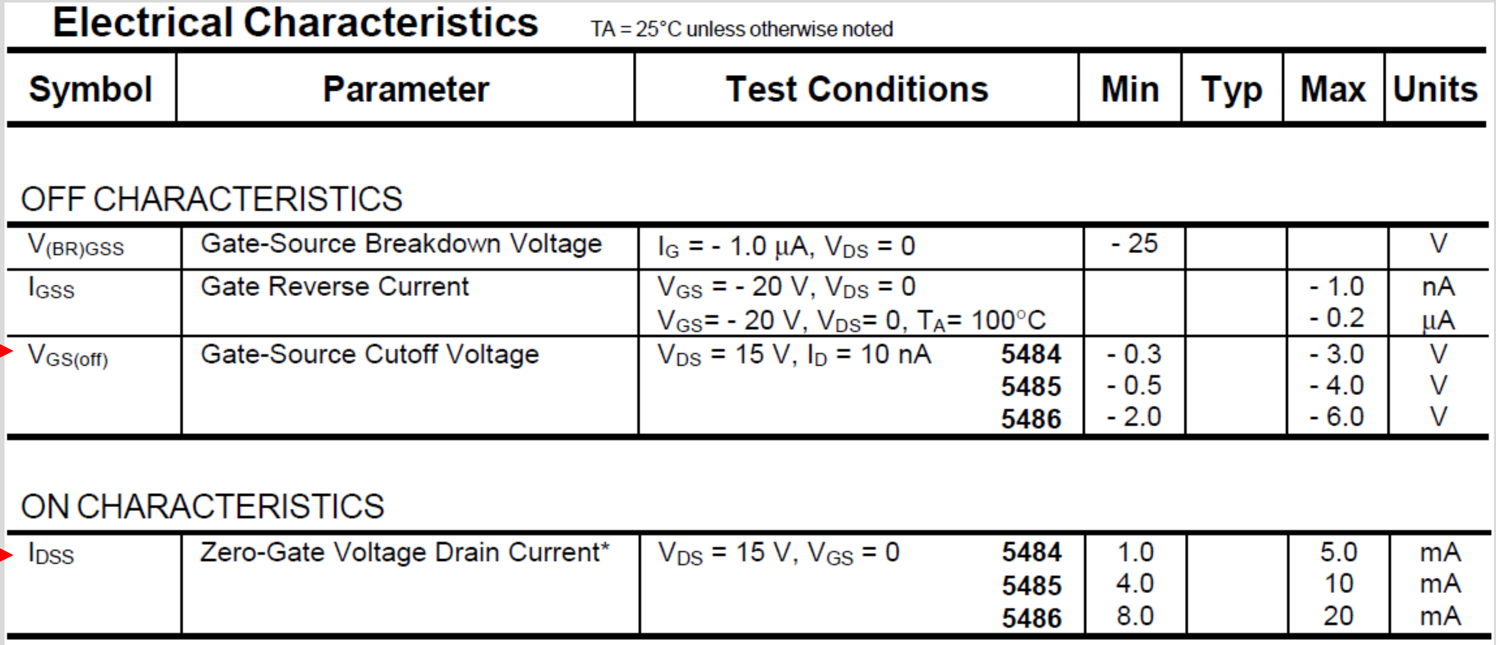


Q-Point Stability of a biased n-channel JFET

Active region

Large signal analysis

The transfer characteristic of JFET can differ considerably from one device to another of same type.



Electrical Characteristics $T_A = 25°C$ unless otherwise noted

Symbol	Parameter	Test Conditions		Min	Typ	Max	Units
OFF CHARACTERISTICS							
$V_{(BR)GSS}$	Gate-Source Breakdown Voltage	$I_G = -1.0\ \mu A$, $V_{DS} = 0$		- 25			V
I_{GSS}	Gate Reverse Current	$V_{GS} = -20\ V$, $V_{DS} = 0$ $V_{GS} = -20\ V$, $V_{DS} = 0$, $T_A = 100°C$				- 1.0 - 0.2	nA µA
$V_{GS(off)}$	Gate-Source Cutoff Voltage	$V_{DS} = 15\ V$, $I_D = 10\ nA$	**5484**	- 0.3		- 3.0	V
			5485	- 0.5		- 4.0	V
			5486	- 2.0		- 6.0	V
ON CHARACTERISTICS							
I_{DSS}	Zero-Gate Voltage Drain Current*	$V_{DS} = 15\ V$, $V_{GS} = 0$	**5484**	1.0		5.0	mA
			5485	4.0		10	mA
			5486	8.0		20	mA

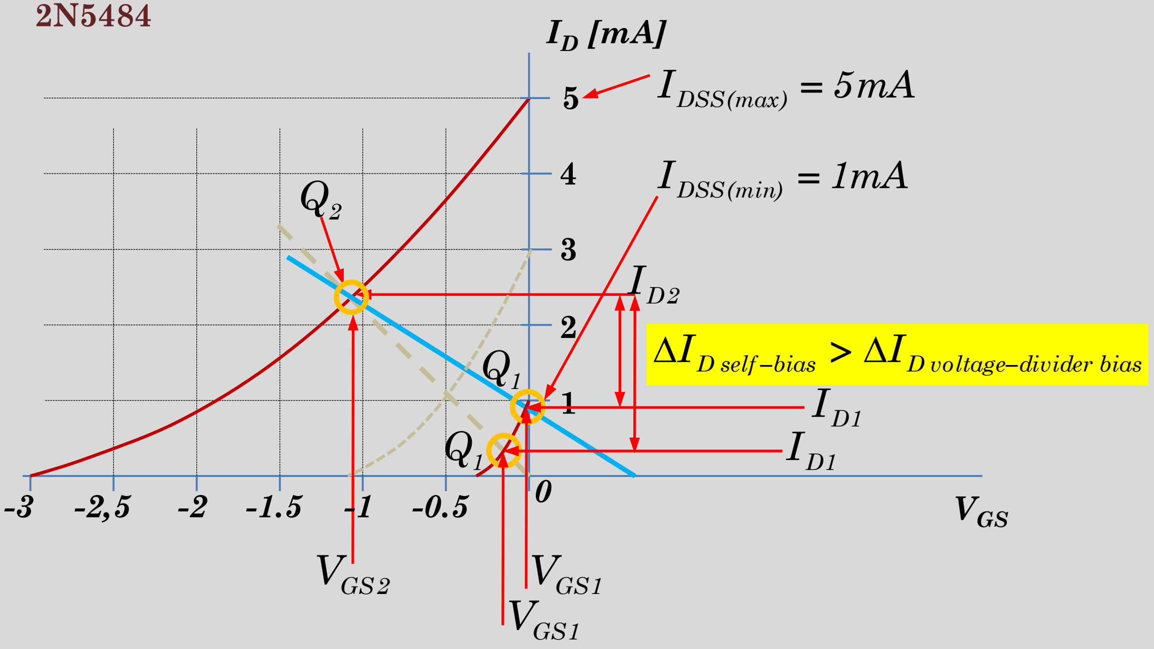
Datasheet 2N5484

Q-Point Stability of a biased n-channel JFET

Active region

Large signal analysis

Transfer characteristic curve for 2N5484



$\Delta I_{D\ self-bias} > \Delta I_{D\ voltage-divider\ bias}$

The drain current I_{DQ} is much more stable with VOLTAGE-DIVIDER bias.

Q-Point Stability of a biased n-channel JFET

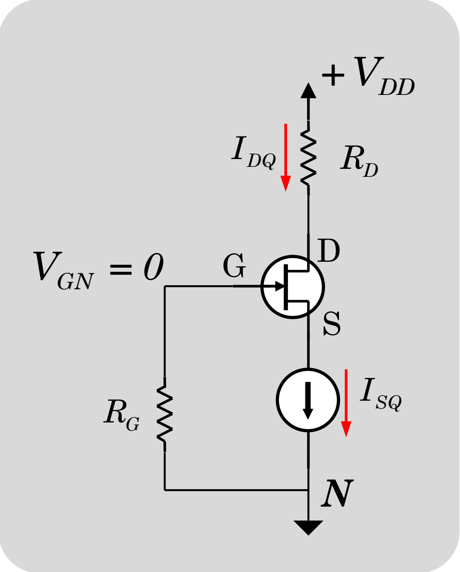
Active region Large signal analysis

SELF-BIAS WITH CURRENT-SOURCE

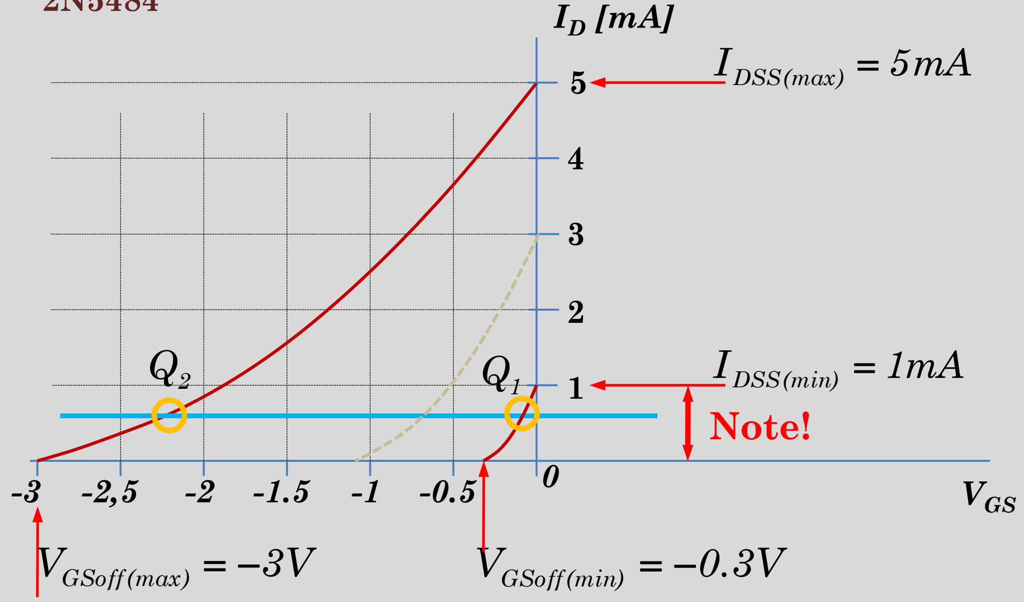
Biasing with the constant-current source.

The drain current I_{DQ} is essentially independent of V_{GS} .

Increased Q-point stability.



Transfer characteristic curve for 2N5484

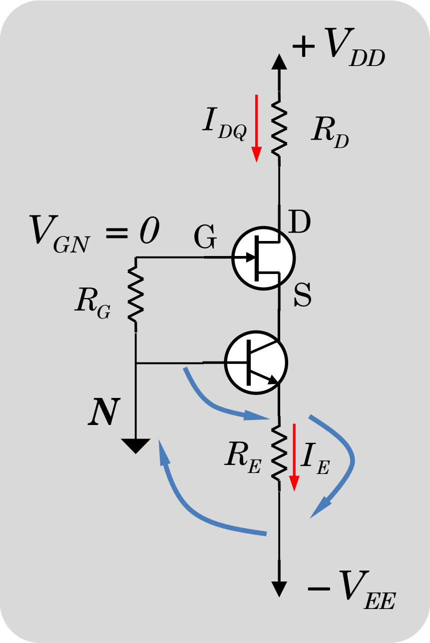


Q-Point Stability of a biased n-channel JFET

Active region

Large signal analysis

SELF-BIAS WITH CURRENT-SOURCE EXAMPLE



$$-V_{BE}-I_ER_E+V_{EE}=0$$

$$V_{EE}>>V_{BE}$$

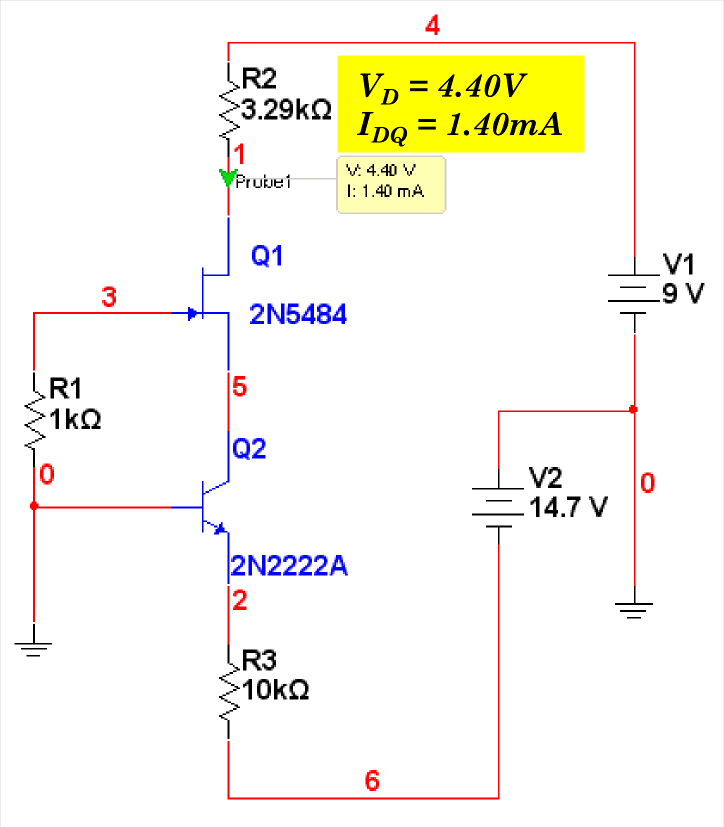
$$I_E=\frac{V_{EE}-V_{BE}}{R_E}\approx\frac{V_{EE}}{R_E}\approx I_{DQ}$$

Q-Point Stability of a biased n-channel JFET

Active region

Large signal analysis

SELF-BIAS WITH CURRENT-SOURCE EXAMPLE



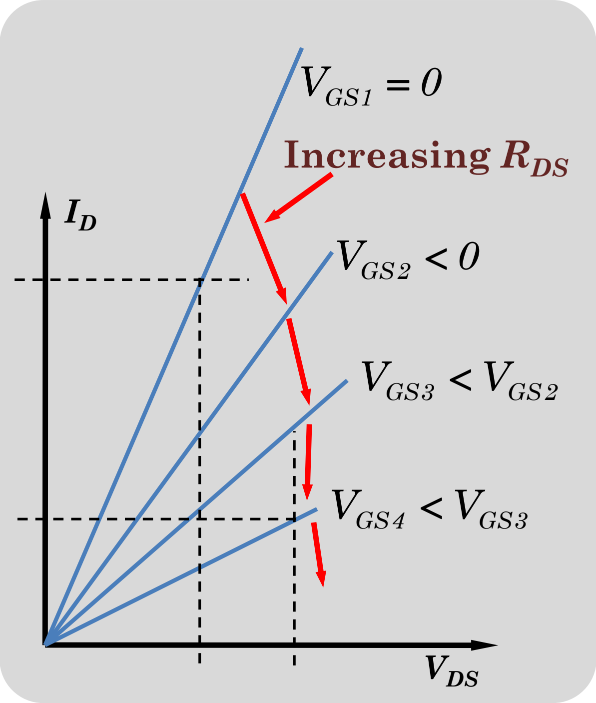
$V_D = 4.40V$
$I_{DQ} = 1.40mA$

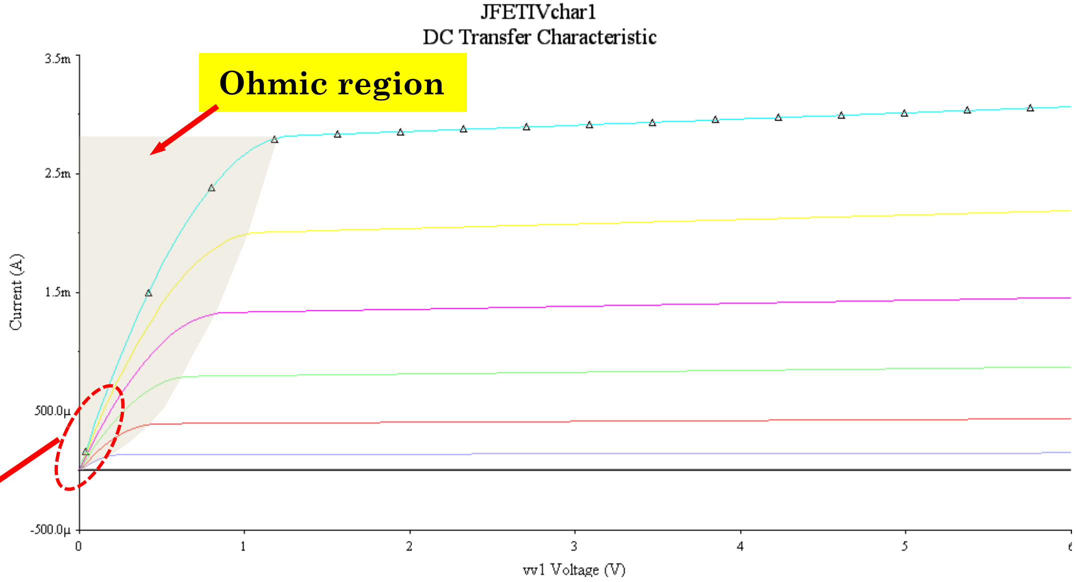
$$I_E = \frac{V_{EE} - V_{BE}}{R_E} = \frac{14.7V - 0.7V}{10k\Omega} = 1.4mA$$

A biased n-channel JFET

Ohmic region

Large signal analysis





Slope

$$G_{DS} = \frac{I_D}{V_{DS}}$$

$$R_{DS} = \frac{V_{DS}}{I_D} = \frac{1}{G_{DS}}$$

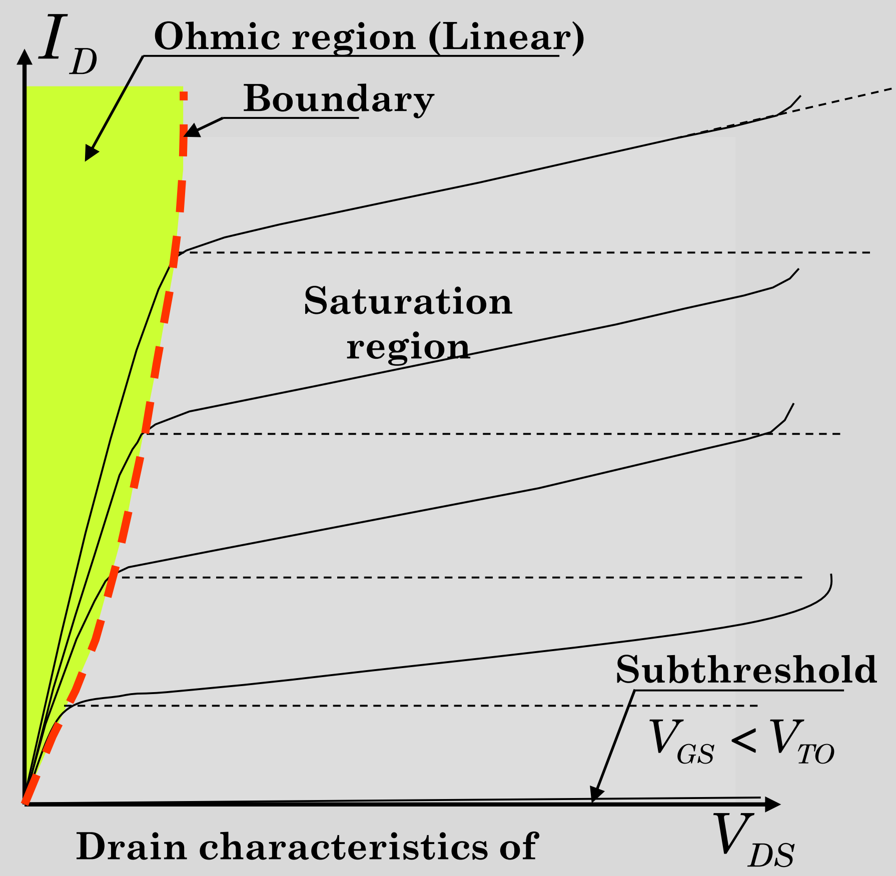
Drain-to-source resistance

Drain-to-source resistance is controlled by V_{GS} .

Enhancement-mode MOSFET

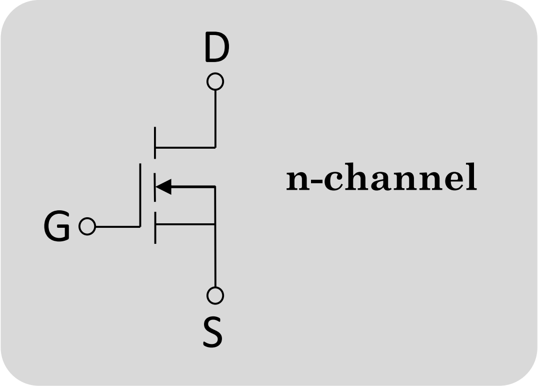
MOSFET (Metal Oxide Semiconductor Field-Effect Transistor)

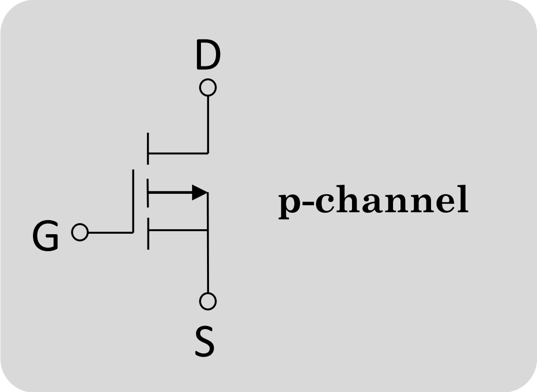
Large signal analysis
Avaustyyppinen



Drain characteristics with Channel-Length Modulation

Drain characteristics of n-channel enhancement MOSFET





Enhancement-mode MOSFET

MOSFET (Metal Oxide Semiconductor Field-Effect Transistor)

Large signal analysis
Avaustyyppinen

Ohmic Region $V_{GS} - V_{TO} > V_{DS}$

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

W/L **= aspect ratio**
W **= channel width**
L **= channel length**
V_{TO} = threshold voltage
k **= process parameter**

Boundary Region $V_{GS} - V_{TO} = V_{DS}$

$$I_D = k\left(\frac{W}{L}\right)V_{DS}^2$$

$$k = \frac{1}{2}\mu_n C_0$$

μ_n = electron mobility
C_0 = gate capacitance per unit area *fF/μm²*

Saturation Region $V_{GS} - V_{TO} < V_{DS}$

$$I_{DS} = k\left(\frac{W}{L}\right)\left(V_{GS} - V_{TO}\right)^2\left(1 + \lambda V_{DS}\right)$$

Early voltage = 1/λ

Typical values of parameter *k*

$$10 \ to \ 50 \ \mu A/V^2$$

MOSFET (Metal Oxide Semiconductor Field-Effect Transistor)

SPICE MODEL
(large signal)

Ohmic Region $V_{GS} - V_{TO} > V_{DS}$

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

Saturation Region $V_{GS} - V_{TO} < V_{DS}$

$$I_{DS} = \frac{KP}{2}\left(\frac{W}{L}\right)\left(V_{GS} - V_{TO}\right)^2$$

Saturation Region with channel-length modulation

$$I_{DS} = \frac{KP}{2}\left(\frac{W}{L}\right)\left(V_{GS} - V_{TO}\right)^2\left(1 + \lambda V_{DS}\right)$$

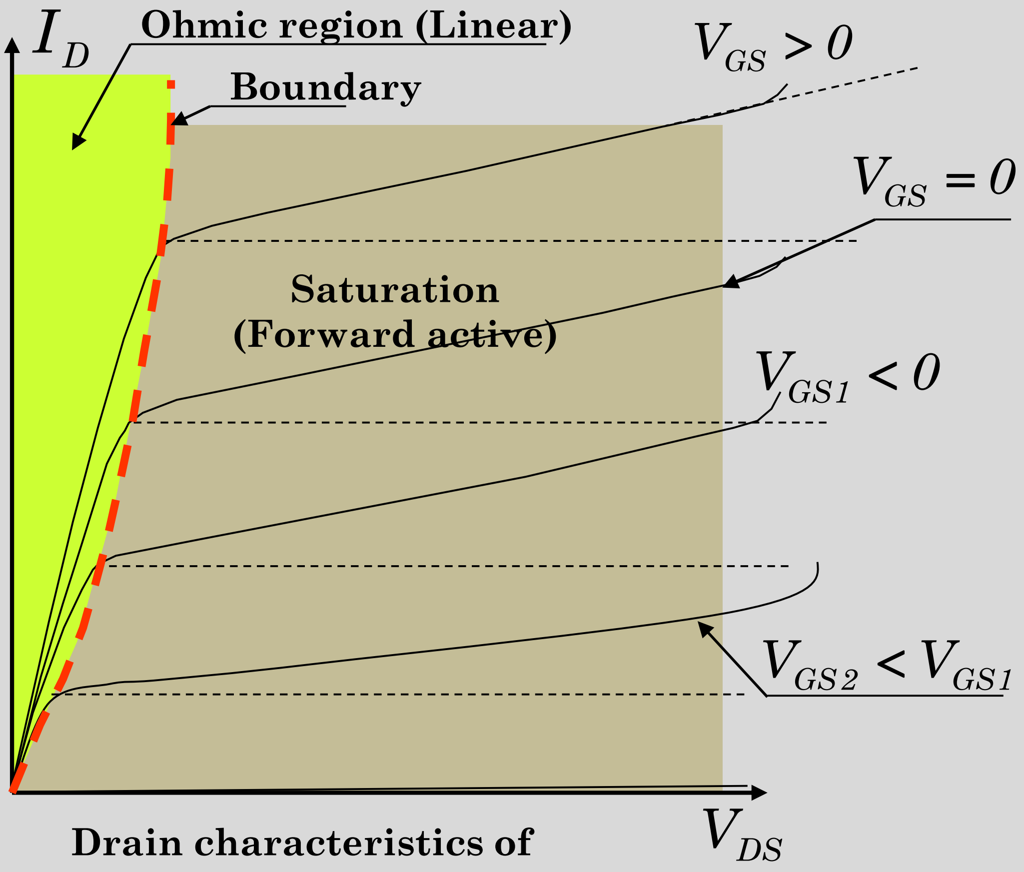
$$KP = \mu_n C_0$$

Typical values :
$V_{TO} = 0.7\text{V}$ $KP = 30\ \mu A/V^2$

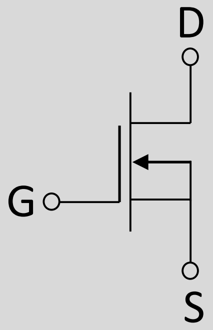
Depletion-mode MOSFET

MOSFET (Metal Oxide Semiconductor Field-Effect Transistor)

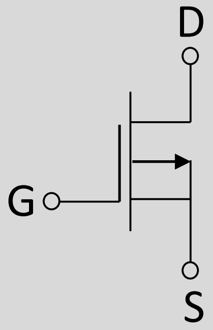
Large signal analysis
Sulkutyyppinen



Drain characteristics of
n-channel depletion MOSFET



n-channel

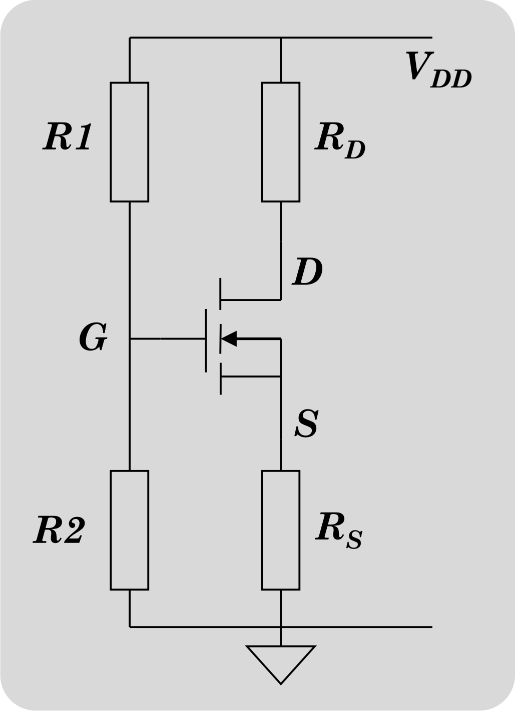


p-channel

Biasing MOSFET EXAMPLE

Large signal analysis
Avaustyyppinen

Assumption: Early Voltage is very high, λ=0

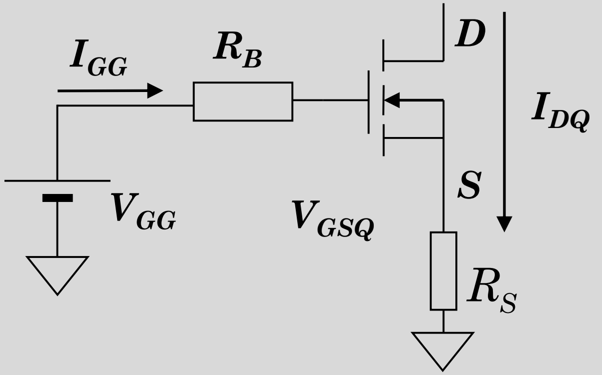


$$KP = 30\ \mu A/V^2 \quad W/L = 1 \quad I_{GG} = 0$$

Bias point in the Saturation Region $V_{GS} - V_{TO} < V_{DS}$

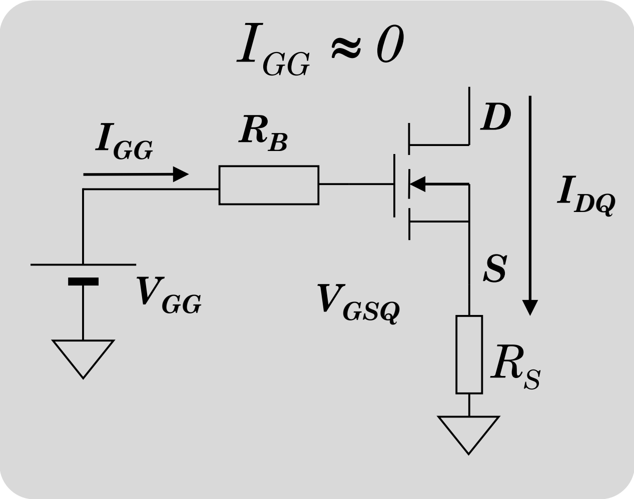
$$R_S = 820\,\Omega \quad R_1 \| R_2 = 100\,k\Omega = R_B$$

$$V_{DD} = 12V$$



Biasing MOSFET EXAMPLE

Large signal analysis
Avaustyyppinen



$$\left|\begin{array}{l} I_{DQ} = \dfrac{KP}{2}\left(\dfrac{W}{L}\right)\left(V_{GSQ} - V_{TO}\right)^2 = 420\,\mu A \\[2ex] V_{GG} - V_{GSQ} - I_{DQ}R_S = 0 \end{array}\right|$$

$$\Rightarrow \qquad I_{DQ} = K\left[\left(V_{GG} - I_{DQ}R_S\right) - V_{TO}\right]^2$$

Where $K = \dfrac{KP}{2} = 15\,\mu A/V^2$

$$KV_{GG}^2 - 2K\left(V_{TO} + I_{DQ}R_S\right)V_{GG} + K\left(V_{TO} + I_{DQ}R_S\right)^2 - I_{DQ} = 0$$

$$\Rightarrow \qquad V_{GG} = V_{TO} + I_{DQ}R_S \pm \sqrt{\frac{I_{DQ}}{K}} \approx 6.34V$$

Biasing MOSFET EXAMPLE

Large signal analysis
Avaustyyppinen

$$R_1 \| R_2 = 100\,k\Omega = R_B$$

$$V_{GG} = \frac{1}{R_1}\left(R_1 \| R_2\right) V_{DD}$$

$$R_1 = \frac{V_{DD}}{V_{GG}} R_B = 189.4 k\Omega$$

$$R_2 = \frac{R_B R_1}{R_1 - R_B} = 212\,k\Omega$$

$$V_{GG} - V_{GSQ} - I_{DQ} R_S = 0 \quad \Rightarrow \quad V_{GSQ} = V_{GG} - I_{DQ} R_S \approx 6.0V$$

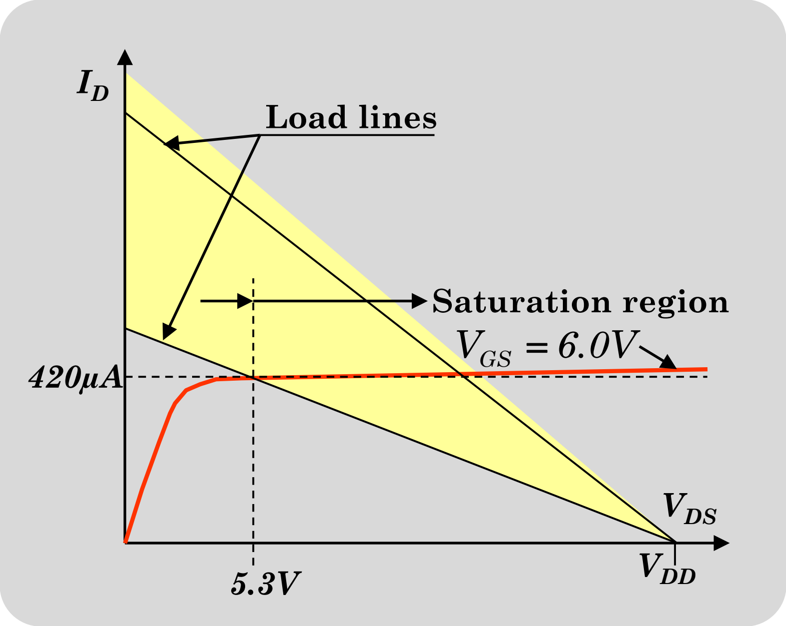
Biasing MOSFET EXAMPLE

Large signal analysis
Avaustyyppinen

Bias point in the Saturation Region $V_{GS} - V_{TO} < V_{DS}$

$$V_{GSQ} - V_{TO} = 6.0V - 0.7V = 5.3V < V_{DS}$$

MOSFET stays in the saturation region if $V_{DSQ} > 5.3V$ when $I_{DQ} = 420\mu A$



$$V_{DD} - I_{DQ}R_D - V_{DSQ} - I_{DQ}R_S = 0$$

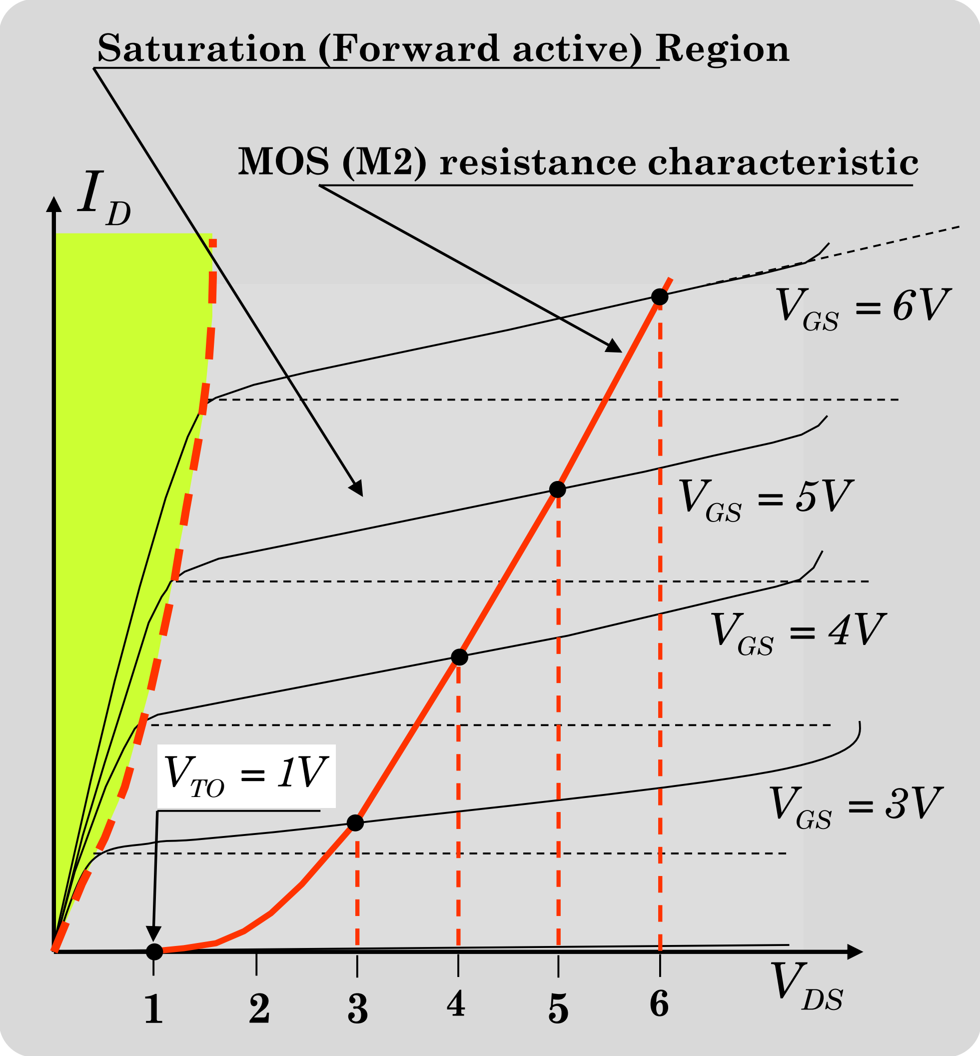
$$\Rightarrow \quad \boxed{R_D < 15k\Omega}$$

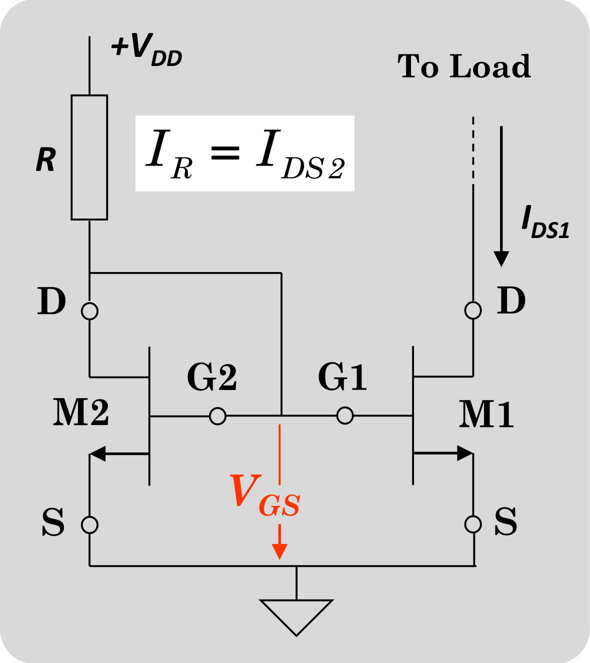
MOSFET Sub Circuit

Current Mirror

Identical MOSFETS

Large signal analysis





$$V_{DS2} = V_{GS2} \qquad V_{GS1} = V_{GS2}$$

Identical FETS $\Longrightarrow$ $I_{DS1} = I_{DS2}$

MOSFET Sub Circuit

Current Mirror

Different MOSFETS

Large signal analysis

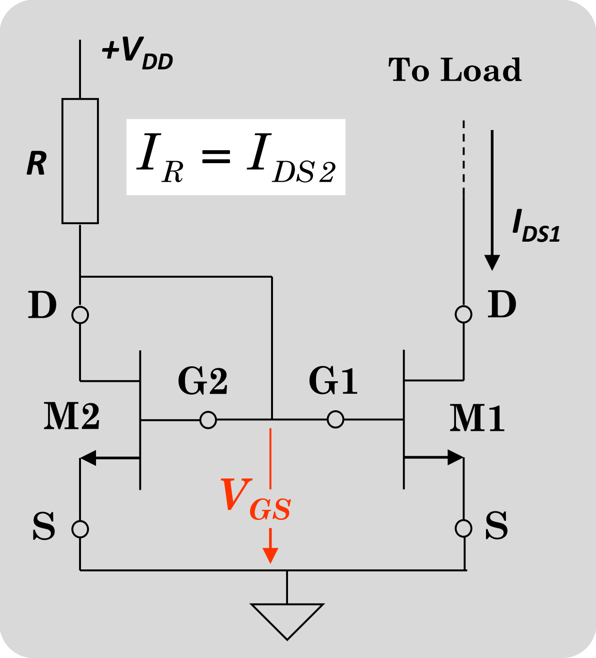
$$V_{DS2} = V_{GS2} \qquad V_{GS1} = V_{GS2}$$

$$M_2 \neq M_1$$

$$\frac{W_2}{L_2} \neq \frac{W_1}{L_1}$$

Different MOSFETs

$$\Rightarrow \quad \frac{I_{DS2}}{I_{DS1}} = \frac{(W/L)_2}{(W/L)_1}$$



$$I_R = I_{DS2}$$

Assumption : λ = 0

$$V_{GS} = V_{TO} - \frac{1}{2RK} \pm \sqrt{\left(\frac{1}{2RK} - V_{TO}\right)^2 - \left(V_{TO}^2 - \frac{V_{DD}}{RK}\right)}$$

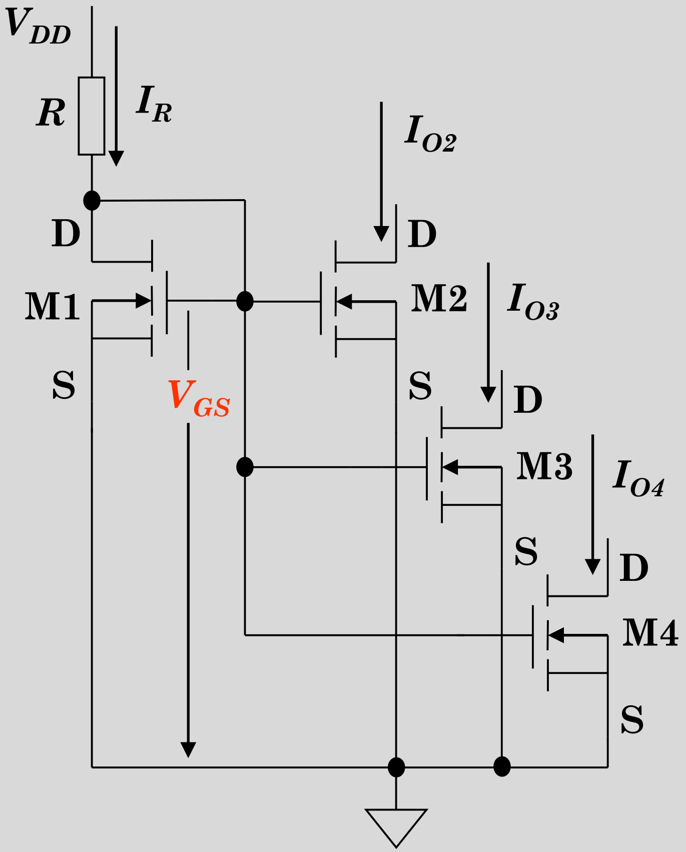
$$I_{DS2} = K\left(V_{GS} - V_{TO}\right)^2$$ **where** $$K = \left(\frac{W_2}{L_2}\right)\frac{KP}{2}$$ **(MOSFET M2)**

MOSFET Sub Circuit

Current Mirror

Different MOSFETS

Large signal analysis



$$V_{GS} = V_{TO} - \frac{1}{2RK} \pm \sqrt{\left(\frac{1}{2RK} - V_{TO}\right)^2 - \left(V_{TO}^2 - \frac{V_{DD}}{RK}\right)}$$

(MOSFET M1)

$$I_{DS1} = K(V_{GS} - V_{TO})^2 \qquad K = \left(\frac{W_1}{L_1}\right)\frac{KP}{2}$$

$$\frac{I_{O2}}{I_{DS1}} = \frac{W_2/L_2}{W_1/L_1}$$

$$\frac{I_{O3}}{I_{DS1}} = \frac{W_3/L_3}{W_1/L_1}$$

$$\frac{I_{O4}}{I_{DS1}} = \frac{W_4/L_4}{W_1/L_1}$$

MOSFET Sub Circuit

The End of Part 4