SCHOOL OF ELECTRICAL ENGINEERING, UNIVERSITY OF THE WITSWATERSRAND

ELEN3002 - Electronics 2

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Lab 2 MOSFET Operations

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1 MOSFET AS A SWITCH

HYPOTHESIS

A MOSFET can be used as a switch in a circuit

ARGUMENT

Object	**Statement**	**Assumption**
A MOSFET	... is a non-linear, active semi-conductor device with 4 terminals.	A1
Applying voltage across a MOSFET's gate/source terminals	... affects the output current flowing from the source terminal to the drain terminal.	A2
The current flowing through a branch of a circuit	... can be found from measurements of voltage across a known resistor the current flows through.	A3
Measurements of input voltage to output voltage in an electric circuit	...can be determined with circuit simulation software	A4
A circuit simulation of a DC sweep across a MOSFET's gate/source terminals	... can plot the transfer function of a MOSFET.	A5
The plot of a MOSFET's transfer function	... can be characterised by three modes of operation: cut-off, triode and saturation.	A6
Sub-argument 1		
In cut-off mode	... no current flows through the output terminals.	A7
In saturation mode	... a constant current flows through the output terminals.	A8
Sub-argument 2		
A switch	... is a device that interrupts the flow of current in a circuit.	Basic knowledge
Conclusion		
By altering voltage across the G/S terminals of a MOSFET, quickly changing between the cut-off and saturation modes of a MOSFET	... it can be used as a switch in a circuit.	A9

2 MOSFET AS AN AMPLIFIER

HYPOTHESIS

A MOSFET can be used as an amplifier in a circuit

ARGUMENT

Object	**Statement**	**Assumption**
A MOSFET	... is a non-linear, active semi-conductor device with 4 terminals.	A1
Applying voltage across a MOSFET's gate/source terminals	... affects the output current flowing from the source terminal to the drain terminal.	A2
The relationship of this behaviour (applied voltage across gate/source to current flowing from source to drain)	... can be modelled as an output/input transfer function.	A3
The transfer function of a MOSFET...	... can be characterised by three modes of operation: cut-off, triode and saturation.	A6
In triode mode	... current flows through the output terminals in an approximately linear proportion to the applied voltage across the gate/source terminals	B1
Sub-argument 1		
The proportion to the applied voltage to output current (the transfer function)	... can be represented as an IV curve	B2
An approximately ohmic IV voltage curve	... can be linearised for small signals at a fixed DC point.	B3
Sub-argument 2		
At a fixed voltage point in the triode region of operation	the slope (of the linearised approximation) of the transfer function is large	B4
A large slope of a transfer function	means a gain >1 for output	B5
A gain >1 from output to input	is amplification.	Basic knowledge
Conclusion		
At a fixed DC point in the triode region of operation of a MOSFET, a change in small signal of the voltage of a linearised small signal	will result in small-signal amplification of the output current	B6

APPENDIX

ASSUMPTION A1

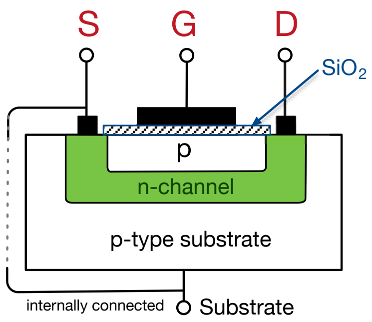

Fig. A1: Cross section of a p-channel enhancement type MOSFET

A MOSFET is a Metal Oxide-Silicon Field Effect Transistor, a widely used electronic device that is constructed as either a p-type (enhancement) and n-type (depletion). There are four terminals, the gate (G), the source (S), the drain (D) and the main body (the substrate). The body of a p-type MOSFET is usually connected internally to the source terminal. A diagram of an enhancing MOFSET used in this experiment is shown in cross section in Figure A1 is made of semiconductor material, with a very thin layer of metal oxide that the metal-oxide gate terminal sits upon, electrically insulated from the p-doped body by an extremely thin layer of glass[1].

ASSUMPTION A2

The separation of the gate from the body and other terminals results in a capacitive effect, and produces a very high input impedance that can be considered as an infinite resistance. Because there is no physical connection between the gate terminal, no current flows into or out of the gate. Instead, the device relies (like most FET) on voltage being applied across the gate and source terminal (V_{GS}), developing an electric field to produce a "n-channel" (a depletion region) between the source and drain, inducing electrons (negative charge carriers) to flow, and allowing a current to move through the device[2]. This current flow starts to occur at a threshold voltage V_{TH} is reached, at the point when the accumulation of positive charge on the gate's metal oxide causes the opposite internal increase of negative charge to produce a sufficient conductive channel between the source and drain terminals. Because of the insulating glass layer separating the gate, $I_S = I_D$. As a semiconducting transistor, the relationship of applied voltage at V_{GS} to current flowing out of I_S is not linear[3]. This non-linear relationship of output current to voltage across the gate/source terminals is modelled by equation 1:

$$I_D = k(V_{GS} - V_T)^2 \tag{1}$$

In the orientation used in this experiment, conventional current is induced to flow out of the contact bench voltage source, across a resistor, through the "drain" terminal and out of the "source" terminal down to ground. V_T is thermal voltage of the transistor, and k is constant associated with the physical characteristics of a particular device.

ASSUMPTION A3

A resistor is an ohmic device, with a linear relationship between voltage and current. Ohm's law, $V = IR$ applies, so with a known or measured resistance value, and by measuring or simulating the voltage across a resistor with current flowing through it, the current can be calculated as $I = {}^{V_R}/_{R}$.

ASSUMPTION A4

MultiSim is a specialised software package for the design and simulation of electric circuits. It has a wide and detailed database of existing electronic devices, and is able to simulate the interaction and connection of a powered circuit through mathematical modelling using parameters that accurately describe the real-world behaviour of these devices. [4]. The circuit shown in Figure A2 was physically constructed and measured under a sweep of DC operating points, and compared to simulated values. The values roughly concurred, but the simulated data is presented as it present a cleaner and more precise representation of the principles of operation in the experiment, without the complications of inaccurate measurement and sensor devices in recording the physical device's performance in an actual circuit.

ASSUMPTION A5

Using the circuit shown in Figure A2 a DC sweep simulation and analysis was performed, measuring DC voltage and the calculated voltage across the output resistor, giving the plot of V_R as V_{DC} rises from $0\,\mathrm{V}$ to $4\,\mathrm{V}$. The MOSFET lets little to no current through I_D until the threshold voltage is reached, at $1.8\,\mathrm{V}$. At this point, the voltage rapidly rises across the $1\,\mathrm{k\Omega}$ resistor, as current begins to quickly flow through the MOSFET's source and drain terminals, induced from the reference voltage V_{DD}, which is a standard bench power source of $5\,\mathrm{V}$. The curve of voltage across the resistor rises in am approximately ohmic region until the "pinch-off" region is reached at around $2.12\,\mathrm{V}$, when the voltage flattens off, due to the increase in free electrons gathered at the underside of the glass layer (in the n-channel) which narrows as the increase in free electrons now begins begin to counteract the flow of current. From above the DC voltage of $2.14\,\mathrm{V}$ the device is now in saturation, with a fairly flat, almost constant current, and V_R remains at $5\,\mathrm{V}$, despite the rise in the DC voltage across the gate/source terminals.

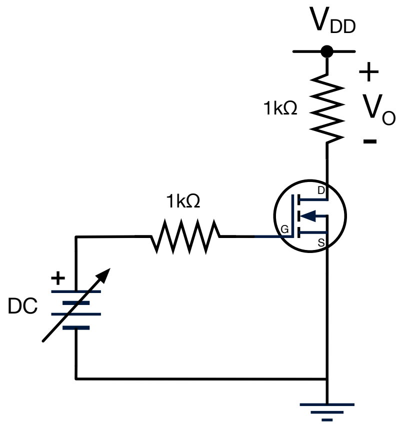

Fig. A2: Circuit used for the experiment and simulation

TABLE 1: Circuit Measurements

V_{DC} [V]	V_R [V]
0.00E+00	5.04E+00
0.00E+00	4.96E+00
9.60E-01	4.96E+00
1.44E+00	4.96E+00
1.76E+00	4.96E+00
2.08E+00	4.96E+00
2.40E+00	3.28E+00
2.48E+00	8.80E-01
2.56E+00	2.40E-01
2.88E+00	-7.99E-02
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4.00E+00	-7.99E-02
1.00E+01	-7.99E-02

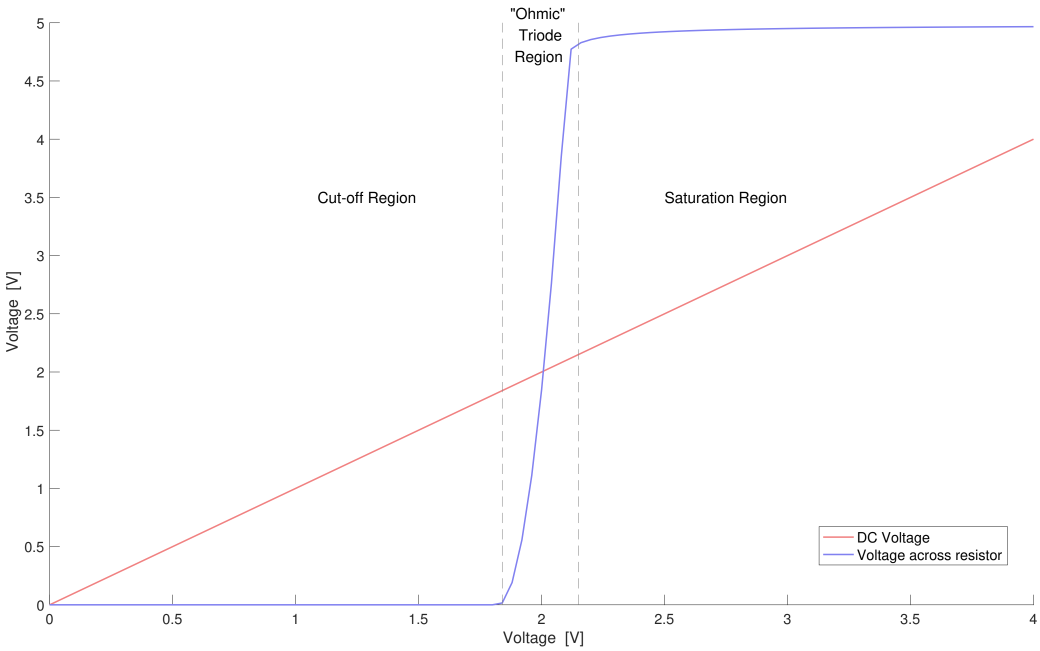

Fig. A3: Plot of input voltage across V_{GS} and the output voltage across a resistor

Assumption A6

The measurements show in Figure A3 has three clear regions, referred to as the "cut-off", triode and saturation modes of a MOSFET. The cut-off region is when no current is flowing, $ID = 0$ while $V_{GS} < V_{TH} = 1.8\,\text{V}$ After this threshold is reached, the triode region, which is roughly linear (ohmic) is characterized by a steep near-linear rise in current flow (and hence voltage across the resistor). The rise in voltage across the resistor is more than commensurate, with V_R rising from $0\,\text{V}$ to $5\,\text{V}$ during the change of V_{GS} from $1.8\,\text{V}$ to $2.12\,\text{V}$. The saturation region, as the "pinch-off" occurs, is marked by a flattening of the voltage curve, becoming a near constant voltage from the near constant electron flow out of I_D (or conventional current out of I_S and through the resistor.

Assumption A7

$$\text{When } V_{GS} < V_{TH}\ ,\ I_D = 0 \text{ the device is in "cut-off" mode, no current flows} \tag{2}$$

Assumption A8

$$\text{When } V_{GS} - V_T > 0\ , \text{ the device is in saturation mode, (pinched off) at maximum current flow} \tag{3}$$

Assumption A9

By rapidly changing the voltage across V_{GS}, from below V_{TH} to above the "pinch" off point, a change of around $0.3\,\text{V}$, a large and rapid change in current can be achieved in a circuit. This property can be exploited to use a MOSFET as an effective and fast switch. Because no current flows through the gate terminal, the device is capable of very rapid switching, rapidly altering the electric field that caused the accumulation and saturation of negative charge below the glass layer in the n-channel.

Assumption B1

As the MOSFET enters the triode mode, there is a non-linear, rapid increase in current through the drain and source terminals. The current then rises with a fairly linear increase until the "pinch-off", when there is another rapid non-linear curve into the the flat saturation mode. The device resembles a resistor during this triode mode[2]. This can be seen in the previous Figure A3, inside the central area marked "Triode Region".

Assumption B2

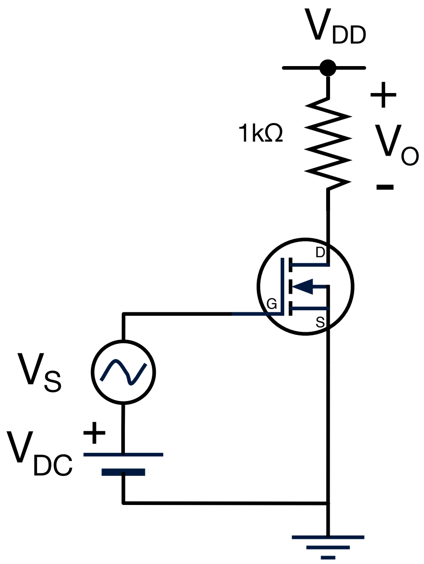

Fig. B1: Circuit used for the experiment and simulation of a MOSFET as an amplifier

The circuit shown in Figure B1 was built and measured, and also simulated in MultiSim, using the model of the BS170 MOSFET used in the physical circuit. A $1\,\mathrm{kV}$ resistor was used to measure voltage across as V_O. A signal generator, producing a voltage of $100\,\mathrm{\mu V}_{p-p}$ sine wave at $1\,\mathrm{kHz}$ was connected in series with a $2\,\mathrm{V}$ DC source, to put the MOSFET in the centre of the triode region, as the midpoint of the ohmic voltage rise.

Assumption B3

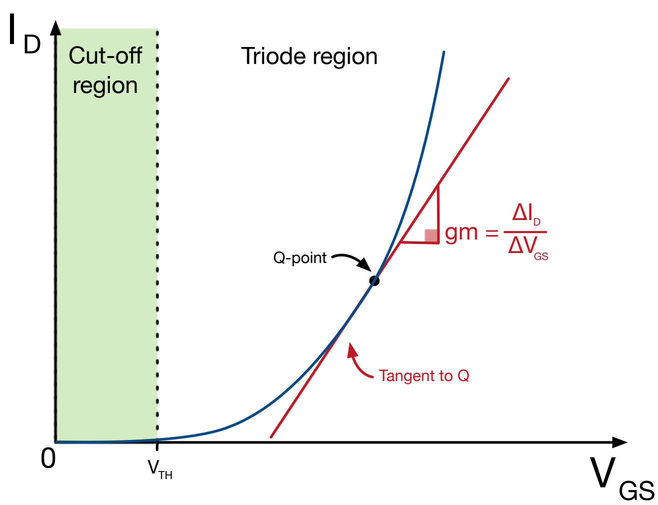

Fig. B2: Linearisation of a small signal using a MOSFET, and small signal equivalent circuit

In the linear section of the IV curve of a MOSFET in the triode region, a small AC signal can "ride" on a fixed DC operating point, as long as the small signal does not increase or decrease the voltage out of the triode region. Choosing the midpoint of the triode region, at $V_{GS} = 2\,\mathrm{V}$, with the small AC signal specified above.

The slope of the curve in the Triode region can be found by taking the derivative of I_D with respect V_D in the Shockley equation that describes IV relationship of diodes in forward or backward bias:

$$I_D = I_S(e^{\frac{V_D}{V_T}-1}) \approx I_S(e^{\frac{V_D}{V_T}})$$
$$\frac{dI_D}{dV} = \frac{1}{V_T} I_S(e^{\frac{V_D}{V_T}})$$
$$\approx \frac{1}{V_T} I_D$$

Another way to consider the slope of the approximate linear IV curve in the triode is the change in I over the change in V, ${}^{\Delta I}/_{\Delta V}$, as shown in Figure B2. This slope can be thought of as the inverse of resistance, and is termed transconductance, and notated by the scaling coefficient gm. Using this factor gm, the current through a MOSFET for a small signal can be

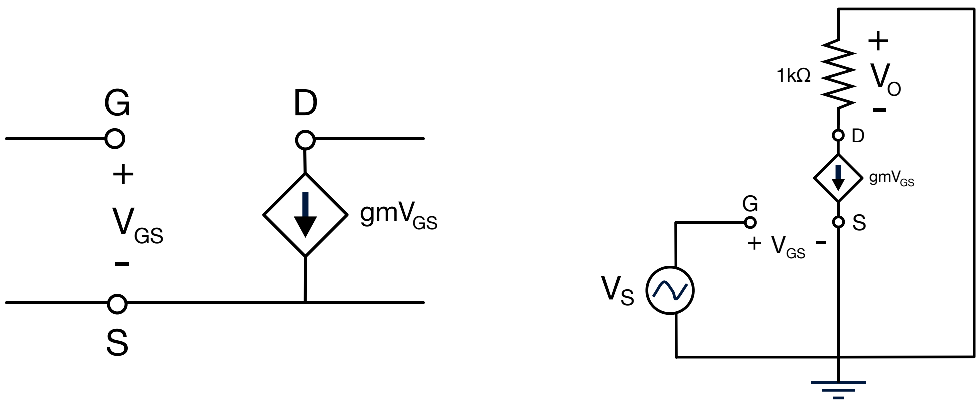

Fig. B3: Small signal equivalent circuit of a MOSFET, and the AC small signal circuit

represented as voltage controlled current source (controlled by V_{GS}), and the equivalent small signal network of a MOSFET can be represented by the circuit seen in Figure B3, along with this network replacing the MOSFET in the AC small signal equivalent of the main circuit. As the circuit is operating in what behaves like a linear region of operation, the DC and AC components of the circuit can be separated according to the principle of superposition.

ASSUMPTION B4

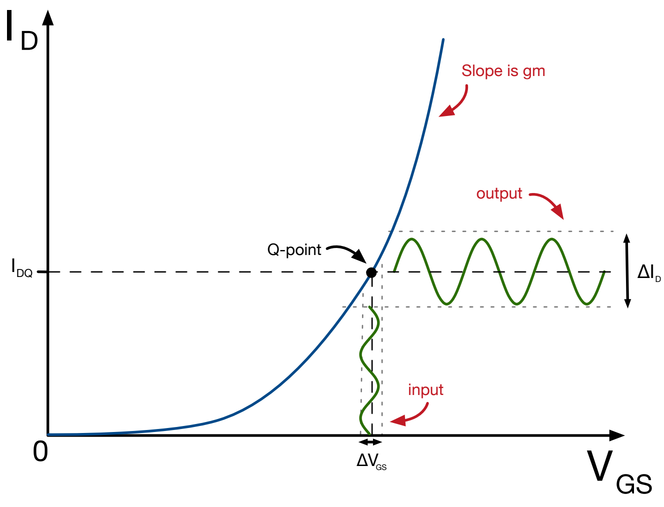

Fig. B4: Amplification of a small signal with a MOSFET in saturation

As the slope during the triode region is steep, this means that the rate of current increase according to voltage, the transconductance, is high. A small change in V_{GS} will lead to a bigger change in I_D (or I_S, depending on the configuration of the MOSFET in the circuit.) This relationship is demonstrated in Figure B4. The change in voltage must be limited to the total voltage of the AC summed with the DC not exceeding the width of the linear portion of the triode region, or the signal will be pushed into cut-off or saturation, distorting the small signal. This characteristic means that the range of a single MOSFET's amplification is only suitable for small signals.

Assumption B5

$$H(t) = \frac{V_{Out}}{V_{In}} = \frac{V_O}{V_S}$$

If H(t) >1, then the transfer function amplifies the output. As can be seen in the measured plot of V_S vs V_O shown in Figure B5, the input signal is amplified by around 20, but it is important to note that there is some signal distortion, as the output signal is not centred perfectly around 0 on the Y axis. The lower half of the sinusoidal signal is entering the non-linear bend of towards the cut-off region.

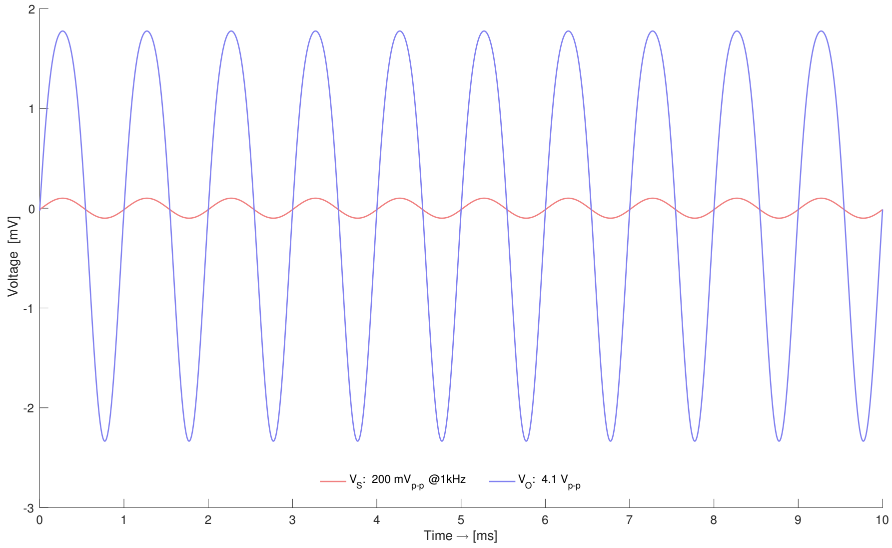

Fig. B5: Plot of small-signal amplification V_s against V_{out}

Assumption B6

Using the techniques of linearising a small signal in a circuit operating at a quiescent point, with the voltage across V_{GS} situated at the midpoint of the triode region, a MOSFET can be used to amplify a signal across a resistor in a circuit.

References

[1] Electronics Tutorials.ws, "Electronics Tutorials.ws," https://www.electronics-tutorials.ws/transistor/tran_6.html, 2017. [Online]. Available: {https://www.electronics-tutorials.ws/transistor/tran_6.html}

[2] N. Anttu and M. Kim, "MOSFET Basics," http://aries.ucsd.edu/NAJMABADI/CLASS/ECE102/10-W/NOTES/ECE102_W10_C03_MOS_large.pdf, ELEC-E3230 NANOTECHNOLOGY Course notes, 2018.

[3] R. L. Boylestad and L. Nashelsky, *Electronic Devices and Circuit theory*, 11th ed. Harlow, Essex, England: Pearson Education, 2014.

[4] J. ZHANG and X.-g. LI, "Multisim based schematic design and simulation [j]," *Computer Simulation*, vol. 5, p. 032, 2005.