# sEKV Parameter Extraction for the IHP 130nm Process

### nMOS

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# Table of contents

# 1 Introduction

In this notebook we will extract the sEKV parameters for nMOS transistors of the 130nm bulk CMOS process from IHP. The extraction is done with data generated by PSP for the typical-typical (t-t) case.

# 2 Transistor geometry parameters

## 2.1 Effective length and width for current

Before we start the extraction we need to account for the geometry dependence. With PSP you can choose between geometry scaling rules or binning rules with parameter $SWGEO$. If $SWGEO = 1$, the scaling rules are chosen. This is the case in the IHP 130nm G2 PDK. The geometrical parameters are defined in Figure 2.1.

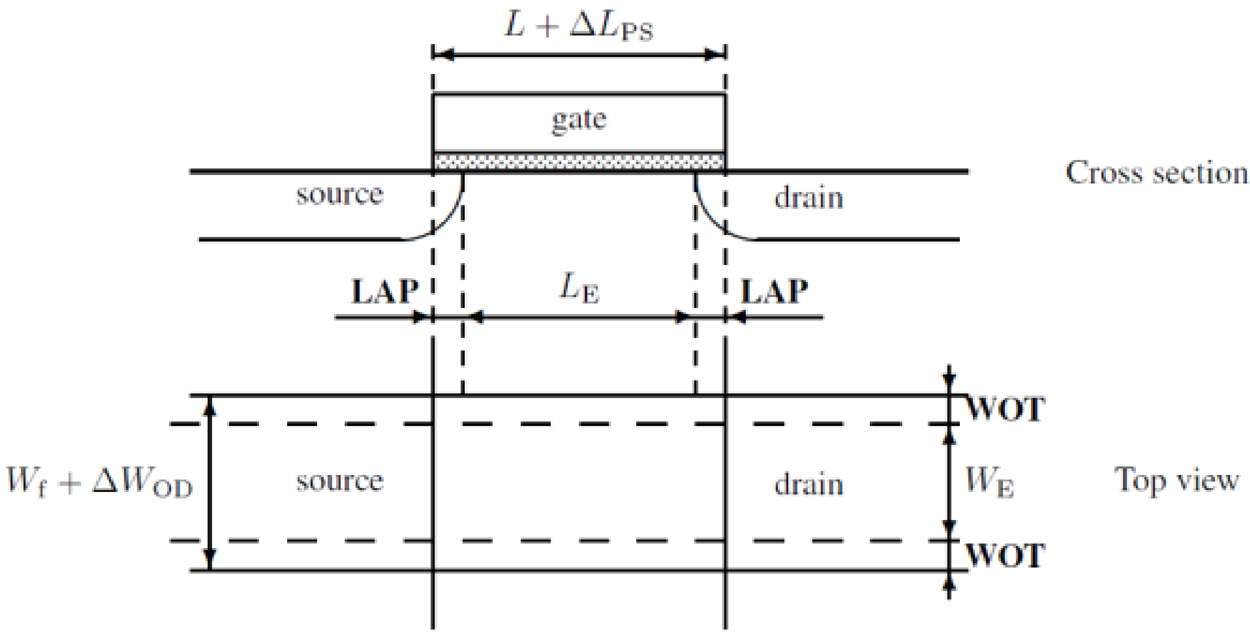



Figure 2.1: Definition of transistor geometrical parameters.

The effective length and width are defined as

$$L_{eff} = L - \Delta L, \tag{2.1}$$
$$W_{eff} = W_f - \Delta W, \tag{2.2}$$

where $W_f$ is the width of one finger defined as

$$W_f = \frac{W}{NF}. \tag{2.3}$$

In our case we will assume that the number of fingers $NF = 1$ and hence that $W_f = W$.

$\Delta L$ and $\Delta W$ are given by

$$\Delta L = 2\,LAP - \Delta L_{PS}, \tag{2.4}$$
$$\Delta W = 2\,WOT - \Delta W_{OD}, \tag{2.5}$$

with

$$\Delta L_{PS} = LVARO \cdot \left(1 + LVARL \cdot \frac{L_{EN}}{L}\right) \cdot \left(1 + LVARW \cdot \frac{W_{EN}}{W_f}\right), \tag{2.6}$$
$$\Delta W_{OD} = WVARO \cdot \left(1 + WVARL \cdot \frac{L_{EN}}{L}\right) \cdot \left(1 + WVARW \cdot \frac{W_{EN}}{W_f}\right). \tag{2.7}$$

In the IHP 130nm G2 DPK $LVARO = 0$ and $WVARO = 0$ for nMOS (not for pMOS!). Therefore $\Delta L_{PS} = 0$ and $\Delta W = 0$ and $\Delta L$ and $\Delta W$ are simply given by

$$\Delta L = 2\,LAP, \tag{2.8}$$
$$\Delta W = 2\,WOT. \tag{2.9}$$

They are given below.

$L = 1.000\ \mu m$

$L_{eff} = 0.941\ \mu m$

$W = 1.000\ \mu m$

$W_{eff} = 1.020\ \mu m$

$DL = 59$ nm

$DW =$ -20 nm

Note that $DWn$ is negative (width gets larger).

## 2.2 Effective length and width for capacitances

The effective length and width are slightly different for the calulation of the capacitances.

The effective length and width for the calculation of the intrinsic and overlap acacitances are defined as

$$L_{E,CV} = L - \Delta L_{CV}, \tag{2.10}$$
$$W_{E,CV} = W - \Delta W_{CV}, \tag{2.11}$$

where

$$\Delta L_{CV} = 2\,LAP - \Delta L_{PS} - DLQ, \tag{2.12}$$
$$\Delta W_{CV} = 2\,WOT - \Delta W_{OD} - DWQ. \tag{2.13}$$

As mentioned above, for the IHP 130nm for nMOS $\Delta L_{PS} = 0$ and $\Delta W_{OD} = 0$ so that

$$\Delta L_{CV} = 2\,LAP - DLQ, \tag{2.14}$$
$$\Delta W_{CV} = 2\,WOT - DWQ. \tag{2.15}$$

The effective length and width for the calculation of the fringing field capacitances are defined as

$$L_{G,CV} = L - \Delta L_{G,CV}, \tag{2.16}$$
$$W_{G,ov} = W - \Delta W_{G,CV}, \tag{2.17}$$

where

$$\Delta L_{G,CV} = -\Delta L_{PS} - DLQ, \tag{2.18}$$
$$\Delta W_{G,CV} = -\Delta W_{OD} - DWQ. \tag{2.19}$$

```
Length and width correction for intrinsic and overlap capacitances:
```

$L = 1.000\ \mu m$

$L_{CV} = 0.927\ \mu m$

$W = 1.000\ \mu m$

$W_{CV} = 1.010\ \mu m$

```
Length and width correction for fringing capacitances:
```

$L = 1.000\ \mu m$

$L_{CVG} = 0.986\ \mu m$

$W = 1.000\ \mu m$

$W_{CVG} = 0.990\ \mu m$

```
Length and width correction for intrinsic and overlap capacitances:
```

$\Delta L_{CV} =$ 73 nm

$\Delta W_{CV} =$ -10 nm

```
Length and width correction for fringing capacitances:
```

$\Delta L_{G,CV} =$ 14 nm

$\Delta W_{G,CV} =$ 10 nm

Table 2.1: Length and width corrections.

| | Length correction DL | Width correction DW | Comment |
|---|---|---|---|
| For current | 5.885e-08 | -2.000e-08 | extracted from PDK |
| For intrinsic and overlap capacitances | 7.257e-08 | -1.000e-08 | extracted from PDK |
| For fringing-field capacitances | 1.372e-08 | 1.000e-08 | extracted from PDK |

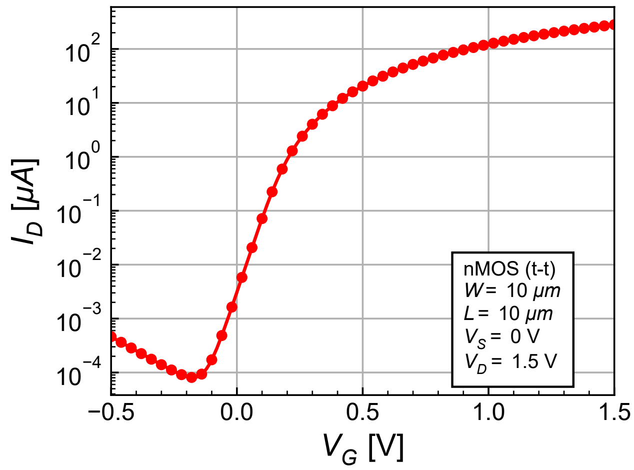
# 3 Long-channel parameters

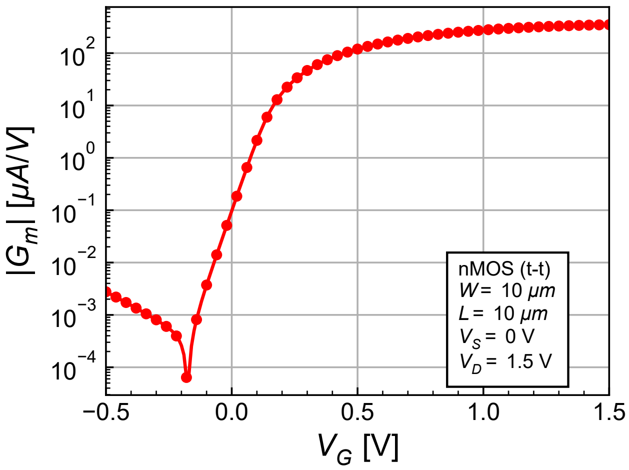
## 3.1 DC Transfer Characteristic Parameters

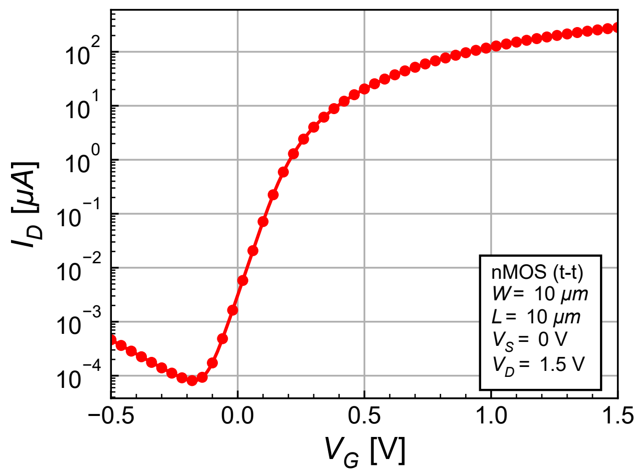
### 3.1.1 Generating the data

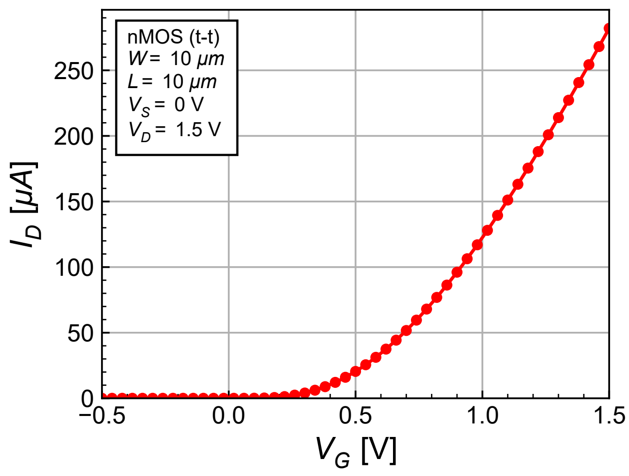
### 3.1.2 Importing and plotting the data

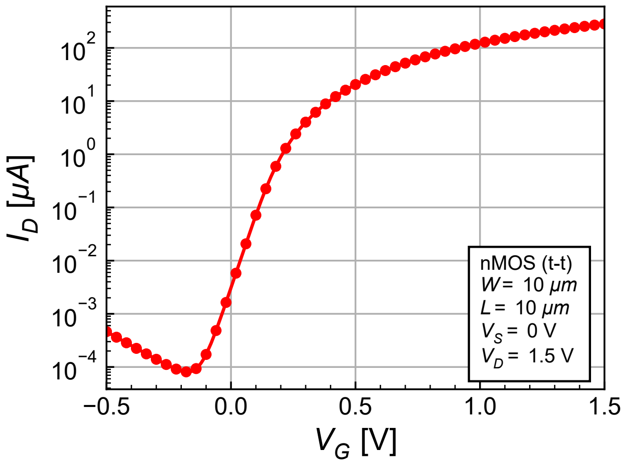
#### 3.1.2.1 $I_D$ and $G_m$ versus $V_G$

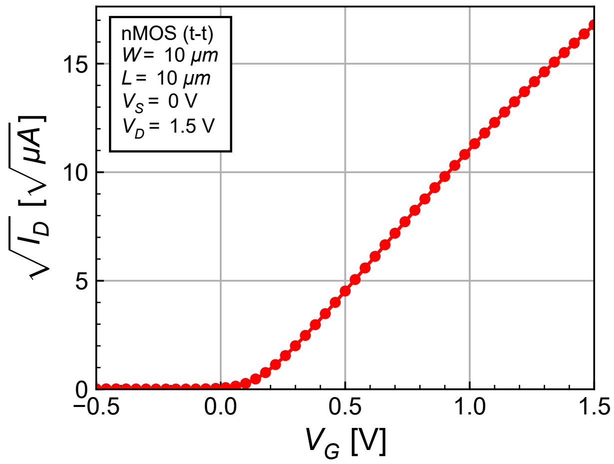


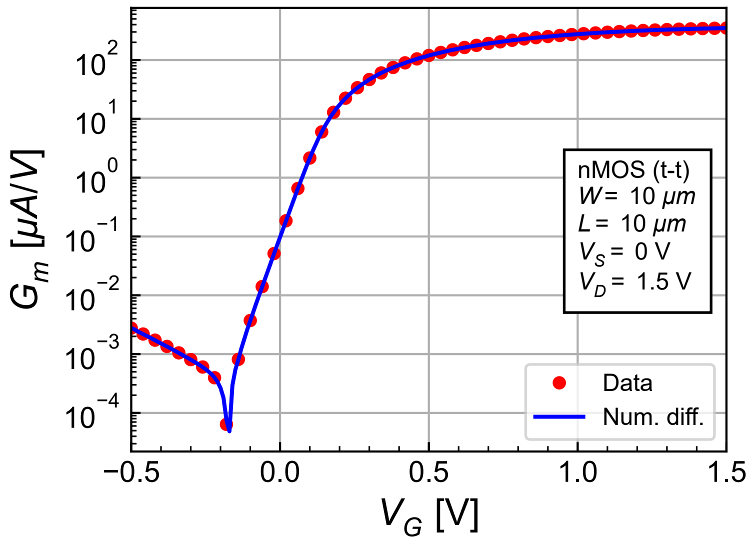





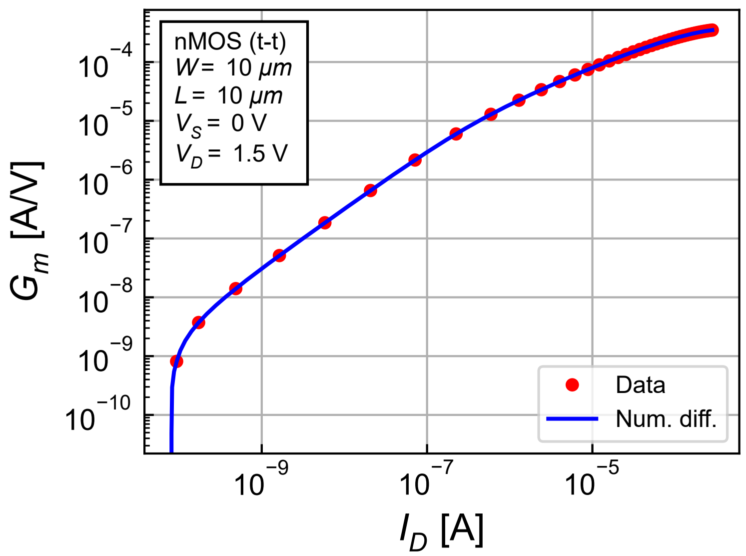




#### 3.1.2.2 $G_m$-$V_G$

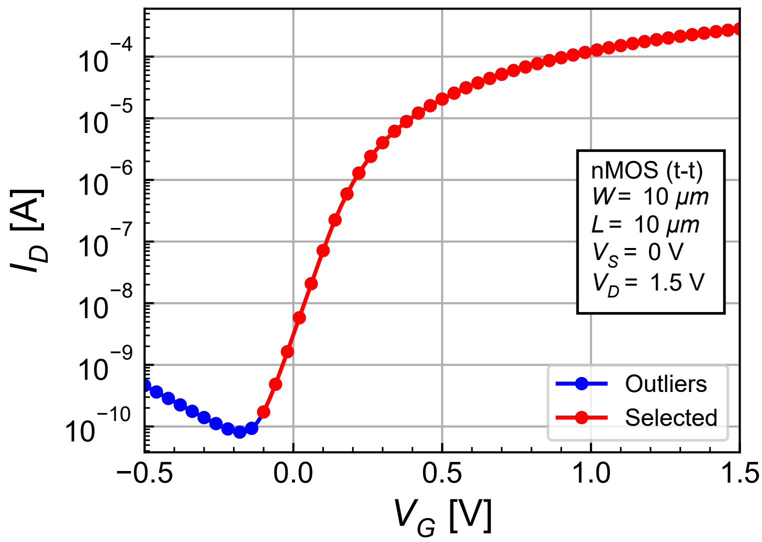


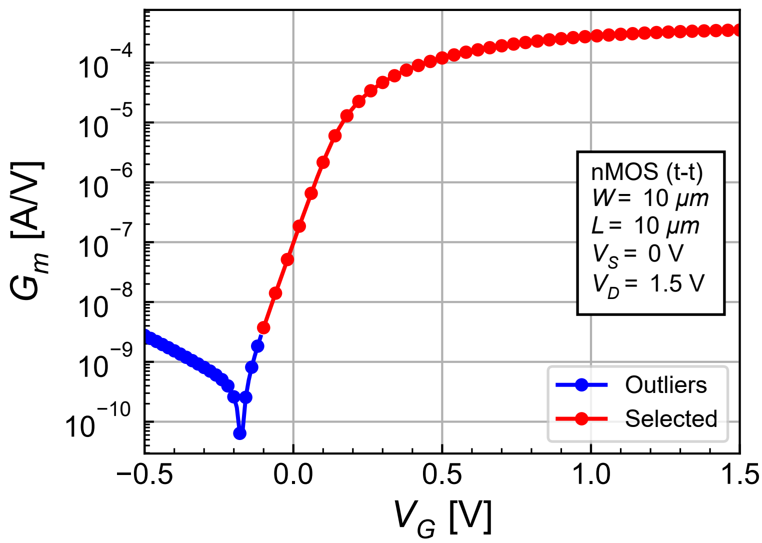

We see that the transconductance obtained by differentiating the large-signal $I_D$-$V_G$ characteristic is equal to the transconductance extracted from the PSP model. We will keep the value extracted from the PSP model.

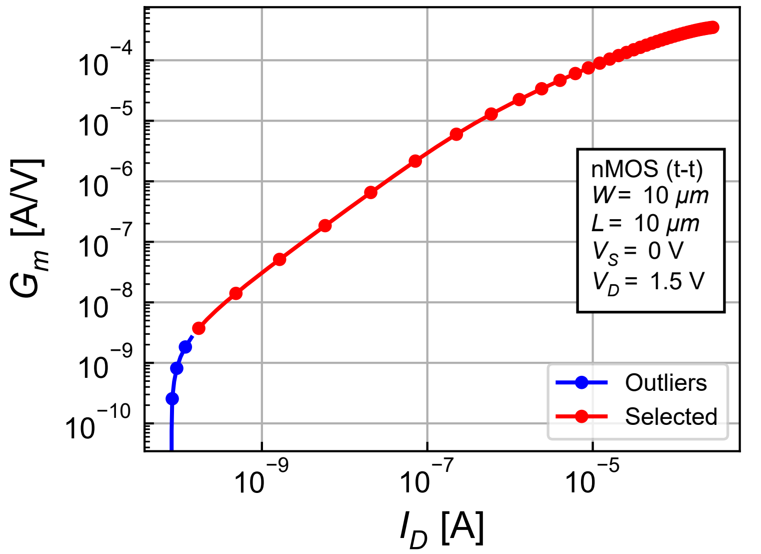
#### 3.1.2.3 $G_m$-$I_D$




#### 3.1.2.4 Filtering the outliers






### 3.1.3 Direct extraction with $\lambda_c = 0$

#### 3.1.3.1 Slope factor $n$ and $I_{spec}$ extraction

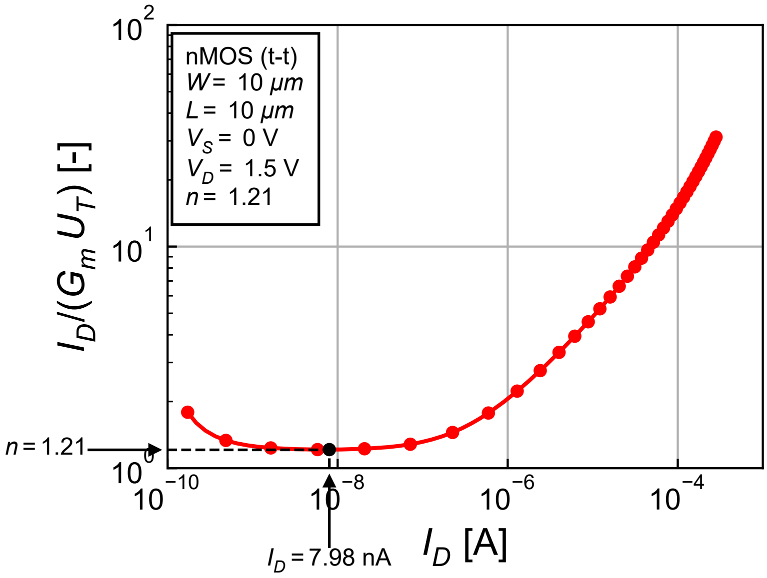
The gate transconductance in weak inversion and saturation is given by

$$G_m = \frac{I_D}{n\,U_T}. \tag{3.1}$$

So if we plot $I_D/(G_m\,U_T)$ we should see a plateau in weak inversion the value of which is equal to the slope factor $n$.

$n = 1.21$

$I_{D,ext} = 7.98\ nA$




On the other hand the normalized $G_m/I_D$ function for a long-channel transistor in strong inversion and saturation is given by

$$\frac{G_m\, n\, U_T}{I_D} = \frac{1}{\sqrt{IC}} = \sqrt{\frac{I_{spec}}{I_D}}. \tag{3.2}$$

We can then plot $(G_m\, n\, U_T)^2/I_D$ which should find a maximum value equal to $I_{spec}$.

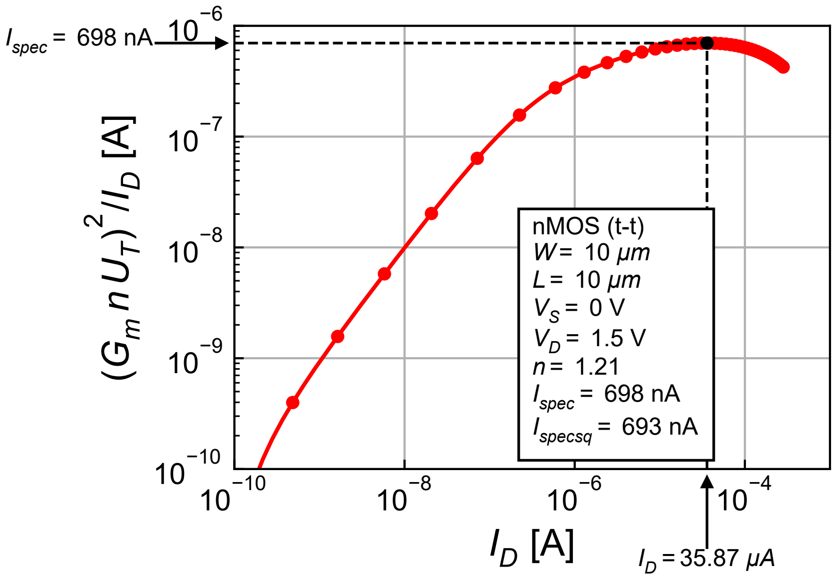
$W_{eff} = 10.020\ \mu m$

$L_{eff} = 9.941\ \mu m$

$I_{spec} = 698\ nA$

$I_{spec\square} = 693\ nA$

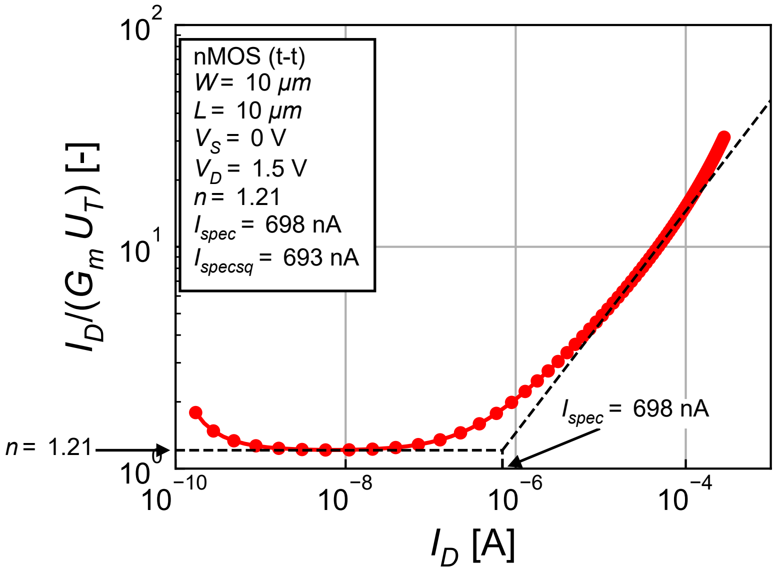
$I_{D,ext} = 35.871\ \mu A$




$n = 1.21$

$I_{spec} = 698\ nA$

$I_{spec\square} = 693\ nA$



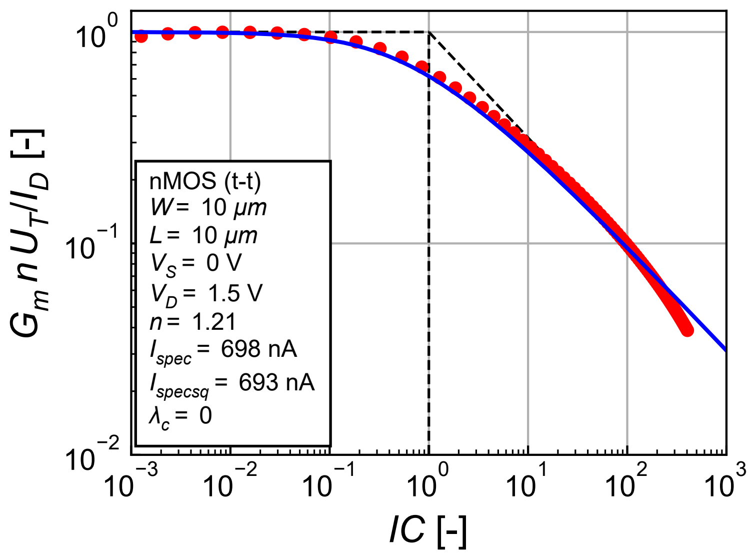

Having extracted $n$ and $I_{spec}$, we can now plot the normalized $G_m/I_D$ function.

$n = 1.21$

$I_{spec} = 698\ nA$

$I_{spec\square} = 693\ nA$

$\lambda_c = 0$



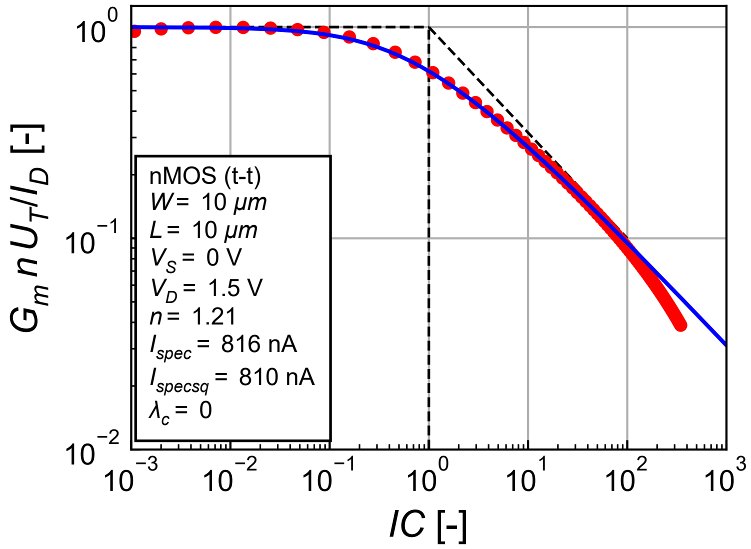

The fit is reasonable over the entire $IC$ span. There is some discrepancy in the moderate inversion region which is due to the mobility reduction due to the vertical field appearing for $IC > 10^2$. The latter can be accounted for by using the $\lambda_c$ parameter which is normally used for modeling the effect of velocity saturation in short-channel transistor but can also be used to correct the effect of mobility reduction due to the vertical field appearing in long-channel transistors. We will not do this here since we want to extract the long-channel parameters keeping $\lambda_c = 0$, but since we are mostly interested in the moderate inversion region, we can slightly increase $I_{spec}$ to improve the fit in moderate inversion at the cost of a degradation in strong inversion.

$n = 1.21$

$I_{spec} = 816\ nA$

$I_{spec\square} = 810\ nA$

$\lambda_c = 0$




The fit is now much better in moderate inversion but less in strong inversion. This is due to mobility reduction due to the vertical field an effect that is not accounted for in the model. However, we will keep the new values.

#### 3.1.3.2 Threshold voltage extraction

We can extract the threshold voltage in weak inversion (assuming $V_S = 0$) from the normalized current (inversion coefficient) given by

$$IC = e^{\frac{V_G - V_{T0}}{nU_T}}. \tag{3.3}$$

We can now plot

$$V_{T0} = V_G - nU_T \ln(IC) \tag{3.4}$$

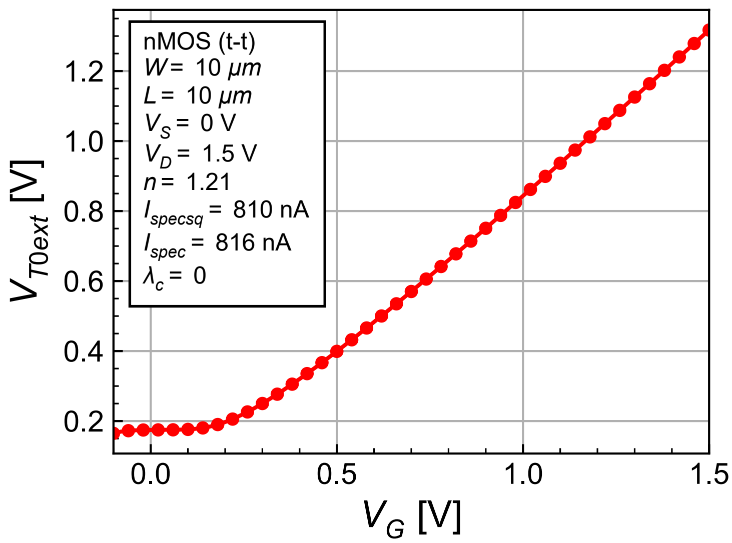
to extract the threshold voltage.

$n = 1.21$

$I_{spec} = 816\ nA$

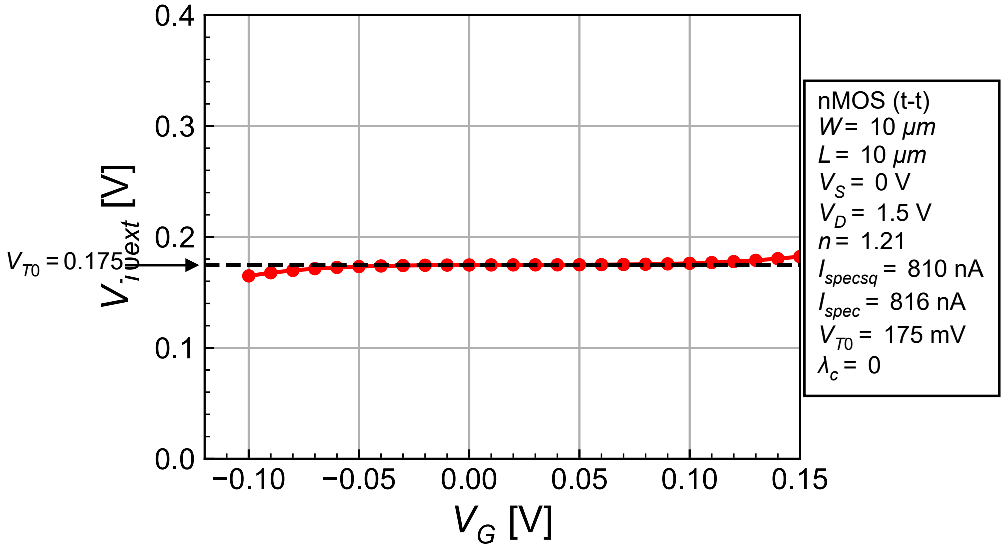
$I_{spec\square} = 810\ nA$

$\lambda_c = 0$




We see a plateau in weak inversion where we can average its value to get the threshold voltage in weak inversion.

$V_{T0,wi} = 175$ mV




The threshold voltage for this wide and long device is surprisingly small. It is in accordance with the documentation giving a typical-typical $V_{TH} \cong 200\,mV$ for $W = 10\,\mu m$ and $L = 10\,\mu m$.

We can now plot the $I_D$-$V_G$ for this threshold voltage.

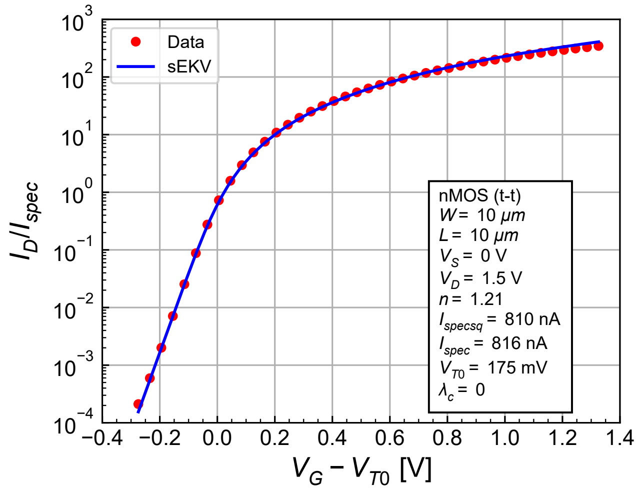
$n = 1.21$

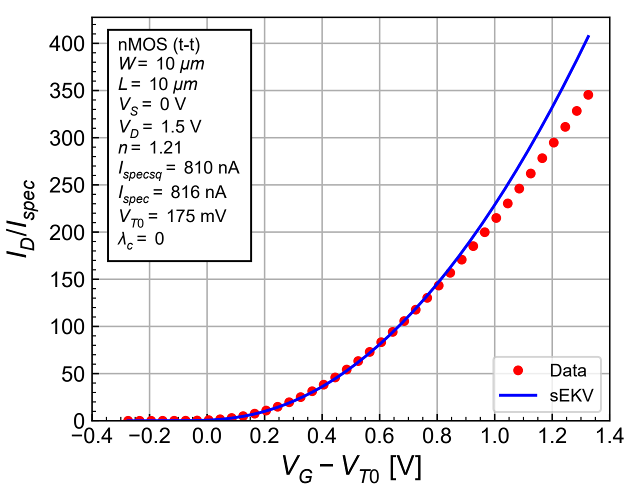
$I_{spec} = 816\ nA$

$I_{spec\square} = 810\ nA$

$\lambda_c = 0$

$V_{T0,wi} = 175$ mV




We get a reasonable fit with some deviations in the moderate inversion, which is expected since we fitted with the asymptotes.

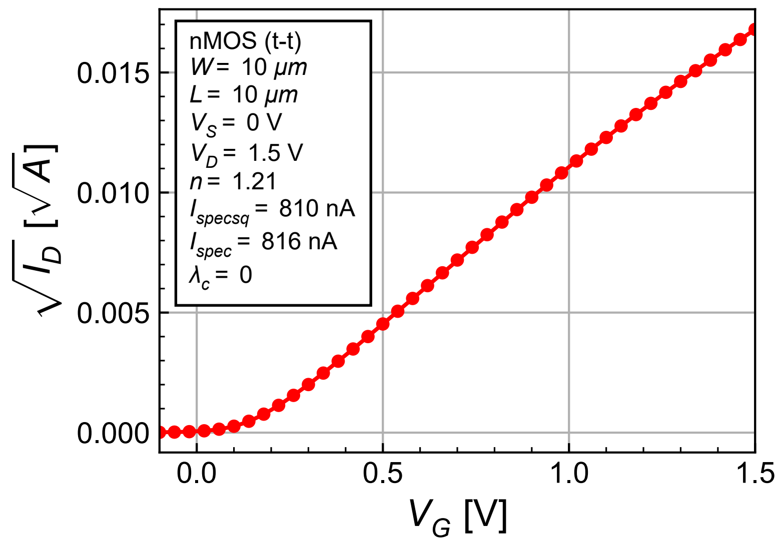
We can also extract the threshold voltage in strong inversion.

$n = 1.21$

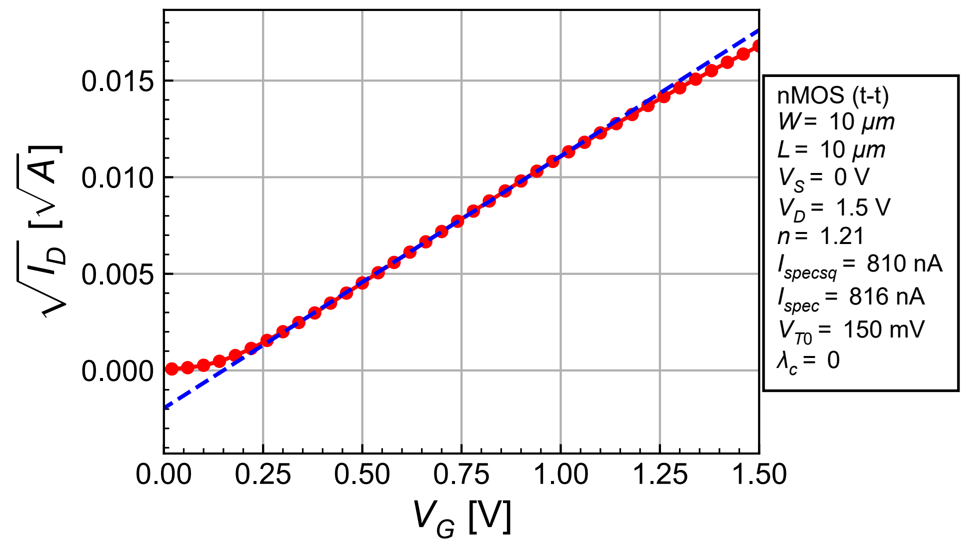
$I_{spec} = 816\ nA$

$I_{spec\square} = 810\ nA$

$\lambda_c = 0$




$V_{T0,si} = 150$ mV




We get a very small threshold voltage even smaller than the value extracted in weak inversion.

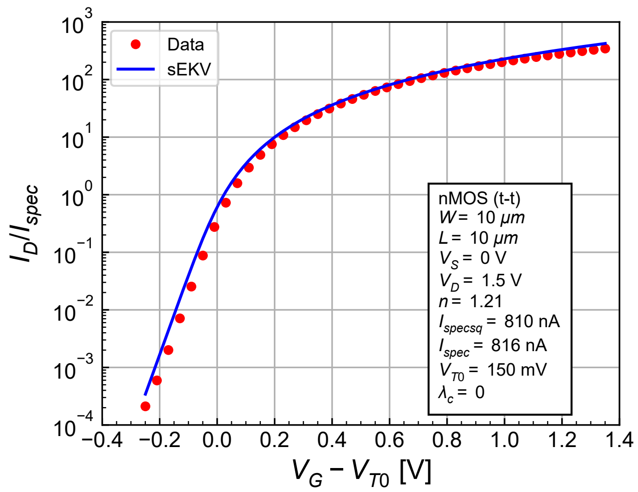
$n = 1.21$

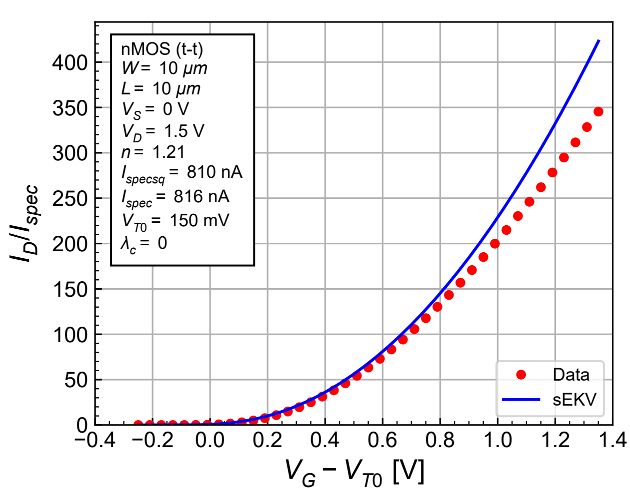
$I_{spec} = 816\ nA$

$I_{spec\square} = 810\ nA$

$\lambda_c = 0$

$V_{T0,si} = 150$ mV




As expected, we get a less good fit in weak inversion. We therefore keep the value of the threshold voltage extracted in weak inversion.

#### 3.1.3.3 Summary

$n = 1.21$

$I_{spec} = 816\ nA$

$I_{spec\square} = 810\ nA$

$V_{T0,wi} = 175$ mV

$\lambda_c = 0$

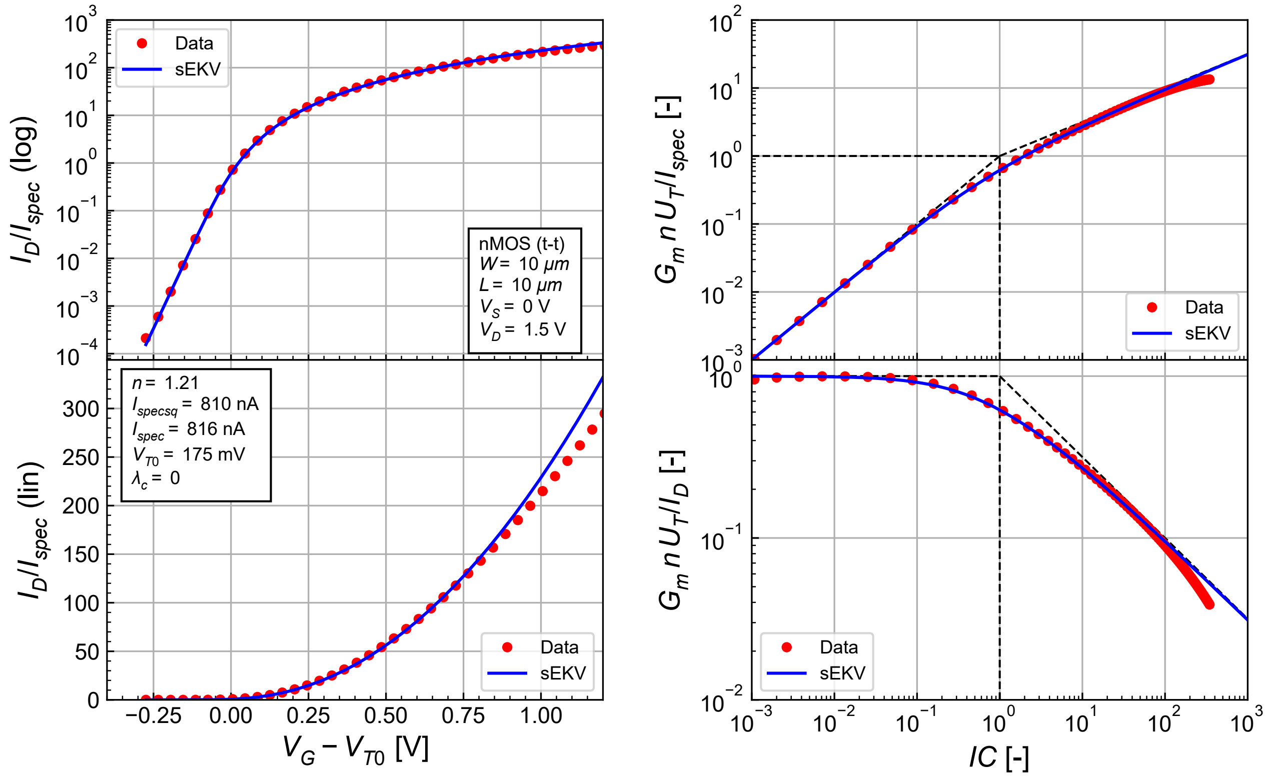



Table 3.1: Direct extraction of the sEKV parameters for the long-channel transistor with $\lambda_c = 0$

| | W | Weff | L | Leff | n | Ispecsq | VT0 | lambdac | Lsat | Com |
|---|---|---|---|---|---|---|---|---|---|---|
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.210e+00 | 8.100e-07 | 1.746e-01 | 0 | 0 | direc |

### 3.1.4 Extraction using optimization with $\lambda_c = 0$

#### 3.1.4.1 Slope factor $n$ and $I_{spec}$ extraction

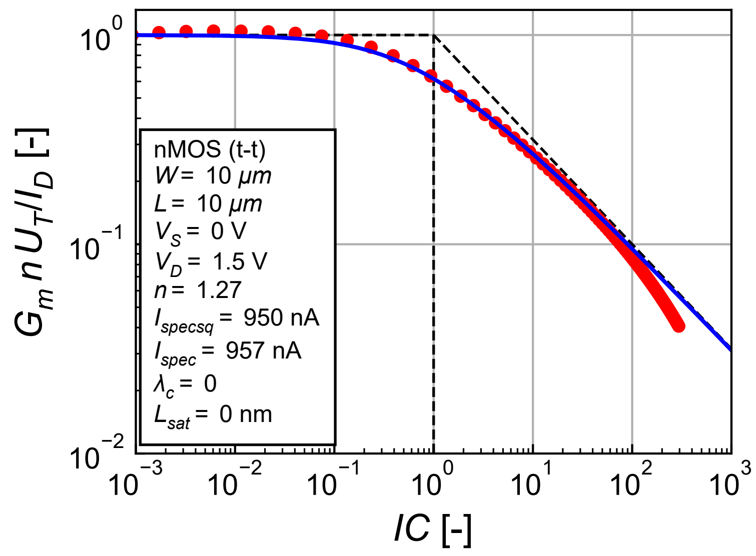
We can try to extract $n$ and $I_{spec}$ for a long-channel directly from the normalized $G_m/I_d$ function.

$n = 1.27$

$I_{spec} = 957\ nA$

$I_{spec\square} = 950\ nA$

$\lambda_c = 0$




We get a reasonable fit and values that similar to the direct extraction.

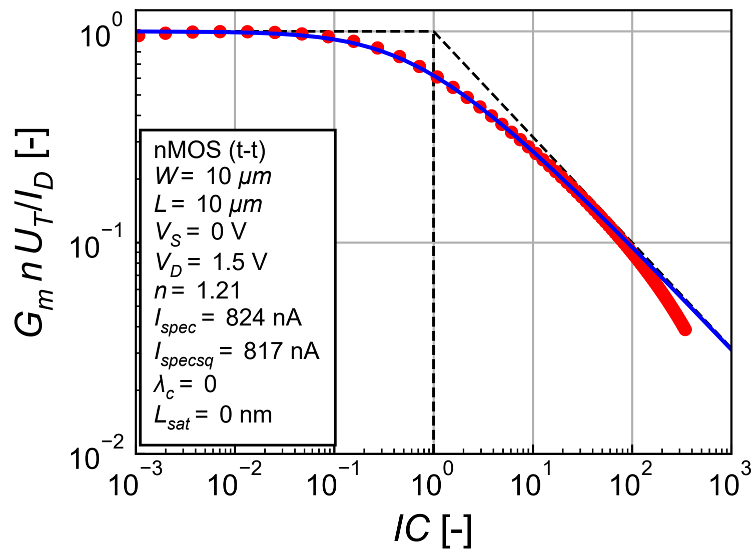
We can also try to keep the value of $n$ extracted from the direct extraction above and optimize for $I_{spec}$ only.

$n = 1.21$

$I_{spec} = 824\ nA$

$I_{spec\square} = 817\ nA$

$\lambda_c = 0$



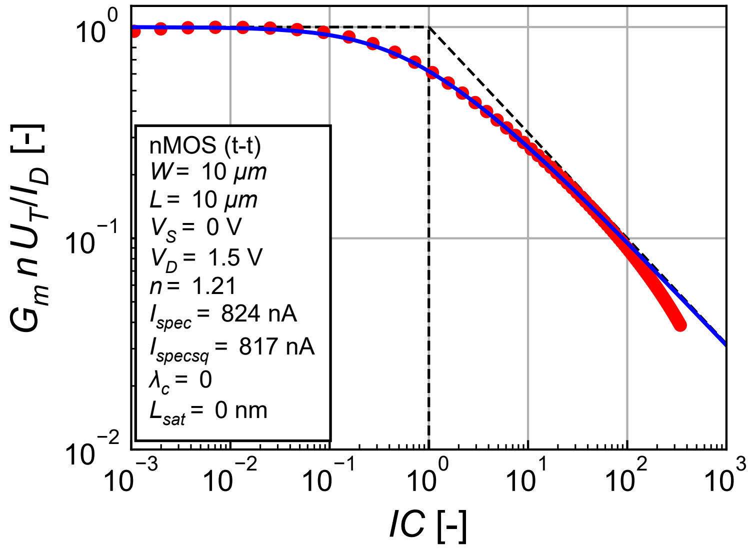

The fit is good in weak and moderate inversion, but we still have some discrepancies in strong inversion which is due to mobility reduction due to the vertical field. We will keep the last extracted values for $I_{specsq}$.

$n = 1.21$

$I_{spec} = 824\ nA$

$I_{spec\square} = 817\ nA$

$\lambda_c = 0$




#### 3.1.4.2 Threshold voltage extraction

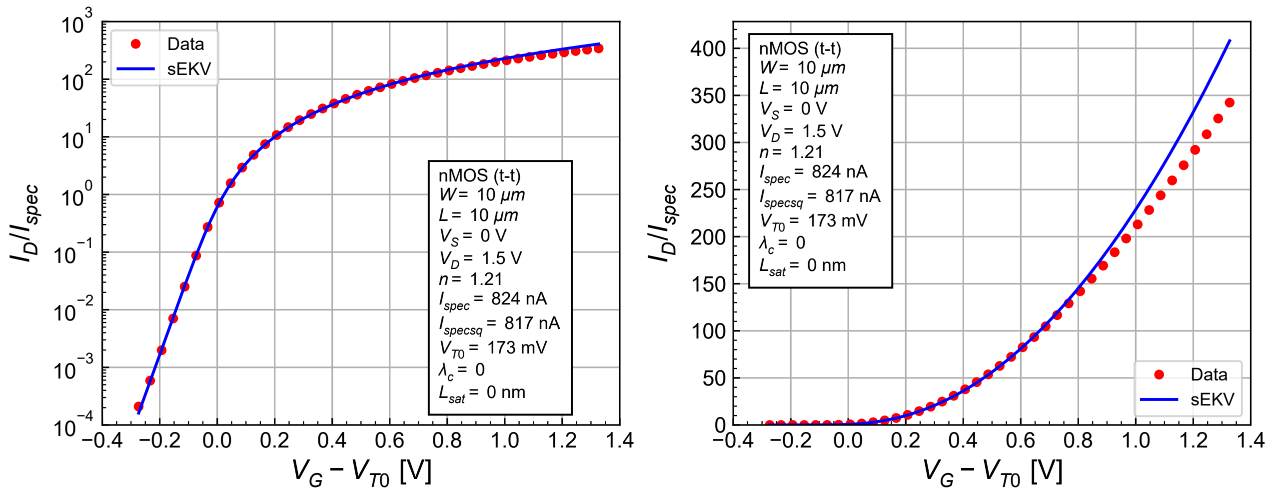
$n = 1.21$

$I_{spec} = 824\ nA$

$I_{spec\square} = 817\ nA$

$V_{T0} = 173$ mV

$\lambda_c = 0$




We see a reasonable fit except in strong inversion. This is expected since we optimized the moderate inversion region.

#### 3.1.4.3 Summary

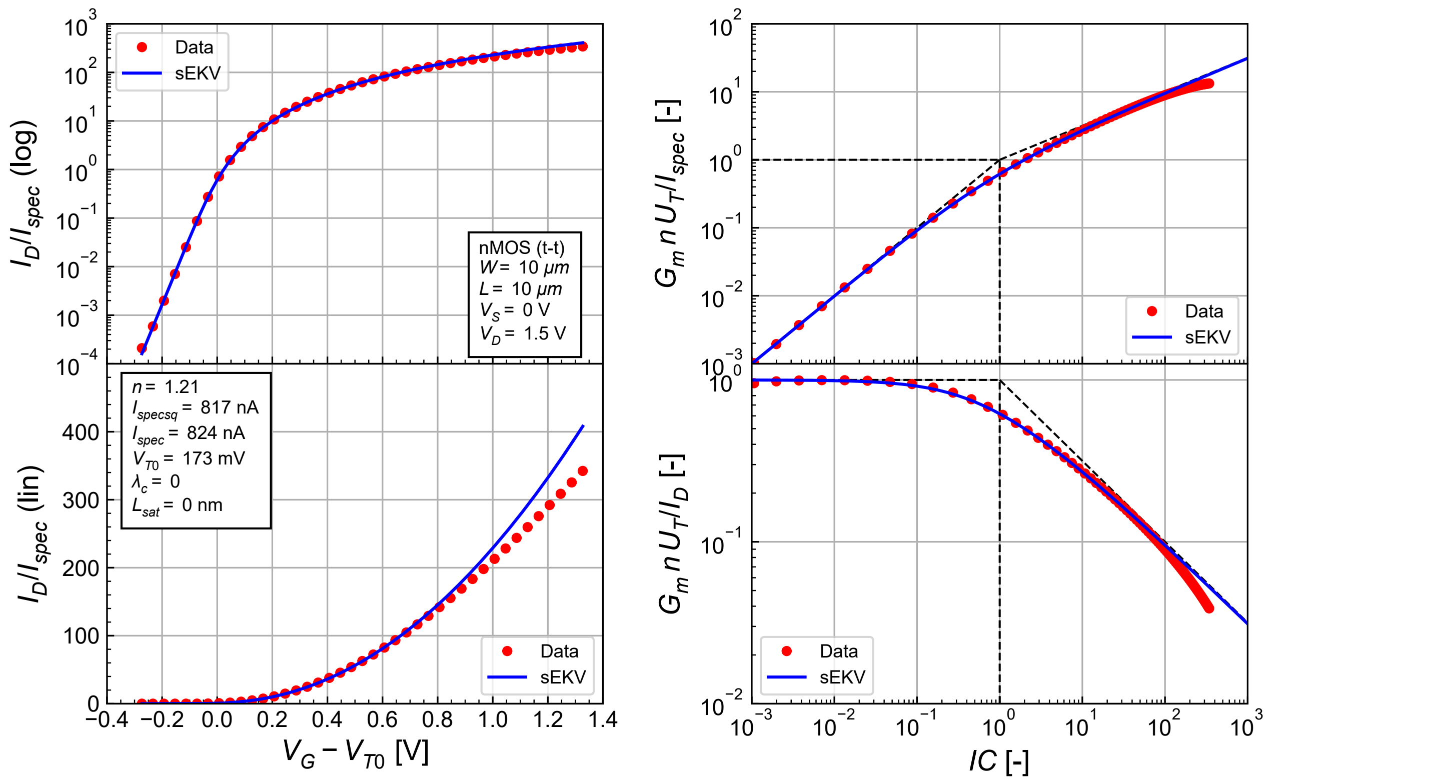
$n = 1.21$

$I_{spec} = 824\ nA$

$I_{spec\square} = 817\ nA$

$V_{T0} = 173$ mV

$\lambda_c = 0$




The extraction using curve-fitting gives a better fit in moderate inversion but less in strong inversion.

Table 3.2: Extraction of the sEKV parameters by optimization for the long-channel transistor $\lambda_c = 0$.

| | W | Weff | L | Leff | n | Ispecsq | VT0 | lambdac | Lsat | Comm |
|---|---|---|---|---|---|---|---|---|---|---|
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.210e+00 | 8.100e-07 | 1.746e-01 | 0 | 0 | direc |
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.210e+00 | 8.173e-07 | 1.733e-01 | 0 | 0 | optin |

### 3.1.5 Extraction using optimization with $\lambda_c > 0$

We start extracting $n$, $I_{spec}$ and $\lambda_c$ using curve fitting on $G_m/I_D$.

$n = 1.27$

$I_{spec} = 1046\ nA$

$I_{spec\square} = 1046\ nA$

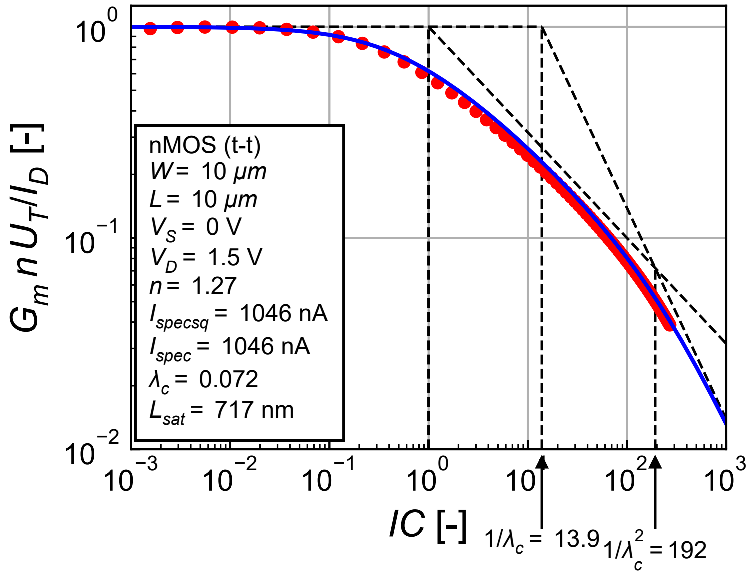
$V_{T0} = 173$ mV

$\lambda_c = 0.072$

$L_{sat} = 717.208$ nm

$1/\lambda_c = 14$

$1/\lambda_c^2 = 192$




We now have a good fit in strong inversion that we can still improve by slightly reducing the value of $I_{specsq}$, which seems too high and $\lambda_c$.

$n = 1.27$

$I_{spec} = 857\ nA$

$I_{spec\square} = 850\ nA$

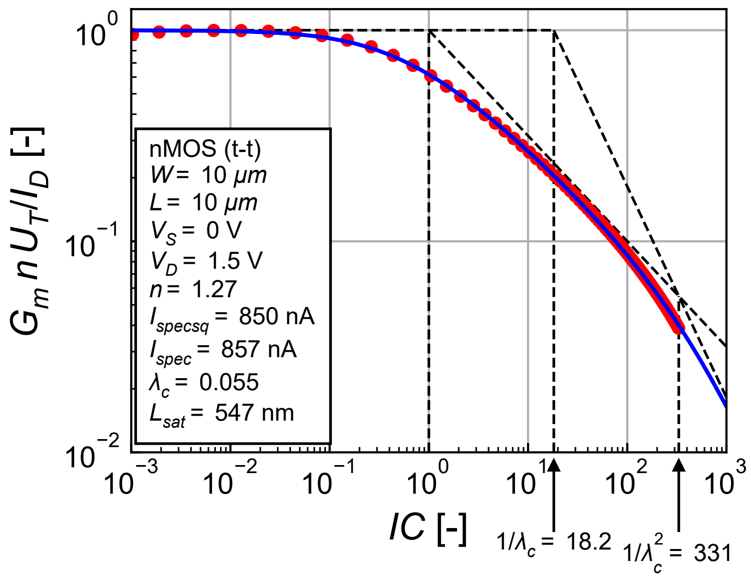
$V_{T0} = 173$ mV

$\lambda_c = 0.055$

$L_{sat} = 547$ nm

$1/\lambda_c = 18$

$1/\lambda_c^2 = 331$




We now have an almost perfect fit.

#### 3.1.5.1 Summary

We can now check the large and small-signal characteristics.

$n = 1.27$

$I_{spec} = 857\ nA$

$I_{spec\square} = 850\ nA$

$V_{T0} = 173$ mV

$\lambda_c = 0.055$

$L_{sat} = 547$ nm

$1/\lambda_c = 18$

$1/\lambda_c^2 = 331$

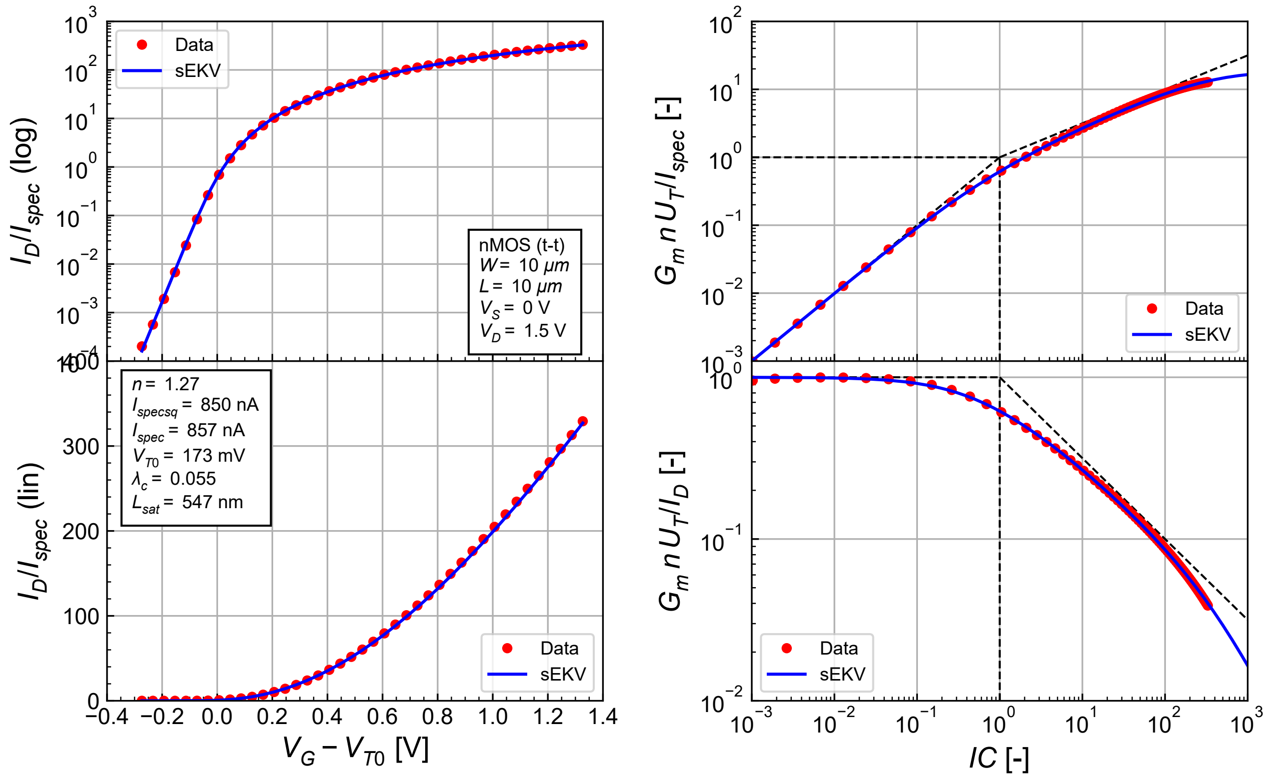



Table 3.3: Extraction of the sEKV parameters by optimization for the long-channel trans
$\lambda_c > 0$.

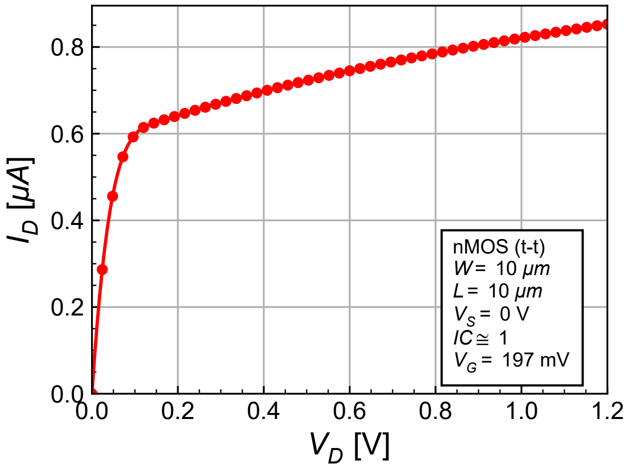
| | W | Weff | L | Leff | n | Ispecsq | VT0 | lambdac | Lsat |
|---|---|---|---|---|---|---|---|---|---|
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.210e+00 | 8.100e-07 | 1.746e-01 | 0.000e+00 | 0.000e+0 |
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.210e+00 | 8.173e-07 | 1.733e-01 | 0.000e+00 | 0.000e+0 |
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.272e+00 | 8.500e-07 | 1.733e-01 | 5.500e-02 | 5.468e-07 |

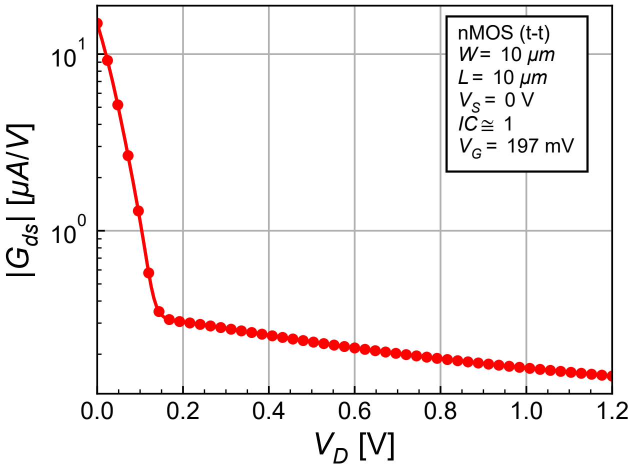
## 3.2 Output characteristic

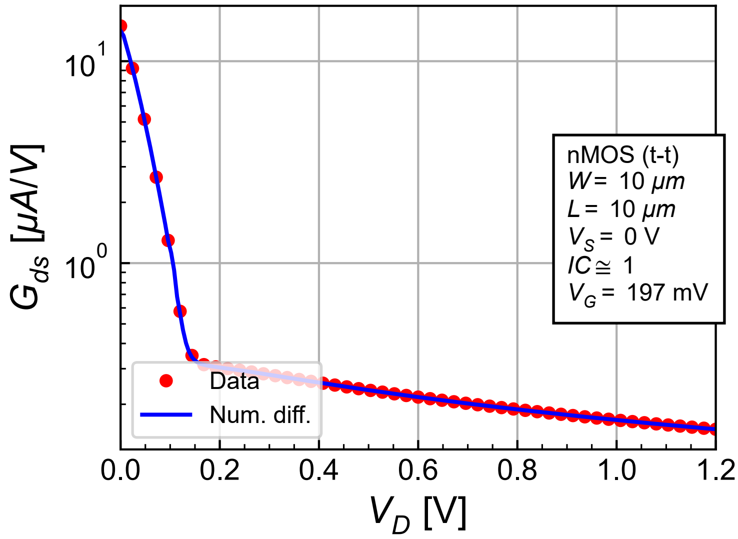
### 3.2.1 Generating the data

### 3.2.2 Importing and plotting the data

#### 3.2.2.1 $I_D$ and $G_{ds}$ versus $V_D$

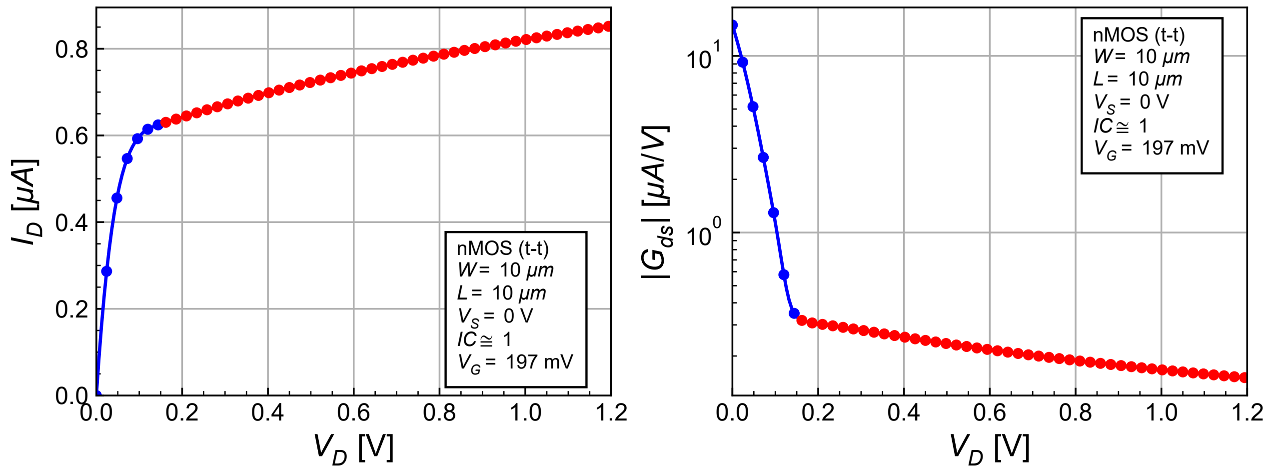



The output conductance calculated by differentiating the large-signal $I_D$-$V_D$ matches the value extracted from the PSP model. We will keep the value from PSP.

#### 3.2.2.2 Filtering the outliers



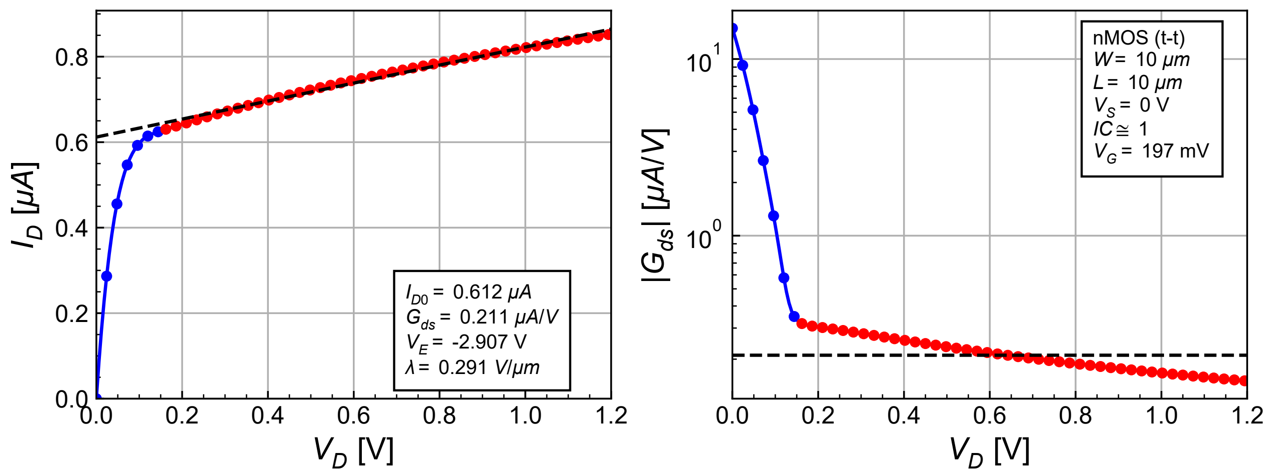

### 3.2.3 Extracting the CLM parameter

$G_{ds}$ = 0.211 $\mu A/V$

$I_{D0}$ = 0.612 $\mu A$

$V_E$ = -2.907 $V$

$\lambda$ = 0.291 $V/\mu m$




We get a rather high output conductance and hence low value of the $\lambda$ parameter for such a long transistor.

Table 3.4: CLM parameters extracted for the long-channel transistor in moderate inversion.

| | W | Weff | L | Leff | IC | Gds | ID0 | VE | lambda | Com |
|---|---|---|---|---|---|---|---|---|---|---|
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1 | 2.105e-07 | 6.119e-07 | -2.907e+00 | 2.907e+05 | mod |

## 3.3 Noise

In this section we will extract the flicker noise parameters to be used with sEKV and check the white noise power spectral desnity (PSD). We reuse the flicker noise model from EKV 2.6, where the input (gate) referred PSD is given by

$$S_{nin,fl}(f) = \frac{KF}{W_{eff}\, L_{eff}\, C_{ox}\, f^{AF}} \tag{3.5}$$

In this model the flicker noise is assumed to scale as $1/C_{ox}$, which is correct if the noise follows the the Hooge model (i.e. originates from mobility fluctuations). In the case of the Mc Worther model (i.e. flicker noise originating from traps in Si-SiO$_2$ interface and in the oxyde), the PSD scales as $C_{ox}^2$. Despiet the flicker noise is usually domanted by the trapping mechanism, we will keep the above model with a $1/C_{ox}$ scaling.

In EKV , we like to rewrite the flicker noise PSD like the thermal noise in terms of a input-referred noise resistance

$$S_{nin,fl}(f) = 4kT\, R_{nin,fl}(f) \tag{3.6}$$

where

$$R_{nin,fl}(f) = \frac{\rho}{W_{eff}\, L_{eff}\, f^{AF}} \tag{3.7}$$

with

$$\rho = \frac{KF}{4kT\, C_{ox}} \tag{3.8}$$

Note that the flicker noise parameter have some weird units. Indeed, $KF$ is in $A \cdot V \cdot s^{2-AF}$ and $\rho$ is in $V \cdot m^2/(A \cdot s^{AF})$. If $AF = 1$, like it is often the case, then $KF$ is in $A \cdot V \cdot s$ and $\rho$ is in $V \cdot m^2/(A \cdot s)$.

To extract the noise parameters, we use a common-source stage loaded by a noiseless resistor. We first will set the bias condition in terms of $IC$ and calculate the input-referred white noise to compare it to the result obtained from the PSP simulations.

### 3.3.1 Setting bias conditions

Having extracted $n$, $I_{spec\square}$ and $V_{T0}$, we can impose the inversion coefficient and calculate the corresponding gate voltage $V_G$. We nee to make sure the transistor remains in saturation.

$W = 10\ \mu m$

$L = 10\ \mu m$

$IC = 1$

$I_D = 0.824\ \mu A$

$V_G = 0.197\ V$

$V_S = 0.000\ V$

$G_m = 16.267\ \mu A/V$

$\gamma_n = 0.682$

$R_{n,th} = 41.926\ k\Omega$

$S_{n,th} = 6.950\text{e-}16\ V^2/Hz$

$V_{n,th} = 26.362\ nV/\sqrt{Hz}$

$A_v = 10$

$R_L = 614.727\ k\Omega$

$V_{DD} = 1.200\ V$

$V_{RL} = 0.506\ V$

$V_{DS} = 0.694\ V$

$V_{DSsat} = 0.116\ V$

```
The transistor is biased in the saturation region
```

### 3.3.2 Extract operating point information

We can extract the values of the PSP noise parameters from the operating point informations.

$V_{n,th} = 28.007\ nV/\sqrt{Hz}$ (PSP)

$f_k = 2.637\ kHz$ (PSP)

$KF = 3.175\text{e-}24\ VAs$ (PSP)

$\rho = 0.012\ Vm^2/(As)$ (PSP)

$AF = 1.000$ (PSP)

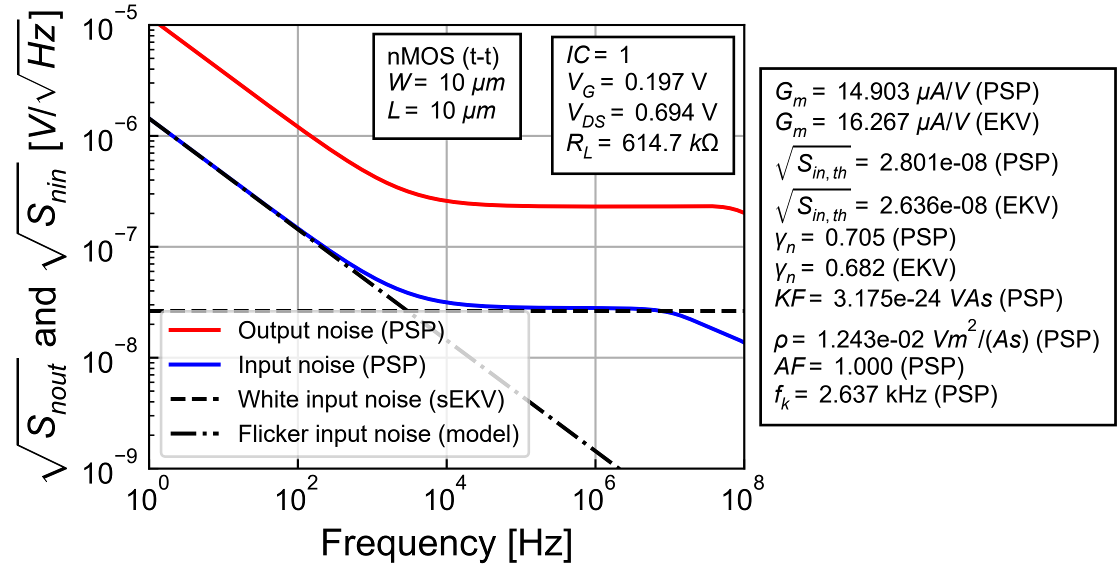
$R_{n,th} = 47.320\ k\Omega$ (PSP)

$\gamma_n = 0.705$ (PSP)

| | Weff | Leff | IDS | Gm | Gds | Snidth | Vninth | Snidfl @ 1Hz | Vninfl @ |
|---|---|---|---|---|---|---|---|---|---|
| Mn | 1.002e-05 | 9.941e-06 | 7.304e-07 | 1.490e-05 | 1.858e-07 | 1.742e-25 | 2.801e-08 | 4.593e-22 | 4.548e-08 |

### 3.3.3 Simulating noise PSD

We can now simulate the PSD and check against the EKV model.




The flicker noise parameters are given by

Table 3.6: Extraction of the noise parameters for the long-channel transistor.

| | W | Weff | L | Leff | IC | KF | AF | rho | Comment |
|---|---|---|---|---|---|---|---|---|---|
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1 | 3.175e-24 | 1.000e+00 | 1.243e-02 | moderate |

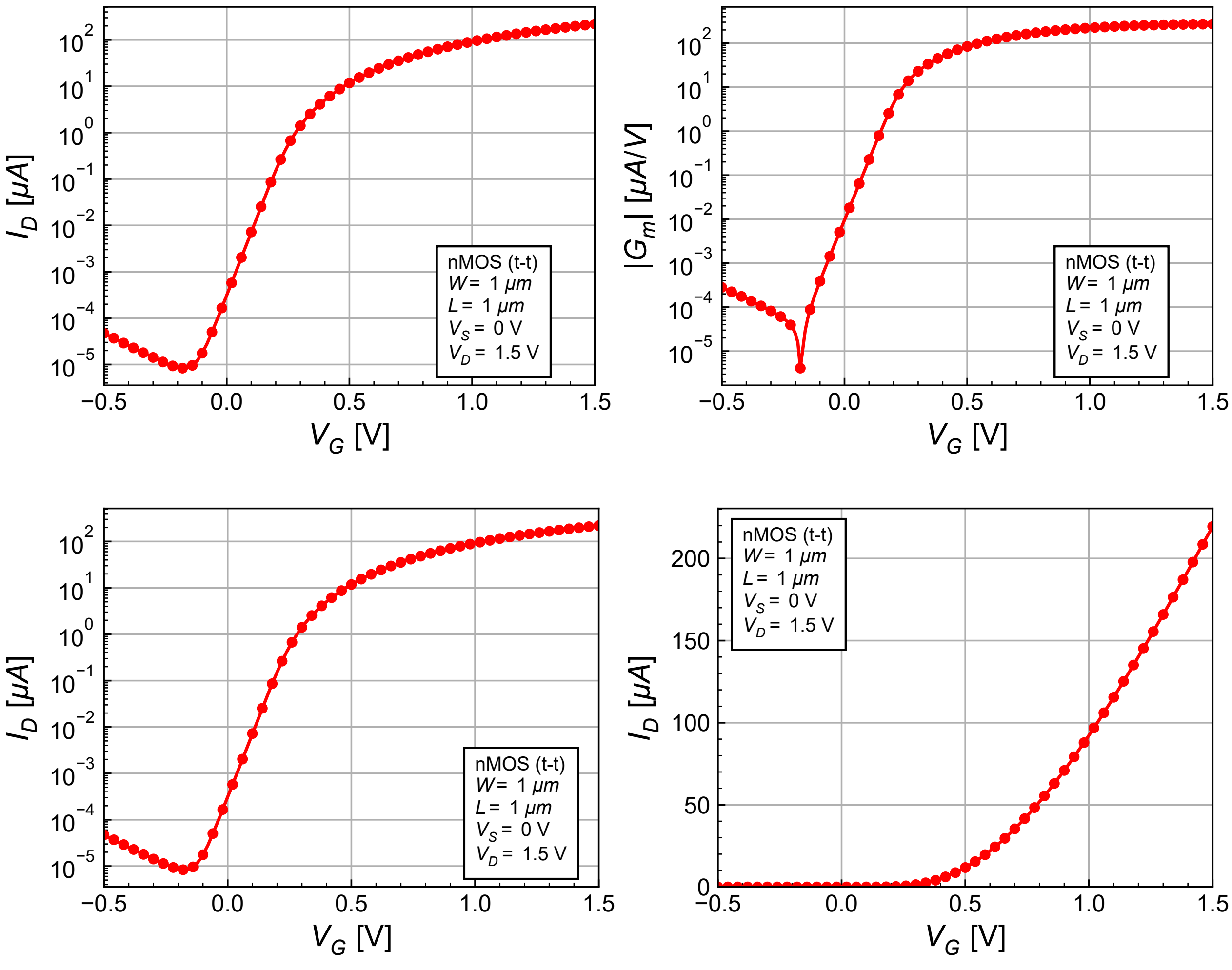
# 4 Medium-channel parameters

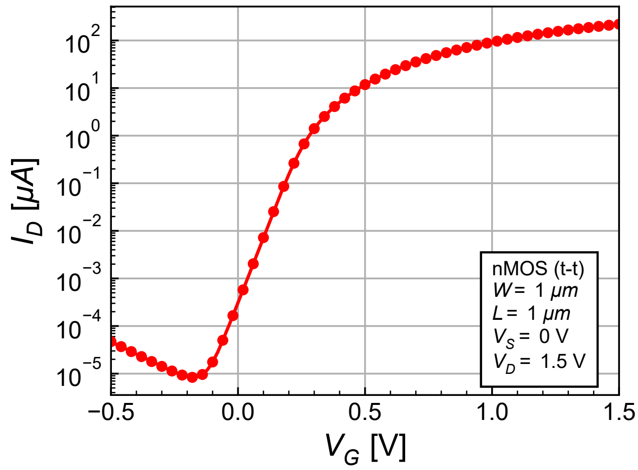
## 4.1 DC Transfer Characteristic Parameters

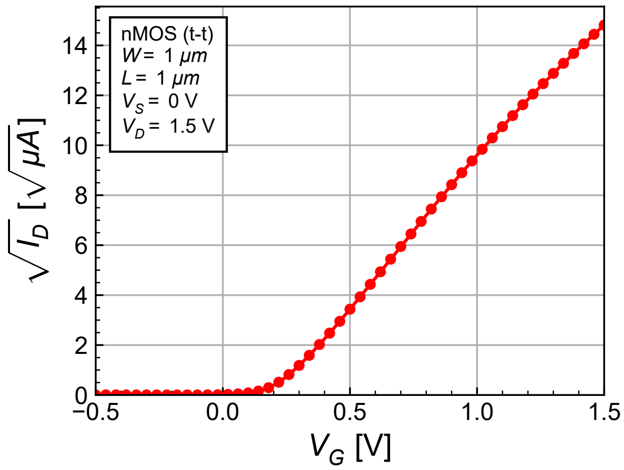
### 4.1.1 Generating the data

### 4.1.2 Importing and plotting the data

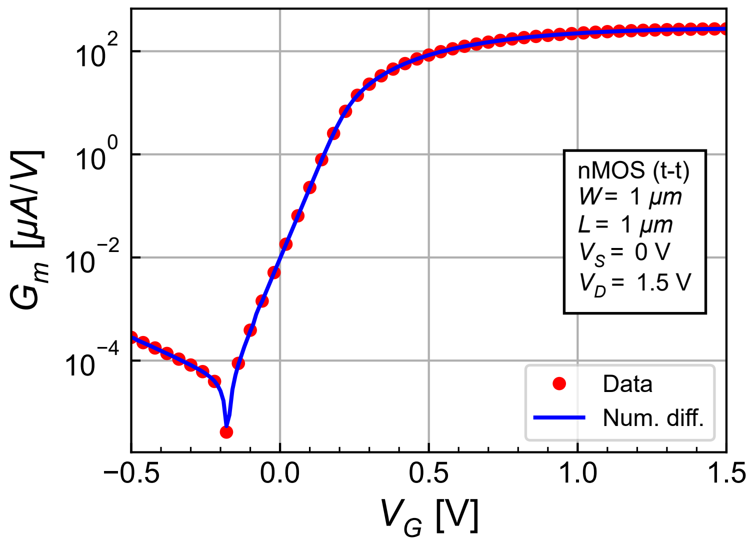
#### 4.1.2.1 $I_D$ and $G_m$ versus $V_G$





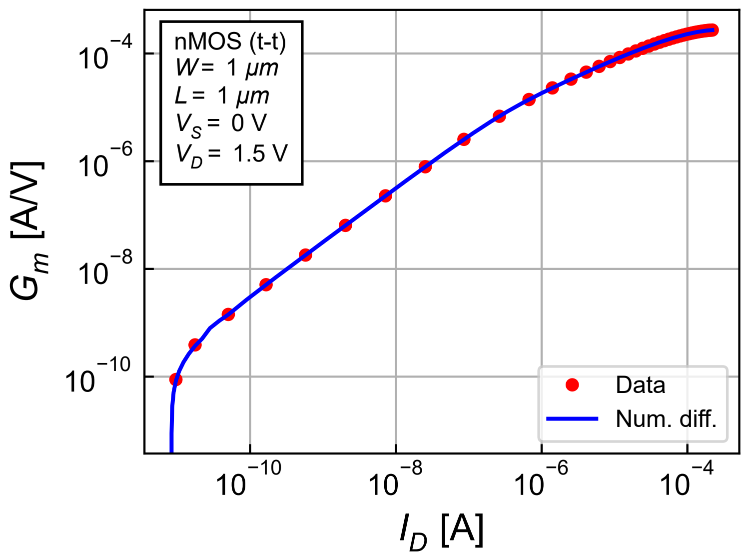




#### 4.1.2.2 $G_m$-$V_G$

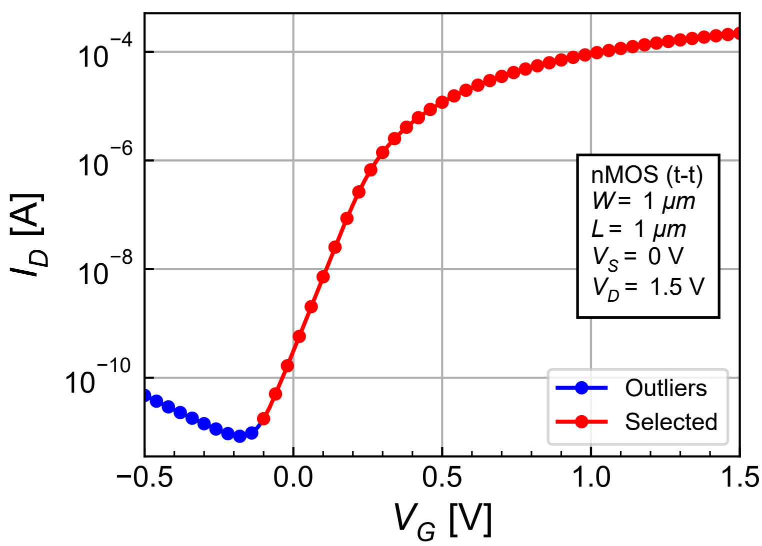


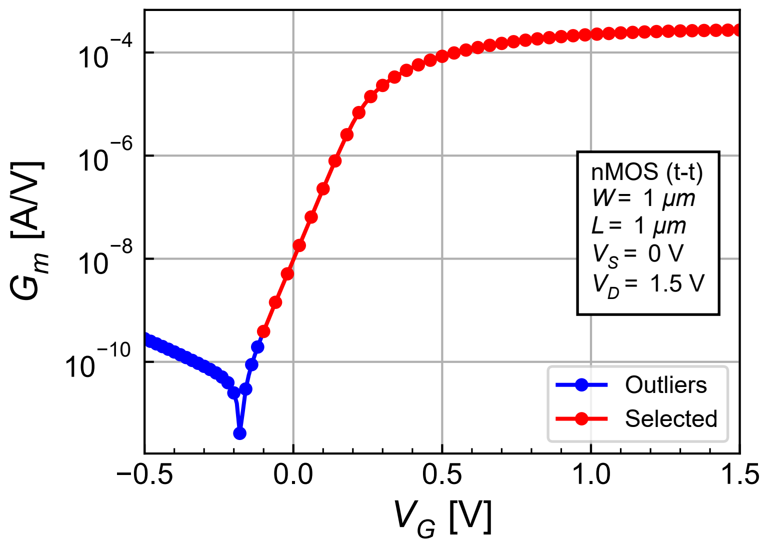

We see that the transconductance obtained by differentiating the large-signal $I_D$-$V_G$ characteristic is equal to the transconductance extracted from the PSP model. We will keep the value extracted from the PSP model.

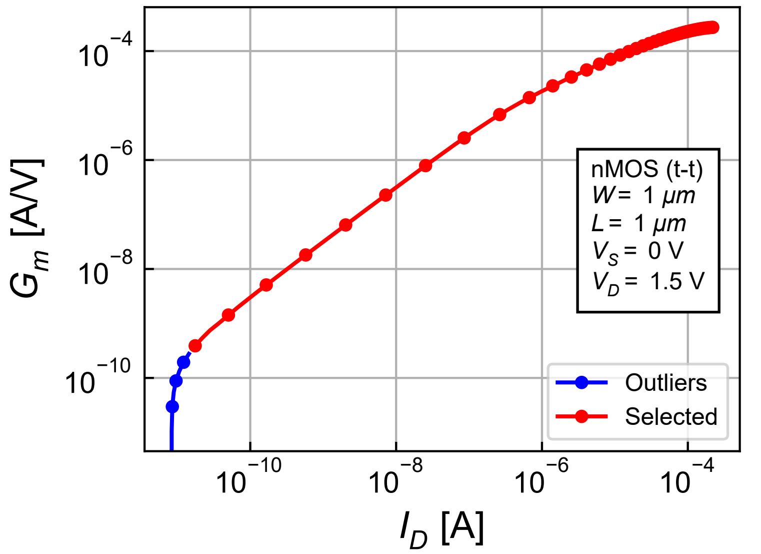
#### 4.1.2.3 $G_m$-$I_D$




#### 4.1.2.4 Filtering the outliers






### 4.1.3 Direct extraction with $\lambda_c = 0$

#### 4.1.3.1 Slope factor $n$ and $I_{spec}$ extraction

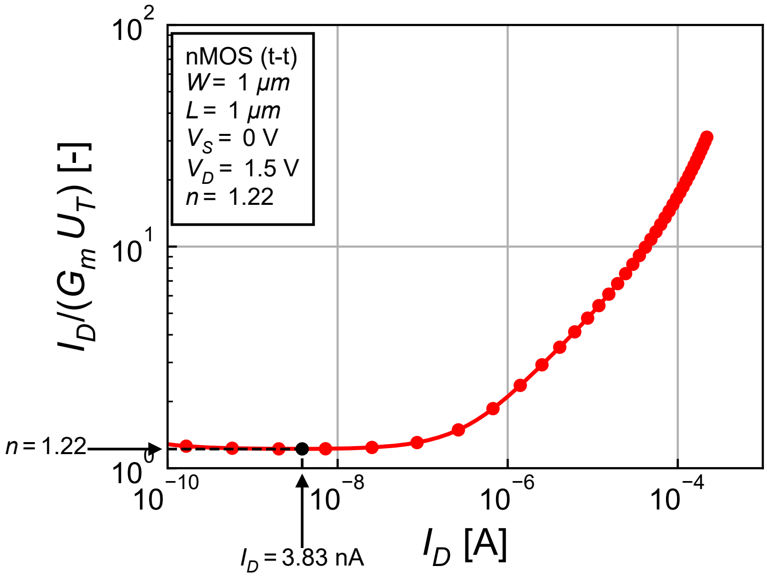
The gate transconductance in weak inversion and saturation is given by

$$G_m = \frac{I_D}{n\,U_T}. \tag{4.1}$$

So if we plot $I_D/(G_m\,U_T)$ we should see a plateau in weak inversion the value of which is equal to the slope factor $n$.

$n = 1.22$

$I_{D,ext} = 3.83\ nA$




On the other hand the normalized $G_m/I_D$ function for a long-channel transistor in strong inversion and saturation is given by

$$\frac{G_m\, n\, U_T}{I_D} = \frac{1}{\sqrt{IC}} = \sqrt{\frac{I_{spec}}{I_D}}. \tag{4.2}$$

We can then plot $(G_m\, n\, U_T)^2/I_D$ which should find a maximum value equal to $I_{spec}$.

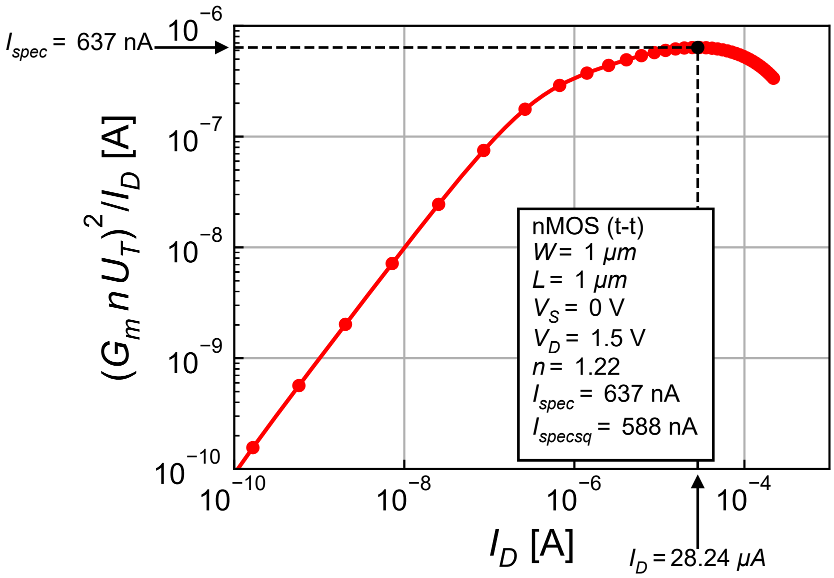
$W_{eff} = 1.020\ \mu m$

$L_{eff} = 0.941\ \mu m$

$I_{spec} = 637\ nA$

$I_{spec\square} = 588\ nA$

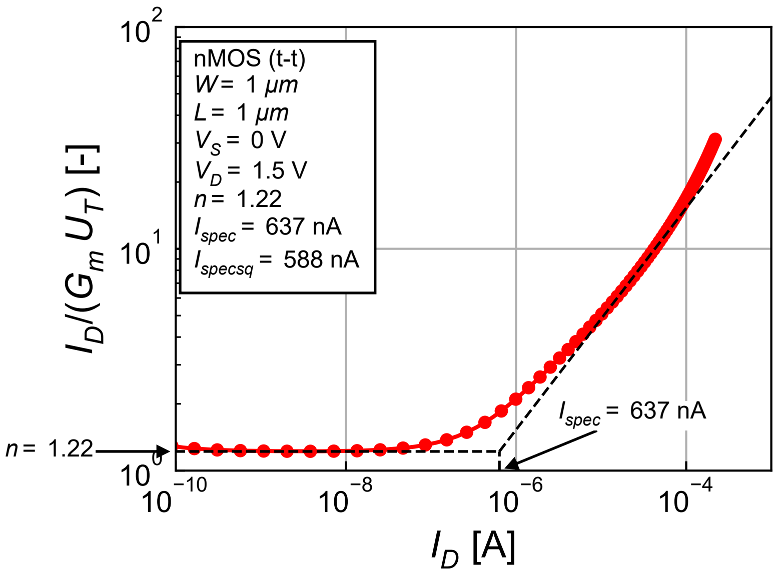
$I_{D,ext} = 28.245\ \mu A$




$n = 1.22$

$I_{spec} = 637\ nA$

$I_{spec\square} = 588\ nA$




Having extracted $n$ and $I_{spec}$, we can now plot the normalized $G_m/I_D$ function.

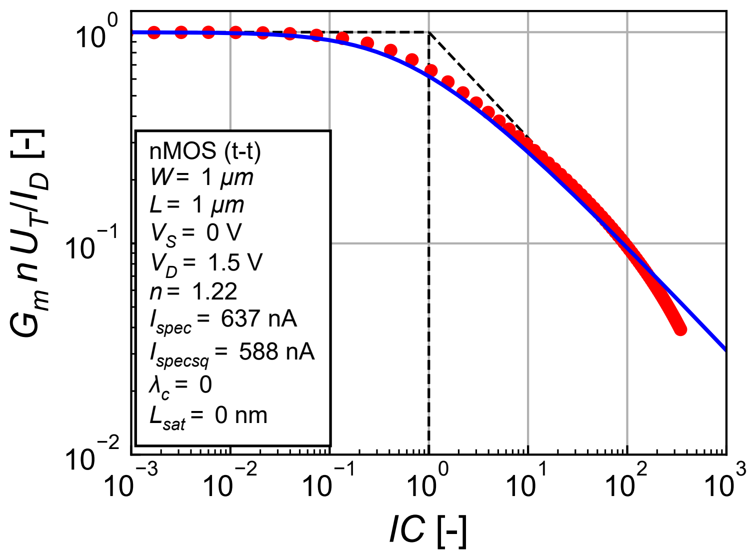
$n = 1.22$

$I_{spec} = 637\ nA$

$I_{spec\square} = 588\ nA$

$\lambda_c = 0$

$L_{sat} = 0$




The fit is reasonable over the entire $IC$ span. There is some discrepancy in the moderate inversion region which is due to the mobility reduction due to the vertical field appearing for $IC > 10^2$. The latter can be accounted for by using the $\lambda_c$ parameter which is normally used for modeling the effect of velocity saturation in short-channel transistor but can also be used to correct the effect of mobility reduction due to the vertical field appearing in long-channel transistors. We will not do this here since we want to extract the long-channel parameters keeping $\lambda_c = 0$, but since we are mostly interested in the moderate inversion region, we can slightly increase $I_{spec}$ to improve the fit in moderate inversion at the cost of a degradation in strong inversion.

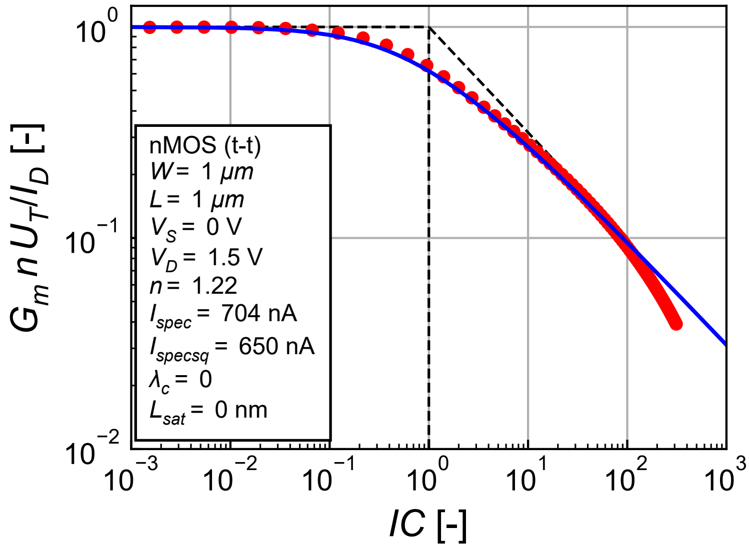
$n = 1.22$

$I_{spec\square} = 650\ nA$

$I_{spec} = 704\ nA$

$\lambda_c = 0$

$L_{sat} = 0$




The fit is now much better in moderate inversion but less in strong inversion. This is due to mobility reduction due to the vertical field an effect that is not accounted for in the model. However, we will keep the new values.

#### 4.1.3.2 Threshold voltage extraction

We can extract the threshold voltage in weak inversion (assuming $V_S = 0$) from the normalized current (inversion coefficient) given by

$$IC = e^{\frac{V_G - V_{T0}}{nU_T}}. \tag{4.3}$$

We can now plot

$$V_{T0} = V_G - nU_T \ln(IC) \tag{4.4}$$

to extract the threshold voltage.

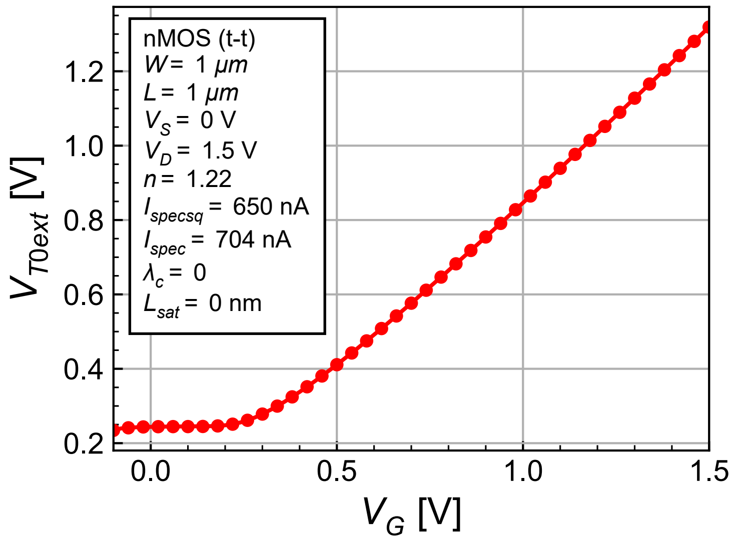
$n = 1.22$

$I_{spec} = 704\ nA$

$I_{spec\square} = 650\ nA$

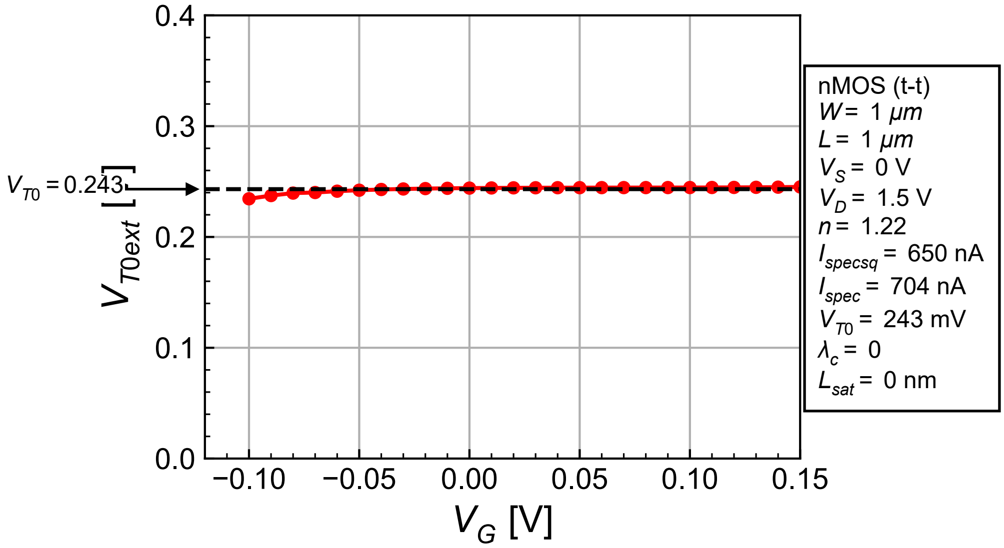
$\lambda_c = 0$

$L_{sat} = 0$




We see a plateau in weak inversion where we can average its value to get the threshold voltage in weak inversion.

$V_{T0,wi} = 243$ mV




The threshold voltage for this wide and long device is surprisingly small. It is in accordance with the documentation giving a typical-typical $V_{TH} \cong 200\, mV$ for $W = 10\, \mu m$ and $L = 10\, \mu m$.

We can now plot the $I_D$-$V_G$ for this threshold voltage.

$n = 1.22$

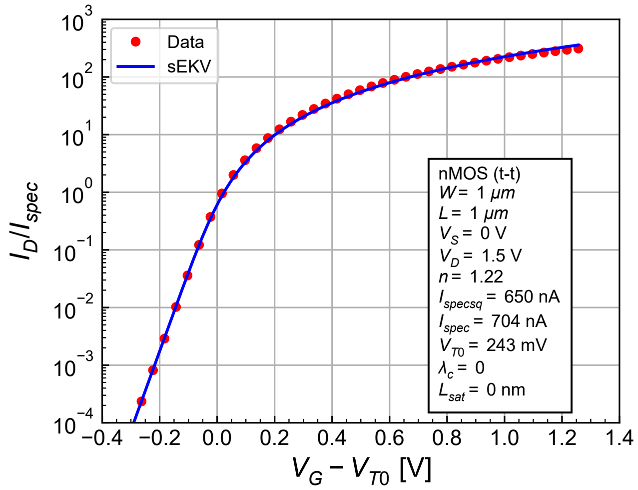
$I_{spec} = 704\ nA$

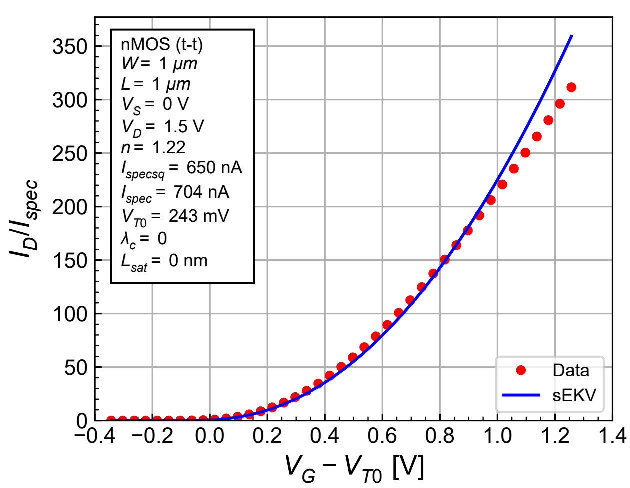
$I_{spec\square} = 650\ nA$

$\lambda_c = 0$

$L_{sat} = 0$

$V_{T0,wi} = 243$ mV




We get a reasonable fit with some deviations in the moderate inversion, which is expected since we fitted with the asymptotes.

#### 4.1.3.3 Summary

$n = 1.22$

$I_{spec} = 704\ nA$

$I_{spec\square} = 650\ nA$

$V_{T0,wi} = 243$ mV

$\lambda_c = 0$

$L_{sat} = 0$

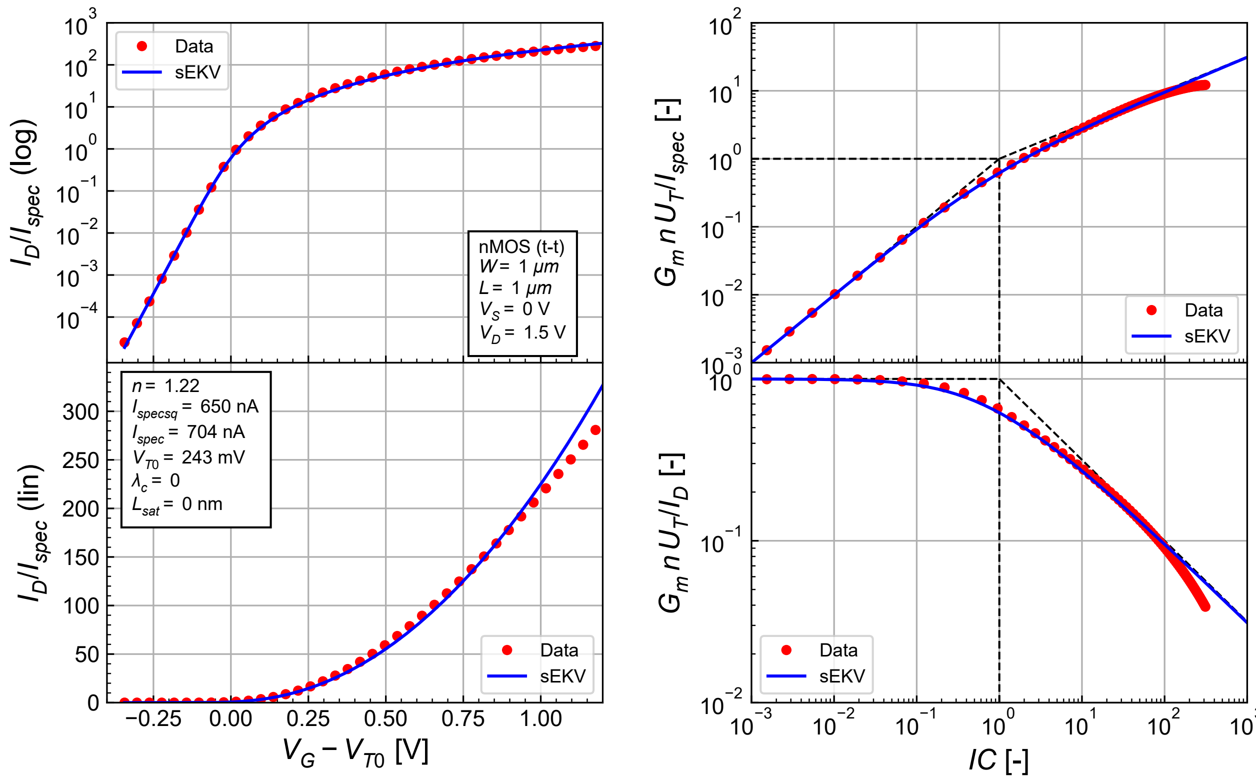


Table 4.1: Direct extraction of the sEKV parameters for the medium-channel transistor v

| | W | Weff | L | Leff | n | Ispecsq | VT0 | lambdac | Lsat |
|---|---|---|---|---|---|---|---|---|---|
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.210e+00 | 8.100e-07 | 1.746e-01 | 0.000e+00 | 0.000e |
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.210e+00 | 8.173e-07 | 1.733e-01 | 0.000e+00 | 0.000e |
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.272e+00 | 8.500e-07 | 1.733e-01 | 5.500e-02 | 5.468e |
| medium | 1.000e-06 | 1.020e-06 | 1.000e-06 | 9.412e-07 | 1.220e+00 | 6.500e-07 | 2.431e-01 | 0.000e+00 | 0.000e |

### 4.1.4 Extraction using optimization with $\lambda_c = 0$

#### 4.1.4.1 Slope factor $n$ and $I_{spec}$ extraction

We can try to extract $n$ and $I_{spec}$ for a long-channel directly from the normalized $G_m/I_d$ function.

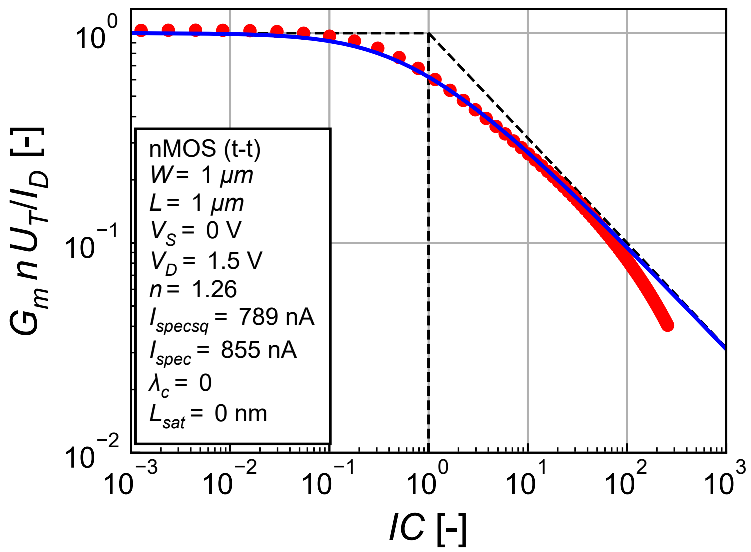
$n = 1.26$

$I_{spec} = 855\ nA$

$I_{spec\square} = 789\ nA$

$\lambda_c = 0$

$L_{sat} = 0$




We get a reasonable fit and values that similar to the direct extraction.

We can also try to keep the value of $n$ extracted from the direct extraction above and optimize for $I_{spec}$ only.

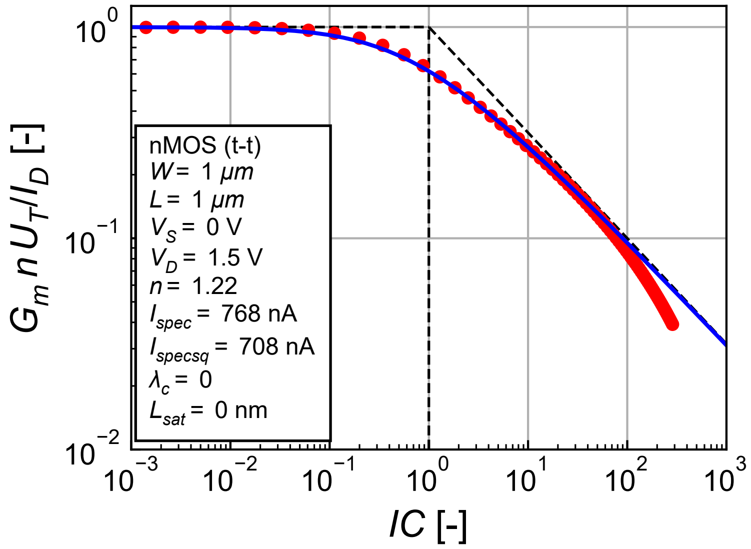
$n = 1.22$

$I_{spec} = 768\ nA$

$I_{spec\square} = 708\ nA$

$\lambda_c = 0$

$L_{sat} = 0$




The fit is good in weak and moderate inversion, but we still have some discrepancies in strong inversion which is due to mobility reduction due to the vertical field. We will keep the last extracted values for $I_{specsq}$.

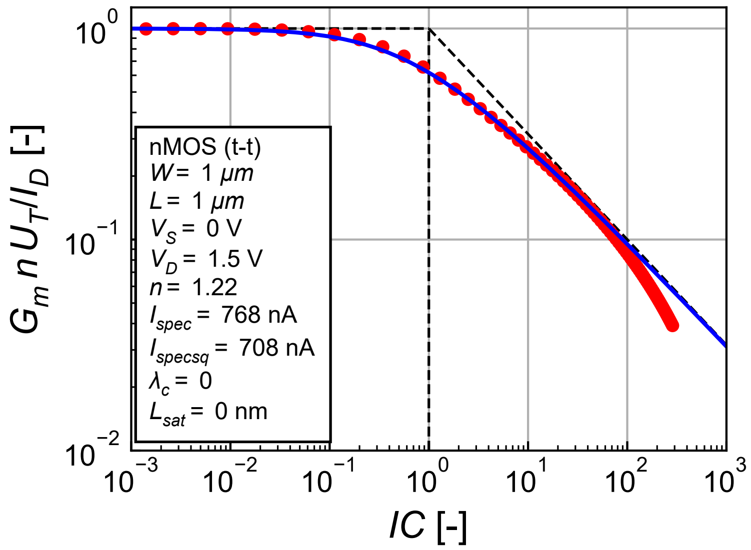
$n = 1.22$

$I_{spec} = 768\ nA$

$I_{spec\square} = 708\ nA$

$\lambda_c = 0$

$L_{sat} = 0$




#### 4.1.4.2 Threshold voltage extraction

$n = 1.22$

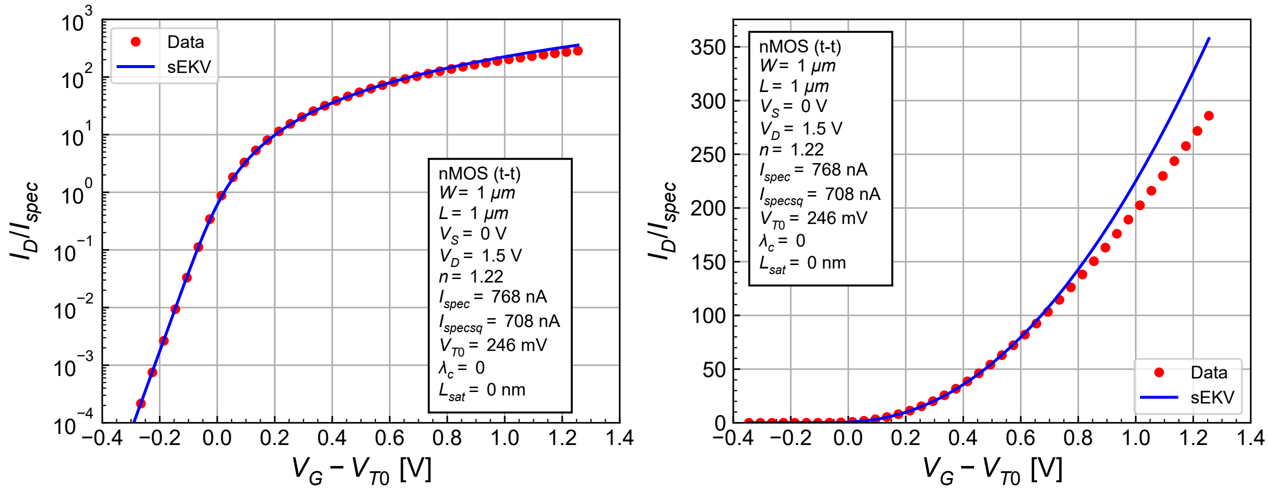
$I_{spec} = 768\ nA$

$I_{spec\square} = 708\ nA$

$V_{T0} = 246$ mV

$\lambda_c = 0$

$L_{sat} = 0$




We see a reasonable fit except in strong inversion. This is expected since we optimized the moderate inversion region.

#### 4.1.4.3 Summary

$n = 1.22$

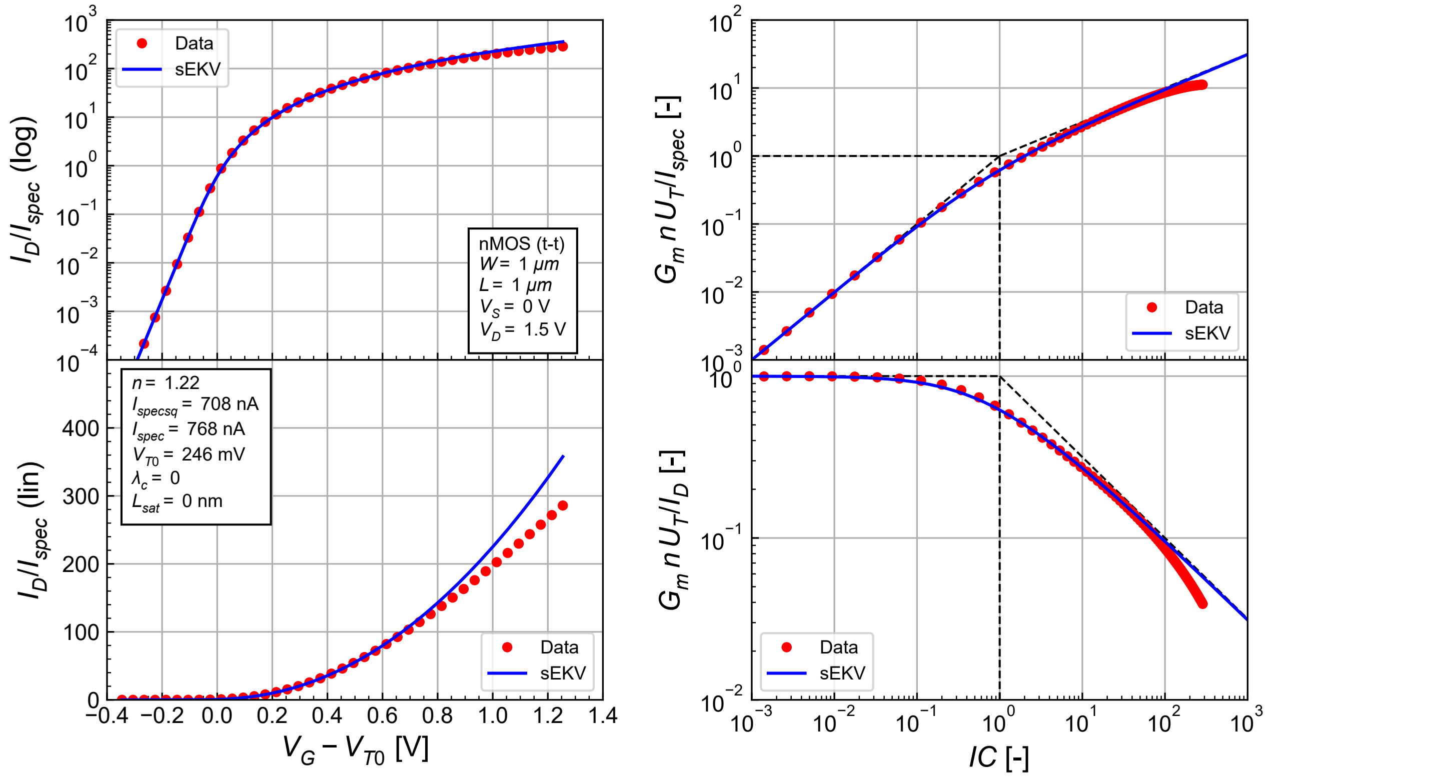
$I_{spec} = 768\ nA$

$I_{spec\square} = 708\ nA$

$V_{T0} = 246$ mV

$\lambda_c = 0$

$L_{sat} = 0$




The extraction using curve-fitting gives a better fit in moderate inversion but less in strong inversion.

Table 4.2: Extraction of the sEKV parameters by optimization for the medium-channel tra
$\lambda_c = 0$.

| | W | Weff | L | Leff | n | Ispecsq | VT0 | lambdac | Lsat |
|---|---|---|---|---|---|---|---|---|---|
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.210e+00 | 8.100e-07 | 1.746e-01 | 0.000e+00 | 0.000e |
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.210e+00 | 8.173e-07 | 1.733e-01 | 0.000e+00 | 0.000e |
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.272e+00 | 8.500e-07 | 1.733e-01 | 5.500e-02 | 5.468e |
| medium | 1.000e-06 | 1.020e-06 | 1.000e-06 | 9.412e-07 | 1.220e+00 | 6.500e-07 | 2.431e-01 | 0.000e+00 | 0.000e |
| medium | 1.000e-06 | 1.020e-06 | 1.000e-06 | 9.412e-07 | 1.220e+00 | 7.083e-07 | 2.456e-01 | 0.000e+00 | 0.000e |

### 4.1.5 Extraction using optimization with $\lambda_c > 0$

We start extracting $n$, $I_{spec}$ and $\lambda_c$ using curve fitting on $G_m/I_D$.

$n = 1.27$

$I_{spec} = 953\ nA$

$I_{spec\square} = 953\ nA$

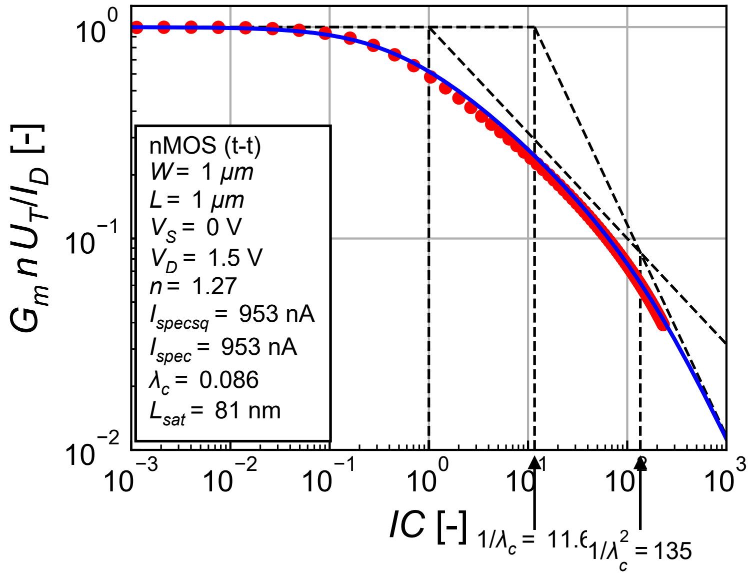
$V_{T0} = 246$ mV

$\lambda_c = 0$

$L_{sat} = 81$

$1/\lambda_c = 12$

$1/\lambda_c^2 = 135$




We now have a good fit in strong inversion that we can still improve by slightly reducing the value of $I_{specsq}$, which seems too high and $\lambda_c$.

$n = 1.27$

$I_{spec} = 867\ nA$

$I_{spec\square} = 800\ nA$

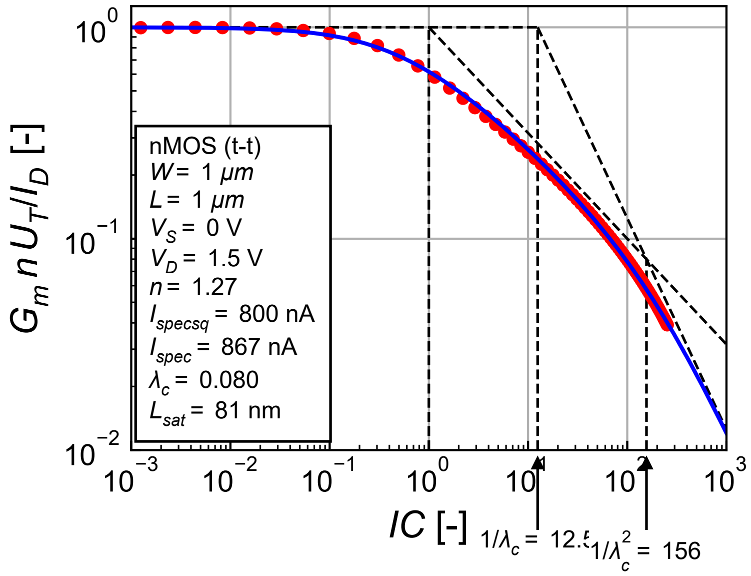
$V_{T0} = 246$ mV

$\lambda_c = 0.080$

$L_{sat} = 81$

$1/\lambda_c = 12$

$1/\lambda_c^2 = 156$




We now have an almost perfect fit.

#### 4.1.5.1 Summary

We can now check the large and small-signal characteristics.

$n = 1.27$

$I_{spec} = 867\ nA$

$I_{spec\square} = 800\ nA$

$V_{T0} = 246$ mV

$\lambda_c = 0.080$

$L_{sat} = 81$

$1/\lambda_c = 12$

$1/\lambda_c^2 = 156$

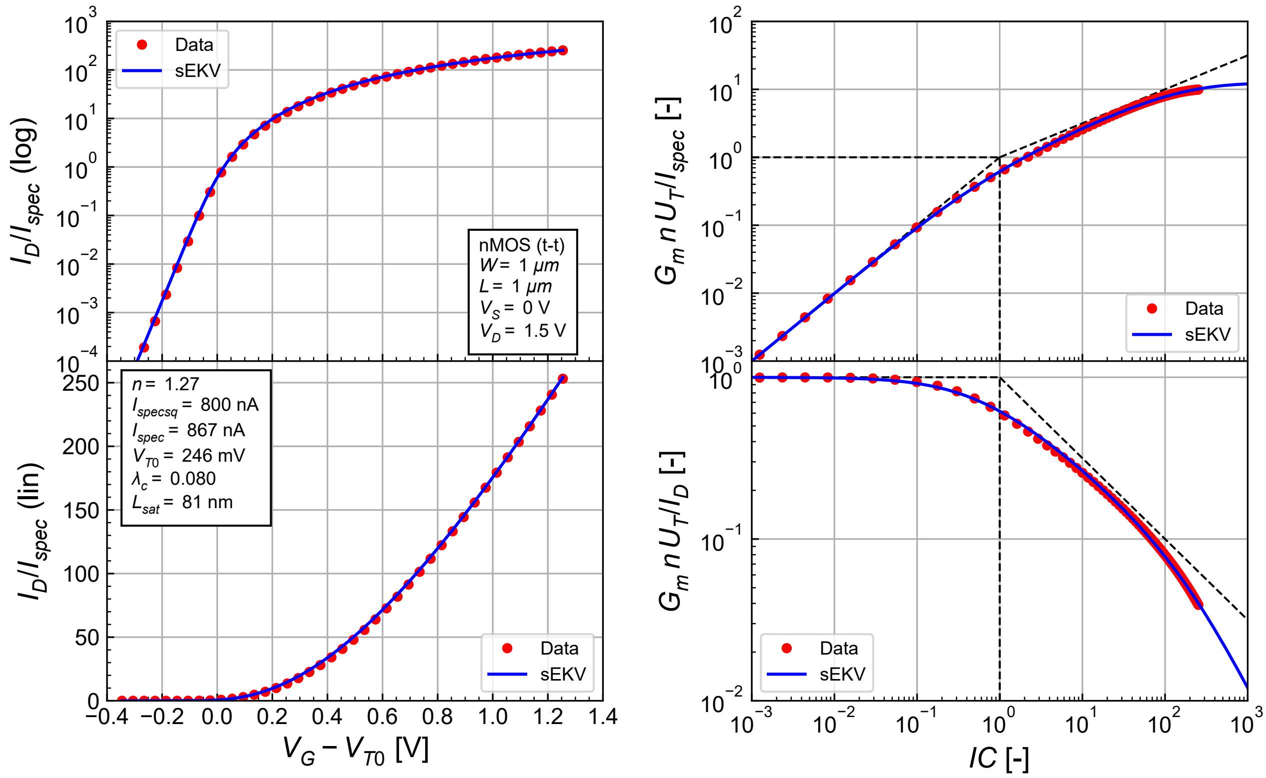



Table 4.3: Extraction of the sEKV parameters by optimization for the medium-channel tra
$\lambda_c > 0$.

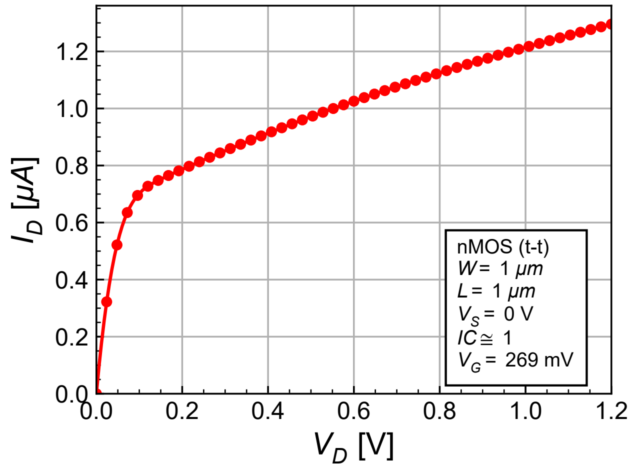
| | W | Weff | L | Leff | n | Ispecsq | VT0 | lambdac | Lsat |
|---|---|---|---|---|---|---|---|---|---|
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.210e+00 | 8.100e-07 | 1.746e-01 | 0.000e+00 | 0.000e |
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.210e+00 | 8.173e-07 | 1.733e-01 | 0.000e+00 | 0.000e |
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.272e+00 | 8.500e-07 | 1.733e-01 | 5.500e-02 | 5.468e |
| medium | 1.000e-06 | 1.020e-06 | 1.000e-06 | 9.412e-07 | 1.220e+00 | 6.500e-07 | 2.431e-01 | 0.000e+00 | 0.000e |
| medium | 1.000e-06 | 1.020e-06 | 1.000e-06 | 9.412e-07 | 1.220e+00 | 7.083e-07 | 2.456e-01 | 0.000e+00 | 0.000e |
| medium | 1.000e-06 | 1.020e-06 | 1.000e-06 | 9.412e-07 | 1.266e+00 | 8.000e-07 | 2.456e-01 | 8.000e-02 | 8.089e |

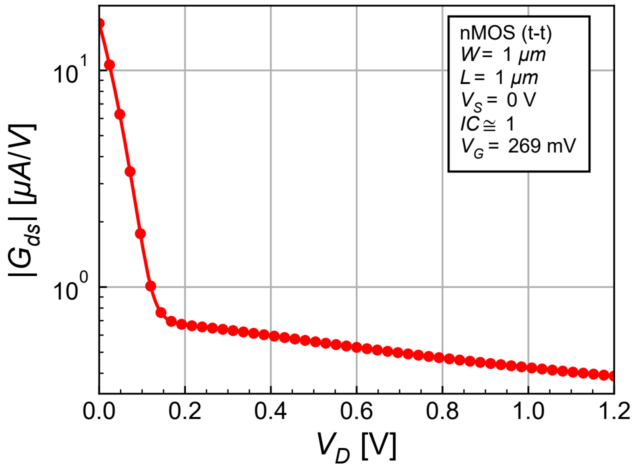
## 4.2 Output characteristic

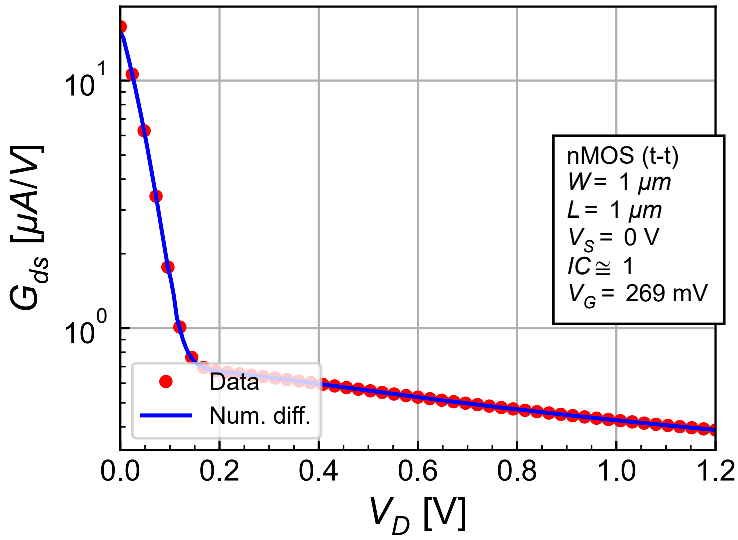
### 4.2.1 Generating the data

### 4.2.2 Importing and plotting the data

#### 4.2.2.1 $I_D$ and $G_{ds}$ versus $V_D$

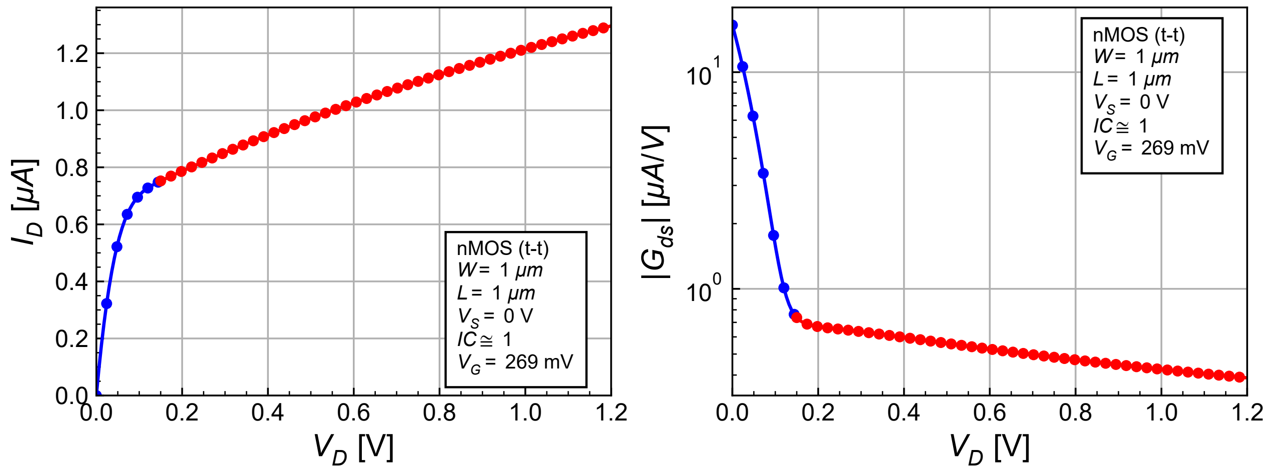



The output conductance calculated by differentiating the large-signal $I_D$-$V_D$ matches the value extracted from the PSP model. We will keep the value from PSP.

#### 4.2.2.2 Filtering the outliers



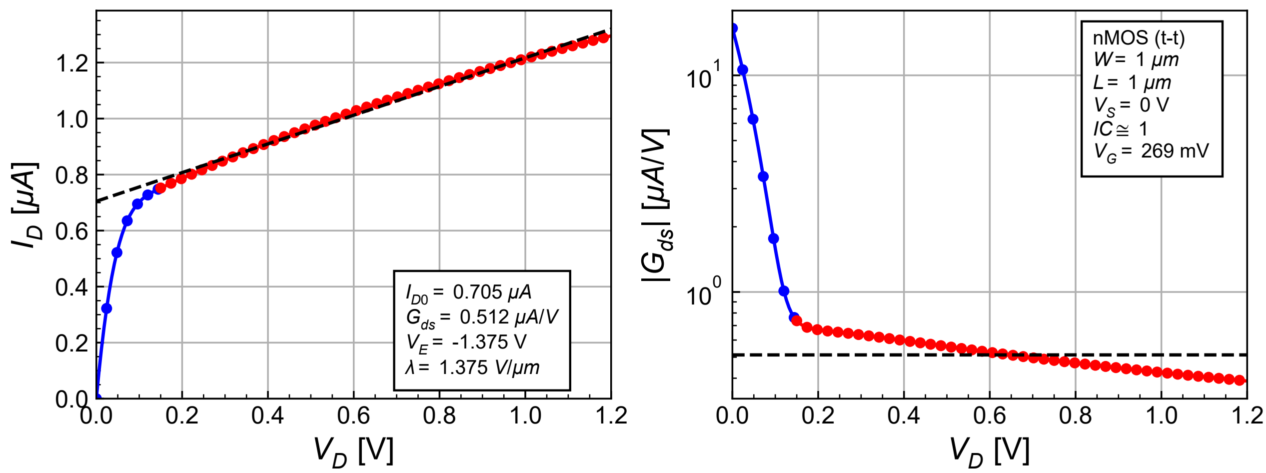

### 4.2.3 Extracting the CLM parameter

$G_{ds} = 0.512\ \mu A/V$

$I_{D0} = 0.705\ \mu A$

$V_E$ = -1.375 $V$

$\lambda = 1.375\ V/\mu m$




We get a rather high output conductance and hence low value of the $\lambda$ parameter for such a long transistor.

Table 4.4: CLM parameters extracted for the medium-channel transistor in moderate inversion.

| | W | Weff | L | Leff | IC | Gds | ID0 | VE | lambda |
|---|---|---|---|---|---|---|---|---|---|
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1 | 2.105e-07 | 6.119e-07 | -2.907e+00 | 2.907e+05 |
| medium | 1.000e-06 | 1.020e-06 | 1.000e-06 | 9.412e-07 | 1 | 5.124e-07 | 7.048e-07 | -1.375e+00 | 1.375e+06 |

## 4.3 Noise

In this section we will extract the flicker noise parameters to be used with sEKV and check the white noise power spectral desnity (PSD). We reuse the flicker noise model from EKV 2.6, where the input (gate) referred PSD is given by

$$S_{nin,fl}(f) = \frac{KF}{W_{eff}\, L_{eff}\, C_{ox}\; f^{AF}} \tag{4.5}$$

In this model the flicker noise is assumed to scale as $1/C_{ox}$, which is correct if the noise follows the the Hooge model (i.e. originates from mobility fluctuations). In the case of the Mc Worther model (i.e. flicker noise originating from traps in Si-SiO$_2$ interface and in the oxyde), the PSD scales as $C_{ox}^2$. Despiet the flicker noise is usually domanted by the trapping mechanism, we will keep the above model with a $1/C_{ox}$ scaling.

In EKV , we like to rewrite the flicker noise PSD like the thermal noise in terms of a input-referred noise resistance

$$S_{nin,fl}(f) = 4kT\, R_{nin,fl}(f) \tag{4.6}$$

where

$$R_{nin,fl}(f) = \frac{\rho}{W_{eff}\, L_{eff}\, f^{AF}} \tag{4.7}$$

with

$$\rho = \frac{KF}{4kT\, C_{ox}} \tag{4.8}$$

Note that the flicker noise parameter have some weird units. Indeed, $KF$ is in $A \cdot V \cdot s^{2-AF}$ and $\rho$ is in $V \cdot m^2/(A \cdot s^{AF})$. If $AF = 1$, like it is often the case, then $KF$ is in $A \cdot V \cdot s$ and $\rho$ is in $V \cdot m^2/(A \cdot s)$.

To extract the noise parameters, we use a common-source stage loaded by a noiseless resistor. We first will set the bias condition in terms of $IC$ and calculate the input-referred white noise to compare it to the result obtained from the PSP simulations.

### 4.3.1 Setting bias conditions

Having extracted $n$, $I_{spec\square}$ and $V_{T0}$, we can impose the inversion coefficient and calculate the corresponding gate voltage $V_G$. We nee to make sure the transistor remains in saturation.

$W = 1\ \mu m$

$L = 1\ \mu m$

$IC = 1$

$I_D = 0.768\ \mu A$

$V_G = 0.269\ V$

$V_S = 0.000\ V$

$G_m = 15.036\ \mu A/V$

$\gamma_n = 0.688$

$R_{n,th} = 45.736\ k\Omega$

$S_{n,th} = 7.581\text{e-}16\ V^2/Hz$

$V_{n,th} = 27.534\ nV/\sqrt{Hz}$

$A_v = 10$

$R_L = 665.085\ k\Omega$

$V_{DD} = 1.500\ V$

$V_{RL} = 0.511\ V$

$V_{DS} = 0.989\ V$

$V_{DSsat} = 0.116\ V$

```
The transistor is biased in the saturation region
```

### 4.3.2 Extract operating point information

We can extract the values of the PSP noise parameters from the operating point informations.

$V_{n,th} = 29.790\ nV/\sqrt{Hz}$ (PSP)

$f_k = 168.143\ kHz$ (PSP)

$KF = 2.208\text{e-}24\ VAs$ (PSP)

$\rho = 0.009\ Vm^2/(As)$ (PSP)

$AF = 1.000$ (PSP)

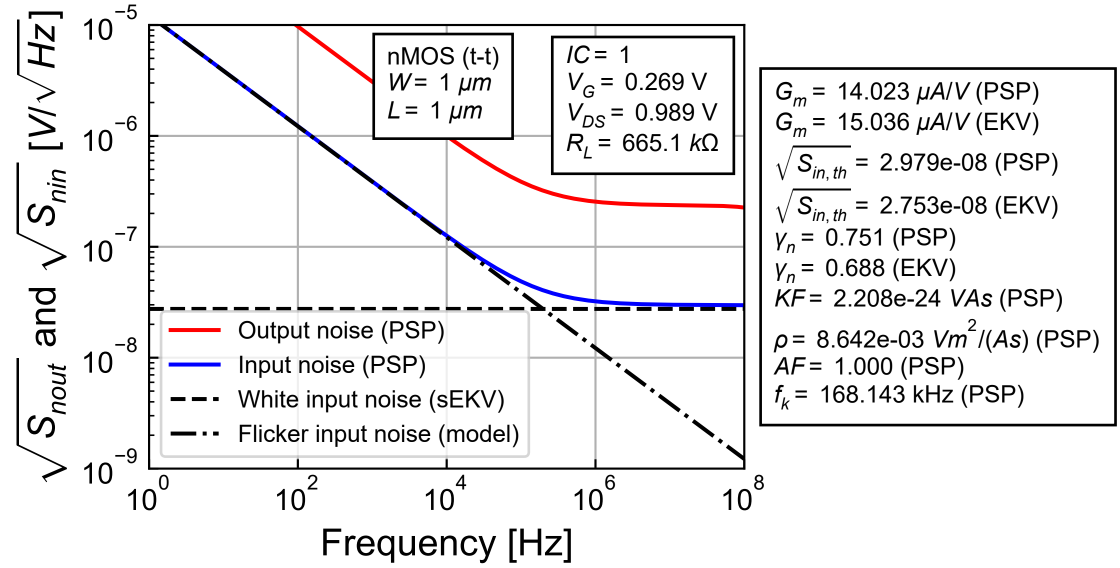
$R_{n,th} = 53.538\ k\Omega$ (PSP)

$\gamma_n = 0.751$ (PSP)

| | Weff | Leff | IDS | Gm | Gds | Snidth | Vninth | Snidfl @ 1Hz | Vninfl @ |
|---|---|---|---|---|---|---|---|---|---|
| Mn | 1.020e-06 | 9.412e-07 | 6.936e-07 | 1.402e-05 | 2.666e-07 | 1.745e-25 | 2.979e-08 | 2.934e-20 | 3.863e-07 |

### 4.3.3 Simulating noise PSD

We can now simulate the PSD and check against the EKV model.




The flicker noise parameters are given by

Table 4.6: Extraction of the noise parameters for the medium-channel transistor.

| | W | Weff | L | Leff | IC | KF | AF | rho | Comment |
|---|---|---|---|---|---|---|---|---|---|
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1 | 3.175e-24 | 1.000e+00 | 1.243e-02 | moderate |
| medium | 1.000e-06 | 1.020e-06 | 1.000e-06 | 9.412e-07 | 1 | 2.208e-24 | 1.000e+00 | 8.642e-03 | moderate |

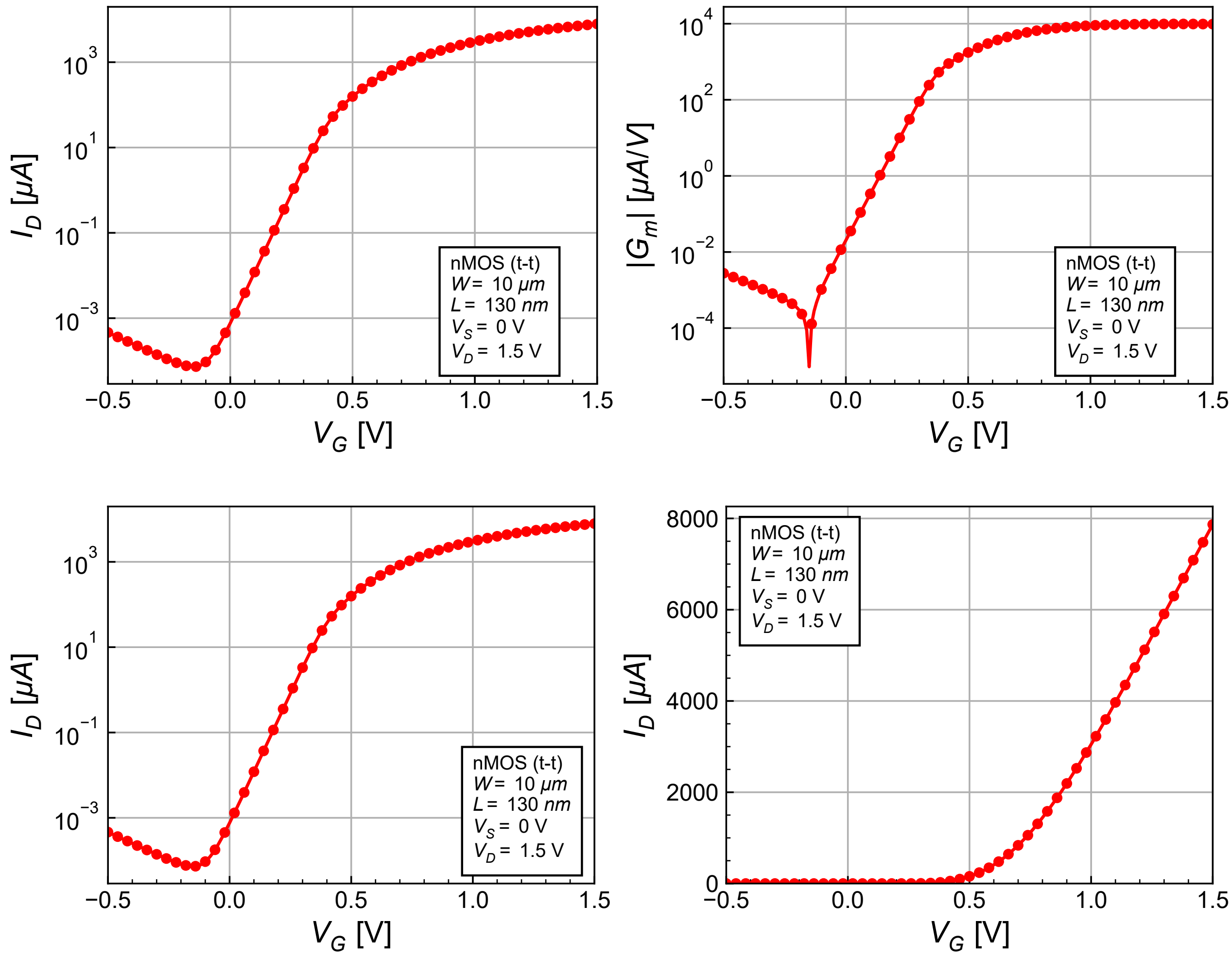
# 5 Short-channel parameters

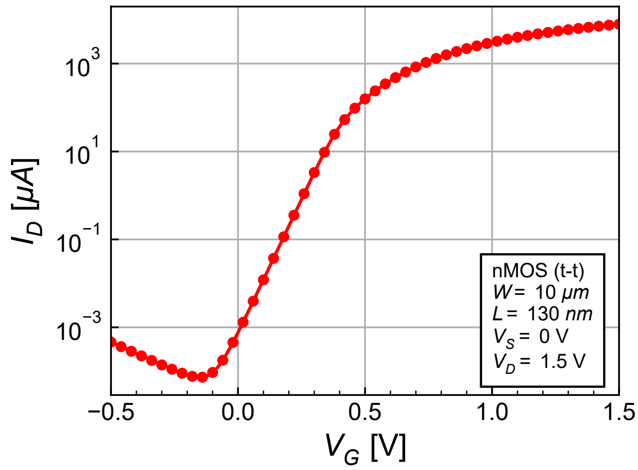
## 5.1 DC Transfer Characteristic Parameters

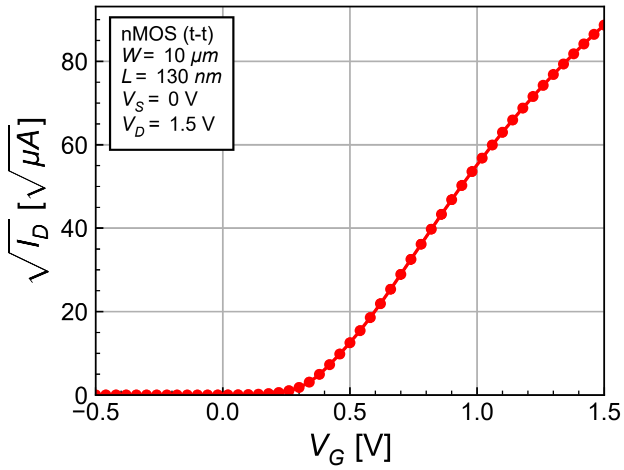
### 5.1.1 Generating the data

### 5.1.2 Importing and plotting the data

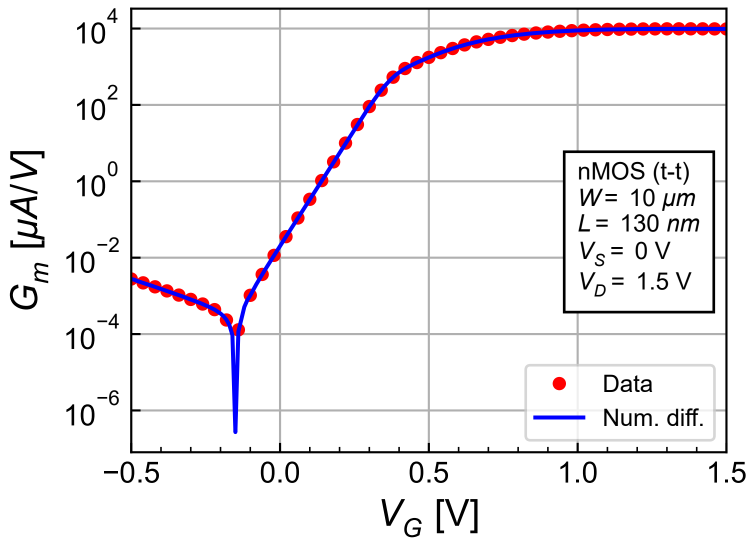
#### 5.1.2.1 $I_D$ and $G_m$ versus $V_G$





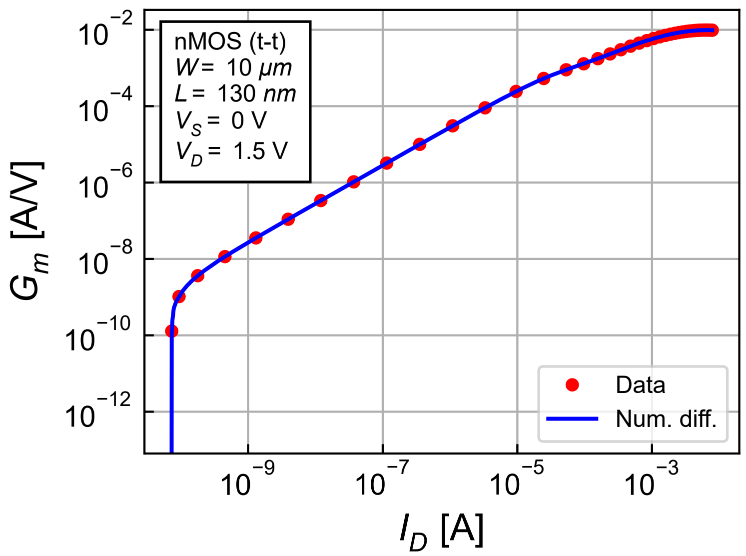




#### 5.1.2.2 $G_m$-$V_G$

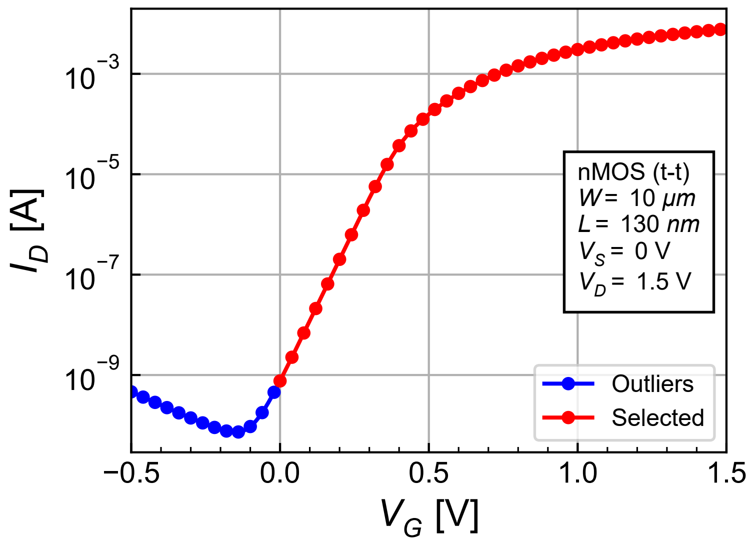


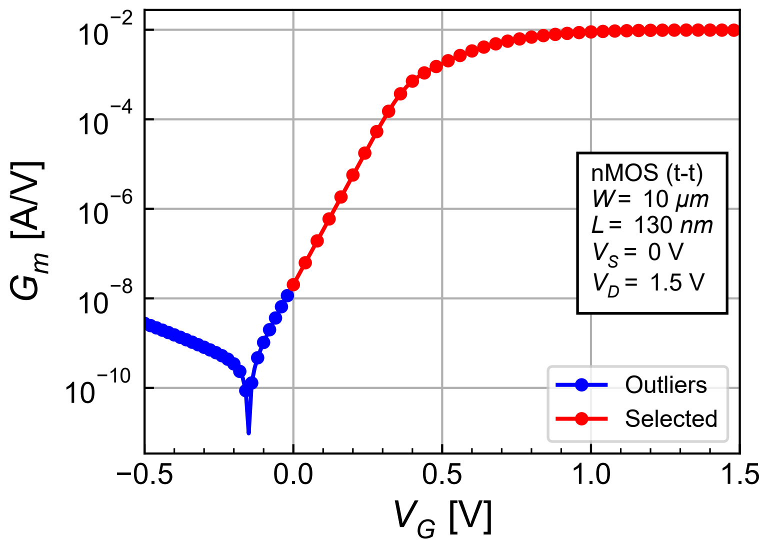

We see that the transconductance obtained by differentiating the large-signal $I_D$-$V_G$ characteristic is equal to the transconductance extracted from the PSP model. We will keep the value extracted from the PSP model.

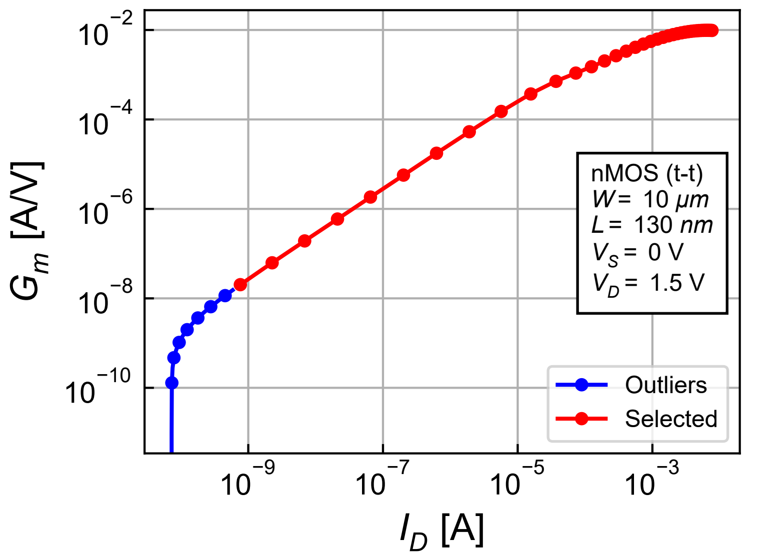
#### 5.1.2.3 $G_m$-$I_D$




#### 5.1.2.4 Filtering the outliers






## 5.2 Direct extraction with $\lambda_c = 0$

### 5.2.1 Slope factor $n$ and $I_{spec}$ extraction

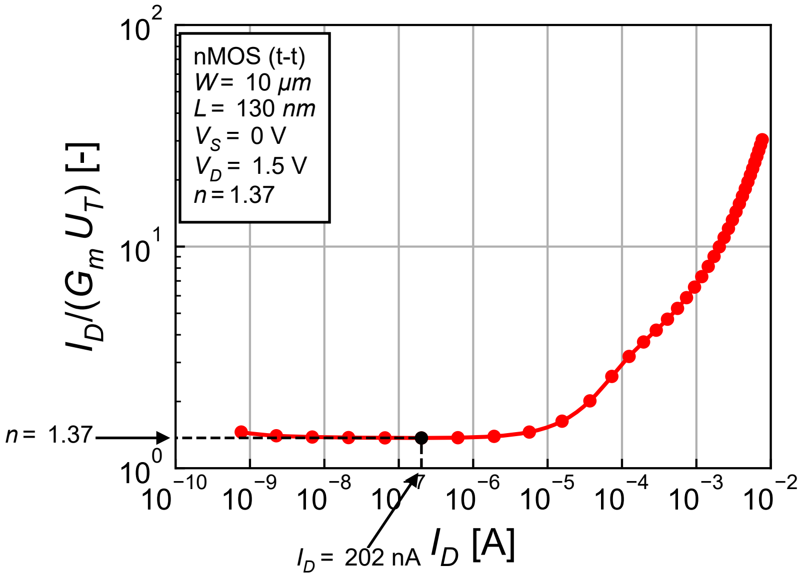
The gate transconductance in weak inversion and saturation is given by

$$G_m = \frac{I_D}{n\,U_T}. \tag{5.1}$$

So if we plot $I_D/(G_m\,U_T)$ we should see a plateau in weak inversion the value of which is equal to the slope factor $n$.

$n = 1.37$

$I_{D,ext} = 201.63\ nA$



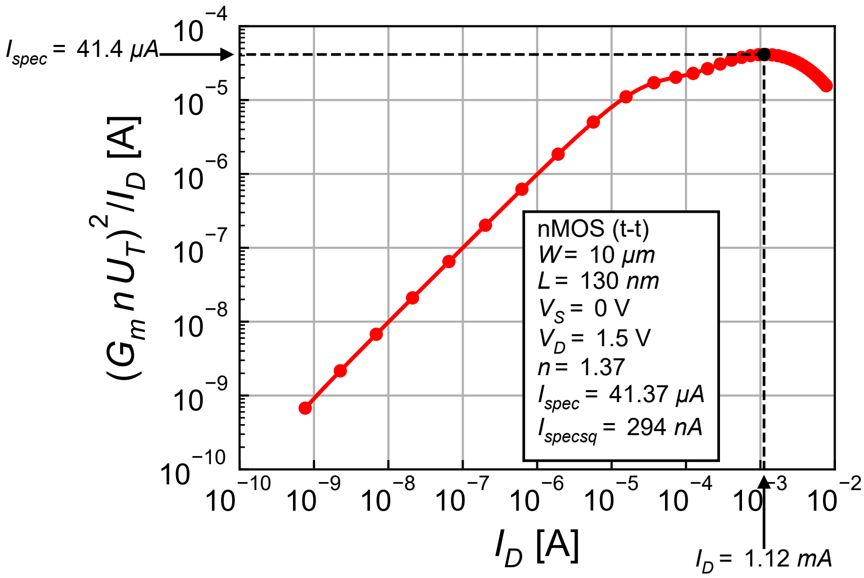

$W_{eff} = 10.020\ \mu m$

$L_{eff} = 71.154\ nm$

$I_{spec} = 41.374\ \mu A$

$I_{spec\square} = 294\ nA$

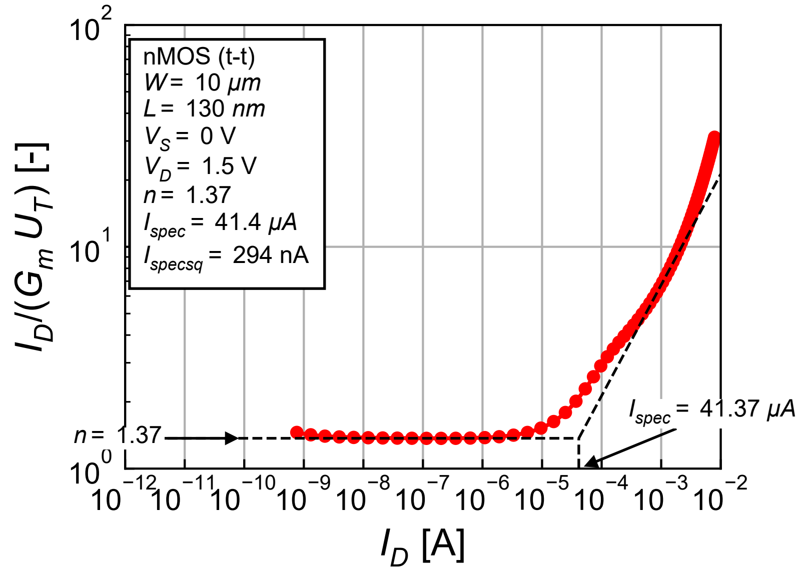
$I_{D,ext} = 1.119\ mA$




$n = 1.37$

$I_{spec} = 41.374\ \mu A$

$I_{spec\square} = 294\ nA$




Having extracted $n$ and $I_{spec}$, we can now plot the normalized $G_m/I_D$ function.

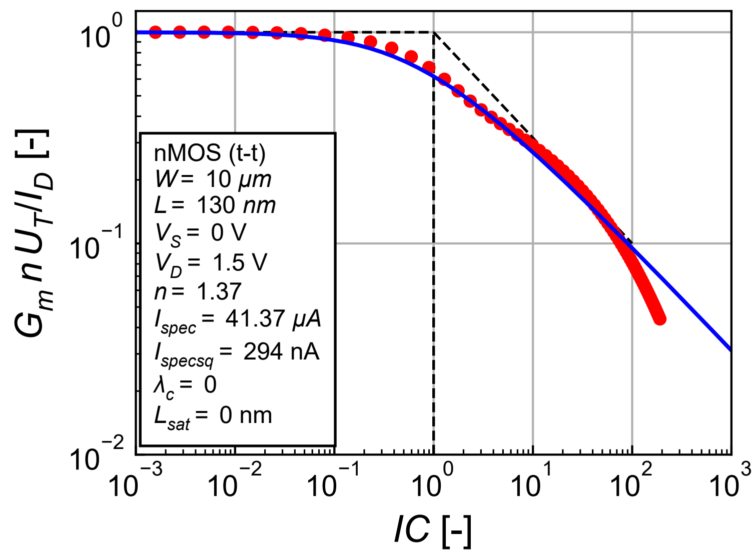
$n = 1.37$

$I_{spec} = 41\ \mu A$

$I_{spec\square} = 294\ nA$

$\lambda_c = 0$

$L_{sat} = 0$




The fit is reasonable over the entire $IC$ span. There is a strange bump in the moderate inversion which comes from the simulation data. There is some discrepancy in the moderate inversion region which is due to the mobility reduction due to the vertical field appearing for $IC > 10^2$. The latter can be accounted for by using the $\lambda_c$ parameter which is normally used for modeling the effect of velocity saturation in short-channel transistor but can also be used to correct the effect of mobility reduction due to the vertical field appearing in long-channel transistors. We will not do this here since we want to extract the long-channel parameters keeping $\lambda_c = 0$, but since we are mostly interested in the moderate inversion region, we can slightly increase $I_{spec}$ to improve the fit in moderate inversion at the cost of a degradation in strong inversion.

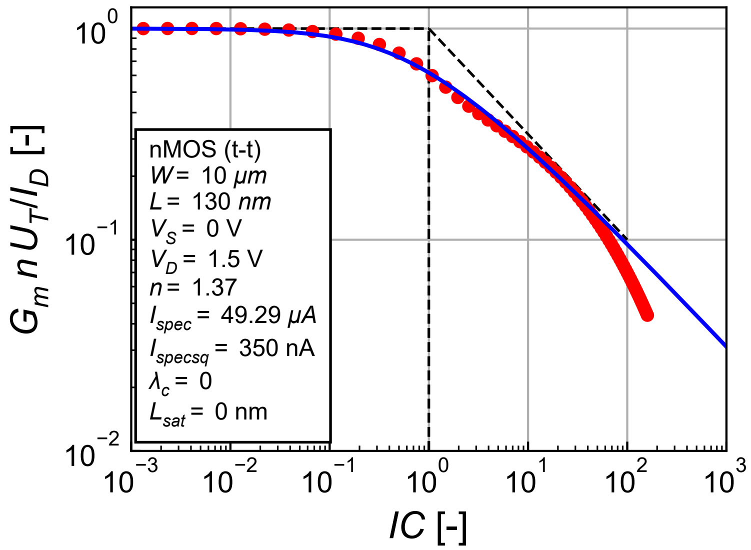
$n = 1.37$

$I_{spec} = 49\ \mu A$

$I_{spec\square} = 350\ nA$

$\lambda_c = 0$

$L_{sat} = 0$




The fit is now much better in moderate inversion but less in strong inversion. This is due to mobility reduction due to the vertical field an effect that is not accounted for in the model. However, we will keep the new values.

### 5.2.2 Threshold voltage extraction

We can extract the threshold voltage in weak inversion (assuming $V_S = 0$) from the normalized current (inversion coefficient) given by

$$IC = e^{\frac{V_G - V_{T0}}{nU_T}}. \tag{5.2}$$

We can now plot

$$V_{T0} = V_G - nU_T \ln(IC) \tag{5.3}$$

to extract the threshold voltage.

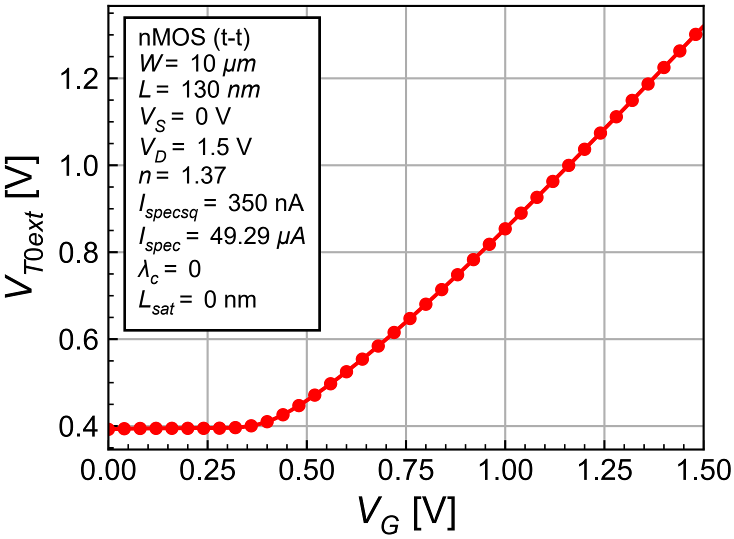
$n = 1.37$

$I_{spec} = 49\ \mu A$

$I_{spec\square} = 350\ nA$

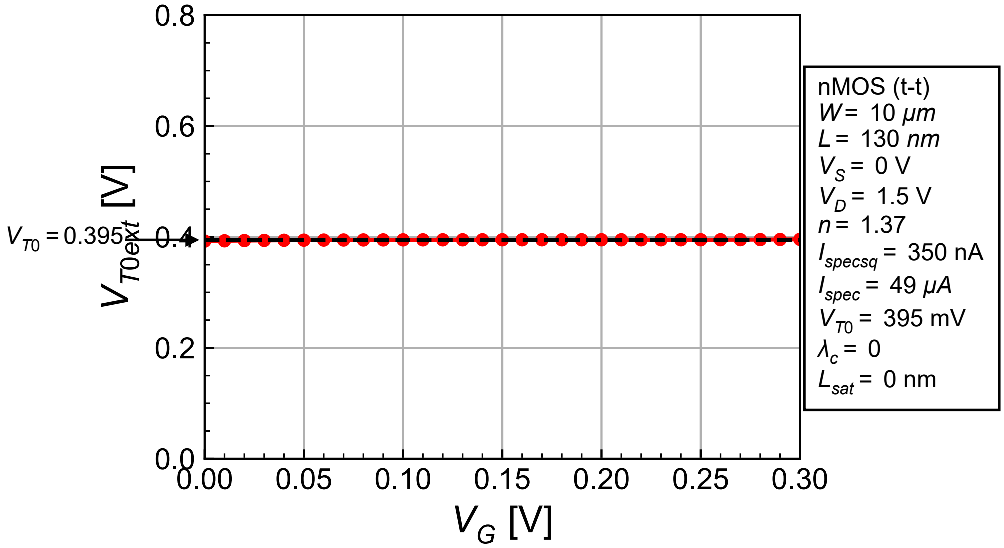
$\lambda_c = 0$

$L_{sat} = 0$




We see a plateau in weak inversion where we can average its value to get the threshold voltage in weak inversion.

$V_{T0,wi} = 395$ mV




The threshold voltage for this wide and short device is smaller than what is given in the documentation giving a typical-typical $V_{TH} \cong 500\,mV$ for $W = 10\,\mu m$ and $L = 130\,nm$.

We can now plot the $I_D$-$V_G$ for this threshold voltage.

$n = 1.37$

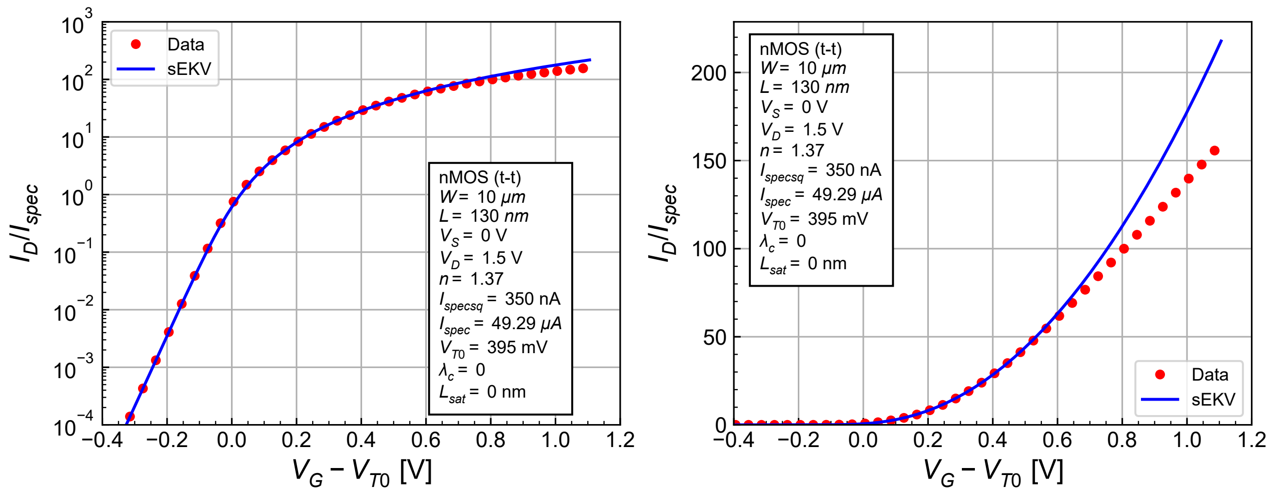
$I_{spec} = 49287\ nA$

$I_{spec\square} = 350\ nA$

$\lambda_c = 0$

$L_{sat} = 0$

$V_{T0} = 395$ mV




We get a reasonable fit in weak and moderate inversion. However, there is a strong deviation in strong inversion due to short channel effects (mainly velocity saturation).

### 5.2.3 Summary

$n = 1.37$

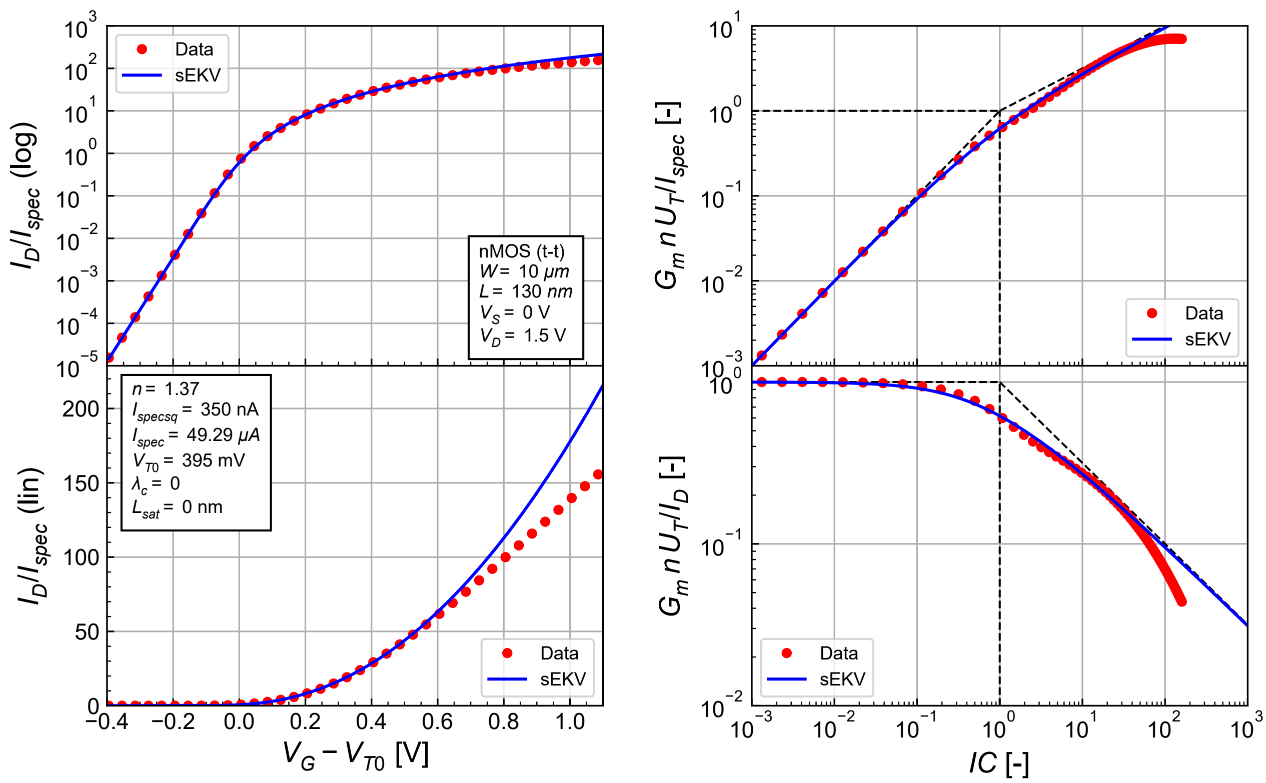
$I_{spec} = 49287\ nA$

$I_{spec\square} = 350\ nA$

$V_{T0} = 395$ mV

$\lambda_c = 0$

$L_{sat} = 0$



We see a big discrepancy in moderate and even larger in strong inversion. This explain the discrepancy between model and simulations for short-channel transistors when using the long-channel model with $\lambda_c = 0$.

### 5.2.4 Direct extraction with $\lambda_c > 0$

#### 5.2.4.1 Slope factor $n$ extraction

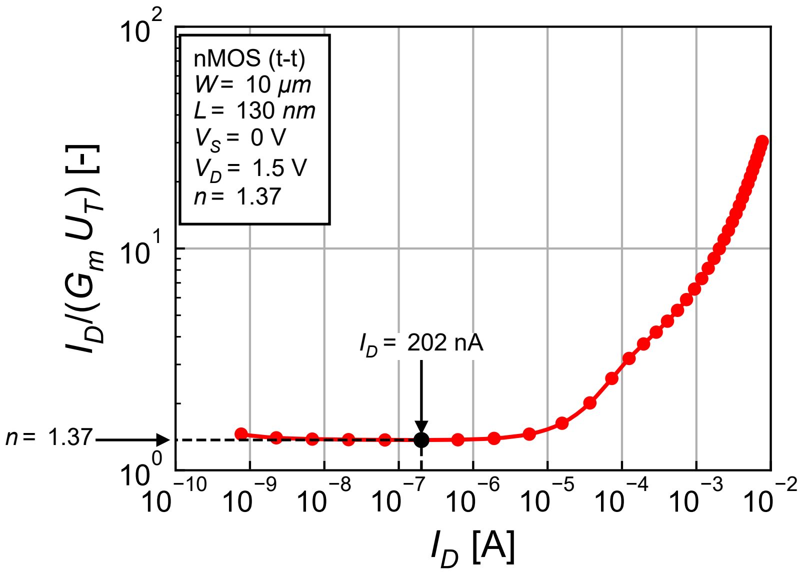
The gate transconductance in weak inversion and saturation is given by

$$G_m = \frac{I_D}{n\,U_T}. \tag{5.4}$$

So if we plot $I_D/(G_m)\,U_T$ we should see a plateau in weak inversion the value of which is equal to the slope factor $n$.

$n = 1.37$

$I_{D,ext} = 201.63\ nA$




#### 5.2.4.2 Specific current $I_{spec}$ extraction

On the other hand the normalized $G_m/I_D$ function for a long-channel transistor in strong inversion and saturation is given by

$$\frac{G_m\,n\,U_T}{I_D} = \frac{1}{\sqrt{IC}} = \sqrt{\frac{I_{spec}}{I_D}}. \tag{5.5}$$

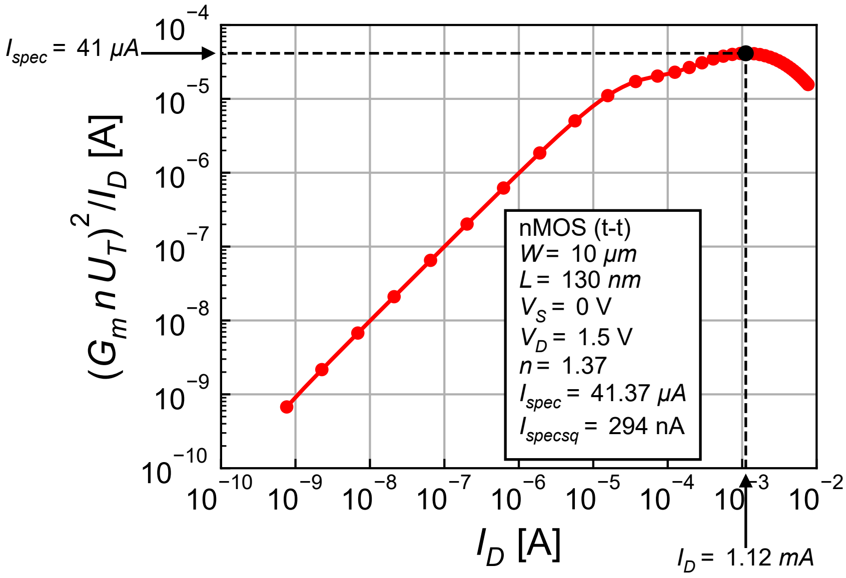
We can then plot $(G_m\,n\,U_T)^2/I_D$ which should find a maximum value equal to $I_{spec}$.

$n = 1.37$

$I_{spec} = 41.374\ \mu A$

$I_{spec\square} = 294\ nA$

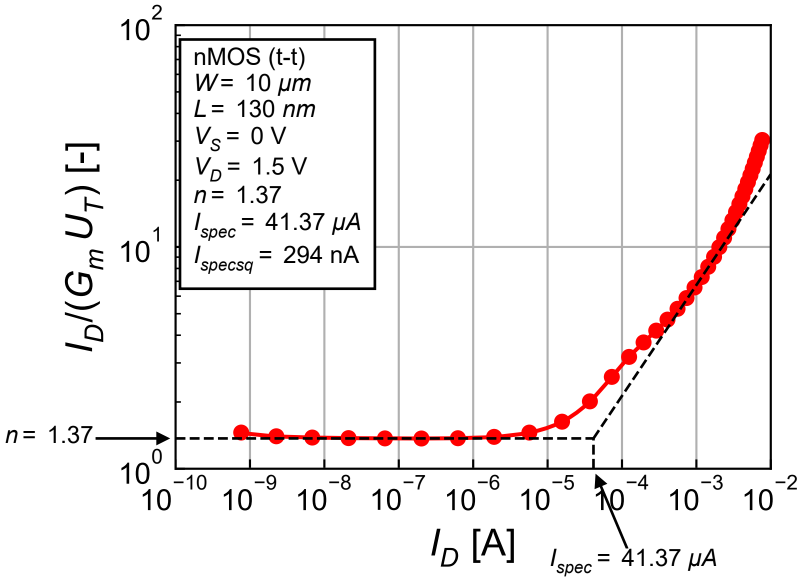
$I_{D,ext} = 1.119\ mA$




$n = 1.37$

$I_{spec} = 41\ \mu A$

$I_{spec\square} = 294\ nA$




#### 5.2.4.3 Velocity saturation parameter $\lambda_c$ extraction

We can extract $\lambda_c$ by looking at the asymptote in very strong inversion. For a short-channel transistor in strong inversion and saturation, the normalized $G_m/I_D$ is given by

$$\frac{G_m\, n\, U_T}{I_D} = \frac{1}{\lambda_c\, IC} = \frac{I_{spec}}{\lambda_c\, I_D}. \tag{5.6}$$

So if we plot $I_{spec}/(G_m\, n\, U_T)$ it will have a minimum at $\lambda_c$.

$n = 1.37$

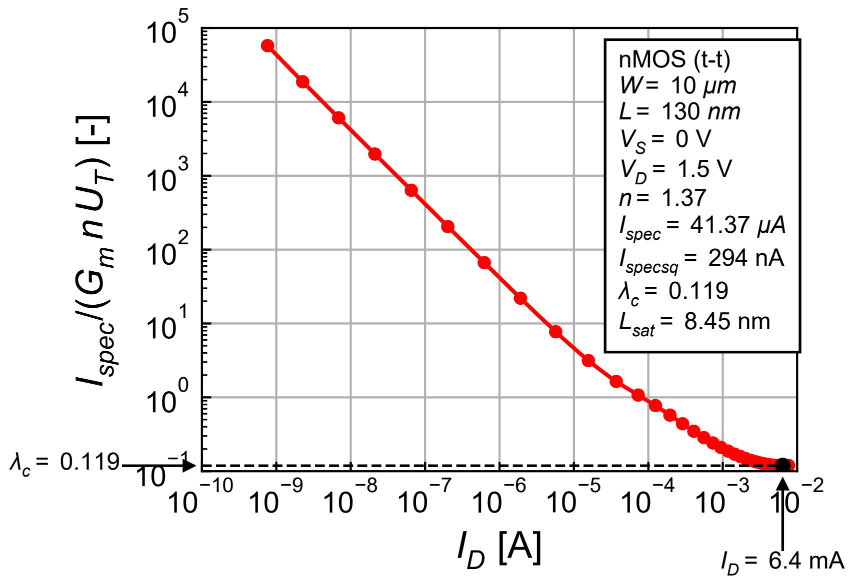
$I_{spec} = 41.374\ \mu A$

$I_{spec\square} = 294\ nA$

$\lambda_c = 0.119$

$L_{sat} = 8.447\ nm$

$I_{D,ext} = 6.397\ mA$



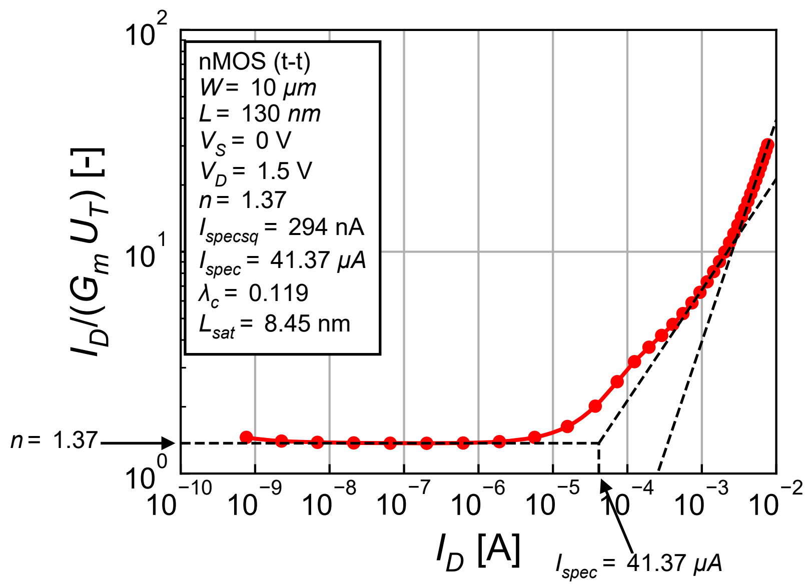

$n = 1.37$

$I_{spec} = 41.374\ \mu A$

$I_{spec\square} = 294\ nA$

$\lambda_c = 0.119$

$L_{sat} = 8.447\ nm$




We can now check the normalized $G_m/I_D$ characteristic.

$n = 1.37$

$I_{spec} = 41374\ nA$

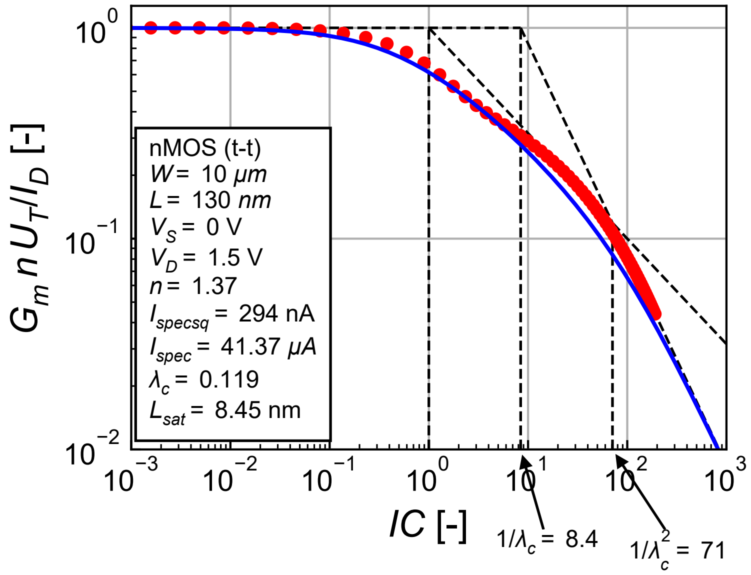
$I_{spec\square} = 294\ nA$

$\lambda_c = 0.119$

$1/\lambda_c = 8.42$

$1/\lambda_c^2 = 71$

$L_{sat} = 8.447\ nm$




The fit is OK at the asymptotes but not good in the moderate inversion region. Notice the bump in the lower part of strong inversion. This is most probably an artifact of the PSP model. We can try to increase $I_{spec}$ and $\lambda_c$ in order to have a better fit in moderate and strong inversion.

$n = 1.37$

$I_{spec} = 58\ \mu A$

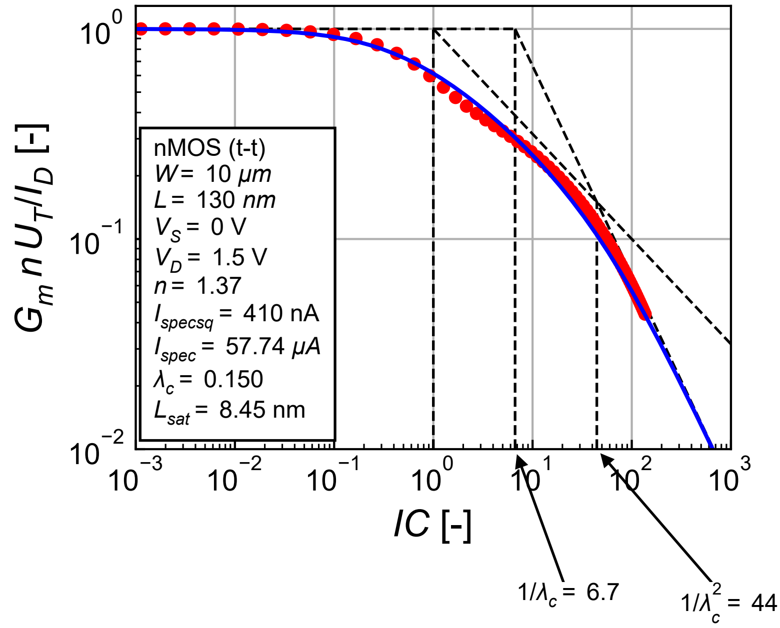
$I_{spec\square} = 410\ nA$

$\lambda_c = 0$

$1/\lambda_c = 6.67$

$1/\lambda_c^2 = 44$

$L_{sat} = 8.447\ nm$




The fit is now better, offering a good trade-off between moderate and strong inversion.

#### 5.2.4.4 Threshold voltage extraction

$n = 1.37$

$I_{spec} = 57.737\ \mu A$

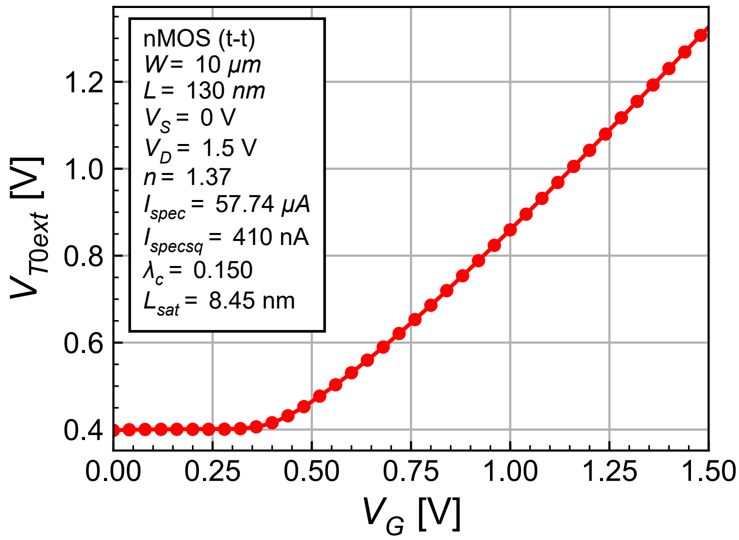
$I_{spec\square} = 410\ nA$

$\lambda_c = 0.150$

$1/\lambda_c = 6.667$

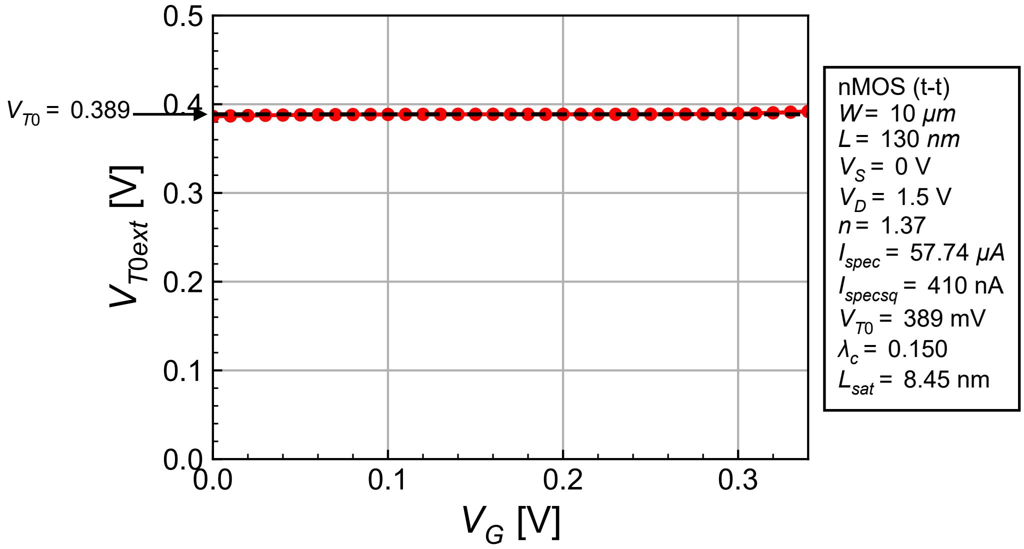
$1/\lambda_c^2 = 44.444$

$L_{sat} = 8.447\ nm$




We see a plateau in weak inversion where we can average its value to get the threshold voltage in weak inversion.

$V_{T0,wi} = 389$ mV




We can now check the $I_D$-$V_G$ curves.

$n = 1.37$

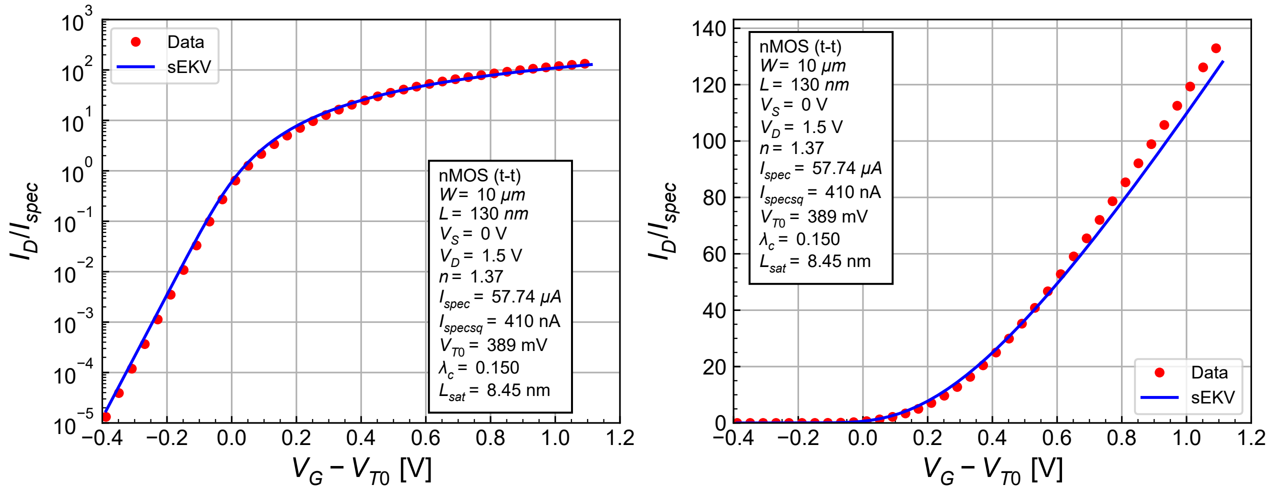
$I_{spec} = 57.737\ \mu A$

$I_{spec\square} = 410\ nA$

$V_{T0} = 389$ mV

$\lambda_c = 0.150$

$L_{sat} = 8.447\ nm$




We see that the threshold voltage is not correct. We can fine tune it manually.

$n = 1.37$

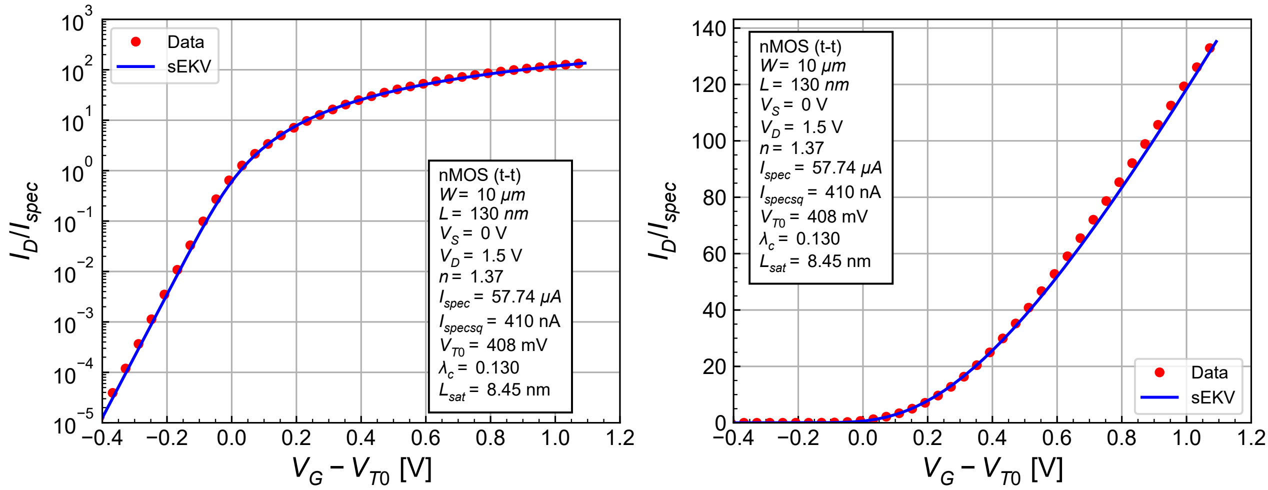
$I_{spec} = 57.737\ \mu A$

$I_{spec\square} = 410\ nA$

$V_{T0} = 408$ mV

$\lambda_c = 0.130$

$L_{sat} = 8.447\ nm$




We now have a good fit of the $I_D$-$V_G$ characteristic.

#### 5.2.4.5 Summary

$n = 1.37$

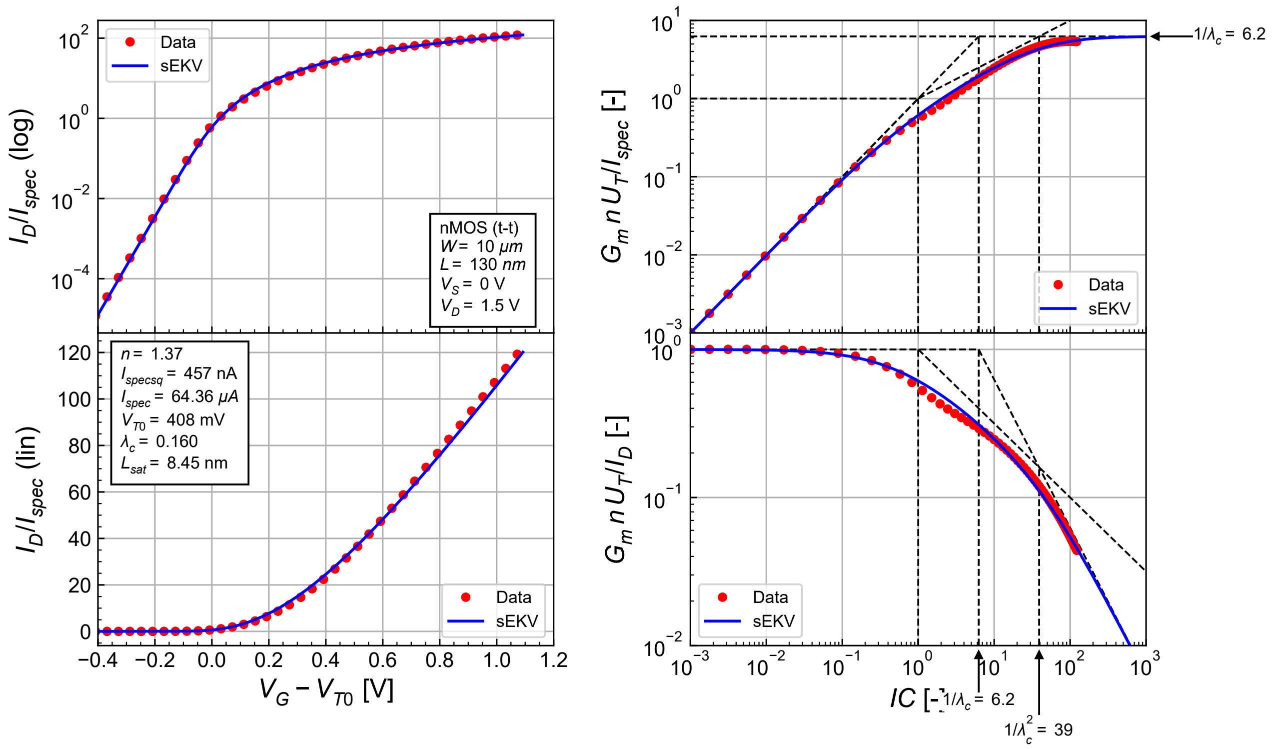
$I_{spec} = 64.355\ \mu A$

$I_{spec\square} = 457\ nA$

$V_{T0} = 408$ mV

$\lambda_c = 0.160$

$L_{sat} = 8.447\ nm$




We finally get a reasonable fit of all characteristics.

Table 5.1: Direct extraction of the sEKV parameters for the short-channel transistor wi

| | W | Weff | L | Leff | n | Ispecsq | VT0 | lambdac | Lsat |
|---|---|---|---|---|---|---|---|---|---|
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.210e+00 | 8.100e-07 | 1.746e-01 | 0.000e+00 | 0.000e |
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.210e+00 | 8.173e-07 | 1.733e-01 | 0.000e+00 | 0.000e |
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.272e+00 | 8.500e-07 | 1.733e-01 | 5.500e-02 | 5.468e |
| medium | 1.000e-06 | 1.020e-06 | 1.000e-06 | 9.412e-07 | 1.220e+00 | 6.500e-07 | 2.431e-01 | 0.000e+00 | 0.000e |
| medium | 1.000e-06 | 1.020e-06 | 1.000e-06 | 9.412e-07 | 1.220e+00 | 7.083e-07 | 2.456e-01 | 0.000e+00 | 0.000e |
| medium | 1.000e-06 | 1.020e-06 | 1.000e-06 | 9.412e-07 | 1.266e+00 | 8.000e-07 | 2.456e-01 | 8.000e-02 | 8.089e |
| short | 1.000e-05 | 1.002e-05 | 1.300e-07 | 7.115e-08 | 1.370e+00 | 4.570e-07 | 4.080e-01 | 1.600e-01 | 8.447e |

### 5.2.5 Extraction using optimization

#### 5.2.5.1 Specific current $I_{spec}$ and $\lambda_c$ extraction

We can extract the slope factor $n$, the specific current $I_{spec}$ and the velocity saturation parameter $\lambda_c$ using curve-fitting.

$n = 1.37$

$I_{spec} = 51.391\ \mu A$

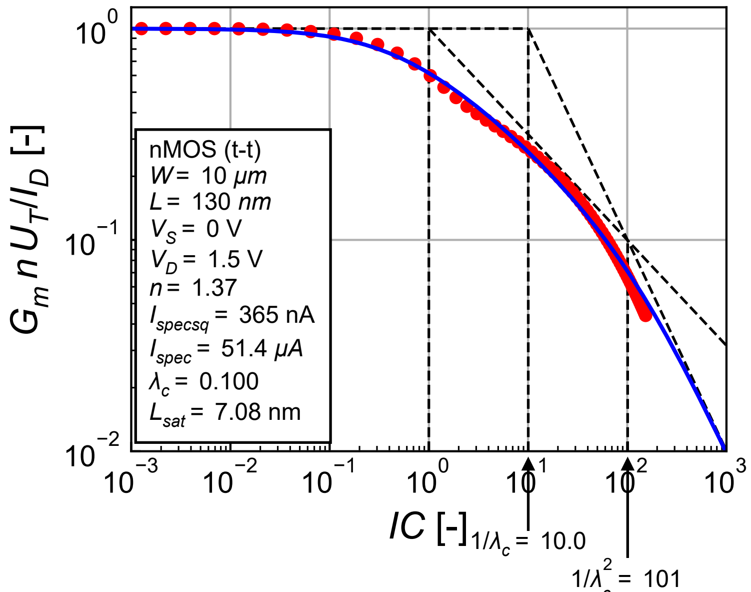
$I_{spec\square} = 365\ nA$

$\lambda_c = 0.100$

$1/\lambda_c = 10.05$

$1/\lambda_c^2 = 101$

$L_{sat} = 7.083\ nm$




We get a good fit across all regions.

#### 5.2.5.2 Threshold voltage extraction

$n = 1.37$

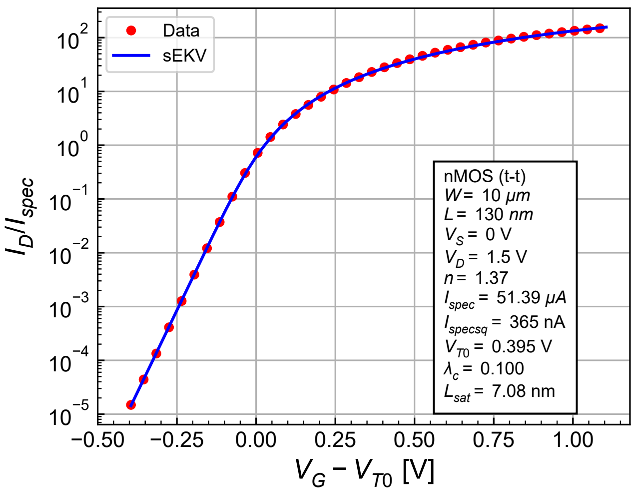
$I_{spec} = 51.391\ \mu A$

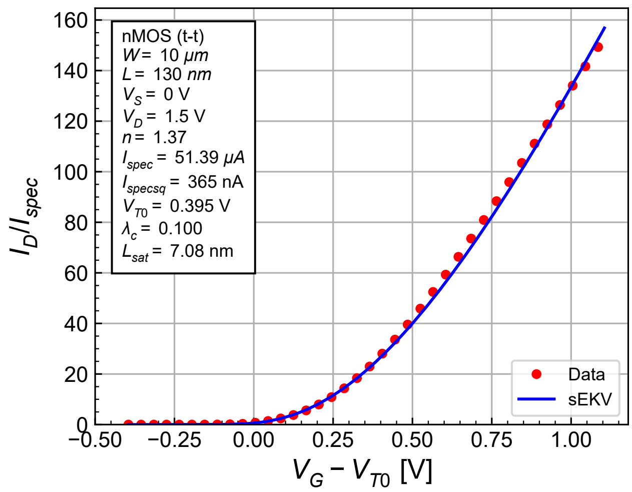
$I_{spec\square} = 365\ nA$

$V_{T0} = 395$ mV

$\lambda_c = 0.100$

$L_{sat} = 7.083\ nm$




We finally get a very good fit!

#### 5.2.5.3 Summary

$n = 1.37$

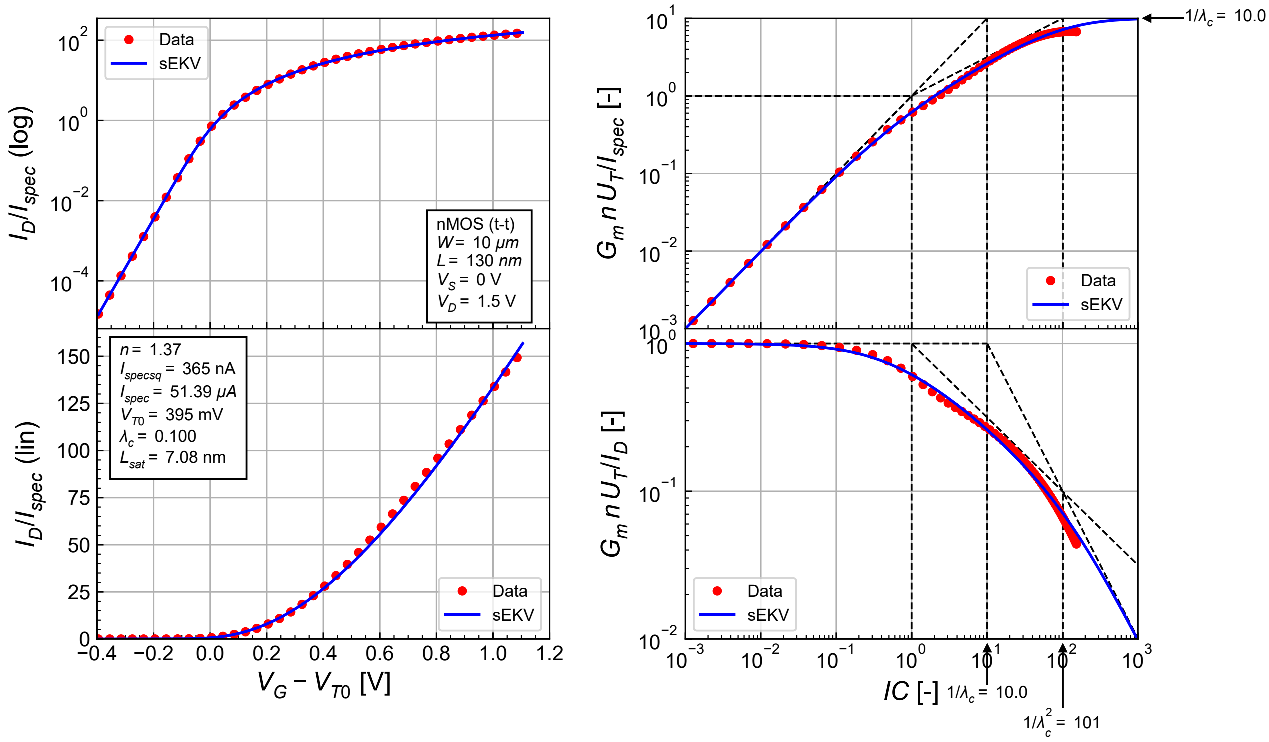
$I_{spec} = 51.391\ \mu A$

$I_{spec\square} = 365\ nA$

$V_{T0} = 395$ mV

$\lambda_c = 0.100$

$L_{sat} = 7.083\ nm$




We have an overall very good fit.

Table 5.2: Extraction of the sEKV parameters by optimization for the short-channel tra
$\lambda_c > 0$.

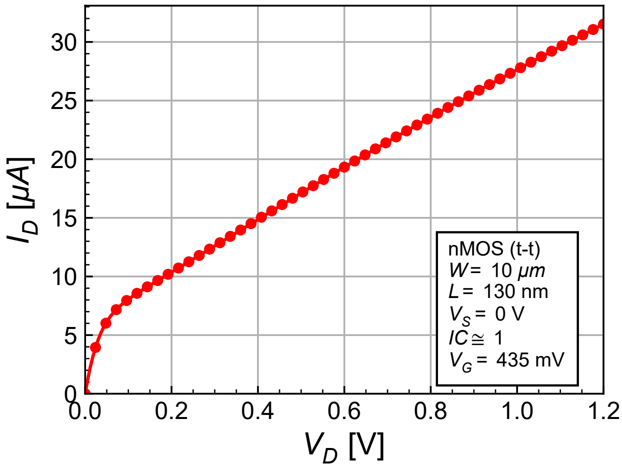
| | W | Weff | L | Leff | n | Ispecsq | VT0 | lambdac | Lsat |
|---|---|---|---|---|---|---|---|---|---|
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.210e+00 | 8.100e-07 | 1.746e-01 | 0.000e+00 | 0.000e |
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.210e+00 | 8.173e-07 | 1.733e-01 | 0.000e+00 | 0.000e |
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1.272e+00 | 8.500e-07 | 1.733e-01 | 5.500e-02 | 5.468e |
| medium | 1.000e-06 | 1.020e-06 | 1.000e-06 | 9.412e-07 | 1.220e+00 | 6.500e-07 | 2.431e-01 | 0.000e+00 | 0.000e |
| medium | 1.000e-06 | 1.020e-06 | 1.000e-06 | 9.412e-07 | 1.220e+00 | 7.083e-07 | 2.456e-01 | 0.000e+00 | 0.000e |
| medium | 1.000e-06 | 1.020e-06 | 1.000e-06 | 9.412e-07 | 1.266e+00 | 8.000e-07 | 2.456e-01 | 8.000e-02 | 8.089e |
| short | 1.000e-05 | 1.002e-05 | 1.300e-07 | 7.115e-08 | 1.370e+00 | 4.570e-07 | 4.080e-01 | 1.600e-01 | 8.447e |
| short | 1.000e-05 | 1.002e-05 | 1.300e-07 | 7.115e-08 | 1.370e+00 | 3.649e-07 | 3.950e-01 | 9.955e-02 | 7.083e |

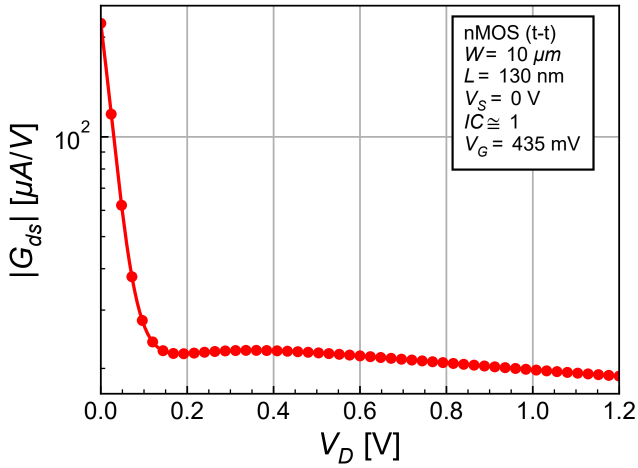
## 5.3 Output characteristic

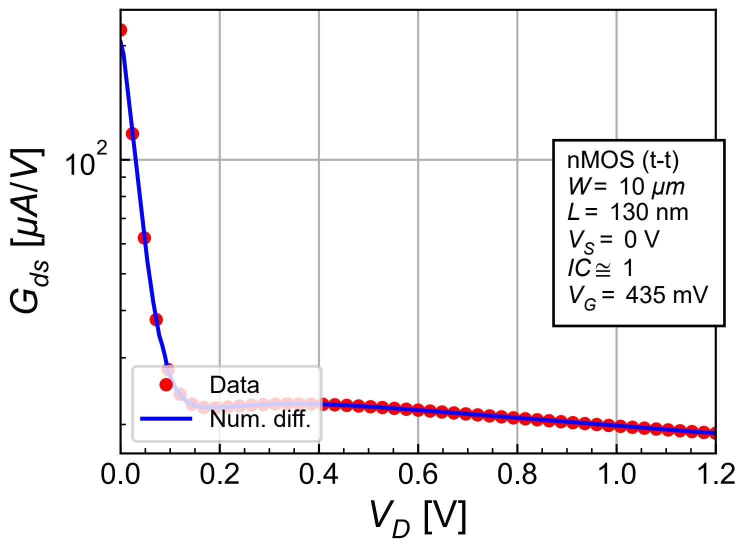
### 5.3.1 Generating the data

### 5.3.2 Importing and plotting the data

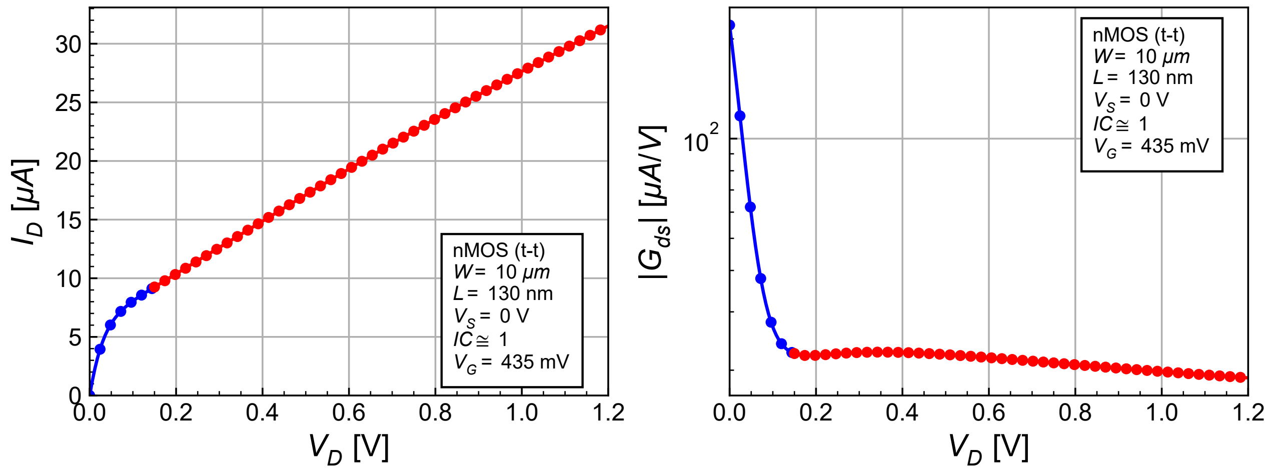
#### 5.3.2.1 $I_D$ and $G_{ds}$ versus $V_D$



#### 5.3.2.2 Filtering the outliers




#### 5.3.2.3 Extracting the CLM parameter

$G_{ds}$ = 21.324 $\mu A/V$

$I_{D0}$ = 6.341 $\mu A$

$V_E$ = -0.297 $V$

$\lambda$ = 2.288 $V/\mu m$

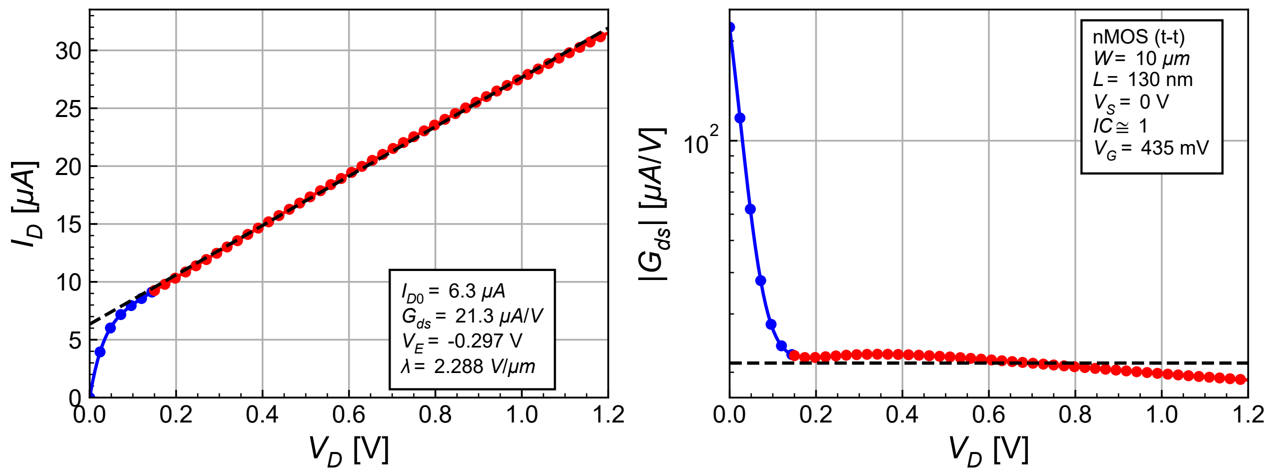



Table 5.3: CLM parameters extracted for the short-channel transistor in moderate inversion.

| | W | Weff | L | Leff | IC | Gds | ID0 | VE | lambda |
|---|---|---|---|---|---|---|---|---|---|
| long | 1.000e-05 | 1.002e-05 | 1.000e-05 | 9.941e-06 | 1 | 2.105e-07 | 6.119e-07 | -2.907e+00 | 2.907e+05 |
| medium | 1.000e-06 | 1.020e-06 | 1.000e-06 | 9.412e-07 | 1 | 5.124e-07 | 7.048e-07 | -1.375e+00 | 1.375e+06 |
| short | 1.000e-05 | 1.002e-05 | 1.300e-07 | 7.115e-08 | 1 | 2.132e-05 | 6.341e-06 | -2.974e-01 | 2.288e+06 |

## 5.4 Noise

In this section we will extract the flicker noise parameters to be used with sEKV and check the white noise power spectral density (PSD) for the short channel transistor. We first will set the bias condition in terms of $IC$ and calculate the input-referred white noise to compare it to the result obtained from the PSP simulations.

### 5.4.1 Setting bias conditions

$W = 10\ \mu m$

$L = 130\ nm$

$IC = 1.0$

$I_D = 64.355\ \mu A$

$V_G = 0.435\ V$

$V_S = 0.000\ V$

$G_m = 1122.446\ \mu A/V$

$\gamma_n = 0.772$

$R_{n,th} = 0.688\ k\Omega$

$S_{n,th} = 1.140\text{e-}17\ V^2/Hz$

$V_{n,th} = 3.377\ nV/\sqrt{Hz}$

$A_v = 10$

$R_L = 8.909\ k\Omega$

$V_{DD} = 1.800\ V$

$V_{RL} = 0.573\ V$

$V_{DS} = 1.227\ V$

$V_{DSsat} = 0.116\ V$

```
The transistor is biased in the saturation region
```

### 5.4.2 Extract operating point information

We can extract the values of the PSP noise parameters from the operating point informations.

$V_{n,th} = 3.850\ nV/\sqrt{Hz}$ (PSP)

$f_k = 3533.760\ kHz$ (PSP)

$KF = 5.755\text{e-}25\ VAs$ (PSP)

$\rho = 2.253\text{e-}03\ Vm^2/(As)$ (PSP)

$AF = 1.000$ (PSP)

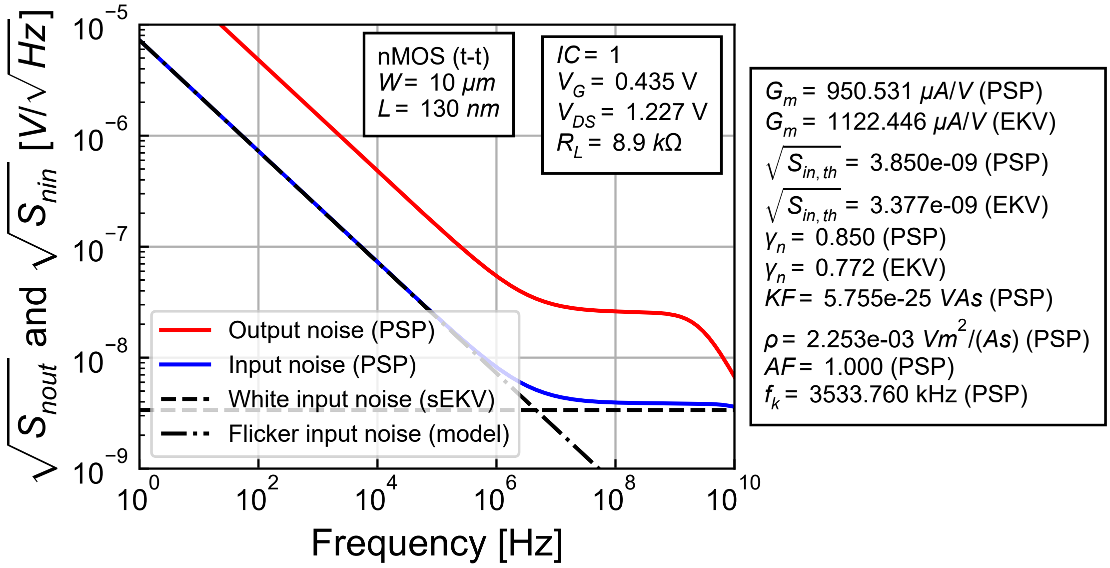
$R_{n,th} = 0.894\ k\Omega$ (PSP)

$\gamma_n = 0.850$ (PSP)

| | Weff | Leff | IDS | Gm | Gds | Snidth | Vninth | Snidfl @ 1Hz | Vninfl @ 1kH |
|---|---|---|---|---|---|---|---|---|---|
| Mn | 1.00E-05 | 7.12E-08 | 6.04E-05 | 9.51E-04 | 3.12E-05 | 1.34E-23 | 3.85E-09 | 4.73E-17 | 2.29E-07 |

### 5.4.3 Simulating noise PSD

We can now simulate the PSD and check against the EKV model.




The flicker noise parameter for the long- and short-channel transistors are different as shown below

Table 5.5: Extraction of the noise parameters for the short-channel transistor.

| | W | Weff | L | Leff | IC | KF | AF | rho | Comment |
|---|---|---|---|---|---|---|---|---|---|
| long | 1.00E-05 | 1.00E-05 | 1.00E-05 | 9.94E-06 | 1 | 3.18E-24 | 1.00E+00 | 1.24E-02 | moderate |
| medium | 1.00E-06 | 1.02E-06 | 1.00E-06 | 9.41E-07 | 1 | 2.21E-24 | 1.00E+00 | 8.64E-03 | moderate |
| short | 1.00E-05 | 1.00E-05 | 1.30E-07 | 7.12E-08 | 1 | 5.76E-25 | 1.00E+00 | 2.25E-03 | moderate |

We will keep the long-channel value since it is larger.

# 6 Extrinsic capacitances

## 6.1 Junction capacitances

The calculation of the junction capacitances depends on the value used for the **SWJUNCAP** parameter. In this PDK **SWJUNCAP** is equal to 3 for which the junction area $AB$, junction length of side-wall capacitance along the STI edge $LS$ and junction length of the side-wall capacitance along the gate edge $LG$ are calculated according to

$$AB = AS, \tag{6.1}$$
$$LS = PS - W_E, \tag{6.2}$$
$$LG = W_E, \tag{6.3}$$
$$\tag{6.4}$$

where $AS$ is the source junction area and $PS$ the total source junction perimeter and

$$AB = AD, \tag{6.5}$$
$$LS = PD - W_E, \tag{6.6}$$
$$LG = W_E, \tag{6.7}$$
$$\tag{6.8}$$

where $AD$ is the drain junction area and $PD$ the total drain junction perimeter.

The total junction capacitance on the source $CJS$ and drain side $CJD$ are then given by

$$CJS = AS \cdot CJORBOT + (PS - W_E) \cdot CJORSTI + W_E \cdot CJORGAT, \tag{6.9}$$
$$CJD = AD \cdot CJORBOT + (PD - W_E) \cdot CJORSTI + W_E \cdot CJORGAT, \tag{6.10}$$

where:

- **CJORBOT** is the zero-bias bottom capacitance per unit-area,
- **CJORSTI** is the zero-bias capacitance per unit-of-length along the STI-edge,
- **CJORGAT** is the zero-bias capacitance per unit-of-length along the gate-edge.

The above junction capacitance parameters are extracted directly from the PDK. We will use the the zero-bias bias value of th various junctions capacitances.

If $AS$, $PD$, $AD$ and $PD$ are not specified, they are calculated automatically in the sg13g2_moslv_mod.lib file.

In the circuit examples, we will calculate $AS$, $PD$, $AD$ and $PD$ for avoiding the automatic cal.culation

$CJn =$ 9.764e-04 $\frac{F}{m^2}$

$CJSWSTIn = 2.528\text{e-}11\ \frac{F}{m}$

$CJSWGATn = 3.000\text{e-}11\ \frac{F}{m}$

$CJn = 0.976\ \frac{fF}{\mu m^2}$

$CJSWSTIn = 0.025\ \frac{fF}{\mu m}$

$CJSWGATn = 0.030\ \frac{fF}{\mu m}$

Table 6.1: Extraction of the junction capacitance parameters.

| | Zero-bias junction capacitance | Comment |
|---|---|---|
| Bottom cap per area | 9.76E-04 | extracted from PDK |
| Side-wall cap per unit length (along STI) | 2.53E-11 | extracted from PDK |
| Side-wall cap per unit length (along gate) | 3.00E-11 | extracted from PDK |

## 6.2 Overlap capacitances

In PSP, the gate-to-source and gate-to-drain overlap capacitances are equal and given by

$$CGOV = \epsilon_{ox} \cdot \frac{W_{E,CV} \cdot LOV}{TOXOV}, \tag{6.11}$$

where $W_{E,CV}$ has already been defined above and is repeated here

The effective length and width for the calculation of the intrinsic and overlap acacitances are defined as

$$L_{E,CV} = L + \Delta L_{CV}, \tag{6.12}$$
$$W_{E,CV} = W + \Delta W_{CV}, \tag{6.13}$$

where

$$\Delta L_{CV} = 2\,LAP - \Delta L_{PS} - DLQ, \tag{6.14}$$
$$\Delta W_{CV} = 2\,WOT - \Delta W_{OD} - DWQ. \tag{6.15}$$

As mentioned above, for the IHP 130nm for nMOS $\Delta L_{PS} = 0$ and $\Delta W_{OD} = 0$ so that

$$\Delta L_{CV} = 2\,LAP - DLQ, \tag{6.16}$$
$$\Delta W_{CV} = 2\,WOT - DWQ. \tag{6.17}$$

`Gate-to-source and gate-to-drain overlap capacitances per effective unit width`

$C_{GSo} = 4.535\text{e-}10\ \frac{F}{m}$

$C_{GDo} = 4.535\text{e-}10\ \frac{F}{m}$

$C_{GSo} = 0.453\ \frac{fF}{\mu m}$

$C_{GDo} = 0.453\ \frac{fF}{\mu m}$

`Gate-to-bulk overlap capacitances per effective unit length`

$C_{GBo} = 4.441\text{e-}22\ \frac{F}{m}$

$C_{GBo} = 0.000\ \frac{fF}{\mu m}$

In PSP, the fringing field capacitance is given by

$$CFR = CFRW \cdot \frac{W_{G,CV}}{W_{EN}}, \tag{6.18}$$

where

$$W_{G,CV} = W_f + \Delta W_{OD} + DWQ \tag{6.19}$$

Since $\Delta W_{OD} = 0$ it reduces to

$$W_{G,CV} = W_f + DWQ \tag{6.20}$$

`Gate-to-source and gate-to-drain fringing capacitances per effective unit width`

$C_{GSf} = 2.000\text{e-}10\ \frac{F}{m}$

$C_{GDf} = 2.000\text{e-}10\ \frac{F}{m}$

$C_{GSf} = 0.200\ \frac{fF}{\mu m}$

$C_{GDf} = 0.200\ \frac{fF}{\mu m}$

`Total gate-to-source and gate-to-drain extrinsic capacitances per effective unit width`

$C_{GSe} = 6.535\text{e-}10\ \frac{F}{m}$

$C_{GDe} = 6.535\text{e-}10\ \frac{F}{m}$

$C_{GSe} = 0.653\ \frac{fF}{\mu m}$

$C_{GDe} = 0.653\ \frac{fF}{\mu m}$

Table 6.2: Extraction of the junction capacitance parameters.

| | CGS per effective unit width | CGD per effective unit width | CGB per effective unit length | Comm |
|---|---|---|---|---|
| Overlap | 4.53E-10 | 4.53E-10 | 4.44E-22 | extract |
| Fringing | 2.00E-10 | 2.00E-10 | - | extract |
| Total | 6.53E-10 | 6.53E-10 | - | extract |

# 7 Conclusion

The sEKV parameters have been extracted for a long, medium and short nMOS transistors using the data generated from the the PDK with the PSP compact model. The overall extraction results are good.

For the long-channel transistor both the direct extraction and optimization with $\lambda_c = 0$ give similar results. The fit is good up to about $IC = 100$. Above that the model cannot catch the effect due to the mobility reduction due to the vertical field. Notice the very low threshold voltage which is consistent with the IHP 130nm documentation. Also, the output conductance for the long and medium length device is very high compared to what we get for the pMOS transistors. This is confirmed by the measurements, but the physical origin of this high output conductance remains unclear.

For the short-channel transistor, again the direct extraction and the optimization with $\lambda_c > 0$ give similar results. The fit is good over the whole range of $IC$. Notice the bump observed in moderate inversion coming from the PSP simulations. This bumps is probably not realistic.

Overall, the sEKV can do a good job for the long, medium and short nMOS transistors.