In [1]:
```
%%capture
import math
!python3 -m pip install matplotlib
import matplotlib.pyplot as plt
import matplotlib.gridspec as gridspec
%matplotlib inline
plt.style.use('seaborn-v0_8-whitegrid')
from matplotlib.legend_handler import HandlerTuple
import matplotlib.ticker as tickerbb
!pip install scipy
!pip freeze > requirements.txt
#!pip freeze | grep -v -f requirements.txt - | grep -v '^#' | grep -v '^-e ' | xargs pip uninstall -y
```

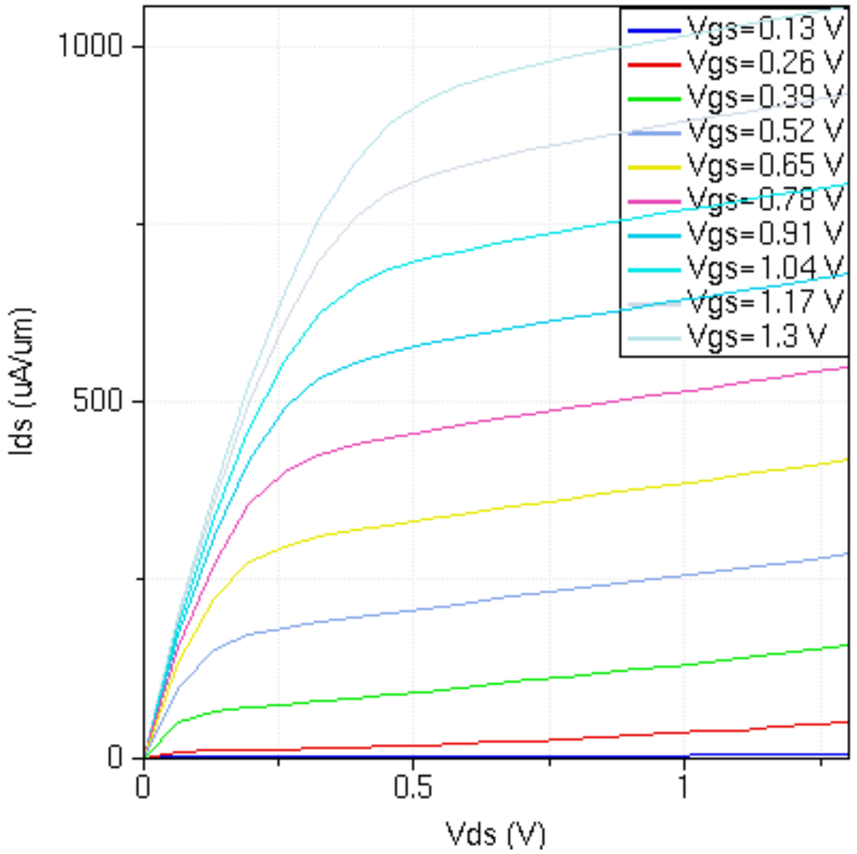
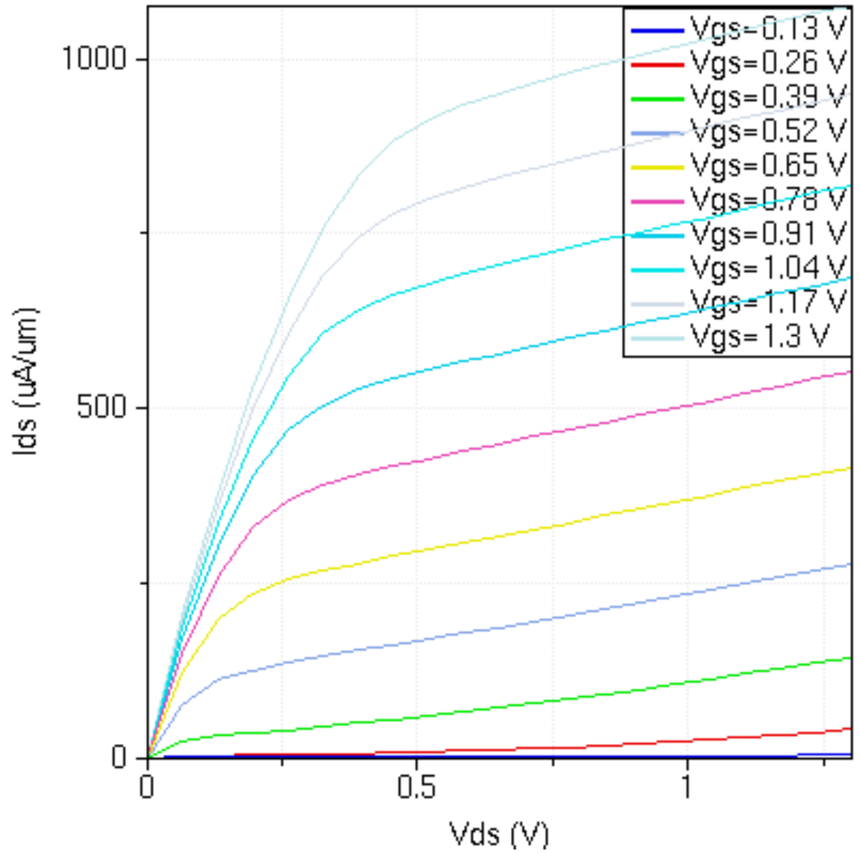
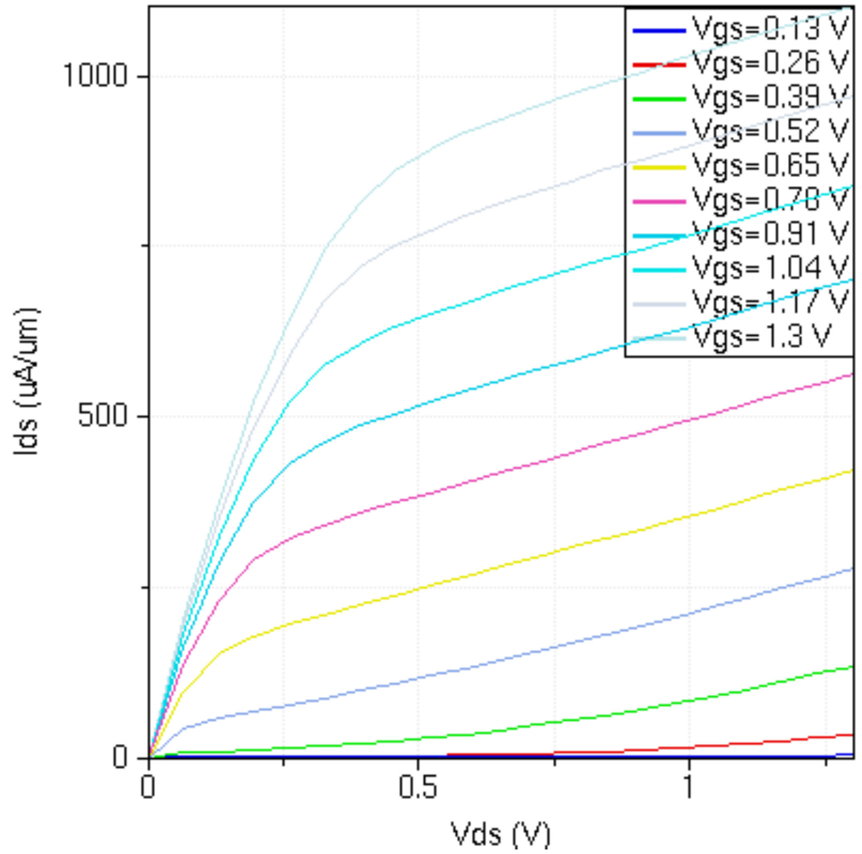
Abstract

This compact model MOSFET IV simulation work pertains to 130nm and 45nm CMOS technology nodes, using nanoHUB's '**Nano-CMOS**' tool.

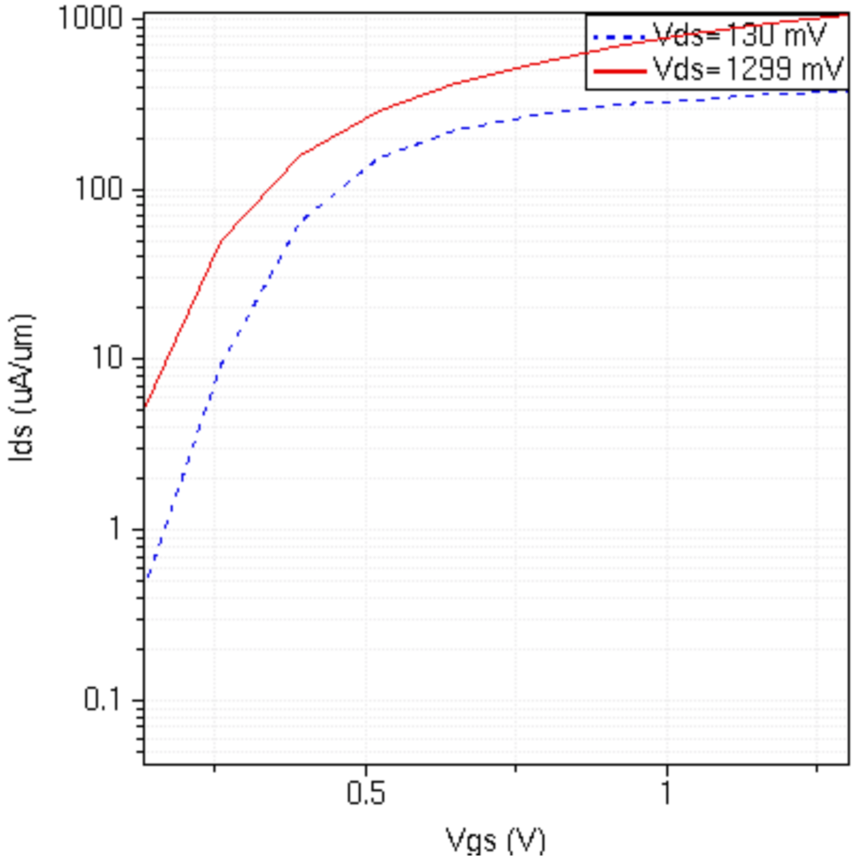
Table of Contents

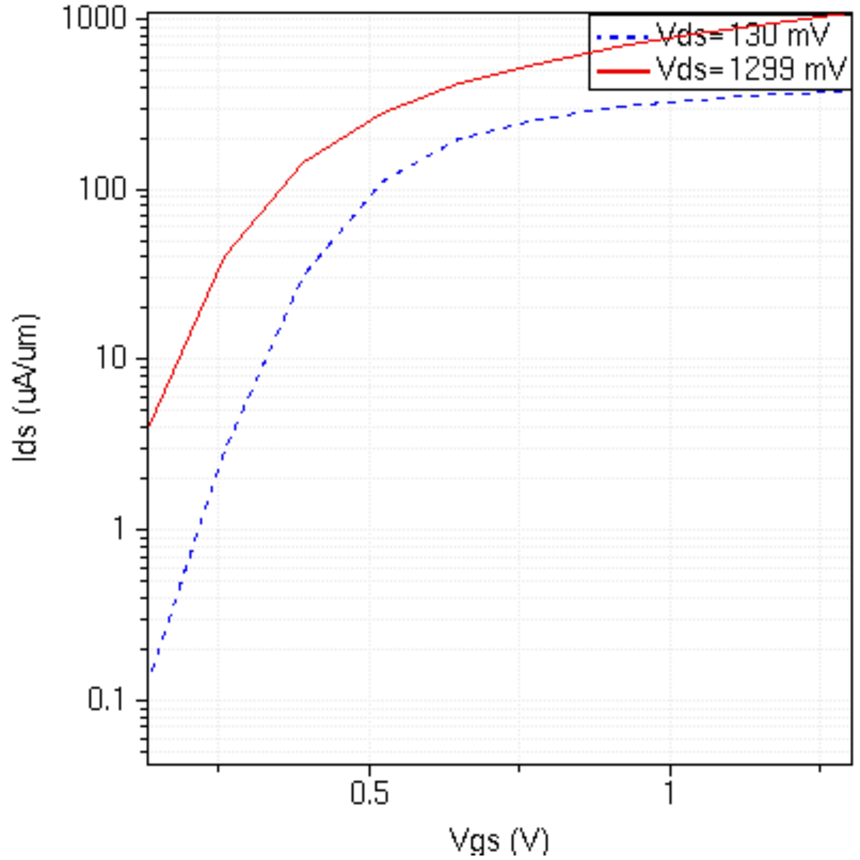
Part I: 130nm NMOS Output and Transfer IV

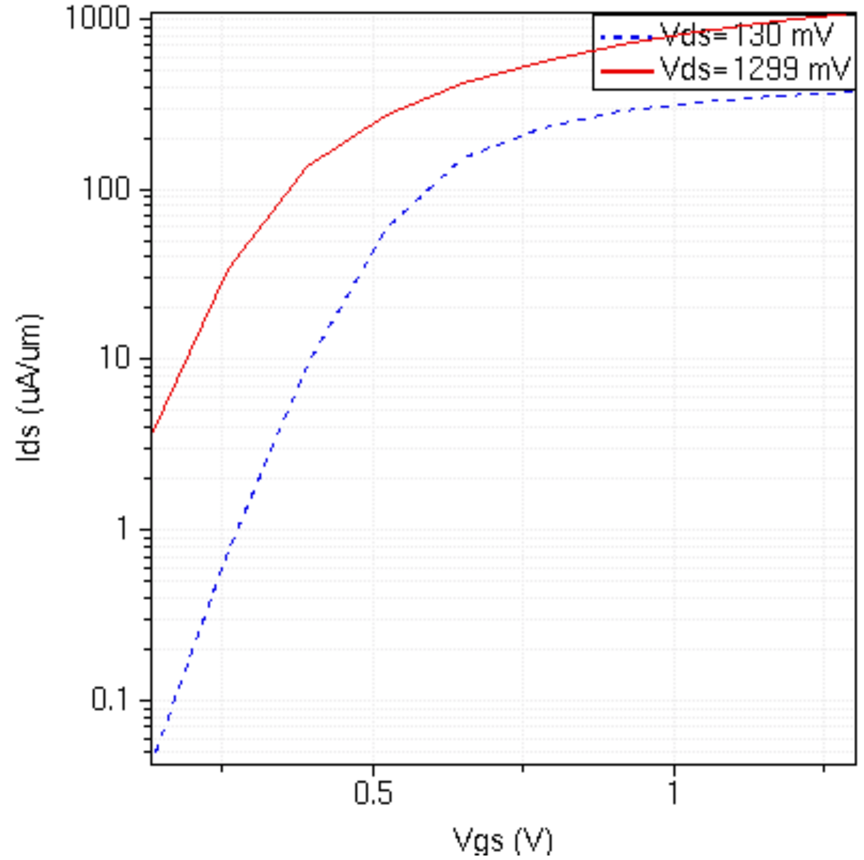
Simulations at $T = \text{min, nominal \& max}$

	$T = 218K$	$T = 300K$	$T = 398K$
Output IV			

Transfer IV







Summary

1. I_d vs $V_d \forall V_g$ plots of 130nm NMOS transistor can be seen to follow the generic MOSFET IV trend:

$$I_d = \frac{W}{L} \cdot C_{oxe} \cdot \mu \cdot (V_g - V_T - \frac{1}{2}V_d) \cdot V_d \tag{1}$$

2. $\log I_d$ vs $V_g \forall V_d$ plots of 130nm NMOS transistor indicate the linear subthreshold region leading up to the first curvature transition point (V_T). This linear region can be represented by the following equation:

$$I_d = 100 \cdot \frac{W}{L} \cdot 10^{\frac{q(V_g - V_T)}{\eta kT}} = 100 \cdot \frac{W}{L} \cdot 10^{\frac{(V_g - V_T)}{S}} \tag{2}$$

3. From the above plots it can be observed that the effect of increasing T leads to a corresponding lowering of V_T, and hence following from Eq. (1) \& Eq. (2) it can also be observed to lead to a higher I_d in the above plots.

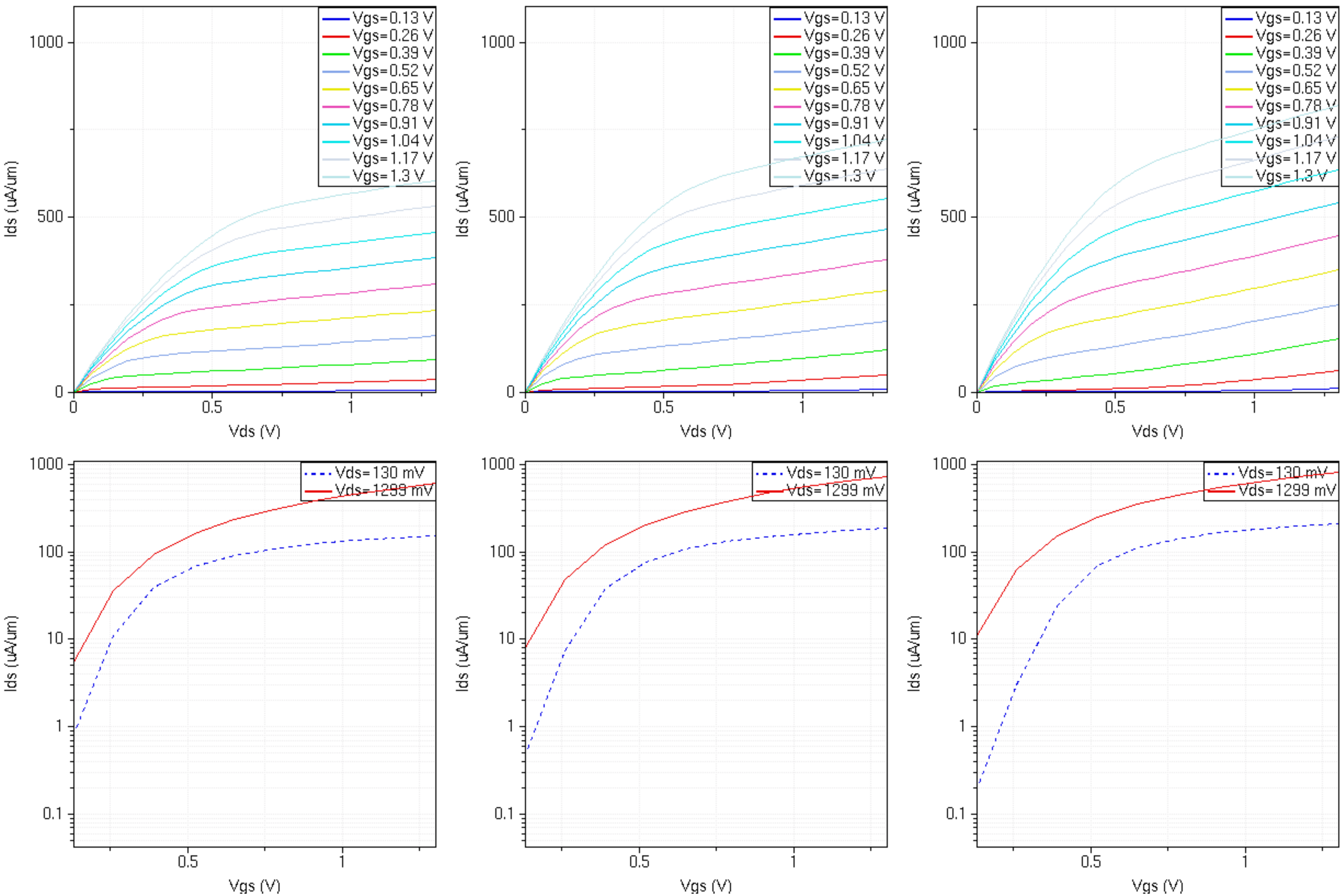
Part II: 130nm PMOS Output and Transfer IV

Simulations at $T = \text{ min, nominal \& max}$

$T = 218K$	$T = 300K$	$T = 398K$

Output IV

Transfer IV



Summary

1. I_d vs $V_d \forall V_g$ plots of 130nm PMOS transistor can be seen to follow the same generic MOSFET IV trend as Eq. (1) (with a lower μ than NMOS).
2. $\log I_d$ vs $V_g \forall V_d$ plots of 130nm PMOS transistor indicate the linear subthreshold region leading up to the first curvature transition point (V_T). This linear region can be represented by an equation similar to Eq. (2).
3. From the above plots it can be observed that the effect of increasing T leads to a corresponding lowering of V_T, and hence following from Eq. (1) \& Eq. (2) it can also be observed to lead to a higher I_d in the above plots.
4. Except in 130nm PMOS plots the effect of increasing I_d (or lowering V_T) with increasing T is more pronounced than 130nm NMOS. And this is due to lower channel length modulation effect $(1/\lambda)$ in PMOS transistors than in NMOS transistors.

Part III: 130nm NMOS model parameter extraction

Calculation of T Parameters for V_{th} (all units appropriated from nanoHUB's 'Nano-CMOS' compact model)

$$V_{\mathrm{th}}(T) = V_{\mathrm{th}}(\mathrm{TNOM}) + \left(\mathrm{KT1} + \frac{\mathrm{KT1L}}{L_{\mathrm{eff}}} + \mathrm{KT2} \cdot V_{\mathrm{bs,eff}}\right) \cdot \left(\frac{T}{\mathrm{TNOM}} - 1\right) \tag{3}$$

(as noted in page 105 of **[2] BSIM 4.8.2 Technical Manual**)

where,

$$V_{\mathrm{bs,eff}} = V_{\mathrm{bc}} + 0.5 \cdot \left[(V_{\mathrm{bs}} - V_{\mathrm{bc}} - 0.001) + \sqrt{(V_{\mathrm{bs}} - V_{\mathrm{bc}} - 0.001)^2 - 4 \cdot 0.001 \cdot V_{\mathrm{bc}}}\right] \tag{4}$$

(as noted in page 2-11 of **[3] BSIM 4.3.0 Technical Manual**)

where,

$$V_{\mathrm{bc}} = 0.9 \cdot \left(\Phi_s - \frac{\mathrm{K1}^2}{4 \cdot \mathrm{K2}^2}\right) \tag{5}$$

(as noted in page 2-11 of **[3] BSIM 4.3.0 Technical Manual**)

where,

$$\Phi_s = 0.4 + \frac{k_B \cdot T}{q} \ln\left(\frac{\mathrm{NDEP}}{n_i}\right) + \mathrm{PHIN} \tag{6}$$

(as noted in Note-2 of Appendix A-31 of **[3] BSIM 4.3.0 Technical Manual**)

where,

$$n_i = 1.45e10 \cdot \left(\frac{\mathrm{T}}{300.15}\right)^{3/2} \cdot \exp\left(\left[21.5565981 - \frac{q \cdot E_g(T)}{2 \cdot k_B \cdot T}\right]\right) \tag{7}$$

(as noted in page 112 of **[2] BSIM 4.8.2 Technical Manual**)

where,

$$E_g(T) = 1.16 - \frac{7.02 \times 10^{-4} \times T^2}{T + 1108} \tag{8}$$

(as noted in page 112 of **[2] BSIM 4.8.2 Technical Manual**)

where,

$$\mathrm{TNOM} = 300, \mathrm{PHIN} = 0, L_{\mathrm{eff}} = 49, V_{\mathrm{bs}} = 0 \tag{9}$$

(which are defaults of the Nano-CMOS compact model)

Table summarising T parameter extracts from Nano-CMOS compact model relating to V_{th}

$T\ (K)$	$vth0\ (V)$ (with $V_{bs}=0$)	$V_{th}(\text{TNOM})\ (V)$ or vth0 @ T=TNOM	$kt1\ (V)$	$kt1l\ (V \cdot m)$	$kt2$	$NDEP\ (\text{cm}^{-3})$	$k1\ (V^{0.5})$	**k2**
218	0.289	0.371	-0.11	0	0.022	2.39e18	0.58	0.01
300	0.371	0.371	-0.11	0	0.022	1.5e18	0.459	0.01
398	0.46	0.371	-0.11	0	0.022	9.2e17	0.36	0.01

In [2]:
```python
from scipy.constants import k,e

TNOM, PHIN, Leff, VBS = 300, 0, 49, 0 # Nano-CMOS compact model presets, as collated in eq (9)
kB, q = k, e # natural constants
kt1, kt1l, kt2, k2 = -0.11, 0, 0.022, 0.01  # Nano-CMOS compact model constant parameter extracts
```

In [3]:

```
class VThreshold:
    def __init__(self, vth0:float, k1:float, T:float, NDEP:float):
        self.vth0 = vth0
        self.kt1 = kt1
        self.kt1l = kt1l
        self.kt2 = kt2
        self.Leff = Leff
        self.TNOM = TNOM
        self.T = T
        self.PHIN = PHIN
        self.VBS = VBS
        self.NDEP = NDEP
        self.k1 = k1
        self.k2 = k2
        self.kB = kB
        self.q = q

    def Eg(self) -> float:
        # calculates Energy-band gap of Silicon according to eq (6)
        x = 1.16 - (7.02*1e-4*self.T**2)/(self.T+1108)
        return x

    def ni(self) -> float:
        # calculates intrinsic carrier concentration according to eq (5)
        x = 1.45e10*((self.T/300.15)**1.5)*math.exp(21.5565981-((self.q*VThreshold.Eg(self))/(2*self.kB*self.T)))
        return x

    def PhiS(self) -> float:
        # calculates surface potential along the channel according to eq (4)
        x = 0.4 + ((self.kB*self.T)/self.q)*math.log(self.NDEP/VThreshold.ni(self)) + self.PHIN
        return x

    def VBC(self) -> float:
        # calculates VBC according to eq (3)
        x = 0.9*(VThreshold.PhiS(self) - ((self.k1**2)/(4*self.k2**2)))
        return x

    def VBSEFF(self) -> float:
        # calculates VBSEFF according to eq (2)
        x = VThreshold.VBC(self) + 0.5*((self.VBS-VThreshold.VBC(self)-0.001)+(math.sqrt((self.VBS-VThreshold.VBC(self)-0.001)**2-(4*0.001*VThreshold.VBC(self)))))
        return x

    def VTH(self) -> float:
        # calculates VTH as a function of T according to eq (1)
        x = self.vth0 + (self.kt1+(self.kt1l/self.Leff)+(self.kt2*VThreshold.VBSEFF(self)))*((self.T/self.TNOM)-1)
        return x
```

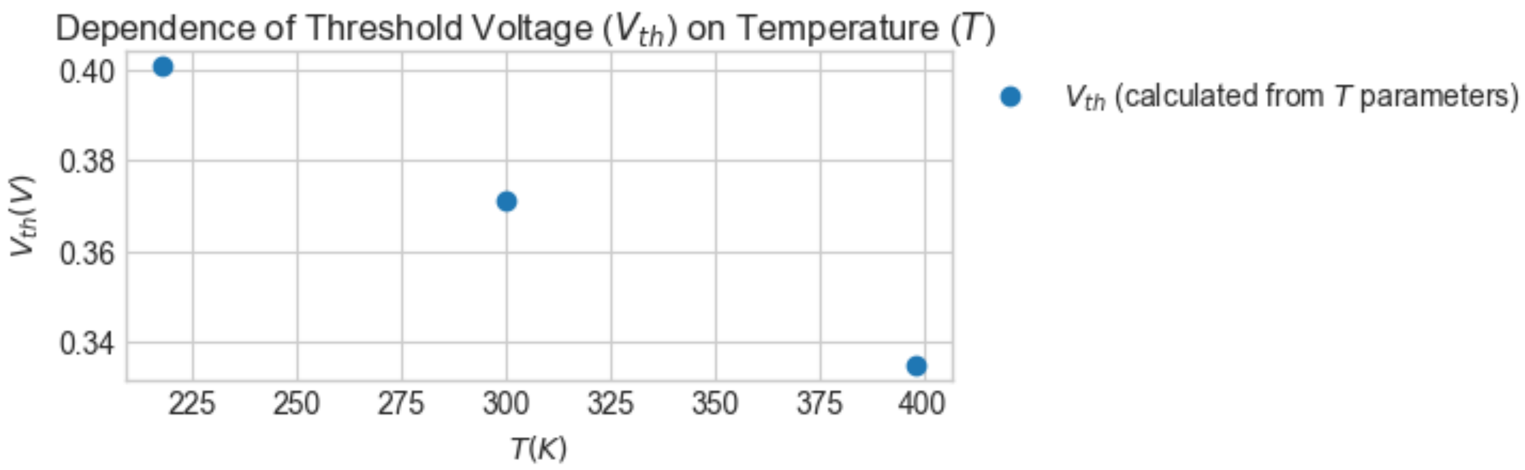
In [4]:

```
print(f"Calculated V_T values (218K,300K,398K): {VThreshold(T=218, vth0=0.371, NDEP=2.39e18, k1=0.58).VTH()}, {VThreshold(T=300, vth0=0.371, NDEP=1.5e18, k1=0.459).VTH()}
{VThreshold(T=398, vth0=0.371, NDEP=9.2e17, k1=0.36).VTH()}")
```

```
Calculated V_T values (218K,300K,398K): 0.4010666666666667, 0.371,0.33506666666666707
```

In [5]:
```
fig,axes = plt.subplots(figsize=(5,2))
fig.suptitle('Dependence of Threshold Voltage ($V_{th}$) on Temperature ($T$)')
plt.scatter([218,300,398],[VThreshold(T=218, vth0=0.371, NDEP=2.39e18, k1=0.58).VTH(),VThreshold(T=300, vth0=0.371, NDEP=1.5e18, k1=0.459).VTH(),\
                           VThreshold(T=398, vth0=0.371, NDEP=9.2e17, k1=0.36).VTH()],label='$V_{th}$ (calculated from $T$ parameters)')
axes.legend(bbox_to_anchor=(1, 1), loc="upper left")
axes.set_xlabel('$T (K)$')
axes.set_ylabel('$V_{th} (V)$')
```

Out[5]:
```
Text(0, 0.5, '$V_{th} (V)$')
```



Summary

1. The $V_{th}(T)$ shifts for 130nm NMOS calculated from the T parameter extracts using Eq. (3) - Eq. (9) and as plotted above, are in line with a decreasing V_T with increasing T as can be seen in the simulated Output IV and Transfer IV curves of **Part I** and **Part II**.

Calculation of T Parameters for μ (all units appropriated from 'Nano-CMOS' compact model, $TEMPMOD/MOBMOD = 0$)

$$U0(T) = U0(\mathrm{TNOM}) \cdot \left(\frac{T}{\mathrm{TNOM}}\right)^{\mathrm{UTE}} \tag{10}$$

$$UA(T) = UA(\mathrm{TNOM}) + UA1 \cdot \left(\frac{T}{\mathrm{TNOM}} - 1\right) \tag{11}$$

$$UB(T) = UB(\mathrm{TNOM}) + UB1 \cdot \left(\frac{T}{\mathrm{TNOM}} - 1\right) \tag{12}$$

$$UC(T) = UC(\mathrm{TNOM}) + UC1 \cdot \left(\frac{T}{\mathrm{TNOM}} - 1\right) \tag{13}$$

(Eqs. (10) - (13) as noted in page 106 of **[2] BSIM 4.8.2 Technical Manual**)

Table summarising T parameter extracts from Nano-CMOS compact model relating to μ

$T\ (K)$	$u0\ (m^2/V \cdot s)$	u0(TNOM) $(m^2/V \cdot s)$ or u0 @ T = TNOM	ute	$ua\ (m/V)$	$ua1\ (m/V)$	$ub\ (m^2/V^2)$	$ub1\ (m^2/V^2)$	$uc\ (m/V^2)$	$uc1\ (m/V^2)$
218	0.05036	0.05979	-1.5	6e-10	4.31e-9	1.2e-18	7.61e-18	0	-5.6e-11
300	0.05979	0.05979	-1.5	6e-10	4.31e-9	1.2e-18	7.61e-18	0	-5.6e-11
398	0.0689	0.05979	-1.5	6e-10	4.31e-9	1.2e-18	7.61e-18	0	-5.6e-11

In [6]:

```
ute, ua, ua1, ub, ub1, uc, uc1, TNOM = -1.5, 6e-10, 4.31e-9, 1.2e-18, 7.61e-18, 0, -5.6e-11, 300  # Nano-CMOS compact model constant parameter extracts
```

In [7]:

```
class mu:
    def __init__(self, u0:float, T:float):
        self.u0 = u0
        self.ute = ute
        self.ua = ua
        self.ua1 = ua1
        self.ub = ub
        self.ub1 = ub1
        self.uc = uc
        self.uc1 = uc1
        self.TNOM = TNOM
        self.T = T

    def mu0(self) -> float:
        # calculates Low-field mobility according to eq (8)
        x = self.u0*((self.T/self.TNOM)**self.ute)
        return x

    def mua(self) -> float:
        # calculates `Coefficient of first-order mobility degradation due to vertical field' according to eq (9)
        x = self.ua + ua1*((self.T/self.TNOM)-1)
        return x

    def mub(self) -> float:
        # calculates `Coefficient of secon-order mobility degradation due to vertical field' according to eq (10)
        x = self.ub + ub1*((self.T/self.TNOM)-1)
        return x

    def muc(self) -> float:
        # calculates `Coefficient of mobility degradation due to body-bias effect' according to eq (11)
        x = self.uc + uc1*((self.T/self.TNOM)-1)
        return x
```

In [8]:

```
print(f"Calculated u0 values (218K,300K,398K): {mu(T=218, u0=0.05979).mu0()},{mu(T=300, u0=0.05979).mu0()},{mu(T=398, u0=0.05979).mu0()}")
print(f"Calculated ua values (218K,300K,398K): {mu(T=218, u0=0.05979).mua()},{mu(T=300, u0=0.05979).mua()},{mu(T=398, u0=0.05979).mua()}")
print(f"Calculated ub values (218K,300K,398K): {mu(T=218, u0=0.05979).mub()},{mu(T=300, u0=0.05979).mub()},{mu(T=398, u0=0.05979).mub()}")
print(f"Calculated uc values (218K,300K,398K): {mu(T=218, u0=0.05979).muc()},{mu(T=300, u0=0.05979).muc()},{mu(T=398, u0=0.05979).muc()}")
#Note that ua/ub/uc~0
```

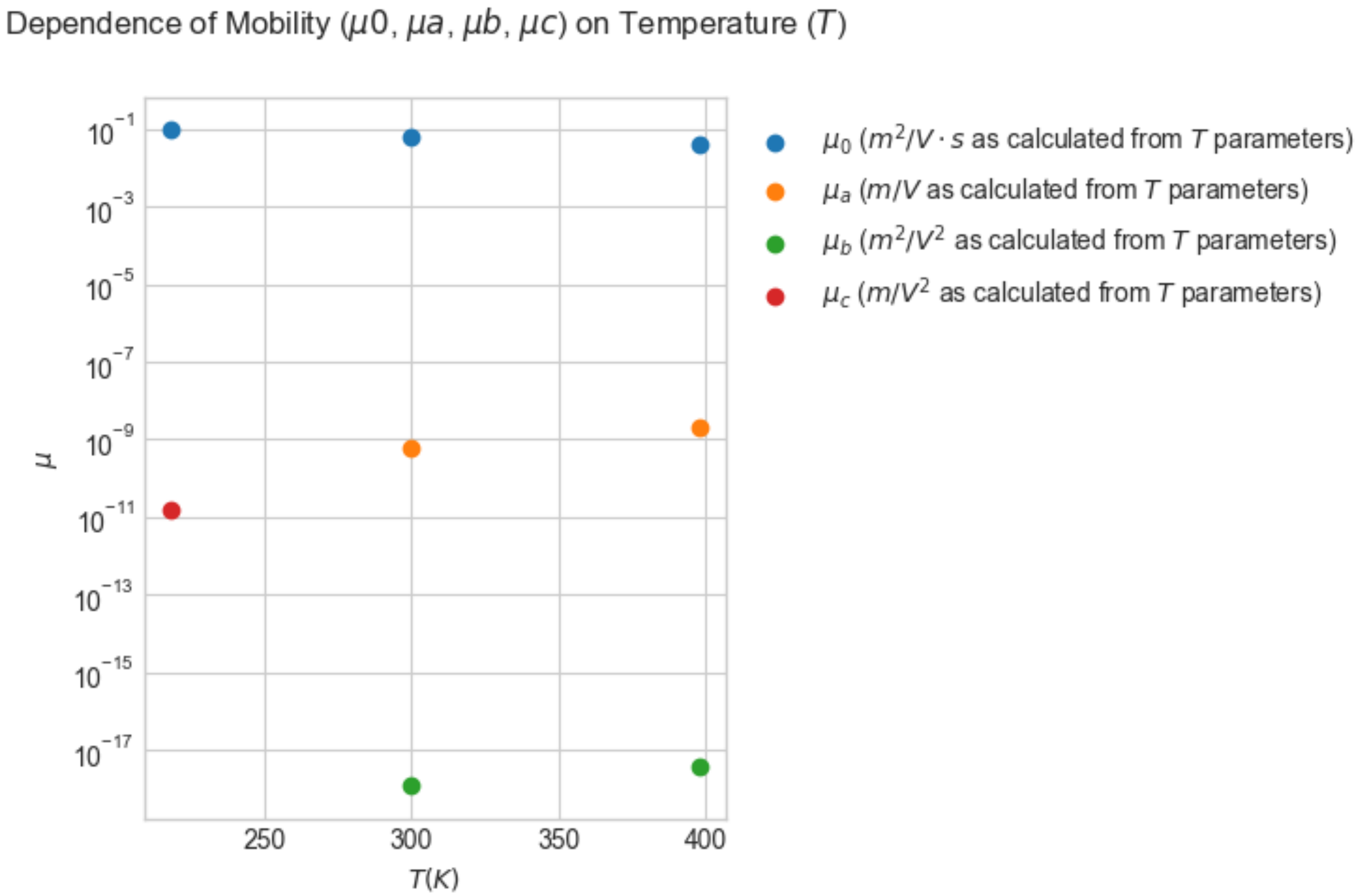
```
Calculated u0 values (218K,300K,398K): 0.09652186284786184,0.05979,0.039127835808042494
Calculated ua values (218K,300K,398K): -5.780666666666668e-10,6e-10,2.0079333333333334e-09
Calculated ub values (218K,300K,398K): -8.800666666666667e-19,1.2e-18,3.6859333333333333e-18
Calculated uc values (218K,300K,398K): 1.5306666666666665e-11,0.0,-1.8293333333333334e-11
```

In [9]:

```
fig,axes = plt.subplots(figsize=(4,5))
fig.suptitle('Dependence of Mobility ($\mu 0$, $\mu a$, $\mu b$, $\mu c$) on Temperature ($T$)')
plt.scatter([218,300,398],[mu(T=218, u0=0.05979).mu0(), mu(T=300, u0=0.05979).mu0(), mu(T=398, u0=0.05979).mu0()],label='$\mu_0$ ($m^2/V\cdot s$ as calculated from $T$ pa
plt.scatter([218,300,398],[mu(T=218, u0=0.05979).mua(), mu(T=300, u0=0.05979).mua(), mu(T=398, u0=0.05979).mua()],label='$\mu_a$ ($m/V$ as calculated from $T$ parameters)
plt.scatter([218,300,398],[mu(T=218, u0=0.05979).mub(), mu(T=300, u0=0.05979).mub(), mu(T=398, u0=0.05979).mub()],label='$\mu_b$ ($m^2/V^2$ as calculated from $T$ paramet
plt.scatter([218,300,398],[mu(T=218, u0=0.05979).muc(), mu(T=300, u0=0.05979).muc(), mu(T=398, u0=0.05979).muc()],label='$\mu_c$ ($m/V^2$ as calculated from $T$ parameter
plt.yscale('log')
axes.legend(bbox_to_anchor=(1, 1), loc="upper left")
axes.set_xlabel('$T (K)$')
axes.set_ylabel('$\mu$')
```

Out[9]:

```
Text(0, 0.5, '$\\mu$')
```



Summary

1. Mobility (μ_0) decreases with increasing T while mobility coefficients (μ_a, μ_b, μ_c) increase with T. This is due to an incresing scattering of charge carriers with increasing T inside the MOS channel lattice.
2. This effect cannot be seen qualitatively in the plots of **Part I** and **Part II**, which is due to other competing effects like channel length modulation and lowering V_T with increasing T.

Part IV: 45nm NMOS corner simulations

Table summarising Process Variability-Sensitive Global Device Parameter extracts from Nano-CMOS compact model relating to corner simulations

(parameters as noted in Table 8.2 of **[1]**)

Corner Modeling	$vth0\ (V)$	$xl\ (m)$	$toxe/toxm\ (m)$	$u0\ (m^2/V \cdot s)$	$k1\ (V^{1/2})$	$rdsw\ (\Omega(\mu m)^{WR})$	$cgsl/cgdl\ (F/m)$	$cgso/cgdo\ (F/m)$	$cjs/cjd\ (F/m^2)$	$cjsws/cjswd\ (F/m)$	$cjswgs/cjswgd\ (F/m)$
Nominal	0.41	-2e-8	1.75-9	0.04805	0.477	150	2.653e-10	1.1e-10	0.0005	5e-10	3e-10/5e-10
Fast-Fast	0.379	-2e-8	1.75-9	0.05045	0.45	150	2.653e-10	1.1e-10	0.0005	5e-10	3e-10/5e-10
Slow-Slow	0.439	-2e-8	1.75-9	0.04588	0.502	150	2.653e-10	1.1e-10	0.0005	5e-10	3e-10/5e-10

Summary

1. Since the only varying parameters in the table above are vth0, u0 and k1; key Nano-CMOS compact model parameters for the Nominal, Fast-Fast and Slow-Slow corners are: vth0, u0 and k1.

References

- [1] **Compact Models For Integrated Circuit Design - Samar K. Saha**
- [2] **BSIM 4.8.2 Technical Manual**
- [3] **BSIM 4.3.0 Technical Manual**

Additional information

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IH2653 Examiner: Dr. Gunnar Malm, Professor KTH

Data and config files at: Github