Import necessary libraries and packages

In [1]:
```
#import os #Might want to reset kernel/env
import math
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import matplotlib.gridspec as gridspec
%matplotlib inline
plt.style.use('seaborn-whitegrid')
from matplotlib.legend_handler import HandlerTuple
import matplotlib.ticker as ticker
import sys
!{sys.executable} -m pip install piecewise-regression
import piecewise_regression #For piecewise fit of a continuous curve
```

```
Requirement already satisfied: piecewise-regression in /usr/local/anaconda3/lib/python3.9/site-packages (1.3.0)
Requirement already satisfied: statsmodels in /usr/local/anaconda3/lib/python3.9/site-packages (from piecewise-regression) (0.13.2)
Requirement already satisfied: scipy in /usr/local/anaconda3/lib/python3.9/site-packages (from piecewise-regression) (1.7.3)
Requirement already satisfied: numpy in /usr/local/anaconda3/lib/python3.9/site-packages (from piecewise-regression) (1.21.5)
Requirement already satisfied: matplotlib in /usr/local/anaconda3/lib/python3.9/site-packages (from piecewise-regression) (3.5.1)
Requirement already satisfied: python-dateutil>=2.7 in /usr/local/anaconda3/lib/python3.9/site-packages (from matplotlib->piecewise-regression) (2.8.2)
Requirement already satisfied: packaging>=20.0 in /usr/local/anaconda3/lib/python3.9/site-packages (from matplotlib->piecewise-regression) (21.3)
Requirement already satisfied: fonttools>=4.22.0 in /usr/local/anaconda3/lib/python3.9/site-packages (from matplotlib->piecewise-regression) (4.25.0)
Requirement already satisfied: pyparsing>=2.2.1 in /usr/local/anaconda3/lib/python3.9/site-packages (from matplotlib->piecewise-regression) (3.0.4)
Requirement already satisfied: pillow>=6.2.0 in /usr/local/anaconda3/lib/python3.9/site-packages (from matplotlib->piecewise-regression) (9.0.1)
Requirement already satisfied: kiwisolver>=1.0.1 in /usr/local/anaconda3/lib/python3.9/site-packages (from matplotlib->piecewise-regression) (1.3.2)
Requirement already satisfied: cycler>=0.10 in /usr/local/anaconda3/lib/python3.9/site-packages (from matplotlib->piecewise-regression) (0.11.0)
Requirement already satisfied: six>=1.5 in /usr/local/anaconda3/lib/python3.9/site-packages (from python-dateutil>=2.7->matplotlib->piecewise-regression) (1.16.0)
Requirement already satisfied: patsy>=0.5.2 in /usr/local/anaconda3/lib/python3.9/site-packages (from statsmodels->piecewise-regression) (0.5.2)
Requirement already satisfied: pandas>=0.25 in /usr/local/anaconda3/lib/python3.9/site-packages (from statsmodels->piecewise-regression) (1.4.2)
Requirement already satisfied: pytz>=2020.1 in /usr/local/anaconda3/lib/python3.9/site-packages (from pandas>=0.25->statsmodels->piecewise-regression) (2021.3)
```

Abstract

As MOSFET gate lengths (L) are scaled ever lower to achieve greater compute per unit die area, studies [1] indicate an increasing subthreshold leakage current (I_{OFF}) and an increasing drain current w.r.t source (I_{ON}/I_d) due to lowering gate threshold barrier (V_T), according to the following equations -

$$V'_T = V_{T-long} - (V_d + 0.4V) \cdot e^{\frac{-L}{\sqrt[3]{T_{oxe} \cdot W_{dep} \cdot X_j}}} \tag{1}$$

$$I_{OFF} = 100 \cdot \frac{W}{L} \cdot 10^{\frac{-qV_T}{\eta kT}} = 100 \cdot \frac{W}{L} \cdot 10^{\frac{-V_T}{S}} \tag{2}$$

$$I_{ON} = 100 \cdot \frac{W}{L} \cdot 10^{\frac{q(V_g - V_T)}{\eta kT}} = 100 \cdot \frac{W}{L} \cdot 10^{\frac{(V_g - V_T)}{S}} \tag{3}$$

Hence the purpose of this Lab is to verify these relations in scaling down of horizontal MOSEFET dimensions (L), vertical MOSFET dimensions (electrical equivalent oxide thickness T_{oxe} / depletion-layer width W_{dep} / drain junction depth X_j) and the supply voltage (V_{DD}) - through nanoHUB simulations and experimental measurements at 300K. Additionally, the effect of gate electrode workfunction (ψ_g) on V_T (as studied in [1]) is verified, according to the following equation -

$$V'_T = V_T + \Delta\psi_g \tag{4}$$

Table of Contents

Part I: Gate-characteristics and threshold voltage roll-off

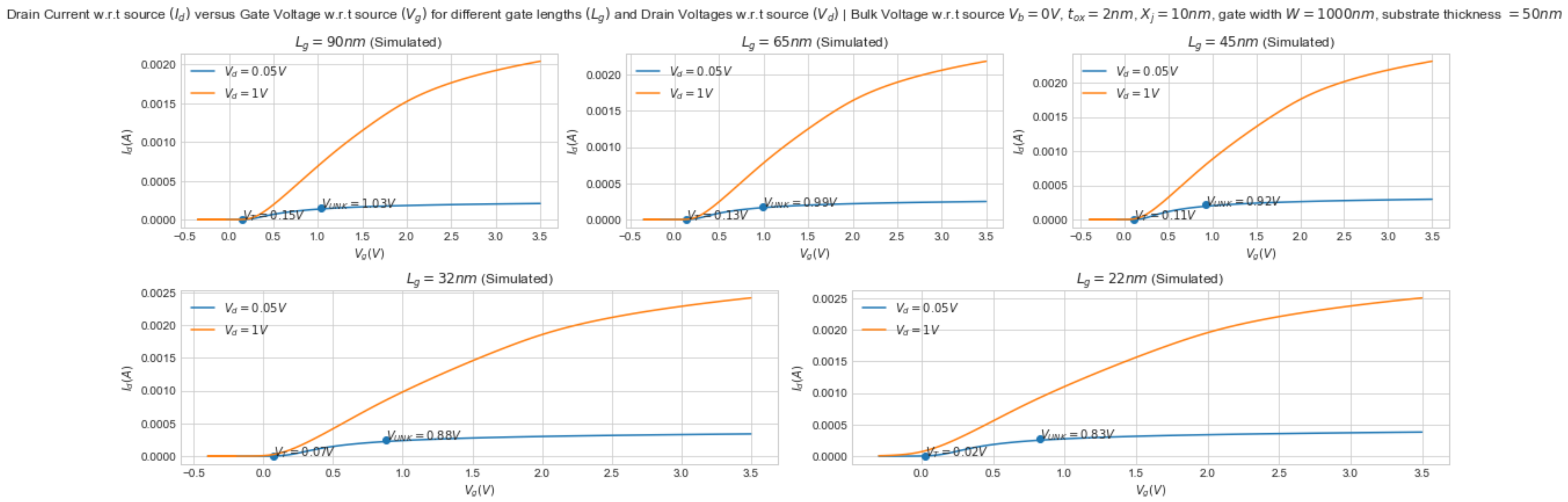
[Simulated] I_d/V_g for N-MOSFET with constant oxide thickness (t_{ox})

In [2]:
```
#Reading data
NIdVg_90nm_Vd005 = pd.read_csv('Simulations/N-L90nm-IdVg.txt', skiprows=4,nrows=100,header=None)
NIdVg_90nm_Vd1 = pd.read_csv('Simulations/N-L90nm-IdVg.txt', skiprows=109,nrows=118,header=None)

NIdVg_65nm_Vd005 = pd.read_csv('Simulations/N-L65nm-IdVg.txt', skiprows=4,nrows=100,header=None)
NIdVg_65nm_Vd1 = pd.read_csv('Simulations/N-L65nm-IdVg.txt', skiprows=109,nrows=118,header=None)

NIdVg_45nm_Vd005 = pd.read_csv('Simulations/N-L45nm-IdVg.txt', skiprows=4,nrows=100,header=None)
NIdVg_45nm_Vd1 = pd.read_csv('Simulations/N-L45nm-IdVg.txt', skiprows=109,nrows=302,header=None)

NIdVg_32nm_Vd005 = pd.read_csv('Simulations/N-L32nm-IdVg.txt', skiprows=4,nrows=100,header=None)
NIdVg_32nm_Vd1 = pd.read_csv('Simulations/N-L32nm-IdVg.txt', skiprows=109,nrows=105,header=None)

NIdVg_22nm_Vd005 = pd.read_csv('Simulations/N-L22nm-IdVg.txt', skiprows=4,nrows=100,header=None)
NIdVg_22nm_Vd1 = pd.read_csv('Simulations/N-L22nm-IdVg.txt', skiprows=109,nrows=118,header=None)
```

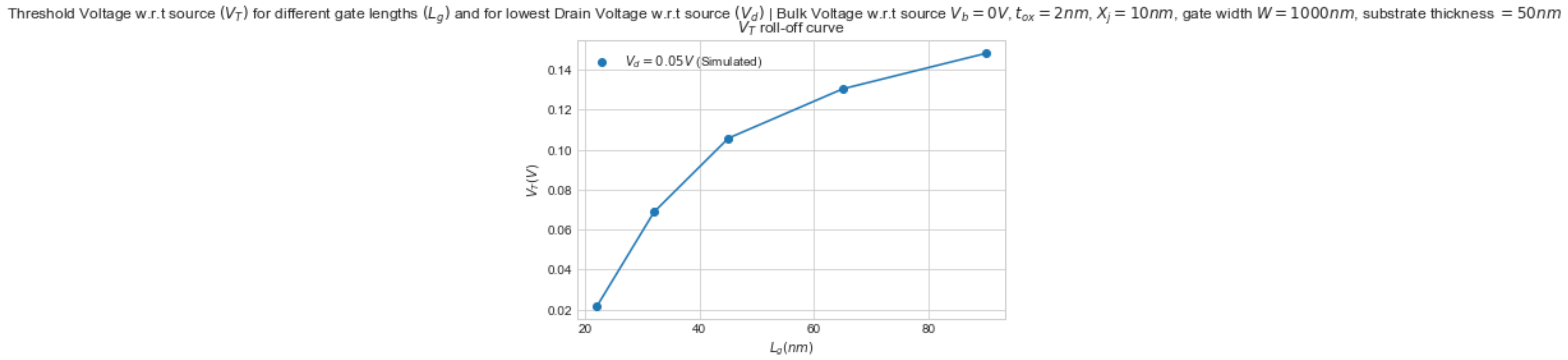
In [3]:
```
#Plotting data
fig = plt.figure(constrained_layout=True,figsize=(16, 6))
fig.suptitle('Drain Current w.r.t source $(I_d)$ versus Gate Voltage w.r.t source $(V_g)$ for different gate leng
gs0 = fig.add_gridspec(2, 1)
gs00 = gs0[0].subgridspec(1, 3)
gs01 = gs0[1].subgridspec(1, 2)

fig.add_subplot(gs00[0, 0])
plt.plot(NIdVg_90nm_Vd005[0], NIdVg_90nm_Vd005[1], label='$V_d = 0.05V$')
plt.plot(NIdVg_90nm_Vd1[0], NIdVg_90nm_Vd1[1], label='$V_d = 1V$')
pw_fit_NIdVg_90nm_Vd005 = piecewise_regression.Fit(NIdVg_90nm_Vd005[0].to_numpy(), NIdVg_90nm_Vd005[1].to_numpy()
VT_NIdVg_90nm_Vd005 = pw_fit_NIdVg_90nm_Vd005.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_90nm_Vd005 = pw_fit_NIdVg_90nm_Vd005.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_90nm_V
plt.scatter(VT_NIdVg_90nm_Vd005,Id_VT_NIdVg_90nm_Vd005,marker='o')
plt.annotate(f'$V_T = {VT_NIdVg_90nm_Vd005:.2f}V$', (VT_NIdVg_90nm_Vd005, Id_VT_NIdVg_90nm_Vd005))
#Beyond linear regime of I_d vs V_g for V_d = 0.05V
Vunk_NIdVg_90nm_Vd005 = pw_fit_NIdVg_90nm_Vd005.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_90nm_Vd005 = pw_fit_NIdVg_90nm_Vd005.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdVg_
plt.scatter(Vunk_NIdVg_90nm_Vd005,Idunk_VT_NIdVg_90nm_Vd005,marker='o',c='#1f77b4')
plt.annotate(f'$V_{{UNK}} = {Vunk_NIdVg_90nm_Vd005:.2f}V$', (Vunk_NIdVg_90nm_Vd005, Idunk_VT_NIdVg_90nm_Vd005))
plt.legend(loc='best')
plt.title('$L_g = 90nm$ (Simulated)')
plt.xlabel('$V_g (V)$')
plt.ylabel('$I_d (A)$')

fig.add_subplot(gs00[0, 1])
plt.plot(NIdVg_65nm_Vd005[0], NIdVg_65nm_Vd005[1], label='$V_d = 0.05V$')
plt.plot(NIdVg_65nm_Vd1[0], NIdVg_65nm_Vd1[1], label='$V_d = 1V$')
pw_fit_NIdVg_65nm_Vd005 = piecewise_regression.Fit(NIdVg_65nm_Vd005[0].to_numpy(), NIdVg_65nm_Vd005[1].to_numpy()
VT_NIdVg_65nm_Vd005 = pw_fit_NIdVg_65nm_Vd005.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_65nm_Vd005 = pw_fit_NIdVg_65nm_Vd005.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_65nm_V
```

```
plt.scatter(VT_NIdVg_65nm_Vd005,Id_VT_NIdVg_65nm_Vd005,marker='o')
plt.annotate(f'$V_T = {VT_NIdVg_65nm_Vd005:.2f}V$', (VT_NIdVg_65nm_Vd005, Id_VT_NIdVg_65nm_Vd005))
#Beyond linear regime of I_d vs V_g for V_d = 0.05V
Vunk_NIdVg_65nm_Vd005 = pw_fit_NIdVg_65nm_Vd005.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_65nm_Vd005 = pw_fit_NIdVg_65nm_Vd005.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdVg_
plt.scatter(Vunk_NIdVg_65nm_Vd005,Idunk_VT_NIdVg_65nm_Vd005,marker='o',c='#1f77b4')
plt.annotate(f'$V_{{UNK}} = {Vunk_NIdVg_65nm_Vd005:.2f}V$', (Vunk_NIdVg_65nm_Vd005, Idunk_VT_NIdVg_65nm_Vd005))
plt.legend(loc='best')
plt.title('$L_g = 65nm$ (Simulated)')
plt.xlabel('$V_g (V)$')
plt.ylabel('$I_d (A)$')

fig.add_subplot(gs00[0, 2])
plt.plot(NIdVg_45nm_Vd005[0], NIdVg_45nm_Vd005[1], label='$V_d = 0.05V$')
plt.plot(NIdVg_45nm_Vd1[0], NIdVg_45nm_Vd1[1], label='$V_d = 1V$')
pw_fit_NIdVg_45nm_Vd005 = piecewise_regression.Fit(NIdVg_45nm_Vd005[0].to_numpy(), NIdVg_45nm_Vd005[1].to_numpy()
VT_NIdVg_45nm_Vd005 = pw_fit_NIdVg_45nm_Vd005.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_45nm_Vd005 = pw_fit_NIdVg_45nm_Vd005.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_45nm_V
plt.scatter(VT_NIdVg_45nm_Vd005,Id_VT_NIdVg_45nm_Vd005,marker='o')
plt.annotate(f'$V_T = {VT_NIdVg_45nm_Vd005:.2f}V$', (VT_NIdVg_45nm_Vd005, Id_VT_NIdVg_45nm_Vd005))
#Beyond linear regime of I_d vs V_g for V_d = 0.05V
Vunk_NIdVg_45nm_Vd005 = pw_fit_NIdVg_45nm_Vd005.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_45nm_Vd005 = pw_fit_NIdVg_45nm_Vd005.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdVg_
plt.scatter(Vunk_NIdVg_45nm_Vd005,Idunk_VT_NIdVg_45nm_Vd005,marker='o', c='#1f77b4')
plt.annotate(f'$V_{{UNK}} = {Vunk_NIdVg_45nm_Vd005:.2f}V$', (Vunk_NIdVg_45nm_Vd005, Idunk_VT_NIdVg_45nm_Vd005))
plt.legend(loc='best')
plt.title('$L_g = 45nm$ (Simulated)')
plt.xlabel('$V_g (V)$')
plt.ylabel('$I_d (A)$')

fig.add_subplot(gs01[0, 0])
plt.plot(NIdVg_32nm_Vd005[0], NIdVg_32nm_Vd005[1], label='$V_d = 0.05V$')
plt.plot(NIdVg_32nm_Vd1[0], NIdVg_32nm_Vd1[1], label='$V_d = 1V$')
pw_fit_NIdVg_32nm_Vd005 = piecewise_regression.Fit(NIdVg_32nm_Vd005[0].to_numpy(),NIdVg_32nm_Vd005[1].to_numpy(),
VT_NIdVg_32nm_Vd005 = pw_fit_NIdVg_32nm_Vd005.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_32nm_Vd005 = pw_fit_NIdVg_32nm_Vd005.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_32nm_V
plt.scatter(VT_NIdVg_32nm_Vd005,Id_VT_NIdVg_32nm_Vd005,marker='o')
plt.annotate(f'$V_T = {VT_NIdVg_32nm_Vd005:.2f}V$', (VT_NIdVg_32nm_Vd005, Id_VT_NIdVg_32nm_Vd005))
#Beyond linear regime of I_d vs V_g for V_d = 0.05V
Vunk_NIdVg_32nm_Vd005 = pw_fit_NIdVg_32nm_Vd005.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_32nm_Vd005 = pw_fit_NIdVg_32nm_Vd005.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdVg_
plt.scatter(Vunk_NIdVg_32nm_Vd005,Idunk_VT_NIdVg_32nm_Vd005,marker='o',c='#1f77b4')
plt.annotate(f'$V_{{UNK}} = {Vunk_NIdVg_32nm_Vd005:.2f}V$', (Vunk_NIdVg_32nm_Vd005, Idunk_VT_NIdVg_32nm_Vd005))
plt.legend(loc='best')
plt.title('$L_g = 32nm$ (Simulated)')
plt.xlabel('$V_g (V)$')
plt.ylabel('$I_d (A)$')

fig.add_subplot(gs01[0, 1])
plt.plot(NIdVg_22nm_Vd005[0], NIdVg_22nm_Vd005[1], label='$V_d = 0.05V$')
plt.plot(NIdVg_22nm_Vd1[0], NIdVg_22nm_Vd1[1], label='$V_d = 1V$')
pw_fit_NIdVg_22nm_Vd005 = piecewise_regression.Fit(NIdVg_22nm_Vd005[0].to_numpy(),NIdVg_22nm_Vd005[1].to_numpy(),
VT_NIdVg_22nm_Vd005 = pw_fit_NIdVg_22nm_Vd005.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_22nm_Vd005 = pw_fit_NIdVg_22nm_Vd005.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_22nm_V
plt.scatter(VT_NIdVg_22nm_Vd005,Id_VT_NIdVg_22nm_Vd005,marker='o')
plt.annotate(f'$V_T = {VT_NIdVg_22nm_Vd005:.2f}V$', (VT_NIdVg_22nm_Vd005, Id_VT_NIdVg_22nm_Vd005))
#Beyond linear regime of I_d vs V_g for V_d = 0.05V
Vunk_NIdVg_22nm_Vd005 = pw_fit_NIdVg_22nm_Vd005.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_22nm_Vd005 = pw_fit_NIdVg_22nm_Vd005.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdVg_
plt.scatter(Vunk_NIdVg_22nm_Vd005,Idunk_VT_NIdVg_22nm_Vd005,marker='o',c='#1f77b4')
plt.annotate(f'$V_{{UNK}} = {Vunk_NIdVg_22nm_Vd005:.2f}V$', (Vunk_NIdVg_22nm_Vd005, Idunk_VT_NIdVg_22nm_Vd005))
plt.legend(loc='best')
plt.title('$L_g = 22nm$ (Simulated)')
plt.xlabel('$V_g (V)$')
plt.ylabel('$I_d (A)$')
```

Out[3]:
```
Text(0, 0.5, '$I_d (A)$')
```



In [4]:
```
fig,axes = plt.subplots()
fig.suptitle('Threshold Voltage w.r.t source $(V_T)$ for different gate lengths $(L_g)$ and for lowest Drain Volt
plt.scatter([22,32,45,65,90],[VT_NIdVg_22nm_Vd005,VT_NIdVg_32nm_Vd005,VT_NIdVg_45nm_Vd005,VT_NIdVg_65nm_Vd005,VT_
plt.plot([22,32,45,65,90],[VT_NIdVg_22nm_Vd005,VT_NIdVg_32nm_Vd005,VT_NIdVg_45nm_Vd005,VT_NIdVg_65nm_Vd005,VT_NIc
axes.legend(loc='best')
axes.set_xlabel('$L_g (nm)$')
axes.set_ylabel('$V_T (V)$')
axes.set_title('$V_T$ roll-off curve')
axes.xaxis.set_major_locator(ticker.MultipleLocator(20))
```

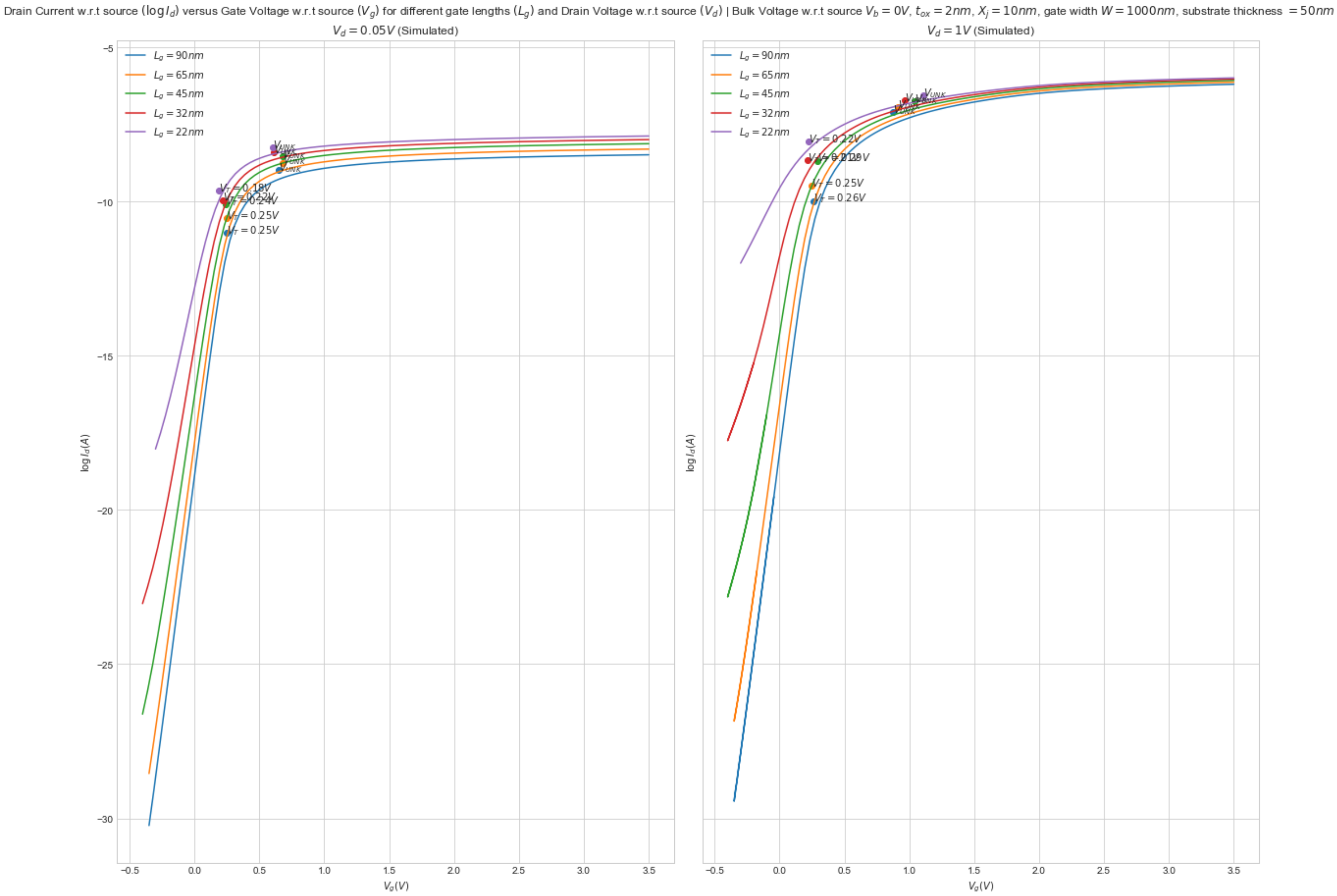


In [5]:
```
#Plotting data (logy vs x)
fig_SS, ax_SS = plt.subplots(nrows=1,ncols=2,tight_layout=True,sharex=True,sharey=True,figsize=(17, 13))
fig_SS.suptitle('Drain Current w.r.t source $(\log I_d)$ versus Gate Voltage w.r.t source $(V_g)$ for different g

plt.subplot(121)
plt.plot(NIdVg_90nm_Vd005[0].to_numpy(), np.log(NIdVg_90nm_Vd005[1].to_numpy()), label='$L_g = 90nm$')
logpw_fit_NIdVg_90nm_Vd005 = piecewise_regression.Fit(NIdVg_90nm_Vd005[0].to_numpy(),np.log(NIdVg_90nm_Vd005[1].t
VTSS_NIdVg_90nm_Vd005 = logpw_fit_NIdVg_90nm_Vd005.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_90nm_Vd005 = logpw_fit_NIdVg_90nm_Vd005.get_results()['estimates']['alpha1']['estimate']*VTSS_NIdVg
plt.scatter(VTSS_NIdVg_90nm_Vd005,IdSS_VT_NIdVg_90nm_Vd005,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_90nm_Vd005:.2f}V$', (VTSS_NIdVg_90nm_Vd005, IdSS_VT_NIdVg_90nm_Vd005))
#Beyond linear regime of I_d vs V_g for V_d = 0.05V
VSSunk_NIdVg_90nm_Vd005 = logpw_fit_NIdVg_90nm_Vd005.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_90nm_Vd005 = logpw_fit_NIdVg_90nm_Vd005.get_results()['estimates']['alpha2']['estimate']*(VSSunk
plt.scatter(VSSunk_NIdVg_90nm_Vd005,IdSSunk_VT_NIdVg_90nm_Vd005,marker='o',c='#1f77b4')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_90nm_Vd005, IdSSunk_VT_NIdVg_90nm_Vd005))

plt.plot(NIdVg_65nm_Vd005[0].to_numpy(), np.log(NIdVg_65nm_Vd005[1].to_numpy()), label='$L_g = 65nm$')
logpw_fit_NIdVg_65nm_Vd005 = piecewise_regression.Fit(NIdVg_65nm_Vd005[0].to_numpy(),np.log(NIdVg_65nm_Vd005[1].t
VTSS_NIdVg_65nm_Vd005 = logpw_fit_NIdVg_65nm_Vd005.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_65nm_Vd005 = logpw_fit_NIdVg_65nm_Vd005.get_results()['estimates']['alpha1']['estimate']*VTSS_NIdVg
plt.scatter(VTSS_NIdVg_65nm_Vd005,IdSS_VT_NIdVg_65nm_Vd005,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_65nm_Vd005:.2f}V$', (VTSS_NIdVg_65nm_Vd005, IdSS_VT_NIdVg_65nm_Vd005))
#Beyond linear regime of I_d vs V_g for V_d = 0.05V
VSSunk_NIdVg_65nm_Vd005 = logpw_fit_NIdVg_65nm_Vd005.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_65nm_Vd005 = logpw_fit_NIdVg_65nm_Vd005.get_results()['estimates']['alpha2']['estimate']*(VSSunk
plt.scatter(VSSunk_NIdVg_65nm_Vd005,IdSSunk_VT_NIdVg_65nm_Vd005,marker='o',c='#ff7f0e')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_65nm_Vd005, IdSSunk_VT_NIdVg_65nm_Vd005))

plt.plot(NIdVg_45nm_Vd005[0].to_numpy(), np.log(NIdVg_45nm_Vd005[1].to_numpy()), label='$L_g = 45nm$')
logpw_fit_NIdVg_45nm_Vd005 = piecewise_regression.Fit(NIdVg_45nm_Vd005[0].to_numpy(),np.log(NIdVg_45nm_Vd005[1].t
VTSS_NIdVg_45nm_Vd005 = logpw_fit_NIdVg_45nm_Vd005.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_45nm_Vd005 = logpw_fit_NIdVg_45nm_Vd005.get_results()['estimates']['alpha1']['estimate']*VTSS_NIdVg
plt.scatter(VTSS_NIdVg_45nm_Vd005,IdSS_VT_NIdVg_45nm_Vd005,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_45nm_Vd005:.2f}V$', (VTSS_NIdVg_45nm_Vd005, IdSS_VT_NIdVg_45nm_Vd005))
#Beyond linear regime of I_d vs V_g for V_d = 0.05V
VSSunk_NIdVg_45nm_Vd005 = logpw_fit_NIdVg_45nm_Vd005.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_45nm_Vd005 = logpw_fit_NIdVg_45nm_Vd005.get_results()['estimates']['alpha2']['estimate']*(VSSunk
plt.scatter(VSSunk_NIdVg_45nm_Vd005,IdSSunk_VT_NIdVg_45nm_Vd005,marker='o',c='#2ca02c')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_45nm_Vd005, IdSSunk_VT_NIdVg_45nm_Vd005))
```

```
plt.plot(NIdVg_32nm_Vd005[0].to_numpy(), np.log(NIdVg_32nm_Vd005[1].to_numpy()), label='$L_g = 32nm$')
logpw_fit_NIdVg_32nm_Vd005 = piecewise_regression.Fit(NIdVg_32nm_Vd005[0].to_numpy(),np.log(NIdVg_32nm_Vd005[1].t
VTSS_NIdVg_32nm_Vd005 = logpw_fit_NIdVg_32nm_Vd005.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_32nm_Vd005 = logpw_fit_NIdVg_32nm_Vd005.get_results()['estimates']['alpha1']['estimate']*VTSS_NIdVg
plt.scatter(VTSS_NIdVg_32nm_Vd005,IdSS_VT_NIdVg_32nm_Vd005,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_32nm_Vd005:.2f}V$', (VTSS_NIdVg_32nm_Vd005, IdSS_VT_NIdVg_32nm_Vd005))
#Beyond linear regime of I_d vs V_g for V_d = 0.05V
VSSunk_NIdVg_32nm_Vd005 = logpw_fit_NIdVg_32nm_Vd005.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_32nm_Vd005 = logpw_fit_NIdVg_32nm_Vd005.get_results()['estimates']['alpha2']['estimate']*(VSSunk
plt.scatter(VSSunk_NIdVg_32nm_Vd005,IdSSunk_VT_NIdVg_32nm_Vd005,marker='o',c='#d62728')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_32nm_Vd005, IdSSunk_VT_NIdVg_32nm_Vd005))

plt.plot(NIdVg_22nm_Vd005[0].to_numpy(), np.log(NIdVg_22nm_Vd005[1].to_numpy()), label='$L_g = 22nm$')
logpw_fit_NIdVg_22nm_Vd005 = piecewise_regression.Fit(NIdVg_22nm_Vd005[0].to_numpy(),np.log(NIdVg_22nm_Vd005[1].t
VTSS_NIdVg_22nm_Vd005 = logpw_fit_NIdVg_22nm_Vd005.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_22nm_Vd005 = logpw_fit_NIdVg_22nm_Vd005.get_results()['estimates']['alpha1']['estimate']*VTSS_NIdVg
plt.scatter(VTSS_NIdVg_22nm_Vd005,IdSS_VT_NIdVg_22nm_Vd005,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_22nm_Vd005:.2f}V$', (VTSS_NIdVg_22nm_Vd005, IdSS_VT_NIdVg_22nm_Vd005))
#Beyond linear regime of I_d vs V_g for V_d = 0.05V
VSSunk_NIdVg_22nm_Vd005 = logpw_fit_NIdVg_22nm_Vd005.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_22nm_Vd005 = logpw_fit_NIdVg_22nm_Vd005.get_results()['estimates']['alpha2']['estimate']*(VSSunk
plt.scatter(VSSunk_NIdVg_22nm_Vd005,IdSSunk_VT_NIdVg_22nm_Vd005,marker='o',c='#9467bd')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_22nm_Vd005, IdSSunk_VT_NIdVg_22nm_Vd005))

plt.legend(loc='best')
plt.title('$V_d = 0.05V$ (Simulated)')
plt.xlabel('$V_g (V)$')
plt.ylabel('$\log I_d (A)$')

plt.subplot(122)
plt.plot(NIdVg_90nm_Vd1[0].to_numpy(), np.log(NIdVg_90nm_Vd1[1].to_numpy()), label='$L_g = 90nm$')
logpw_fit_NIdVg_90nm_Vd1 = piecewise_regression.Fit(NIdVg_90nm_Vd1[0].to_numpy(),np.log(NIdVg_90nm_Vd1[1].to_nump
VTSS_NIdVg_90nm_Vd1 = logpw_fit_NIdVg_90nm_Vd1.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_90nm_Vd1 = logpw_fit_NIdVg_90nm_Vd1.get_results()['estimates']['alpha1']['estimate']*VTSS_NIdVg_90r
plt.scatter(VTSS_NIdVg_90nm_Vd1,IdSS_VT_NIdVg_90nm_Vd1,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_90nm_Vd1:.2f}V$', (VTSS_NIdVg_90nm_Vd1, IdSS_VT_NIdVg_90nm_Vd1))
#Beyond linear regime of I_d vs V_g for V_d = 1V
VSSunk_NIdVg_90nm_Vd1 = logpw_fit_NIdVg_90nm_Vd1.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_90nm_Vd1 = logpw_fit_NIdVg_90nm_Vd1.get_results()['estimates']['alpha2']['estimate']*(VSSunk_NIc
plt.scatter(VSSunk_NIdVg_90nm_Vd1,IdSSunk_VT_NIdVg_90nm_Vd1,marker='o',c='#1f77b4')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_90nm_Vd1, IdSSunk_VT_NIdVg_90nm_Vd1))

plt.plot(NIdVg_65nm_Vd1[0].to_numpy(), np.log(NIdVg_65nm_Vd1[1].to_numpy()), label='$L_g = 65nm$')
logpw_fit_NIdVg_65nm_Vd1 = piecewise_regression.Fit(NIdVg_65nm_Vd1[0].to_numpy(),np.log(NIdVg_65nm_Vd1[1].to_nump
VTSS_NIdVg_65nm_Vd1 = logpw_fit_NIdVg_65nm_Vd1.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_65nm_Vd1 = logpw_fit_NIdVg_65nm_Vd1.get_results()['estimates']['alpha1']['estimate']*VTSS_NIdVg_65r
plt.scatter(VTSS_NIdVg_65nm_Vd1,IdSS_VT_NIdVg_65nm_Vd1,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_65nm_Vd1:.2f}V$', (VTSS_NIdVg_65nm_Vd1, IdSS_VT_NIdVg_65nm_Vd1))
#Beyond linear regime of I_d vs V_g for V_d = 1V
VSSunk_NIdVg_65nm_Vd1 = logpw_fit_NIdVg_65nm_Vd1.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_65nm_Vd1 = logpw_fit_NIdVg_65nm_Vd1.get_results()['estimates']['alpha2']['estimate']*(VSSunk_NIc
plt.scatter(VSSunk_NIdVg_65nm_Vd1,IdSSunk_VT_NIdVg_65nm_Vd1,marker='o',c='#ff7f0e')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_65nm_Vd1, IdSSunk_VT_NIdVg_65nm_Vd1))

plt.plot(NIdVg_45nm_Vd1[0].to_numpy(), np.log(NIdVg_45nm_Vd1[1].to_numpy()), label='$L_g = 45nm$')
logpw_fit_NIdVg_45nm_Vd1 = piecewise_regression.Fit(NIdVg_45nm_Vd1[0].to_numpy()[33:],np.log(NIdVg_45nm_Vd1[1].tc
VTSS_NIdVg_45nm_Vd1 = logpw_fit_NIdVg_45nm_Vd1.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_45nm_Vd1 = logpw_fit_NIdVg_45nm_Vd1.get_results()['estimates']['alpha1']['estimate']*VTSS_NIdVg_45r
plt.scatter(VTSS_NIdVg_45nm_Vd1,IdSS_VT_NIdVg_45nm_Vd1,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_45nm_Vd1:.2f}V$', (VTSS_NIdVg_45nm_Vd1, IdSS_VT_NIdVg_45nm_Vd1))
#Beyond linear regime of I_d vs V_g for V_d = 1V
VSSunk_NIdVg_45nm_Vd1 = logpw_fit_NIdVg_45nm_Vd1.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_45nm_Vd1 = logpw_fit_NIdVg_45nm_Vd1.get_results()['estimates']['alpha2']['estimate']*(VSSunk_NIc
plt.scatter(VSSunk_NIdVg_45nm_Vd1,IdSSunk_VT_NIdVg_45nm_Vd1,marker='o',c='#2ca02c')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_45nm_Vd1, IdSSunk_VT_NIdVg_45nm_Vd1))

plt.plot(NIdVg_32nm_Vd1[0].to_numpy(), np.log(NIdVg_32nm_Vd1[1].to_numpy()), label='$L_g = 32nm$')
logpw_fit_NIdVg_32nm_Vd1 = piecewise_regression.Fit(NIdVg_32nm_Vd1[0].to_numpy(),np.log(NIdVg_32nm_Vd1[1].to_nump
VTSS_NIdVg_32nm_Vd1 = logpw_fit_NIdVg_32nm_Vd1.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_32nm_Vd1 = logpw_fit_NIdVg_32nm_Vd1.get_results()['estimates']['alpha1']['estimate']*VTSS_NIdVg_32r
plt.scatter(VTSS_NIdVg_32nm_Vd1,IdSS_VT_NIdVg_32nm_Vd1,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_32nm_Vd1:.2f}V$', (VTSS_NIdVg_32nm_Vd1, IdSS_VT_NIdVg_32nm_Vd1))
#Beyond linear regime of I_d vs V_g for V_d = 1V
VSSunk_NIdVg_32nm_Vd1 = logpw_fit_NIdVg_32nm_Vd1.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_32nm_Vd1 = logpw_fit_NIdVg_32nm_Vd1.get_results()['estimates']['alpha2']['estimate']*(VSSunk_NIc
plt.scatter(VSSunk_NIdVg_32nm_Vd1,IdSSunk_VT_NIdVg_32nm_Vd1,marker='o',c='#d62728')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_32nm_Vd1, IdSSunk_VT_NIdVg_32nm_Vd1))

plt.plot(NIdVg_22nm_Vd1[0].to_numpy(), np.log(NIdVg_22nm_Vd1[1].to_numpy()), label='$L_g = 22nm$')
logpw_fit_NIdVg_22nm_Vd1 = piecewise_regression.Fit(NIdVg_22nm_Vd1[0].to_numpy(),np.log(NIdVg_22nm_Vd1[1].to_nump
VTSS_NIdVg_22nm_Vd1 = logpw_fit_NIdVg_22nm_Vd1.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_22nm_Vd1 = logpw_fit_NIdVg_22nm_Vd1.get_results()['estimates']['alpha1']['estimate']*VTSS_NIdVg_22r
plt.scatter(VTSS_NIdVg_22nm_Vd1,IdSS_VT_NIdVg_22nm_Vd1,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_22nm_Vd1:.2f}V$', (VTSS_NIdVg_22nm_Vd1, IdSS_VT_NIdVg_22nm_Vd1))
```

```
#Beyond linear regime of I_d vs V_g for V_d = 1V
VSSunk_NIdVg_22nm_Vd1 = logpw_fit_NIdVg_22nm_Vd1.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_22nm_Vd1 = logpw_fit_NIdVg_22nm_Vd1.get_results()['estimates']['alpha2']['estimate']*(VSSunk_NIc
plt.scatter(VSSunk_NIdVg_22nm_Vd1,IdSSunk_VT_NIdVg_22nm_Vd1,marker='o',c='#9467bd')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_22nm_Vd1, IdSSunk_VT_NIdVg_22nm_Vd1))

plt.legend(loc='best')
plt.title('$V_d = 1V$ (Simulated)')
plt.xlabel('$V_g (V)$')
plt.ylabel('$\log I_d (A)$')
```

Out[5]: `Text(0, 0.5, '$\\log I_d (A)$')`



In [6]:
```
SS_NIdVg_90nm_Vd005 = (1/(logpw_fit_NIdVg_90nm_Vd005.get_results()['estimates']['alpha1']['estimate']))*1000 #Sub
SS_NIdVg_65nm_Vd005 = (1/(logpw_fit_NIdVg_65nm_Vd005.get_results()['estimates']['alpha1']['estimate']))*1000
SS_NIdVg_45nm_Vd005 = (1/(logpw_fit_NIdVg_45nm_Vd005.get_results()['estimates']['alpha1']['estimate']))*1000
SS_NIdVg_32nm_Vd005 = (1/(logpw_fit_NIdVg_32nm_Vd005.get_results()['estimates']['alpha1']['estimate']))*1000
SS_NIdVg_22nm_Vd005 = (1/(logpw_fit_NIdVg_22nm_Vd005.get_results()['estimates']['alpha1']['estimate']))*1000

pw_fit_NIdVg_90nm_Vd1 = piecewise_regression.Fit(NIdVg_90nm_Vd1[0].to_numpy(),NIdVg_90nm_Vd1[1].to_numpy(), n_bre
VT_NIdVg_90nm_Vd1 = pw_fit_NIdVg_90nm_Vd1.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_90nm_Vd1 = pw_fit_NIdVg_90nm_Vd1.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_90nm_Vd1+p
Vunk_NIdVg_90nm_Vd1 = pw_fit_NIdVg_90nm_Vd1.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_90nm_Vd1 = pw_fit_NIdVg_90nm_Vd1.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdVg_90nm
Ion_NIdVg_90nm_Vd1 = pw_fit_NIdVg_90nm_Vd1.get_results()['estimates']['alpha3']['estimate']*(1-Vunk_NIdVg_90nm_Vd

pw_fit_NIdVg_65nm_Vd1 = piecewise_regression.Fit(NIdVg_65nm_Vd1[0].to_numpy(),NIdVg_65nm_Vd1[1].to_numpy(), n_bre
VT_NIdVg_65nm_Vd1 = pw_fit_NIdVg_65nm_Vd1.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_65nm_Vd1 = pw_fit_NIdVg_65nm_Vd1.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_65nm_Vd1+p
Vunk_NIdVg_65nm_Vd1 = pw_fit_NIdVg_65nm_Vd1.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_65nm_Vd1 = pw_fit_NIdVg_65nm_Vd1.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdVg_65nm
Ion_NIdVg_65nm_Vd1 = pw_fit_NIdVg_65nm_Vd1.get_results()['estimates']['alpha3']['estimate']*(1-Vunk_NIdVg_65nm_Vd

pw_fit_NIdVg_45nm_Vd1 = piecewise_regression.Fit(NIdVg_45nm_Vd1[0].to_numpy(),NIdVg_45nm_Vd1[1].to_numpy(), n_bre
VT_NIdVg_45nm_Vd1 = pw_fit_NIdVg_45nm_Vd1.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_45nm_Vd1 = pw_fit_NIdVg_45nm_Vd1.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_45nm_Vd1+p
Vunk_NIdVg_45nm_Vd1 = pw_fit_NIdVg_45nm_Vd1.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_45nm_Vd1 = pw_fit_NIdVg_45nm_Vd1.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdVg_45nm
Ion_NIdVg_45nm_Vd1 = pw_fit_NIdVg_45nm_Vd1.get_results()['estimates']['alpha3']['estimate']*(1-Vunk_NIdVg_45nm_Vd

pw_fit_NIdVg_32nm_Vd1 = piecewise_regression.Fit(NIdVg_32nm_Vd1[0].to_numpy(),NIdVg_32nm_Vd1[1].to_numpy(), n_bre
VT_NIdVg_32nm_Vd1 = pw_fit_NIdVg_32nm_Vd1.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_32nm_Vd1 = pw_fit_NIdVg_32nm_Vd1.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_32nm_Vd1+p
Vunk_NIdVg_32nm_Vd1 = pw_fit_NIdVg_32nm_Vd1.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_32nm_Vd1 = pw_fit_NIdVg_32nm_Vd1.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdVg_32nm
Ion_NIdVg_32nm_Vd1 = pw_fit_NIdVg_32nm_Vd1.get_results()['estimates']['alpha3']['estimate']*(1-Vunk_NIdVg_32nm_Vd

pw_fit_NIdVg_22nm_Vd1 = piecewise_regression.Fit(NIdVg_22nm_Vd1[0].to_numpy(),NIdVg_22nm_Vd1[1].to_numpy(), n_bre
VT_NIdVg_22nm_Vd1 = pw_fit_NIdVg_22nm_Vd1.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_22nm_Vd1 = pw_fit_NIdVg_22nm_Vd1.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_22nm_Vd1+p
Vunk_NIdVg_22nm_Vd1 = pw_fit_NIdVg_22nm_Vd1.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_22nm_Vd1 = pw_fit_NIdVg_22nm_Vd1.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdVg_22nm
Ion_NIdVg_22nm_Vd1 = pw_fit_NIdVg_22nm_Vd1.get_results()['estimates']['alpha3']['estimate']*(1-Vunk_NIdVg_22nm_Vd

logIoff_NIdVg_90nm_Vd1 = logpw_fit_NIdVg_90nm_Vd1.get_results()['estimates']['const']['estimate']
Ioff_NIdVg_90nm_Vd1 = math.pow(10,logIoff_NIdVg_90nm_Vd1)
logIoff_NIdVg_65nm_Vd1 = logpw_fit_NIdVg_65nm_Vd1.get_results()['estimates']['const']['estimate']
Ioff_NIdVg_65nm_Vd1 = math.pow(10,logIoff_NIdVg_65nm_Vd1)
logIoff_NIdVg_45nm_Vd1 = logpw_fit_NIdVg_45nm_Vd1.get_results()['estimates']['const']['estimate']
Ioff_NIdVg_45nm_Vd1 = math.pow(10,logIoff_NIdVg_45nm_Vd1)
logIoff_NIdVg_32nm_Vd1 = logpw_fit_NIdVg_32nm_Vd1.get_results()['estimates']['const']['estimate']
Ioff_NIdVg_32nm_Vd1 = math.pow(10,logIoff_NIdVg_32nm_Vd1)
logIoff_NIdVg_22nm_Vd1 = logpw_fit_NIdVg_22nm_Vd1.get_results()['estimates']['const']['estimate']
Ioff_NIdVg_22nm_Vd1 = math.pow(10,logIoff_NIdVg_22nm_Vd1)

DIBL_NIdVg_90nm = ((VTSS_NIdVg_90nm_Vd1-VTSS_NIdVg_90nm_Vd005)/(1-0.05))*1000 #Drain-induced barrier lowering (DI
DIBL_NIdVg_65nm = ((VTSS_NIdVg_65nm_Vd1-VTSS_NIdVg_65nm_Vd005)/(1-0.05))*1000
DIBL_NIdVg_45nm = ((VTSS_NIdVg_45nm_Vd1-VTSS_NIdVg_45nm_Vd005)/(1-0.05))*1000
DIBL_NIdVg_32nm = ((VTSS_NIdVg_32nm_Vd1-VTSS_NIdVg_32nm_Vd005)/(1-0.05))*1000
DIBL_NIdVg_22nm = ((VTSS_NIdVg_22nm_Vd1-VTSS_NIdVg_22nm_Vd005)/(1-0.05))*1000
```

In [7]:
```
print("%.3e" % SS_NIdVg_90nm_Vd005) #To print necessary variable values and enter in summary below
```

```
3.131e+01
```

Summary

$L_g\ (nm)$	$V_T\ (V)$ $@V_d = 0.05V$ **Simulated**	$SS\ (mV/dec)$ $@V_d = 0.05V$ **Simulated**	$I_{ON}\ (A)$ $@V_d(V_g) = 1V$ **Simulated**	$I_{OFF}\ (A)$ $@V_d = 1V$ **Simulated**	$DIBL\ (mV/V)$ **Simulated**
90	0.251	31.305	1.248e-03	5.574e-19	8.137
65	0.246	33.124	1.341e-03	1.725e-17	1.657
45	0.241	37.871	1.444e-03	1.833e-15	51.303
32	0.218	45.175	1.540e-03	1.115e-12	-4.178
22	0.185	56.649	1.631e-03	2.095e-10	37.028

1. X_j and # channel nodes were changed (-20% and $+120\%$) accordingly for simulation of decreasing L_g, to get better plot convergence.
2. V_T extracted from $\log I_d$ vs V_g plot has been reported in the table above because piecewise regression fit of $\log I_d$ vs V_g plot better captures feautures which lie in the well modeled subthreshold and linear regions of MOSFET operation (as demonstrated in comparisons of experimental and simulated V_T values in Part IV).
3. I_{ON} extracted from I_d vs V_g plot has been reported in the table above because $I_{ON}@V_g = 1V$ lies beyond the linear region of MOSFET operation and is not well modeled through a $\log I_d$ vs V_g regression fit (reason for it is explained below in point 4).
4. V_{UNK} in $\log I_d$ (or I_d) vs V_g plot indicates V_g from which the MOSFET enters a non-linear operating region that needs 5 coupled equations (Poisson, Electron continuity, Hole continuity, Electron transport and Hole transport) to be modeled.
5. $DIBL\ \forall L_g$ (except 32nm) seem to be off because -
   A. $\log I_d$ vs $V_g @V_d = 1V$ simulated plot has a slight curvature in the subthreshold region at very low V_g.
   B. Hence, $V_T@V_d = 1V$ is overestimated in the respective piecewise regression fit.
6. Simulations in this section were carried out using the abacus tool at nanoHUB. It contains generic physical models for simulating various IV relations of MOSFETs.

Part II: Scaling of oxide thickness and supply voltage

[Simulated] I_d/V_g for N-MOSFET with scaled oxide thickness (t'_{ox}) and supply voltage (V'_{DD})

In [8]:
```
#Reading data
NIdVg_90nm_t16_Vd005 = pd.read_csv('Simulations/N-L90nm-t16-IdVg.txt', skiprows=4,nrows=100,header=None)
NIdVg_90nm_t16_Vd1 = pd.read_csv('Simulations/N-L90nm-t16-IdVg.txt', skiprows=109,nrows=123,header=None)

NIdVg_65nm_t12_Vd005 = pd.read_csv('Simulations/N-L65nm-t12-IdVg.txt', skiprows=4,nrows=100,header=None)
NIdVg_65nm_t12_Vd1 = pd.read_csv('Simulations/N-L65nm-t12-IdVg.txt', skiprows=109,nrows=120,header=None)

NIdVg_45nm_t1_Vd005 = pd.read_csv('Simulations/N-L45nm-t1-IdVg.txt', skiprows=4,nrows=200,header=None)
NIdVg_45nm_t1_Vd09 = pd.read_csv('Simulations/N-L45nm-t1-IdVg.txt', skiprows=209,nrows=268,header=None)
```

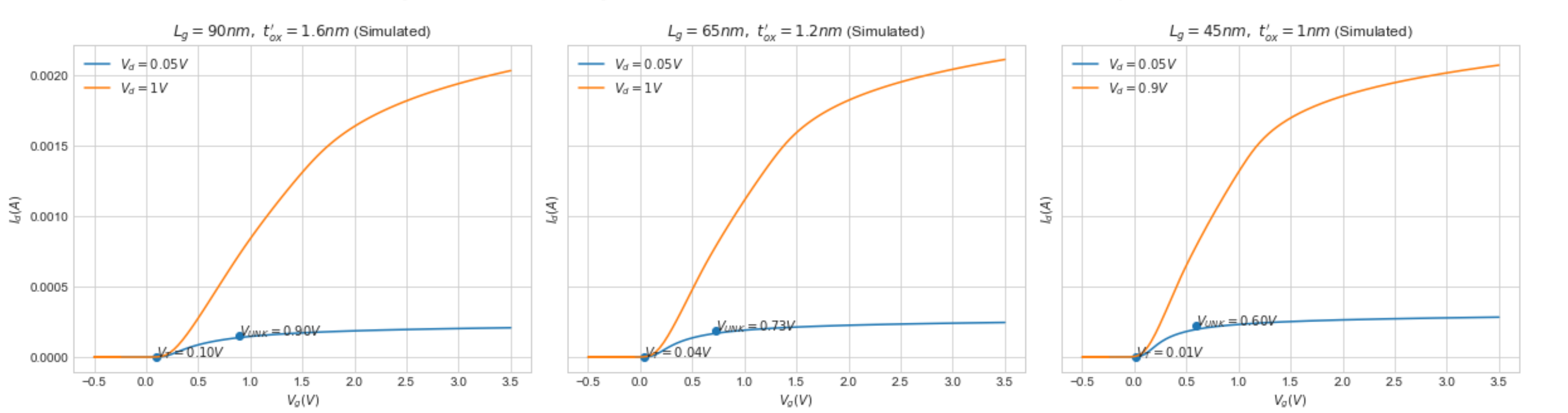
In [9]:

```
#Plotting data
fig,axes = plt.subplots(nrows=1,ncols=3,tight_layout=True,sharex=True,sharey=True, figsize=(17, 5))
fig.suptitle('Drain Current w.r.t source $(I_d)$ versus Gate Voltage w.r.t source $(V_g)$ for different gate leng

plt.subplot(131)
plt.plot(NIdVg_90nm_t16_Vd005[0], NIdVg_90nm_t16_Vd005[1], label='$V_d = 0.05V$')
plt.plot(NIdVg_90nm_t16_Vd1[0], NIdVg_90nm_t16_Vd1[1], label='$V_d = 1V$')
pw_fit_NIdVg_90nm_t16_Vd005 = piecewise_regression.Fit(NIdVg_90nm_t16_Vd005[0].to_numpy(), NIdVg_90nm_t16_Vd005[1
VT_NIdVg_90nm_t16_Vd005 = pw_fit_NIdVg_90nm_t16_Vd005.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_90nm_t16_Vd005 = pw_fit_NIdVg_90nm_t16_Vd005.get_results()['estimates']['alpha1']['estimate']*VT_NIdV
plt.scatter(VT_NIdVg_90nm_t16_Vd005,Id_VT_NIdVg_90nm_t16_Vd005,marker='o')
axes[0].annotate(f'$V_T = {VT_NIdVg_90nm_t16_Vd005:.2f}V$', (VT_NIdVg_90nm_t16_Vd005, Id_VT_NIdVg_90nm_t16_Vd005)
#Beyond linear regime of I_d vs V_g for V_d = 0.05V
Vunk_NIdVg_90nm_t16_Vd005 = pw_fit_NIdVg_90nm_t16_Vd005.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_90nm_t16_Vd005 = pw_fit_NIdVg_90nm_t16_Vd005.get_results()['estimates']['alpha2']['estimate']*(Vun
plt.scatter(Vunk_NIdVg_90nm_t16_Vd005,Idunk_VT_NIdVg_90nm_t16_Vd005,marker='o',c='#1f77b4')
axes[0].annotate(f'$V_{{UNK}} = {Vunk_NIdVg_90nm_t16_Vd005:.2f}V$', (Vunk_NIdVg_90nm_t16_Vd005, Idunk_VT_NIdVg_90
axes[0].set_title('$L_g = 90nm,~t^{\prime}_{ox} = 1.6nm$ (Simulated)')
axes[0].set_xlabel('$V_g (V)$')
axes[0].set_ylabel('$I_d (A)$')
axes[0].legend(loc='best')

plt.subplot(132)
plt.plot(NIdVg_65nm_t12_Vd005[0], NIdVg_65nm_t12_Vd005[1], label='$V_d = 0.05V$')
plt.plot(NIdVg_65nm_t12_Vd1[0], NIdVg_65nm_t12_Vd1[1], label='$V_d = 1V$')
pw_fit_NIdVg_65nm_t12_Vd005 = piecewise_regression.Fit(NIdVg_65nm_t12_Vd005[0].to_numpy(), NIdVg_65nm_t12_Vd005[1
VT_NIdVg_65nm_t12_Vd005 = pw_fit_NIdVg_65nm_t12_Vd005.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_65nm_t12_Vd005 = pw_fit_NIdVg_65nm_t12_Vd005.get_results()['estimates']['alpha1']['estimate']*VT_NIdV
plt.scatter(VT_NIdVg_65nm_t12_Vd005,Id_VT_NIdVg_65nm_t12_Vd005,marker='o')
axes[1].annotate(f'$V_T = {VT_NIdVg_65nm_t12_Vd005:.2f}V$', (VT_NIdVg_65nm_t12_Vd005, Id_VT_NIdVg_65nm_t12_Vd005)
#Beyond linear regime of I_d vs V_g for V_d = 0.05V
Vunk_NIdVg_65nm_t12_Vd005 = pw_fit_NIdVg_65nm_t12_Vd005.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_65nm_t12_Vd005 = pw_fit_NIdVg_65nm_t12_Vd005.get_results()['estimates']['alpha2']['estimate']*(Vun
plt.scatter(Vunk_NIdVg_65nm_t12_Vd005,Idunk_VT_NIdVg_65nm_t12_Vd005,marker='o',c='#1f77b4')
axes[1].annotate(f'$V_{{UNK}} = {Vunk_NIdVg_65nm_t12_Vd005:.2f}V$', (Vunk_NIdVg_65nm_t12_Vd005, Idunk_VT_NIdVg_65
axes[1].set_title('$L_g = 65nm,~t^{\prime}_{ox} = 1.2nm$ (Simulated)')
axes[1].set_xlabel('$V_g (V)$')
axes[1].set_ylabel('$I_d (A)$')
axes[1].legend(loc='best')

plt.subplot(133)
plt.plot(NIdVg_45nm_t1_Vd005[0], NIdVg_45nm_t1_Vd005[1], label='$V_d = 0.05V$')
plt.plot(NIdVg_45nm_t1_Vd09[0], NIdVg_45nm_t1_Vd09[1], label='$V_d = 0.9V$')
pw_fit_NIdVg_45nm_t1_Vd005 = piecewise_regression.Fit(NIdVg_45nm_t1_Vd005[0].to_numpy(), NIdVg_45nm_t1_Vd005[1].t
VT_NIdVg_45nm_t1_Vd005 = pw_fit_NIdVg_45nm_t1_Vd005.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_45nm_t1_Vd005 = pw_fit_NIdVg_45nm_t1_Vd005.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_
plt.scatter(VT_NIdVg_45nm_t1_Vd005,Id_VT_NIdVg_45nm_t1_Vd005,marker='o')
axes[2].annotate(f'$V_T = {VT_NIdVg_45nm_t1_Vd005:.2f}V$', (VT_NIdVg_45nm_t1_Vd005, Id_VT_NIdVg_45nm_t1_Vd005))
#Beyond linear regime of I_d vs V_g for V_d = 0.05V
Vunk_NIdVg_45nm_t1_Vd005 = pw_fit_NIdVg_45nm_t1_Vd005.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_45nm_t1_Vd005 = pw_fit_NIdVg_45nm_t1_Vd005.get_results()['estimates']['alpha2']['estimate']*(Vunk_
plt.scatter(Vunk_NIdVg_45nm_t1_Vd005,Idunk_VT_NIdVg_45nm_t1_Vd005,marker='o',c='#1f77b4')
axes[2].annotate(f'$V_{{UNK}} = {Vunk_NIdVg_45nm_t1_Vd005:.2f}V$', (Vunk_NIdVg_45nm_t1_Vd005, Idunk_VT_NIdVg_45nm
axes[2].set_title('$L_g = 45nm,~t^{\prime}_{ox} = 1nm$ (Simulated)')
axes[2].set_xlabel('$V_g (V)$')
axes[2].set_ylabel('$I_d (A)$')
axes[2].legend(loc='best')
```

Out[9]:

```
<matplotlib.legend.Legend at 0x7f9ad755e8b0>
```

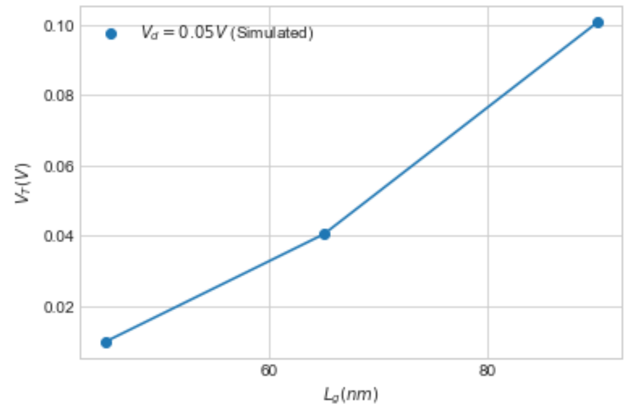
Drain Current w.r.t source (I_d) versus Gate Voltage w.r.t source (V_g) for different gate lengths (L_g) and Drain Voltages w.r.t source (V_d) | Bulk Voltage w.r.t source $V_b = 0V$, $X_j = 10nm$, gate width $W = 1000nm$, substrate thickness $= 50nm$



In [10]:
```
fig,axes = plt.subplots()
fig.suptitle('Threshold Voltage w.r.t source $(V_T)$ for different gate lengths $(L_g)$ and for lowest Drain Volt
plt.scatter([45,65,90],[VT_NIdVg_45nm_t1_Vd005,VT_NIdVg_65nm_t12_Vd005,VT_NIdVg_90nm_t16_Vd005],marker='o',label=
plt.plot([45,65,90],[VT_NIdVg_45nm_t1_Vd005,VT_NIdVg_65nm_t12_Vd005,VT_NIdVg_90nm_t16_Vd005])
axes.legend(loc='best')
axes.set_xlabel('$L_g (nm)$')
axes.set_ylabel('$V_T (V)$')
axes.set_title('$V_T$ roll-off curve')
axes.xaxis.set_major_locator(ticker.MultipleLocator(20))
```

Threshold Voltage w.r.t source (V_T) for different gate lengths (L_g) and for lowest Drain Voltage w.r.t source (V_d) | Bulk Voltage w.r.t source $V_b = 0V, X_j = 10nm$, gate width $W = 1000nm$, substrate thickness $= 50nm$

V_T roll-off curve

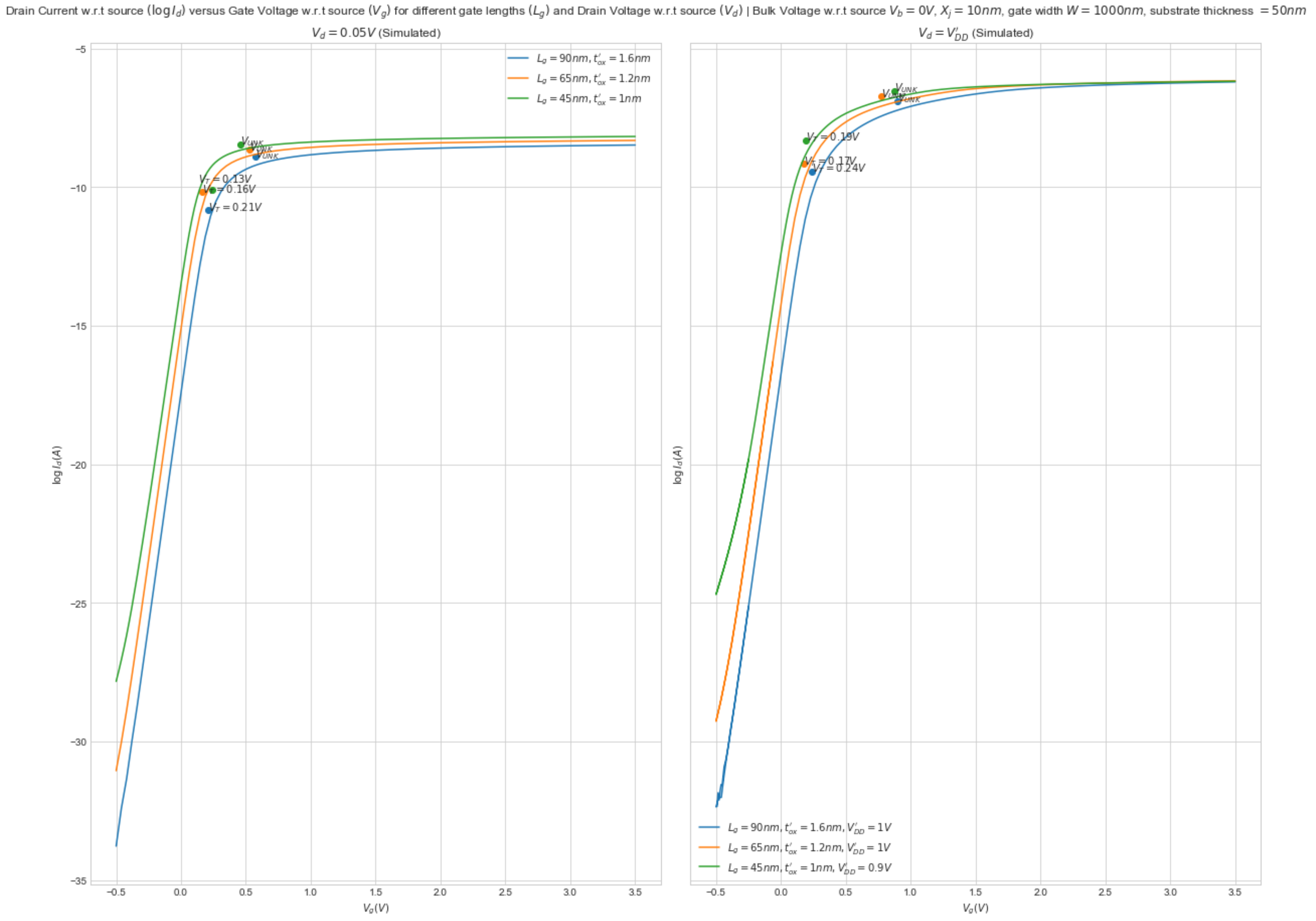


In [11]:
```
#Plotting data (logy vs x)
fig_SS, ax_SS = plt.subplots(nrows=1,ncols=2,tight_layout=True,sharex=True,sharey=True,figsize=(17, 13))
fig_SS.suptitle('Drain Current w.r.t source $(\log I_d)$ versus Gate Voltage w.r.t source $(V_g)$ for different g

plt.subplot(121)
plt.plot(NIdVg_90nm_t16_Vd005[0].to_numpy(), np.log(NIdVg_90nm_t16_Vd005[1].to_numpy()), label='$L_g = 90nm, t_{o
logpw_fit_NIdVg_90nm_t16_Vd005 = piecewise_regression.Fit(NIdVg_90nm_t16_Vd005[0].to_numpy(),np.log(NIdVg_90nm_t1
VTSS_NIdVg_90nm_t16_Vd005 = logpw_fit_NIdVg_90nm_t16_Vd005.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_90nm_t16_Vd005 = logpw_fit_NIdVg_90nm_t16_Vd005.get_results()['estimates']['alpha1']['estimate']*VT
plt.scatter(VTSS_NIdVg_90nm_t16_Vd005,IdSS_VT_NIdVg_90nm_t16_Vd005,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_90nm_t16_Vd005:.2f}V$', (VTSS_NIdVg_90nm_t16_Vd005, IdSS_VT_NIdVg_90nm_t16_Vd00
#Beyond linear regime of I_d vs V_g for V_d = 0.05V
VSSunk_NIdVg_90nm_t16_Vd005 = logpw_fit_NIdVg_90nm_t16_Vd005.get_results()['estimates']['breakpoint2']['estimate'
IdSSunk_VT_NIdVg_90nm_t16_Vd005 = logpw_fit_NIdVg_90nm_t16_Vd005.get_results()['estimates']['alpha2']['estimate']
plt.scatter(VSSunk_NIdVg_90nm_t16_Vd005,IdSSunk_VT_NIdVg_90nm_t16_Vd005,marker='o',c='#1f77b4')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_90nm_t16_Vd005, IdSSunk_VT_NIdVg_90nm_t16_Vd005))

plt.plot(NIdVg_65nm_t12_Vd005[0].to_numpy(), np.log(NIdVg_65nm_t12_Vd005[1].to_numpy()), label='$L_g = 65nm, t_{o
logpw_fit_NIdVg_65nm_t12_Vd005 = piecewise_regression.Fit(NIdVg_65nm_t12_Vd005[0].to_numpy(),np.log(NIdVg_65nm_t1
VTSS_NIdVg_65nm_t12_Vd005 = logpw_fit_NIdVg_65nm_t12_Vd005.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_65nm_t12_Vd005 = logpw_fit_NIdVg_65nm_t12_Vd005.get_results()['estimates']['alpha1']['estimate']*VT
plt.scatter(VTSS_NIdVg_65nm_t12_Vd005,IdSS_VT_NIdVg_65nm_t12_Vd005,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_65nm_t12_Vd005:.2f}V$', (VTSS_NIdVg_65nm_t12_Vd005, IdSS_VT_NIdVg_65nm_t12_Vd00
#Beyond linear regime of I_d vs V_g for V_d = 0.05V
VSSunk_NIdVg_65nm_t12_Vd005 = logpw_fit_NIdVg_65nm_t12_Vd005.get_results()['estimates']['breakpoint2']['estimate'
IdSSunk_VT_NIdVg_65nm_t12_Vd005 = logpw_fit_NIdVg_65nm_t12_Vd005.get_results()['estimates']['alpha2']['estimate']
plt.scatter(VSSunk_NIdVg_65nm_t12_Vd005,IdSSunk_VT_NIdVg_65nm_t12_Vd005,marker='o',c='#ff7f0e')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_65nm_t12_Vd005, IdSSunk_VT_NIdVg_65nm_t12_Vd005))

plt.plot(NIdVg_45nm_t1_Vd005[0].to_numpy(), np.log(NIdVg_45nm_t1_Vd005[1].to_numpy()), label='$L_g = 45nm, t_{ox}
logpw_fit_NIdVg_45nm_t1_Vd005 = piecewise_regression.Fit(NIdVg_45nm_t1_Vd005[0].to_numpy(),np.log(NIdVg_45nm_t1_V
VTSS_NIdVg_45nm_t1_Vd005 = logpw_fit_NIdVg_45nm_t1_Vd005.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_45nm_t1_Vd005 = logpw_fit_NIdVg_45nm_t1_Vd005.get_results()['estimates']['alpha1']['estimate']*VTSS
plt.scatter(VTSS_NIdVg_45nm_Vd005,IdSS_VT_NIdVg_45nm_Vd005,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_45nm_t1_Vd005:.2f}V$', (VTSS_NIdVg_45nm_t1_Vd005, IdSS_VT_NIdVg_45nm_t1_Vd005))
#Beyond linear regime of I_d vs V_g for V_d = 0.05V
VSSunk_NIdVg_45nm_t1_Vd005 = logpw_fit_NIdVg_45nm_t1_Vd005.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_45nm_t1_Vd005 = logpw_fit_NIdVg_45nm_t1_Vd005.get_results()['estimates']['alpha2']['estimate']*(
plt.scatter(VSSunk_NIdVg_45nm_t1_Vd005,IdSSunk_VT_NIdVg_45nm_t1_Vd005,marker='o',c='#2ca02c')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_45nm_t1_Vd005, IdSSunk_VT_NIdVg_45nm_t1_Vd005))

plt.legend(loc='best')
plt.title('$V_d = 0.05V$ (Simulated)')
plt.xlabel('$V_g (V)$')
plt.ylabel('$\log I_d (A)$')

plt.subplot(122)
plt.plot(NIdVg_90nm_t16_Vd1[0].to_numpy(), np.log(NIdVg_90nm_t16_Vd1[1].to_numpy()), label='$L_g = 90nm, t_{ox}^{
logpw_fit_NIdVg_90nm_t16_Vd1 = piecewise_regression.Fit(NIdVg_90nm_t16_Vd1[0].to_numpy(),np.log(NIdVg_90nm_t16_Vd
VTSS_NIdVg_90nm_t16_Vd1 = logpw_fit_NIdVg_90nm_t16_Vd1.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_90nm_t16_Vd1 = logpw_fit_NIdVg_90nm_t16_Vd1.get_results()['estimates']['alpha1']['estimate']*VTSS_N
plt.scatter(VTSS_NIdVg_90nm_t16_Vd1,IdSS_VT_NIdVg_90nm_t16_Vd1,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_90nm_t16_Vd1:.2f}V$', (VTSS_NIdVg_90nm_t16_Vd1, IdSS_VT_NIdVg_90nm_t16_Vd1))
#Beyond linear regime of I_d vs V_g for V_d = 1V
VSSunk_NIdVg_90nm_t16_Vd1 = logpw_fit_NIdVg_90nm_t16_Vd1.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_90nm_t16_Vd1 = logpw_fit_NIdVg_90nm_t16_Vd1.get_results()['estimates']['alpha2']['estimate']*(VS
plt.scatter(VSSunk_NIdVg_90nm_t16_Vd1,IdSSunk_VT_NIdVg_90nm_t16_Vd1,marker='o',c='#1f77b4')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_90nm_t16_Vd1, IdSSunk_VT_NIdVg_90nm_t16_Vd1))
```

```
plt.plot(NIdVg_65nm_t12_Vd1[0].to_numpy(), np.log(NIdVg_65nm_t12_Vd1[1].to_numpy()), label='$L_g = 65nm, t_{ox}^{
logpw_fit_NIdVg_65nm_t12_Vd1 = piecewise_regression.Fit(NIdVg_65nm_t12_Vd1[0].to_numpy(),np.log(NIdVg_65nm_t12_Vc
VTSS_NIdVg_65nm_t12_Vd1 = logpw_fit_NIdVg_65nm_t12_Vd1.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_65nm_t12_Vd1 = logpw_fit_NIdVg_65nm_t12_Vd1.get_results()['estimates']['alpha1']['estimate']*VTSS_N
plt.scatter(VTSS_NIdVg_65nm_t12_Vd1,IdSS_VT_NIdVg_65nm_t12_Vd1,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_65nm_t12_Vd1:.2f}V$', (VTSS_NIdVg_65nm_t12_Vd1, IdSS_VT_NIdVg_65nm_t12_Vd1))
#Beyond linear regime of I_d vs V_g for V_d = 1V
VSSunk_NIdVg_65nm_t12_Vd1 = logpw_fit_NIdVg_65nm_t12_Vd1.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_65nm_t12_Vd1 = logpw_fit_NIdVg_65nm_t12_Vd1.get_results()['estimates']['alpha2']['estimate']*(VS
plt.scatter(VSSunk_NIdVg_65nm_t12_Vd1,IdSSunk_VT_NIdVg_65nm_t12_Vd1,marker='o',c='#ff7f0e')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_65nm_t12_Vd1, IdSSunk_VT_NIdVg_65nm_t12_Vd1))

plt.plot(NIdVg_45nm_t1_Vd09[0].to_numpy(), np.log(NIdVg_45nm_t1_Vd09[1].to_numpy()), label='$L_g = 45nm, t_{ox}^{
logpw_fit_NIdVg_45nm_t1_Vd09 = piecewise_regression.Fit(NIdVg_45nm_t1_Vd09[0].to_numpy(),np.log(NIdVg_45nm_t1_Vd(
VTSS_NIdVg_45nm_t1_Vd09 = logpw_fit_NIdVg_45nm_t1_Vd09.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_45nm_t1_Vd09 = logpw_fit_NIdVg_45nm_t1_Vd09.get_results()['estimates']['alpha1']['estimate']*VTSS_N
plt.scatter(VTSS_NIdVg_45nm_t1_Vd09,IdSS_VT_NIdVg_45nm_t1_Vd09,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_45nm_t1_Vd09:.2f}V$', (VTSS_NIdVg_45nm_t1_Vd09, IdSS_VT_NIdVg_45nm_t1_Vd09))
#Beyond linear regime of I_d vs V_g for V_d = 1V
VSSunk_NIdVg_45nm_t1_Vd09 = logpw_fit_NIdVg_45nm_t1_Vd09.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_45nm_t1_Vd09 = logpw_fit_NIdVg_45nm_t1_Vd09.get_results()['estimates']['alpha2']['estimate']*(VS
plt.scatter(VSSunk_NIdVg_45nm_t1_Vd09,IdSSunk_VT_NIdVg_45nm_t1_Vd09,marker='o',c='#2ca02c')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_45nm_t1_Vd09, IdSSunk_VT_NIdVg_45nm_t1_Vd09))

plt.legend(loc='best')
plt.title('$V_d = V_{DD}^{\prime}$ (Simulated)')
plt.xlabel('$V_g (V)$')
plt.ylabel('$\log I_d (A)$')
```

Out[11]:

```
Text(0, 0.5, '$\\log I_d (A)$')
```



In [12]:
```
SS_NIdVg_90nm_t16_Vd005 = (1/(logpw_fit_NIdVg_90nm_t16_Vd005.get_results()['estimates']['alpha1']['estimate']))*1
SS_NIdVg_65nm_t12_Vd005 = (1/(logpw_fit_NIdVg_65nm_t12_Vd005.get_results()['estimates']['alpha1']['estimate']))*1
SS_NIdVg_45nm_t1_Vd005 = (1/(logpw_fit_NIdVg_45nm_t1_Vd005.get_results()['estimates']['alpha1']['estimate']))*100

pw_fit_NIdVg_90nm_t16_Vd1 = piecewise_regression.Fit(NIdVg_90nm_t16_Vd1[0].to_numpy(),NIdVg_90nm_t16_Vd1[1].to_nu
VT_NIdVg_90nm_t16_Vd1 = pw_fit_NIdVg_90nm_t16_Vd1.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_90nm_t16_Vd1 = pw_fit_NIdVg_90nm_t16_Vd1.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_90
Vunk_NIdVg_90nm_t16_Vd1 = pw_fit_NIdVg_90nm_t16_Vd1.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_90nm_t16_Vd1 = pw_fit_NIdVg_90nm_t16_Vd1.get_results()['estimates']['alpha2']['estimate']*(Vunk_NI
Ion_NIdVg_90nm_t16_Vd1 = pw_fit_NIdVg_90nm_t16_Vd1.get_results()['estimates']['alpha3']['estimate']*(1-Vunk_NIdVg

pw_fit_NIdVg_65nm_t12_Vd1 = piecewise_regression.Fit(NIdVg_65nm_t12_Vd1[0].to_numpy(),NIdVg_65nm_t12_Vd1[1].to_nu
VT_NIdVg_65nm_t12_Vd1 = pw_fit_NIdVg_65nm_t12_Vd1.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_65nm_t12_Vd1 = pw_fit_NIdVg_65nm_t12_Vd1.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_65
Vunk_NIdVg_65nm_t12_Vd1 = pw_fit_NIdVg_65nm_t12_Vd1.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_65nm_t12_Vd1 = pw_fit_NIdVg_65nm_t12_Vd1.get_results()['estimates']['alpha2']['estimate']*(Vunk_NI
Ion_NIdVg_65nm_t12_Vd1 = pw_fit_NIdVg_65nm_t12_Vd1.get_results()['estimates']['alpha3']['estimate']*(1-Vunk_NIdVg

pw_fit_NIdVg_45nm_t1_Vd09 = piecewise_regression.Fit(NIdVg_45nm_t1_Vd09[0].to_numpy(),NIdVg_45nm_t1_Vd09[1].to_nu
VT_NIdVg_45nm_t1_Vd09 = pw_fit_NIdVg_45nm_t1_Vd09.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_45nm_t1_Vd09 = pw_fit_NIdVg_45nm_t1_Vd09.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_45
Vunk_NIdVg_45nm_t1_Vd09 = pw_fit_NIdVg_45nm_t1_Vd09.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_45nm_t1_Vd09 = pw_fit_NIdVg_45nm_t1_Vd09.get_results()['estimates']['alpha2']['estimate']*(Vunk_NI
Ion_NIdVg_45nm_t1_Vd09 = pw_fit_NIdVg_45nm_t1_Vd09.get_results()['estimates']['alpha3']['estimate']*(1-Vunk_NIdVg

logIoff_NIdVg_90nm_t16_Vd1 = logpw_fit_NIdVg_90nm_t16_Vd1.get_results()['estimates']['const']['estimate']
Ioff_NIdVg_90nm_t16_Vd1 = math.pow(10,logIoff_NIdVg_90nm_t16_Vd1)
logIoff_NIdVg_65nm_t12_Vd1 = logpw_fit_NIdVg_65nm_t12_Vd1.get_results()['estimates']['const']['estimate']
Ioff_NIdVg_65nm_t12_Vd1 = math.pow(10,logIoff_NIdVg_65nm_t12_Vd1)
logIoff_NIdVg_45nm_t1_Vd09 = logpw_fit_NIdVg_45nm_t1_Vd09.get_results()['estimates']['const']['estimate']
Ioff_NIdVg_45nm_t1_Vd09 = math.pow(10,logIoff_NIdVg_45nm_t1_Vd09)

DIBL_NIdVg_90nm_t16_Vd1 = ((VTSS_NIdVg_90nm_t16_Vd1-VTSS_NIdVg_90nm_t16_Vd005)/(1-0.05))*1000 #Drain-induced barr
DIBL_NIdVg_65nm_t12_Vd1 = ((VTSS_NIdVg_65nm_t12_Vd1-VTSS_NIdVg_65nm_t12_Vd005)/(1-0.05))*1000
DIBL_NIdVg_45nm_t1_Vd09 = ((VTSS_NIdVg_45nm_t1_Vd09-VTSS_NIdVg_45nm_t1_Vd005)/(0.9-0.05))*1000
```

In [13]:
```
print("%.3e" % SS_NIdVg_90nm_t16_Vd005) #To print necessary variable values and enter in summary below
```

```
3.060e+01
```

Summary

$L_g\ (nm)$	$t'_{ox}\ (nm)$	$V'_{DD}\ (V)$	$V_T\ (V)$ $@V_d = 0.05V$ **Simulated**	$SS\ (mV/dec)$ $@V_d = 0.05V$ **Simulated**	$I_{ON}\ (A)$ $@V_d(V_g) = V'_{DD}$ **Simulated**	$I_{OFF}\ (A)$ $@V_d = V'_{DD}$ **Simulated**	$DIBL\ (mV/V)$ **Simulated**
90	1.6	1	0.206	30.604	1.373e-03	9.642e-18	33.813
65	1.2	1	0.160	31.106	1.569e-03	2.783e-15	16.082
45	1	0.9	0.133	33.741	1.626e-03	9.234e-14	70.566

1. t'_{ox} and $V'_{DD}\ \forall L_g$ were chosen from the ITRS roadmap presented in Table 3.3 of **[2]** to keep inline with performance requirements of the respective technology nodes.
2. # channel nodes, # oxide nodes and # bias steps were progressively increased accordingly for simulation of decreasing L_g, for better plot convergence.
3. V_T extracted from $\log I_d$ vs V_g plot has been reported in the table above because piecewise regression fit of $\log I_d$ vs V_g plot better captures feautures which lie in the well modeled subthreshold and linear regions of MOSFET operation (as demonstrated in comparisons of experimental and simulated V_T values in Part IV).
4. I_{ON} extracted from I_d vs V_g plot has been reported in the table above because $I_{ON}@V_g = 1V$ lies beyond the linear region of MOSFET operation and is not well modeled through a $\log I_d$ vs V_g regression fit (reason for it is explained below in point 4).
5. V_{UNK} in $\log I_d$ (or I_d) vs V_g plot indicates V_g from which the MOSFET enters a non-linear operating region that needs 5 coupled equations (Poisson, Electron continuity, Hole continuity, Electron transport and Hole transport) to be modeled.
6. $DIBL\ \forall L_g$ seem to be off because -
   A. $\log I_d$ vs $V_g@V_d = V'_{DD}$ simulated plot has a slight curvature in the subthreshold region at very low V_g.
   B. Hence, $V_T@V_d = 1V$ is overestimated in the respective piecewise regression fit.
7. The effect of scaling down t'_{ox} and V'_{DD} can be observed in higher I_{OFF} (and hence higher I_{ON}) values when compared to respective values in Part I. This follows directly from a lowered SS due to lower t'_{ox} ($SS \propto 1/C'_{ox} \propto t'_{ox}$ and hence Eq. (2),Eq. (3)).
8. Simulations in this section were carried out using the abacus tool at nanoHUB. It contains generic physical models for simulating various IV relations of MOSFETs.

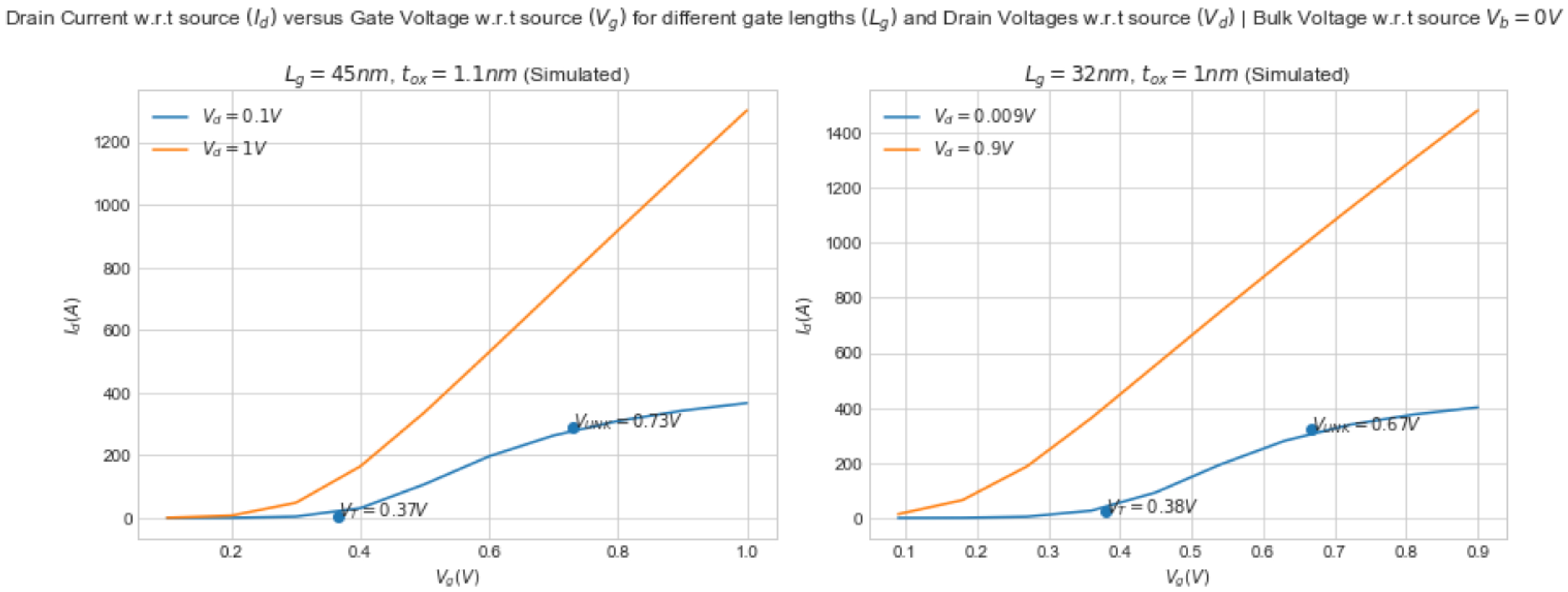
Part III: Compact model comparison

[Simulated] I_d/V_g for N-MOSFET with constant oxide thickness (t_{ox})

In [14]:
```
NIdVg_45nm_Compact_Vd01 = pd.read_csv('Simulations/N-L45nm-IdVg-Compact.txt', skiprows=4,nrows=10,header=None)
NIdVg_45nm_Compact_Vd1 = pd.read_csv('Simulations/N-L45nm-IdVg-Compact.txt', skiprows=19,nrows=10,header=None)

NIdVg_32nm_Compact_Vd009 = pd.read_csv('Simulations/N-L32nm-IdVg-Compact.txt', skiprows=4,nrows=10,header=None)
NIdVg_32nm_Compact_Vd09 = pd.read_csv('Simulations/N-L32nm-IdVg-Compact.txt', skiprows=19,nrows=10,header=None)
```

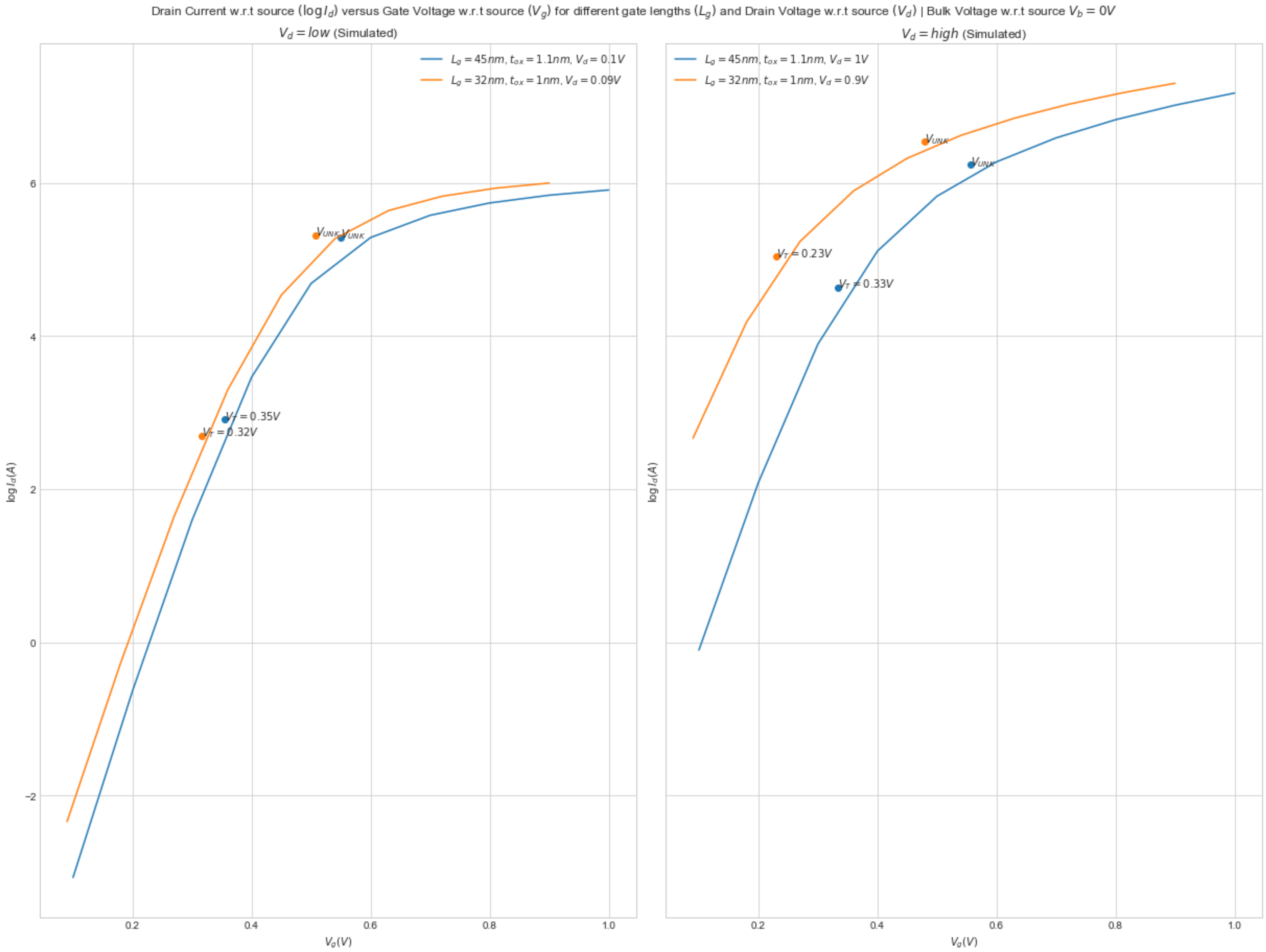
In [15]:
```
#Plotting data
fig,axes = plt.subplots(nrows=1,ncols=3,tight_layout=True,sharex=True,sharey=True, figsize=(12, 5))
fig.suptitle('Drain Current w.r.t source $(I_d)$ versus Gate Voltage w.r.t source $(V_g)$ for different gate leng

plt.subplot(121)
plt.plot(NIdVg_45nm_Compact_Vd01[0], NIdVg_45nm_Compact_Vd01[1], label='$V_d = 0.1V$')
plt.plot(NIdVg_45nm_Compact_Vd1[0], NIdVg_45nm_Compact_Vd1[1], label='$V_d = 1V$')
pw_fit_NIdVg_45nm_Compact_Vd01 = piecewise_regression.Fit(NIdVg_45nm_Compact_Vd01[0].to_numpy(), NIdVg_45nm_Compa
VT_NIdVg_45nm_Compact_Vd01 = pw_fit_NIdVg_45nm_Compact_Vd01.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_45nm_Compact_Vd01 = pw_fit_NIdVg_45nm_Compact_Vd01.get_results()['estimates']['alpha1']['estimate']*V
plt.scatter(VT_NIdVg_45nm_Compact_Vd01,Id_VT_NIdVg_45nm_Compact_Vd01,marker='o')
plt.annotate(f'$V_T = {VT_NIdVg_45nm_Compact_Vd01:.2f}V$', (VT_NIdVg_45nm_Compact_Vd01, Id_VT_NIdVg_45nm_Compact_
#Beyond linear regime of I_d vs V_g for V_d = 0.1V
Vunk_NIdVg_45nm_Compact_Vd01 = pw_fit_NIdVg_45nm_Compact_Vd01.get_results()['estimates']['breakpoint2']['estimate
Idunk_VT_NIdVg_45nm_Compact_Vd01 = pw_fit_NIdVg_45nm_Compact_Vd01.get_results()['estimates']['alpha2']['estimate'
plt.scatter(Vunk_NIdVg_45nm_Compact_Vd01,Idunk_VT_NIdVg_45nm_Compact_Vd01,marker='o',c='#1f77b4')
plt.annotate(f'$V_{{UNK}} = {Vunk_NIdVg_45nm_Compact_Vd01:.2f}V$', (Vunk_NIdVg_45nm_Compact_Vd01, Idunk_VT_NIdVg_
plt.title('$L_g = 45nm$, $t_{ox} = 1.1nm$ (Simulated)')
plt.xlabel('$V_g (V)$')
plt.ylabel('$I_d (A)$')
plt.legend(loc='best')

plt.subplot(122)
plt.plot(NIdVg_32nm_Compact_Vd009[0], NIdVg_32nm_Compact_Vd009[1], label='$V_d = 0.009V$')
plt.plot(NIdVg_32nm_Compact_Vd09[0], NIdVg_32nm_Compact_Vd09[1], label='$V_d = 0.9V$')
pw_fit_NIdVg_32nm_Compact_Vd009 = piecewise_regression.Fit(NIdVg_32nm_Compact_Vd009[0].to_numpy(), NIdVg_32nm_Com
VT_NIdVg_32nm_Compact_Vd009 = pw_fit_NIdVg_32nm_Compact_Vd009.get_results()['estimates']['breakpoint1']['estimate
Id_VT_NIdVg_32nm_Compact_Vd009 = pw_fit_NIdVg_32nm_Compact_Vd009.get_results()['estimates']['alpha1']['estimate']
plt.scatter(VT_NIdVg_32nm_Compact_Vd009,Id_VT_NIdVg_32nm_Compact_Vd009,marker='o')
plt.annotate(f'$V_T = {VT_NIdVg_32nm_Compact_Vd009:.2f}V$', (VT_NIdVg_32nm_Compact_Vd009, Id_VT_NIdVg_32nm_Compac
#Beyond linear regime of I_d vs V_g for V_d = 0.09V
Vunk_NIdVg_32nm_Compact_Vd009 = pw_fit_NIdVg_32nm_Compact_Vd009.get_results()['estimates']['breakpoint2']['estima
Idunk_VT_NIdVg_32nm_Compact_Vd009 = pw_fit_NIdVg_32nm_Compact_Vd009.get_results()['estimates']['alpha2']['estimat
plt.scatter(Vunk_NIdVg_32nm_Compact_Vd009,Idunk_VT_NIdVg_32nm_Compact_Vd009,marker='o',c='#1f77b4')
plt.annotate(f'$V_{{UNK}} = {Vunk_NIdVg_32nm_Compact_Vd009:.2f}V$', (Vunk_NIdVg_32nm_Compact_Vd009, Idunk_VT_NId\
plt.title('$L_g = 32nm$, $t_{ox} = 1nm$ (Simulated)')
plt.xlabel('$V_g (V)$')
plt.ylabel('$I_d (A)$')
plt.legend(loc='best')
```

Out[15]:
```
<matplotlib.legend.Legend at 0x7f9ad9c595b0>
```



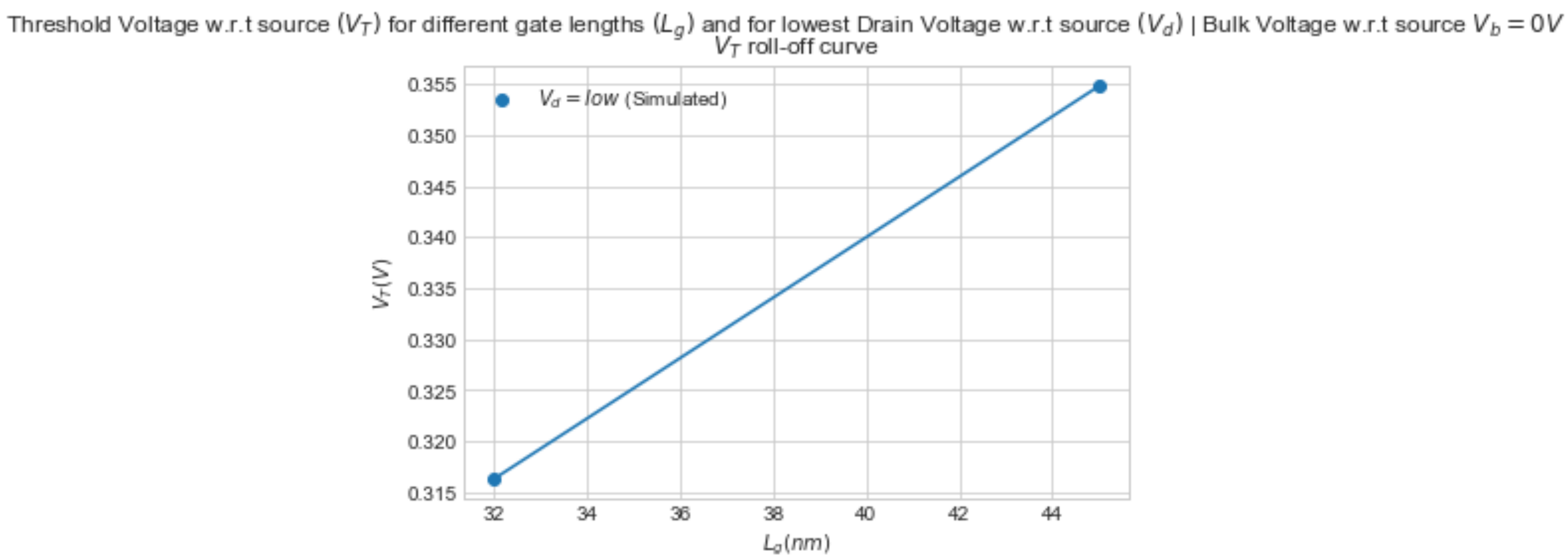
In [16]:
```
#Plotting data (logy vs x)
fig_SS, ax_SS = plt.subplots(nrows=1,ncols=2,tight_layout=True,sharex=True,sharey=True,figsize=(17, 13))
fig_SS.suptitle('Drain Current w.r.t source $(\log I_d)$ versus Gate Voltage w.r.t source $(V_g)$ for different g

plt.subplot(121)
plt.plot(NIdVg_45nm_Compact_Vd01[0].to_numpy(), np.log(NIdVg_45nm_Compact_Vd01[1].to_numpy()), label='$L_g = 45nm
logpw_fit_NIdVg_45nm_Compact_Vd01 = piecewise_regression.Fit(NIdVg_45nm_Compact_Vd01[0].to_numpy(),np.log(NIdVg_4
VTSS_NIdVg_45nm_Compact_Vd01 = logpw_fit_NIdVg_45nm_Compact_Vd01.get_results()['estimates']['breakpoint1']['estin
IdSS_VT_NIdVg_45nm_Compact_Vd01 = logpw_fit_NIdVg_45nm_Compact_Vd01.get_results()['estimates']['alpha1']['estimat
plt.scatter(VTSS_NIdVg_45nm_Compact_Vd01,IdSS_VT_NIdVg_45nm_Compact_Vd01,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_45nm_Compact_Vd01:.2f}V$', (VTSS_NIdVg_45nm_Compact_Vd01, IdSS_VT_NIdVg_45nm_Co
#Beyond linear regime of I_d vs V_g for V_d = 0.1V
VSSunk_NIdVg_45nm_Compact_Vd01 = logpw_fit_NIdVg_45nm_Compact_Vd01.get_results()['estimates']['breakpoint2']['est
IdSSunk_VT_NIdVg_45nm_Compact_Vd01 = logpw_fit_NIdVg_45nm_Compact_Vd01.get_results()['estimates']['alpha2']['esti
plt.scatter(VSSunk_NIdVg_45nm_Compact_Vd01,IdSSunk_VT_NIdVg_45nm_Compact_Vd01,marker='o',c='#1f77b4')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_45nm_Compact_Vd01, IdSSunk_VT_NIdVg_45nm_Compact_Vd01))

plt.plot(NIdVg_32nm_Compact_Vd009[0].to_numpy(), np.log(NIdVg_32nm_Compact_Vd009[1].to_numpy()), label='$L_g = 32
logpw_fit_NIdVg_32nm_Compact_Vd009 = piecewise_regression.Fit(NIdVg_32nm_Compact_Vd009[0].to_numpy(),np.log(NIdVg
VTSS_NIdVg_32nm_Compact_Vd009 = logpw_fit_NIdVg_32nm_Compact_Vd009.get_results()['estimates']['breakpoint1']['est
IdSS_VT_NIdVg_32nm_Compact_Vd009 = logpw_fit_NIdVg_32nm_Compact_Vd009.get_results()['estimates']['alpha1']['estin
plt.scatter(VTSS_NIdVg_32nm_Compact_Vd009,IdSS_VT_NIdVg_32nm_Compact_Vd009,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_32nm_Compact_Vd009:.2f}V$', (VTSS_NIdVg_32nm_Compact_Vd009, IdSS_VT_NIdVg_32nm_
#Beyond linear regime of I_d vs V_g for V_d = 0.09V
VSSunk_NIdVg_32nm_Compact_Vd009 = logpw_fit_NIdVg_32nm_Compact_Vd009.get_results()['estimates']['breakpoint2']['e
IdSSunk_VT_NIdVg_32nm_Compact_Vd009 = logpw_fit_NIdVg_32nm_Compact_Vd009.get_results()['estimates']['alpha2']['es
plt.scatter(VSSunk_NIdVg_32nm_Compact_Vd009,IdSSunk_VT_NIdVg_32nm_Compact_Vd009,marker='o',c='#ff7f0e')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_32nm_Compact_Vd009, IdSSunk_VT_NIdVg_32nm_Compact_Vd009))

plt.legend(loc='best')
plt.title('$V_d = low$ (Simulated)')
plt.xlabel('$V_g (V)$')
plt.ylabel('$\log I_d (A)$')

plt.subplot(122)
plt.plot(NIdVg_45nm_Compact_Vd1[0].to_numpy(), np.log(NIdVg_45nm_Compact_Vd1[1].to_numpy()), label='$L_g = 45nm$,
logpw_fit_NIdVg_45nm_Compact_Vd1 = piecewise_regression.Fit(NIdVg_45nm_Compact_Vd1[0].to_numpy(),np.log(NIdVg_45r
VTSS_NIdVg_45nm_Compact_Vd1 = logpw_fit_NIdVg_45nm_Compact_Vd1.get_results()['estimates']['breakpoint1']['estimat
IdSS_VT_NIdVg_45nm_Compact_Vd1 = logpw_fit_NIdVg_45nm_Compact_Vd1.get_results()['estimates']['alpha1']['estimate'
plt.scatter(VTSS_NIdVg_45nm_Compact_Vd1,IdSS_VT_NIdVg_45nm_Compact_Vd1,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_45nm_Compact_Vd1:.2f}V$', (VTSS_NIdVg_45nm_Compact_Vd1, IdSS_VT_NIdVg_45nm_Comp
#Beyond linear regime of I_d vs V_g for V_d = 1V
VSSunk_NIdVg_45nm_Compact_Vd1 = logpw_fit_NIdVg_45nm_Compact_Vd1.get_results()['estimates']['breakpoint2']['estin
IdSSunk_VT_NIdVg_45nm_Compact_Vd1 = logpw_fit_NIdVg_45nm_Compact_Vd1.get_results()['estimates']['alpha2']['estima
plt.scatter(VSSunk_NIdVg_45nm_Compact_Vd1,IdSSunk_VT_NIdVg_45nm_Compact_Vd1,marker='o',c='#1f77b4')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_45nm_Compact_Vd1, IdSSunk_VT_NIdVg_45nm_Compact_Vd1))

plt.plot(NIdVg_32nm_Compact_Vd09[0].to_numpy(), np.log(NIdVg_32nm_Compact_Vd09[1].to_numpy()), label='$L_g = 32nm
logpw_fit_NIdVg_32nm_Compact_Vd09 = piecewise_regression.Fit(NIdVg_32nm_Compact_Vd09[0].to_numpy(),np.log(NIdVg_3
VTSS_NIdVg_32nm_Compact_Vd09 = logpw_fit_NIdVg_32nm_Compact_Vd09.get_results()['estimates']['breakpoint1']['estin
IdSS_VT_NIdVg_32nm_Compact_Vd09 = logpw_fit_NIdVg_32nm_Compact_Vd09.get_results()['estimates']['alpha1']['estimat
plt.scatter(VTSS_NIdVg_32nm_Compact_Vd09,IdSS_VT_NIdVg_32nm_Compact_Vd09,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_32nm_Compact_Vd09:.2f}V$', (VTSS_NIdVg_32nm_Compact_Vd09, IdSS_VT_NIdVg_32nm_Co
#Beyond linear regime of I_d vs V_g for V_d = 0.9V
VSSunk_NIdVg_32nm_Compact_Vd09 = logpw_fit_NIdVg_32nm_Compact_Vd09.get_results()['estimates']['breakpoint2']['est
IdSSunk_VT_NIdVg_32nm_Compact_Vd09 = logpw_fit_NIdVg_32nm_Compact_Vd09.get_results()['estimates']['alpha2']['esti
plt.scatter(VSSunk_NIdVg_32nm_Compact_Vd09,IdSSunk_VT_NIdVg_32nm_Compact_Vd09,marker='o',c='#ff7f0e')
plt.annotate(f'$V_{{UNK}}$', (VSSunk_NIdVg_32nm_Compact_Vd09, IdSSunk_VT_NIdVg_32nm_Compact_Vd09))

plt.legend(loc='best')
plt.title('$V_d = high$ (Simulated)')
plt.xlabel('$V_g (V)$')
plt.ylabel('$\log I_d (A)$')
```

Out[16]:
```
Text(0, 0.5, '$\\log I_d (A)$')
```



In [17]:
```
fig,axes = plt.subplots()
fig.suptitle('Threshold Voltage w.r.t source $(V_T)$ for different gate lengths $(L_g)$ and for lowest Drain Volt
plt.scatter([32,45],[VTSS_NIdVg_32nm_Compact_Vd009,VTSS_NIdVg_45nm_Compact_Vd01],marker='o',label='$V_d = low$ ($
plt.plot([32,45],[VTSS_NIdVg_32nm_Compact_Vd009,VTSS_NIdVg_45nm_Compact_Vd01])
axes.legend(loc='best')
axes.set_xlabel('$L_g (nm)$')
axes.set_ylabel('$V_T (V)$')
axes.set_title('$V_T$ roll-off curve')
```

Out[17]:
```
Text(0.5, 1.0, '$V_T$ roll-off curve')
```



In [18]:
```
SS_NIdVg_45nm_Compact_Vd01 = (1/(logpw_fit_NIdVg_45nm_Compact_Vd01.get_results()['estimates']['alpha1']['estimate
SS_NIdVg_32nm_Compact_Vd009 = (1/(logpw_fit_NIdVg_32nm_Compact_Vd009.get_results()['estimates']['alpha1']['estima

pw_fit_NIdVg_45nm_Compact_Vd1 = piecewise_regression.Fit(NIdVg_45nm_Compact_Vd1[0].to_numpy(),NIdVg_45nm_Compact_
VT_NIdVg_45nm_Compact_Vd1 = pw_fit_NIdVg_45nm_Compact_Vd1.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_45nm_Compact_Vd1 = pw_fit_NIdVg_45nm_Compact_Vd1.get_results()['estimates']['alpha1']['estimate']*VT_
Vunk_NIdVg_45nm_Compact_Vd1 = pw_fit_NIdVg_45nm_Compact_Vd1.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_45nm_Compact_Vd1 = pw_fit_NIdVg_45nm_Compact_Vd1.get_results()['estimates']['alpha2']['estimate']*
Ion_NIdVg_45nm_Compact_Vd1 = pw_fit_NIdVg_45nm_Compact_Vd1.get_results()['estimates']['alpha3']['estimate']*(1-Vu

pw_fit_NIdVg_32nm_Compact_Vd09 = piecewise_regression.Fit(NIdVg_32nm_Compact_Vd09[0].to_numpy(),NIdVg_32nm_Compac
VT_NIdVg_32nm_Compact_Vd09 = pw_fit_NIdVg_32nm_Compact_Vd09.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_32nm_Compact_Vd09 = pw_fit_NIdVg_32nm_Compact_Vd09.get_results()['estimates']['alpha1']['estimate']*V
Vunk_NIdVg_32nm_Compact_Vd09 = pw_fit_NIdVg_32nm_Compact_Vd09.get_results()['estimates']['breakpoint2']['estimate
Idunk_VT_NIdVg_32nm_Compact_Vd09 = pw_fit_NIdVg_32nm_Compact_Vd09.get_results()['estimates']['alpha2']['estimate'
Ion_NIdVg_32nm_Compact_Vd09 = pw_fit_NIdVg_32nm_Compact_Vd09.get_results()['estimates']['alpha3']['estimate']*(1-

logIoff_NIdVg_45nm_Compact_Vd1 = logpw_fit_NIdVg_45nm_Compact_Vd1.get_results()['estimates']['const']['estimate']
Ioff_NIdVg_45nm_Compact_Vd1 = math.pow(10,logIoff_NIdVg_45nm_Compact_Vd1)
logIoff_NIdVg_32nm_Compact_Vd09 = logpw_fit_NIdVg_32nm_Compact_Vd09.get_results()['estimates']['const']['estimate
Ioff_NIdVg_32nm_Compact_Vd09 = math.pow(10,logIoff_NIdVg_32nm_Compact_Vd09)

DIBL_NIdVg_45nm_Compact = ((VTSS_NIdVg_45nm_Compact_Vd1-VTSS_NIdVg_45nm_Compact_Vd01)/(1-0.1))*1000 #Drain-induce
DIBL_NIdVg_32nm_Compact = ((VTSS_NIdVg_32nm_Compact_Vd09-VTSS_NIdVg_32nm_Compact_Vd009)/(0.9-0.09))*1000
```

In [19]:
```
print("%.3e" % SS_NIdVg_45nm_Compact_Vd01) #To print necessary variable values and enter in summary below
```

```
4.286e+01
```

Summary

$L_g\ (nm)$	$V_T\ (V)$ $@V_d = low$ **Simulated**	$SS\ (mV/dec)$ $@V_d = low$ **Simulated**	$I_{ON}\ (A)$ $@V_d(V_g) = high$ **Simulated**	$I_{OFF}\ (A)$ $@V_d = high$ **Simulated**	$DIBL\ (mV/V)$ **Simulated**
45	0.355	42.864	1302.682	9.178e-03	-23.280
32	0.316	45.152	1679.011	14.043	-105.559

1. V_T extracted from $\log I_d$ vs V_g plot has been reported in the table above because piecewise regression fit of $\log I_d$ vs V_g plot better captures feautures which lie in the well modeled subthreshold and linear regions of MOSFET operation (as demonstrated in comparisons of experimental and simulated V_T values in Part IV).
2. V_T extracted from $\log I_d$ vs V_g plot has been used to plot V_T roll-off curve this time, because piecewise regression fit of I_d vs V_g plot isn't accurate with very few data points (10 in this case).
3. I_{ON} extracted from I_d vs V_g plot has been reported in the table above because $I_{ON}@V_g = 1V$ lies beyond the linear region of MOSFET operation and is not well modeled through a $\log I_d$ vs V_g regression fit (reason for it is explained below in point 4).
4. V_{UNK} in $\log I_d$ (or I_d) vs V_g plot indicates V_g from which the MOSFET enters a non-linear operating region that needs 5 coupled equations (Poisson, Electron continuity, Hole continuity, Electron transport and Hole transport) to be modeled.
5. $DIBL\ \forall L_g$ has been captured well this time due to the perfect linearity at very low V_g in the subthreshold region of $\log I_d$ vs $V_g @V_d = high$ simulated plot.
6. Simulations in this section were carried out using compact models present in the nano-CMOS tool at nanoHUB. In addition to generic IV models of MOSFETs, compact models include - capacitance models, gate dielectric leakage current models, source-drain junction diode models and Noise / high-frequency models. Hence, compact models can simulate lower L_g more accurately than a generic MOSFET IV simulator (as can be observed from respective values in table above w.r.t those in Part I).

Part IV: Comparison with measured data for N SOI MOSFETs

[Measured vs Simulated] I_d/V_g for NMOS SOI MOSFET with constant oxide thickness (t_{ox})

In [20]:
```
#Reading Measured data
NIdVg_06um = pd.read_excel('B774W4/N-L0.6um-IdVg.xls', sheet_name='Data')
NIdVg_1um = pd.read_excel('B774W4/N-L1um-IdVg.xls', sheet_name='Data')
NIdVg_6um = pd.read_excel('B774W4/N-L6um-IdVg.xls', sheet_name='Data')

NIdVg_06um_Vd01 = NIdVg_06um[['GateV(1)','DrainI(1)']]
NIdVg_06um_Vd1 = NIdVg_06um[['GateV(2)','DrainI(2)']]

NIdVg_1um_Vd01 = NIdVg_1um[['GateV(1)','DrainI(1)']]
NIdVg_1um_Vd1 = NIdVg_1um[['GateV(2)','DrainI(2)']]

NIdVg_6um_Vd01 = NIdVg_6um[['GateV(1)','DrainI(1)']]
NIdVg_6um_Vd1 = NIdVg_6um[['GateV(2)','DrainI(2)']]

#Reading Simulated data
NIdVg_06um_Sim_Vd01 = pd.read_csv('Simulations/N-L06um-IdVg-Sim.txt', skiprows=4,nrows=71,header=None)
NIdVg_06um_Sim_Vd1 = pd.read_csv('Simulations/N-L06um-IdVg-Sim.txt', skiprows=80,nrows=71,header=None)

NIdVg_1um_Sim_Vd01 = pd.read_csv('Simulations/N-L1um-IdVg-Sim.txt', skiprows=4,nrows=71,header=None)
NIdVg_1um_Sim_Vd1 = pd.read_csv('Simulations/N-L1um-IdVg-Sim.txt', skiprows=80,nrows=71,header=None)

NIdVg_6um_Sim_Vd01 = pd.read_csv('Simulations/N-L6um-IdVg-Sim.txt', skiprows=4,nrows=71,header=None)
NIdVg_6um_Sim_Vd1 = pd.read_csv('Simulations/N-L6um-IdVg-Sim.txt', skiprows=80,nrows=71,header=None)
```

```
WARNING *** OLE2 inconsistency: SSCS size is 0 but SSAT size is non-zero
WARNING *** OLE2 inconsistency: SSCS size is 0 but SSAT size is non-zero
WARNING *** OLE2 inconsistency: SSCS size is 0 but SSAT size is non-zero
```

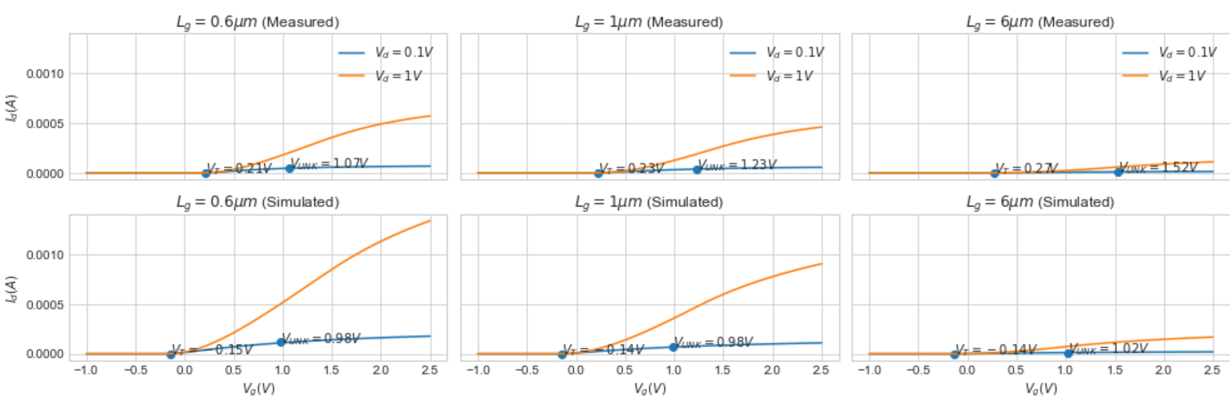
In [21]:
```
#Plotting data
fig,axes = plt.subplots(nrows=2,ncols=3,tight_layout=True,sharex=True,sharey=True, figsize=(14, 5))
fig.suptitle('Drain Current w.r.t source $(I_d)$ versus Gate Voltage w.r.t source $(V_g)$ for different gate leng

plt.subplot(231)
NIdVg_06um_Vd01.plot(x = 'GateV(1)', y = 'DrainI(1)', ax=axes[0,0], label='$V_d = 0.1V$')
NIdVg_06um_Vd1.plot(x='GateV(2)', y='DrainI(2)', ax=axes[0,0], label='$V_d = 1V$')
pw_fit_NIdVg_06um_Vd01 = piecewise_regression.Fit(NIdVg_06um_Vd01['GateV(1)'].to_numpy(),NIdVg_06um_Vd01['DrainI(
VT_NIdVg_06um_Vd01 = pw_fit_NIdVg_06um_Vd01.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_06um_Vd01 = pw_fit_NIdVg_06um_Vd01.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_06um_Vd0
plt.scatter(VT_NIdVg_06um_Vd01,Id_VT_NIdVg_06um_Vd01,marker='o')
axes[0,0].annotate(f'$V_T = {VT_NIdVg_06um_Vd01:.2f}V$', (VT_NIdVg_06um_Vd01, Id_VT_NIdVg_06um_Vd01))
#Beyond linear regime of I_d vs V_g for V_d = 0.1V
Vunk_NIdVg_06um_Vd01 = pw_fit_NIdVg_06um_Vd01.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_06um_Vd01 = pw_fit_NIdVg_06um_Vd01.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdVg_06
plt.scatter(Vunk_NIdVg_06um_Vd01,Idunk_VT_NIdVg_06um_Vd01,marker='o', label='$V_ov$',c='#1f77b4')
axes[0,0].annotate(f'$V_{{UNK}} = {Vunk_NIdVg_06um_Vd01:.2f}V$', (Vunk_NIdVg_06um_Vd01, Idunk_VT_NIdVg_06um_Vd01)
axes[0,0].set_title('$L_g = 0.6\mu m$ (Measured)')
axes[0,0].set_xlabel('$V_g (V)$')
axes[0,0].set_ylabel('$I_d (A)$')

plt.subplot(232)
NIdVg_1um_Vd01.plot(x = 'GateV(1)', y = 'DrainI(1)', ax=axes[0,1], label='$V_d = 0.1V$')
NIdVg_1um_Vd1.plot(x='GateV(2)', y='DrainI(2)', ax=axes[0,1], label='$V_d = 1V$')
pw_fit_NIdVg_1um_Vd01 = piecewise_regression.Fit(NIdVg_1um_Vd01['GateV(1)'].to_numpy(),NIdVg_1um_Vd01['DrainI(1)'
VT_NIdVg_1um_Vd01 = pw_fit_NIdVg_1um_Vd01.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_1um_Vd01 = pw_fit_NIdVg_1um_Vd01.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_1um_Vd01+p
plt.scatter(VT_NIdVg_1um_Vd01,Id_VT_NIdVg_1um_Vd01,marker="o")
axes[0,1].annotate(f'$V_T = {VT_NIdVg_1um_Vd01:.2f}V$', (VT_NIdVg_1um_Vd01, Id_VT_NIdVg_1um_Vd01))
#Beyond linear regime of I_d vs V_g for V_d = 0.1V
Vunk_NIdVg_1um_Vd01 = pw_fit_NIdVg_1um_Vd01.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_1um_Vd01 = pw_fit_NIdVg_1um_Vd01.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdVg_1um_
plt.scatter(Vunk_NIdVg_1um_Vd01,Idunk_VT_NIdVg_1um_Vd01,c='#1f77b4',marker='o')
axes[0,1].annotate(f'$V_{{UNK}} = {Vunk_NIdVg_1um_Vd01:.2f}V$', (Vunk_NIdVg_1um_Vd01, Idunk_VT_NIdVg_1um_Vd01))
axes[0,1].set_title('$L_g = 1\mu m$ (Measured)')
axes[0,1].set_xlabel('$V_g (V)$')
axes[0,1].set_ylabel('$I_d (A)$')

plt.subplot(233)
NIdVg_6um_Vd01.plot(x='GateV(1)', y='DrainI(1)', ax=axes[0,2], label='$V_d = 0.1V$')
NIdVg_6um_Vd1.plot(x='GateV(2)', y='DrainI(2)', ax=axes[0,2], label='$V_d = 1V$')
pw_fit_NIdVg_6um_Vd01 = piecewise_regression.Fit(NIdVg_6um_Vd01['GateV(1)'].to_numpy(),NIdVg_6um_Vd01['DrainI(1)'
VT_NIdVg_6um_Vd01 = pw_fit_NIdVg_6um_Vd01.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_6um_Vd01 = pw_fit_NIdVg_6um_Vd01.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_6um_Vd01+p
plt.scatter(VT_NIdVg_6um_Vd01,Id_VT_NIdVg_6um_Vd01,marker="o")
axes[0,2].annotate(f'$V_T = {VT_NIdVg_6um_Vd01:.2f}V$', (VT_NIdVg_6um_Vd01, Id_VT_NIdVg_6um_Vd01))
#Beyond linear regime of I_d vs V_g for V_d = 0.1V
Vunk_NIdVg_6um_Vd01 = pw_fit_NIdVg_6um_Vd01.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_6um_Vd01 = pw_fit_NIdVg_6um_Vd01.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdVg_6um_
plt.scatter(Vunk_NIdVg_6um_Vd01,Idunk_VT_NIdVg_6um_Vd01,c='#1f77b4',marker='o')
axes[0,2].annotate(f'$V_{{UNK}} = {Vunk_NIdVg_6um_Vd01:.2f}V$', (Vunk_NIdVg_6um_Vd01, Idunk_VT_NIdVg_6um_Vd01))
axes[0,2].set_title('$L_g = 6\mu m$ (Measured)')
axes[0,2].set_xlabel('$V_g (V)$')
axes[0,2].set_ylabel('$I_d (A)$')

plt.subplot(234)
```

```
plt.plot(NIdVg_06um_Sim_Vd01[0], NIdVg_06um_Sim_Vd01[1], label='$V_d = 0.1V$')
plt.plot(NIdVg_06um_Sim_Vd1[0], NIdVg_06um_Sim_Vd1[1], label='$V_d = 1V$')
pw_fit_NIdVg_06um_Sim_Vd01 = piecewise_regression.Fit(NIdVg_06um_Sim_Vd01[0].to_numpy(),NIdVg_06um_Sim_Vd01[1].tc
VT_NIdVg_06um_Sim_Vd01 = pw_fit_NIdVg_06um_Sim_Vd01.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_06um_Sim_Vd01 = pw_fit_NIdVg_06um_Sim_Vd01.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_
plt.scatter(VT_NIdVg_06um_Sim_Vd01,Id_VT_NIdVg_06um_Sim_Vd01,marker='o')
axes[1,0].annotate(f'$V_T = {VT_NIdVg_06um_Sim_Vd01:.2f}V$', (VT_NIdVg_06um_Sim_Vd01, Id_VT_NIdVg_06um_Sim_Vd01))
#Beyond linear regime of I_d vs V_g for V_d = 0.1V
Vunk_NIdVg_06um_Sim_Vd01 = pw_fit_NIdVg_06um_Sim_Vd01.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_06um_Sim_Vd01 = pw_fit_NIdVg_06um_Sim_Vd01.get_results()['estimates']['alpha2']['estimate']*(Vunk_
plt.scatter(Vunk_NIdVg_06um_Sim_Vd01,Idunk_VT_NIdVg_06um_Sim_Vd01,marker='o', label='$V_ov$',c='#1f77b4')
axes[1,0].annotate(f'$V_{{UNK}} = {Vunk_NIdVg_06um_Sim_Vd01:.2f}V$', (Vunk_NIdVg_06um_Sim_Vd01, Idunk_VT_NIdVg_06
axes[1,0].set_title('$L_g = 0.6\mu m$ (Simulated)')
axes[1,0].set_xlabel('$V_g (V)$')
axes[1,0].set_ylabel('$I_d (A)$')

plt.subplot(235)
plt.plot(NIdVg_1um_Sim_Vd01[0], NIdVg_1um_Sim_Vd01[1], label='$V_d = 0.1V$')
plt.plot(NIdVg_1um_Sim_Vd1[0], NIdVg_1um_Sim_Vd1[1], label='$V_d = 1V$')
pw_fit_NIdVg_1um_Sim_Vd01 = piecewise_regression.Fit(NIdVg_1um_Sim_Vd01[0].to_numpy(),NIdVg_1um_Sim_Vd01[1].to_nu
VT_NIdVg_1um_Sim_Vd01 = pw_fit_NIdVg_1um_Sim_Vd01.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_1um_Sim_Vd01 = pw_fit_NIdVg_1um_Sim_Vd01.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_1u
plt.scatter(VT_NIdVg_1um_Sim_Vd01,Id_VT_NIdVg_1um_Sim_Vd01,marker="o")
axes[1,1].annotate(f'$V_T = {VT_NIdVg_1um_Sim_Vd01:.2f}V$', (VT_NIdVg_1um_Sim_Vd01, Id_VT_NIdVg_1um_Sim_Vd01))
#Beyond linear regime of I_d vs V_g for V_d = 0.1V
Vunk_NIdVg_1um_Sim_Vd01 = pw_fit_NIdVg_1um_Sim_Vd01.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_1um_Sim_Vd01 = pw_fit_NIdVg_1um_Sim_Vd01.get_results()['estimates']['alpha2']['estimate']*(Vunk_NI
plt.scatter(Vunk_NIdVg_1um_Sim_Vd01,Idunk_VT_NIdVg_1um_Sim_Vd01,c='#1f77b4',marker='o')
axes[1,1].annotate(f'$V_{{UNK}} = {Vunk_NIdVg_1um_Sim_Vd01:.2f}V$', (Vunk_NIdVg_1um_Sim_Vd01, Idunk_VT_NIdVg_1um_
axes[1,1].set_title('$L_g = 1\mu m$ (Simulated)')
axes[1,1].set_xlabel('$V_g (V)$')
axes[1,1].set_ylabel('$I_d (A)$')

plt.subplot(236)
plt.plot(NIdVg_6um_Sim_Vd01[0], NIdVg_6um_Sim_Vd01[1], label='$V_d = 0.1V$')
plt.plot(NIdVg_6um_Sim_Vd1[0], NIdVg_6um_Sim_Vd1[1], label='$V_d = 1V$')
pw_fit_NIdVg_6um_Sim_Vd01 = piecewise_regression.Fit(NIdVg_6um_Sim_Vd01[0].to_numpy(),NIdVg_6um_Sim_Vd01[1].to_nu
VT_NIdVg_6um_Sim_Vd01 = pw_fit_NIdVg_6um_Sim_Vd01.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_6um_Sim_Vd01 = pw_fit_NIdVg_6um_Sim_Vd01.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_6u
plt.scatter(VT_NIdVg_6um_Sim_Vd01,Id_VT_NIdVg_6um_Sim_Vd01,marker="o")
axes[1,2].annotate(f'$V_T = {VT_NIdVg_6um_Sim_Vd01:.2f}V$', (VT_NIdVg_6um_Sim_Vd01, Id_VT_NIdVg_6um_Sim_Vd01))
#Beyond linear regime of I_d vs V_g for V_d = 0.1V
Vunk_NIdVg_6um_Sim_Vd01 = pw_fit_NIdVg_6um_Sim_Vd01.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_6um_Sim_Vd01 = pw_fit_NIdVg_6um_Sim_Vd01.get_results()['estimates']['alpha2']['estimate']*(Vunk_NI
plt.scatter(Vunk_NIdVg_6um_Sim_Vd01,Idunk_VT_NIdVg_6um_Sim_Vd01,c='#1f77b4',marker='o')
axes[1,2].annotate(f'$V_{{UNK}} = {Vunk_NIdVg_6um_Sim_Vd01:.2f}V$', (Vunk_NIdVg_6um_Sim_Vd01, Idunk_VT_NIdVg_6um_
axes[1,2].set_title('$L_g = 6\mu m$ (Simulated)')
axes[1,2].set_xlabel('$V_g (V)$')
axes[1,2].set_ylabel('$I_d (A)$')
```

Out[21]:

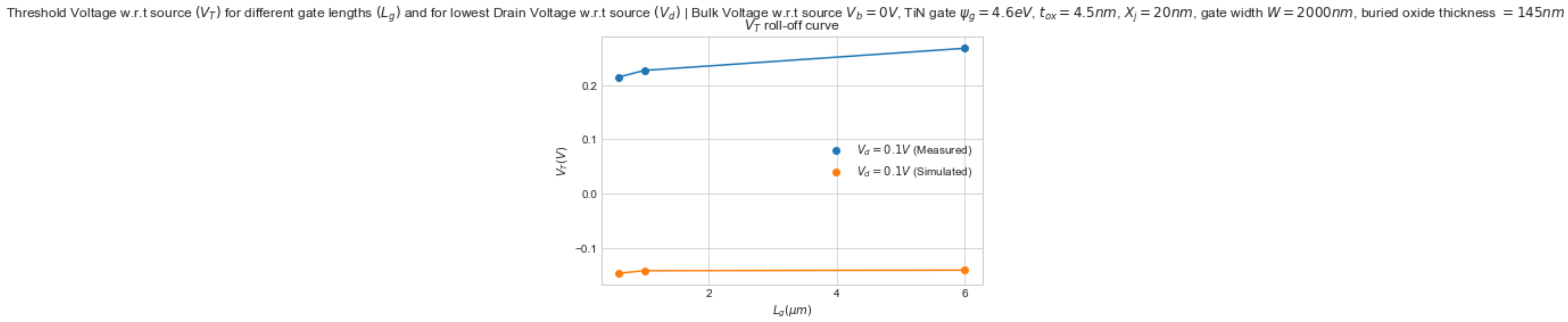
```
Text(0, 0.5, '$I_d (A)$')
```

Drain Current w.r.t source (I_d) versus Gate Voltage w.r.t source (V_g) for different gate lengths (L_g) and Drain Voltages w.r.t source (V_d) | Bulk Voltage w.r.t source $V_b = 0V$, TiN gate $\psi_g = 4.6eV$, $t_{ox} = 4.5nm$, $X_j = 20nm$, gate width $W = 2000nm$, buried oxide thickness $= 145nm$



In [22]:

```
fig,axes = plt.subplots()
fig.suptitle('Threshold Voltage w.r.t source $(V_T)$ for different gate lengths $(L_g)$ and for lowest Drain Volt
plt.scatter([0.6,1,6],[VT_NIdVg_06um_Vd01,VT_NIdVg_1um_Vd01,VT_NIdVg_6um_Vd01],marker='o',label='$V_d = 0.1V$ (Me
plt.plot([0.6,1,6],[VT_NIdVg_06um_Vd01,VT_NIdVg_1um_Vd01,VT_NIdVg_6um_Vd01])
plt.scatter([0.6,1,6],[VT_NIdVg_06um_Sim_Vd01,VT_NIdVg_1um_Sim_Vd01,VT_NIdVg_6um_Sim_Vd01],marker='o',label='$V_c
plt.plot([0.6,1,6],[VT_NIdVg_06um_Sim_Vd01,VT_NIdVg_1um_Sim_Vd01,VT_NIdVg_6um_Sim_Vd01])
axes.legend(loc='best')
axes.set_xlabel('$L_g (\mu m)$')
axes.set_ylabel('$V_T (V)$')
axes.set_title('$V_T$ roll-off curve')
axes.xaxis.set_major_locator(ticker.MultipleLocator(2))
```



In [23]:

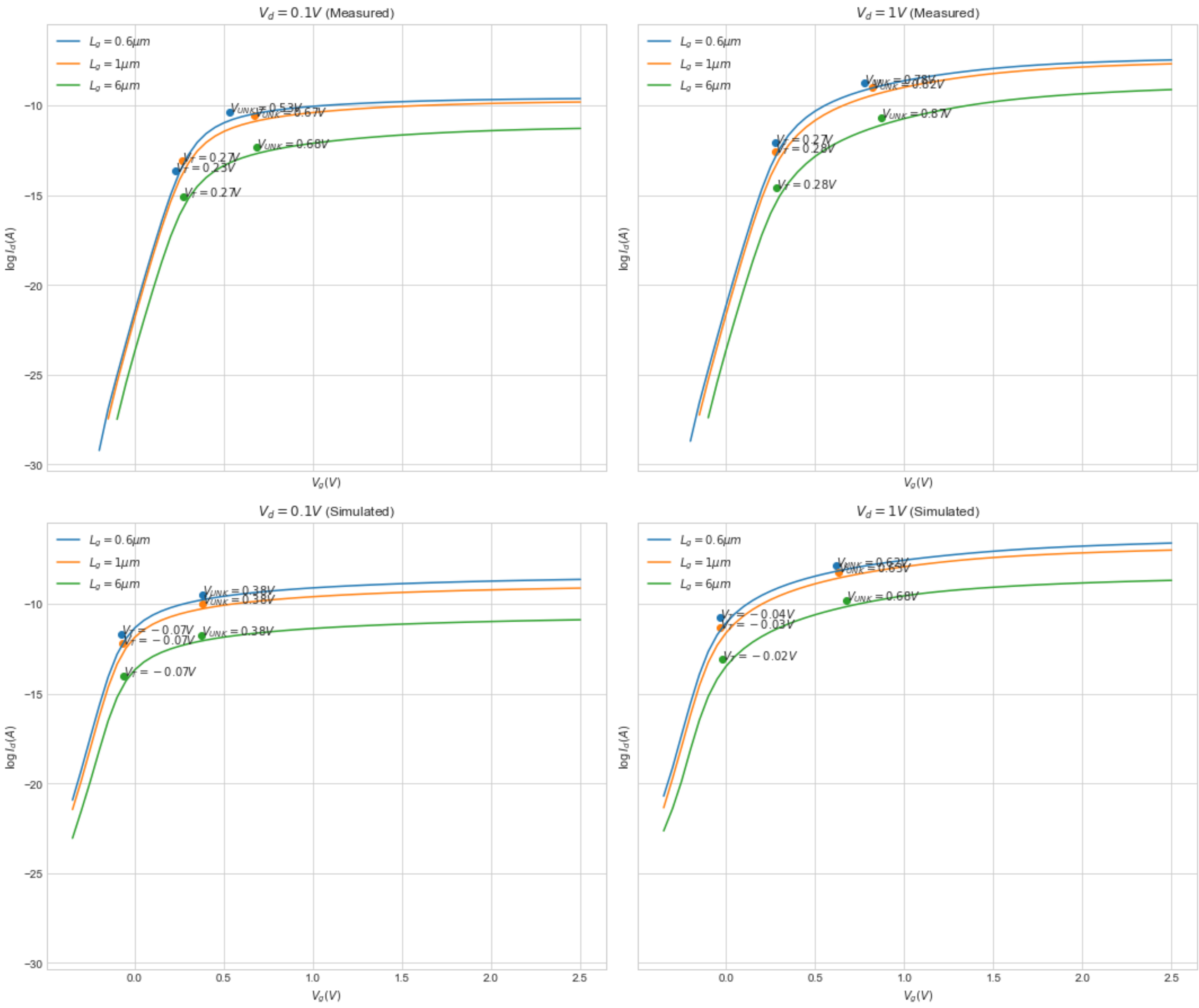
```
#Plotting data (logy vs x)
fig_SS, ax_SS = plt.subplots(nrows=2,ncols=2,tight_layout=True,sharex=True,sharey=True,figsize=(15, 13))
fig_SS.suptitle('Drain Current w.r.t source $(\log I_d)$ versus Gate Voltage w.r.t source $(V_g)$ for different g

plt.subplot(221)
#inds = np.where(np.asanyarray(np.isnan(np.log(NIdVg_06um_Vd01['DrainI(1)'].to_numpy()))))
plt.plot(NIdVg_06um_Vd01['GateV(1)'].to_numpy()[16:], np.log(NIdVg_06um_Vd01['DrainI(1)'].to_numpy()[16:]), label
logpw_fit_NIdVg_06um_Vd01 = piecewise_regression.Fit(NIdVg_06um_Vd01['GateV(1)'].to_numpy()[16:],np.log(NIdVg_06u
VTSS_NIdVg_06um_Vd01 = logpw_fit_NIdVg_06um_Vd01.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_06um_Vd01 = logpw_fit_NIdVg_06um_Vd01.get_results()['estimates']['alpha1']['estimate']*VTSS_NIdVg_0
plt.scatter(VTSS_NIdVg_06um_Vd01,IdSS_VT_NIdVg_06um_Vd01,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_06um_Vd01:.2f}V$', (VTSS_NIdVg_06um_Vd01, IdSS_VT_NIdVg_06um_Vd01))
#Beyond linear regime of I_d vs V_g for V_d = 0.1V
VSSunk_NIdVg_06um_Vd01 = logpw_fit_NIdVg_06um_Vd01.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_06um_Vd01 = logpw_fit_NIdVg_06um_Vd01.get_results()['estimates']['alpha2']['estimate']*(VSSunk_N
plt.scatter(VSSunk_NIdVg_06um_Vd01,IdSSunk_VT_NIdVg_06um_Vd01,marker='o',c='#1f77b4')
plt.annotate(f'$V_{{UNK}} = {VSSunk_NIdVg_06um_Vd01:.2f}V$', (VSSunk_NIdVg_06um_Vd01, IdSSunk_VT_NIdVg_06um_Vd01)

#inds = np.where(np.asanyarray(np.isnan(np.log(NIdVg_1um_Vd01['DrainI(1)'].to_numpy()))))
plt.plot(NIdVg_1um_Vd01['GateV(1)'].to_numpy()[17:], np.log(NIdVg_1um_Vd01['DrainI(1)'].to_numpy()[17:]), label='
logpw_fit_NIdVg_1um_Vd01 = piecewise_regression.Fit(NIdVg_1um_Vd01['GateV(1)'].to_numpy()[17:],np.log(NIdVg_1um_V
VTSS_NIdVg_1um_Vd01 = logpw_fit_NIdVg_1um_Vd01.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_1um_Vd01 = logpw_fit_NIdVg_1um_Vd01.get_results()['estimates']['alpha1']['estimate']*VTSS_NIdVg_1um
plt.scatter(VTSS_NIdVg_1um_Vd01,IdSS_VT_NIdVg_1um_Vd01,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_1um_Vd01:.2f}V$', (VTSS_NIdVg_1um_Vd01, IdSS_VT_NIdVg_1um_Vd01))
#Beyond linear regime of I_d vs V_g for V_d = 0.1V
VSSunk_NIdVg_1um_Vd01 = logpw_fit_NIdVg_1um_Vd01.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_1um_Vd01 = logpw_fit_NIdVg_1um_Vd01.get_results()['estimates']['alpha2']['estimate']*(VSSunk_NIc
plt.scatter(VSSunk_NIdVg_1um_Vd01,IdSSunk_VT_NIdVg_1um_Vd01,marker='o',c='#ff7f0e')
plt.annotate(f'$V_{{UNK}} = {VSSunk_NIdVg_1um_Vd01:.2f}V$', (VSSunk_NIdVg_1um_Vd01, IdSSunk_VT_NIdVg_1um_Vd01))

#inds = np.where(np.asanyarray(np.isnan(np.log(NIdVg_6um_Vd01['DrainI(1)'].to_numpy()))))
plt.plot(NIdVg_6um_Vd01['GateV(1)'].to_numpy()[18:], np.log(NIdVg_6um_Vd01['DrainI(1)'].to_numpy()[18:]), label='
logpw_fit_NIdVg_6um_Vd01 = piecewise_regression.Fit(NIdVg_6um_Vd01['GateV(1)'].to_numpy()[18:],np.log(NIdVg_6um_V
VTSS_NIdVg_6um_Vd01 = logpw_fit_NIdVg_6um_Vd01.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_6um_Vd01 = logpw_fit_NIdVg_6um_Vd01.get_results()['estimates']['alpha1']['estimate']*VTSS_NIdVg_6um
plt.scatter(VTSS_NIdVg_6um_Vd01,IdSS_VT_NIdVg_6um_Vd01,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_6um_Vd01:.2f}V$', (VTSS_NIdVg_6um_Vd01, IdSS_VT_NIdVg_6um_Vd01))
#Beyond linear regime of I_d vs V_g for V_d = 0.1V
VSSunk_NIdVg_6um_Vd01 = logpw_fit_NIdVg_6um_Vd01.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_6um_Vd01 = logpw_fit_NIdVg_6um_Vd01.get_results()['estimates']['alpha2']['estimate']*(VSSunk_NIc
plt.scatter(VSSunk_NIdVg_6um_Vd01,IdSSunk_VT_NIdVg_6um_Vd01,marker='o',c='#2ca02c')
plt.annotate(f'$V_{{UNK}} = {VSSunk_NIdVg_6um_Vd01:.2f}V$', (VSSunk_NIdVg_6um_Vd01, IdSSunk_VT_NIdVg_6um_Vd01))

plt.legend(loc='best')
plt.title('$V_d = 0.1V$ (Measured)')
plt.xlabel('$V_g (V)$')
plt.ylabel('$\log I_d (A)$')

plt.subplot(222)
#inds = np.where(np.asanyarray(np.isnan(np.log(NIdVg_06um_Vd1['DrainI(2)'].to_numpy()))))
plt.plot(NIdVg_06um_Vd1['GateV(2)'].to_numpy()[16:], np.log(NIdVg_06um_Vd1['DrainI(2)'].to_numpy()[16:]), label='
logpw_fit_NIdVg_06um_Vd1 = piecewise_regression.Fit(NIdVg_06um_Vd1['GateV(2)'].to_numpy()[16:],np.log(NIdVg_06um_
VTSS_NIdVg_06um_Vd1 = logpw_fit_NIdVg_06um_Vd1.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_06um_Vd1 = logpw_fit_NIdVg_06um_Vd1.get_results()['estimates']['alpha1']['estimate']*VTSS_NIdVg_06u
plt.scatter(VTSS_NIdVg_06um_Vd1,IdSS_VT_NIdVg_06um_Vd1,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_06um_Vd1:.2f}V$', (VTSS_NIdVg_06um_Vd1, IdSS_VT_NIdVg_06um_Vd1))
#Beyond linear regime of I_d vs V_g for V_d = 1V
VSSunk_NIdVg_06um_Vd1 = logpw_fit_NIdVg_06um_Vd1.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_06um_Vd1 = logpw_fit_NIdVg_06um_Vd1.get_results()['estimates']['alpha2']['estimate']*(VSSunk_NIc
plt.scatter(VSSunk_NIdVg_06um_Vd1,IdSSunk_VT_NIdVg_06um_Vd1,marker='o',c='#1f77b4')
plt.annotate(f'$V_{{UNK}} = {VSSunk_NIdVg_06um_Vd1:.2f}V$', (VSSunk_NIdVg_06um_Vd1, IdSSunk_VT_NIdVg_06um_Vd1))

#inds = np.where(np.asanyarray(np.isnan(np.log(NIdVg_1um_Vd1['DrainI(2)'].to_numpy()))))
plt.plot(NIdVg_1um_Vd1['GateV(2)'].to_numpy()[17:], np.log(NIdVg_1um_Vd1['DrainI(2)'].to_numpy()[17:]), label='$I
logpw_fit_NIdVg_1um_Vd1 = piecewise_regression.Fit(NIdVg_1um_Vd1['GateV(2)'].to_numpy()[17:],np.log(NIdVg_1um_Vd1
VTSS_NIdVg_1um_Vd1 = logpw_fit_NIdVg_1um_Vd1.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_1um_Vd1 = logpw_fit_NIdVg_1um_Vd1.get_results()['estimates']['alpha1']['estimate']*VTSS_NIdVg_1um_V
plt.scatter(VTSS_NIdVg_1um_Vd1,IdSS_VT_NIdVg_1um_Vd1,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_1um_Vd1:.2f}V$', (VTSS_NIdVg_1um_Vd1, IdSS_VT_NIdVg_1um_Vd1))
#Beyond linear regime of I_d vs V_g for V_d = 1V
```

```
VSSunk_NIdVg_1um_Vd1 = logpw_fit_NIdVg_1um_Vd1.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_1um_Vd1 = logpw_fit_NIdVg_1um_Vd1.get_results()['estimates']['alpha2']['estimate']*(VSSunk_NIdVg
plt.scatter(VSSunk_NIdVg_1um_Vd1,IdSSunk_VT_NIdVg_1um_Vd1,marker='o',c='#ff7f0e')
plt.annotate(f'$V_{{UNK}} = {VSSunk_NIdVg_1um_Vd1:.2f}V$', (VSSunk_NIdVg_1um_Vd1, IdSSunk_VT_NIdVg_1um_Vd1))

#inds = np.where(np.asanyarray(np.isnan(np.log(NIdVg_6um_Vd1['DrainI(2)'].to_numpy()))))
plt.plot(NIdVg_6um_Vd1['GateV(2)'].to_numpy()[18:], np.log(NIdVg_6um_Vd1['DrainI(2)'].to_numpy()[18:]), label='$I
logpw_fit_NIdVg_6um_Vd1 = piecewise_regression.Fit(NIdVg_6um_Vd1['GateV(2)'].to_numpy()[18:],np.log(NIdVg_6um_Vd1
VTSS_NIdVg_6um_Vd1 = logpw_fit_NIdVg_6um_Vd1.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_6um_Vd1 = logpw_fit_NIdVg_6um_Vd1.get_results()['estimates']['alpha1']['estimate']*VTSS_NIdVg_6um_V
plt.scatter(VTSS_NIdVg_6um_Vd1,IdSS_VT_NIdVg_6um_Vd1,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_6um_Vd1:.2f}V$', (VTSS_NIdVg_6um_Vd1, IdSS_VT_NIdVg_6um_Vd1))
#Beyond linear regime of I_d vs V_g for V_d = 1V
VSSunk_NIdVg_6um_Vd1 = logpw_fit_NIdVg_6um_Vd1.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_6um_Vd1 = logpw_fit_NIdVg_6um_Vd1.get_results()['estimates']['alpha2']['estimate']*(VSSunk_NIdVg
plt.scatter(VSSunk_NIdVg_6um_Vd1,IdSSunk_VT_NIdVg_6um_Vd1,marker='o',c='#2ca02c')
plt.annotate(f'$V_{{UNK}} = {VSSunk_NIdVg_6um_Vd1:.2f}V$', (VSSunk_NIdVg_6um_Vd1, IdSSunk_VT_NIdVg_6um_Vd1))

plt.legend(loc='best')
plt.title('$V_d = 1V$ (Measured)')
plt.xlabel('$V_g (V)$')
plt.ylabel('$\log I_d (A)$')

plt.subplot(223)
plt.plot(NIdVg_06um_Sim_Vd01[0].to_numpy()[13:], np.log(NIdVg_06um_Sim_Vd01[1].to_numpy())[13:], label='$L_g = 0.
logpw_fit_NIdVg_06um_Sim_Vd01 = piecewise_regression.Fit(NIdVg_06um_Sim_Vd01[0].to_numpy()[13:],np.log(NIdVg_06um
VTSS_NIdVg_06um_Sim_Vd01 = logpw_fit_NIdVg_06um_Sim_Vd01.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_06um_Sim_Vd01 = logpw_fit_NIdVg_06um_Sim_Vd01.get_results()['estimates']['alpha1']['estimate']*VTSS
plt.scatter(VTSS_NIdVg_06um_Sim_Vd01,IdSS_VT_NIdVg_06um_Sim_Vd01,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_06um_Sim_Vd01:.2f}V$', (VTSS_NIdVg_06um_Sim_Vd01, IdSS_VT_NIdVg_06um_Sim_Vd01))
#Beyond linear regime of I_d vs V_g for V_d = 0.1V
VSSunk_NIdVg_06um_Sim_Vd01 = logpw_fit_NIdVg_06um_Sim_Vd01.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_06um_Sim_Vd01 = logpw_fit_NIdVg_06um_Sim_Vd01.get_results()['estimates']['alpha2']['estimate']*(
plt.scatter(VSSunk_NIdVg_06um_Sim_Vd01,IdSSunk_VT_NIdVg_06um_Sim_Vd01,marker='o',c='#1f77b4')
plt.annotate(f'$V_{{UNK}} = {VSSunk_NIdVg_06um_Sim_Vd01:.2f}V$', (VSSunk_NIdVg_06um_Sim_Vd01, IdSSunk_VT_NIdVg_06

plt.plot(NIdVg_1um_Sim_Vd01[0].to_numpy()[13:], np.log(NIdVg_1um_Sim_Vd01[1].to_numpy()[13:]), label='$L_g = 1\mu
logpw_fit_NIdVg_1um_Sim_Vd01 = piecewise_regression.Fit(NIdVg_1um_Sim_Vd01[0].to_numpy()[13:],np.log(NIdVg_1um_Si
VTSS_NIdVg_1um_Sim_Vd01 = logpw_fit_NIdVg_1um_Sim_Vd01.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_1um_Sim_Vd01 = logpw_fit_NIdVg_1um_Sim_Vd01.get_results()['estimates']['alpha1']['estimate']*VTSS_N
plt.scatter(VTSS_NIdVg_1um_Sim_Vd01,IdSS_VT_NIdVg_1um_Sim_Vd01,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_1um_Sim_Vd01:.2f}V$', (VTSS_NIdVg_1um_Sim_Vd01, IdSS_VT_NIdVg_1um_Sim_Vd01))
#Beyond linear regime of I_d vs V_g for V_d = 0.1V
VSSunk_NIdVg_1um_Sim_Vd01 = logpw_fit_NIdVg_1um_Sim_Vd01.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_1um_Sim_Vd01 = logpw_fit_NIdVg_1um_Sim_Vd01.get_results()['estimates']['alpha2']['estimate']*(VS
plt.scatter(VSSunk_NIdVg_1um_Sim_Vd01,IdSSunk_VT_NIdVg_1um_Sim_Vd01,marker='o',c='#ff7f0e')
plt.annotate(f'$V_{{UNK}} = {VSSunk_NIdVg_1um_Sim_Vd01:.2f}V$', (VSSunk_NIdVg_1um_Sim_Vd01, IdSSunk_VT_NIdVg_1um_

plt.plot(NIdVg_6um_Sim_Vd01[0].to_numpy()[13:], np.log(NIdVg_6um_Sim_Vd01[1].to_numpy()[13:]), label='$L_g = 6\mu
logpw_fit_NIdVg_6um_Sim_Vd01 = piecewise_regression.Fit(NIdVg_6um_Sim_Vd01[0].to_numpy()[13:],np.log(NIdVg_6um_Si
VTSS_NIdVg_6um_Sim_Vd01 = logpw_fit_NIdVg_6um_Sim_Vd01.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_6um_Sim_Vd01 = logpw_fit_NIdVg_6um_Sim_Vd01.get_results()['estimates']['alpha1']['estimate']*VTSS_N
plt.scatter(VTSS_NIdVg_6um_Sim_Vd01,IdSS_VT_NIdVg_6um_Sim_Vd01,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_6um_Sim_Vd01:.2f}V$', (VTSS_NIdVg_6um_Sim_Vd01, IdSS_VT_NIdVg_6um_Sim_Vd01))
#Beyond linear regime of I_d vs V_g for V_d = 0.1V
VSSunk_NIdVg_6um_Sim_Vd01 = logpw_fit_NIdVg_6um_Sim_Vd01.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_6um_Sim_Vd01 = logpw_fit_NIdVg_6um_Sim_Vd01.get_results()['estimates']['alpha2']['estimate']*(VS
plt.scatter(VSSunk_NIdVg_6um_Sim_Vd01,IdSSunk_VT_NIdVg_6um_Sim_Vd01,marker='o',c='#2ca02c')
plt.annotate(f'$V_{{UNK}} = {VSSunk_NIdVg_6um_Sim_Vd01:.2f}V$', (VSSunk_NIdVg_6um_Sim_Vd01, IdSSunk_VT_NIdVg_6um_

plt.legend(loc='best')
plt.title('$V_d = 0.1V$ (Simulated)')
plt.xlabel('$V_g (V)$')
plt.ylabel('$\log I_d (A)$')

plt.subplot(224)
plt.plot(NIdVg_06um_Sim_Vd1[0].to_numpy()[13:], np.log(NIdVg_06um_Sim_Vd1[1].to_numpy()[13:]), label='$L_g = 0.6\
logpw_fit_NIdVg_06um_Sim_Vd1 = piecewise_regression.Fit(NIdVg_06um_Sim_Vd1[0].to_numpy()[13:],np.log(NIdVg_06um_S
VTSS_NIdVg_06um_Sim_Vd1 = logpw_fit_NIdVg_06um_Sim_Vd1.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_06um_Sim_Vd1 = logpw_fit_NIdVg_06um_Sim_Vd1.get_results()['estimates']['alpha1']['estimate']*VTSS_N
plt.scatter(VTSS_NIdVg_06um_Sim_Vd1,IdSS_VT_NIdVg_06um_Sim_Vd1,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_06um_Sim_Vd1:.2f}V$', (VTSS_NIdVg_06um_Sim_Vd1, IdSS_VT_NIdVg_06um_Sim_Vd1))
#Beyond linear regime of I_d vs V_g for V_d = 1V
VSSunk_NIdVg_06um_Sim_Vd1 = logpw_fit_NIdVg_06um_Sim_Vd1.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_06um_Sim_Vd1 = logpw_fit_NIdVg_06um_Sim_Vd1.get_results()['estimates']['alpha2']['estimate']*(VS
plt.scatter(VSSunk_NIdVg_06um_Sim_Vd1,IdSSunk_VT_NIdVg_06um_Sim_Vd1,marker='o',c='#1f77b4')
plt.annotate(f'$V_{{UNK}} = {VSSunk_NIdVg_06um_Sim_Vd1:.2f}V$', (VSSunk_NIdVg_06um_Sim_Vd1, IdSSunk_VT_NIdVg_06um

plt.plot(NIdVg_1um_Sim_Vd1[0].to_numpy()[13:], np.log(NIdVg_1um_Sim_Vd1[1].to_numpy()[13:]), label='$L_g = 1\mu m
logpw_fit_NIdVg_1um_Sim_Vd1 = piecewise_regression.Fit(NIdVg_1um_Sim_Vd1[0].to_numpy()[13:],np.log(NIdVg_1um_Sim_
VTSS_NIdVg_1um_Sim_Vd1 = logpw_fit_NIdVg_1um_Sim_Vd1.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_1um_Sim_Vd1 = logpw_fit_NIdVg_1um_Sim_Vd1.get_results()['estimates']['alpha1']['estimate']*VTSS_NIc
plt.scatter(VTSS_NIdVg_1um_Sim_Vd1,IdSS_VT_NIdVg_1um_Sim_Vd1,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_1um_Sim_Vd1:.2f}V$', (VTSS_NIdVg_1um_Sim_Vd1, IdSS_VT_NIdVg_1um_Sim_Vd1))
```

```
#Beyond linear regime of I_d vs V_g for V_d = 1V
VSSunk_NIdVg_1um_Sim_Vd1 = logpw_fit_NIdVg_1um_Sim_Vd1.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_1um_Sim_Vd1 = logpw_fit_NIdVg_1um_Sim_Vd1.get_results()['estimates']['alpha2']['estimate']*(VSSu
plt.scatter(VSSunk_NIdVg_1um_Sim_Vd1,IdSSunk_VT_NIdVg_1um_Sim_Vd1,marker='o',c='#ff7f0e')
plt.annotate(f'$V_{{UNK}} = {VSSunk_NIdVg_1um_Sim_Vd1:.2f}V$', (VSSunk_NIdVg_1um_Sim_Vd1, IdSSunk_VT_NIdVg_1um_Si

plt.plot(NIdVg_6um_Sim_Vd1[0].to_numpy()[13:], np.log(NIdVg_6um_Sim_Vd1[1].to_numpy()[13:]), label='$L_g = 6\mu m
logpw_fit_NIdVg_6um_Sim_Vd1 = piecewise_regression.Fit(NIdVg_6um_Sim_Vd1[0].to_numpy()[13:],np.log(NIdVg_6um_Sim_
VTSS_NIdVg_6um_Sim_Vd1 = logpw_fit_NIdVg_6um_Sim_Vd1.get_results()['estimates']['breakpoint1']['estimate']
IdSS_VT_NIdVg_6um_Sim_Vd1 = logpw_fit_NIdVg_6um_Sim_Vd1.get_results()['estimates']['alpha1']['estimate']*VTSS_NIc
plt.scatter(VTSS_NIdVg_6um_Sim_Vd1,IdSS_VT_NIdVg_6um_Sim_Vd1,marker='o')
plt.annotate(f'$V_T = {VTSS_NIdVg_6um_Sim_Vd1:.2f}V$', (VTSS_NIdVg_6um_Sim_Vd1, IdSS_VT_NIdVg_6um_Sim_Vd1))
#Beyond linear regime of I_d vs V_g for V_d = 1V
VSSunk_NIdVg_6um_Sim_Vd1 = logpw_fit_NIdVg_6um_Sim_Vd1.get_results()['estimates']['breakpoint2']['estimate']
IdSSunk_VT_NIdVg_6um_Sim_Vd1 = logpw_fit_NIdVg_6um_Sim_Vd1.get_results()['estimates']['alpha2']['estimate']*(VSSu
plt.scatter(VSSunk_NIdVg_6um_Sim_Vd1,IdSSunk_VT_NIdVg_6um_Sim_Vd1,marker='o',c='#2ca02c')
plt.annotate(f'$V_{{UNK}} = {VSSunk_NIdVg_6um_Sim_Vd1:.2f}V$', (VSSunk_NIdVg_6um_Sim_Vd1, IdSSunk_VT_NIdVg_6um_Si

plt.legend(loc='best')
plt.title('$V_d = 1V$ (Simulated)')
plt.xlabel('$V_g (V)$')
plt.ylabel('$\log I_d (A)$')
```

Out[23]:
```
Text(0, 0.5, '$\\log I_d (A)$')
```

Drain Current w.r.t source ($\log I_d$) versus Gate Voltage w.r.t source (V_g) for different gate lengths (L_g) and Drain Voltage w.r.t source (V_d) | Bulk Voltage w.r.t source $V_b = 0V$, TiN gate $\psi_g = 4.6eV$, $t_{ox} = 4.5nm$, $X_j = 20nm$, gate width $W = 2000nm$, buried oxide thickness $= 145nm$



In [24]:
```
SS_NIdVg_06um_Vd01 = (1/(logpw_fit_NIdVg_06um_Vd01.get_results()['estimates']['alpha1']['estimate']))*1000 #Sub-t
SS_NIdVg_06um_Sim_Vd01 = (1/(logpw_fit_NIdVg_06um_Sim_Vd01.get_results()['estimates']['alpha1']['estimate']))*100
SS_NIdVg_1um_Vd01 = (1/(logpw_fit_NIdVg_1um_Vd01.get_results()['estimates']['alpha1']['estimate']))*1000
SS_NIdVg_1um_Sim_Vd01 = (1/(logpw_fit_NIdVg_1um_Sim_Vd01.get_results()['estimates']['alpha1']['estimate']))*1000
SS_NIdVg_6um_Vd01 = (1/(logpw_fit_NIdVg_6um_Vd01.get_results()['estimates']['alpha1']['estimate']))*1000
SS_NIdVg_6um_Sim_Vd01 = (1/(logpw_fit_NIdVg_6um_Sim_Vd01.get_results()['estimates']['alpha1']['estimate']))*1000

pw_fit_NIdVg_06um_Vd1 = piecewise_regression.Fit(NIdVg_06um_Vd1['GateV(2)'].to_numpy(),NIdVg_06um_Vd1['DrainI(2)'
VT_NIdVg_06um_Vd1 = pw_fit_NIdVg_06um_Vd1.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_06um_Vd1 = pw_fit_NIdVg_06um_Vd1.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_06um_Vd1+p
Vunk_NIdVg_06um_Vd1 = pw_fit_NIdVg_06um_Vd1.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_06um_Vd1 = pw_fit_NIdVg_06um_Vd1.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdVg_06um
Ion_NIdVg_06um_Vd1 = pw_fit_NIdVg_06um_Vd1.get_results()['estimates']['alpha3']['estimate']*(1-Vunk_NIdVg_06um_Vd

pw_fit_NIdVg_06um_Sim_Vd1 = piecewise_regression.Fit(NIdVg_06um_Sim_Vd1[0].to_numpy(),NIdVg_06um_Sim_Vd1[1].to_nu
VT_NIdVg_06um_Sim_Vd1 = pw_fit_NIdVg_06um_Sim_Vd1.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_06um_Sim_Vd1 = pw_fit_NIdVg_06um_Sim_Vd1.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_06
Vunk_NIdVg_06um_Sim_Vd1 = pw_fit_NIdVg_06um_Sim_Vd1.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_06um_Sim_Vd1 = pw_fit_NIdVg_06um_Sim_Vd1.get_results()['estimates']['alpha2']['estimate']*(Vunk_NI
Ion_NIdVg_06um_Sim_Vd1 = pw_fit_NIdVg_06um_Sim_Vd1.get_results()['estimates']['alpha3']['estimate']*(1-Vunk_NIdVg

pw_fit_NIdVg_1um_Vd1 = piecewise_regression.Fit(NIdVg_1um_Vd1['GateV(2)'].to_numpy(),NIdVg_1um_Vd1['DrainI(2)'].t
VT_NIdVg_1um_Vd1 = pw_fit_NIdVg_1um_Vd1.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_1um_Vd1 = pw_fit_NIdVg_1um_Vd1.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_1um_Vd1+pw_f
Vunk_NIdVg_1um_Vd1 = pw_fit_NIdVg_1um_Vd1.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_1um_Vd1 = pw_fit_NIdVg_1um_Vd1.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdVg_1um_Vc
Ion_NIdVg_1um_Vd1 = pw_fit_NIdVg_1um_Vd1.get_results()['estimates']['alpha3']['estimate']*(1-Vunk_NIdVg_1um_Vd1)+

pw_fit_NIdVg_1um_Sim_Vd1 = piecewise_regression.Fit(NIdVg_1um_Sim_Vd1[0].to_numpy(),NIdVg_1um_Sim_Vd1[1].to_numpy
VT_NIdVg_1um_Sim_Vd1 = pw_fit_NIdVg_1um_Sim_Vd1.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_1um_Sim_Vd1 = pw_fit_NIdVg_1um_Sim_Vd1.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_1um_
Vunk_NIdVg_1um_Sim_Vd1 = pw_fit_NIdVg_1um_Sim_Vd1.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_1um_Sim_Vd1 = pw_fit_NIdVg_1um_Sim_Vd1.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdV
Ion_NIdVg_1um_Sim_Vd1 = pw_fit_NIdVg_1um_Sim_Vd1.get_results()['estimates']['alpha3']['estimate']*(1-Vunk_NIdVg_1

pw_fit_NIdVg_6um_Vd1 = piecewise_regression.Fit(NIdVg_6um_Vd1['GateV(2)'].to_numpy(),NIdVg_6um_Vd1['DrainI(2)'].t
VT_NIdVg_6um_Vd1 = pw_fit_NIdVg_6um_Vd1.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_6um_Vd1 = pw_fit_NIdVg_6um_Vd1.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_6um_Vd1+pw_f
Vunk_NIdVg_6um_Vd1 = pw_fit_NIdVg_6um_Vd1.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_6um_Vd1 = pw_fit_NIdVg_6um_Vd1.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdVg_6um_Vc
Ion_NIdVg_6um_Vd1 = pw_fit_NIdVg_6um_Vd1.get_results()['estimates']['alpha3']['estimate']*(1-Vunk_NIdVg_6um_Vd1)+

pw_fit_NIdVg_6um_Sim_Vd1 = piecewise_regression.Fit(NIdVg_6um_Sim_Vd1[0].to_numpy(),NIdVg_6um_Sim_Vd1[1].to_numpy
VT_NIdVg_6um_Sim_Vd1 = pw_fit_NIdVg_6um_Sim_Vd1.get_results()['estimates']['breakpoint1']['estimate']
Id_VT_NIdVg_6um_Sim_Vd1 = pw_fit_NIdVg_6um_Sim_Vd1.get_results()['estimates']['alpha1']['estimate']*VT_NIdVg_6um_
Vunk_NIdVg_6um_Sim_Vd1 = pw_fit_NIdVg_6um_Sim_Vd1.get_results()['estimates']['breakpoint2']['estimate']
Idunk_VT_NIdVg_6um_Sim_Vd1 = pw_fit_NIdVg_6um_Sim_Vd1.get_results()['estimates']['alpha2']['estimate']*(Vunk_NIdV
Ion_NIdVg_6um_Sim_Vd1 = pw_fit_NIdVg_6um_Sim_Vd1.get_results()['estimates']['alpha3']['estimate']*(1-Vunk_NIdVg_6

logIoff_NIdVg_06um_Vd1 = logpw_fit_NIdVg_06um_Vd1.get_results()['estimates']['const']['estimate']
Ioff_NIdVg_06um_Vd1 = math.pow(10,logIoff_NIdVg_06um_Vd1)
logIoff_NIdVg_06um_Sim_Vd1 = logpw_fit_NIdVg_06um_Sim_Vd1.get_results()['estimates']['const']['estimate']
Ioff_NIdVg_06um_Sim_Vd1 = math.pow(10,logIoff_NIdVg_06um_Sim_Vd1)
logIoff_NIdVg_1um_Vd1 = logpw_fit_NIdVg_1um_Vd1.get_results()['estimates']['const']['estimate']
Ioff_NIdVg_1um_Vd1 = math.pow(10,logIoff_NIdVg_1um_Vd1)
logIoff_NIdVg_1um_Sim_Vd1 = logpw_fit_NIdVg_1um_Sim_Vd1.get_results()['estimates']['const']['estimate']
Ioff_NIdVg_1um_Sim_Vd1 = math.pow(10,logIoff_NIdVg_1um_Sim_Vd1)
logIoff_NIdVg_6um_Vd1 = logpw_fit_NIdVg_6um_Vd1.get_results()['estimates']['const']['estimate']
Ioff_NIdVg_6um_Vd1 = math.pow(10,logIoff_NIdVg_6um_Vd1)
logIoff_NIdVg_6um_Sim_Vd1 = logpw_fit_NIdVg_6um_Sim_Vd1.get_results()['estimates']['const']['estimate']
Ioff_NIdVg_6um_Sim_Vd1 = math.pow(10,logIoff_NIdVg_6um_Sim_Vd1)

DIBL_NIdVg_06um = ((VTSS_NIdVg_06um_Vd1-VTSS_NIdVg_06um_Vd01)/(1-0.1))*1000 #Drain-induced barrier lowering (DIBL
DIBL_NIdVg_06um_Sim = ((VTSS_NIdVg_06um_Sim_Vd1-VTSS_NIdVg_06um_Sim_Vd01)/(1-0.1))*1000
DIBL_NIdVg_1um = ((VTSS_NIdVg_1um_Vd1-VTSS_NIdVg_1um_Vd01)/(1-0.1))*1000
DIBL_NIdVg_1um_Sim = ((VTSS_NIdVg_1um_Sim_Vd1-VTSS_NIdVg_1um_Sim_Vd01)/(1-0.1))*1000
DIBL_NIdVg_6um = ((VTSS_NIdVg_6um_Vd1-VTSS_NIdVg_6um_Vd01)/(1-0.1))*1000
DIBL_NIdVg_6um_Sim = ((VTSS_NIdVg_6um_Sim_Vd1-VTSS_NIdVg_6um_Sim_Vd01)/(1-0.1))*1000
```

In [25]:
```
print("%.3e" % SS_NIdVg_06um_Vd01) #To print necessary variable values and enter in summary below
```

```
2.841e+01
```

Summary

$L_g\ (\mu m)$	$V_T\ (V)$ $@V_d = 0.1V$ Measured	$V_T\ (V)$ $@V_d = 0.1V$ Simulated	$SS\ (mV/dec)$ $@V_d = 0.1V$ Measured	$SS\ (mV/dec)$ $@V_d = 0.1V$ Simulated	$I_{ON}\ (A)$ $@V_d(V_g) = 1V$ Measured	$I_{ON}\ (A)$ $@V_d(V_g) = 1V$ Simulated	$I_{OFF}\ (A)$ $@V_d = 1V$ Measured	$I_{OFF}\ (A)$ $@V_d = 1V$ Simulated	$DIBL\ (mV/V)$ Measured
0.6	0.229	-0.073	28.412	30.255	3.122e-04	7.126e-04	3.927e-22	2.044e-10	49.676
1	0.268	-0.072	29.886	30.272	2.325e-04	4.970e-04	1.405e-22	5.302e-11	9.596
6	0.269	-0.066	30.675	31.304	4.272e-05	9.340e-05	1.694e-24	4.155e-13	12.783

1. # channel nodes, # oxide nodes and # bias steps were progressively increased accordingly for simulation of decreasing L_g, for better plot convergence.
2. V_T extracted from $\log I_d$ vs V_g plot has been reported in the table above because this value is closer to its experimental measure than V_T extracted from I_d vs V_g. Hence this confirms piecewise regression fit of $\log I_d$ vs V_g plot better captures feautures which lie in the well modeled subthreshold and linear regions of MOSFET operation.
3. I_{ON} extracted from I_d vs V_g plot has been reported in the table above because $I_{ON}@V_g = 1V$ lies beyond the linear region of MOSFET operation and is not well modeled through a $\log I_d$ vs V_g regression fit (reason for it is explained below in point 4).
4. V_{UNK} in $\log I_d$ (or I_d) vs V_g plot indicates V_g from which the MOSFET enters a non-linear operating region that needs 5 coupled equations (Poisson, Electron continuity, Hole continuity, Electron transport and Hole transport) to be modeled.
5. $DIBL\ \forall L_g$ seem to be off because -
   A. $\log I_d$ vs $V_g@V_d = 1V$ measured/simulated plot has a slight curvature in the subthreshold region at very low V_g.
   B. Hence, $V_T@V_d = 1V$ is overestimated in the respective piecewise regression fit.
6. Descrepencies in respective measured vs simulated values $\forall L_g$ can be attributed to slight physical process variations in effective L_g and/or T_{oxe} of the measured SOI MOSFETs.
7. The effect of scaling up $\psi_g = 4.6eV$ can be observed in lower simulated I_{OFF} (and hence lower simulated I_{ON}) values when compared to respective values in Part I. This follows directly from an increased V_T (w.r.t constant t_{ox} and L_g) due to increased ψ_g of TiN w.r.t Si (Eq. (4) and hence Eq. (2), Eq. (3)).
8. Simulations in this section were carried out using the abacus tool at nanoHUB. It contains generic physical models for simulating various IV relations of MOSFETs.

I_d/V_d [Measured vs Simulated] for NMOS SOI MOSFET with constant oxide thickness (t_{ox})

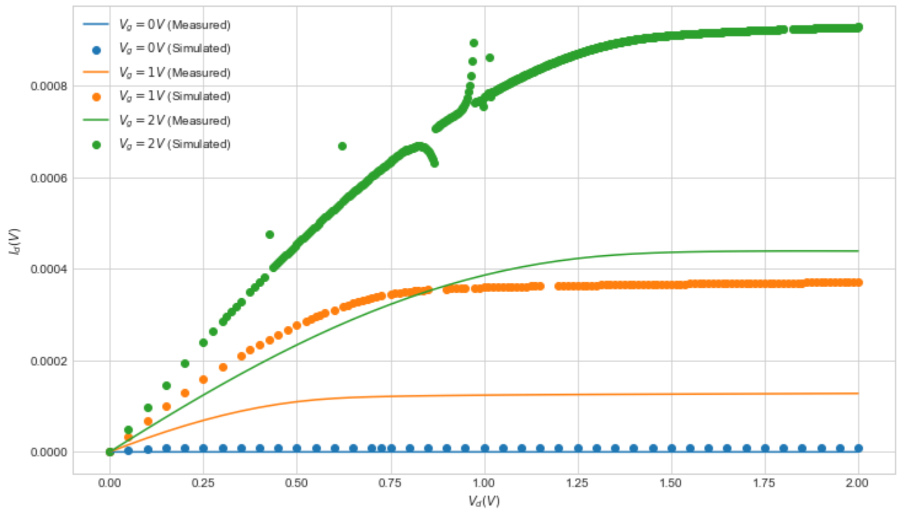
In [26]:
```
#Reading Measured data
NIdVd_1um = pd.read_excel('B774W4/N-L1um-IdVd.xls', sheet_name='Data')
NIdVd_1um_Vg0 = NIdVd_1um[['DrainV(1)','DrainI(1)']]
NIdVd_1um_Vg1 = NIdVd_1um[['DrainV(11)','DrainI(11)']]
NIdVd_1um_Vg2 = NIdVd_1um[['DrainV(21)','DrainI(21)']]

#Reading Simulated data
NIdVd_1um_Sim_Vg0 = pd.read_csv('Simulations/N-L1um-IdVd-Sim.txt', skiprows=4,nrows=42,header=None)
NIdVd_1um_Sim_Vg1 = pd.read_csv('Simulations/N-L1um-IdVd-Sim.txt', skiprows=51,nrows=123,header=None)
NIdVd_1um_Sim_Vg2 = pd.read_csv('Simulations/N-L1um-IdVd-Sim.txt', skiprows=179,nrows=777,header=None)
```

```
WARNING *** OLE2 inconsistency: SSCS size is 0 but SSAT size is non-zero
```

In [27]:
```
fig,axes = plt.subplots(figsize=(12, 7))
fig.suptitle('Drain Current w.r.t source $(I_d)$ versus Drain Voltage w.r.t source $(V_d)$ for gate length $L_g =
plt.plot(NIdVd_1um_Vg0['DrainV(1)'],NIdVd_1um_Vg0['DrainI(1)'],label='$V_g = 0V$ (Measured)')
plt.scatter(NIdVd_1um_Sim_Vg0[0],NIdVd_1um_Sim_Vg0[1],label='$V_g = 0V$ (Simulated)')
plt.plot(NIdVd_1um_Vg1['DrainV(11)'],NIdVd_1um_Vg1['DrainI(11)'],label='$V_g = 1V$ (Measured)')
plt.scatter(NIdVd_1um_Sim_Vg1[0],NIdVd_1um_Sim_Vg1[1],label='$V_g = 1V$ (Simulated)')
plt.plot(NIdVd_1um_Vg2['DrainV(21)'],NIdVd_1um_Vg2['DrainI(21)'],label='$V_g = 2V$ (Measured)')
plt.scatter(NIdVd_1um_Sim_Vg2[0],NIdVd_1um_Sim_Vg2[1],label='$V_g = 2V$ (Simulated)')
axes.legend(loc='best')
axes.set_xlabel('$V_d (V)$')
axes.set_ylabel('$I_d (V)$')
```

Out[27]:
```
Text(0, 0.5, '$I_d (V)$')
```

Drain Current w.r.t source (I_d) versus Drain Voltage w.r.t source (V_d) for gate length $L_g = 1\mu m$ and different Gate Voltages w.r.t source (V_g) | Bulk Voltage w.r.t source $V_b = 0V$, TiN gate $\psi_g = 4.6eV$, $t_{ox} = 4.5nm$, $X_j = 20nm$, gate width $W = 2000nm$, buried oxide thickness $= 145nm$



Summary

1. I_d vs $V_d \forall V_g$ plots of SOI MOSFETs can be seen to follow the generic MOSFET IV trend:

$$I_d = \frac{W}{L} \cdot C_{oxe} \cdot \mu \cdot (V_g - V_T - \frac{1}{2}V_d) \cdot V_d \tag{5}$$

2. Descrepencies in respective measured vs simulated values $\forall L_g$ can be attributed to slight physical process variations in effective L_g and/or T_{oxe} of the measured SOI MOSFETs.

3. Simulations in this section were carried out using the abacus tool at nanoHUB. It contains generic physical models for simulating various IV relations of MOSFETs.
4. Simulated I_d vs $V_d @ V_g = 2V$ curve has points off in $V_d = [0.3 : 1.2]V$ because the physical model in abacus capturing respective I_d / V_d relation has not converged well. This can be resolved with increased channel nodes and shorter bias steps, simulating which can take a day's worth of compute and hence not possible in abacus.

Discussion and Conclusion

The slight curvature in the subthreshold region of $\log I_d$ vs $V_g @ V_d = high$ plots in certain simulated and measured MOSFETs might seem to lead to an overestimated V_T and hence affect respective DIBL values. But generic relations presented in equations Eq. (1), Eq. (2), Eq. (3), Eq. (4) and Eq. (5) have been verified to hold in all respective sections, regardless.

References

- [1] **Modern Semiconductor Devices for Integrated Circuits - Chenming Hu**
- [2] **Nanometer CMOS ICs: From Basics to ASICs - Harry Veendrick**

Additional information

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Data and config file at: Github