TCAD-Based Analysis of a Novel Dual Dielectric Gate MOSFET for High-Speed Applications

25VL681 Analog VLSI and Device Modelling Lab

M. Tech. VLSI Design

Batch: VLDA9

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CB.EN.P2VLD25012	Manju M
CB.EN.P2VLD25016	Navyasree Katragadda
CB.EN.P2VLD25018	Nimeshika T S R V S
CB.EN.P2VLD25035	Vedasri J

Faculty In-charges: Dr. Abhishek Raj

Signature of the Faculty:

Department of Electronics and Communication Engineering

Amrita School of Engineering

Amrita Vishwa Vidyapeetham

Amritanagar, Coimbatore – 641112

Objective

To design, simulate, and analyze various dual-dielectric gate MOSFET architectures using Silvaco TCAD ATLAS and compare their electrostatic performance. The study focuses on the influence of oxide asymmetry, metal gate work function variation, and gate overlap on short-channel effects (SCEs), threshold voltage, drive current (Ion), leakage (Ioff), DIBL, and subthreshold swing (SS).

Software / Hardware Used

Software: Silvaco TCAD ATLAS

Introduction

As the MOSFET channel length scales below 50 nm, classical electrostatic control of the channel by the gate deteriorates due to increased drain-induced barrier lowering (DIBL), high leakage currents, and poor subthreshold slope. These issues stem from short-channel effects, where the drain potential starts to influence the channel barrier formed near the source, reducing the effective threshold voltage.

Using high-k dielectrics like TiO_2 and HfO_2 improves gate capacitance without reducing physical oxide thickness, thereby minimizing gate tunneling currents. Similarly, dual-metal gate engineering allows localized control of the surface potential, balancing charge distribution along the channel.

This project analyzes three structures — SMSDO, SMADO, and DMADO — that apply these principles in different combinations, demonstrating how material and structural asymmetry can effectively suppress SCEs and enhance device performance.

Overview of the System

The MOSFETs were modeled with identical silicon channels, dopant profiles, and geometry, while varying only oxide and gate configurations. The dielectric stack uses TiO_2 (higher k ≈ 80) and HfO_2 (lower k ≈ 25), arranged symmetrically or asymmetrically. The high dielectric constant increases gate capacitance, allowing stronger control of the channel potential for a given gate voltage.

The dual-metal gate configuration (in DMADO) introduces a small work-function difference ($\Delta\Phi m$ = 0.15 eV), creating a controlled potential gradient across the gate. This modulates the barrier height near the drain, improving current drive and reducing DIBL simultaneously.

Device Design and Parameters

Parameter	Value / Range	Description
Channel Length	20 nm	Active silicon channel
Source/Drain Length	40 nm each	Terminal regions
Channel Thickness	2 nm	Thin silicon body
Oxide 1 (TiO_2)	2–2.5 nm	High-k dielectric near source
Oxide 2 (HfO_2)	2 nm	Lower-k dielectric near drain
Source/Drain Doping	1×10^{20} cm^{-3}	Heavy n-type doping
Channel Doping	1×10^{16}–2×10^{16} cm^{-3}	Light p-type doping

Substrate Doping	5×10^{15}–5×10^{16} cm^{-3}	p-type substrate
Gate Metal (SMSDO/SMADO)	5.1 eV	Single metal gate
Gate Metals (DMADO)	5.1 eV / 4.95 eV	Dual-metal gate stack
Gate Overlap	2.5 nm, 7.5 nm	Small-overlap and increased overlap variants (on one side)

Simulation Methodology

1. **Device Setup:**

   All devices were defined in Silvaco ATLAS using the region and doping commands. The structure was partitioned into silicon channel, dual oxides, and gate regions.

SMSDO with small overlap	**SMSDO after increasing overlap**
SMSDO go atlas TITLE SMSDO #meshing mesh space.mult=1 x.mesh loc=0.0 spac=0.01 x.mesh loc=0.010 spac=0.01 x.mesh loc=0.0375 spac=0.005 x.mesh loc=0.040 spac=0.001 x.mesh loc=0.045 spac=0.0005 x.mesh loc=0.048 spac=0.00025 x.mesh loc=0.049 spac=0.0001 x.mesh loc=0.050 spac=0.001 x.mesh loc=0.051 spac=0.0001 x.mesh loc=0.052 spac=0.00025	SMSDO go atlas TITLE SMSDO #meshing mesh space.mult=1 x.mesh loc=0.0 spac=0.01 x.mesh loc=0.010 spac=0.01 x.mesh loc=0.0335 spac=0.005 x.mesh loc=0.040 spac=0.001 x.mesh loc=0.045 spac=0.0005 x.mesh loc=0.048 spac=0.00025 x.mesh loc=0.049 spac=0.0001 x.mesh loc=0.050 spac=0.001 x.mesh loc=0.051 spac=0.0001 x.mesh loc=0.052 spac=0.00025

x.mesh loc=0.055 spac=0.0005 x.mesh loc=0.060 spac=0.001 x.mesh loc=0.0625 spac=0.005 x.mesh loc=0.090 spac=0.01 x.mesh loc=0.1 spac=0.01 y.mesh loc=0.0 spac=0.005 y.mesh loc=0.00025 spac=0.005 y.mesh loc=0.001 spac=0.005 y.mesh loc=0.00125 spac=0.005 y.mesh loc=0.00325 spac=0.00025 y.mesh loc=0.00525 spac=0.0005 y.mesh loc=0.01425 spac=0.005 #regions region num=1 material=air x.min=0.0 x.max=0.1 y.min=0.0 y.max=0.013 region num=2 material=tio2 x.min=0.0375 x.max=0.050 y.min=0.00125 y.max=0.00325 region num=3 material=hfo2 x.min=0.050 x.max=0.0625 y.min=0.00125 y.max=0.00325 region num=4 material=silicon x.min=0.00 x.max=0.040 y.min=0.00325 y.max=0.00525 region num=5 material=silicon x.min=0.040 x.max=0.060 y.min=0.00325 y.max=0.00525 region num=6 material=silicon x.min=0.060 x.max=0.100 y.min=0.00325 y.max=0.00525 region num=7 material=silicon x.min=0.0 x.max=0.100 y.min=0.00525 y.max=0.01425 #electrode electrode name=source x.min=0.0 x.max=0.010 y.min=0.002 y.max=0.00325 electrode name=gate x.min=0.0375 x.max=0.0625 y.min=0.00025 y.max=0.00125 electrode name=drain x.min=0.090 x.max=0.100 y.min=0.002 y.max=0.00325 #doping #doping uniform n.type conc=1e20 reg=4 #doping uniform p.type conc=1e16 reg=5 #doping uniform n.type conc=1e20 reg=6 #doping uniform p.type conc=1e15 reg=7 doping uniform n.type conc=1e20 reg=4 doping uniform p.type conc=2e16 reg=5 doping uniform n.type conc=1e20 reg=6 doping uniform p.type conc=5e15 reg=7	x.mesh loc=0.055 spac=0.0005 x.mesh loc=0.060 spac=0.001 x.mesh loc=0.0665 spac=0.005 x.mesh loc=0.090 spac=0.01 x.mesh loc=0.1 spac=0.01 y.mesh loc=0.0 spac=0.005 y.mesh loc=0.00025 spac=0.005 y.mesh loc=0.001 spac=0.005 y.mesh loc=0.00125 spac=0.005 y.mesh loc=0.00325 spac=0.00025 y.mesh loc=0.00525 spac=0.0005 y.mesh loc=0.01425 spac=0.005 #regions region num=1 material=air x.min=0.0 x.max=0.1 y.min=0.0 y.max=0.013 region num=2 material=tio2 x.min=0.0335 x.max=0.050 y.min=0.00125 y.max=0.00325 region num=3 material=hfo2 x.min=0.050 x.max=0.0665 y.min=0.00125 y.max=0.00325 region num=4 material=silicon x.min=0.00 x.max=0.040 y.min=0.00325 y.max=0.00525 region num=5 material=silicon x.min=0.040 x.max=0.060 y.min=0.00325 y.max=0.00525 region num=6 material=silicon x.min=0.060 x.max=0.100 y.min=0.00325 y.max=0.00525 region num=7 material=silicon x.min=0.0 x.max=0.100 y.min=0.00525 y.max=0.01425 #electrode electrode name=source x.min=0.0 x.max=0.010 y.min=0.002 y.max=0.00325 electrode name=gate x.min=0.0335 x.max=0.0665 y.min=0.00025 y.max=0.00125 electrode name=drain x.min=0.090 x.max=0.100 y.min=0.002 y.max=0.00325 ##doping doping uniform n.type conc=1e20 reg=4 doping uniform p.type conc=2e16 reg=5 doping uniform n.type conc=1e20 reg=6 doping uniform p.type conc=5e15 reg=7 #doping uniform n.type conc=2e20 reg=4 #doping uniform p.type conc=2e16 reg=5 #doping uniform n.type conc=2e20 reg=6

```
#contacts
contact name=source
contact name=gate workfunction=5.1
contact name=drain

save outf=smsdo.str

models srh auger conmob fldmob fermi cvt
quantum name=ldd bgn
output e.field j.electron j.hole j.conduc j.total
ex.field ey.field e.mobility h.mobility qsse.temp
h.temp qfn qfp con.band val.band j.disp

##method
method newton
solve init

#voltage
solve vdrain=0
solve vdrain=0.05
solve vdrain=0.1
solve vdrain=0.2
solve vdrain=0.4
solve vdrain=0.5
solve vdrain=0.6
solve vdrain=0.8
log outf=smsdo_d08_g08_s0.log
solve name=gate vgate=0 vstep=0.1 vfinal=0.8
save outf=smsdo_d08_g08_s0.str
log off

solve init
solve name=gate vfinal=0.3

solve name=gate vfinal=0.6
log outf=smsdo_g06_d08_s0.log master
solve vsource=0 vdrain=0 vstep=0.1 vfinal=0.8
name=drain
save outf=smsdo_g06_d08_s0.str
log off

solve name=gate vfinal=0.8
log outf=smsdo_g08_d08_s0.log master
solve vsource=0 vdrain=0 vstep=0.1 vfinal=0.8
name=drain
save outf=smsdo_g08_d08_s0.str
log off

###################DIBL
solve init
```

```
#doping uniform p.type conc=5e15 reg=7
#
#
##contacts
#contact name=source
#contact name=gate workfunction=5.1
#contact name=drain

#added later (down)
#doping uniform n.type conc=1e20 reg=4
#doping uniform p.type conc=1e16 reg=5
#doping uniform n.type conc=1e20 reg=6
#doping uniform p.type conc=5e16 reg=7


#contacts
contact name=source
contact name=gate workfunction=5.1
#contact name=gate2 workfunction=4.95
contact name=drain
#adder later (up)

save outf=smsdo.str

models srh auger conmob fldmob fermi cvt
quantum name=ldd bgn
output e.field j.electron j.hole j.conduc j.total
ex.field ey.field e.mobility h.mobility qsse.temp
h.temp qfn qfp con.band val.band j.disp

##method
method newton
#solve init

#voltage
solve init
solve vdrain=0
solve vdrain=0.05
solve vdrain=0.1
solve vdrain=0.2
solve vdrain=0.4
solve vdrain=0.6
solve vdrain=0.8
log outf=smsdo_d08_g08_s0.log
solve name=gate vgate=0 vstep=0.1 vfinal=0.8
save outf=smsdo_d08_g08_s0.str
log off

solve init
solve name=gate vfinal=0.6
log outf=smsdo_g06_d08_s0.log master
```

```
solve vdrain=0
solve vdrain=0.01
solve vdrain=0.02
solve vdrain=0.03
solve vdrain=0.04
solve vdrain=0.05
log outf=smsdo_ch20_Vd005.log
solve name=gate vgate=0 vstep=0.1 vfinal=0.8
extract name="vt1" x.val from curve ((v."gate"),
log10(abs(i."drain"))) where y.val=-7
log off

solve init
solve prev
solve vdrain=0
solve vdrain=0.05
solve vdrain=0.1
solve vdrain=0.2
solve vdrain=0.4
solve vdrain=0.6
solve vdrain=0.8
solve vdrain=1
log outf=smsdo_ch20_Vd1.log
solve name=gate vgate=0 vstep=0.1 vfinal=0.8
extract name="vt2" x.val from curve
((v."gate"),log10(abs (i."drain"))) where y.val=-7
log off

go atlas
extract name="dibl" ($"vt1"-$"vt2")/(1-0.05)
extract init infile="smsdo_ch20_Vd005.log"
extract name="subvt"
1.0/slope(maxslope(curve(v."gate",log10(abs(i.
"drain")))))
extract init infile="smsdo_d08_g08_s0.log"
extract name="Ioff_n" y.val from
curve(v."gate",i."drain") where x.val=0.0
extract name="Ion_n" y.val from
curve(v."gate",i."drain") where x.val=0.8
extract name="Ion_Ioff" $Ion_n/$Ioff_n
extract name="vt" x.val from curve
((v."gate"),log10(abs(i."drain"))) where y.val=-7
quit
```

```
solve vsource=0 vdrain=0 vstep=0.1 vfinal=0.8
name=drain
save outf=smsdo_g06_d08_s0.str
log off

solve name=gate vfinal=0.8
log outf=smsdo_g08_d08_s0.log master
solve vsource=0 vdrain=0 vstep=0.1 vfinal=0.8
name=drain
save outf=smsdo_g08_d08_s0.str
log off

####################DIBL
#solve init
solve previous
solve vdrain=0
solve vdrain=0.01
solve vdrain=0.02
solve vdrain=0.03
solve vdrain=0.04
solve vdrain=0.05
log outf=smsdo_ch20_Vd005.log
solve name=gate vgate=0 vstep=0.1 vfinal=0.8
extract name="vt1" x.val from curve ((v."gate"),
log10(abs(i."drain"))) where y.val=-7
log off

#solve init
solve prev
solve vdrain=0
solve vdrain=0.05
solve vdrain=0.1
solve vdrain=0.2
solve vdrain=0.4
solve vdrain=0.6
solve vdrain=0.8
solve vdrain=1
log outf=smsdo_ch20_Vd1.log
solve name=gate vgate=0 vstep=0.1 vfinal=0.8
extract name="vt2" x.val from curve
((v."gate"),log10(abs (i."drain"))) where y.val=-7
log off

go atlas
extract name="dibl" ($"vt1"-$"vt2")/(1-0.05)
extract init infile="smsdo_ch20_Vd005.log"
extract name="subvt"
1.0/slope(maxslope(curve(v."gate",log10(abs(i.
"drain")))))
extract init infile="smsdo_d08_g08_s0.log"
```

	extract name="Ioff_n" y.val from curve(v."gate",i."drain") where x.val=0.0 extract name="Ion_n" y.val from curve(v."gate",i."drain") where x.val=0.8 extract name="Ion_Ioff" $Ion_n/$Ioff_n extract name="vt" x.val from curve ((v."gate"),log10(abs(i."drain"))) where y.val=-7 quit
SMADO with small overlap	**SMADO after increasing overlap**
go atlas TITLE SMADO #meshing mesh space.mult=1 x.mesh loc=0.0 spac=0.01 x.mesh loc=0.010 spac=0.01 x.mesh loc=0.0375 spac=0.005 x.mesh loc=0.040 spac=0.001 x.mesh loc=0.045 spac=0.0005 x.mesh loc=0.048 spac=0.00025 x.mesh loc=0.049 spac=0.0001 x.mesh loc=0.050 spac=0.001 x.mesh loc=0.051 spac=0.0001 x.mesh loc=0.052 spac=0.00025 x.mesh loc=0.055 spac=0.0005 x.mesh loc=0.060 spac=0.001 x.mesh loc=0.0625 spac=0.005 x.mesh loc=0.090 spac=0.01 x.mesh loc=0.1 spac=0.01 y.mesh loc=0.0 spac=0.005 y.mesh loc=0.00025 spac=0.005 y.mesh loc=0.001 spac=0.005 y.mesh loc=0.00125 spac=0.005 y.mesh loc=0.00175 spac=0.005 y.mesh loc=0.00375 spac=0.00025 y.mesh loc=0.00575 spac=0.0005 y.mesh loc=0.01475 spac=0.005 #regions region num=1 material=air x.min=0.0 x.max=0.1 y.min=0.0 y.max=0.013 region num=2 material=tio2 x.min=0.0375 x.max=0.050 y.min=0.00125 y.max=0.00375 region num=3 material=hfo2 x.min=0.050 x.max=0.0625 y.min=0.00175 y.max=0.00375 region num=4 material=silicon x.min=0.00 x.max=0.040 y.min=0.00375 y.max=0.00575	go atlas TITLE SMADO #meshing mesh space.mult=1 x.mesh loc=0.0 spac=0.01 x.mesh loc=0.010 spac=0.01 x.mesh loc=0.0335 spac=0.005 x.mesh loc=0.040 spac=0.001 x.mesh loc=0.045 spac=0.0005 x.mesh loc=0.048 spac=0.00025 x.mesh loc=0.049 spac=0.0001 x.mesh loc=0.050 spac=0.001 x.mesh loc=0.051 spac=0.0001 x.mesh loc=0.052 spac=0.00025 x.mesh loc=0.055 spac=0.0005 x.mesh loc=0.060 spac=0.001 x.mesh loc=0.0665 spac=0.005 x.mesh loc=0.090 spac=0.01 x.mesh loc=0.1 spac=0.01 y.mesh loc=0.0 spac=0.005 y.mesh loc=0.00025 spac=0.005 y.mesh loc=0.001 spac=0.005 y.mesh loc=0.00125 spac=0.005 y.mesh loc=0.00175 spac=0.005 y.mesh loc=0.00375 spac=0.00025 y.mesh loc=0.00575 spac=0.0005 y.mesh loc=0.01475 spac=0.005 #regions region num=1 material=air x.min=0.0 x.max=0.1 y.min=0.0 y.max=0.013 region num=2 material=tio2 x.min=0.0335 x.max=0.050 y.min=0.00125 y.max=0.00375 region num=3 material=hfo2 x.min=0.050 x.max=0.0665 y.min=0.00175 y.max=0.00375 region num=4 material=silicon x.min=0.00 x.max=0.040 y.min=0.00375 y.max=0.00575

region num=5 material=silicon x.min=0.040 x.max=0.060 y.min=0.00375 y.max=0.00575 region num=6 material=silicon x.min=0.060 x.max=0.100 y.min=0.00375 y.max=0.00575 region num=7 material=silicon x.min=0.0 x.max=0.100 y.min=0.00575 y.max=0.01475 #electrode electrode name=source x.min=0.0 x.max=0.010 y.min=0.002 y.max=0.00375 electrode name=gate1 x.min=0.0375 x.max=0.050 y.min=0.00025 y.max=0.00125 electrode name=gate2 x.min=0.050 x.max=0.0625 y.min=0.00025 y.max=0.00175 electrode name=drain x.min=0.090 x.max=0.100 y.min=0.002 y.max=0.00375 #doping doping uniform n.type conc=2e20 reg=4 doping uniform p.type conc=2e16 reg=5 doping uniform n.type conc=2e20 reg=6 doping uniform p.type conc=5e16 reg=7 #contacts contact name=source contact name=gate1 workfunction=5.1 contact name=gate2 workfunction=5.1 contact name=drain save outf=smado.str models srh auger conmob fldmob fermi cvt quantum name=ldd bgn output e.field j.electron j.hole j.conduc j.total ex.field ey.field e.mobility h.mobility qsse.temp h.temp qfn qfp con.band val.band j.disp ##method method newton solve init solve vdrain=0 solve vdrain=0.05 solve vdrain=0.1 solve vdrain=0.2 solve vdrain=0.4 solve vdrain=0.6 solve vdrain=0.8	region num=5 material=silicon x.min=0.040 x.max=0.060 y.min=0.00375 y.max=0.00575 region num=6 material=silicon x.min=0.060 x.max=0.100 y.min=0.00375 y.max=0.00575 region num=7 material=silicon x.min=0.0 x.max=0.100 y.min=0.00575 y.max=0.01475 #electrode electrode name=source x.min=0.0 x.max=0.010 y.min=0.002 y.max=0.00375 electrode name=gate1 x.min=0.0335 x.max=0.050 y.min=0.00025 y.max=0.00125 electrode name=gate2 x.min=0.050 x.max=0.0665 y.min=0.00025 y.max=0.00175 electrode name=drain x.min=0.090 x.max=0.100 y.min=0.002 y.max=0.00375 #doping doping uniform n.type conc=2e20 reg=4 doping uniform p.type conc=2e16 reg=5 doping uniform n.type conc=2e20 reg=6 doping uniform p.type conc=5e16 reg=7 #contacts contact name=source contact name=gate1 workfunction=5.1 contact name=gate2 workfunction=5.1 contact name=drain save outf=smado.str models srh auger conmob fldmob fermi cvt quantum name=ldd bgn output e.field j.electron j.hole j.conduc j.total ex.field ey.field e.mobility h.mobility qsse.temp h.temp qfn qfp con.band val.band j.disp ##method method newton solve init solve vdrain=0 solve vdrain=0.05 solve vdrain=0.1 solve vdrain=0.2 solve vdrain=0.4 solve vdrain=0.6 solve vdrain=0.8

```
log outf=smado_d08_g08_s0.log master
solve name=gate1 vfinal=0
solve name=gate1 vstep=0.1 vfinal=0.8
save outf=smado_d08_g08_s0.str
log off


#voltage
solve init
solve name=gate1 vfinal=0.6
log outf=smado_g06_d08_s0.log master
solve vsource=0 vdrain=0 vstep=0.1 vfinal=0.8
name=drain
save outf=smado_g06_d08_s0.str
log off

solve name=gate1 vfinal=0.8
log outf=smado_g08_d08_s0.log master
solve vsource=0 vdrain=0 vstep=0.1 vfinal=0.8
name=drain
save outf=smado_g08_d08_s0.str
log off

####################DIBL
solve init
solve vdrain=0
solve vdrain=0.01
solve vdrain=0.02
solve vdrain=0.03
solve vdrain=0.04
solve vdrain=0.05
log outf=smado_ch20_Vd005.log
solve name=gate1 vfinal=0
solve name=gate1 vstep=0.1 vfinal=0.8
extract name="vt1" x.val from curve
((v."gate1"), log10(abs(i."drain"))) where y.val=-
7
log off

solve init
solve prev
solve vdrain=0
solve vdrain=0.05
solve vdrain=0.1
solve vdrain=0.2
solve vdrain=0.4
solve vdrain=0.6
solve vdrain=0.8
solve vdrain=1
```


```
log outf=smado_d08_g08_s0.log master
solve name=gate1 vfinal=0
solve name=gate1 vstep=0.1 vfinal=0.8
save outf=smado_d08_g08_s0.str
log off


#voltage
solve init
solve name=gate1 vfinal=0.6
log outf=smado_g06_d08_s0.log master
solve vsource=0 vdrain=0 vstep=0.1 vfinal=0.8
name=drain
save outf=smado_g06_d08_s0.str
log off

solve name=gate1 vfinal=0.8
log outf=smado_g08_d08_s0.log master
solve vsource=0 vdrain=0 vstep=0.1 vfinal=0.8
name=drain
save outf=smado_g08_d08_s0.str
log off

####################DIBL
solve init
solve vdrain=0
solve vdrain=0.01
solve vdrain=0.02
solve vdrain=0.03
solve vdrain=0.04
solve vdrain=0.05
log outf=smado_ch20_Vd005.log
solve name=gate1 vfinal=0
solve name=gate1 vstep=0.1 vfinal=0.8
extract name="vt1" x.val from curve
((v."gate1"), log10(abs(i."drain"))) where y.val=-
7
log off

solve init
solve prev
solve vdrain=0
solve vdrain=0.05
solve vdrain=0.1
solve vdrain=0.2
solve vdrain=0.4
solve vdrain=0.6
solve vdrain=0.8
solve vdrain=1
```

<table>
<tr><td>log outf=smado_ch20_Vd1.log
solve name=gate1 vfinal=0
solve name=gate1 vstep=0.1 vfinal=0.8
extract name="vt2" x.val from curve ((v."gate1"),log10(abs (i."drain"))) where y.val=-7
log off

go atlas
extract name="dibl" ($"vt1"-$"vt2")/(1-0.05)
extract init infile="smado_ch20_Vd005.log"
extract name="subvt" 1.0/slope(maxslope(curve(v."gate1",log10(abs(i."drain")))))
extract init infile="smado_d08_g08_s0.log"
extract name="Ioff_n" y.val from curve(v."gate1",i."drain") where x.val=0.0
extract name="Ion_n" y.val from curve(v."gate1",i."drain") where x.val=0.8
extract name="Ion_Ioff" $Ion_n/$Ioff_n
extract name="vt" x.val from curve ((v."gate1"),log10(abs(i."drain"))) where y.val=-7
quit</td><td>log outf=smado_ch20_Vd1.log
solve name=gate1 vfinal=0
solve name=gate1 vstep=0.1 vfinal=0.8
extract name="vt2" x.val from curve ((v."gate1"),log10(abs (i."drain"))) where y.val=-7
log off

go atlas
extract name="dibl" ($"vt1"-$"vt2")/(1-0.05)
extract init infile="smado_ch20_Vd005.log"
extract name="subvt" 1.0/slope(maxslope(curve(v."gate1",log10(abs(i."drain")))))
extract init infile="smado_d08_g08_s0.log"
extract name="Ioff_n" y.val from curve(v."gate1",i."drain") where x.val=0.0
extract name="Ion_n" y.val from curve(v."gate1",i."drain") where x.val=0.8
extract name="Ion_Ioff" $Ion_n/$Ioff_n
extract name="vt" x.val from curve ((v."gate1"),log10(abs(i."drain"))) where y.val=-7
quit</td></tr>
<tr><td>DMADO with small overlap</td><td>DMADO after increasing overlap</td></tr>
<tr><td>go atlas
TITLE DMADO

#meshing
mesh space.mult=1
x.mesh loc=0.0 spac=0.01
x.mesh loc=0.010 spac=0.01
x.mesh loc=0.0375 spac=0.005
x.mesh loc=0.040 spac=0.001
x.mesh loc=0.045 spac=0.0005
x.mesh loc=0.048 spac=0.00025
x.mesh loc=0.049 spac=0.0001
x.mesh loc=0.050 spac=0.001
x.mesh loc=0.051 spac=0.0001
x.mesh loc=0.052 spac=0.00025
x.mesh loc=0.055 spac=0.0005
x.mesh loc=0.060 spac=0.001
x.mesh loc=0.0625 spac=0.005
x.mesh loc=0.090 spac=0.01
x.mesh loc=0.1 spac=0.01

y.mesh loc=0.0 spac=0.005
y.mesh loc=0.00025 spac=0.005
y.mesh loc=0.001 spac=0.005</td><td>go atlas
TITLE DMADO

#meshing
mesh space.mult=1
x.mesh loc=0.0 spac=0.01
x.mesh loc=0.010 spac=0.01
x.mesh loc=0.0335 spac=0.005
x.mesh loc=0.040 spac=0.001
x.mesh loc=0.045 spac=0.0005
x.mesh loc=0.048 spac=0.00025
x.mesh loc=0.049 spac=0.0001
x.mesh loc=0.050 spac=0.001
x.mesh loc=0.051 spac=0.0001
x.mesh loc=0.052 spac=0.00025
x.mesh loc=0.055 spac=0.0005
x.mesh loc=0.060 spac=0.001
x.mesh loc=0.0665 spac=0.005
x.mesh loc=0.090 spac=0.01
x.mesh loc=0.1 spac=0.01

y.mesh loc=0.0 spac=0.005
y.mesh loc=0.00025 spac=0.005
y.mesh loc=0.001 spac=0.005</td></tr>
</table>

y.mesh loc=0.00125 spac=0.005 y.mesh loc=0.00175 spac=0.005 y.mesh loc=0.00375 spac=0.00025 y.mesh loc=0.00575 spac=0.0005 y.mesh loc=0.01475 spac=0.005	y.mesh loc=0.00125 spac=0.005 y.mesh loc=0.00175 spac=0.005 y.mesh loc=0.00375 spac=0.00025 y.mesh loc=0.00575 spac=0.0005 y.mesh loc=0.01475 spac=0.005
#regions region num=1 material=air x.min=0.0 x.max=0.1 y.min=0.0 y.max=0.013 region num=2 material=tio2 x.min=0.0375 x.max=0.050 y.min=0.00125 y.max=0.00375 region num=3 material=hfo2 x.min=0.050 x.max=0.0625 y.min=0.00175 y.max=0.00375 region num=4 material=silicon x.min=0.00 x.max=0.040 y.min=0.00375 y.max=0.00575 region num=5 material=silicon x.min=0.040 x.max=0.060 y.min=0.00375 y.max=0.00575 region num=6 material=silicon x.min=0.060 x.max=0.100 y.min=0.00375 y.max=0.00575 region num=7 material=silicon x.min=0.0 x.max=0.100 y.min=0.00575 y.max=0.01475	#regions region num=1 material=air x.min=0.0 x.max=0.1 y.min=0.0 y.max=0.013 region num=2 material=tio2 x.min=0.0335 x.max=0.050 y.min=0.00125 y.max=0.00375 region num=3 material=hfo2 x.min=0.050 x.max=0.0665 y.min=0.00175 y.max=0.00375 region num=4 material=silicon x.min=0.00 x.max=0.040 y.min=0.00375 y.max=0.00575 region num=5 material=silicon x.min=0.040 x.max=0.060 y.min=0.00375 y.max=0.00575 region num=6 material=silicon x.min=0.060 x.max=0.100 y.min=0.00375 y.max=0.00575 region num=7 material=silicon x.min=0.0 x.max=0.100 y.min=0.00575 y.max=0.01475
#electrode electrode name=source x.min=0.0 x.max=0.010 y.min=0.002 y.max=0.00375 electrode name=gate1 x.min=0.0375 x.max=0.050 y.min=0.00025 y.max=0.00125 electrode name=gate2 x.min=0.050 x.max=0.0625 y.min=0.00025 y.max=0.00175 electrode name=drain x.min=0.090 x.max=0.100 y.min=0.002 y.max=0.00375	#electrode electrode name=source x.min=0.0 x.max=0.010 y.min=0.002 y.max=0.00375 electrode name=gate1 x.min=0.0335 x.max=0.050 y.min=0.00025 y.max=0.00125 electrode name=gate2 x.min=0.050 x.max=0.0665 y.min=0.00025 y.max=0.00175 electrode name=drain x.min=0.090 x.max=0.100 y.min=0.002 y.max=0.00375
#doping doping uniform n.type conc=1e20 reg=4 doping uniform p.type conc=1e16 reg=5 doping uniform n.type conc=1e20 reg=6 doping uniform p.type conc=5e16 reg=7	#doping doping uniform n.type conc=1e20 reg=4 doping uniform p.type conc=1e16 reg=5 doping uniform n.type conc=1e20 reg=6 doping uniform p.type conc=5e16 reg=7
#contacts contact name=source contact name=gate1 workfunction=5.1 contact name=gate2 workfunction=4.95 contact name=drain	#contacts contact name=source contact name=gate1 workfunction=5.1 contact name=gate2 workfunction=4.95 contact name=drain
save outf=dmado.str	save outf=dmado.str
models srh auger conmob fldmob fermi cvt quantum name=ldd bgn	models srh auger conmob fldmob fermi cvt quantum name=ldd bgn

output e.field j.electron j.hole j.conduc j.total ex.field ey.field e.mobility h.mobility qsse.temp h.temp qfn qfp con.band val.band j.disp ##method method newton solve init solve vdrain=0 solve vdrain=0.05 solve vdrain=0.1 solve vdrain=0.2 solve vdrain=0.4 solve vdrain=0.6 solve vdrain=0.8 log outf=dmado_d08_g08_s0.log master solve name=gate1 vfinal=0 solve name=gate1 vstep=0.1 vfinal=0.8 save outf=dmado_d08_g08_s0.str log off #voltage solve init solve name=gate1 vfinal=0.6 log outf=dmado_g06_d08_s0.log master solve vsource=0 vdrain=0 vstep=0.1 vfinal=0.8 name=drain save outf=dmado_g06_d08_s0.str log off solve name=gate1 vfinal=0.8 log outf=dmado_g08_d08_s0.log master solve vsource=0 vdrain=0 vstep=0.1 vfinal=0.8 name=drain save outf=dmado_g08_d08_s0.str log off ###################DIBL solve init solve vdrain=0 solve vdrain=0.01 solve vdrain=0.02 solve vdrain=0.03 solve vdrain=0.04 solve vdrain=0.05 log outf=dmado_ch20_Vd005.log solve name=gate1 vfinal=0 solve name=gate1 vstep=0.1 vfinal=0.8	output e.field j.electron j.hole j.conduc j.total ex.field ey.field e.mobility h.mobility qsse.temp h.temp qfn qfp con.band val.band j.disp ##method method newton solve init solve vdrain=0 solve vdrain=0.05 solve vdrain=0.1 solve vdrain=0.2 solve vdrain=0.4 solve vdrain=0.6 solve vdrain=0.8 log outf=dmado_d08_g08_s0.log master solve name=gate1 vfinal=0 solve name=gate1 vstep=0.1 vfinal=0.8 save outf=dmado_d08_g08_s0.str log off #voltage solve init solve name=gate1 vfinal=0.6 log outf=dmado_g06_d08_s0.log master solve vsource=0 vdrain=0 vstep=0.1 vfinal=0.8 name=drain save outf=dmado_g06_d08_s0.str log off solve name=gate1 vfinal=0.8 log outf=dmado_g08_d08_s0.log master solve vsource=0 vdrain=0 vstep=0.1 vfinal=0.8 name=drain save outf=dmado_g08_d08_s0.str log off ###################DIBL solve init solve vdrain=0 solve vdrain=0.01 solve vdrain=0.02 solve vdrain=0.03 solve vdrain=0.04 solve vdrain=0.05 log outf=dmado_ch20_Vd005.log solve name=gate1 vfinal=0 solve name=gate1 vstep=0.1 vfinal=0.8

```
extract name="vt1" x.val from curve
((v."gate1"), log10(abs(i."drain"))) where y.val=-
7
log off

solve init
solve prev
solve vdrain=0
solve vdrain=0.05
solve vdrain=0.1
solve vdrain=0.2
solve vdrain=0.4
solve vdrain=0.6
solve vdrain=0.8
solve vdrain=1

log outf=dmado_ch20_Vd1.log
solve name=gate1 vfinal=0
solve name=gate1 vstep=0.1 vfinal=0.8
extract name="vt2" x.val from curve
((v."gate1"),log10(abs (i."drain"))) where y.val=-
7
log off

go atlas
extract name="dibl" ($"vt1"-$"vt2")/(1-0.05)
extract init infile="dmado_ch20_Vd005.log"
extract name="subvt"
1.0/slope(maxslope(curve(v."gate1",log10(abs(i
."drain")))))
extract init infile="dmado_d08_g08_s0.log"
extract name="Ioff_n" y.val from
curve(v."gate1",i."drain") where x.val=0.0
extract name="Ion_n" y.val from
curve(v."gate1",i."drain") where x.val=0.8
extract name="Ion_Ioff" $Ion_n/$Ioff_n
extract name="vt" x.val from curve
((v."gate1"),log10(abs(i."drain"))) where y.val=-
7

quit
```


```
extract name="vt1" x.val from curve
((v."gate1"), log10(abs(i."drain"))) where y.val=-
7
log off

solve init
solve prev
solve vdrain=0
solve vdrain=0.05
solve vdrain=0.1
solve vdrain=0.2
solve vdrain=0.4
solve vdrain=0.6
solve vdrain=0.8
solve vdrain=1

log outf=dmado_ch20_Vd1.log
solve name=gate1 vfinal=0
solve name=gate1 vstep=0.1 vfinal=0.8
extract name="vt2" x.val from curve
((v."gate1"),log10(abs (i."drain"))) where y.val=-
7
log off

go atlas
extract name="dibl" ($"vt1"-$"vt2")/(1-0.05)
extract init infile="dmado_ch20_Vd005.log"
extract name="subvt"
1.0/slope(maxslope(curve(v."gate1",log10(abs(i
."drain")))))
extract init infile="dmado_d08_g08_s0.log"
extract name="Ioff_n" y.val from
curve(v."gate1",i."drain") where x.val=0.0
extract name="Ion_n" y.val from
curve(v."gate1",i."drain") where x.val=0.8
extract name="Ion_Ioff" $Ion_n/$Ioff_n
extract name="vt" x.val from curve
((v."gate1"),log10(abs(i."drain"))) where y.val=-
7

quit
```

2. **Mesh Refinement:**
   A fine mesh (~0.0001 µm) was used near the silicon–oxide interface to improve the accuracy of electric field and potential solutions.

3. **Model Activation:**
   Physical models such as SRH, Auger, CONMOB, FLDMOB, FERMI, CVT, QUANTUM, and BGN were used to capture recombination, mobility degradation, and quantum confinement.

4. **Biasing and Extraction:**

   - Vd swept from 0 to 0.8 V
   - Vg swept from 0 to 0.8 V in 0.1 V steps
   - Extraction of Vth, Ion, Ioff, SS, and DIBL from log files

Device Analysis and Physics

1. SMSDO (Single Metal Symmetric Dual Oxide)

Structure Description

SMSDO uses a single gate metal (5.1 eV) with equal TiO_2 and HfO_2 oxide layers on both sides of the channel. The dielectric symmetry ensures uniform gate control along the channel.

Physics Explanation:

In this structure, the electric field from the gate penetrates symmetrically through both dielectric layers, producing a uniform potential profile in the silicon channel. While this provides stable gate coupling, it lacks localized field enhancement at the source end. As a result, carrier injection remains moderate, and the barrier at the drain end is not sufficiently isolated from the drain bias — leading to significant drain-induced barrier lowering (DIBL).

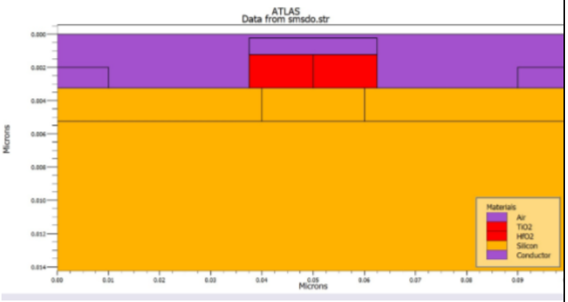
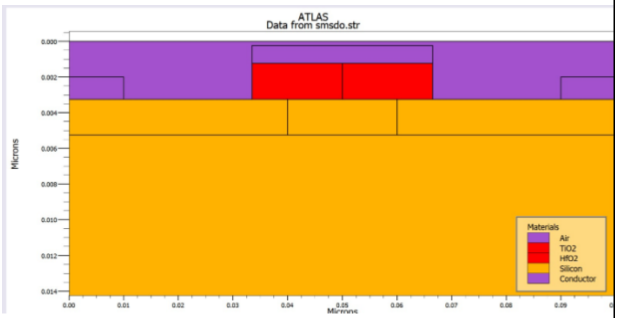
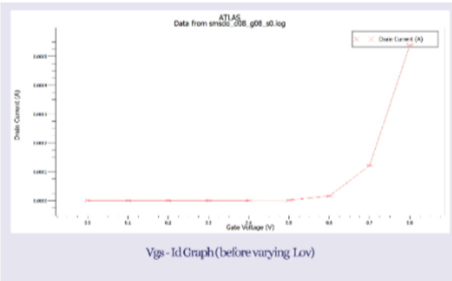
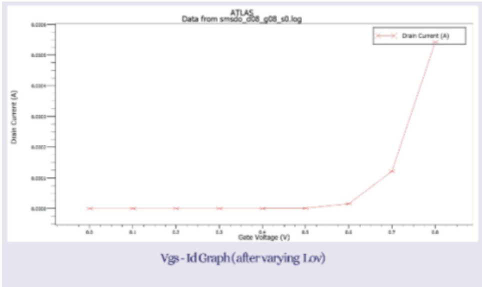
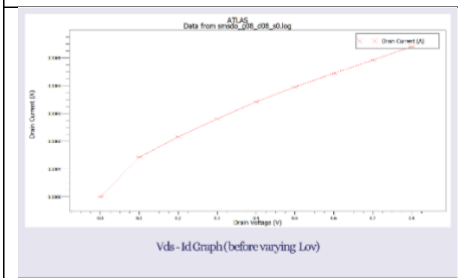
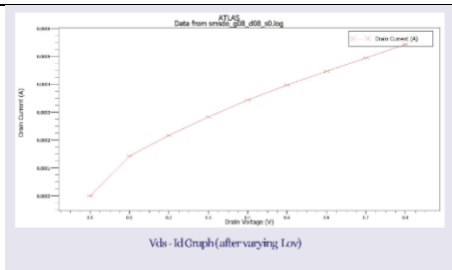
The symmetric dielectric configuration also means that both the source and drain ends experience comparable electric field strength. This uniformity fails to suppress the drain's influence, hence increasing leakage current when Vd rises.

Advantages:

- Balanced potential distribution along the channel
- Stable threshold voltage
- Simple fabrication structure

Disadvantages:

- High DIBL due to drain control over the channel barrier
- Limited Ion/Ioff ratio
- Higher subthreshold swing due to less aggressive field confinement

SMSDO with small overlap length	SMSDO structure after increasing overlap length
Structure 	Structure 
 Vgs - Id Graph (before varying Lov)	 Vgs - Id Graph (after varying Lov)
 Vds - Id Graph (before varying Lov)	 Vds - Id Graph (after varying Lov)
 ATLAS> EXTRACT> init inf="smsdo_ch20_Vd1.log" EXTRACT> extract name="dibl" (0.499777-0.396113)/(1-0.05) dibl=0.10912 EXTRACT> quit EXTRACT> init infile="smsdo_ch20_Vd005.log" EXTRACT> extract name="subvt" 1.0/slope(maxslope(curve(v."gate",log10(abs(i."drain"))))) subvt=0.0772964 V/decade EXTRACT> quit EXTRACT> init infile="smsdo_d08_g08_s0.log" EXTRACT> extract name="Ioff_n" y.val from curve(v."gate",i."drain") where x.val=0.0 Ioff_n=5.91399e-013 EXTRACT> extract name="Ion_n" y.val from curve(v."gate",i."drain") where x.val=0.8 Ion_n=0.000539667 EXTRACT> extract name="Ion_Ioff" 0.000539667/5.91399e-013 Ion_Ioff=9.12526e+008 EXTRACT> extract name="vt" x.val from curve ((v."gate"),log10(abs(i."drain"))) where y.val=-7 vt=0.41292 V EXTRACT> quit quit Device Parameters (before varying Lov)	 ATLAS> EXTRACT> init inf="smsdo_ch20_Vd1.log" EXTRACT> extract name="dibl" (0.499339-0.395648)/(1-0.05) dibl=0.109148 EXTRACT> quit EXTRACT> init infile="smsdo_ch20_Vd005.log" EXTRACT> extract name="subvt" 1.0/slope(maxslope(curve(v."gate",log10(abs(i."drain"))))) subvt=0.077321 V/decade EXTRACT> quit EXTRACT> init infile="smsdo_d08_g08_s0.log" EXTRACT> extract name="Ioff_n" y.val from curve(v."gate",i."drain") where x.val=0.0 Ioff_n=5.89487e-013 EXTRACT> extract name="Ion_n" y.val from curve(v."gate",i."drain") where x.val=0.8 Ion_n=0.000542202 EXTRACT> extract name="Ion_Ioff" 0.000542202/5.89487e-013 Ion_Ioff=9.19786e+008 EXTRACT> extract name="vt" x.val from curve ((v."gate"),log10(abs(i."drain"))) where y.val=-7 vt=0.41245 V EXTRACT> quit quit Device Parameters (after varying Lov)

2. SMADO (Single Metal Asymmetric Dual Oxide)

Structure Description:

SMADO retains a single gate metal but introduces oxide asymmetry — TiO_2 near the source (higher k) and HfO_2 near the drain (lower k).

Physics Explanation:

The asymmetry in dielectric constants alters the electric field distribution across the channel. Since the TiO_2 side (source end) has a higher k-value, it effectively strengthens the gate's control near the source junction. This allows stronger modulation of the source barrier, leading to improved carrier injection into the channel during ON-state.

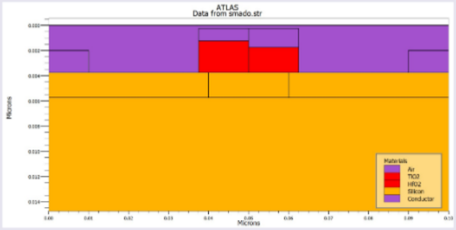
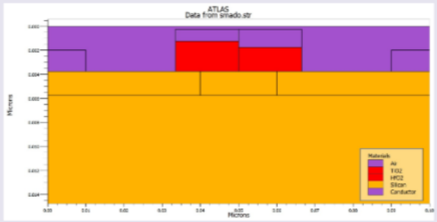
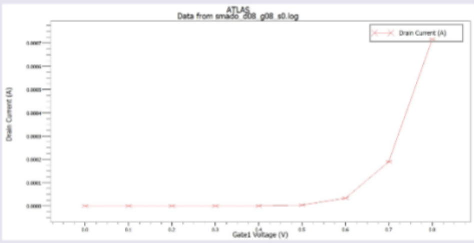
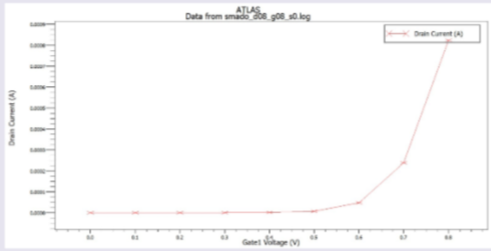
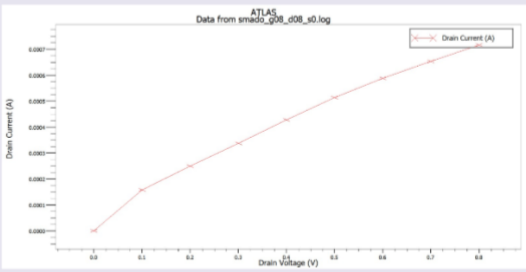
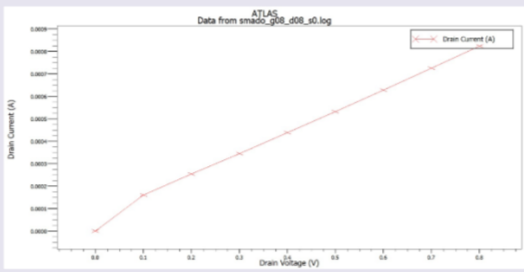
On the other hand, the HfO_2 near the drain (with lower k) weakens the drain's electric field penetration, reducing DIBL by shielding the channel from drain potential fluctuations. The result is a more uniform channel potential gradient, minimizing hot-carrier effects and improving threshold voltage stability.

Advantages:

- Enhanced source-end control improves carrier injection
- Reduced DIBL due to weaker drain coupling
- Improved Ion/Ioff ratio and subthreshold slope
- Better energy band alignment and lower effective barrier height

Disadvantages:

- Slight asymmetry in gate capacitance can cause non-uniform switching behavior
- Slightly more complex oxide deposition process

SMADO with small overlap	SMADO after increasing overlap
 SMADO Structure (before varying Lov)	 SMADO Structure (after varying Lov)
 Vgs - Id Graph (before varying Lov)	 Vgs - Id Graph (after varying Lov)
 Vds - Id Graph (before varying Lov)	 Vds - Id Graph (after varying Lov)
 ATLAS> EXTRACT> init inf="smado_ch20_Vd1.log" EXTRACT> extract name="dibl" (0.461349-0.30717)/(1-0.05) dibl=0.162294 EXTRACT> quit EXTRACT> init infile="smado_ch20_Vd005.log" EXTRACT> extract name="subvt" 1.0/slope(maxslope(curve(v."gate1",log10(abs(i."drain"))))) subvt=0.0832709 V/decade EXTRACT> quit EXTRACT> init infile="smado_d08_g08_s0.log" EXTRACT> extract name="Ioff_n" y.val from curve(v."gate1",i."drain") where x.val=0.0 Ioff_n=9.67879e-012 EXTRACT> extract name="Ion_n" y.val from curve(v."gate1",i."drain") where x.val=0.8 Ion_n=0.000823073 EXTRACT> extract name="Ion_Ioff" 0.000823073/9.67879e-012 Ion_Ioff=8.50388e+007 EXTRACT> extract name="vt" x.val from curve ((v."gate1"),log10(abs(i."drain"))) where y.val=-7 vt=0.327289 V EXTRACT> quit quit Device Parameters (before varying Lov)	 ATLAS> EXTRACT> init inf="smado_ch20_Vd1.log" EXTRACT> extract name="dibl" (0.468351-0.363782)/(1-0.05) dibl=0.110073 EXTRACT> quit EXTRACT> init infile="smado_ch20_Vd005.log" EXTRACT> extract name="subvt" 1.0/slope(maxslope(curve(v."gate1",log10(abs(i."drain"))))) subvt=0.0722207 V/decade EXTRACT> quit EXTRACT> init infile="smado_d08_g08_s0.log" EXTRACT> extract name="Ioff_n" y.val from curve(v."gate1",i."drain") where x.val=0.0 Ioff_n=7.07963e-013 EXTRACT> extract name="Ion_n" y.val from curve(v."gate1",i."drain") where x.val=0.8 Ion_n=0.000716196 EXTRACT> extract name="Ion_Ioff" 0.000716196/7.07963e-013 Ion_Ioff=1.01163e+009 EXTRACT> extract name="vt" x.val from curve ((v."gate1"),log10(abs(i."drain"))) where y.val=-7 vt=0.373742 V EXTRACT> quit quit Device Parameters (after varying Lov)

3. DMADO (Dual Metal Asymmetric Dual Oxide)

Structure Description:

DMADO combines both dual-dielectric and dual-metal engineering. It uses TiO_2 (near source) and HfO_2 (near drain) oxides, with Gate1 (5.1 eV) and Gate2 (4.95 eV) metals, forming a graded work-function gate stack.

Physics Explanation:

The DMADO structure introduces a lateral work-function gradient across the gate, which directly modulates the electrostatic potential along the channel. The slightly lower work function at the drain end (4.95 eV) reduces the potential barrier there, maintaining a smooth potential drop from source to drain.

This configuration enhances carrier transport by facilitating easier injection at the source and smoother collection at the drain, thereby improving current drive while suppressing DIBL. The combined effect of high-k TiO_2 near the source (strong gate control) and low-k HfO_2 near the drain (reduced drain coupling) produces the best possible trade-off between drive current and leakage.

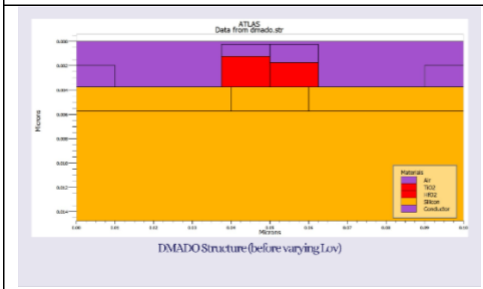
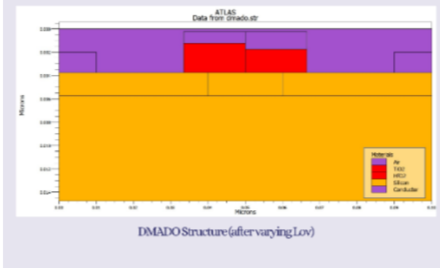
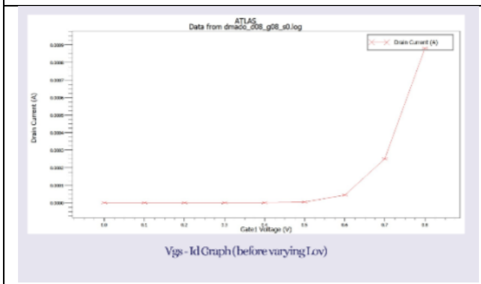
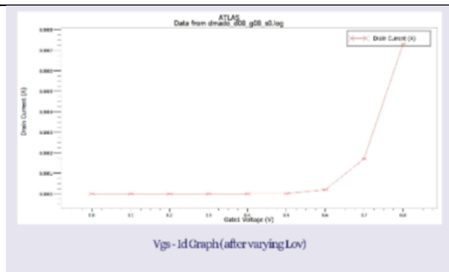
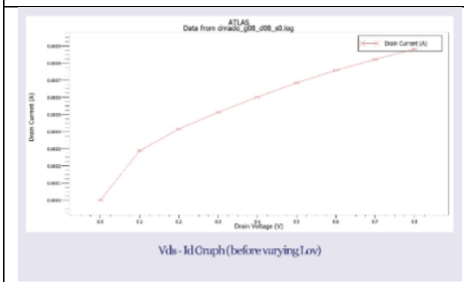
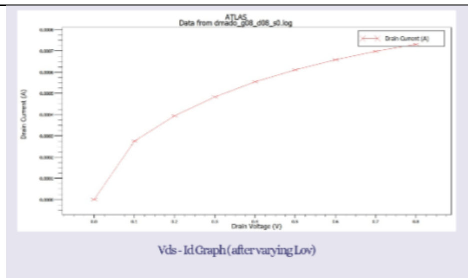
The asymmetric gate work function also creates an internal electric field gradient that helps “pull” electrons toward the drain in ON-state, effectively increasing mobility and lowering subthreshold swing.

Advantages:

- Strongest gate control and channel modulation
- Lowest DIBL and subthreshold slope among all designs
- High Ion/Ioff ratio and improved switching speed
- Excellent electrostatic integrity and short-channel suppression

Disadvantages:

- Slightly higher fabrication complexity due to dual-metal integration
- Careful alignment needed between two gate metals during deposition

DMADO with small overlap	DMADO after increasing overlap
 DMADO Structure (before varying Lov)	 DMADO Structure (after varying Lov)
 Vgs - Id Graph (before varying Lov)	 Vgs - Id Graph (after varying Lov)
 Vds - Id Graph (before varying Lov)	 Vds - Id Graph (after varying Lov)
 Device Parameters (before varying Lov)	 Device Parameters (after varying Lov)

Comparative Performance Summary

Parameter	SMSDO	SMADO	DMADO
Ion/Ioff Ratio	Low	Higher	Highest
DIBL	High	Moderate	Lowest
Subthreshold Slope	Steep	Improved	Best
Threshold Tunability	Minimal	Good	Excellent
Channel Control	Balanced	Asymmetric Control	Optimal
Fabrication Complexity	Simple	Moderate	High

Discussion:

The results reveal that electrostatic control improves progressively from SMSDO to SMADO to DMADO. The key reason lies in how the gate field interacts with the channel.

- In SMSDO, symmetric gate fields allow drain influence to leak into the channel.
- In SMADO, field asymmetry localizes gate control near the source, shielding the drain.
- In DMADO, dual work-function gating introduces a deliberate potential slope along the channel, optimizing transport while suppressing leakage.

Gate overlap further enhances control but adds minimal parasitic capacitance — an acceptable trade-off for higher Ion and reduced SS.

Conclusion

The TCAD simulations conclusively demonstrate that the DMADO structure offers the most optimized trade-off between drive strength and leakage control among the analyzed configurations. The integration of dual dielectrics (TiO_2/HfO_2) with dual-metal gates effectively tailors the electrostatic profile, minimizing short-channel degradation and improving overall performance.

The project successfully verifies that work-function engineering combined with dielectric asymmetry is an effective strategy for next-generation MOSFET scaling.

Future Work

1. Include temperature and process variation analysis for thermal reliability.
2. Extract analog and RF parameters (gm, gain, fT).
3. Extend the study to 3D structures for fringe-field impact.
4. Compare with experimental data once fabrication is complete.

References

1. A. S. Al-Jawadi, M. T. Yaseen, and Q. T. Algwari, "TCAD-Based Analysis of a Novel Dual Dielectric Gate MOSFET for High-Speed Applications," *Journal of Computational Electronics*, Springer, 2025.