

Term 7- Sept 2024

Nanoelectronics and Technology
(01.119/99.503)

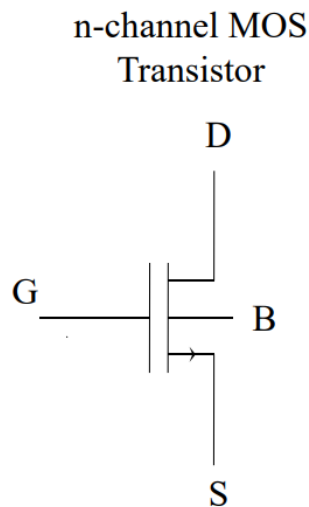
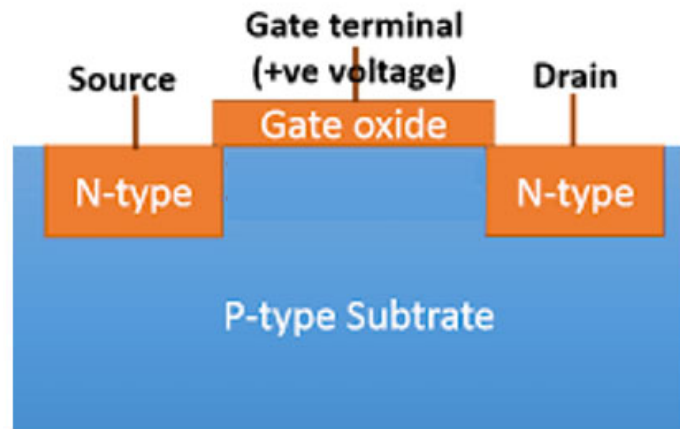
Week 2 Day 2 (26-Sept 2024)

Outline

- CMOS scaling
- Impact of Scaling on different CMOS parameters
- Scaling Challenges

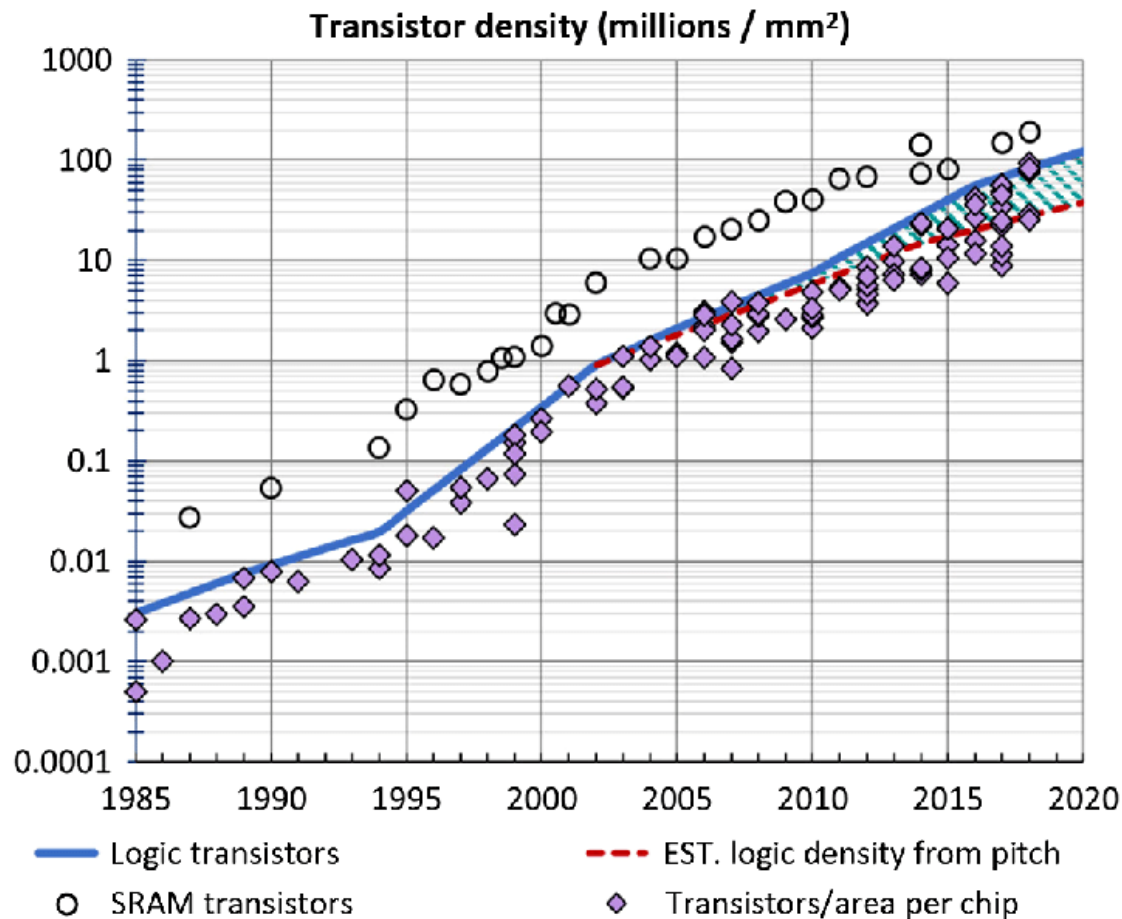
Review of MOSFETs

$$\beta = \mu C_{ox} \frac{W}{L}$$



$$I_{ds} = \begin{cases} 0 & V_{gs} < V_t & \text{cutoff} \\ \beta \left(V_{gs} - V_t - \frac{V_{ds}}{2} \right) V_{ds} & V_{ds} < V_{dsat} & \text{linear} \\ \frac{\beta}{2} (V_{gs} - V_t)^2 & V_{ds} > V_{dsat} & \text{saturation} \end{cases}$$

CMOS scaling: Moore's Law

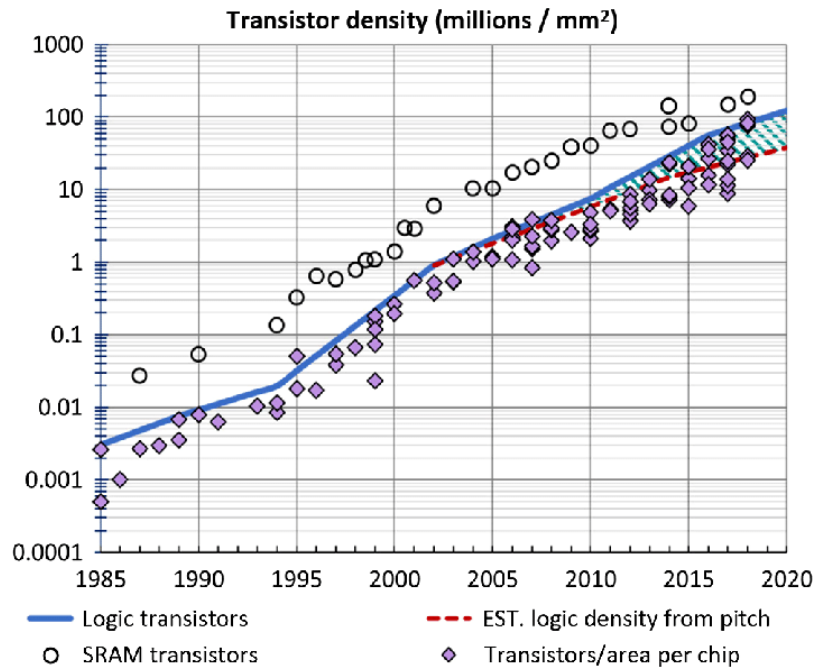


Moore's law says that the number of transistors doubles approximately every two years.

- CMOS scaling
 - Speed
 - High density
 - Less power
 - Reduced cost/transistor

Ref: M. L. Rieger, "Retrospective on VLSI value scaling and lithography" Journal of Micro/Nanolithography-2019

CMOS scaling: Dennard's scaling

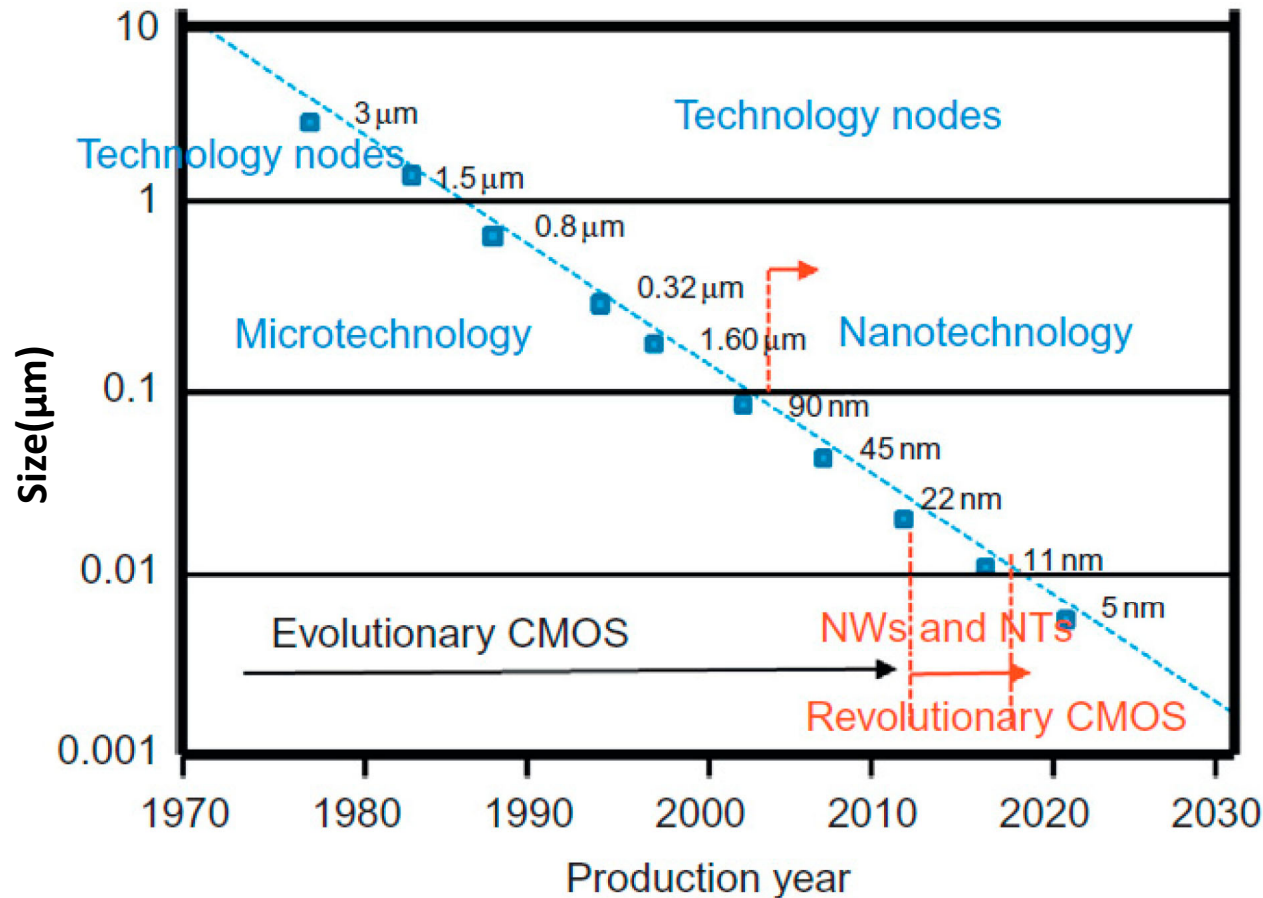


Dennard scaling, also known as MOSFET scaling, is a scaling law which states roughly that, as transistors get smaller, their power density stays constant, so that the power use stays in proportion with area; both voltage and current scale (downward) with length.

With feature sizes below 65nm, these rules could no longer be sustained, because of the exponential growth of the leakage current.”

Ref: M. L. Rieger, “ Retrospective on VLSI value scaling and lithography” Journal of Micro/Nanolithography-2019

CMOS scaling: Moore's Law



Ref: H. H. Radamson, et al., "Miniaturization of CMOS" Micromachines 10(5) 293-2019

CMOS scaling: ITRS Roadmap

ITRS Projections			
Year of Production	2007	2010	2013
Technology Node (nm)	65	45	32
Transistor Gate Length in Microprocessors circuits (nm)	25	18	13
Wafer diameter (inch)	12	12	18
Number of masks required for fabrication of Microprocessor	33	35	37
Number of Transistors in Microprocessor (billion)	1.1	2.2	4.4
Number of interconnect wiring levels in the Microprocessor	15	16	17

<http://www.itrs2.net/>

CMOS scaling: ITRS Roadmap

ITRS Projections

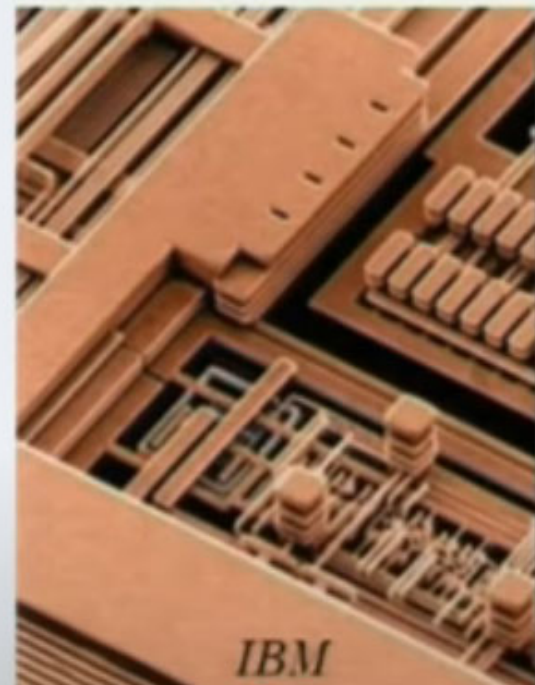
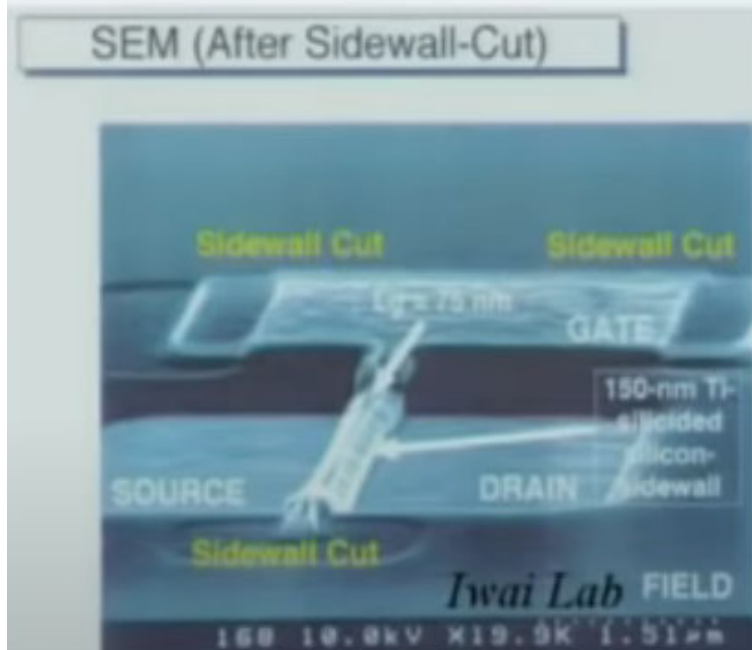
Year of Production	2007	2010	2013	2016	2019	2022
Technology Node (nm)	65	45	32	22	16	11
Transistor Gate Length in Microprocessors circuits (nm)	25	18	13	9	6.3	4.5
Wafer diameter (inch)	12	12	18	18	18	18

	2021	2022	2025	2028	2031	2034
G51M30	G51M30	G48M24	G45M20	G42M16	G40M16/T2	G38M16/T4
Logic industry "Node Range" Labeling (nm)	"5"	"3"	"2.1"	"1.5"	"1.0 eq"	"0.7 eq"
IDM-Foundry node labeling	i7-f5	i5-f3	i3-f2.1	i2.1-f1.5	i1.5e-f1.0e	i1.0e-f0.7e
Logic device structure options	FinFET	finFET LGAA	LGAA	LGAA	LGAA-3D	LGAA-3D
Platform device for logic	finFET	finFET	LGAA	LGAA	LGAA-3D	LGAA-3D
Frequency scaling - node-to-node	-	0.02	0.16	0.09	-0.08	-0.01
CPU frequency at constant power density (GHz)	3.13	2.83	3.53	2.50	1.48	0.86
Power at iso frequency - node-to-node	-	-0.16	-0.27	-0.05	-0.06	-0.08
Power density - relative	1.00	1.12	1.04	1.59	2.51	4.27
LOGIC TECHNOLOGY ANCHORS						
Patterning technology inflection for Mx interconnect	193i, EUV DP	193i, EUV DP	193i, EUV DP	193i, High-NA EUV	193i, High-NA EUV	193i, High-NA EUV
Beyond-CMOS as complimentary to platform CMOS	-	-	-	2D Device, FeFET	2D Device, FeFET	2D Device, FeFET
Channel material technology inflection	SiGe25%	SiGe50%	SiGe50%	Ge, 2D Mat	Ge, 2D Mat	Ge, 2D Mat
Process technology inflection	Conformal Doping, Contact	Channel, RMG	Lateral/Atomic Etch	Non-Cu Mx	3DVLSI	3DVLSI
Stacking generation inflection	2D	3D-stacking: W2W, D2W Mem-on-Logic	3D-stacking: W2W, D2W Mem-on-Logic	3D-stacking, Fine-pitch stacking, P-over-N, Mem-on-Logic	3D-stacking, 3DVLSI: Mem-on-Logic with Interconnect	3D-stacking, 3DVLSI: Logic-on-Logic

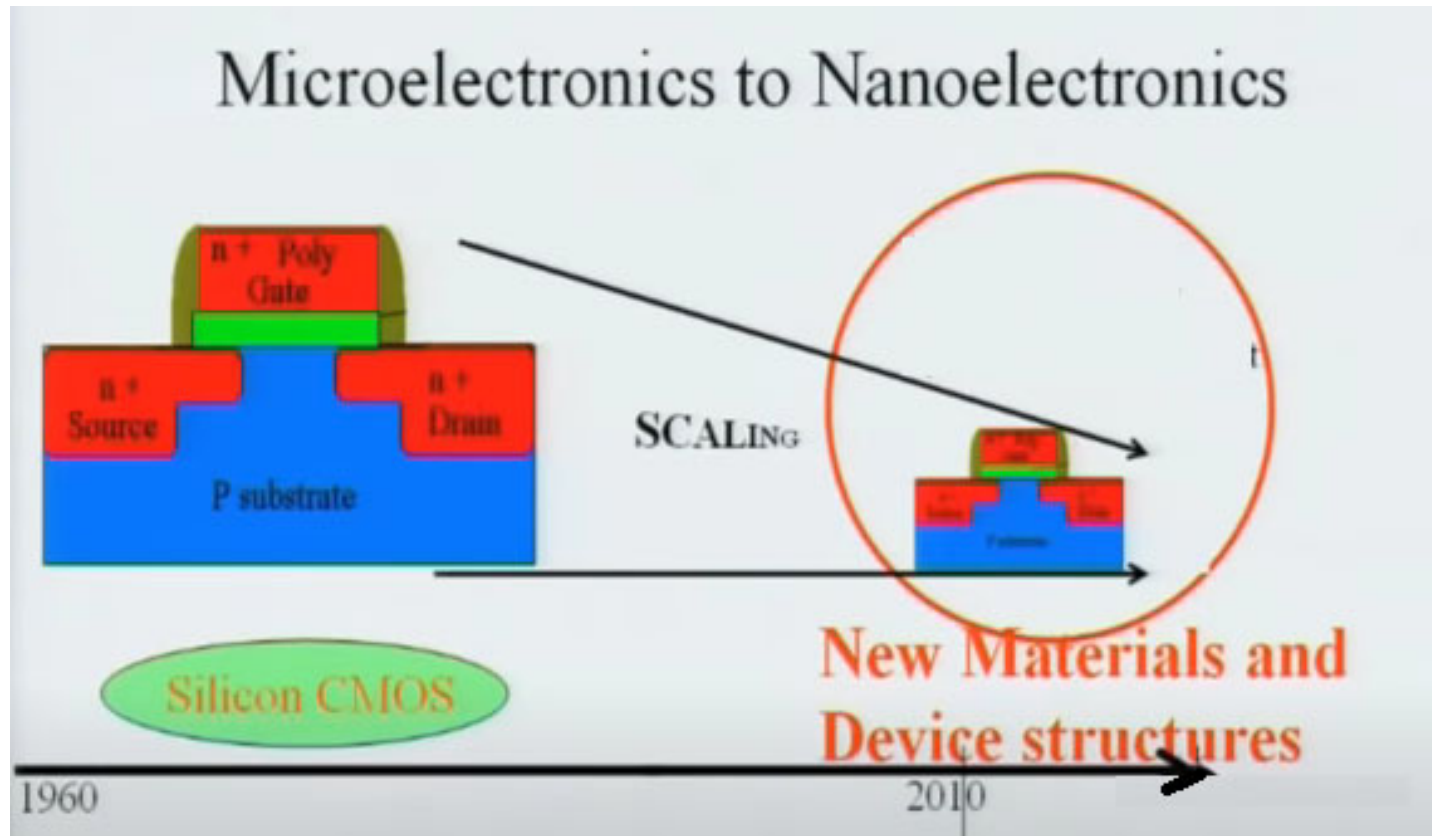
<http://www.itrs2.net/>

CMOS chip

A large ensemble of **transistors** connected “*appropriately*” through multilevel **metal interconnection** lines...



CMOS scaling



Ref: N. Bhat, CeNSE, IISc Bangalore- Nanoelectronic Device Technology

CMOS scaling:

Micro-MOSFET

Periodic Table of the Elements

This periodic table uses color-coding to categorize elements. The legend indicates the following categories:

- State of matter (color of name):** GAS (blue), LIQUID (green), SOLID (orange), UNKNOWN (grey).
- Subcategory in the metal-metalloid-nonmetal trend (color of background):**
 - Alkali metals (red)
 - Alkaline earth metals (orange)
 - Transition metals (yellow)
 - Lanthanides (light blue)
 - Metalloids (green)
 - Nonmetals (light green)
 - Reactive nonmetals (dark green)
 - Unknown chemical properties (grey)

The table includes element symbols, atomic numbers, names, and atomic weights. It also features a detailed legend for element classification and a separate section for the lanthanide and actinide series at the bottom.

Nano-MOSFET

Periodic Table of the Elements







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CMOS scaling

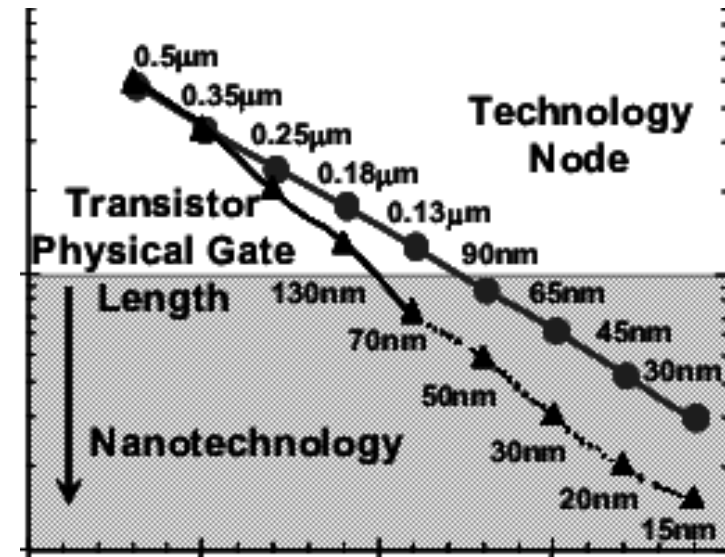
Technology scaling

Parameter	Constant Field	
Supply voltage (V_{dd})	$1/\alpha$	Scaling Variables  
Length (L)	$1/\alpha$	
Width (W)	$1/\alpha$	
Gate-oxide thickness (t_{ox})	$1/\alpha$	
Junction depth (X_j)	$1/\alpha$	
Substrate doping (N_A)	α	
Electric field across gate oxide (E)	1	Device Repercussion  
Depletion layer thickness	$1/\alpha$	
Gate area (Die area)	$1/\alpha^2$	
Gate capacitance (load) (C)	$1/\alpha$	
Drain-current (I_{dss})	$1/\alpha$	
Transconductance (g_m)	1	
Gate delay	$1/\alpha$	Circuit Repercussion  
Current density	α	
DC & Dynamic power dissipation	$1/\alpha^2$	
Power density	1	
Power-Delay product	$1/\alpha^3$	

CMOS scaling

Typical Scaling Scenario

- 1974 : 5 μ m Technology, Vdd = 10V
- 1984 : 1 μ m Technology, Vdd = 5V
- 1994 : 0.35 μ m Technology, Vdd = 3.5V
- 2004 : 90nm Technology, Vdd = 1V



CMOS scaling and FINFET technology

SiO₂/SiON dielectric based

High-k/Metal gate based

FINFET based

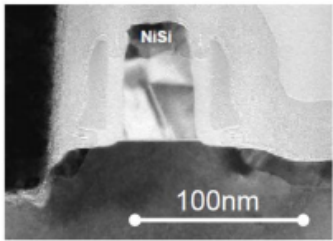
90 nm node

65 nm node

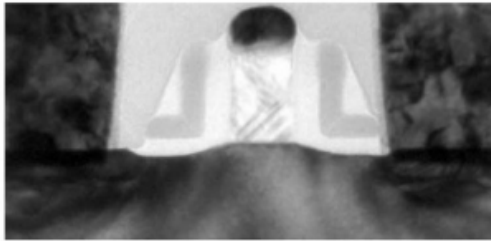
45 nm node

32 nm node

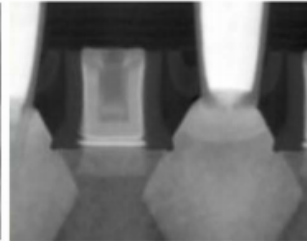
22nm/14nm/10nm/7nm/5nm



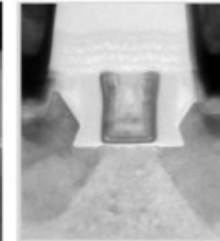
T. Ghani *et al.*,
IEDM 2003



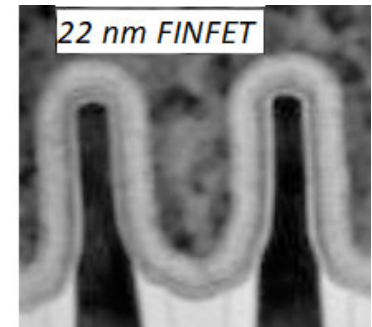
(after S. Tyagi *et al.*, *IEDM 2005*)



K. Mistry *et al.*,
IEDM 2007

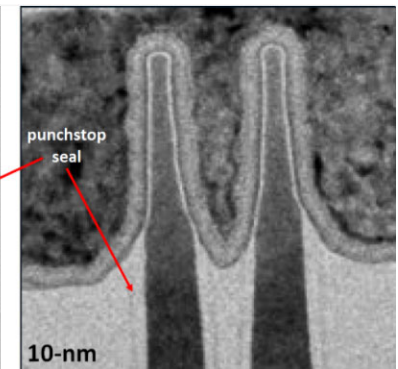
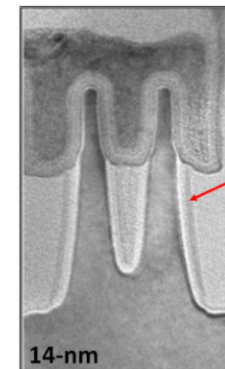


P. Packan *et al.*,
IEDM 2009



Gate length has not scaled proportionately with device pitch (0.7x per generation) in recent generations. – Transistor performance has been boosted by other means.

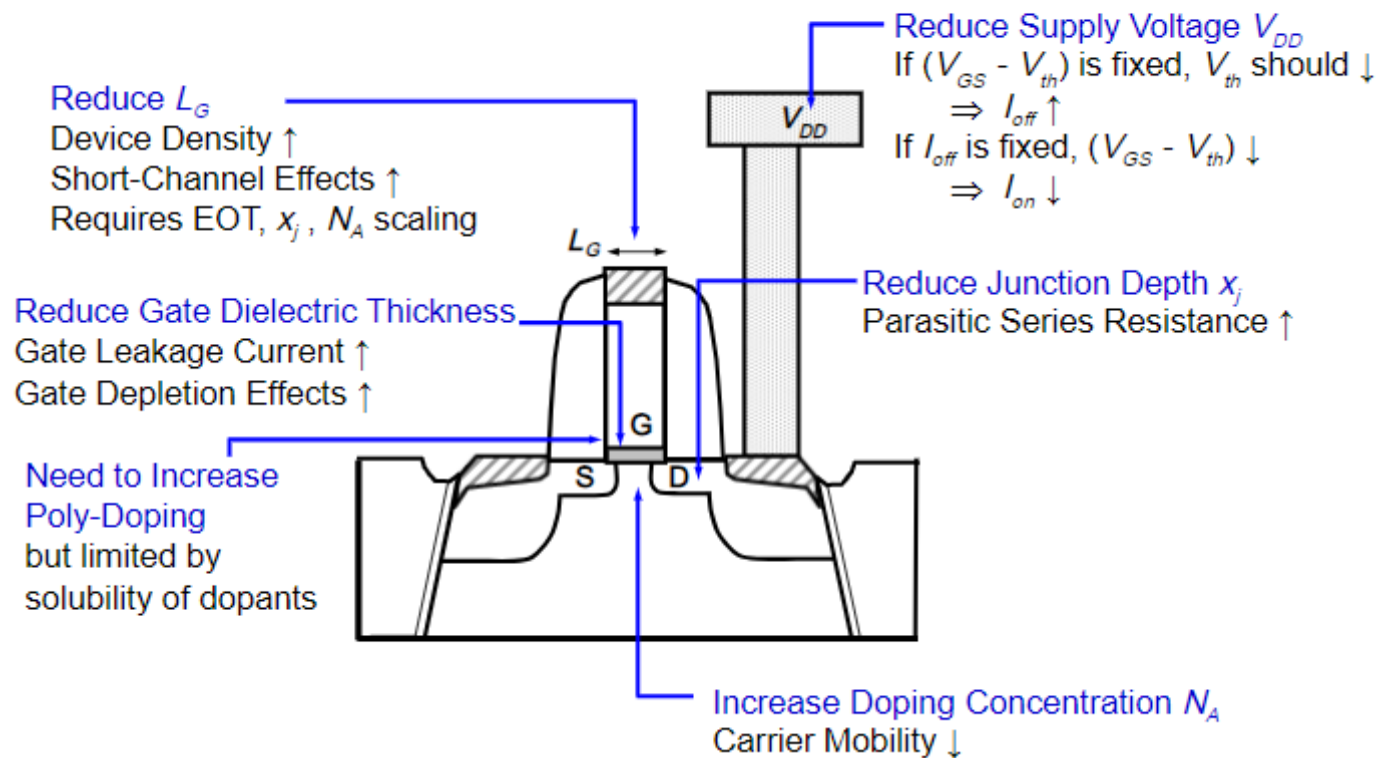
SOURCE:
Intel



CMOS scaling:

- Gate length scaling
- Supply voltage scaling
- Gate oxide scaling
- Scaling of Doping
- Shallow S/D

Overview of Scaling Limitations



CMOS scaling Issues:

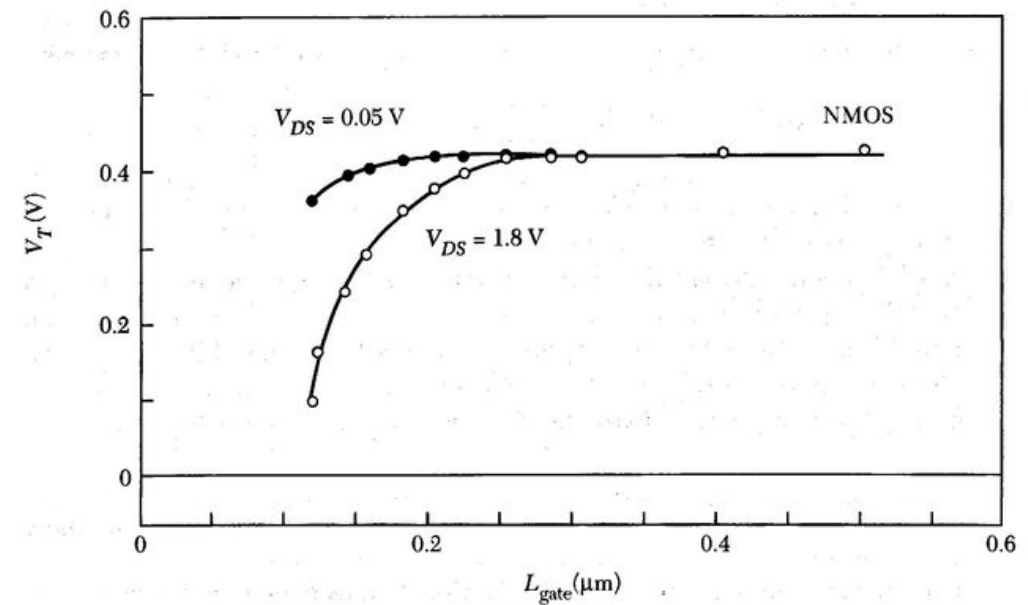
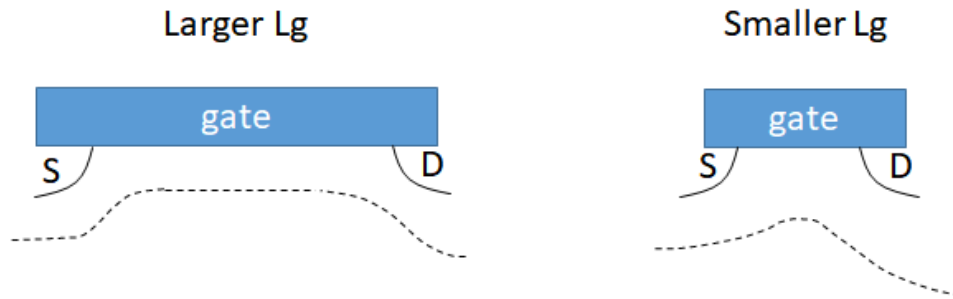
- Short channel effects
- Threshold voltage variation
- DIBL (Drain Induced Barrier Lowering)
- Gate leakage current
- GIDL (Gate Induced Drain Leakage)
- Shallow S/D – Parasitic resistance
- Mobility issues/Velocity saturation/Hot carrier effect

CMOS scaling:

- Gate length scaling

$$I_{ds} = \begin{cases} 0 & V_{gs} < V_t & \text{cutoff} \\ \beta \left(V_{gs} - V_t - \frac{V_{ds}}{2} \right) V_{ds} & V_{ds} < V_{dsat} & \text{linear} \\ \frac{\beta}{2} (V_{gs} - V_t)^2 & V_{ds} > V_{dsat} & \text{saturation} \end{cases} \quad \beta = \mu C_{ox} \frac{W}{L}$$

Threshold Voltage: (V_{th}) Variation



CMOS scaling:

- Gate length scaling

Channel Length Modulation

- It occurs when transistor is in *Saturation region*.

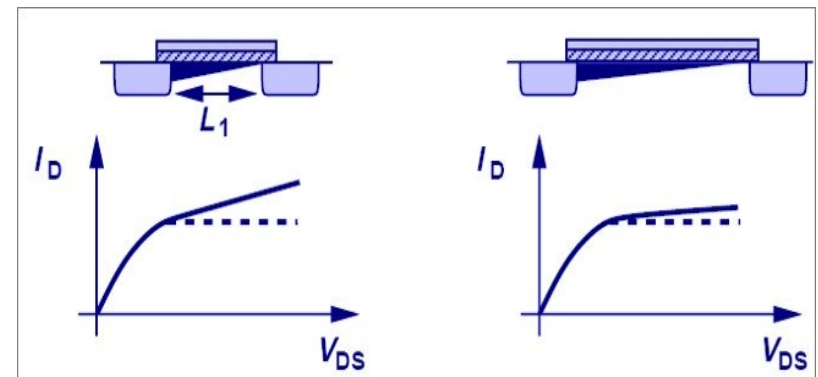
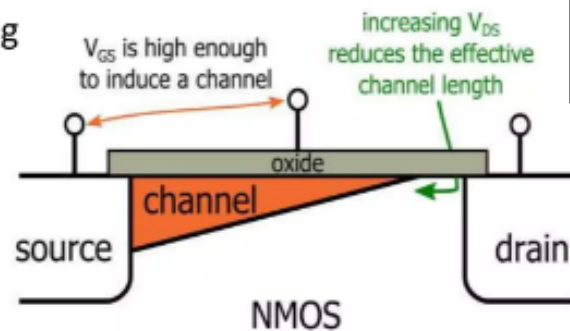
i.e. **Saturation region**,

$$V_{GS} > V_{th} \text{ and } V_{DS} > V_{GS} - V_{th}$$

I_D increases slightly with increasing V_{DS} .

- The pinch-off point moves toward the source as V_{DS} increases.

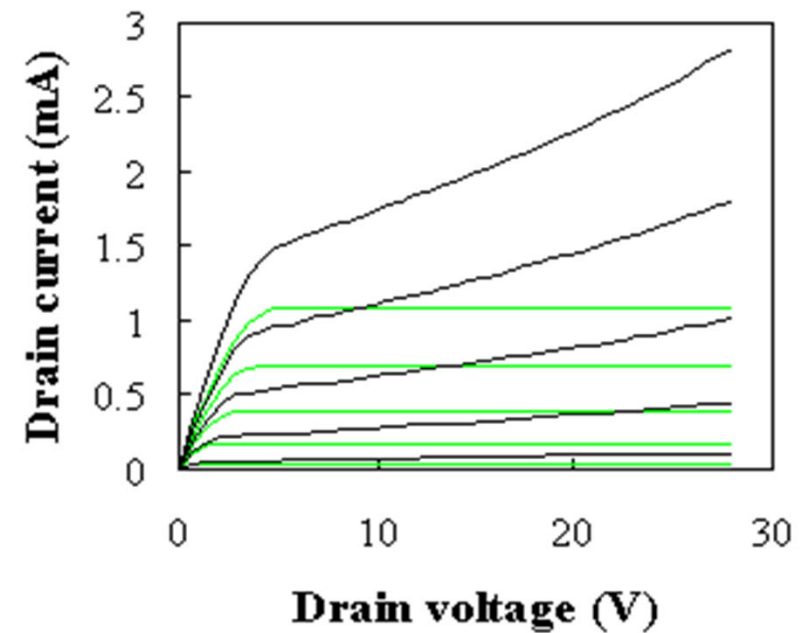
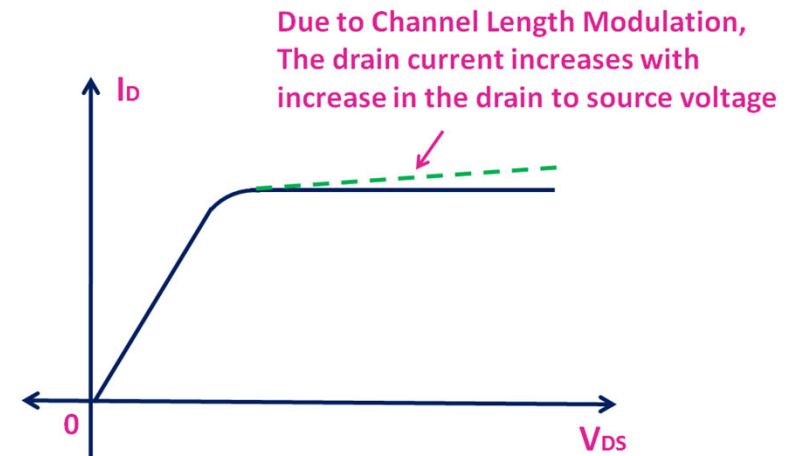
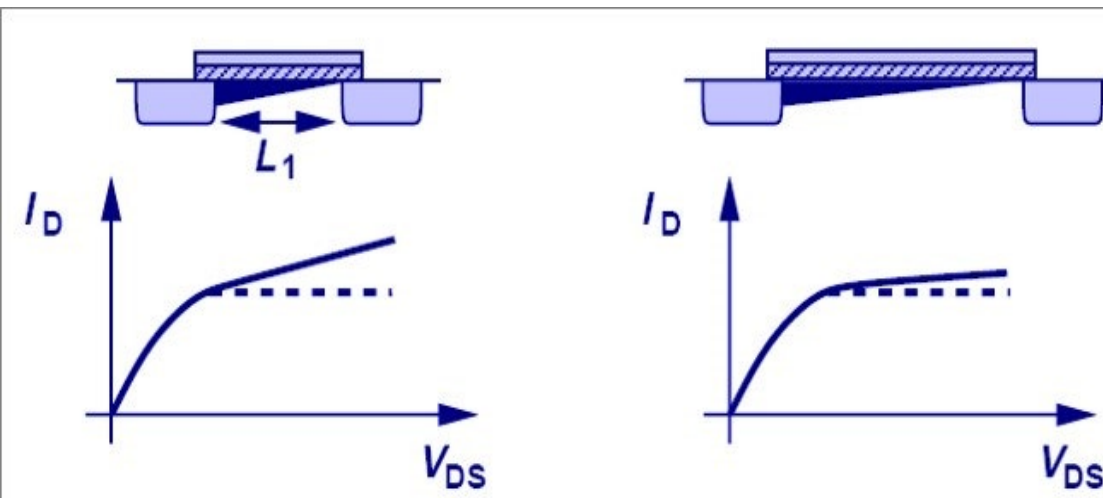
- The length of the channel becomes shorter with increasing V_{DS} .



CMOS scaling:

- Gate length scaling

Channel length Modulation



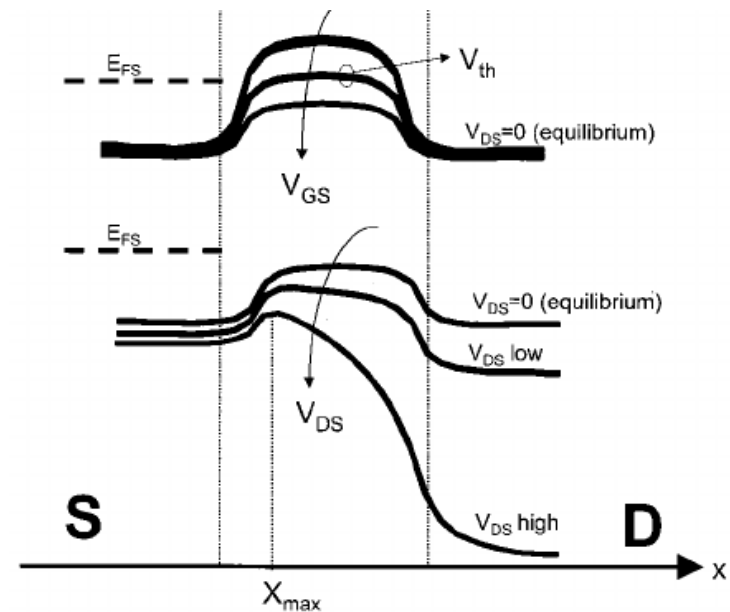
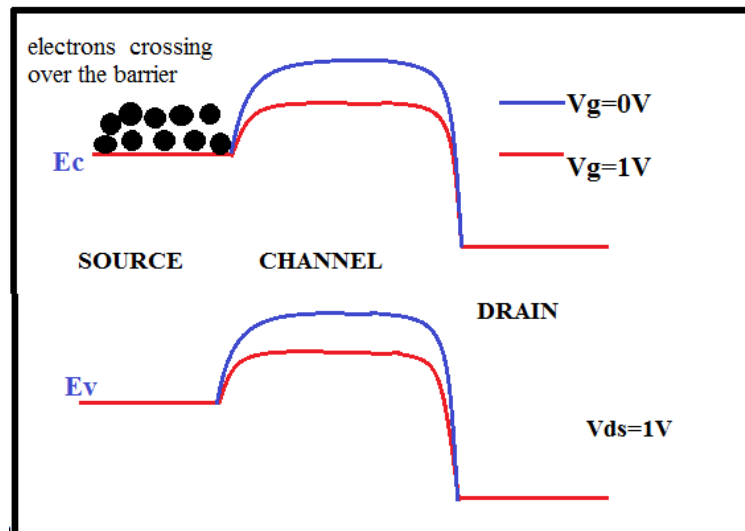
CMOS scaling:

- Gate length scaling

Drain Induced Barrier Lowering (DIBL)

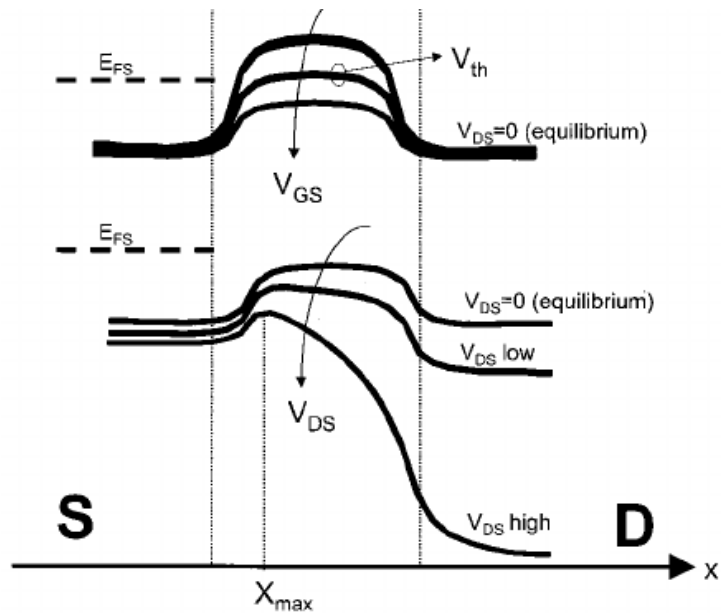
As the source and drain get closer, they become electrostatically coupled, so that the drain bias can affect the potential barrier to carrier diffusion at the source junction

→ V_T decreases (*i.e.* OFF state leakage current increases)

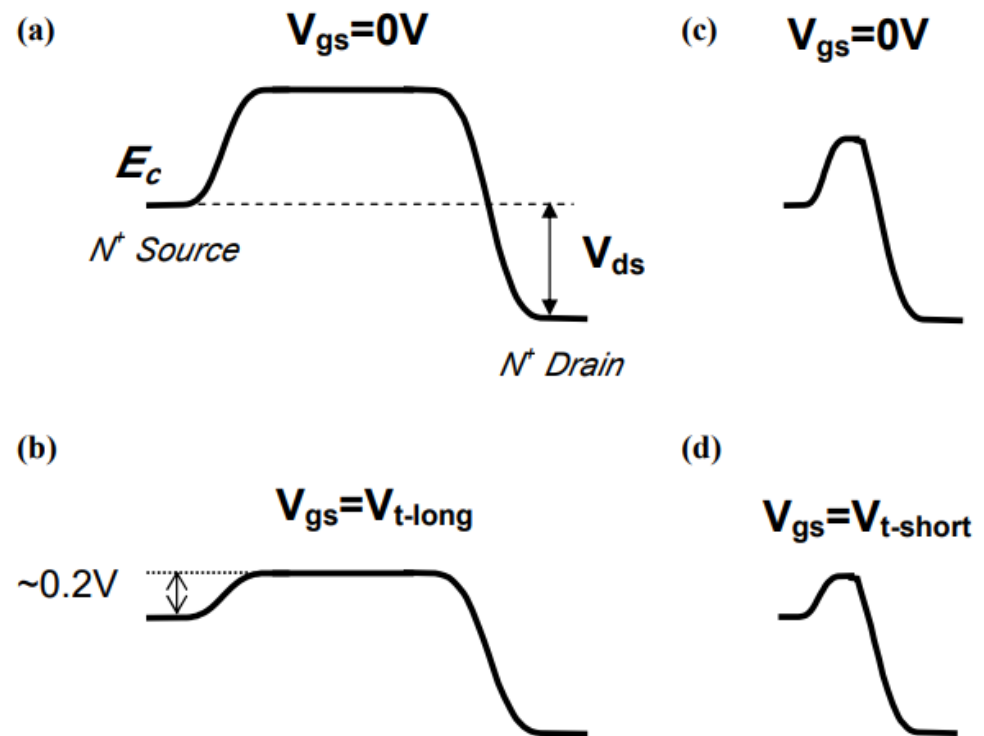


CMOS scaling:

- Gate length scaling



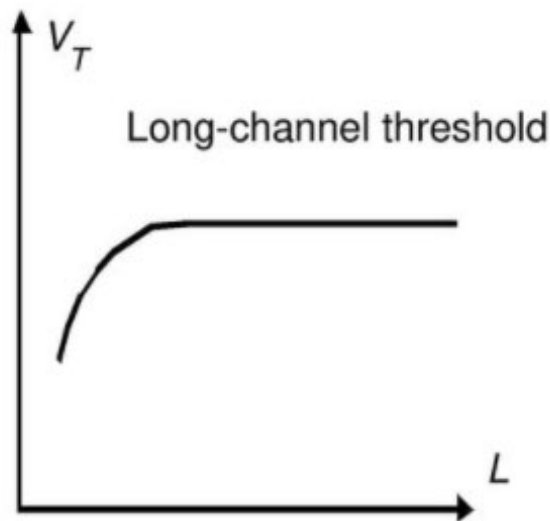
Drain Induced Barrier Lowering (DIBL)



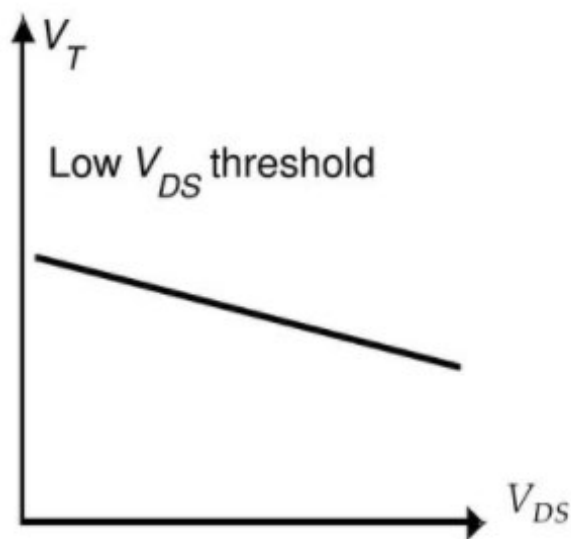
(a)-(d): Energy-band diagram from source to drain when $V_{gs}=0V$ and $V_{gs}=V_t$

Gate length scaling

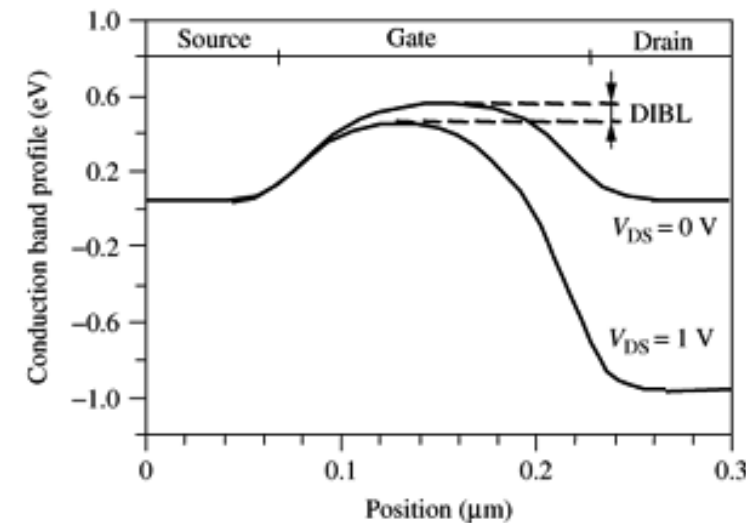
Threshold Voltage: (V_{th}) and DIBL



Threshold as a function of the length (for low V_{DS})



Drain-induced barrier lowering (for low L) ... (DIBL)

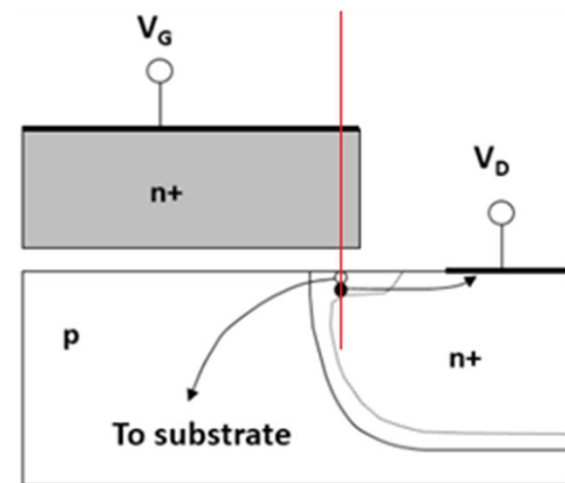
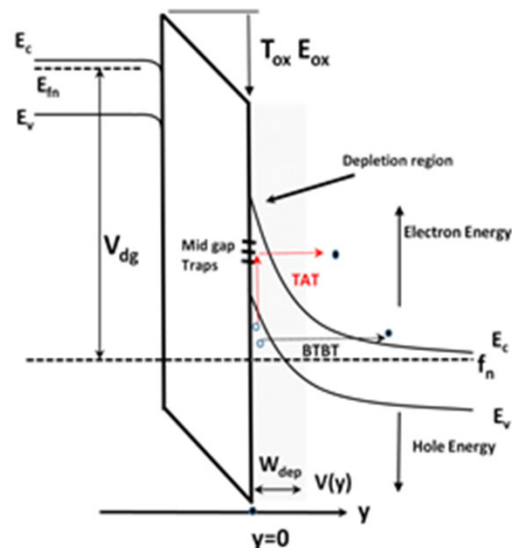


J. Ho, "Introduction and Short Channel Effects", 2014, Semiconductors

Gate length scaling

Gate Induced Drain Leakage (GIDL)

- GIDL occurs when the V_{DG} potential and band bending are high enough to generate electron/hole pairs by valence to conduction band tunneling
- GIDL arises in MOSFETs due primarily to band to band tunneling that occurs between the drain and the gate
- GIDL prevents the drain from reaching a current of zero when it is in its “off” state



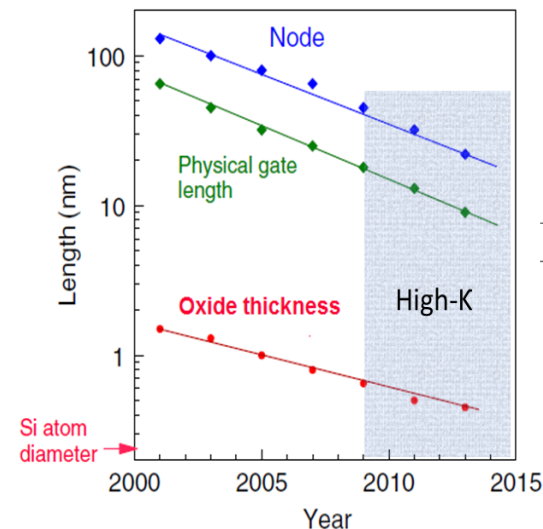
CMOS scaling: Gate dielectric Scaling

- SiO₂/SiON based dielectric till 65 nm CMOS Technology Node
- Best properties with silicon substrate
- Conventional SiON < 12Å loses its intrinsic insulative property.
- SiON < 12Å -Increased leakage current and poses reliability issues
- To reduce leakage, **high-κ dielectrics** with equivalent C_{ox} introduced.

SiO₂/SiON Dielectric based

1st Production	1997	1999	2001	2003	2005	2007	2009
Process Generation	0.25μm	0.18μm	0.13μm	90 nm	65 nm	45 nm	32 nm
Gate dielectric	SiO ₂	SiO ₂	SiO ₂	SiO ₂	SiO ₂	High-k	High-k
Gate electrode	Poly-silicon	Poly-silicon	Poly-silicon	Poly-silicon	Poly-silicon	Metal	Metal

Source: Intel



$$EOT = \left(\frac{\kappa_{ox}}{\kappa_{hi-k}} \right) t_{hi-k}$$

Robertson, Rep. Prog. Phys. 69 (2006) 327-396

CMOS scaling: HK-MG technology

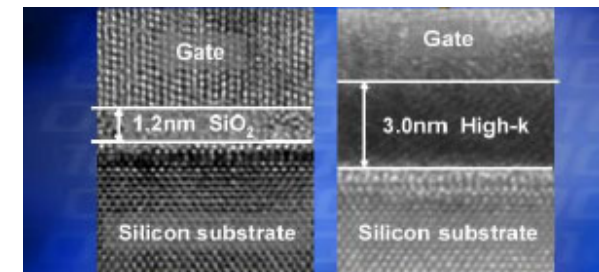
- HK-MG technology: 45 nm and 32 CMOS Technology Node
- k value - high enough and scalable
- Thermal stability
- Compatible with Si CMOS tech.
- Good interface with Si
- Lower defects in the bulk
- Not used after 32nm CMOS technology

HK-MG technology



1st Production	1997	1999	2001	2003	2005	2007	2009
Process Generation	0.25 μ m	0.18 μ m	0.13 μ m	90 nm	65 nm	45 nm	32 nm
Gate dielectric	SiO ₂	SiO ₂	SiO ₂	SiO ₂	SiO ₂	High-k	High-k
Gate electrode	Poly-silicon	Poly-silicon	Poly-silicon	Poly-silicon	Poly-silicon	Metal	Metal

Source: Intel



Benefits compared to current process technologies

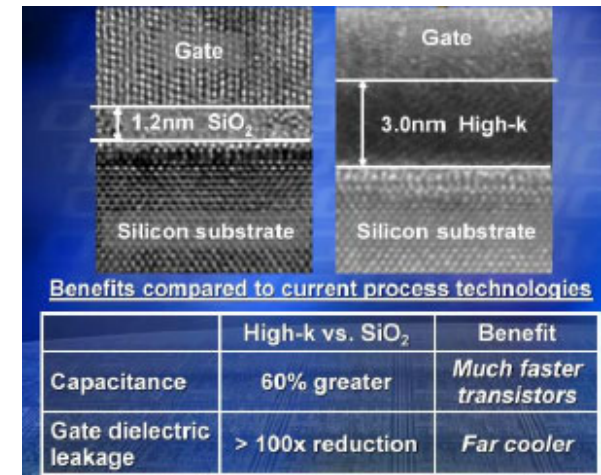
Source: Intel

	High-k vs. SiO ₂	Benefit
Capacitance	60% greater	Much faster transistors
Gate dielectric leakage	> 100x reduction	Far cooler

Same C_{ox} , $\uparrow t_{HK}$

CMOS scaling: HK-MG technology

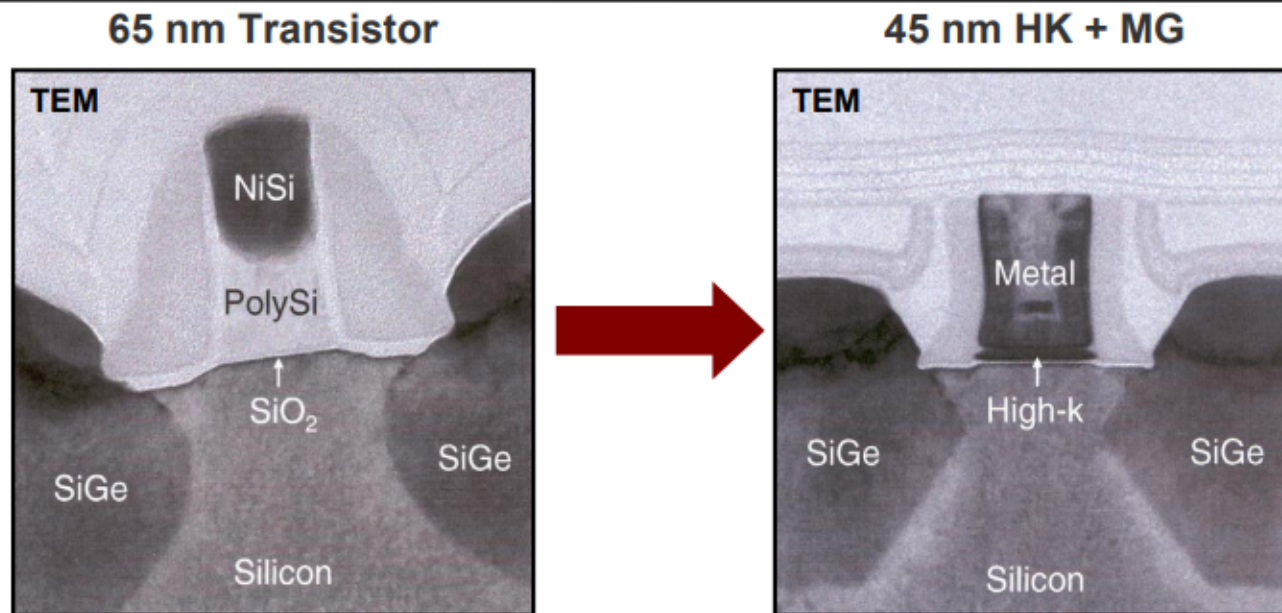
- Challenges:
 - High density of defects
 - Interaction with the polysilicon gate
 - Interaction with the substrate
 - Polycrystallization structure
 - Increased trap-assisted tunneling
 - Increased leakage current
 - Reliability and failure of high-k dielectric



Source: Intel

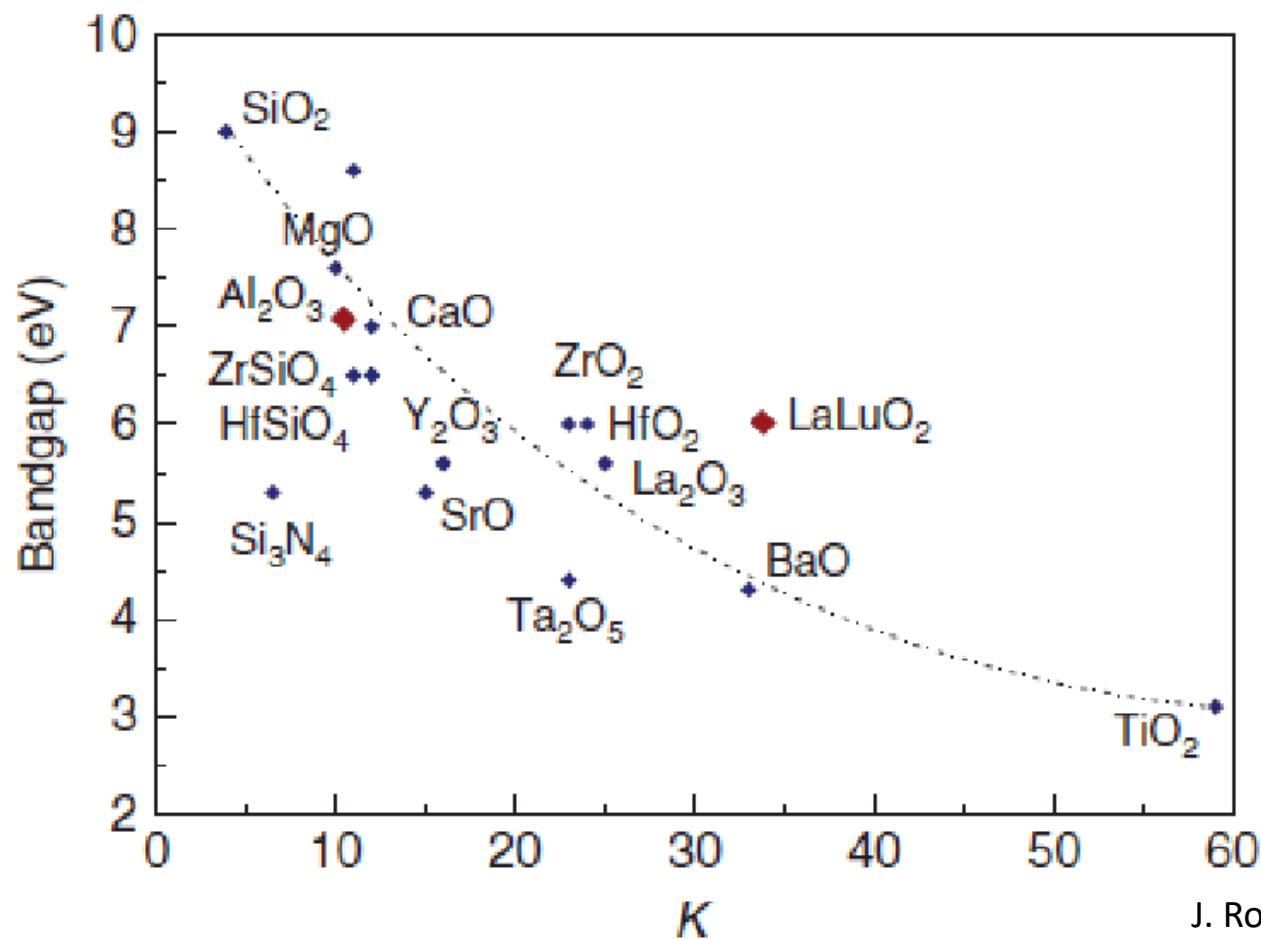
CMOS scaling: HK-MG technology

45nm High-k + Metal Gate Transistors



Source: Intel

CMOS scaling: HK-MG technology



$$\text{EOT} = \left(\frac{K_{\text{ox}}}{K_{\text{hi-k}}} \right) t_{\text{hi-k}}$$

J. Robertson, J. Vac. Sci. Technol. B 18, 1785 (2000)

CMOS scaling:

Micro-MOSFET

Periodic Table of the Elements

1A																		18											
1	H																	2	He										
Atomic Number →		1																		2									
Symbol ←		H																		He									
Name →		Hydrogen																		Helium									
Electrons per shell →		1																		2									
Atomic Weight		1																		4.0026									
State of matter (color of round)																		13		14		15		16		17		18	
GAS SOLID LIQUID PLASMA																		B		C		N		O		F		Ne	
Subcategory in the metal-metalloid nonmetal (color of background)																		Boron		Carbon		Nitrogen		Oxygen		Fluorine		Neon	
Alkali metals																		Metalloids		Nonmetals		Noble gases							
Alkaline earth metals																		Lanthanides		Actinides		Reactive nonmetals							
Transition metals																		Post-transition metals		Metalloids		Noble gases							
																		13		14		15		16		17		18	
																		Al		Si		P		S		Cl		Ar	
																		Aluminum		Silicon		Phosphorus		Sulfur		Chlorine		Argon	
																		27		28		29		30		31		32	
																		K		Ca		Sc		Ti		V		Cr	
																		Potassium		Calcium		Scandium		Titanium		Vanadium		Chromium	
																		39		40		41		42		43		44	
																		Rb		Sr		Y		Zr		Nb		Mo	
																		Rubidium		Strontium		Yttrium		Zirconium		Niobium		Molybdenum	
																		55		56		57		58		59		60	
																		Cs		Ba		La		Ce		Pr		Nd	
																		Cesium		Barium		Lanthanum		Cerium		Praseodymium		Neodymium	
																		87		88		89		90		91		92	
																		Fr		Ra		Ac		Th		Pa		U	
																		Francium		Radium		Actinium		Thorium		Protactinium		Uranium	
																		101		102		103		104		105		106	
																		Mg		Al		Si		P		S		Cl	
																		Magnesium		Aluminum		Silicon		Phosphorus		Sulfur		Chlorine	
																		12		13		14		15		16		17	
																		Zn		Ga		Ge		As		Se		Br	
																		Zinc		Gallium		Germanium		Arsenic		Selenium		Bromine	
																		65		66		67		68		69		70	
																		Ni		Cu		Zn		Ga		Ge		As	
																		Nickel		Copper		Zinc		Gallium		Germanium		Arsenic	
																		28		29		30		31		32		33	
																		Pd		Ag		Cd		In		Sn		Sb	
																		Palladium		Silver		Cadmium		Indium		Tin		Antimony	
																		106		107		108		109		110		111	
																		Ds		Rg		Cn		Nh		Fl		Mc	
																		Darmstadtium		Roentgenium		Copernicium		Nihonium		Flerovium		Moscovium	
																		110		111		112		113		114		115	
																		Hg		Tl		Pb		Bi		Po		At	
																		Mercury		Thallium		Lead		Bismuth		Polonium		Astatine	
																		80		81		82		83		84		85	
																		Au		Hg		Tl		Pb		Bi		Po	
																		Gold		Mercury		Thallium		Lead		Bismuth		Polonium	
																		79		80		81		82		83		84	
																		Pt		Au		Hg		Tl		Pb		Bi	
																		Platinum		Gold		Mercury		Thallium		Lead		Bismuth	
																		78		79		80		81		82		83	
																		Ir		Pt		Au		Hg		Tl		Pb	
																		Iridium		Platinum		Gold		Mercury		Thallium		Lead	
																		77		78		79		80		81		82	
																		Os		Ir		Pt		Au		Hg		Tl	
																		Osmium		Iridium		Platinum		Gold		Mercury		Thallium	
																		76		77		78		79		80		81	
																		W		Re		Os		Ir		Pt		Au	
																		Tungsten		Rhenium		Osmium		Iridium		Platinum		Gold	
																		74		75		76		77		78		79	
																		Ta		W		Re		Os		Ir		Pt	
																		Tantalum		Tungsten		Rhenium		Osmium		Iridium		Platinum	
																		72		73		74		75		76		77	
																		Hf		Ta		W		Re		Os		Ir	
																		Hafnium		Tantalum		Tungsten		Rhenium		Osmium		Iridium	
																		70		71		72		73		74		75	
																		Yb		Lu		Hf		Ta		W		Re	
																		Ytterbium		Lutetium		Hafnium		Tantalum		Tungsten		Rhenium	
																		70		71		72		73		74		75	
																		Er		Tm		Yb		Lu		Hf		Ta	
																		Erbium		Thulium		Ytterbium		Lutetium		Hafnium		Tantalum	
																		68		69		70		71		72		73	
																		Dy		Ho		Er		Tm		Yb		Lu	
																		Dysprosium		Holmium		Erbium		Thulium		Ytterbium		Lutetium	
																		46		47		48		49		50		51	
																		Pd		Ag		Cd		In		Sn		Sb	
																		Palladium		Silver		Cadmium		Indium		Tin		Antimony	
																		46		47		48		49		50		51	
																		Pd		Ag		Cd		In		Sn		Sb	
																		Palladium		Silver		Cadmium		Indium		Tin		Antimony	
																		44		45		46		47		48		49	
																		Ru		Rh		Pd		Ag		Cd		In	
																		Ruthenium		Rhodium		Palladium		Silver		Cadmium		Indium	
																		44		45		46		47		48		49	
																		Ru		Rh		Pd		Ag		Cd		In	
																		Ruthenium		Rhodium		Palladium		Silver		Cadmium		Indium	
																		42		43		44		45		46		47	
																		Mo		Tc		Ru		Rh		Pd		Ag	
																		Molybdenum		Technetium		Ruthenium		Rhodium		Palladium		Silver	
																		42		43		44		45		46		47	
																		Mo		Tc		Ru		Rh		Pd		Ag	
																		Molybdenum		Technetium		Ruthenium		Rhodium		Palladium		Silver	
																		40		41		42		43		44		45	
																		Zr		Nb		Mo		Tc		Ru		Rh	
																		Zirconium		Niobium		Molybdenum		Technetium		Ruthenium		Rhodium	
																		40		41		42		43		44		45	
																		Zr		Nb		Mo		Tc		Ru		Rh	
																		Zirconium		Niobium		Molybdenum		Technetium		Ruthenium		Rhodium	
																		38		39		40		41		42		43	
																		Sr		Y		Zr		Nb		Mo		Tc	
																		Strontium		Yttrium		Zirconium		Niobium		Molybdenum		Technetium	
																		38		39		40		41		42		43	
																		Sr		Y		Zr		Nb		Mo		Tc	
																		Strontium		Yttrium		Zirconium		Niobium		Molybdenum		Technetium	
																		36		37		38		39		40		41	
																		Kr		Rb		Sr		Y		Zr		Nb	
																		Krypton		Rubidium		Strontium		Yttrium		Zirconium		Niobium	
																		36		37		38		39		40		41	
																		Kr		Rb		Sr		Y		Zr		Nb	
																		Krypton		Rubidium		Strontium		Yttrium		Zirconium		Niobium	
																		34		35		36		37		38		39	
																		Se		Br		Kr		Rb		Sr		Y	
																		Selenium		Bromine		Krypton		Rubidium		Strontium		Yttrium	
																		34		35		36		37		38		39	
																		Se		Br		Kr		Rb		Sr		Y	
																		Selenium		Bromine		Krypton		Rubidium		Strontium		Yttrium	
																		32		33		34		35		36		37	
																		Ge		As		Se		Br		Kr		Rb	
																		Germanium		Arsenic		Selenium		Bromine		Krypton		Rubidium	
																		32		33		34		35		36		37	
																		Ge		As		Se		Br		Kr		Rb	
																		Germanium		Arsenic		Selenium		Bromine		Krypton		Rubidium	
																		30		31		32		33		34		35	
																		Zn		Ga		Ge		As		Se		Br	
																		Zinc		Gallium		Germanium		Arsenic		Selenium		Bromine	
																		30		31		32		33		34		35	
																		Zn		Ga		Ge		As		Se		Br	
																		Zinc		Gallium		Germanium		Arsenic		Selenium		Bromine	
																		28		29		30		31		32		33	
																		Ni		Cu		Zn		Ga		Ge		As	
																		Nickel		Copper		Zinc		Gallium		Germanium		Arsenic	
																		28		29		30		31		32		33	
																		Ni		Cu		Zn		Ga		Ge		As	
																		Nickel		Copper		Zinc		Gallium		Germanium		Arsenic	
																		26		27		28		29		30		31	
																		Fe		Co		Ni		Cu		Zn		Ga	
																		Iron		Cobalt		Nickel		Copper		Zinc		Gallium	
																		26		27		28		29		30		31	
																		Fe		Co		Ni		Cu		Zn		Ga	
																		Iron		Cobalt		Nickel		Copper		Zinc		Gallium	
																		24		25		26		27		28		29	
																		Cr		Mn		Fe		Co		Ni		Cu	
																		Chromium		Manganese		Iron		Cobalt		Nickel		Copper	
																		24		25		26		27		28		29	
																		Cr		Mn		Fe		Co		Ni		Cu	
																		Chromium		Manganese		Iron		Cobalt		Nickel		Copper	
																		22		23		24		25		26		27	
																		Ti		V		Cr		Mn		Fe		Co	
																		Titanium		Vanadium		Chromium		Manganese		Iron		Cobalt	
																		22		23		24		25		26		27	
																		Ti		V		Cr		Mn		Fe		Co	
																		Titanium		Vanadium		Chromium		Manganese		Iron		Cobalt	
																		20		21		22		23		24		25	
																		Ca		Sc		Ti		V		Cr		Mn	
																		Calcium		Scandium		Titanium		Vanadium		Chromium		Manganese	
																		20		21		22		23		24		25	
																		Ca		Sc		Ti		V		Cr		Mn	
																		Calcium		Scandium		Titanium		Vanadium		Chromium		Manganese	
																		18		19		20		21		22		23	
																		Ar		K		Ca		Sc		Ti		V	
																		Argon		Potassium		Calcium		Scandium		Titanium		Vanadium	
																		18		19		20		21		22		23	
																		Ar		K		Ca		Sc		Ti		V	
																		Argon		Potassium		Calcium		Scandium		Titanium		Vanadium	
																		16		17		18		19		20		21	
																		S		Cl		Ar		K		Ca		Sc	
																		Sulfur		Chlorine		Argon		Potassium		Calcium		Scandium	
																		16		17		18		19		20		21	
																		S		Cl		Ar		K		Ca		Sc	
																		Sulfur		Chlorine		Argon		Potassium		Calcium		Scandium	
																		14		15		16		17		18		19	
																		Si		P		S		Cl		Ar		K	
																		Silicon		Phosphorus		Sulfur		Chlorine		Argon		Potassium	
																		14		15		16		17					

Nano-MOSFET

Periodic Table of the Elements

1 IA H Hydrogen 1.008																	18 VIIIA He Helium 4.003						
3 IA Li Lithium 6.941	4 IIA Be Beryllium 9.012																	19 IIIA B Boron 10.811	20 IIIA C Carbon 12.011	21 IIIA N Nitrogen 14.007	22 IIIA O Oxygen 15.999	23 IIIA F Fluorine 18.998	24 IIIA Ne Neon 20.180
5 IA Na Sodium 22.990	6 IIA Mg Magnesium 24.305																	31 IIIA Al Aluminum 26.982	32 IIIA Si Silicon 28.086	33 IIIA P Phosphorus 30.974	34 IIIA S Sulfur 32.06	35 IIIA Cl Chlorine 35.45	36 IIIA Ar Argon 39.948
7 IA K Potassium 39.098	8 IIA Ca Calcium 40.078	9 IIIB Sc Scandium 44.956	10 IIIB Ti Titanium 47.88	11 IIIB V Vanadium 50.942	12 IIIB Cr Chromium 51.996	13 IIIB Mn Manganese 54.938	14 IIIB Fe Iron 55.845	15 IIIB Co Cobalt 58.933	16 IIIB Ni Nickel 58.69	17 IIIB Cu Copper 63.546	18 IIIB Zn Zinc 65.38	19 IIIB Ga Gallium 69.723	20 IIIB Ge Germanium 72.64	21 IIIB As Arsenic 74.922	22 IIIB Se Selenium 78.96	23 IIIB Br Bromine 79.904	24 IIIB Kr Krypton 83.798						
11 IA Rb Rubidium 85.468	12 IIA Sr Strontium 87.62	13 IIIB Y Yttrium 88.906	14 IIIB Zr Zirconium 91.224	15 IIIB Nb Niobium 92.906	16 IIIB Mo Molybdenum 95.94	17 IIIB Tc Technetium 98	18 IIIB Ru Ruthenium 101.07	19 IIIB Rh Rhodium 102.906	20 IIIB Pd Palladium 106.36	21 IIIB Ag Silver 107.868	22 IIIB Cd Cadmium 112.411	23 IIIB In Indium 114.818	24 IIIB Sn Tin 118.710	25 IIIB Sb Antimony 121.757	26 IIIB Te Tellurium 127.6	27 IIIB I Iodine 126.905	28 IIIB Xe Xenon 131.29						
17 IA Cs Cesium 132.905	18 IIA Ba Barium 137.327	19 IIIB La Lanthanum 138.905	20 IIIB Ce Cerium 140.12	21 IIIB Pr Praseodymium 140.908	22 IIIB Nd Neodymium 144.24	23 IIIB Pm Promethium 145	24 IIIB Sm Samarium 150.36	25 IIIB Eu Europium 151.964	26 IIIB Gd Gadolinium 157.25	27 IIIB Tb Terbium 158.925	28 IIIB Dy Dysprosium 162.50	29 IIIB Ho Holmium 164.930	30 IIIB Er Erbium 167.259	31 IIIB Tm Thulium 168.930	32 IIIB Yb Ytterbium 173.054	33 IIIB Lu Lutetium 174.967	34 IIIB Og Oganesson 284						
25 IA Fr Francium 223	26 IIA Ra Radium 226	27 IIIB Ac Actinium 227	28 IIIB Th Thorium 232.038	29 IIIB Pa Protactinium 231.036	30 IIIB U Uranium 238.029	31 IIIB Np Neptunium 237.048	32 IIIB Pu Plutonium 244	33 IIIB Am Americium 243	34 IIIB Cm Curium 247	35 IIIB Bk Berkelium 247	36 IIIB Cf Californium 251	37 IIIB Es Einsteinium 252	38 IIIB Fm Fermium 257	39 IIIB Md Mendelevium 258	40 IIIB No Nobelium 259	41 IIIB Lr Lawrencium 262	42 IIIB Og Oganesson 284						

Atomic Number →

← Symbol

Name →

← Atomic Weight

Electrons per shell →

State of matter (color of round)

Subcategory in the metal-metalloid nonmetal (color of background)

Unknown chemical properties

Alkali metals

Alkaline earth metals

Transition metals

Lanthanides

Actinides

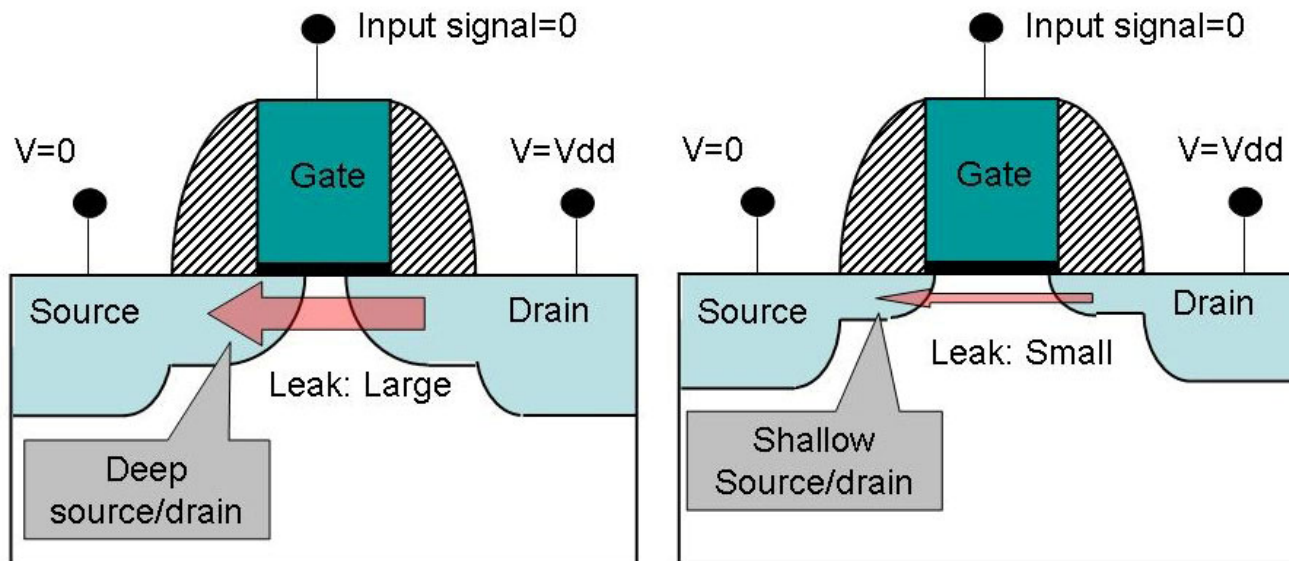
Metalloids

Reactive nonmetals

Noble gases

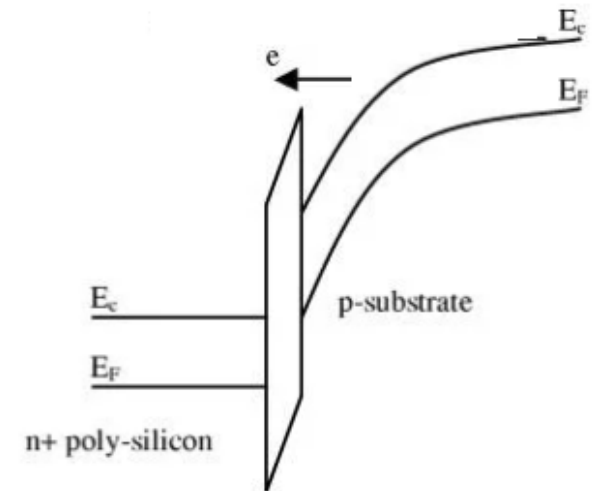
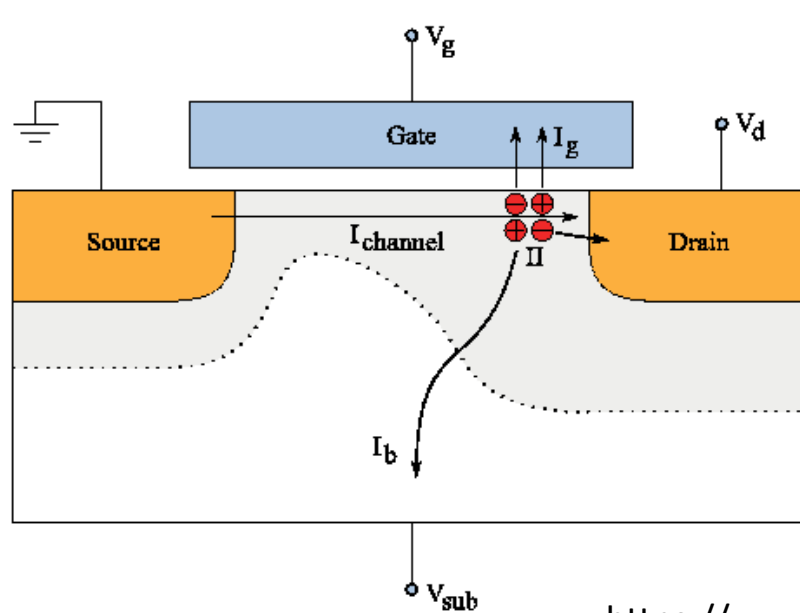
CMOS scaling: Shallow Source/Drain:

- To minimize the short channel effect and DIBL, we want shallow (small r_j) S/D regions – but the parasitic resistance of these regions increases when r_j is reduced.



Hot carrier injection

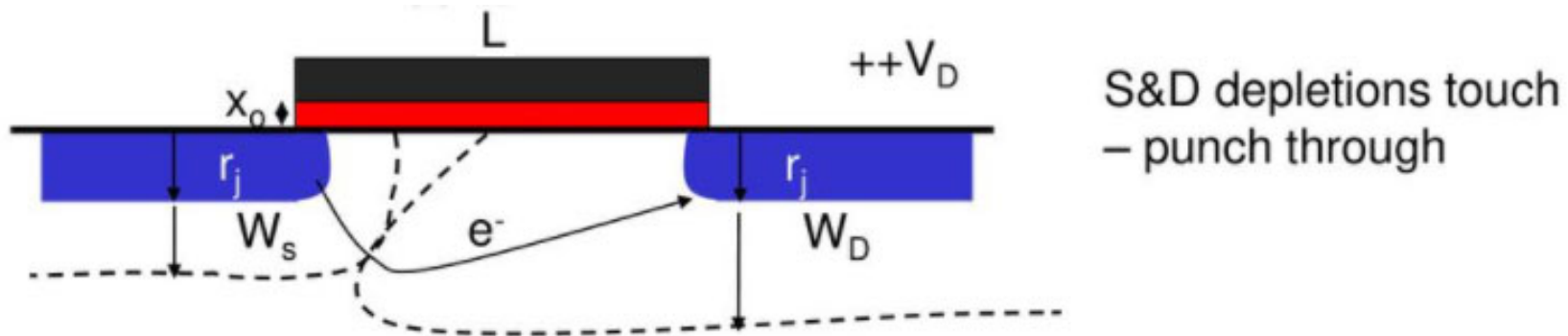
High electric field near the substrate-oxide interface energizes the electrons or holes and they cross the substrate-oxide interface to enter the oxide layer. This phenomenon is known as hot carrier injection.



<https://www.iue.tuwien.ac.at/phd/entner/node21.html>

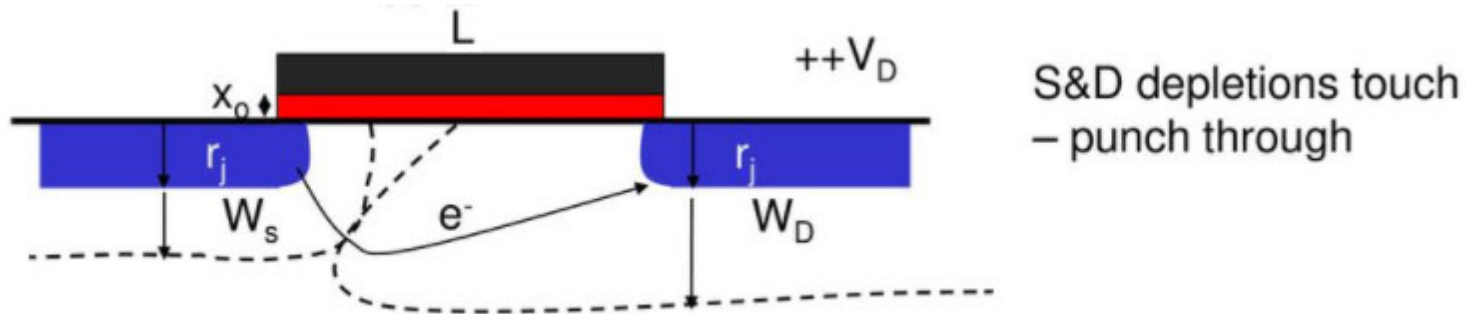
Punch through effect

- In short channel devices, due to the proximity of drain and source terminals, the depletion region of both the terminals come together and eventually merge. In such a condition, "punch-through" is said to have taken place.



J. Ho, "Introduction and Short Channel Effects", 2014, Semiconductors

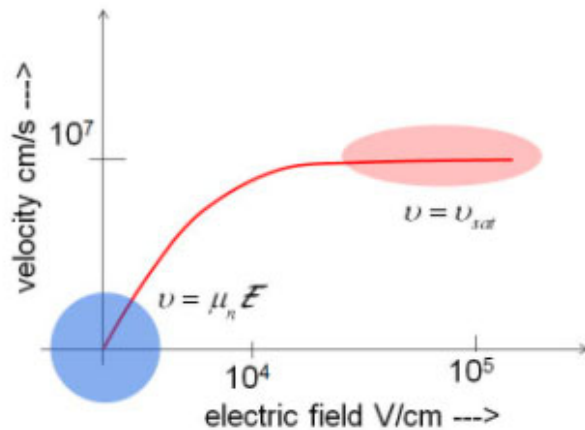
Punch through effect



- Drain current no longer controlled by gate voltage
- Drain current does not saturate
- High subthreshold current

J. Ho, "Introduction and Short Channel Effects",
2014, Semiconductors

Velocity saturation

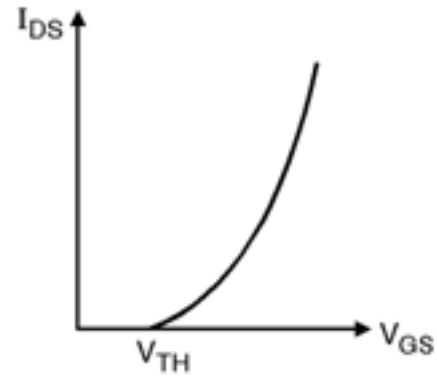
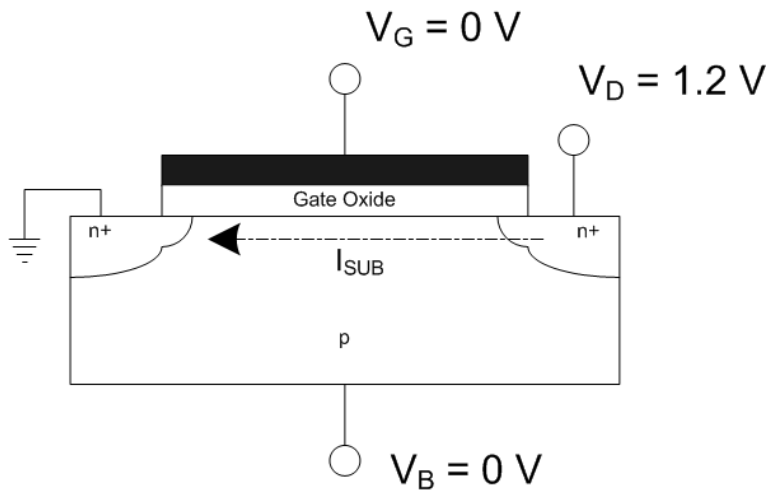


Lundstrom: Nanotransistors 2015

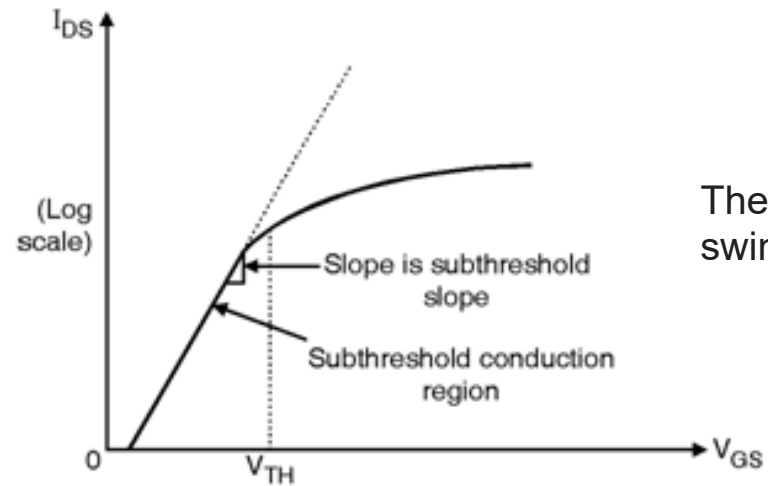
$$V = \mu E$$

- Velocity of charge carriers is linearly proportional to the electric field and the proportionality constant is called as mobility of carrier.
- But when we increase the electric field beyond certain velocity called as the thermal velocity or saturated velocity the velocity of the charge carrier does not change with electric field
- The electric field at which the velocity of carrier saturates is called as the critical electric field. The loss of energy is because of the collisions of carriers called as scattering effect.

Subthreshold current



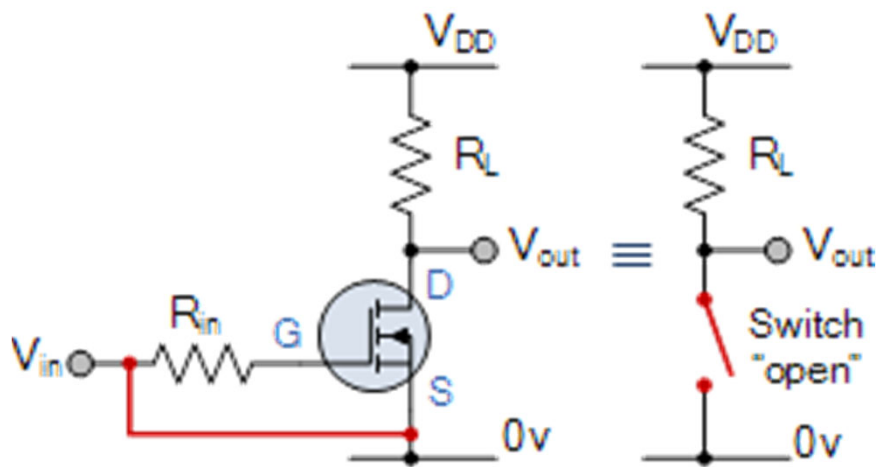
I_{DS} Vs V_{GS} characteristics in linear scale



The minimum subthreshold swing= 60 mV/Dec

I_{DS} Vs V_{GS} characteristics in log scale

Subthreshold current

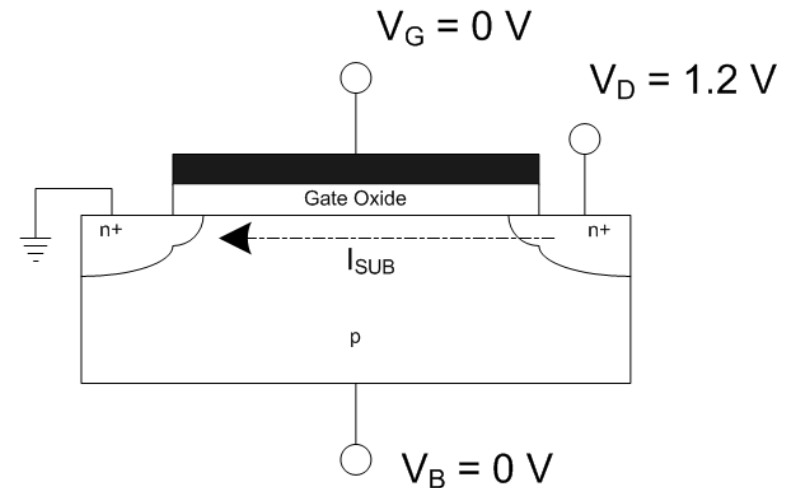
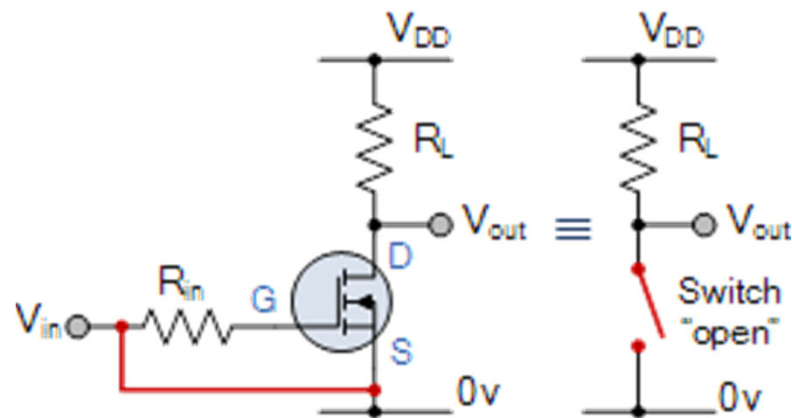


https://www.electronics-tutorials.ws/transistor/tran_7.html

Subthreshold current

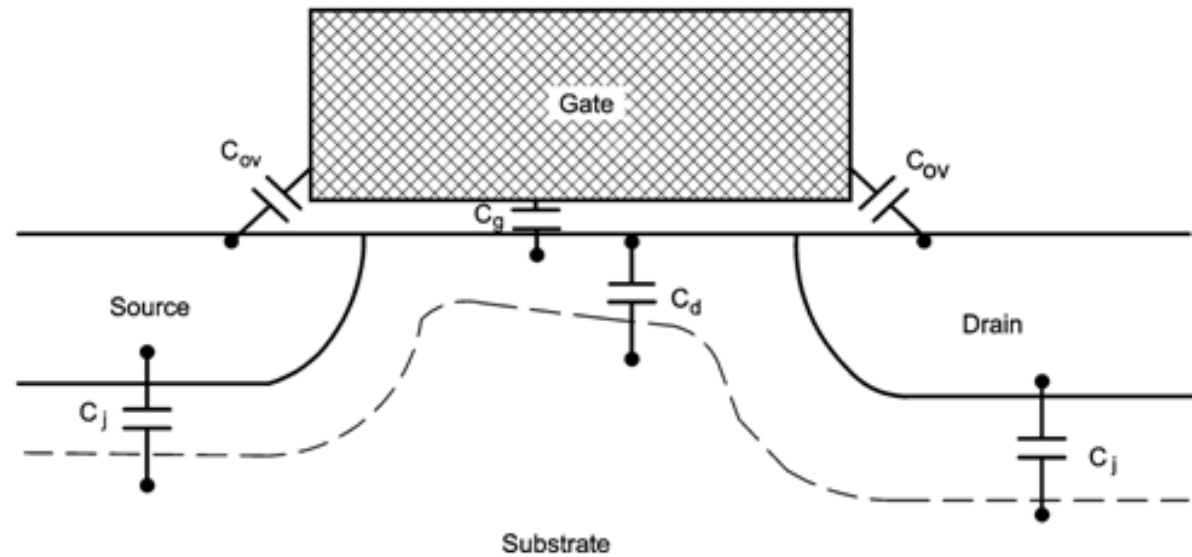
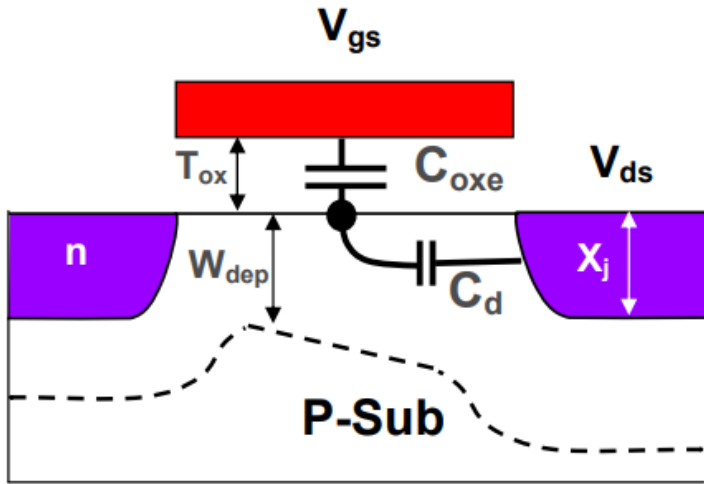
Subthreshold conduction or subthreshold leakage is **the current between the source and drain of a MOSFET** when

- the transistor is in subthreshold region, or
- weak-inversion region, that is, for gate-to-source voltages below the threshold voltage.



https://www.electronics-tutorials.ws/transistor/tran_7.html

Impact of scaling on parasitic C and R

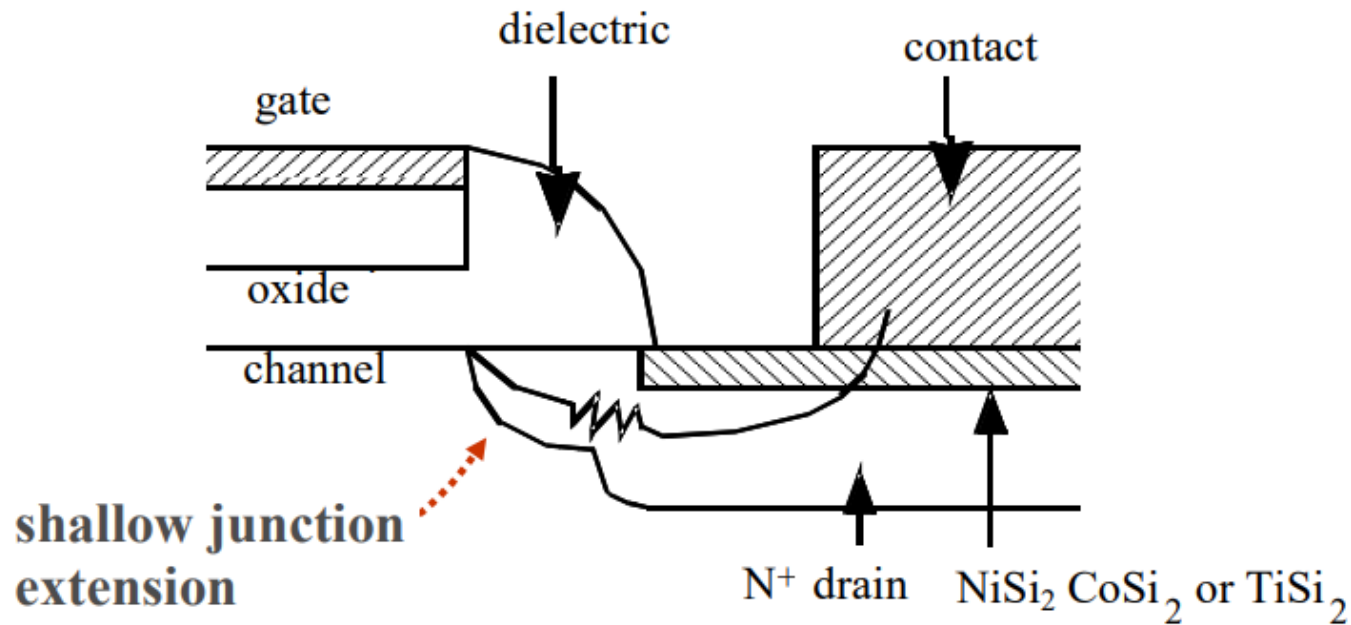


MOSFET parasitic capacitances

<https://inst.eecs.berkeley.edu/~ee130/sp06/chp7full.pdf>

<https://www.electronics-tutorial.net/Analog-CMOS-Design/MOSFET-Parasitics/Parasitic-Capacitances-MOSFETS/>

Impact of scaling on parasitic C and R



<https://inst.eecs.berkeley.edu/~ee130/sp06/chp7full.pdf>