Analytical Study of Vertical Channel Engineering Approaches for Reduction of Threshold Voltage Variation for Low Power Applications

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1. Introduction

Random Variation is caused by random variations in number of dopant atoms in channel region. Threshold Voltage standard deviation for uniform channel doping is given by

$$\sigma_{V_{th}}^2 = \frac{q}{C_{ox}'}\sqrt{\frac{N_A W_{dm}}{3LW}}$$

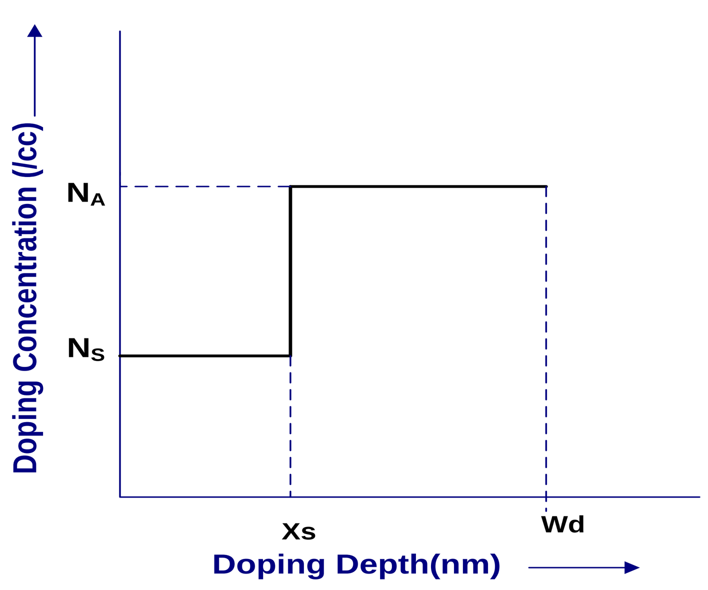
- σ_{Vth}=Threshold Voltage Standard Deviation
- q=Charge
- C_{ox}'=Oxide Capacitance per unit area
- L=Channel Length
- N_A=Substrate Concentration
- W=Channel Width
- W_{dm}=Maximum Depletion Depth
- N(x)=Charge Density along depth
- x=Depth
- ε_{Si}=Silicon Permitivity
- Φ_F=Surface Potential at strong inversion

Effective dopant concentration is given by

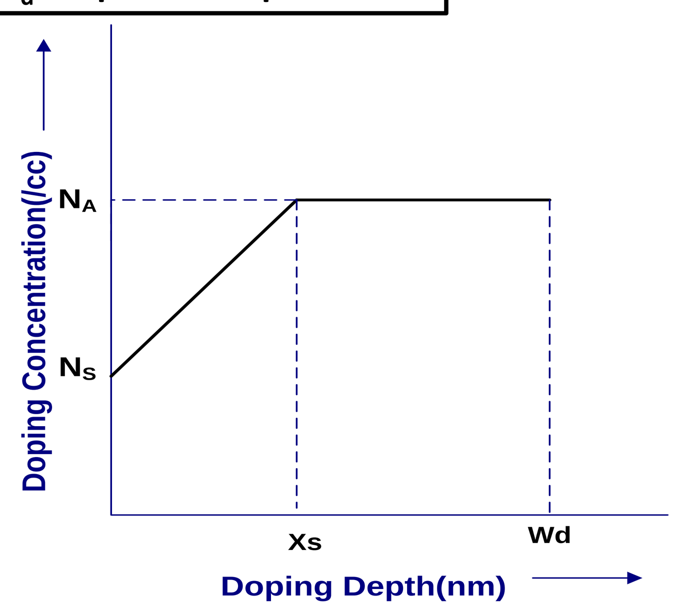
$$N_{EFF} = 3\int_0^{W_{dm}} N(x)\left(1-\frac{x}{W_{dm}}\right)^2 \frac{dx}{W_{dm}}$$

2. Different Doping Profiles

N_A=Uniform Substrate Concentration, N_S=Surface Concentration, X_s=Transition Depth, W_d=Depletion Depth



Abrupt Retrograde



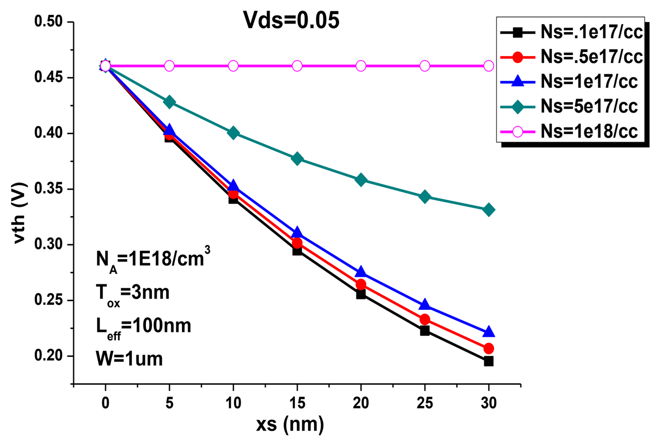
Graded Retrograde

3. Results

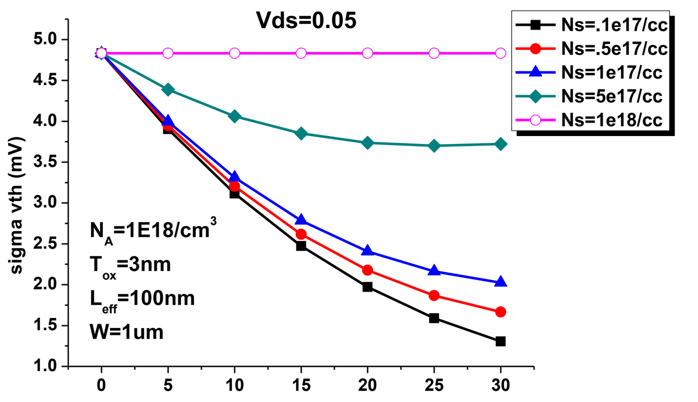
Abrupt Retrograde Profile

$$W_{dm} = \sqrt{\frac{2\varepsilon_{Si}}{qN_A}\left(2\Phi_F + \frac{q(N_A - N_S)x_s^3}{2\varepsilon_{Si}}\right)} \qquad N_{EFF} = \left[N_S + (N_A - N_S)\left(1-\frac{x_s}{W_{dm}}\right)^3\right]$$

$$V_{TH0} = V_{FB} + 2\Phi_F + \frac{1}{C_{ox}'}\sqrt{2\varepsilon_{si} q N_A\left(2\Phi_F - \frac{q(N_S-N_A)x_s^2}{2\varepsilon_{si}}\right)} - \frac{q(N_A-N_S)x_s}{C_{ox}'}$$



Abrupt profile: Variation of threshold voltage with transition depth for different surface concentration



Abrupt profile: Variation of standard deviation of threshold voltage with transition depth for different surface concentration

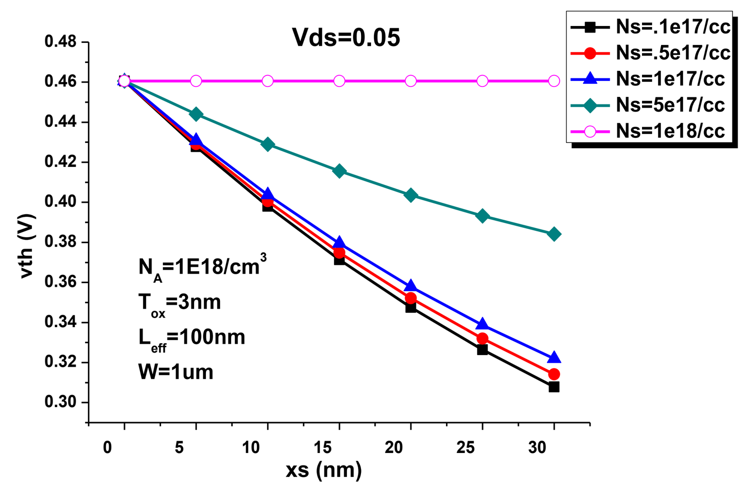
Observations

- σ_{Vth} decreases with x_s
- σ_{Vth} decreases with N_s

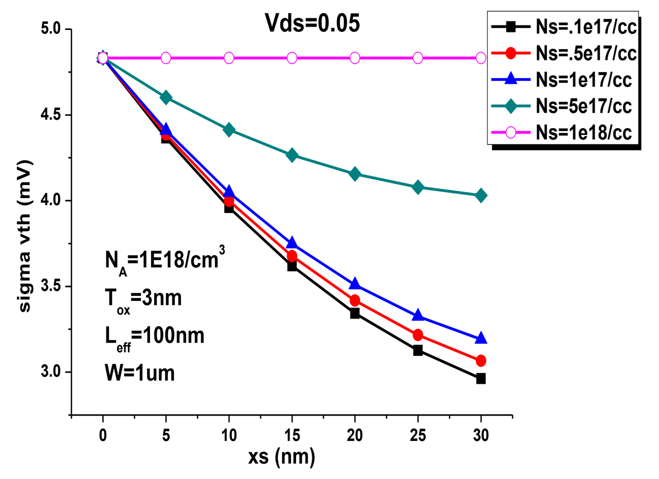
Graded Retrograde Profile

$$W_{dm} = \sqrt{\frac{2\varepsilon_{Si}}{qN_A}\left(2\Phi_F - \frac{q(N_S - N_A)x_s^2}{6\varepsilon_{Si}}\right)} \qquad N_{EFF} = N_s + (N_s - N_A)\left(1-\frac{x_s}{W_{dm}}\right)^3 + (N_A - N_s)\left(\frac{3x_s}{2W_{dm}} + \frac{3x_s^3}{4W_{dm}^3} - \frac{2x_s^2}{W_{dm}^2}\right)$$

$$V_{TH0} = V_{FB} + 2\Phi_F + \frac{1}{C_{ox}'}\sqrt{2\varepsilon_{Si} q N_A\left(2\Phi_F - \frac{q(N_S-N_A)x_s^2}{6\varepsilon_{Si}}\right)} - \frac{q(N_A-N_S)x_s}{2C_{ox}'}$$



Graded profile: Variation of threshold voltage with transition depth for different surface concentration



Graded profile: Variation of standard deviation of threshold voltage with transition depth for different surface concentration

Observations

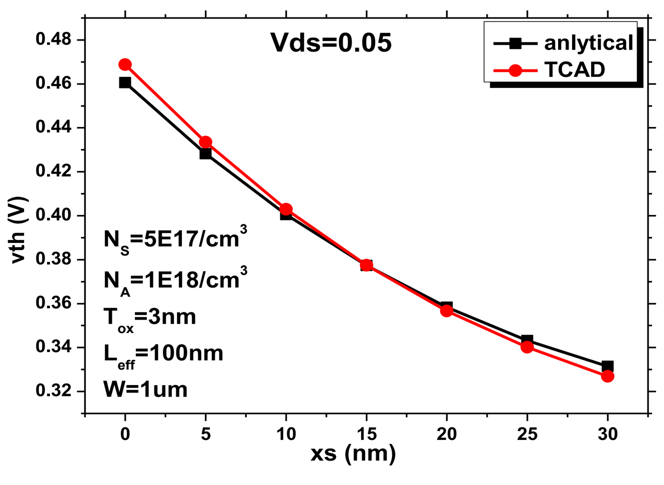
- σ_{Vth} increases with x_s
- σ_{Vth} increases with N_s
- σ_{Vth} is higher than σ_{Vth}(Abrupt Retrograde Profile)

Short Channel Effect

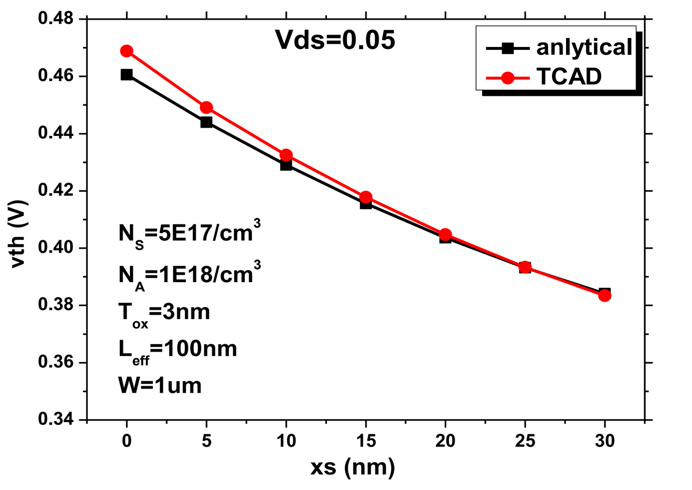
Threshold roll off due to short channel and DIBL effect is represented by ΔVth and the analytical threshold is thus given by Vth

$$\Delta V_{TH} = -\frac{2(V_{bi} - 2\Phi_F) + V_{DS}}{2\cosh\left(\frac{L}{l_t}\right) - 1} \qquad V_{TH} = V_{TH0} - \Delta V_{TH}$$

TCAD Verification



Verification of analytical results with TCAD for threshold voltage vs. transition depth: Abrupt profile



Verification of analytical results with TCAD for threshold voltage vs. transition depth: Graded profile.

Data Tables

TABLE I

Vds=0.05V	Xs=25(nm)			
	Abrupt		Graded	
	Ns=5e17/cm³	Ns=1e17/cm³	Ns=5e17/cm³	Ns=1e17/cm³
Vth (V)	0.3432	0.2453	0.3932	0.3387
sigma Vth (mV)	3.7016	2.1638	4.0783	3.3246

Comparison between abrupt and graded retrograded profile for varying surface concentration with a fixed transition depth.

TABLE II

Vds=0.05V	Ns=5e17/cm³			
	Abrupt		Graded	
	Xs=25(nm)	Xs=20(nm)	Xs=25(nm)	Xs=20(nm)
Vth (V)	0.3432	0.3583	0.3932	0.4036
sigma Vth (mV)	3.7016	3.7371	4.0783	4.1553

Comparison between abrupt and graded retrograded profile for varying transition depth with a fixed surface concentration.

TABLE III

Vds=0.05V	Ns=5e17/cm³ (Nominal value)			
	Abrupt		Graded	
	Xs=20nm	Xs=25nm	Xs=20nm	Xs=25nm
sigma Vth (mV) (From TCAD)	3.971	3.903	4.354	4.2412
sigma Vth (mV) (Analytical)	3.7371	3.7016	4.1553	4.0783

Comparison of σVth for abrupt and graded retrograded profile for varying transition depth with a fixed surface concentration

4. Conclusions

1. ***The threshold voltage can be effectively optimized by profile engineering for minimum leakage current.***
2. ***The variations of the standard deviation of threshold voltage fluctuation of an NMOS transistor for the two profiles have been compared here.***
3. ***The effect of RDD on threshold voltage fluctuation can be minimized by the use of an abrupt retrograde(AR) channel profile more in comparison to graded retrograde(GR) profile.***
4. ***The leakage for abrupt profile is more due low threshold voltage in comparison to graded profile.***
5. ***A combination of AR and GR profile can be implemented effectively to obtain an optimized threshold with reduced fluctuation***

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