Impact of electron velocity on the I_{ON} of n-TFETs

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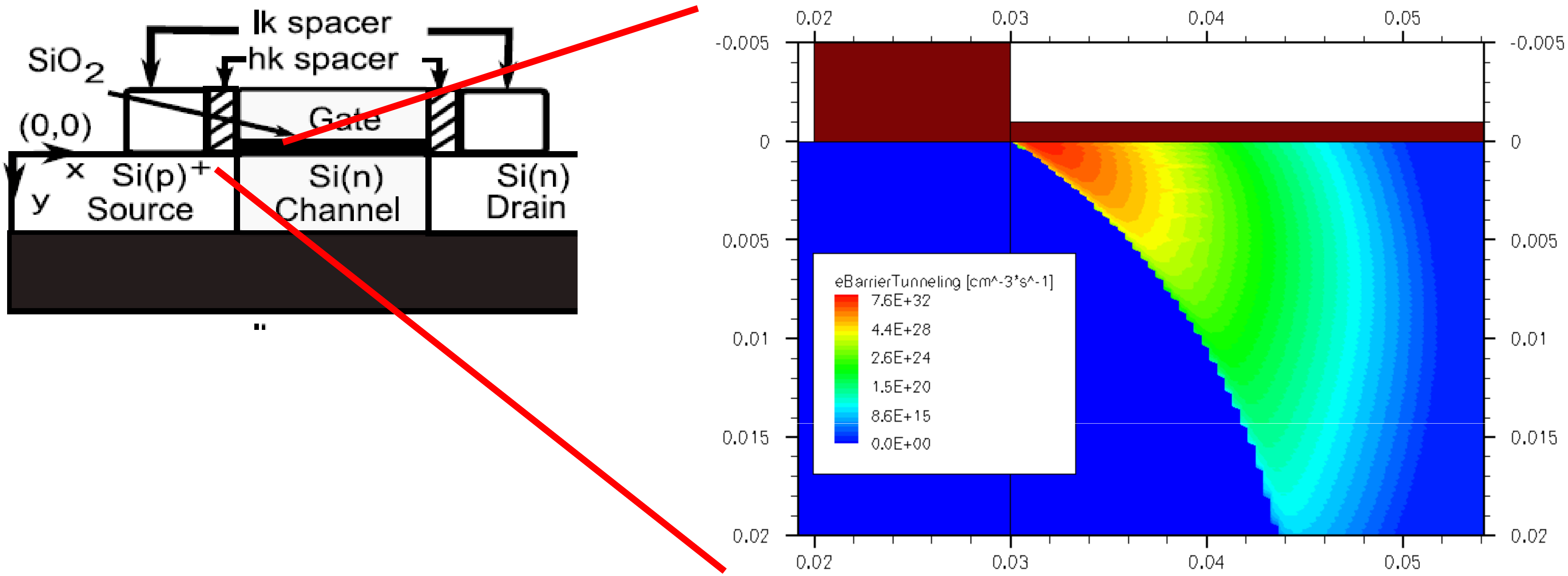
Context and motivation of this study

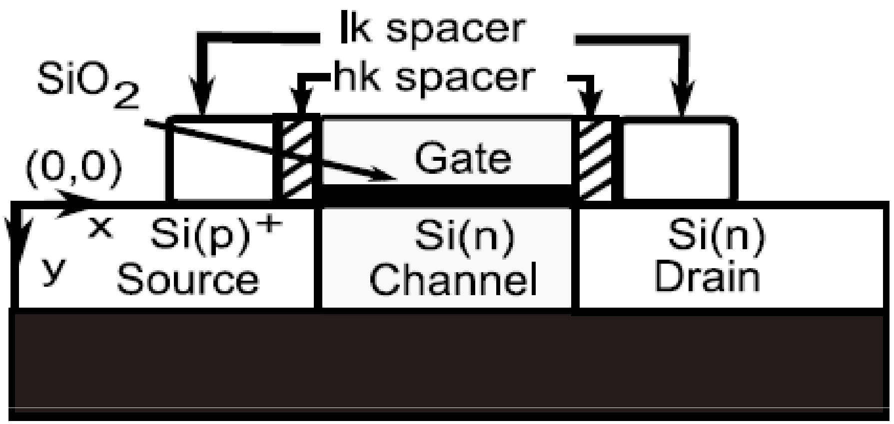


- I_{on} bosters focussed on tunneling generation rate at the source (III-V materials,bandgap engineering, high-k spacers, strain, ….)
  - Electrons generated at the source must be drained out and affect the band edges profile along the channel
  - Can the carrier transport in the channel affect I_{on} ?

Outline

- Device structure, TCAD models and calibration
- Impact of electron velocity: a toy model example
- Impact of electron velocity: engineered Si TFETs
- Conclusions

Device structure and TCAD models



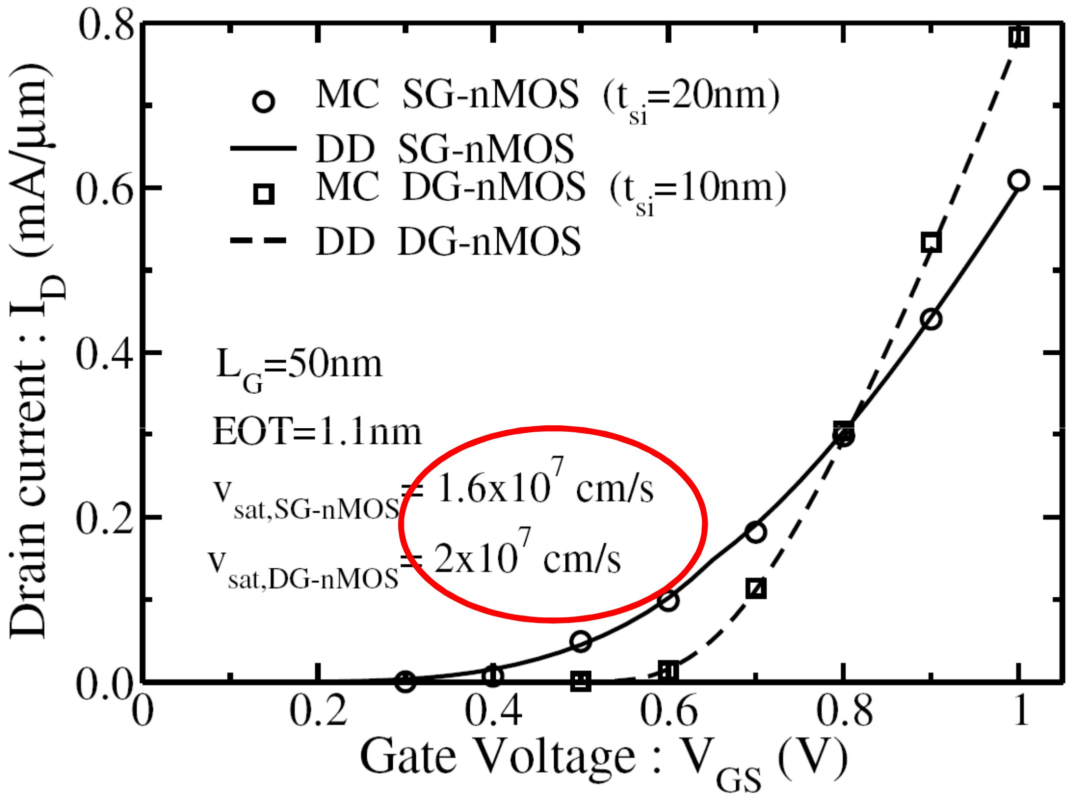
- Single-gate SOI *n*-TFET
  - L_G=50nm, t_{fox}=1.1nm (SiO_2)
  - $N_A=10^{17}cm^{-3}$
  - T_{SI}=20nm, T_{box}=10nm (SiO_2)
  - $N_{SRC}=10^{20}cm^{-3}$ peak value
  - $N_{DR}=10^{18}cm^{-3}$ peak value
  - Decay of SD doping 1dec/2nm

- DESSIS-SENTAURUS simulations
  - Drift-diffusion model (calibration)
  - Non local BTBT model (calibration)

Calibration of the Drift Diffusion model

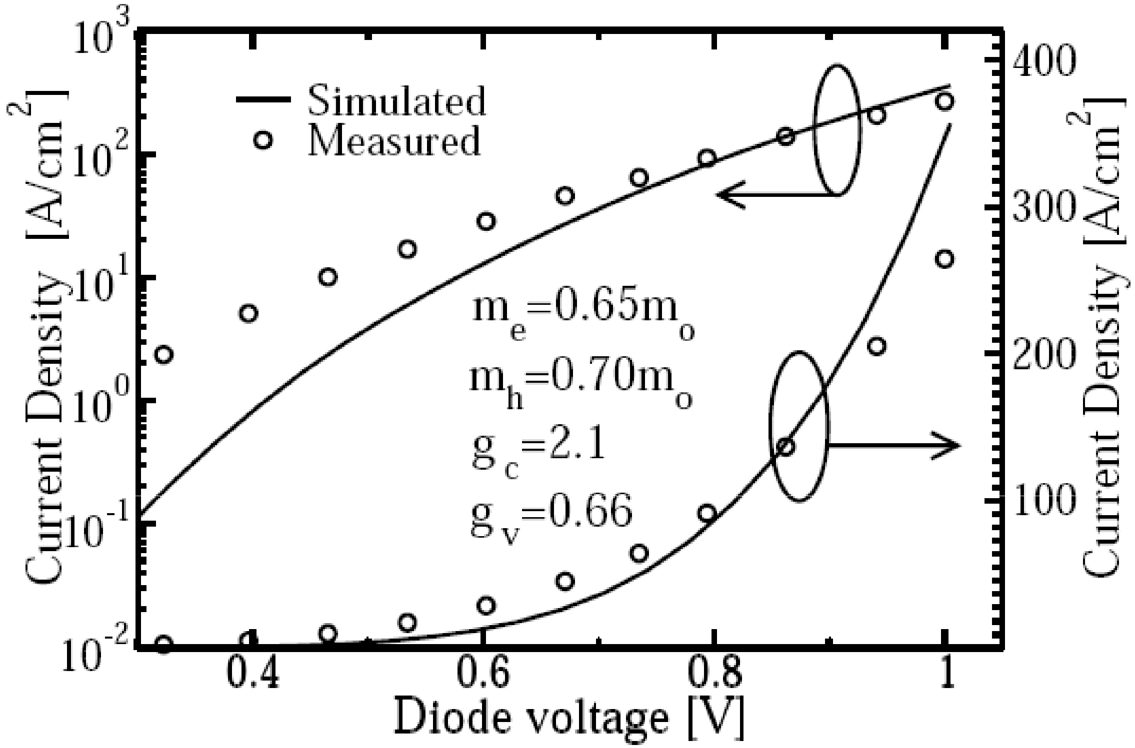
$$v(F) = \frac{\mu_o}{\left[1 + \left(\frac{F\mu_0}{v_{sat}}\right)^{\beta}\right]^{\frac{1}{\beta}}}$$

- Drift diffusion model calibrated to multi-subband Monte Carlo simulations MOSFET with L_G=50nm



- Velocity saturation (v_{sat}) adjusted in *Caughey-Thomas* velocity versus field relation (J.Bude, SISPAD 2000)

Calibration of the Tunneling model



- Non local Tunneling model has been calibrated to experimental data for reverse-biased diodes [P. M. Solomon et al. JAP, vol. 95, No. 10, May 2004] (g_c and g_v at the default value)

Resulting simulated I_{ON} values

- Resulting simulated I_{ON} of about 0.1μA/μm for V_{GS} = V_{DS} =1V

Ref	structure	mode of operation	Channel length (nm)	Gate material	EOT (nm)	V_{DS} (V)	V_{GS} (V)	I_{on} (μA/μm)	I_{off} (pA/μm)	SS (mV/dec)
[17]	vertical pTFET	p-channel	70	p^+ poly	4.5(SiO_2)	0.7	-4.5	1	1	>100
[5]	lateral nTFET	n-channel	70	-	2(SiO_2)	1	1	12	5000	52.8
[7]	gated p^+-n diode	n-channel	50	n^+poly	4(SiO_2)	-3	3	0.001	1	≈50
[18]	Fin-TFET	p-channel	65	TiN	1.6(EOT)	-2	-2	0.004	-	>100
[9]	lateral strained	n-channel	1000	poly	–	–	5	0.01	800	>100
[8],[19]	lateral	p-channel	100	TiN	3(HfO_2)	-1	-2.5	0.05	1	42

17- K. K. Bhuwalka *et al., Jap. J. Appl. Phy., pp.* 3106–3109, 2006.

5- W. Y. Choi *et al., IEEE Elec. Dev. Lett., pp. 742–745, 2007.*

7- O. M. Nayfeh *et al., IEEE Elec. Dev. Lett., pp. 468–470, 2008.*

18- M. Fulde *et al., 2nd IEEE International Nanoelectronics Conference (INEC 2008), March* 2008, pp. 579–584.

8- F. Mayer et al., in Tech. Dig. IEDM, 2008, pp. 163–166.

9- T. Krishnamohan et al, Tech. Dig. IEDM, pp. 947– 949.

19- C.L.Royer and F.Mayer, 10th International Conference on Ultimate Integration of Silicon, 2009, March 2009, pp. 53–56.

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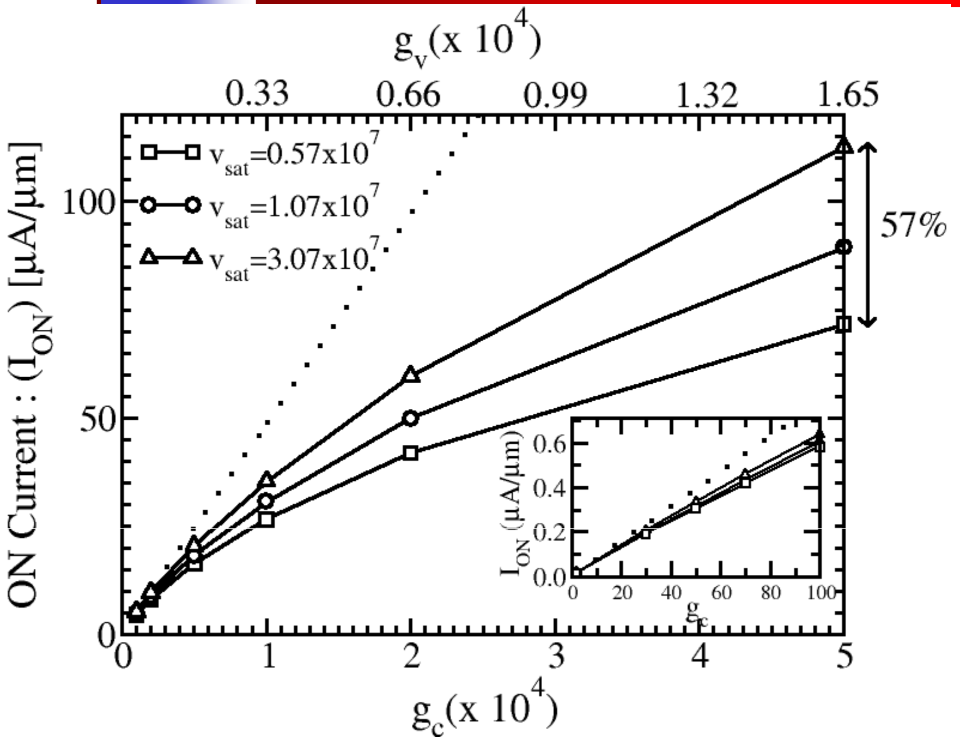
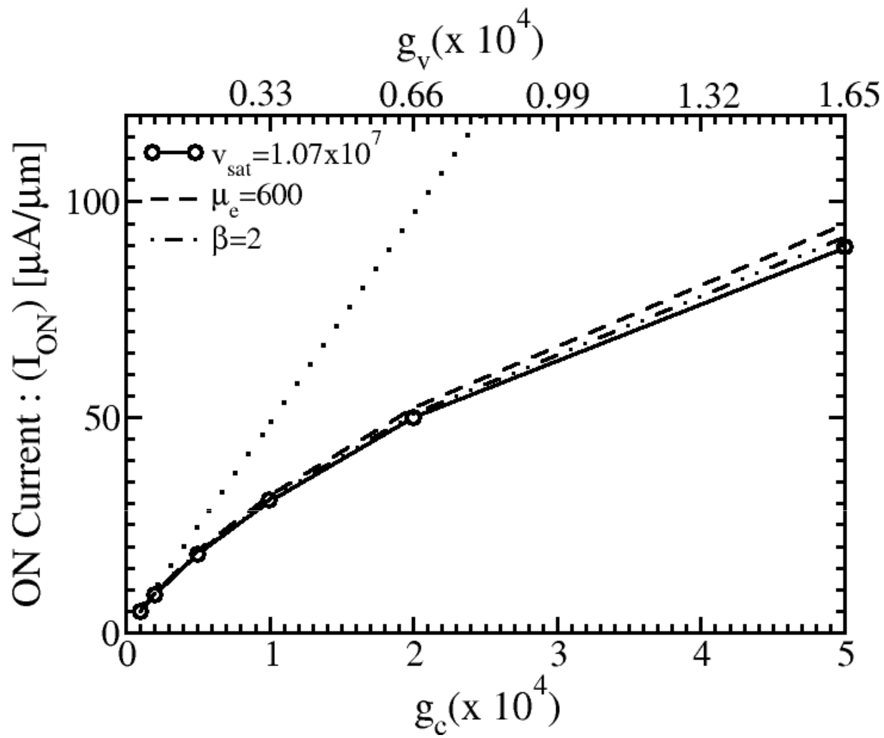
Channel Transport in nTFET: Toy model

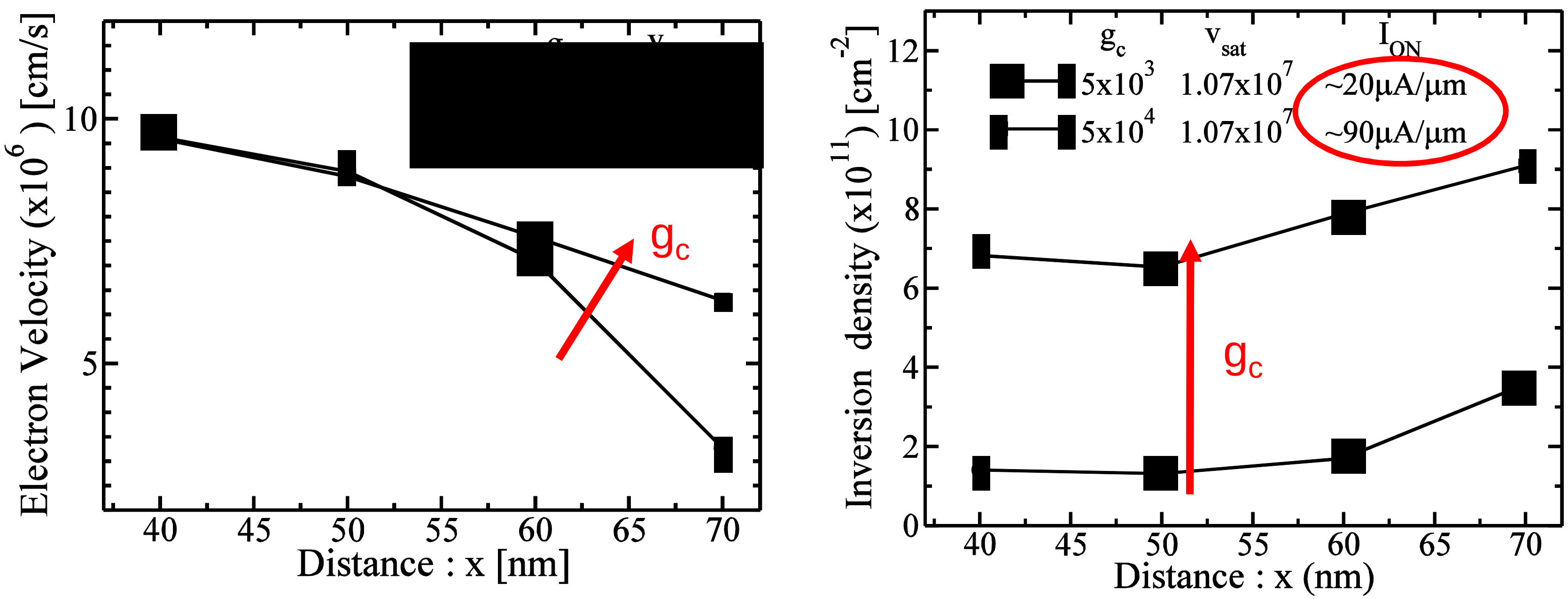




- The g_c and g_v in the tunneling model are artificially increased (by the same factor)
- I_{ON} *is not proportional* to g_c and g_v for I_{ON} larger than few μA/μm
- I_{ON} increases with v_{sat} (μ_e and β have negligible impact)

Electrostatic Feedback: N_{INV} and Velocity

Source-channel junction at 30nm and Drain-channel junction at 80nm

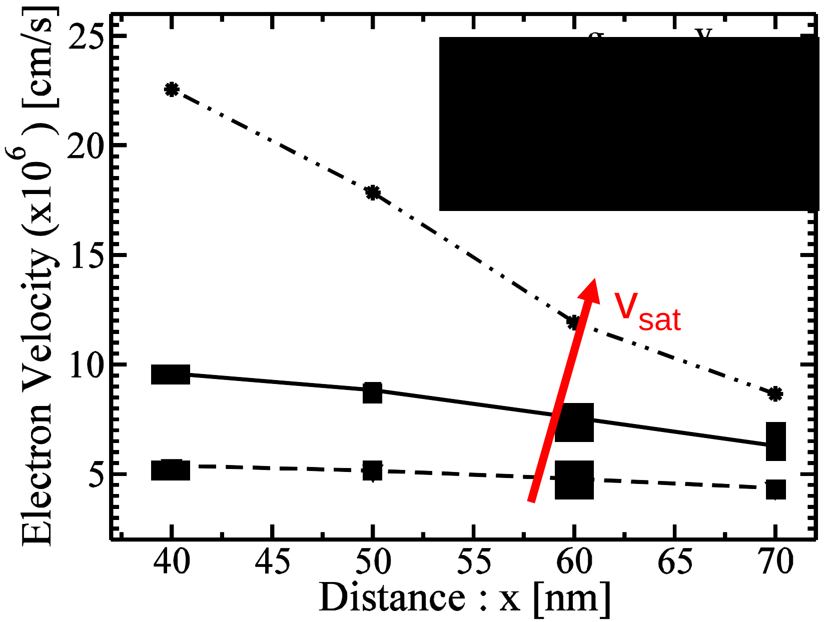


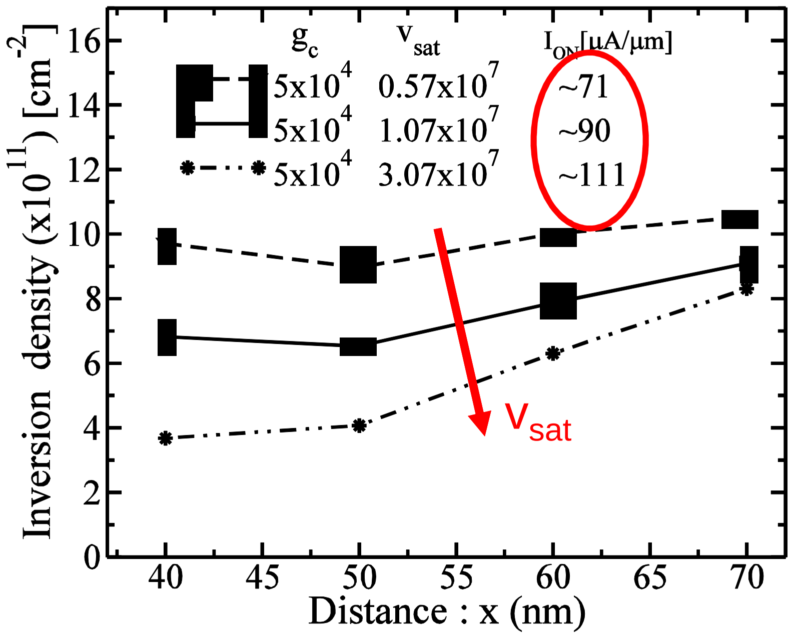
- Electric field at source side is high→ carriers velocity is saturated
- Electric field at drain side is low →the carriers velocity reduces and N_{inv} increases towards the drain (marked difference w.r.t. MOSFETs)
- As the g_c value is increased the generation rate and N_{inv} increase

Band edges are pushed upward ➔ electrostatic feedback

Electrostatic Feedback: the role of carrier velocity

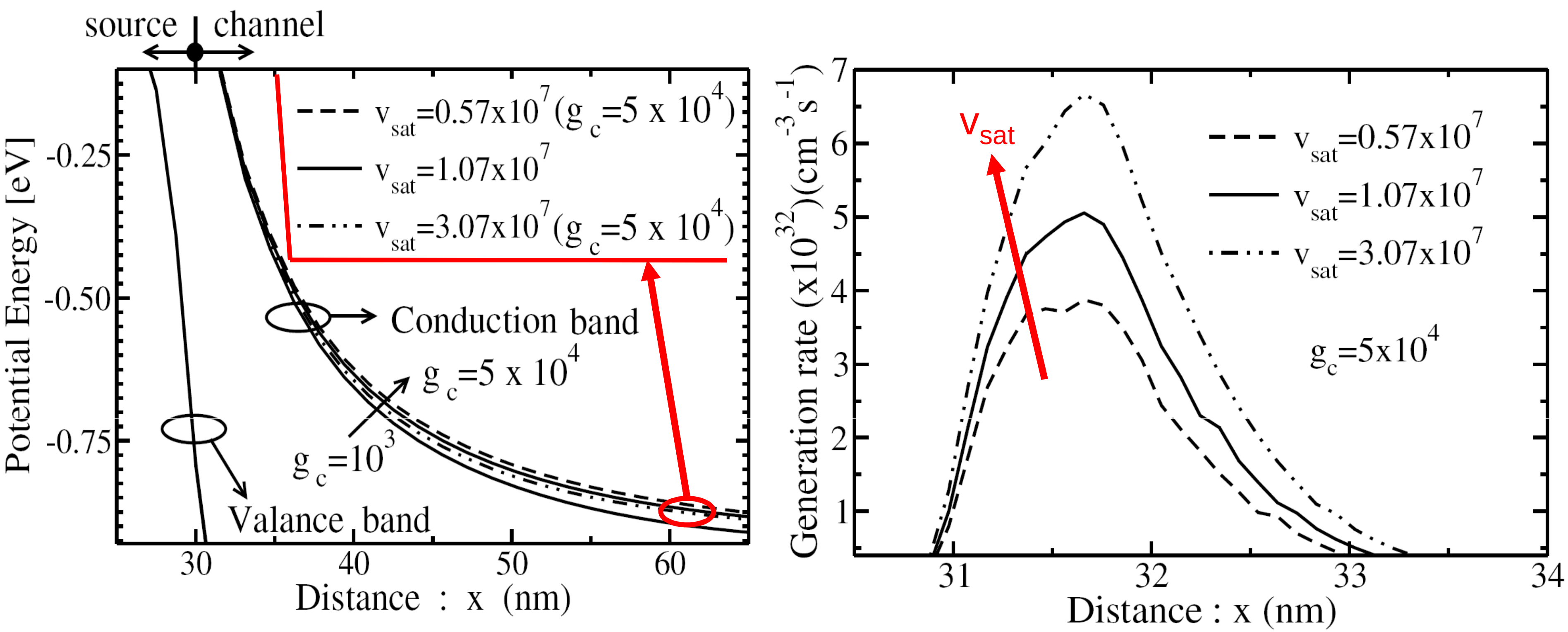
Source-channel junction at 30nm and Drain-channel junction at 80nm





- For a given generation rate (g_c value) the N_{inv} decreases for larger electron velocities
- Increasing carrier velocity is supposed to reduce the electrostatic feedback on the generation rate and thus to enhance I_{ON}

Electrostatic Feedback and carrier velocity



- Increase of generat. rate pushes the band edges upward
- As electron velocity increases the electrostatic feedback decreases, hence the generation rate and the I_{ON} improve

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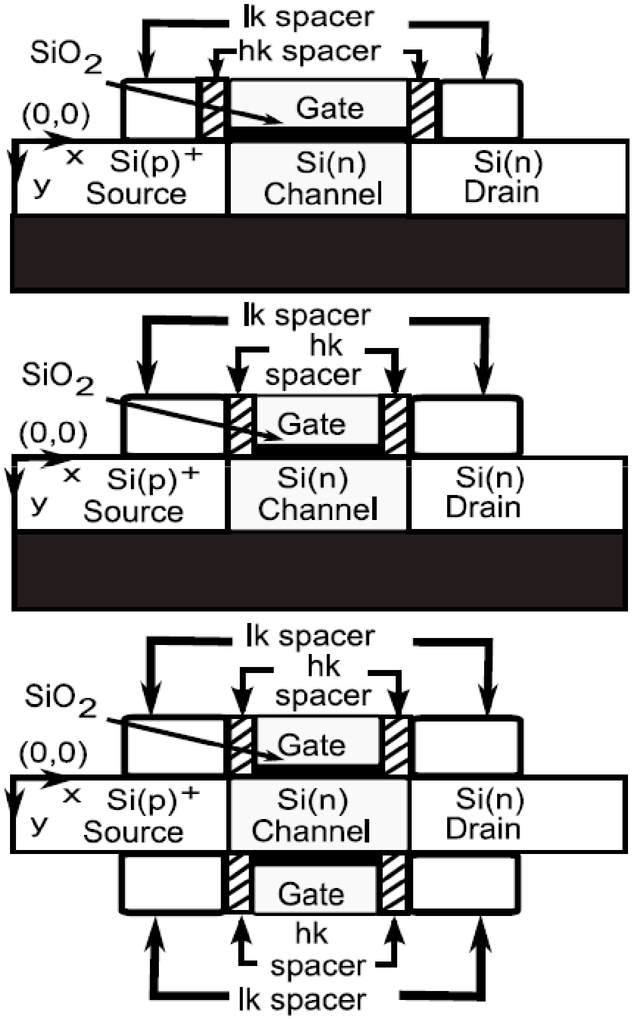
Channel Transport in nTFET:Technology Boosters



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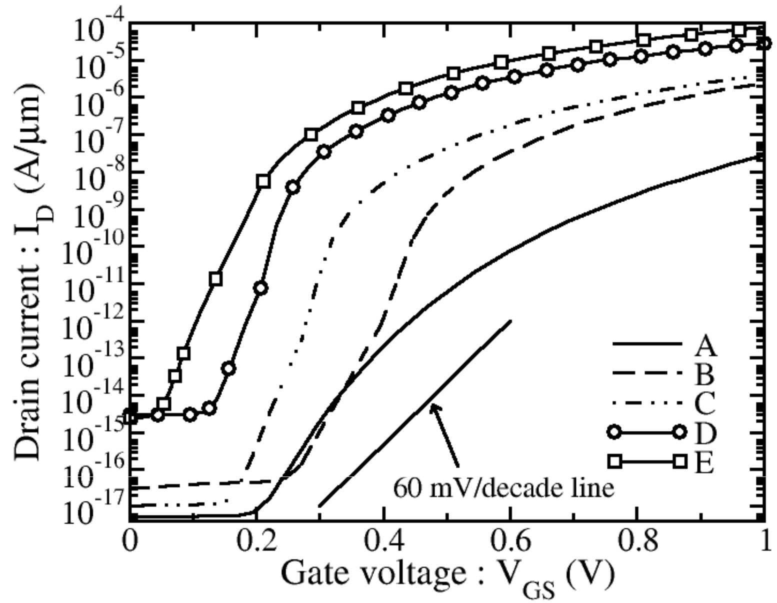


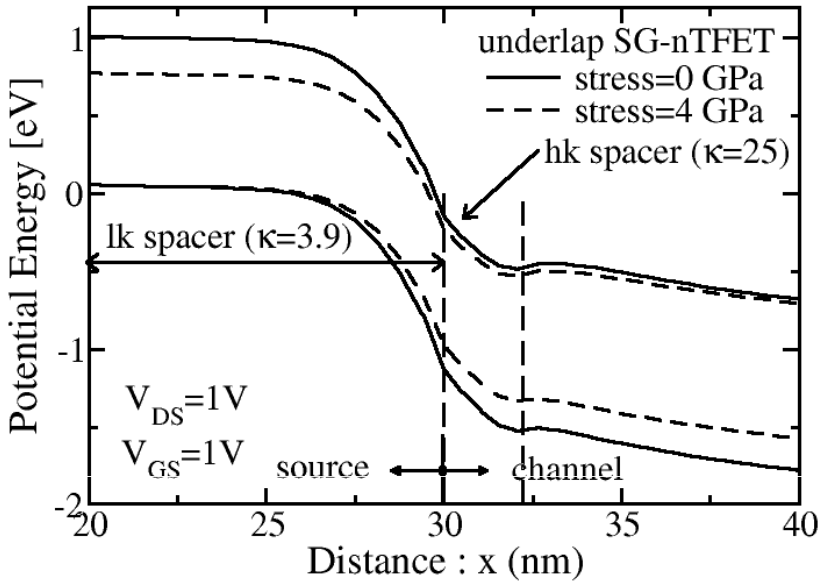
- A→nTFET with SiO_2 spacer
- B→nTFET with dual-k spacer
- C→nTFET with underlap and dual-k spacer
- D→same as C with 4GPa stress
- E→same as D with double gate

(see H.Virani *et al.* accepted for TED, 2010)

Band Diagram : Technology Boosters

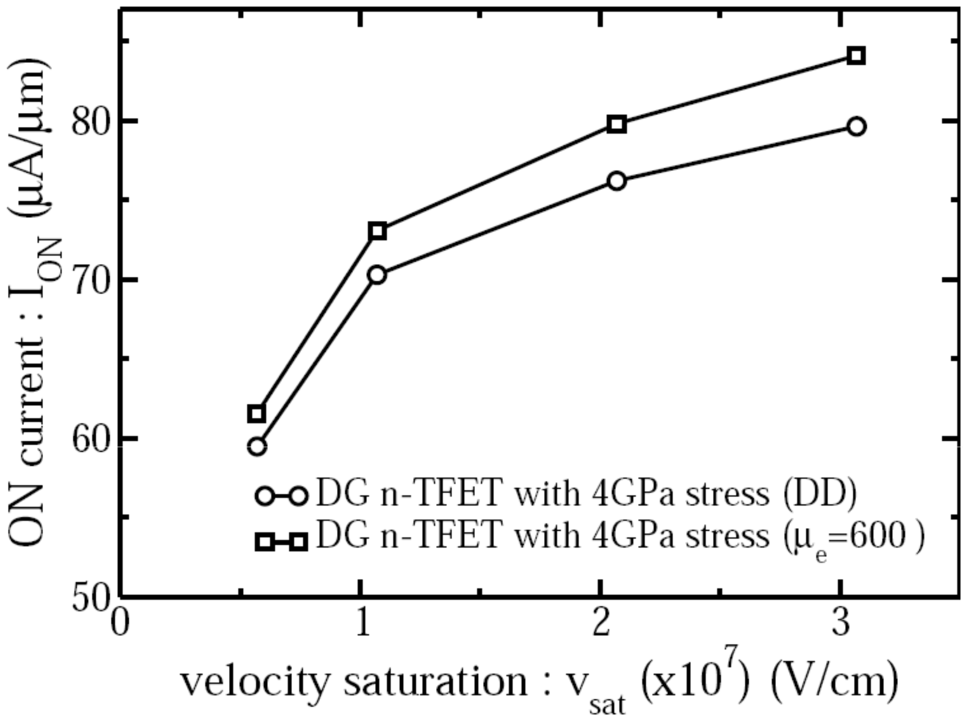
Stress (GPa)	Conduction Band (eV)	Valence Band (eV)	Bandgap (eV)
0	1.170	0	1.170
1	1.149	0.027	1.122
2	1.121	0.054	1.067
3	1.085	0.081	1.004
4	1.043	0.108	0.935

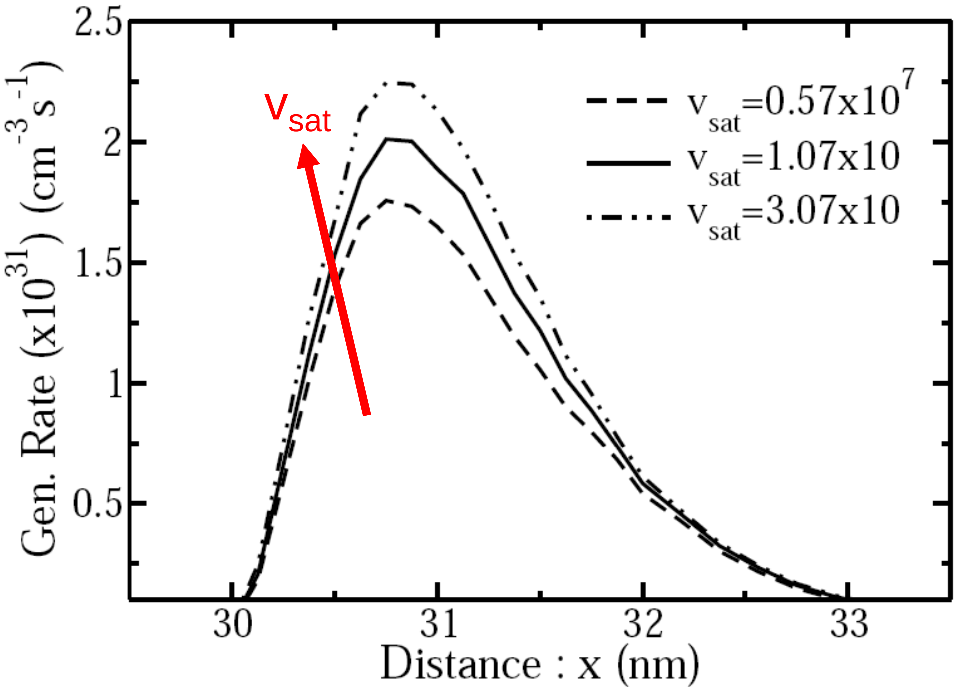
- Conduction band edge: after E.Ungersboeck et al. TED 2007
- Valence band: six-by-six k·p calculations



- Dual-k spacer produces additional band bending at source-channel junction (due to enhanced fringe field) and reduces the tunnelling distance (see H.G.Virani *et al.* TED, 2010)
- Further reduction of the tunnelling distance is obtained by a uniaxial stress in the <110> source-drain direction of a (100) TFET

Channel Transport in nTFET:Technology Boosters





- As velocity increases the electrostatic feedback reduces, hence generation rate and I_{ON} increase
- Mobility has negligible effect on I_{ON} (neglected strain induced mobility modulation)

A few remarks

- Throughout the study we used changes in the velocity saturation to *exemplify* the effects of the carrier velocity
- Verification of the results with more adequate transport models would be interesting
- The electrostatic feedback effect may depend on the channel length of the TFETs → *under investigation*

Conclusions

- For $I_{ON} \geq$ few μA/μm, the tunneling generated electrons in nTFETs tend to accumulate in the channel and produce an electrostatic feedback which affects the I_{ON}
- In this regime the I_{ON} becomes sensitive to the electron velocity and increases with it
- The tunneling barrier is the most important ingredient but not the only ingredient for the I_{ON} optimization
- III-V materials or graphene based devices may help *also in terms* of carrier velocity in the channel

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