TCAD simulation of statistical variability

Andrew R. Brown
&
The Glasgow Device Modelling Group
University of Glasgow

Outline

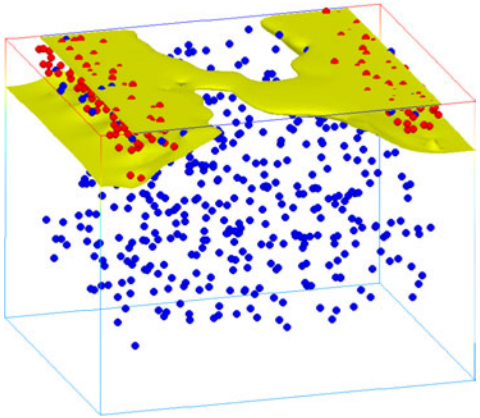
- Introduction
- Sources of variability and TCAD challenges
  - Random discrete dopants
  - Line edge roughness
  - Poly-silicon gate granularity
  - Metal gate granularity
  - Statistical Reliability
- Examples
- Conclusion

Variability Research in Europe

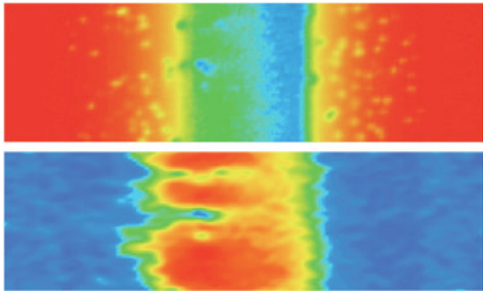
- Modern
  - *MOdeling and DEsign of Reliable, process variation-aware Nanoelectronic devices, circuits and systems*
  - 31 partners in 9 European countries
- Reality
  - *Reliable and Variability tolerant System-on-a-chip Design in More-Moore Technologies*
  - IMEC, STMicroelectronics, ARM, KU Leuven, U. Bologna, U. Glasgow
- Trams
  - *Terascale Reliable Adaptive Memory Systems*
  - UP Catalunya, Intel, IMEC, U. Glasgow
- Mordred
  - *Modelling of the reliability and degradation of next generation nanoelectronic devices*
  - Tampere U. of Tech., UCL, U. Glasgow, Vienna Inst. Micro., IMEC, Infineon, GSS, KU Leuven
- NanoCMOS (UK)
  - *Meeting the design challenges of nanoCMOS electronics*
  - U. Glasgow, U. Manchester, U. Southampton, U. York, U. Edinburgh, NeSC

Glasgow statistical 3D simulation tools

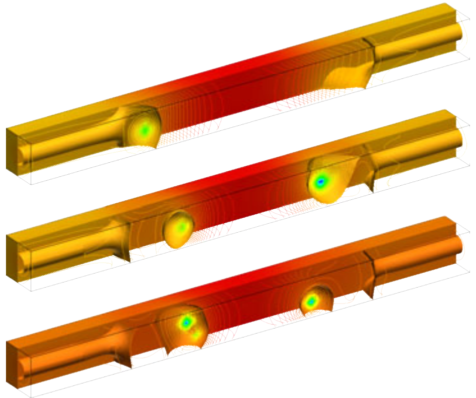
- Drift-Diffusion (DD) with quantum corrections.



- Ensemble Monte Carlo (MC) with *ab-initio* impurity scattering.

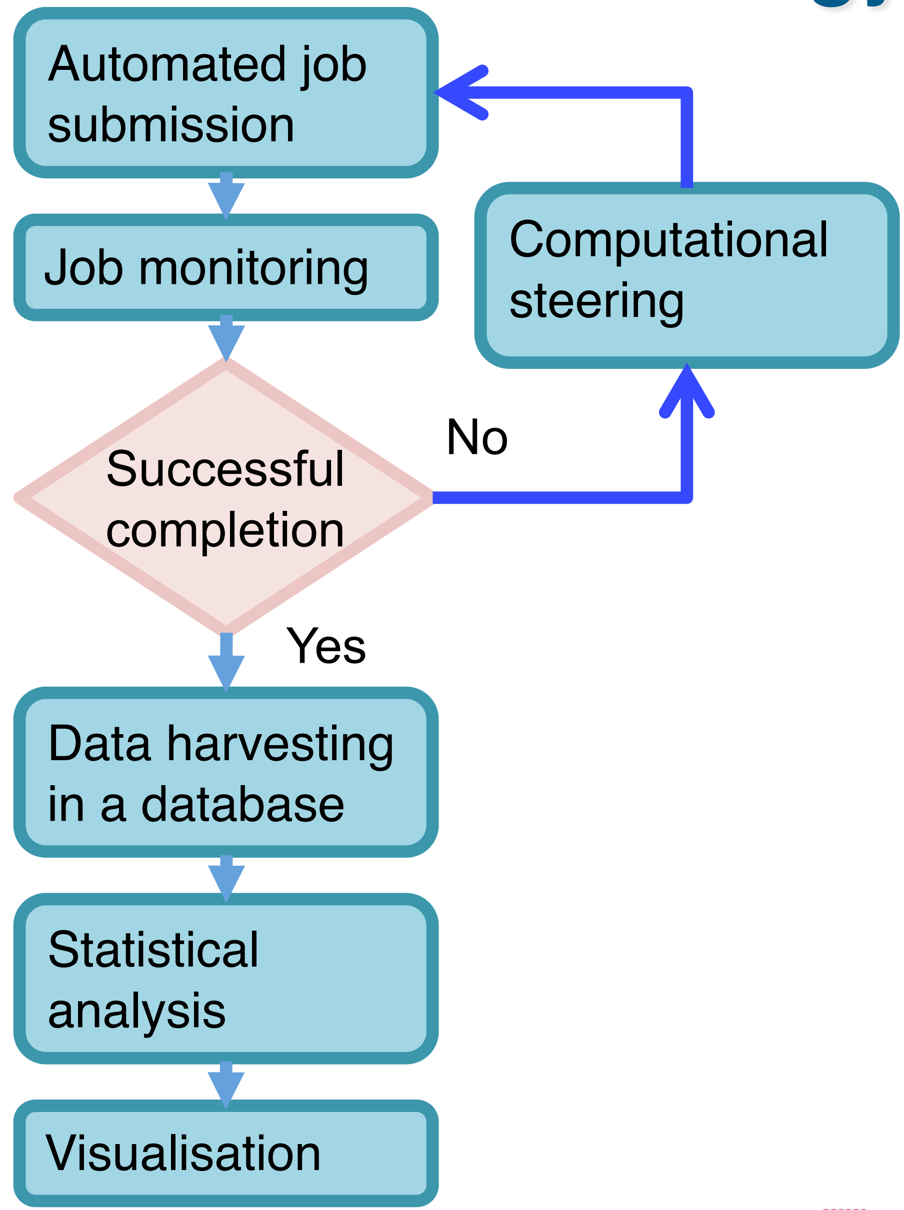


- Non-Equilibrium Green's Functions (NEGF).

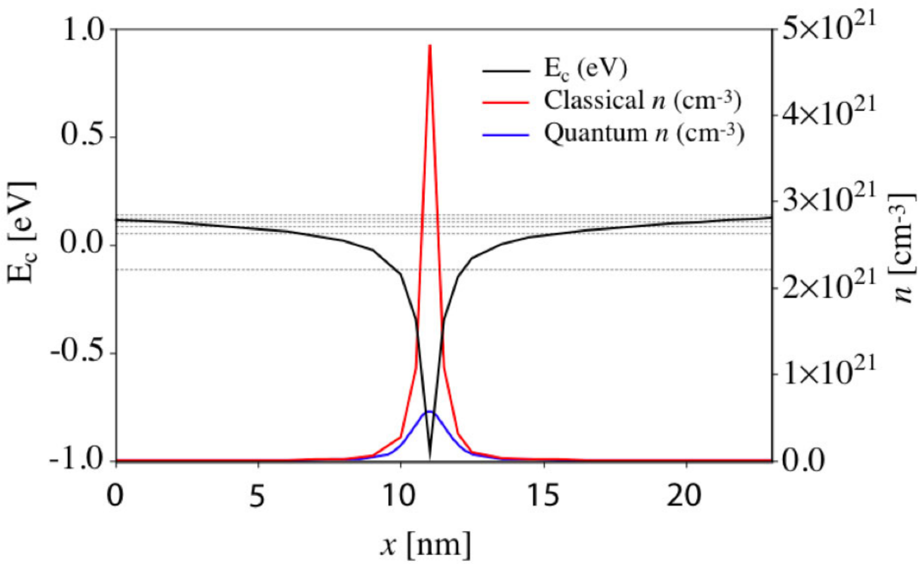


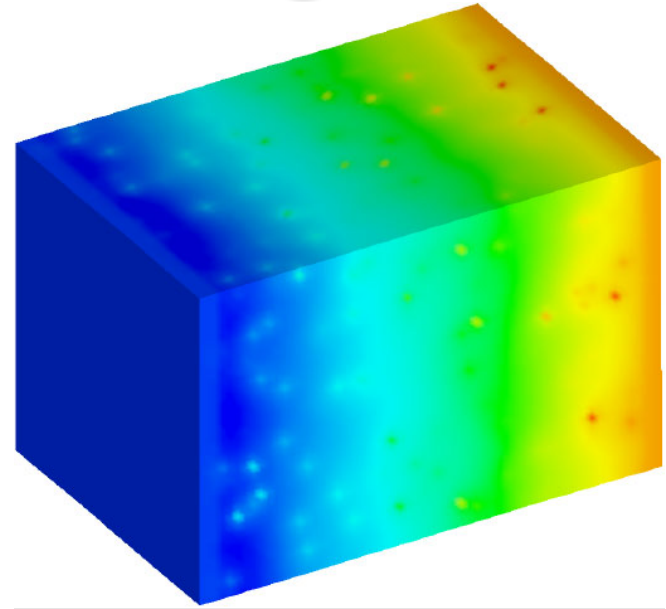
Grid/cluster based simulation technology

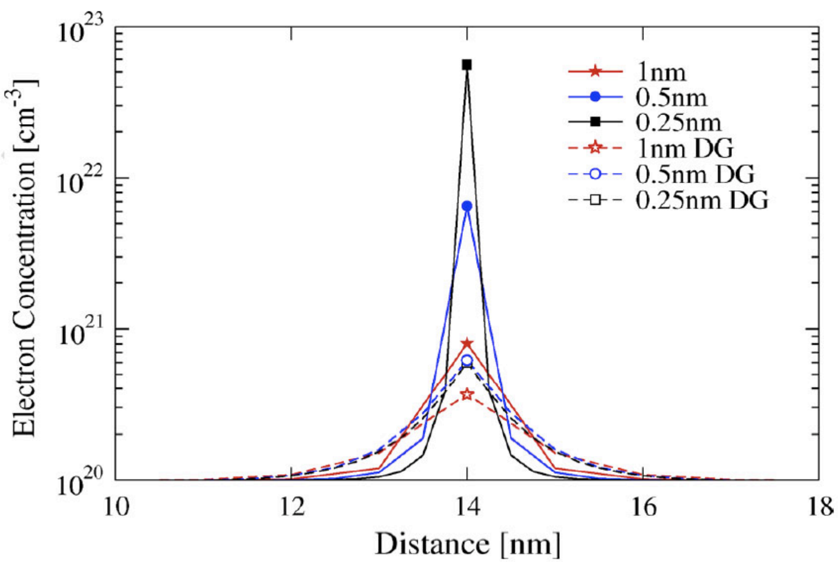
1256 CPUs

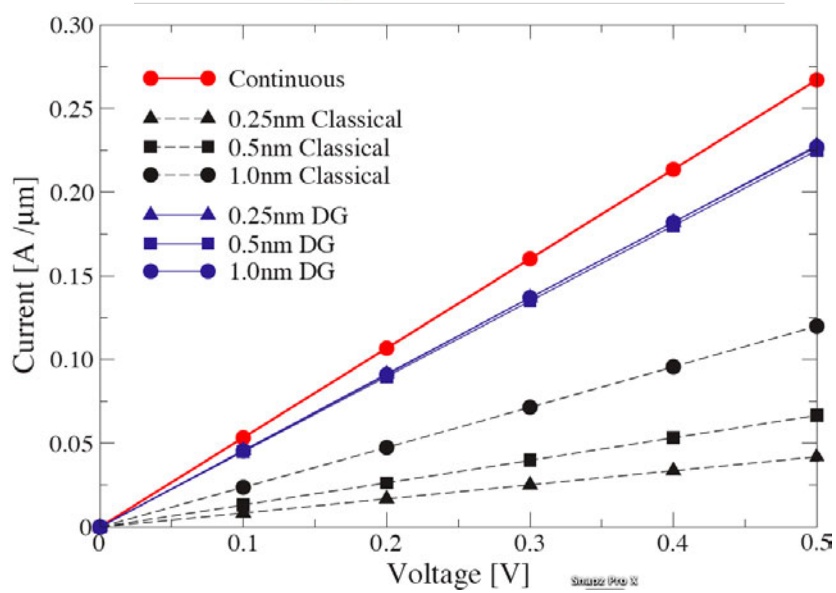


Quantum corrections using DG

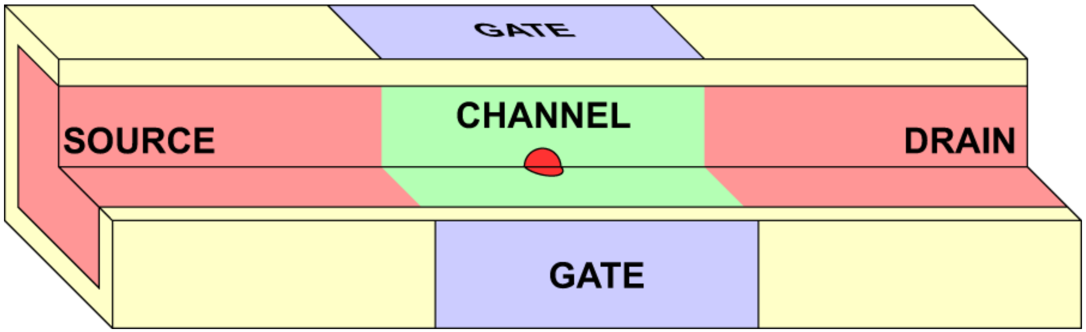


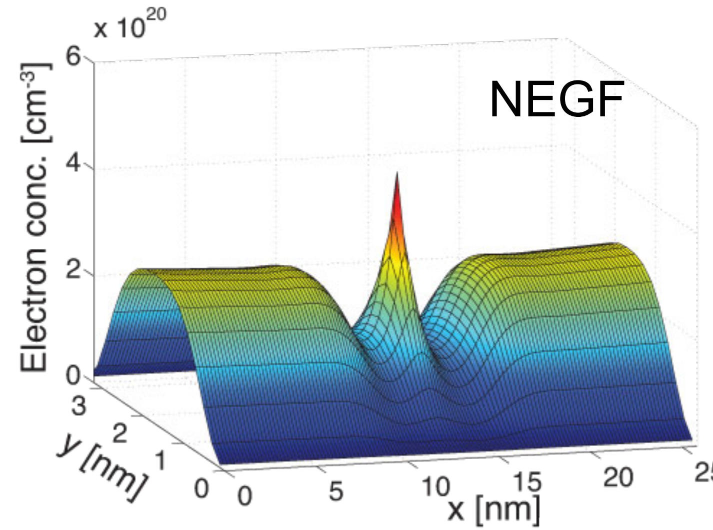


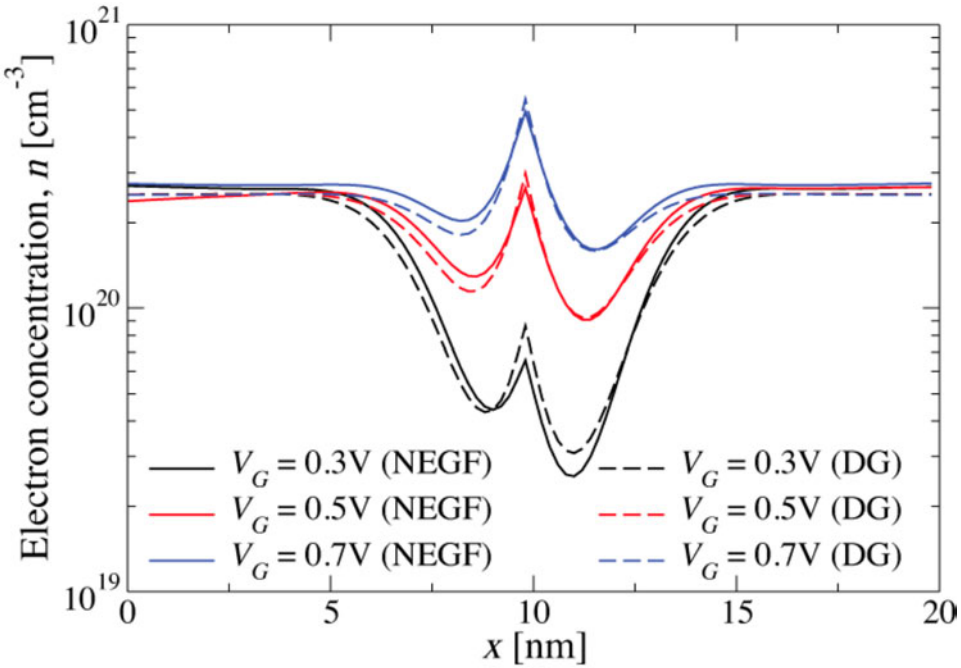


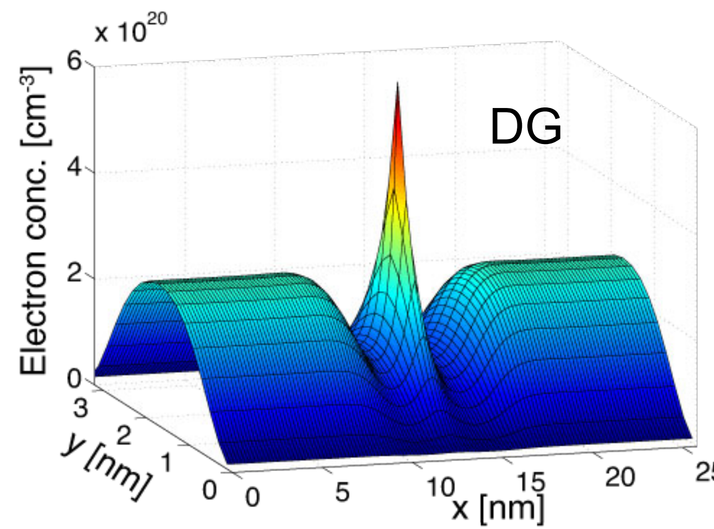


How accurate is the DG solution?





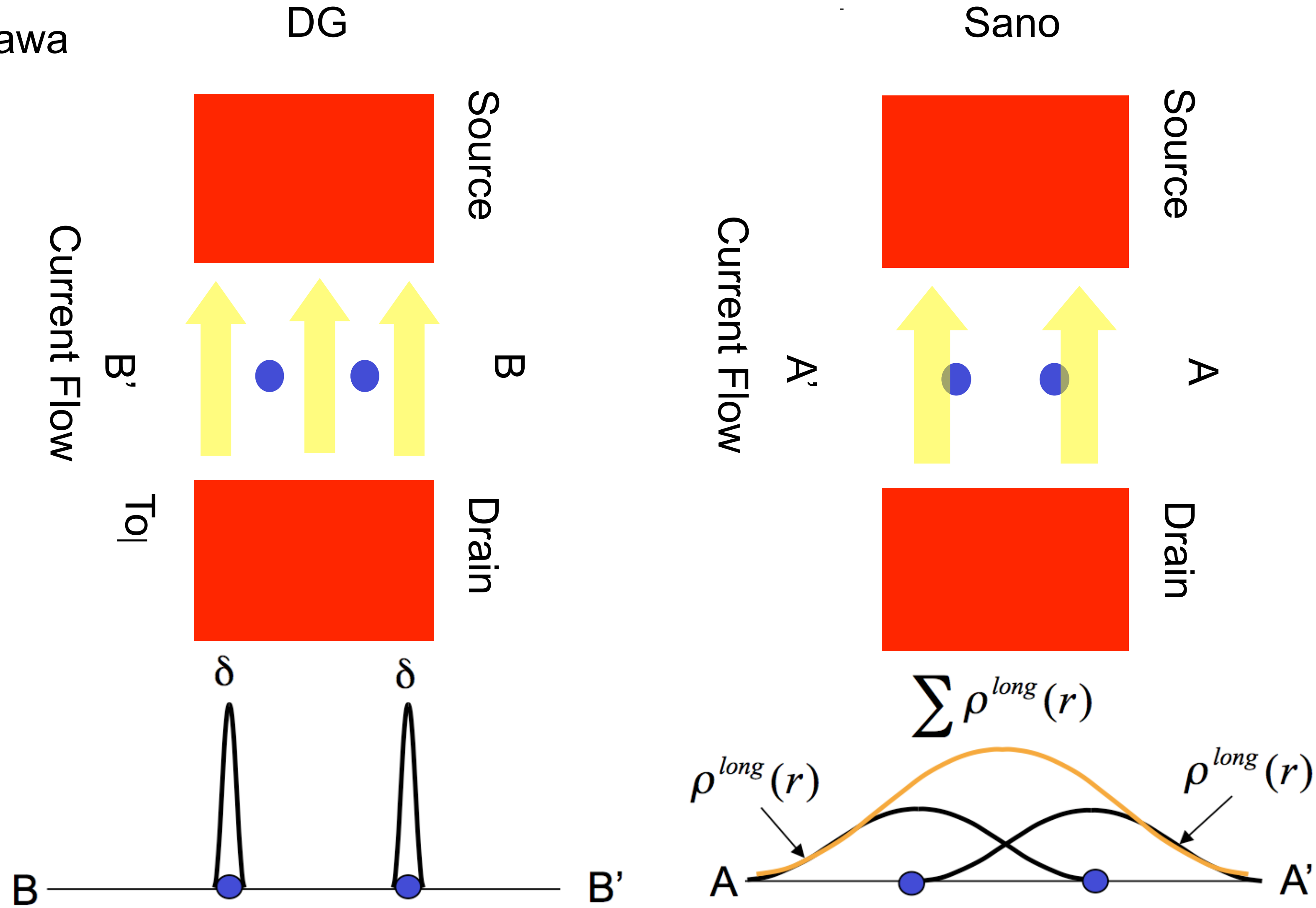




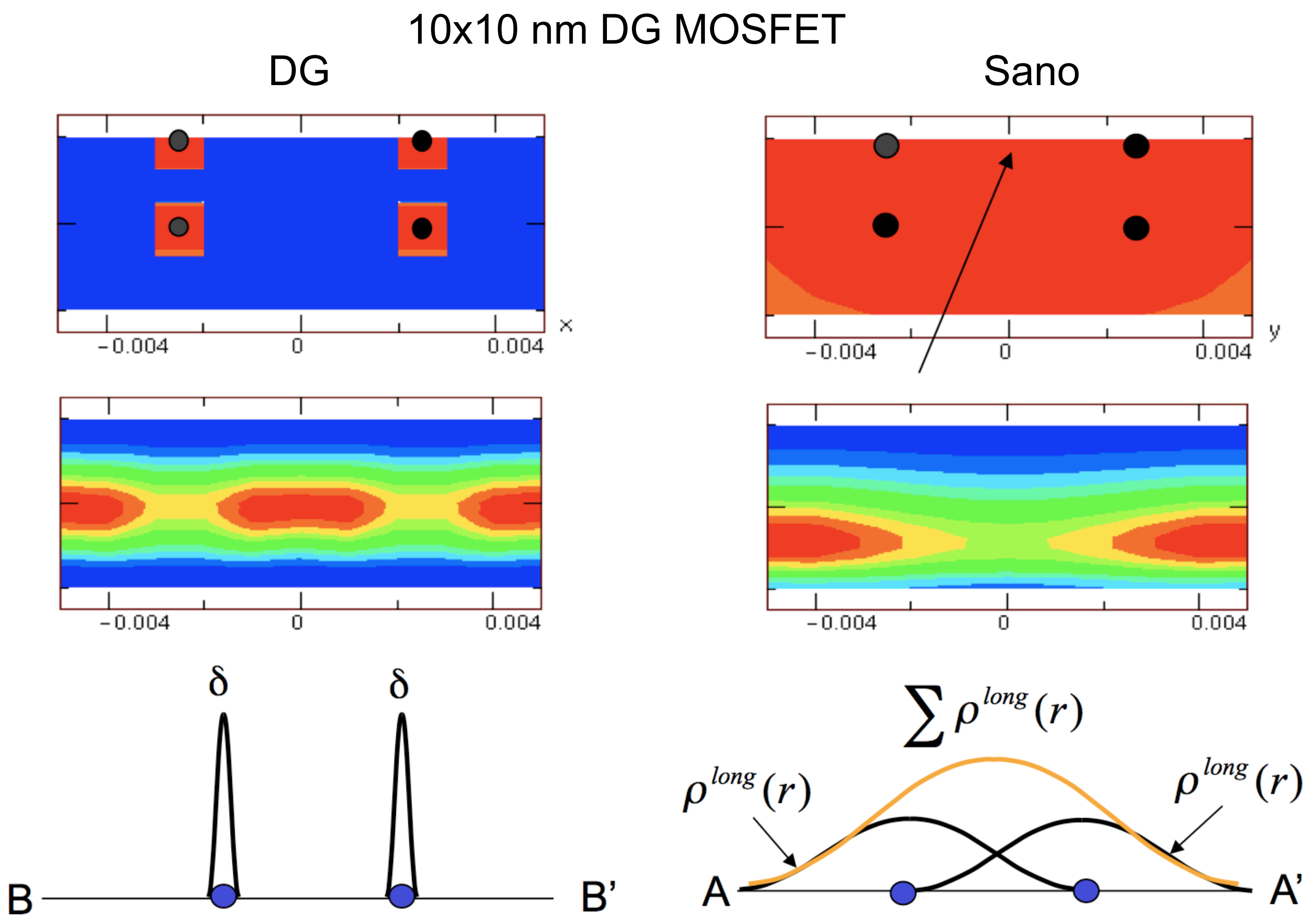
DG vs. the Sano approach

10x10 nm DG MOSFET

Y. Ashizawa (Fujitsu)

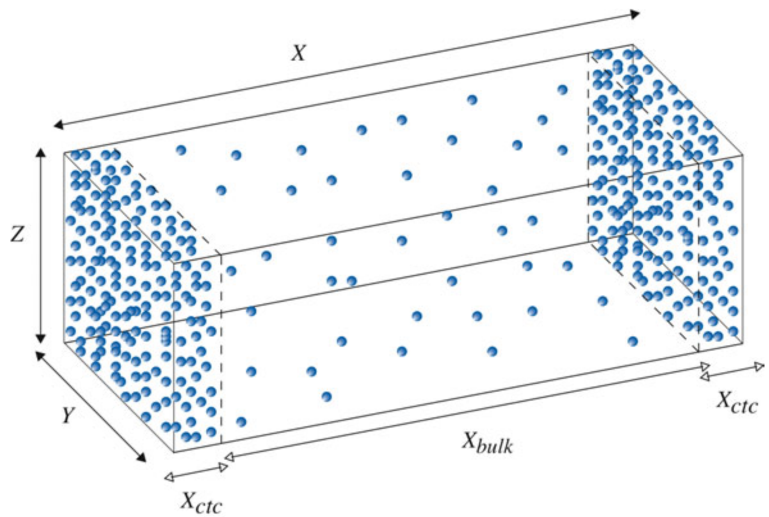


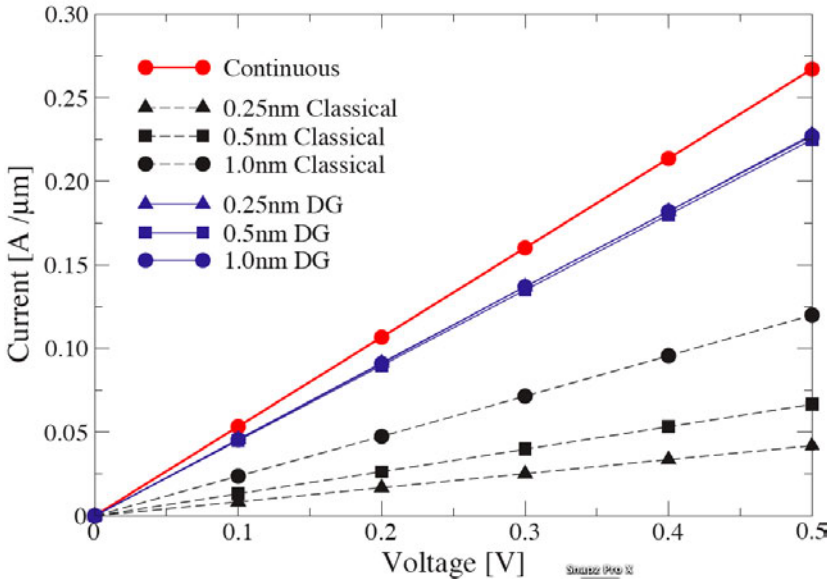
DG vs. the Sano approach



Y. Ashizawa (Fujitsu)

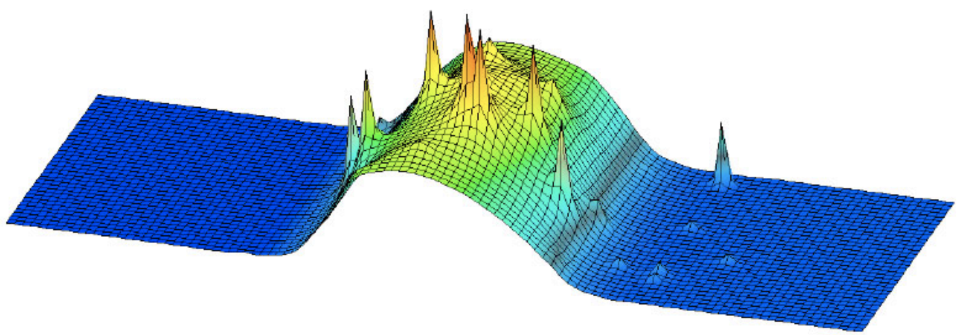
The mobility dilemma (1)
Doping concentration dependent mobility



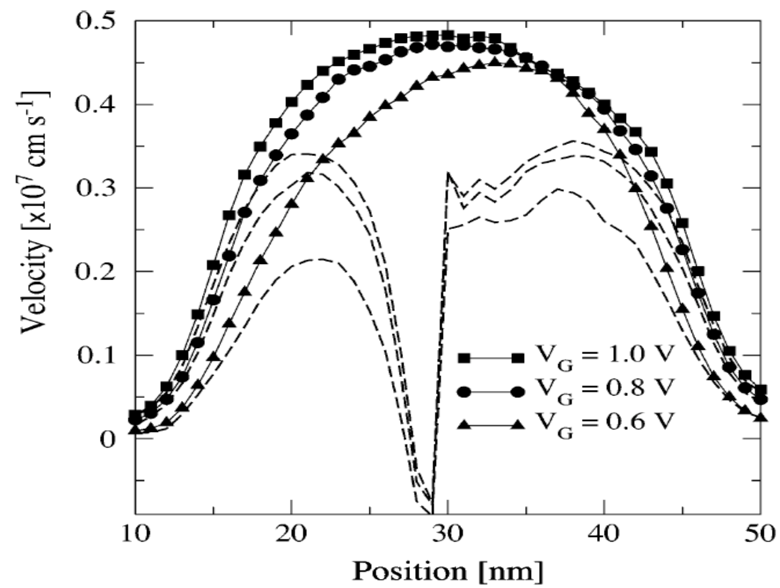


- The mobility is a statistical transport property.
- It has a meaning for sufficiently large self averaging system.
- No mobility can be assigned to individual dopants.
- Best solution is to use the continuous doping from which random dopants were generated.
- Even with DG corrections the resistance of an atomistic slab is larger compared to continuously doped one due to partial localization.

The mobility dilemma (2)
Velocity saturation, field dependence



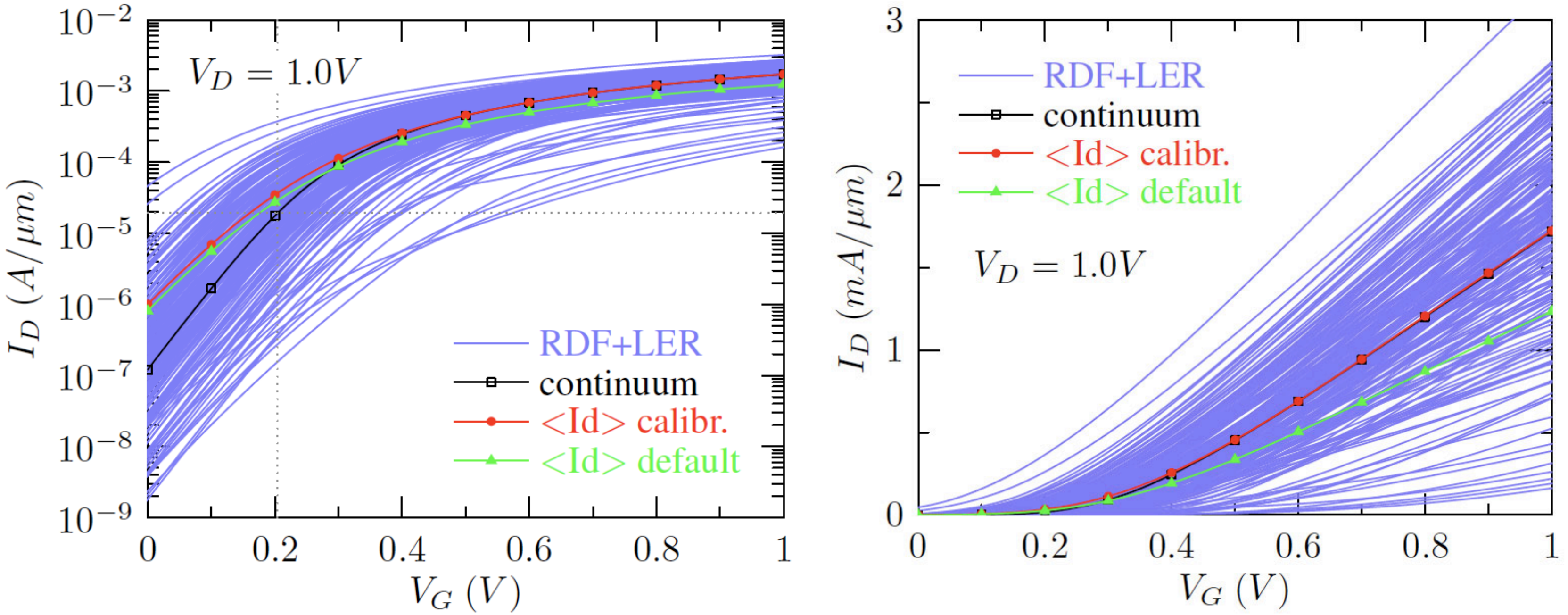
Potential distribution in a MOSFET with random dopants



Velocity distribution in a MOSFET with single dopant

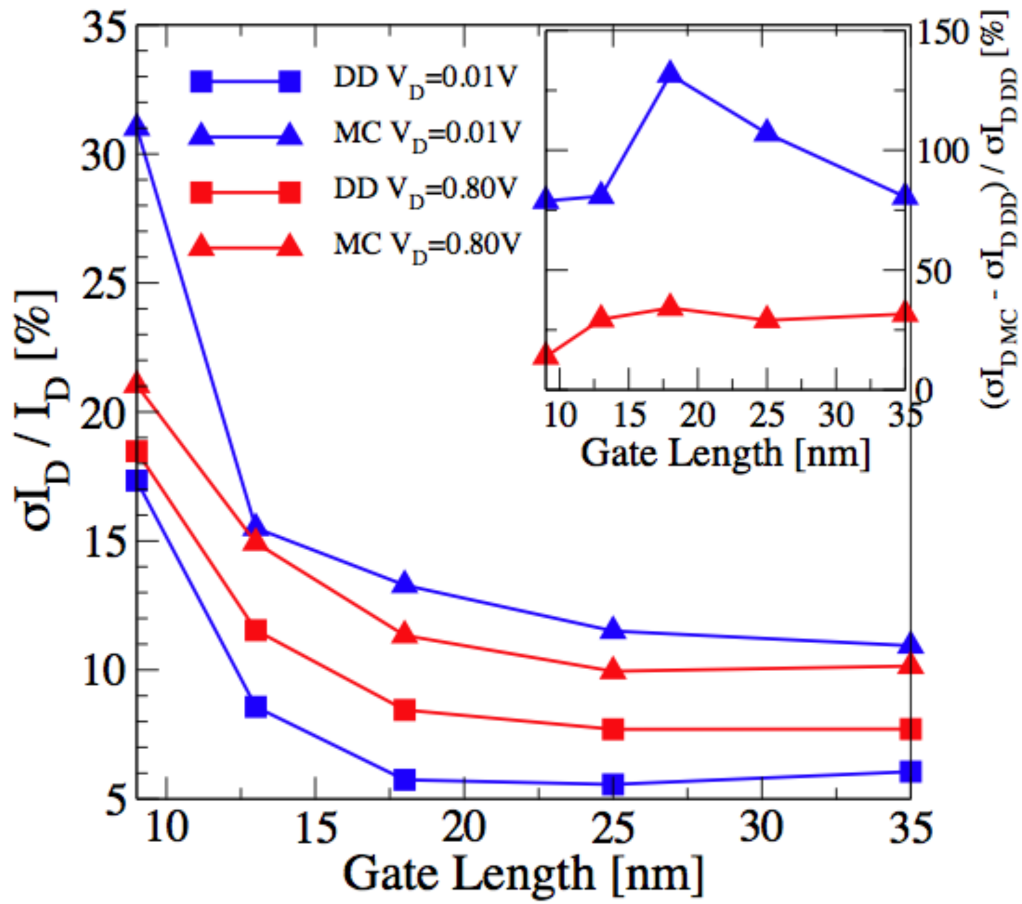
- Field dependent mobility has a meaning in 'adiabatic' conditions.
- The high electric field around single dopant cannot be used in the field dependent mobility model.
- The velocity saturation is associated with dissipative phonon scattering.
- The reduction of velocity around single dopant is associated with Coulomb scattering.

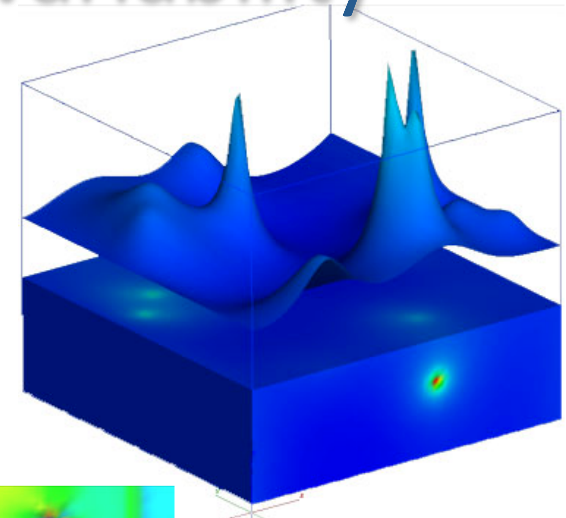
The calibration dilemma

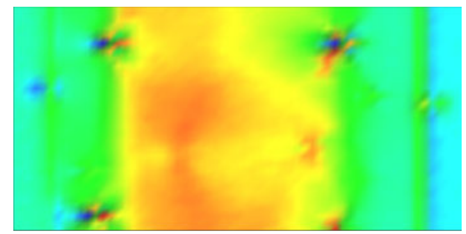


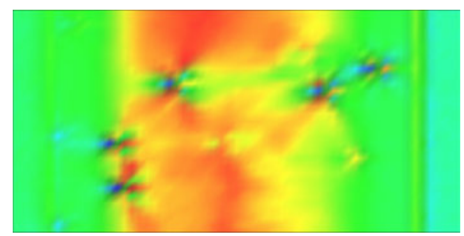
- The shape of the continuous simulation and the average ‘atomistic’ I-V curves are different.
- The calibration of continuous TCAD simulations to measurements which are equivalent to average atomistic simulation results in compensations through the mobility models..

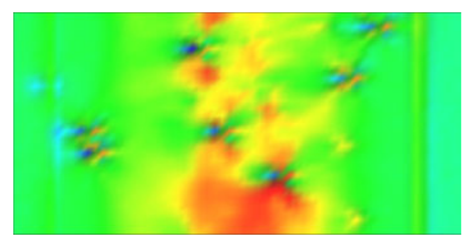
Transport (scattering) related variability





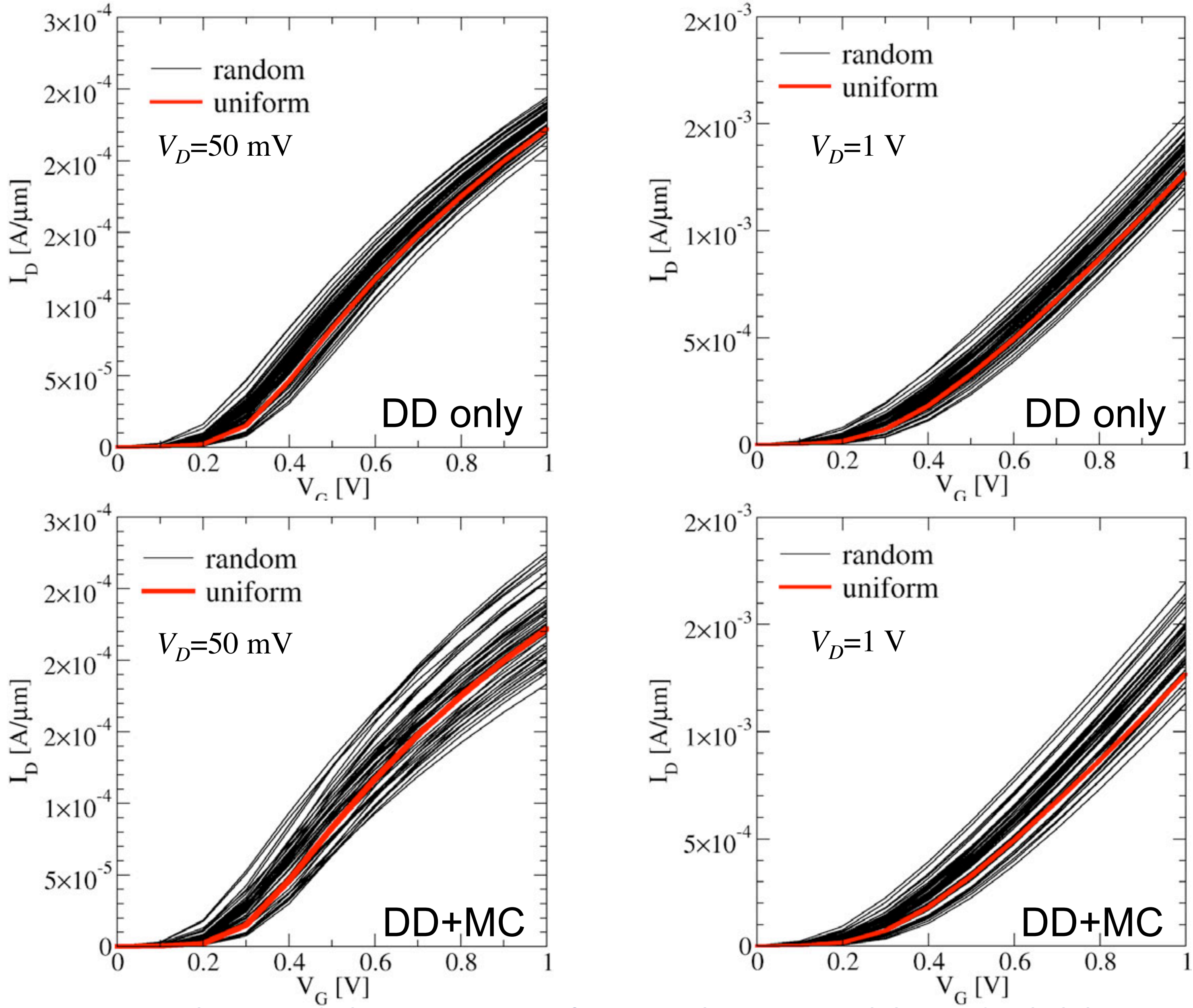




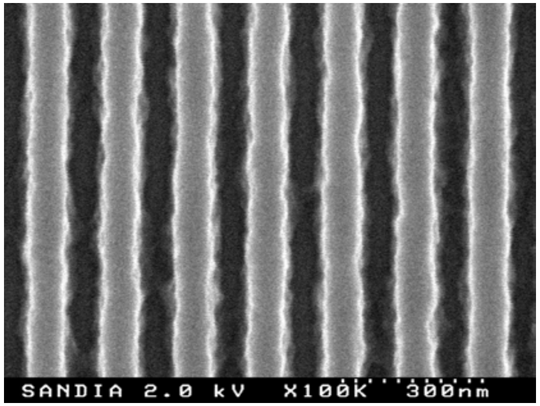


The impact of the transport related variability

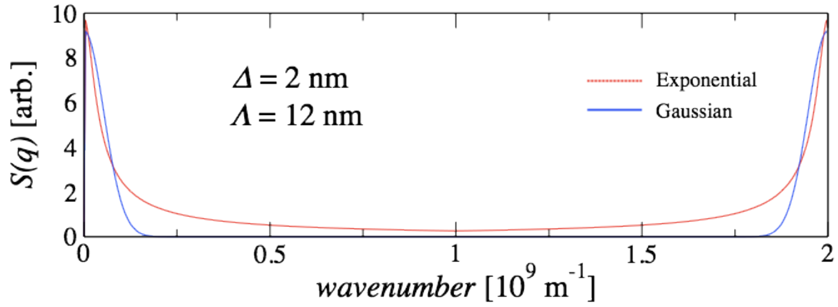
35 nm
MOSFET

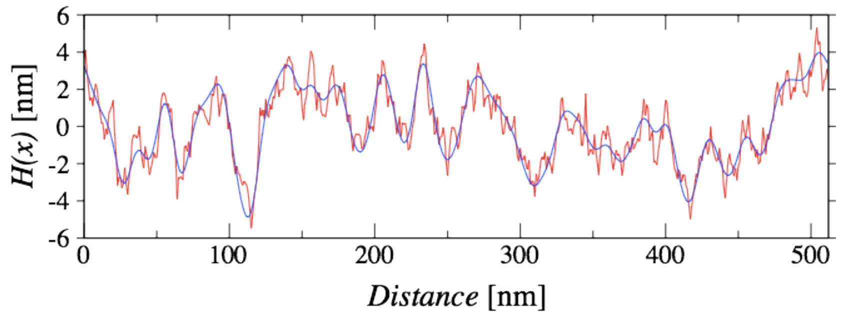


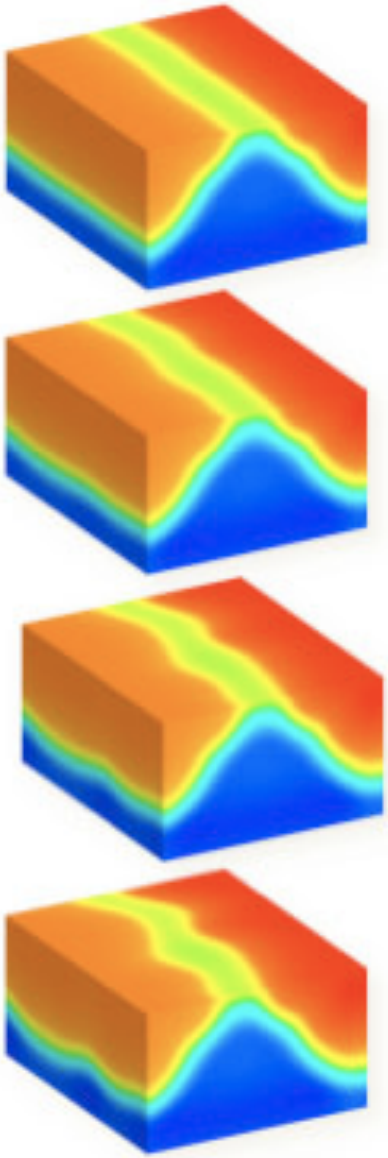
LER is notoriously difficult to reduce



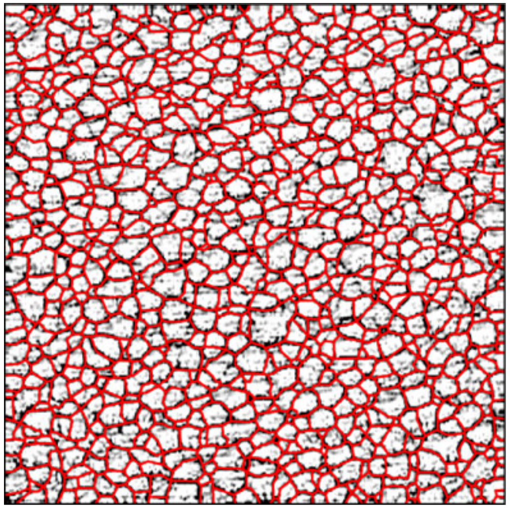
Sandia Labs – EUV

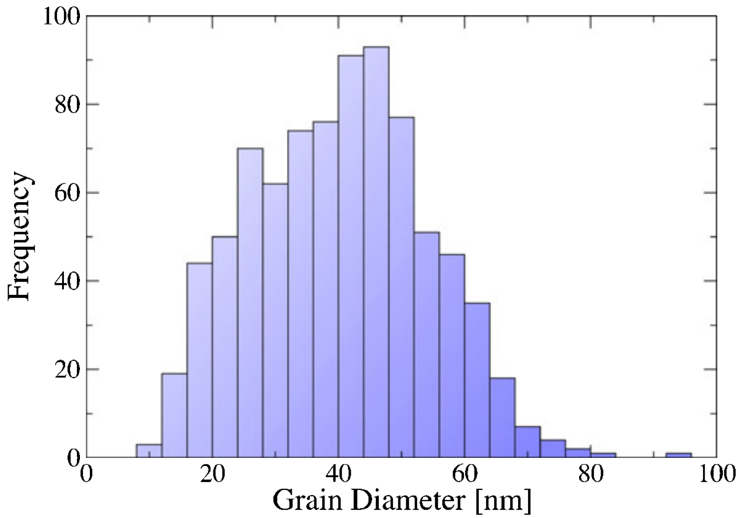


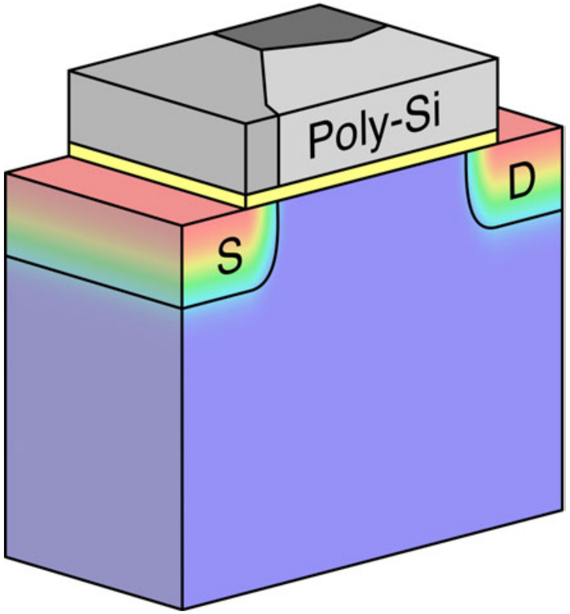


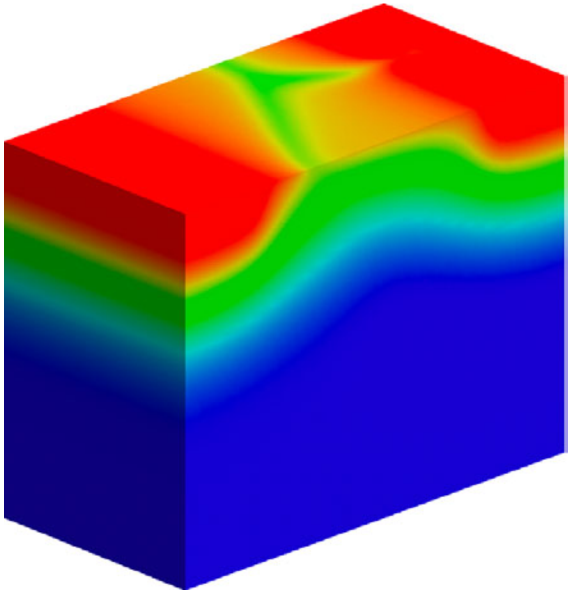


Poly-Silicon Grains

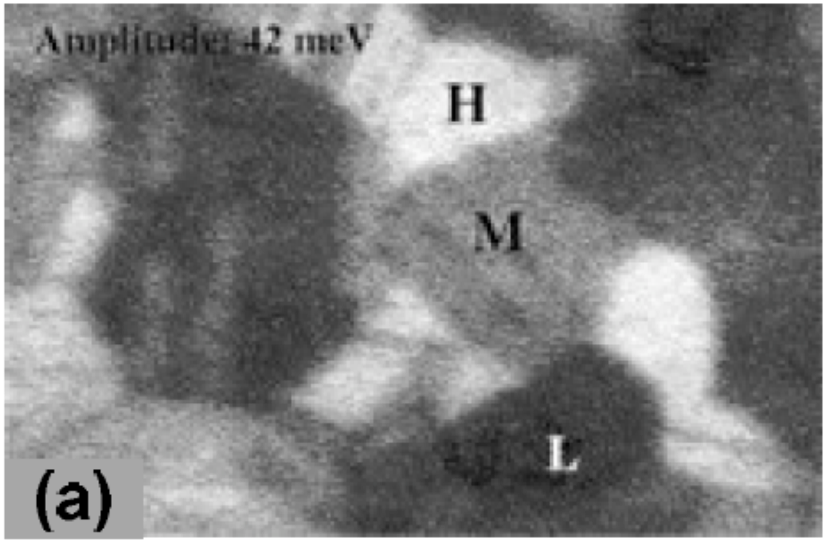




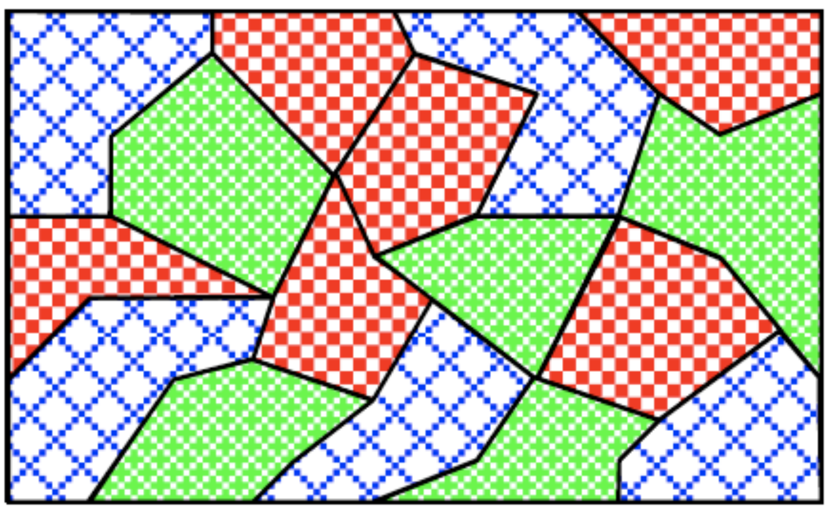


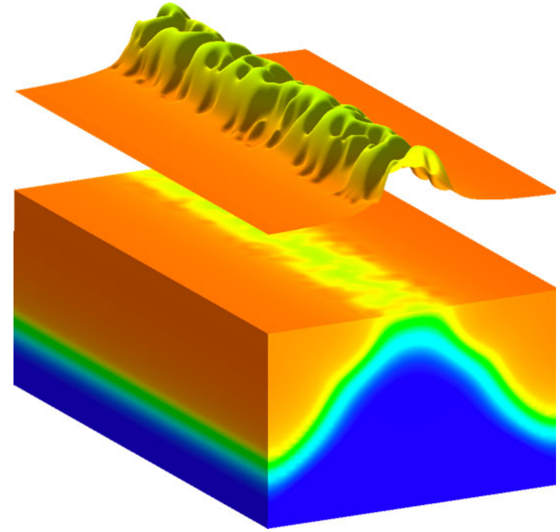


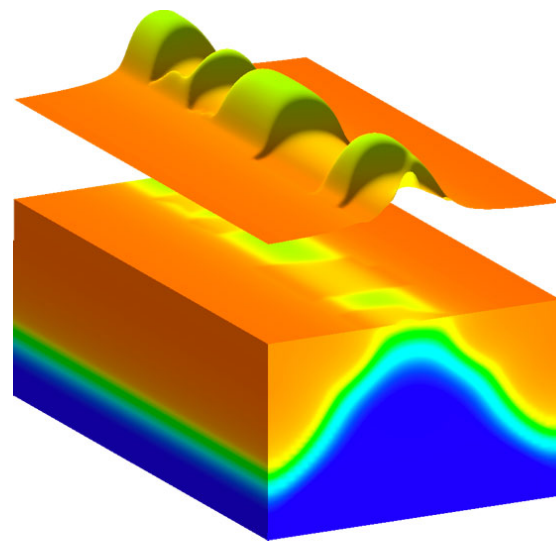
Metal gate granularity (MGG)



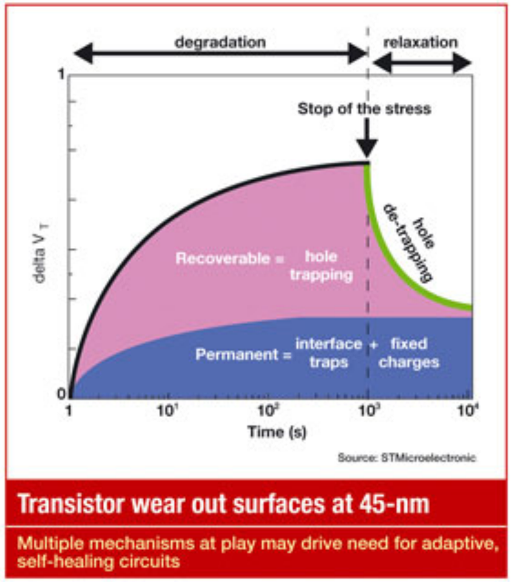
$\Phi_{111}(L) > \Phi_{100}(M) > \Phi_{110}(H)$

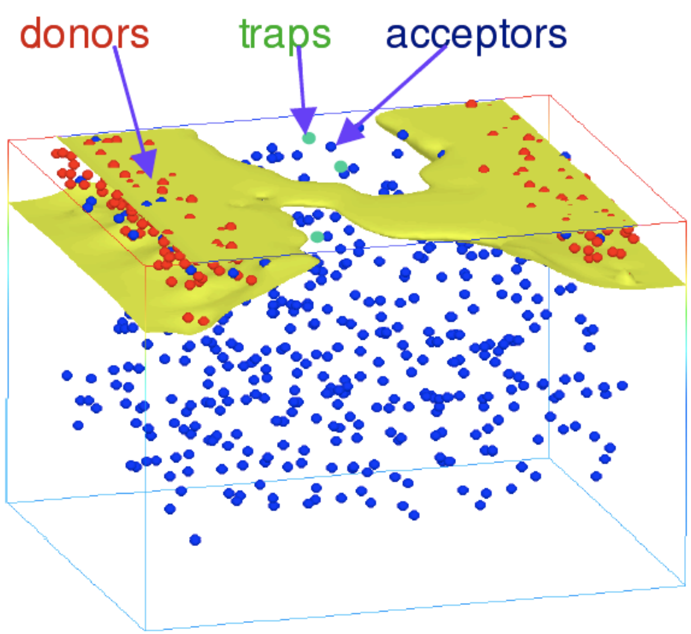


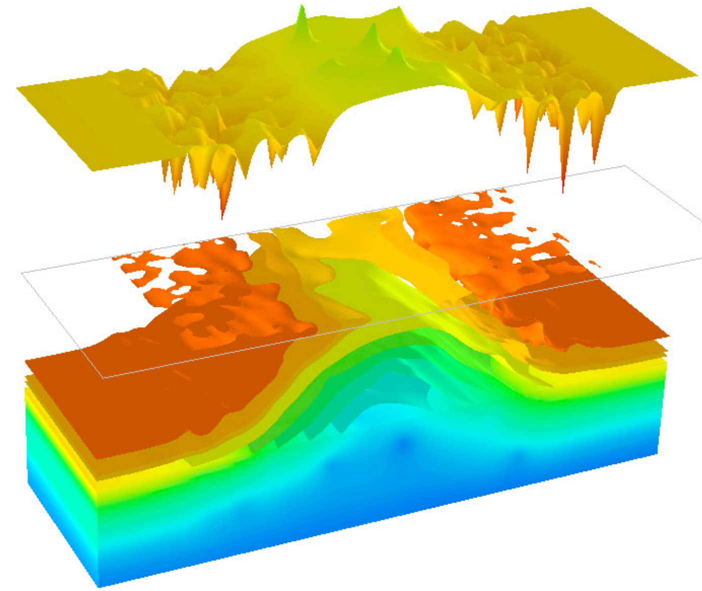


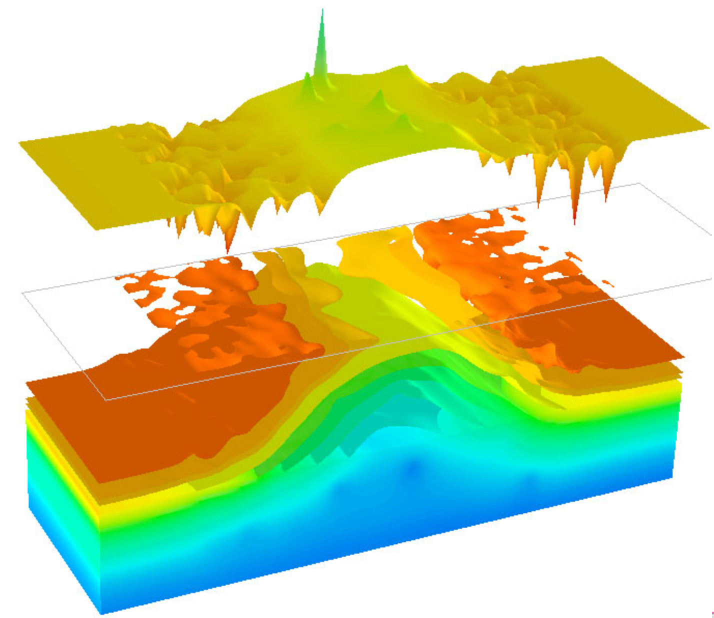


Statistical reliability: electrostatics

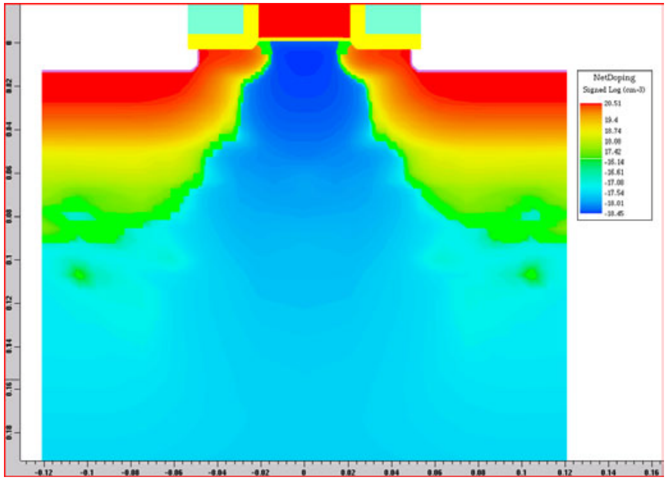


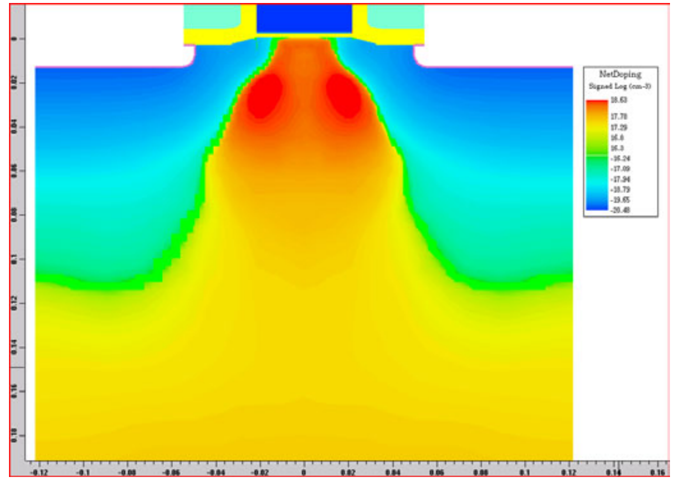


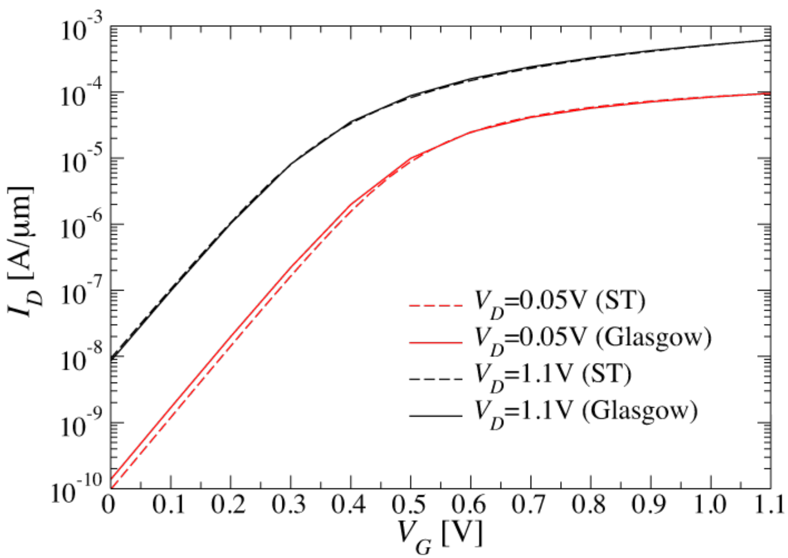


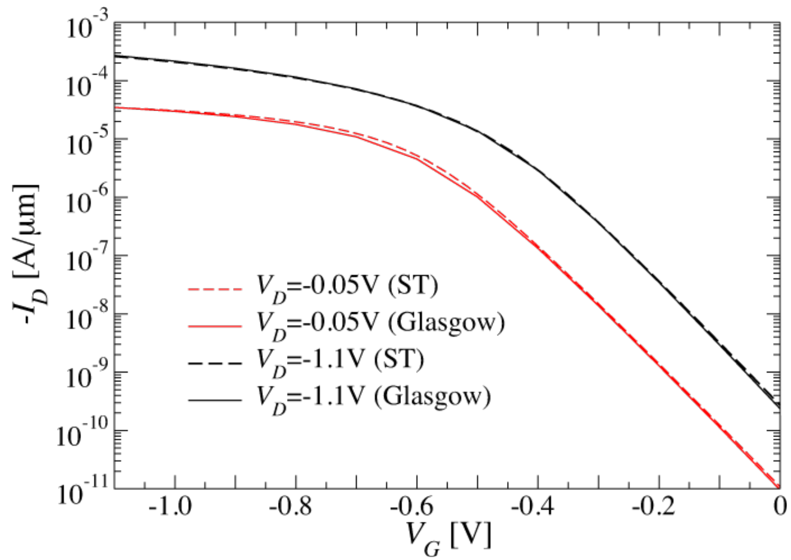


Example: 45nm
Device Structure and Calibration

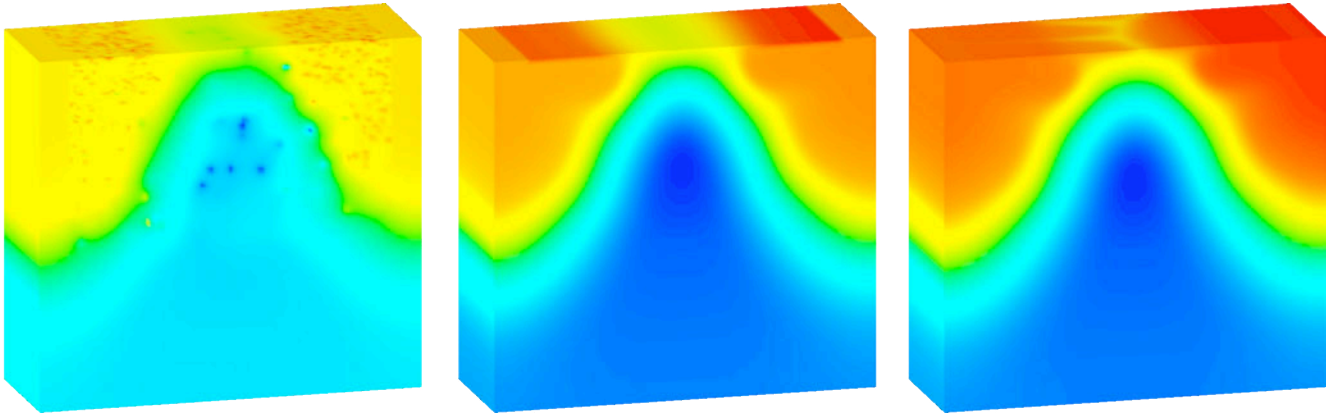






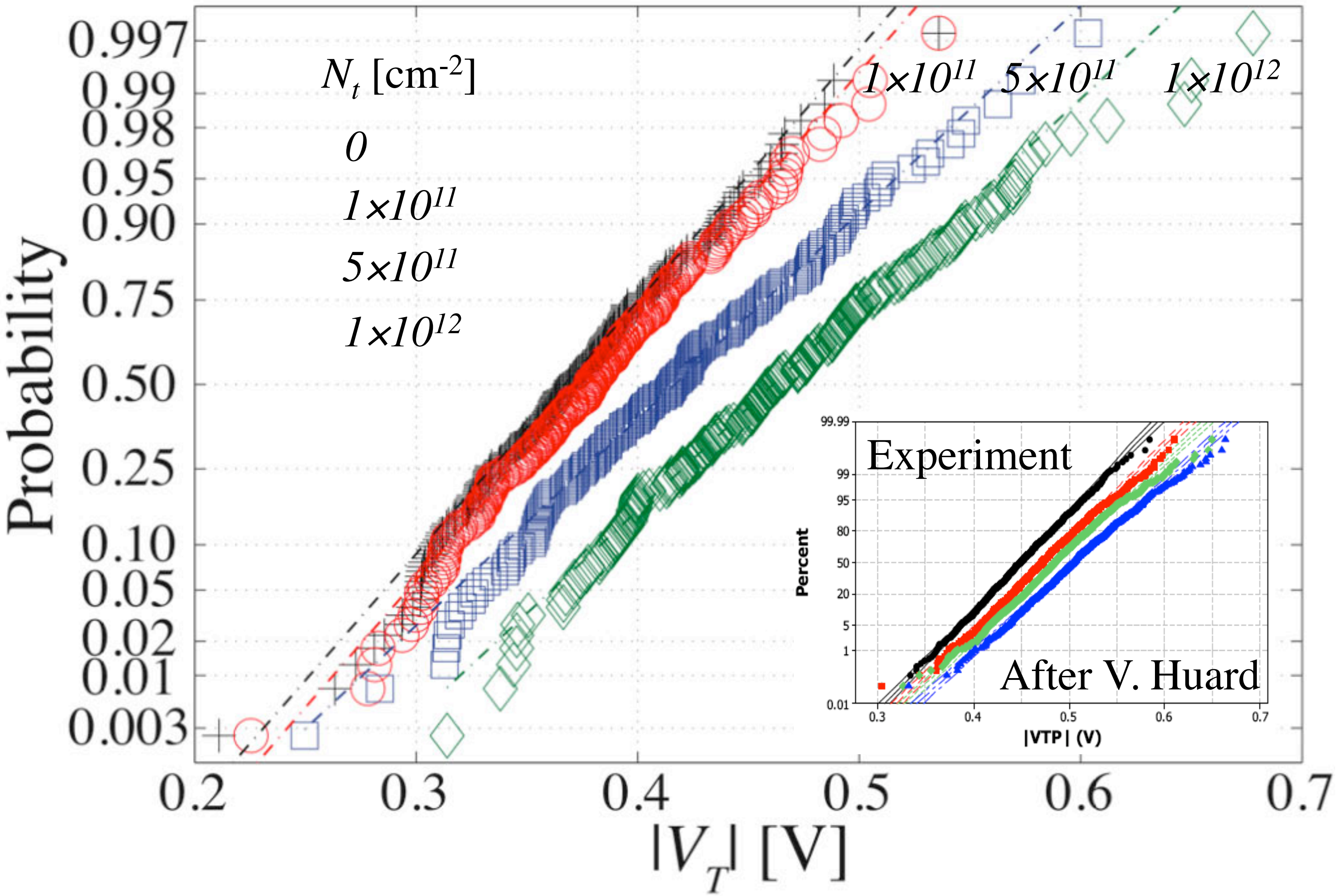


Good agreement with measurements



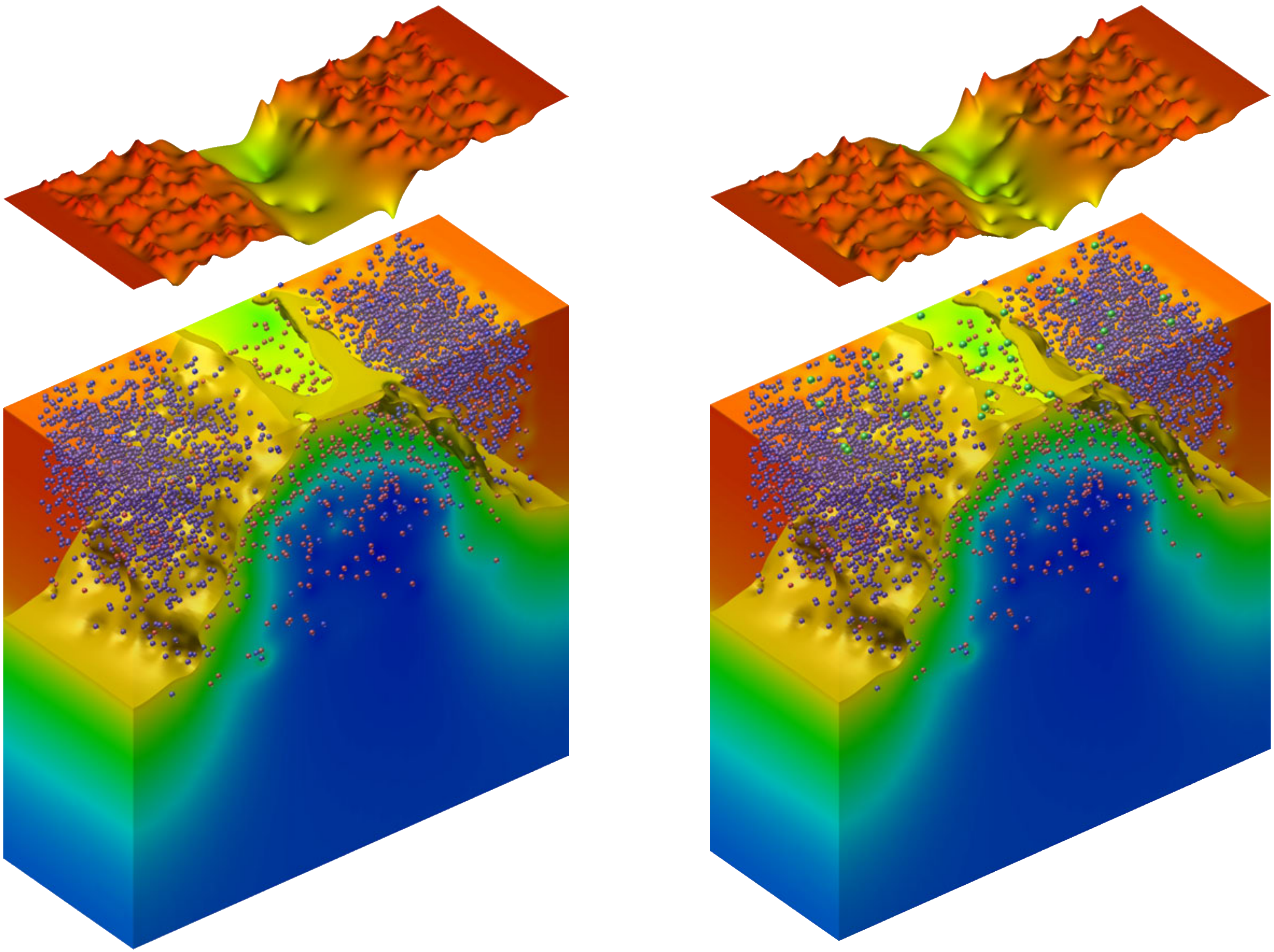
	n-channel MOSFET		*p*-channel MOSFET	
	σV_T [mV] (V_{DS}=0.05 V)	σV_T [mV] (V_{DS}=1.1 V)	σV_T [mV] (V_{DS}=0.05 V)	σV_T [mV] (V_{DS}=1.1 V)
RDD	50	52	51	54
LER	20	33	13	22
PSG	30	26	-	-
Combined	62	69	53	59
Experimental	62	67	54	57

Trapped charges (NBTI)

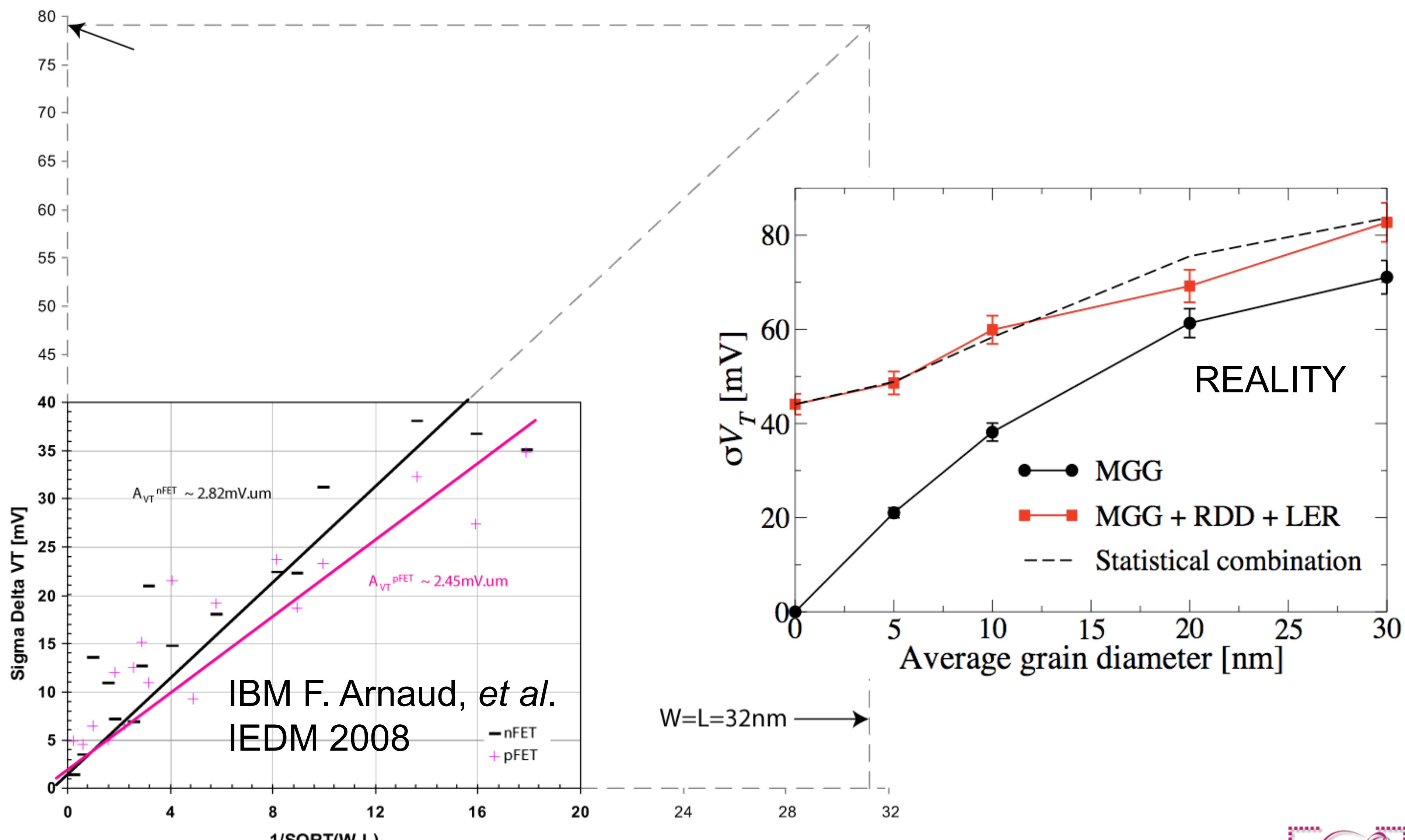


Simulation and Characterisation of Statistical CMOS Variability and Reliability
SISPAD Workshop, Bologna 9/9/2010

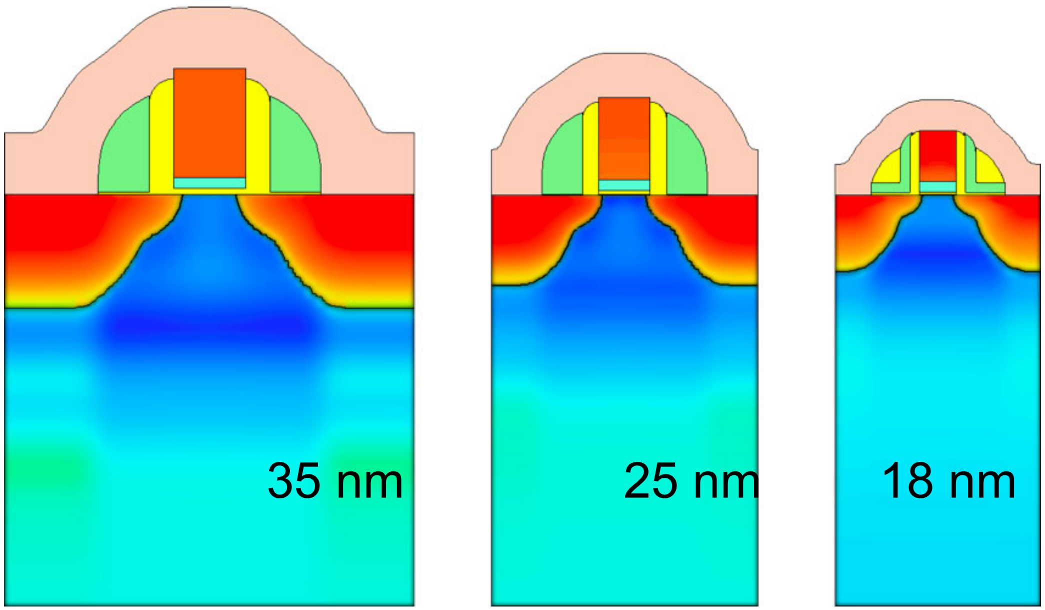
Trapped charges (NBTI)



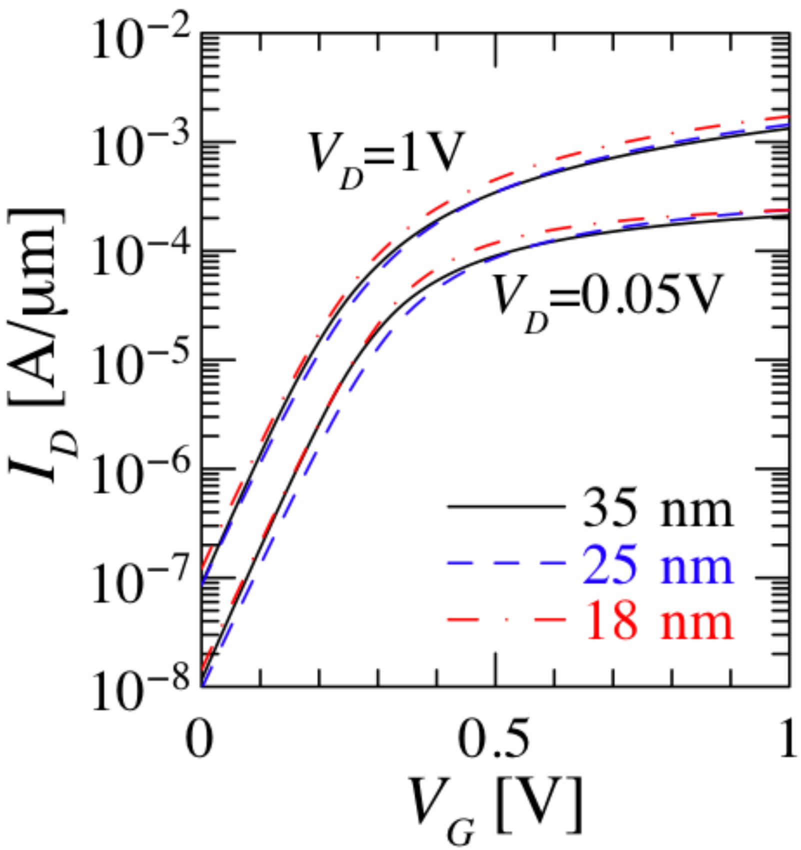
32nm Metal Gate Granularity



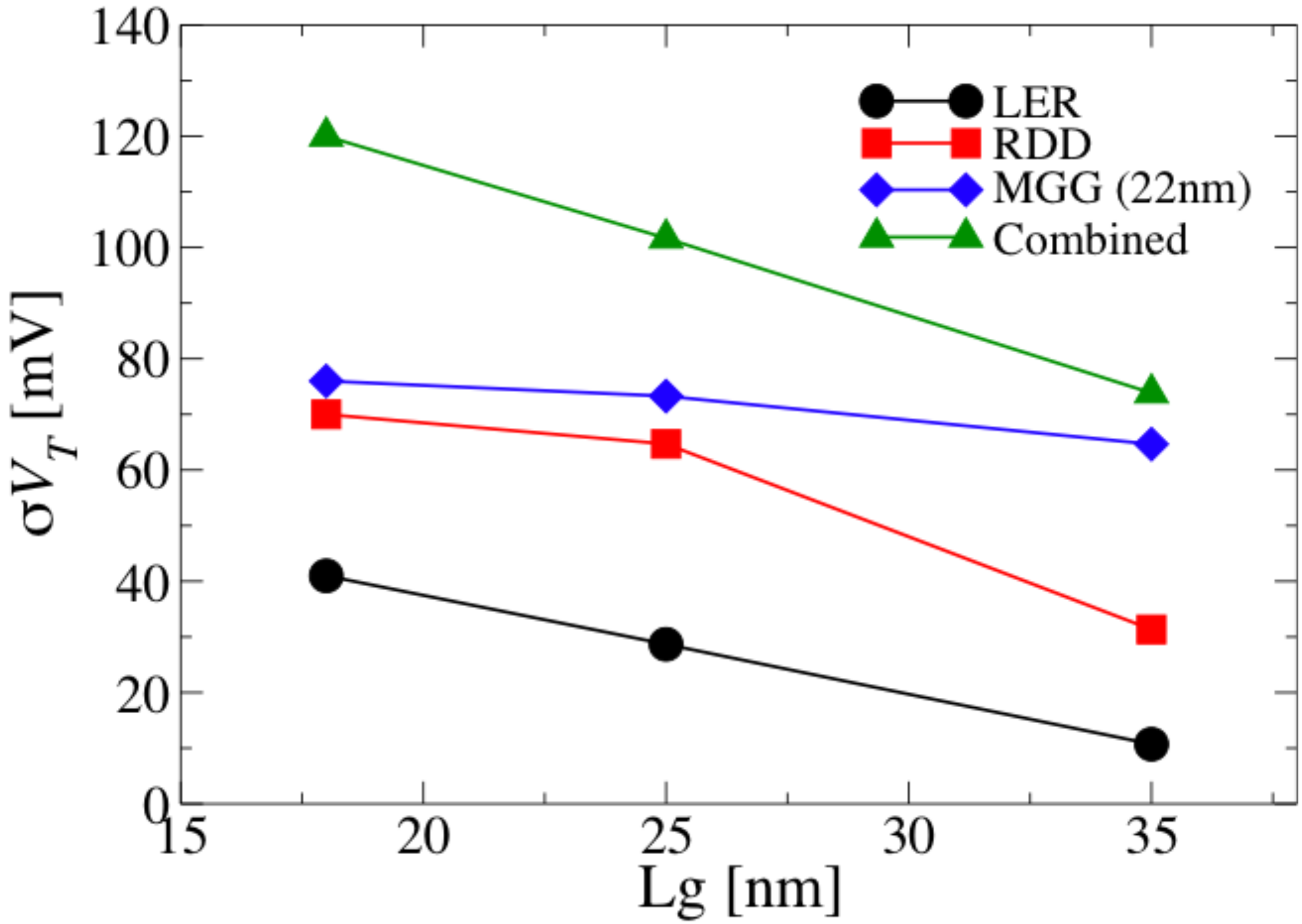
Updated scaling – high-k/metal gate



L_{gate} (nm)	35	25	18
EOT (nm)	1.0	0.9	0.7
Stress liner thickness (nm)	30	22	15
Lateral length (nm)	200	130	100
V_{dd} (V)	1.0	1.0	1.0



Variability in high-k/metal gate MOSFETs



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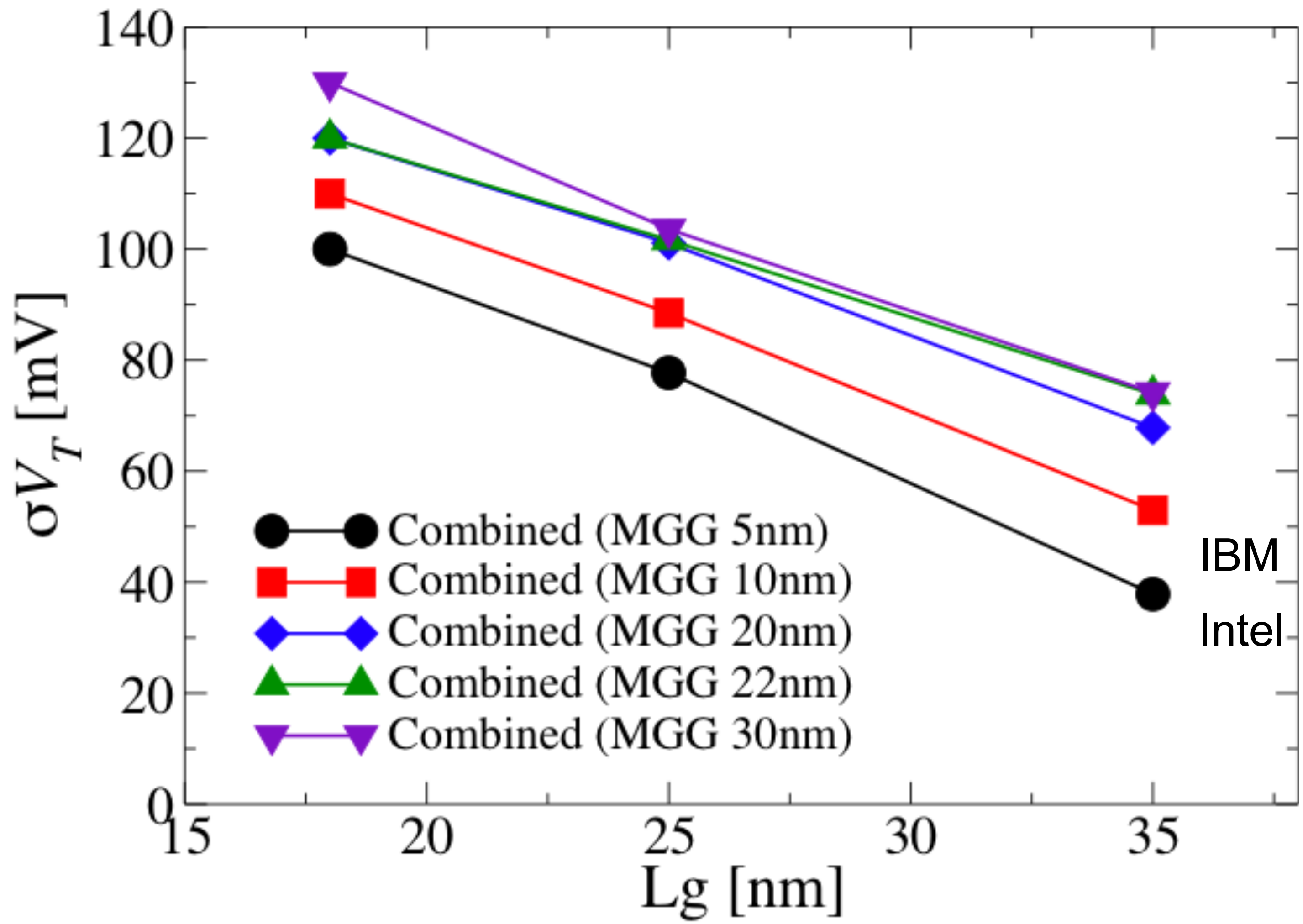
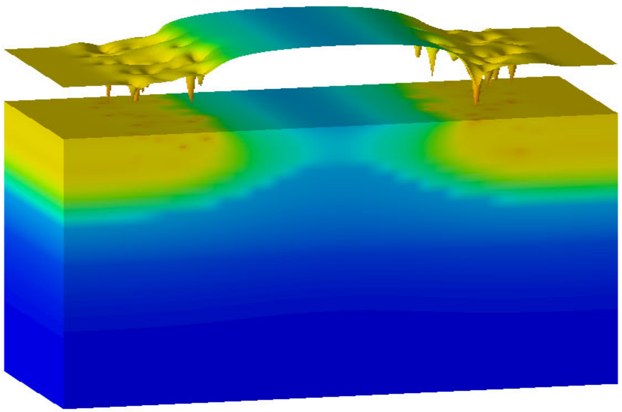


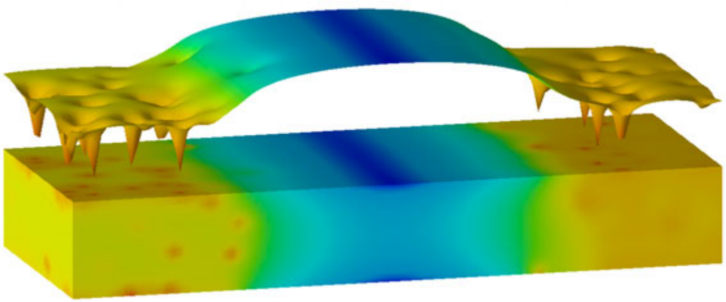
Combined with different MGG size

SOI and DG variability

32 nm FD SOI



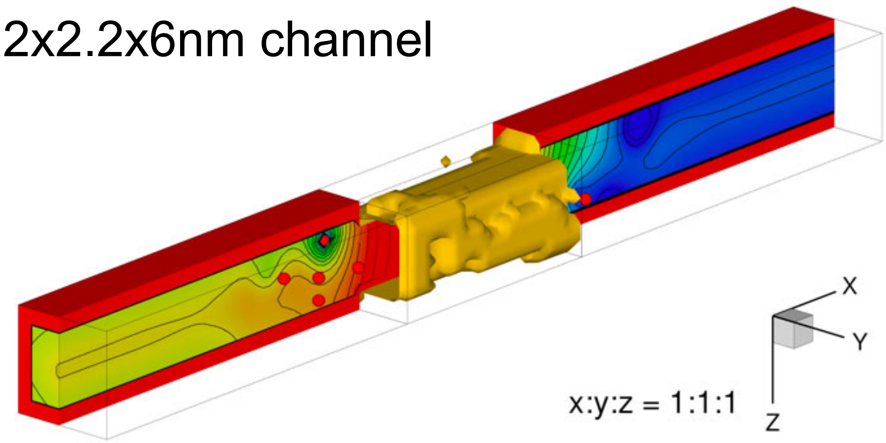
22 nm DG

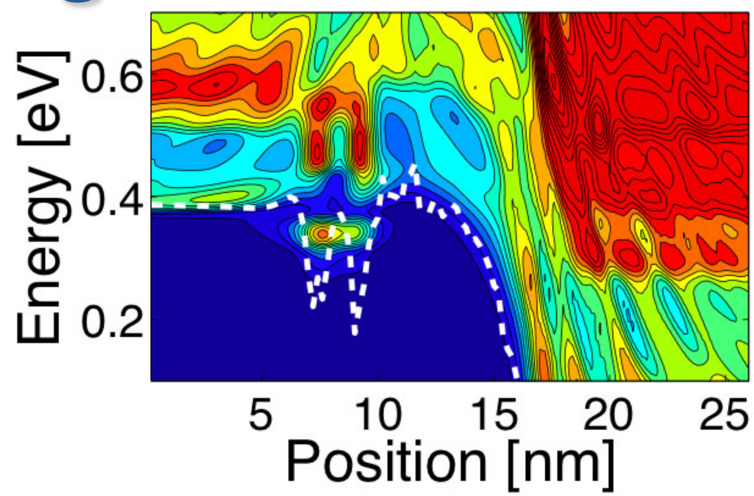


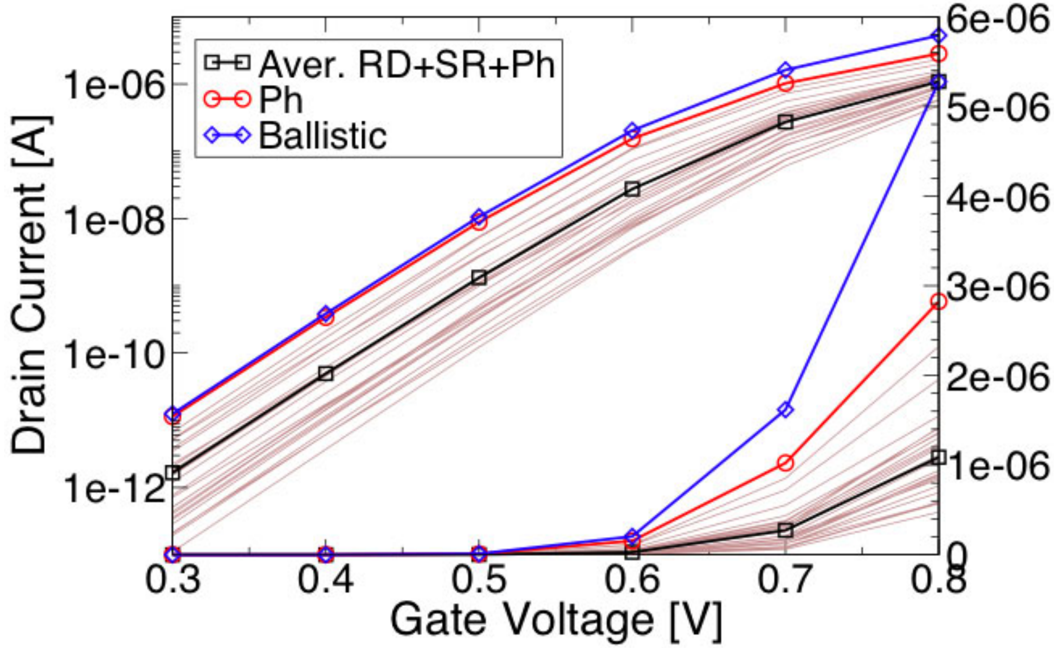
	32nm σV_T (mV)		22nm σV_T (mV)	
	V_{ds} (50mV)	V_{ds} (1.0V)	V_{ds} (50mV)	V_{ds} (1.0V)
RDD	5.3	6.1	6.4	8.1
LER	3.3	8.6	5.8	13
Trap (1e11)	11	11	5.1	4.8
Trap (5e11)	24	25	13	12
Trap (1e12)	36	37	18	17
Combined (1e11)	13	15	10	16
Combined (5e11)	25	27	16	19
Combined (1e12)	37	38	20	23

3D NEGF simulator with variability and scattering

2.2x2.2x6nm channel







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Conclusions

- There is a large amount of research being done in Europe on the study of variability and ways to deal with it in circuits and systems
- Underpinning this work are TCAD simulations which quantify the variability at a device level
- The major sources of statistical variability have been highlighted and some of the issues involved in including them in TCAD modelling have been discussed.