



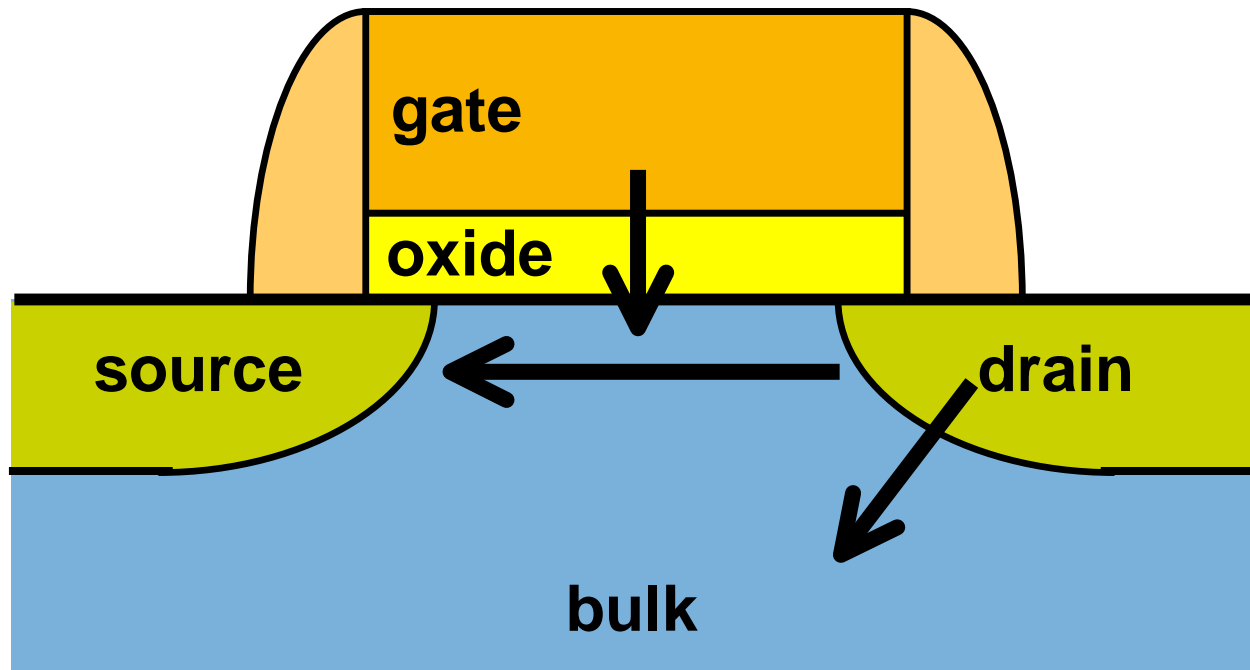
JUNCAP2 Express: *extremely efficient evaluation of the JUNCAP2 model*

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Eindhoven, The Netherlands

MSM-WCM, Boston, June 3rd&4th, 2008



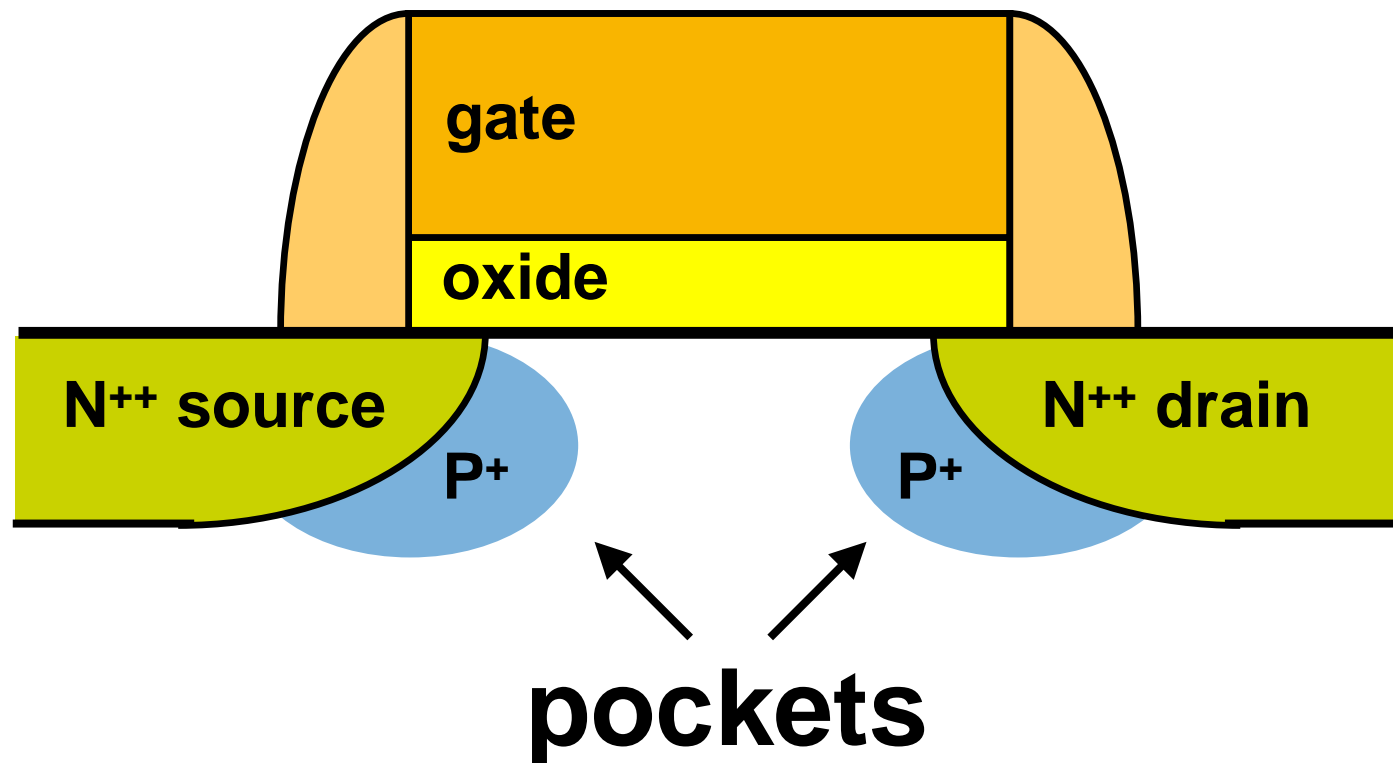
leakage currents in advanced CMOS



- ▶ source-drain leakage
- ▶ gate leakage
- ▶ junction leakage

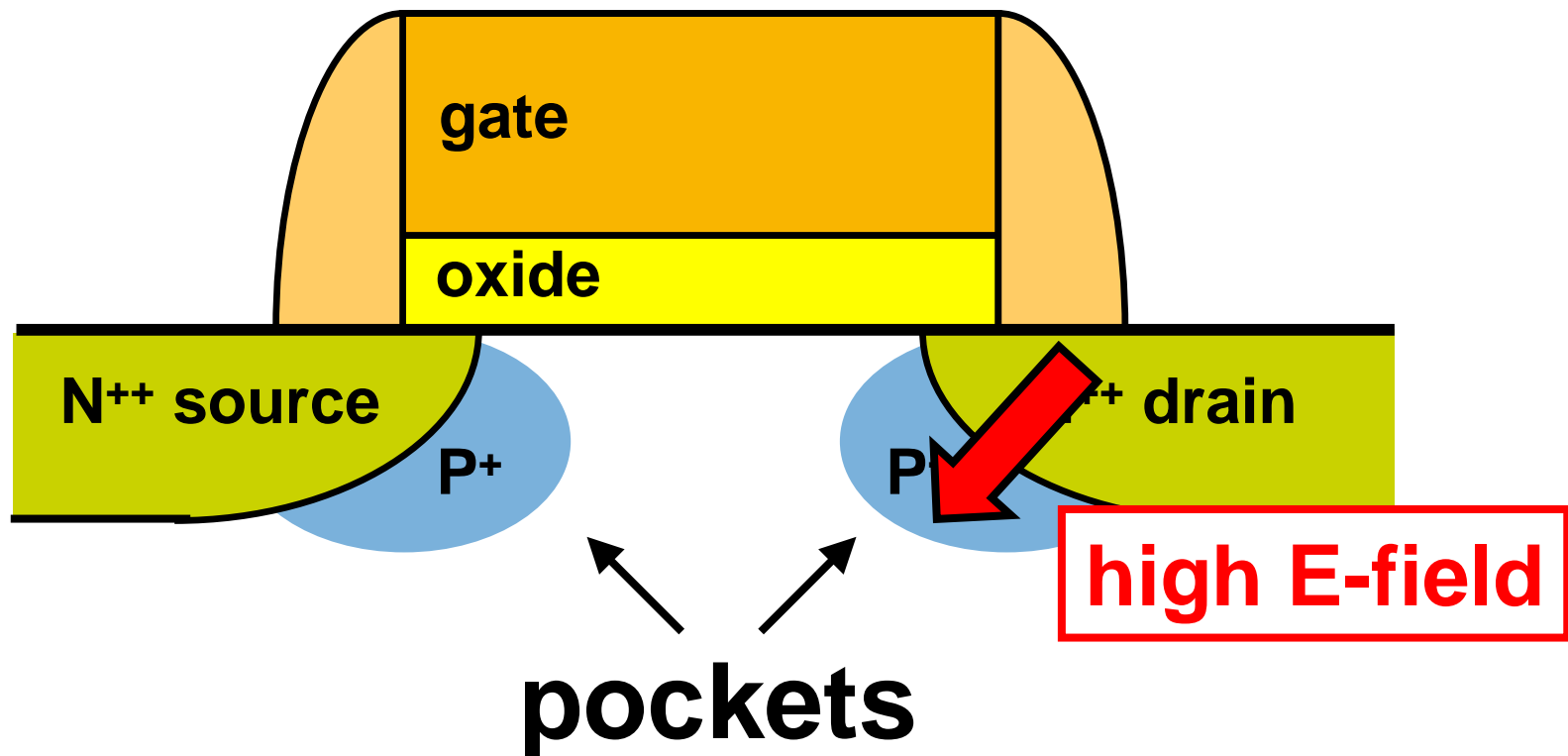
source-drain leakage in advanced CMOS

- ▶ pockets: control of short channel effects

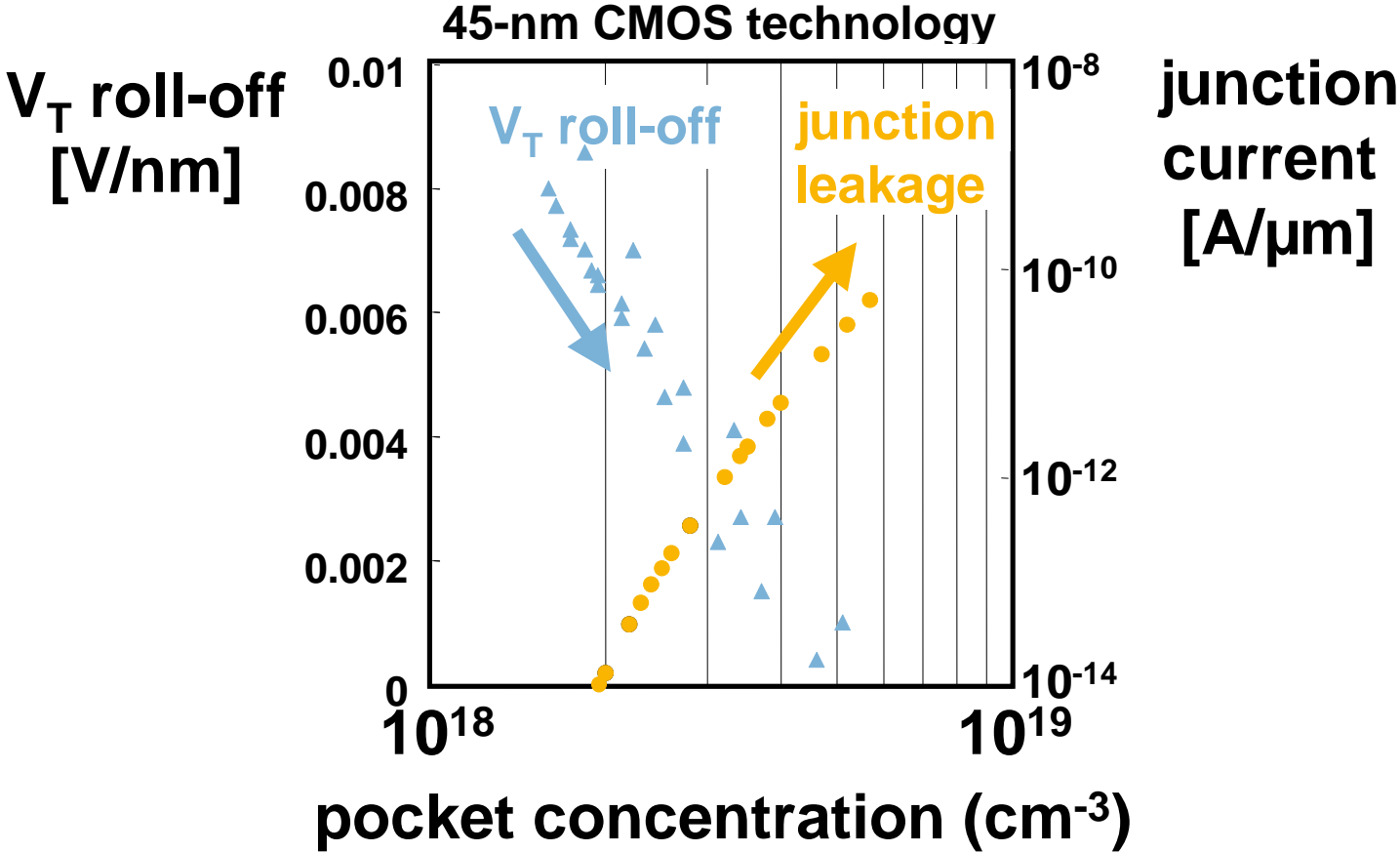


reverse junction leakage

- ▶ pockets: control of short channel effects
- ▶ high E-field at junction \rightarrow leakage!



reverse junction leakage (ii)



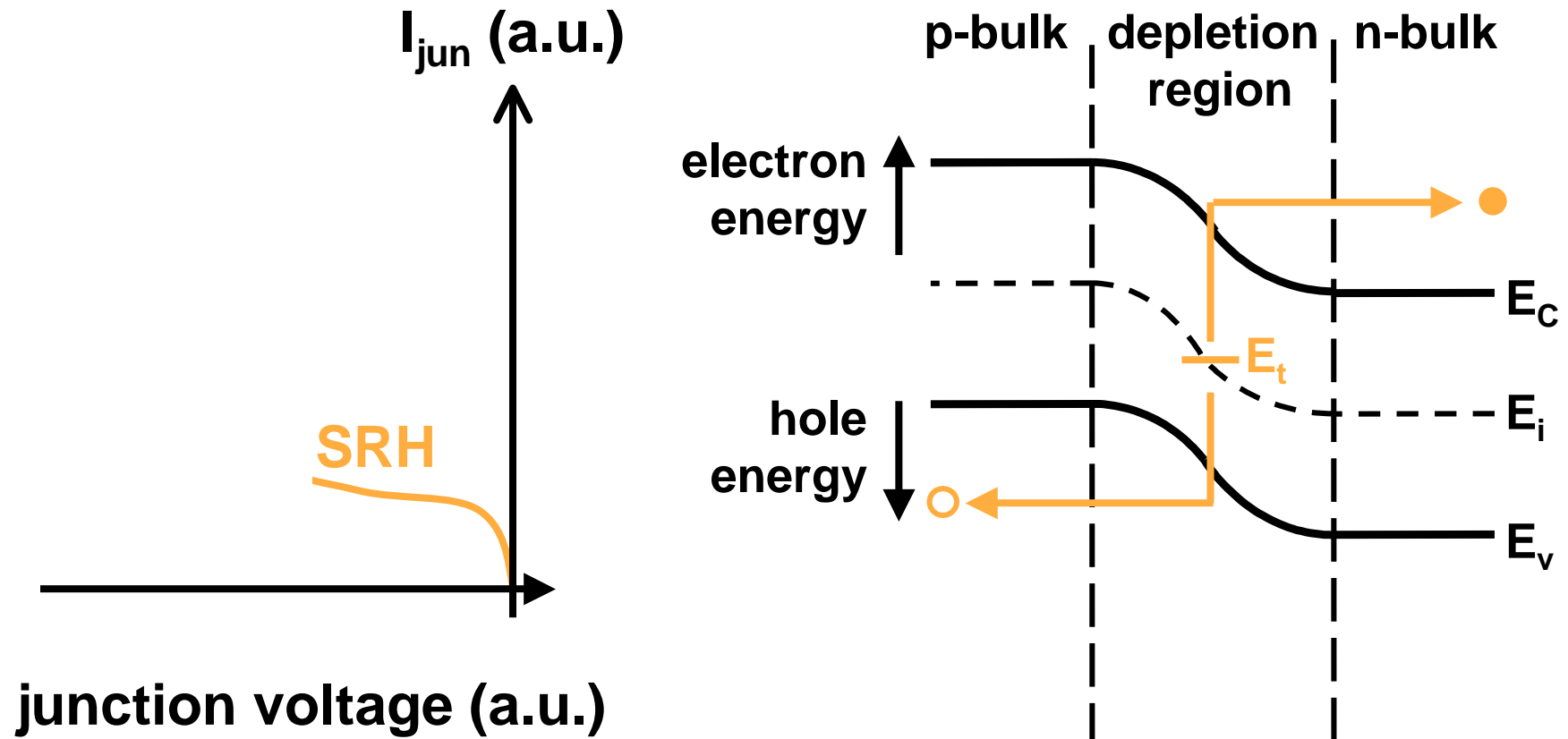
picture: Ray Duffy (Philips Research Leuven)

junction leakage increasing concern in CMOS technology



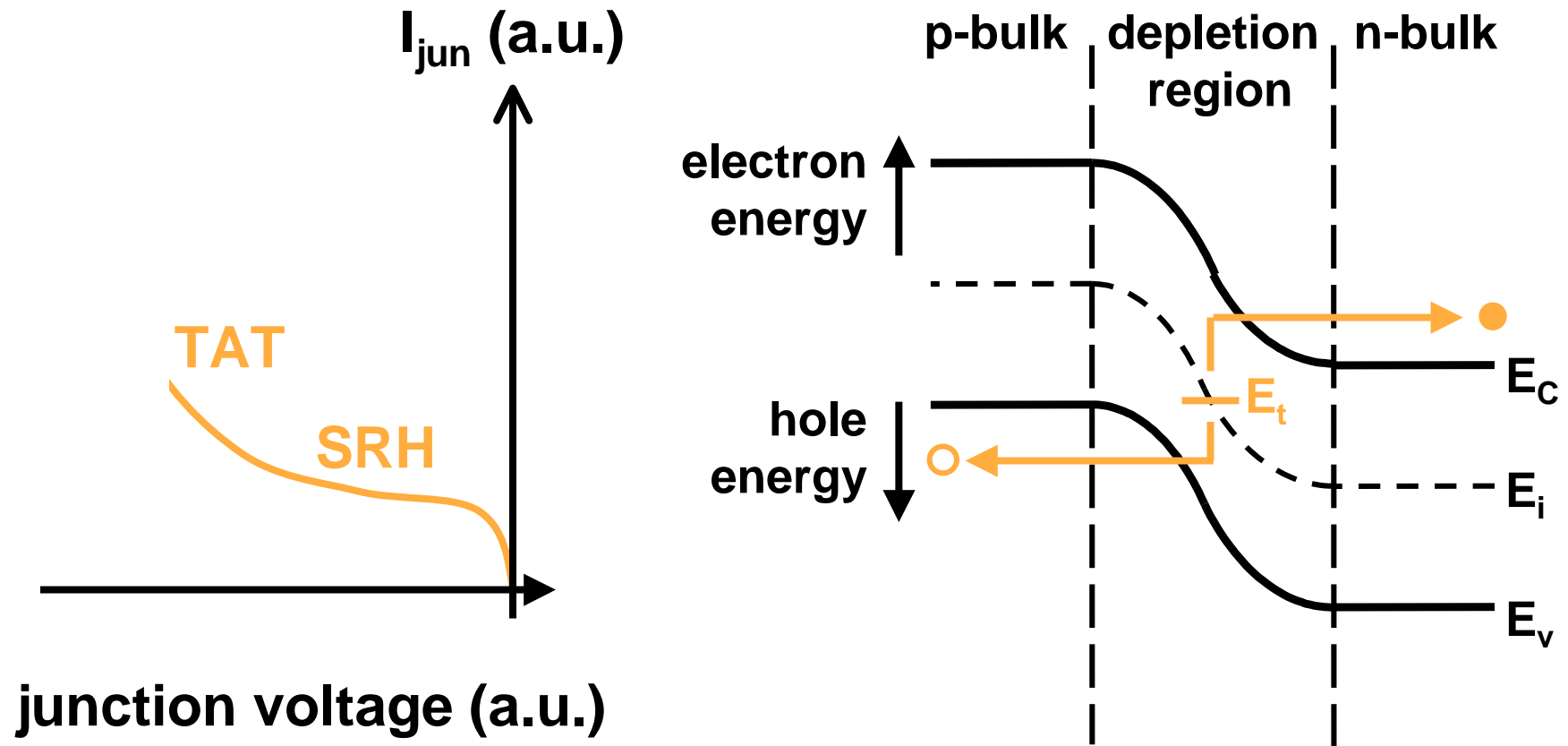
reverse junction leakage (iii)

Shockley-Read-Hall (SRH)



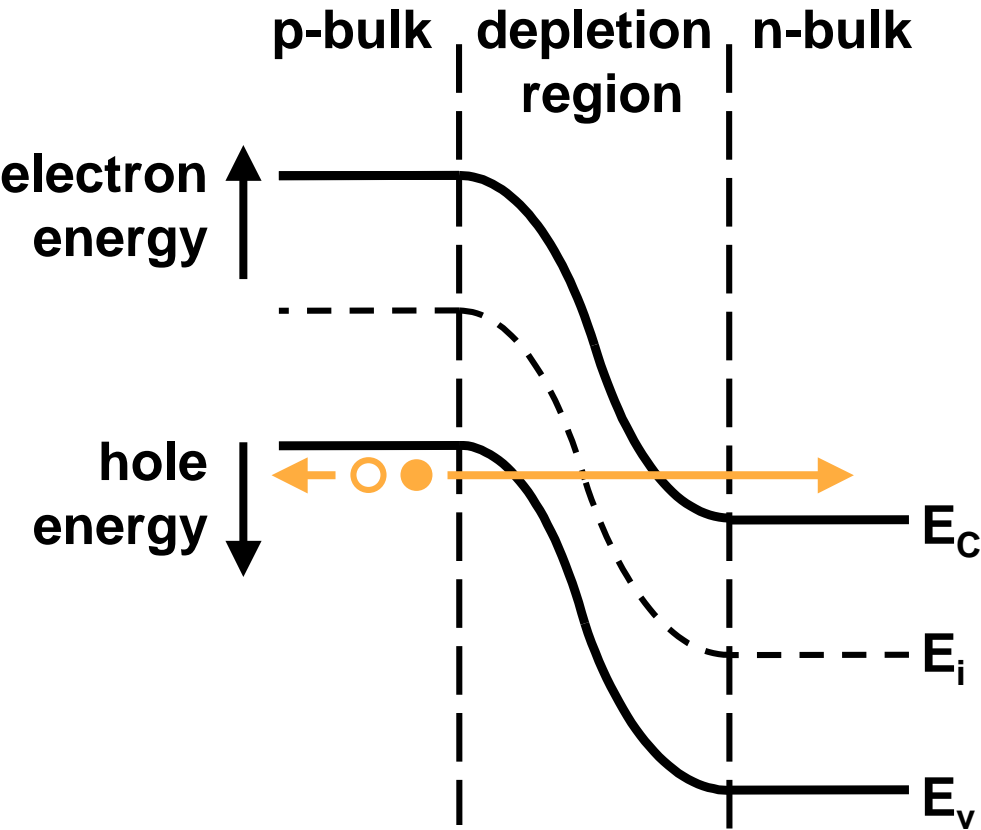
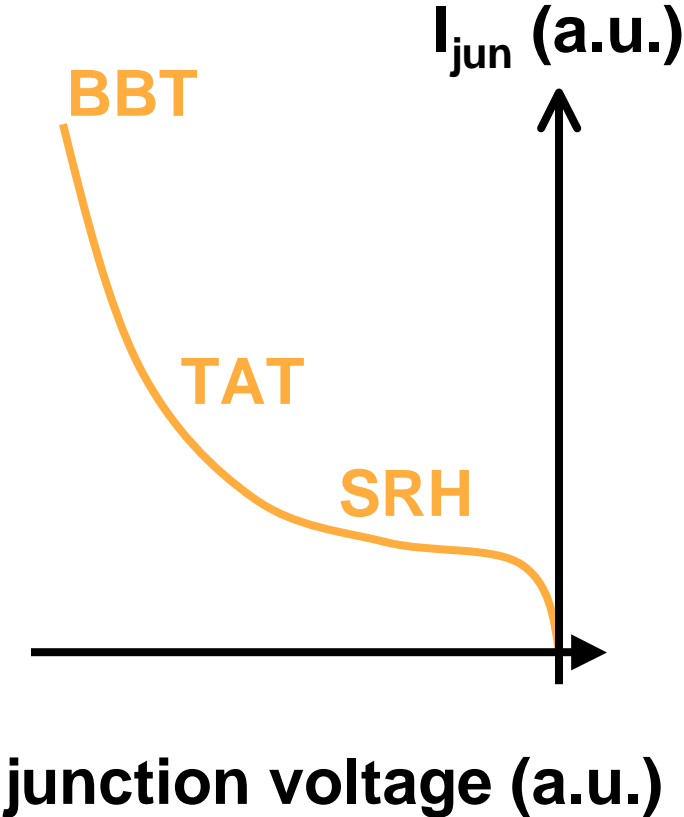
reverse junction leakage (iii)

trap-assisted tunneling (TAT)

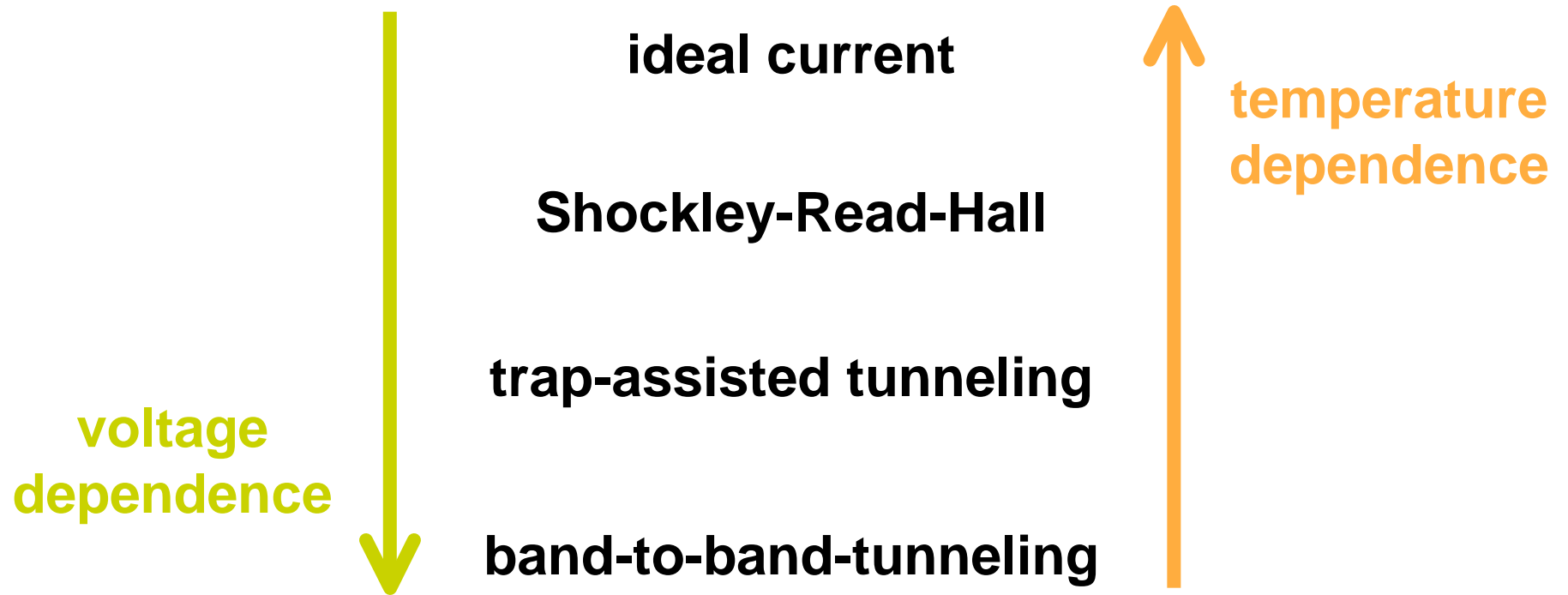


reverse junction leakage (iii)

band-to-band-tunneling (BBT)



reverse junction leakage (iv)



*present-day compact MOSFET models
lack description of SRH, TAT & BBT*

JUNCAP2

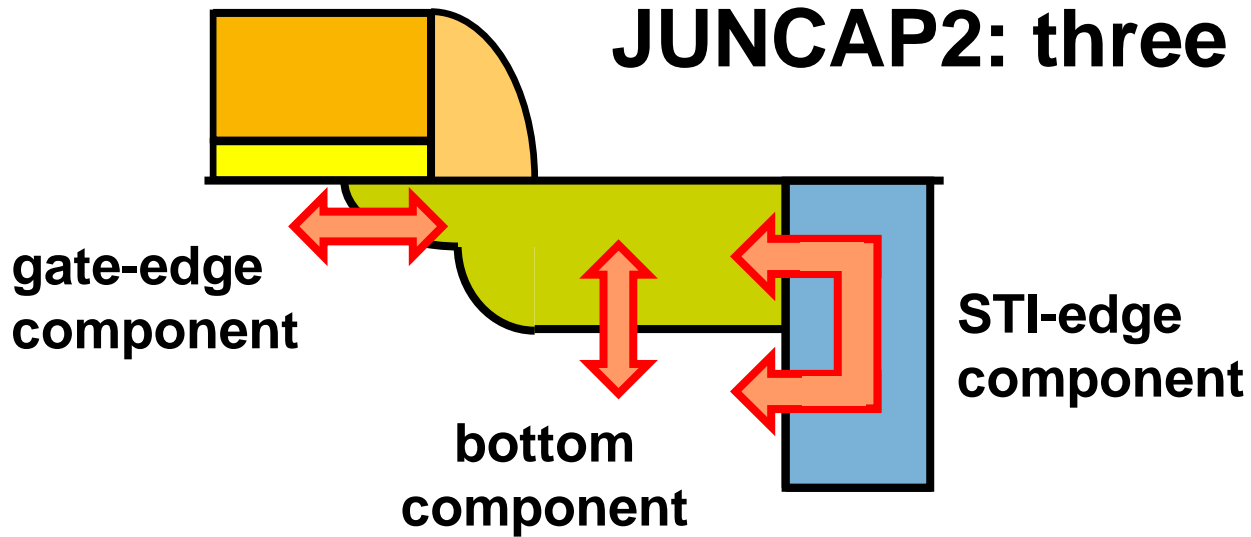
- ▶ **1st comprehensive, physics-based junction model for MOSFETs**
- ▶ **builds on NXP's advanced diode model (= Diode Level 500)**
- ▶ **contains all relevant effects for CMOS applications**



JUNCAP2: survey of modeled effects

- ▶ depletion capacitance
- ▶ ideal current
 - Shockley equation
 - no unphysical ideality factor!
- ▶ Shockley-Read-Hall
- ▶ trap-assisted tunneling
- ▶ band-to-band-tunneling
 - similar to Diode level 500 model
- ▶ avalanche/breakdown
- ▶ junction shot noise
 - partially Depleted SOI

JUNCAP2: three components

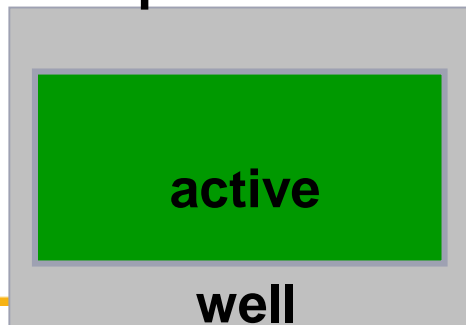


3 equations &
3 unknowns

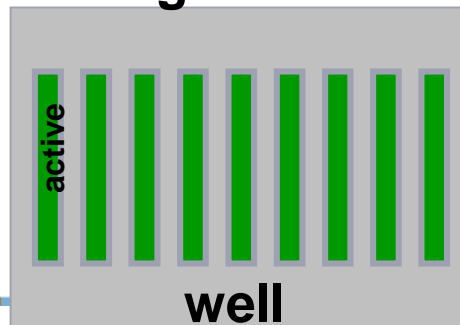


bottom component
STI-edge component
gate-edge component

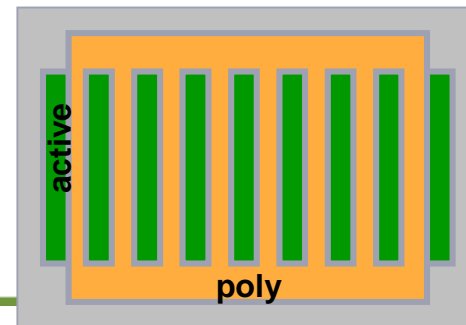
square diode



finger diode

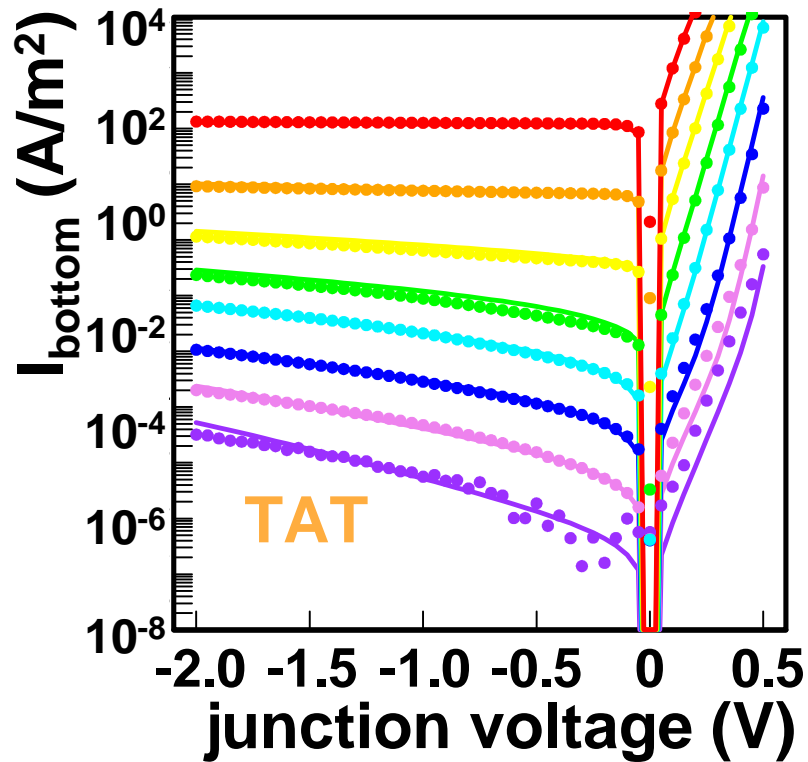


Miller diode

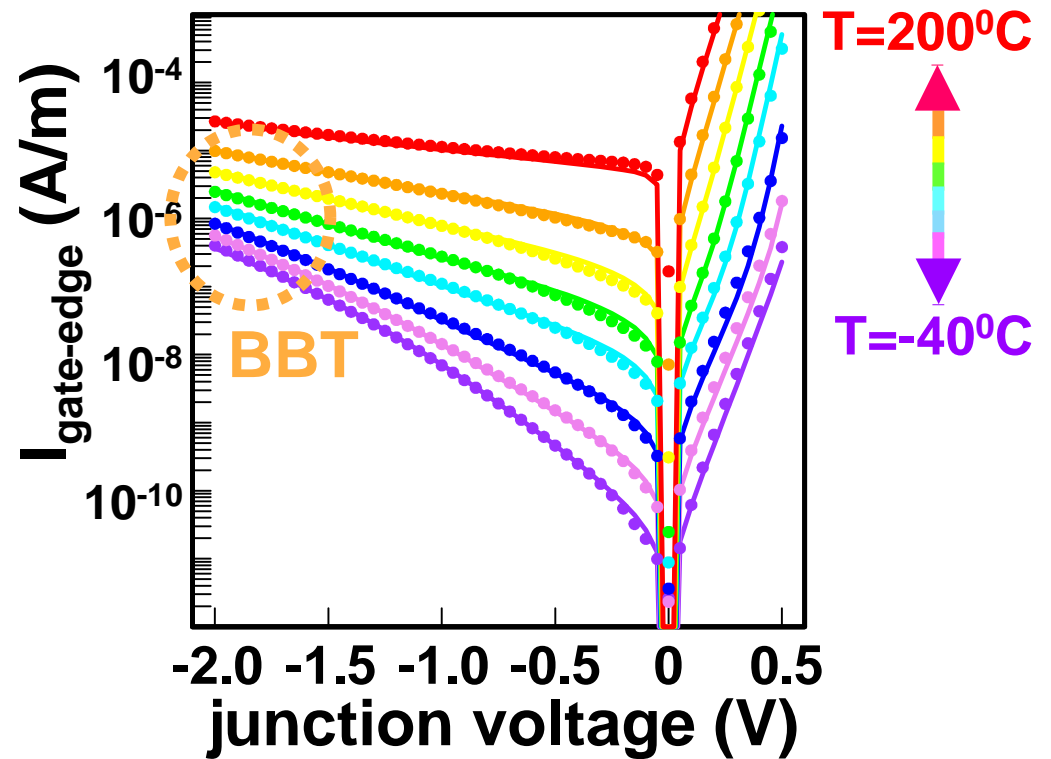


0.12 μm CMOS

bottom component



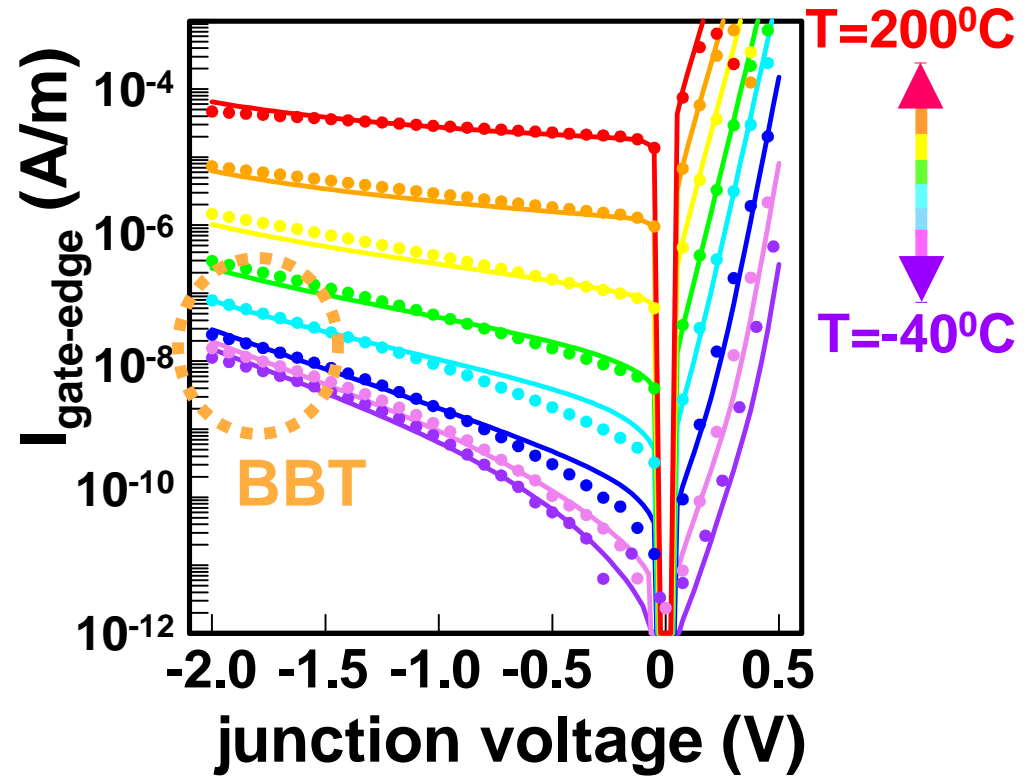
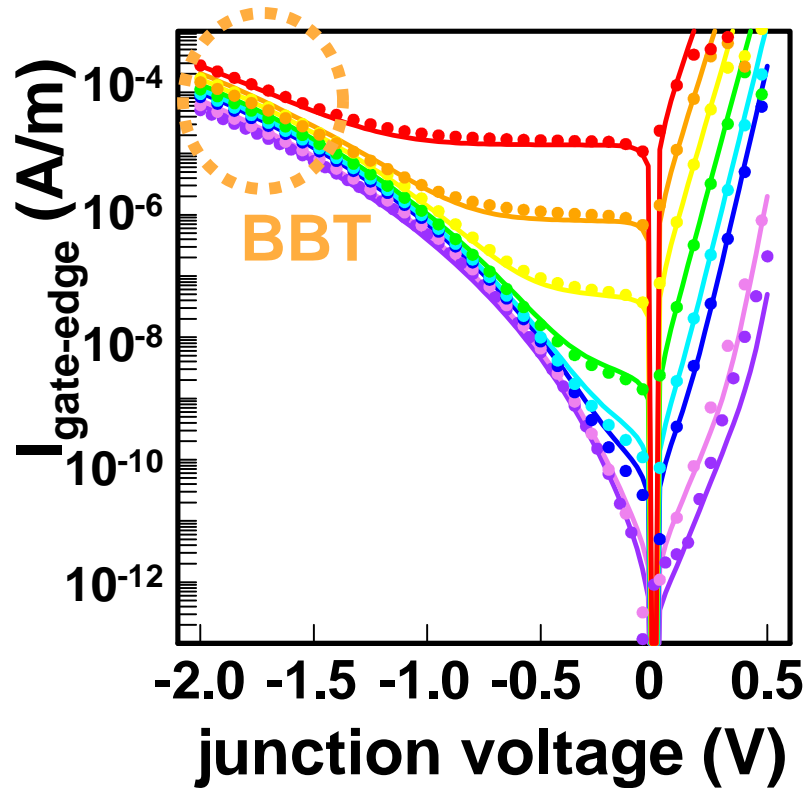
gate edge component



65 nm CMOS: gate edge component

NMOS

PMOS



advanced CMOS: increasing importance of BBT



computational effort

special-function count in *current*-model (voltage-dependent section)

JUNCAP2	exp	sqrt	ln	pow
ideal	1			
SRH		4	2	1
TAT	1	4		1
BBT	1			1
breakdown		1		1
subtotal	3	9	2	4
total (3 comp)	9	27	6	12

Note:

- these numbers are *maxima*
- actual numbers depend on parameter set
- typical parameter set: less than 50%

outline

- ▶ introduction
 - the need for JUNCAP2
 - motivation for JUNCAP2 Express
- ▶ goal
- ▶ method
- ▶ results
 - accuracy
 - simulation speed
- ▶ conclusion



goal

- ▶ JUNCAP2

- very accurate description of junction currents and capacitances
- well-defined and physics-based extraction strategy
- model evaluation time is significant

- ▶ goal JUNCAP2 Express

- generic method to reduce simulation time
- no extra characterization/parameter-extraction
- original JUNCAP2 parameter set has to be used
- to be invoked by simple switch
- no insight needed in, e.g., which components of junction current are important

method

- ▶ current-model is replaced by very simple equation (sum of three exponentials)
- ▶ **only five parameters**
 - automatically computed during model initialization
 - from full parameter set, using full JUNCAP-model

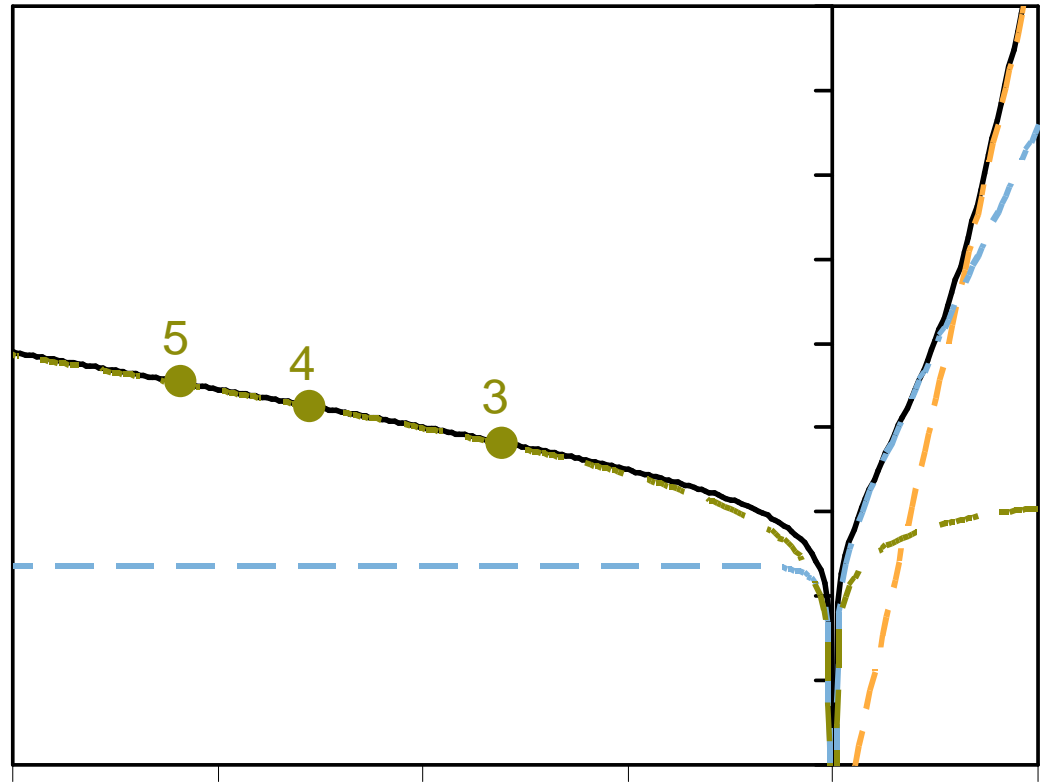
$$I(V) = \underbrace{I_{for,1} \cdot [\exp(V / \phi_T) - 1]}_{\text{ideal forward current}} + \underbrace{I_{for,2} \cdot [\exp(V \cdot m_{for,2} / \phi_T) - 1]}_{\text{non-ideal forward current}} - \underbrace{I_{rev} \cdot [\exp(-V \cdot m_{rev} / \phi_T) - 1]}_{\text{non-ideal reverse current}}$$

- ▶ guaranteed to be continuous and smooth

method: parameter determination

$$I(V) = \underbrace{I_{for,1} \cdot [\exp(V / \varphi_T) - 1]}_{\text{ideal forward}} + \underbrace{I_{for,2} \cdot [\exp(V \cdot m_{for,2} / \varphi_T) - 1]}_{\text{non-ideal forward}} - \underbrace{I_{rev} \cdot [\exp(-V \cdot m_{rev} / \varphi_T) - 1]}_{\text{non-ideal reverse}}$$

- ▶ full model curve
- ▶ **ideal forward**
 - $I_{for,1}$ from parameters and T
- ▶ **non-ideal forward**
 - $m_{for,2}$ from I_1 and I_2
 - $I_{for,2}$ from I_2
- ▶ **non-ideal reverse**
 - m_{rev} from I_3 and I_4
 - I_{rev} from I_5



this is done in the bias-independent initialization part of the model

method: user input

- ▶ V_1 and V_2 (forward) are fixed in model
- ▶ supply voltage may vary from 1V to more than 5V, depending on process and application
 - V_3, V_4, V_5 are related to parameter **VJUNREF**
 - parameter **VJUNREF** is accessible by user
 - **VJUNREF** should be set to about $2 \cdot V_{\text{sup}}$

method: computational effort

special-function count in *current*-model (voltage-dependent section)

JUNCAP2

	exp	sqrt	ln	pow
ideal	1			
SRH		4	2	1
TAT	1	4		1
BBT	1			1
breakdown		1		1
subtotal	3	9	2	4
total (3 comp)	9	27	6	12

Note:

- these numbers are *maxima*
- actual numbers depend on parameter set
- typical parameter set: less than 50%

JUNCAP-Express

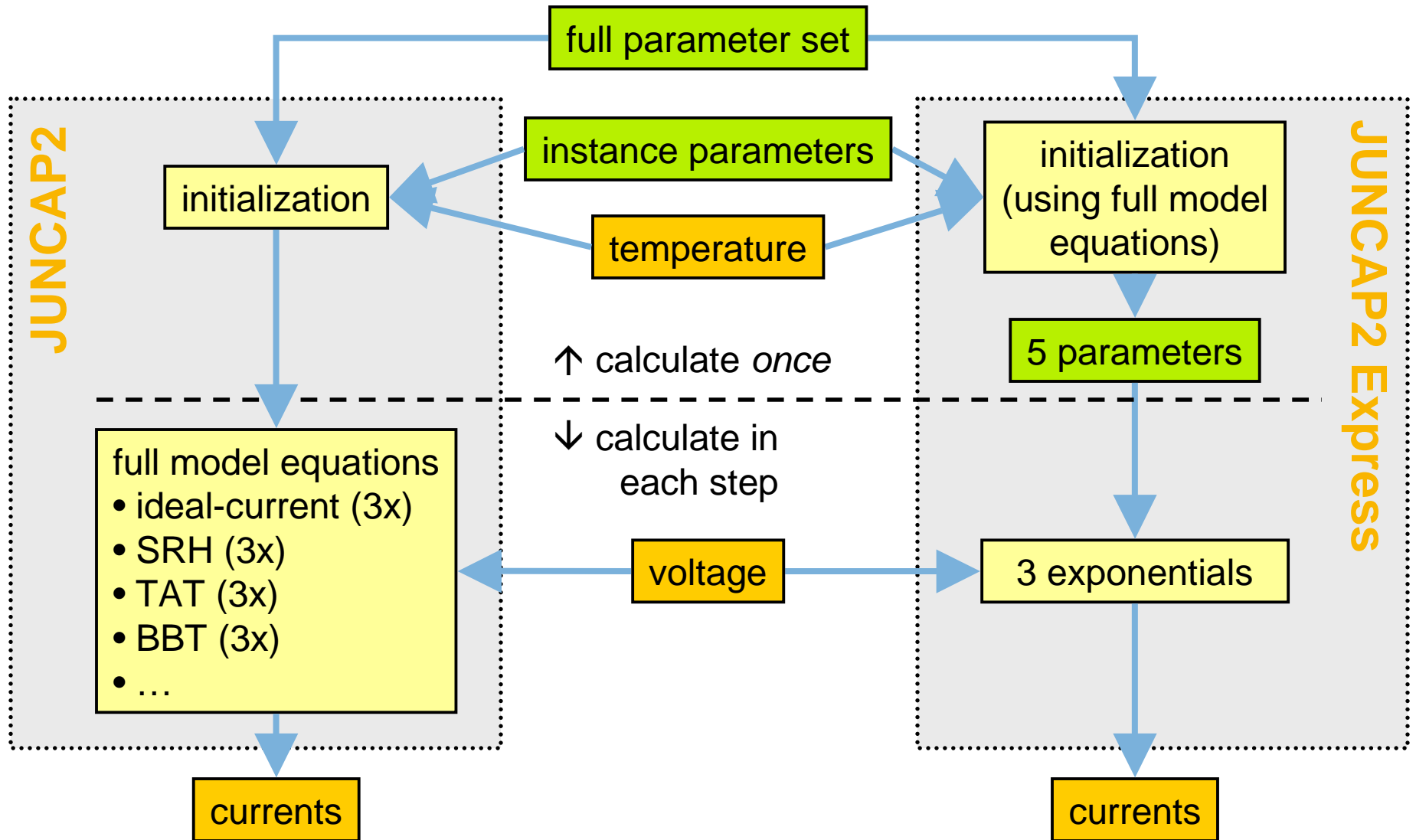


	exp
total	3

Note:

- these numbers are independent of parameter set

method: schematic overview



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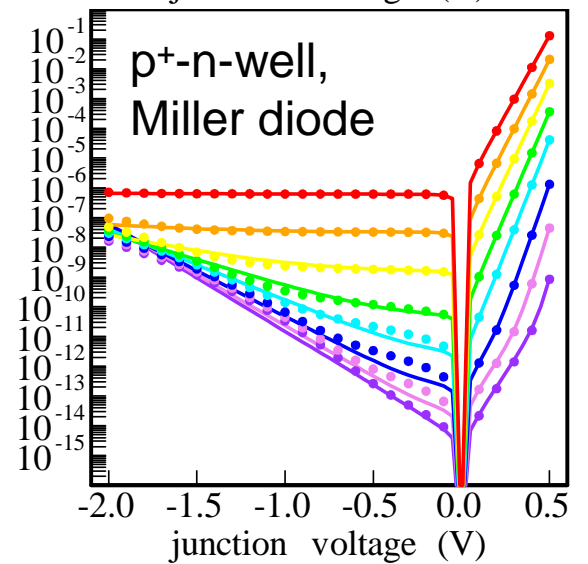
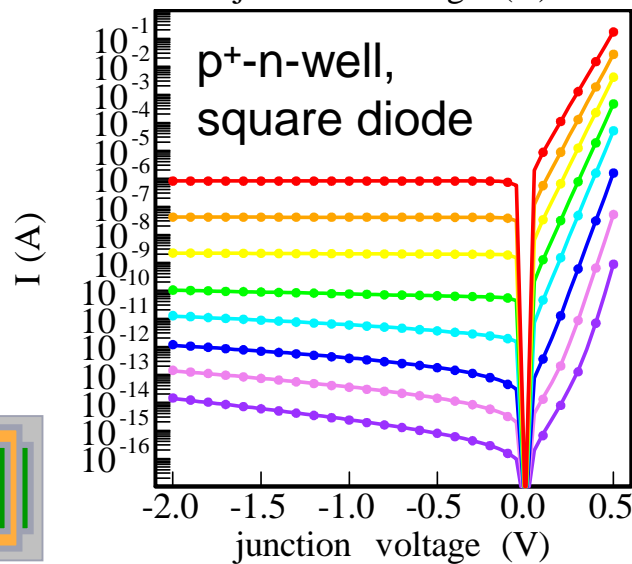
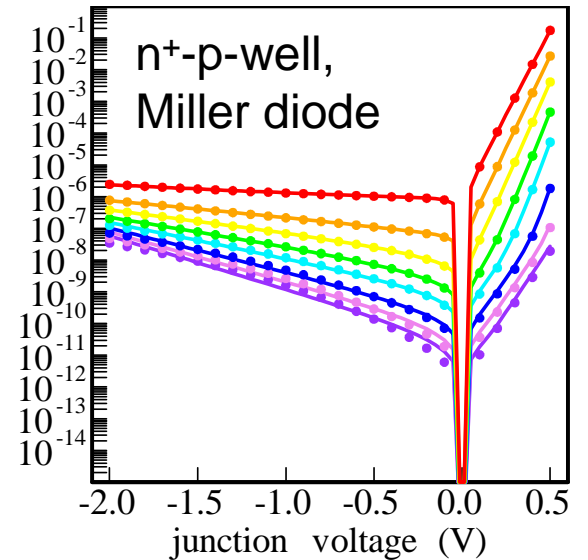
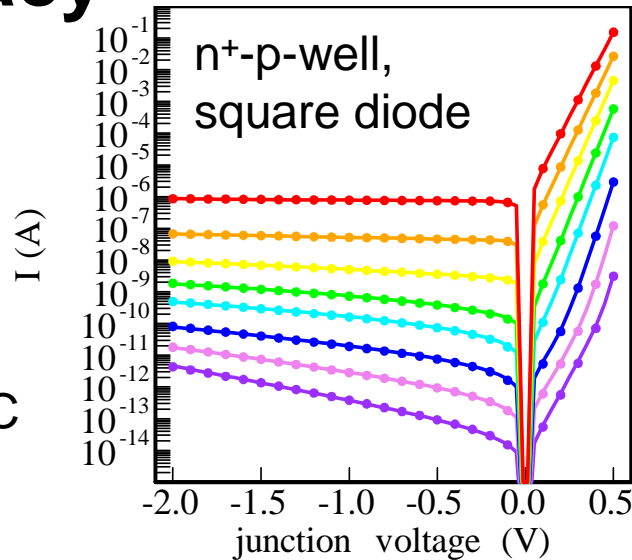
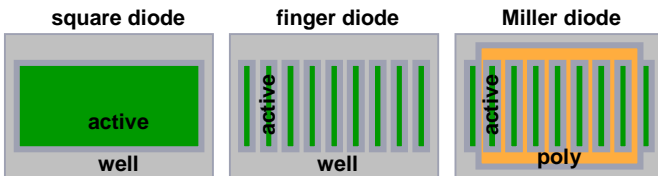
results: accuracy

- ▶ Process 1
- ▶ $V_{JUNREF}=2V$
- ▶ $T = -40, -10, 21, 60, 90, 125, 160, 200$ °C

symbols:
full JUNCAP2

lines:
JUNCAP2 Express

see slide 12



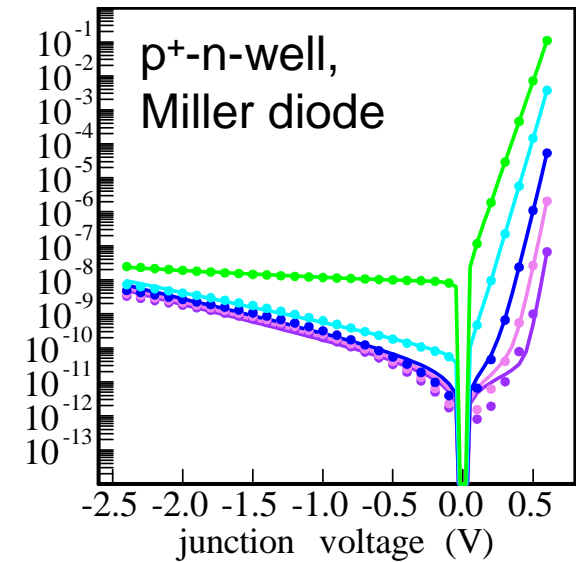
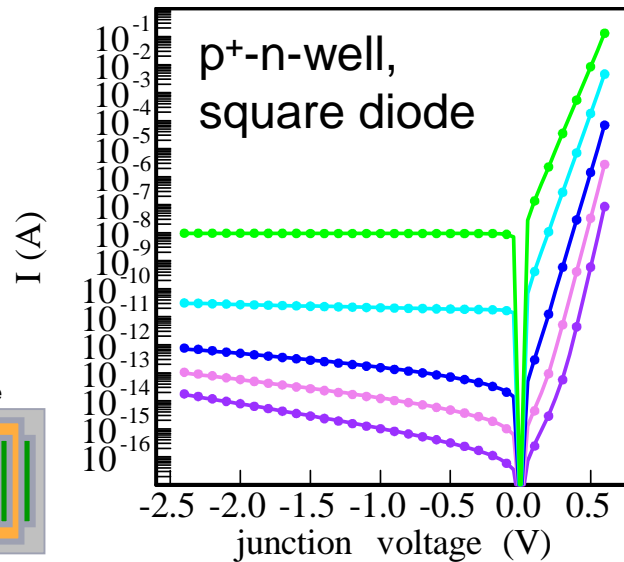
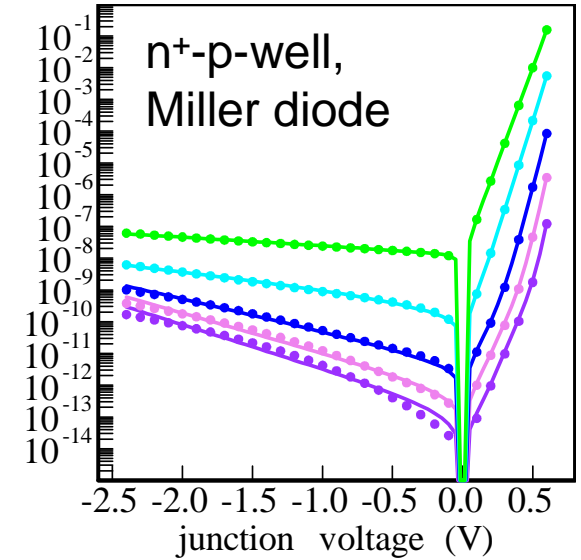
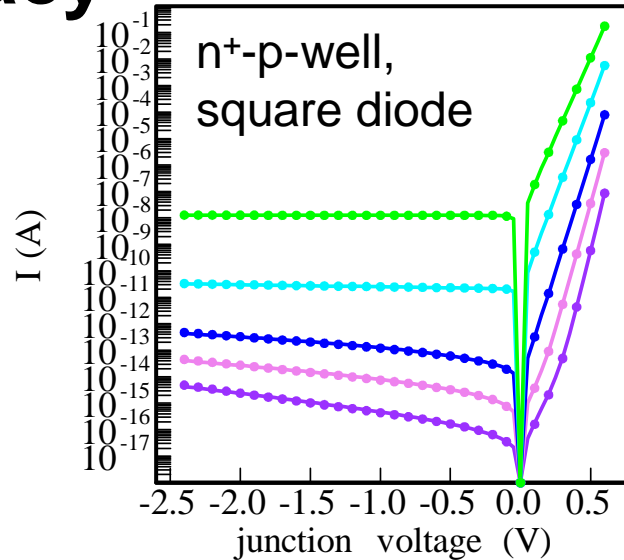
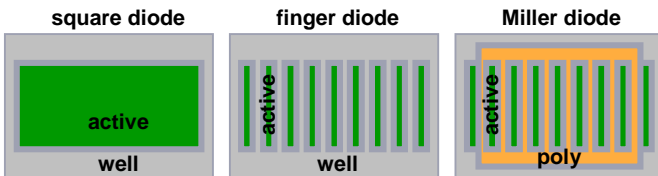
results: accuracy

- ▶ Process 2
- ▶ $V_{JUNREF} = 2.4V$
- ▶ $T = -40, -10, 25, 85, 150$ °C

symbols:
full JUNCAP2

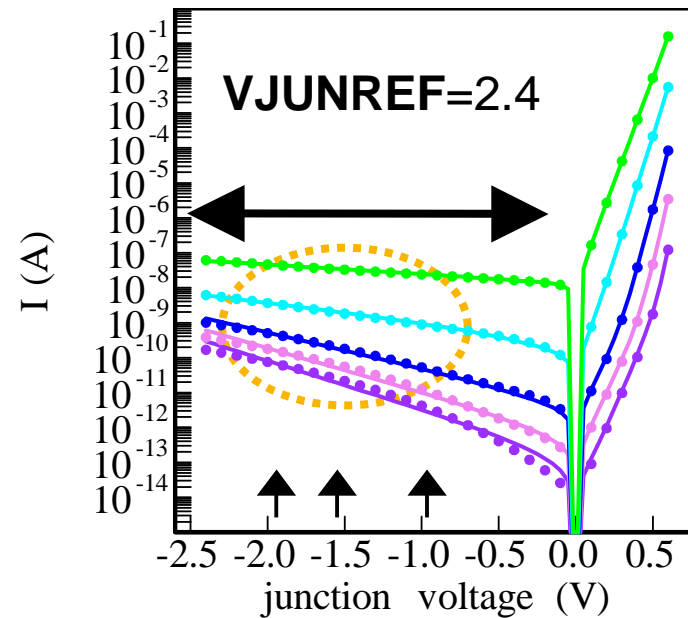
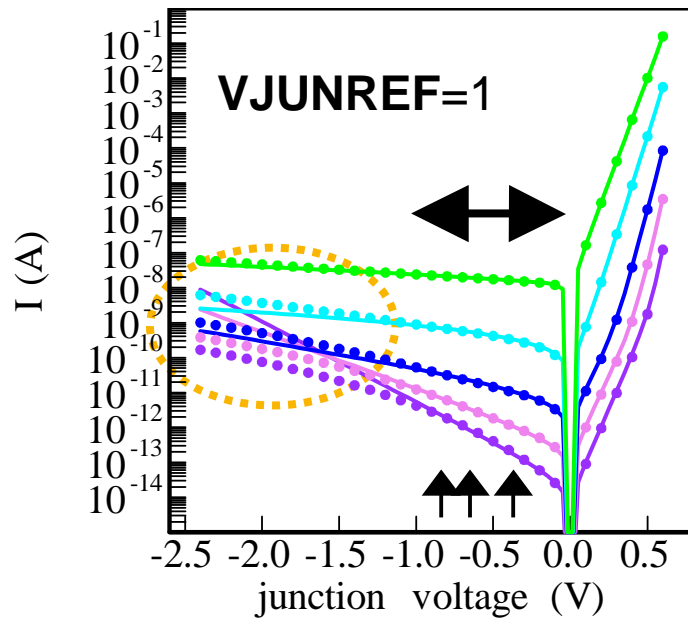
lines:
JUNCAP2 Express

see slide 12



results: accuracy beyond VJUNREF

- ▶ V_3 , V_4 , V_5 are related to parameter **VJUNREF**
- ▶ **VJUNREF** defines V-range in which reverse current fit-parameters are determined
- ▶ extrapolation works, provided TAT and BBT are small



charge model

- ▶ charge-model: 3 components
 - bottom
 - STI-edge
 - gate-edge
- ▶ component(s) which constitute less than a certain fraction of total are neglected
- ▶ fraction accessible to user by **FJUNQ**
- ▶ saves 0 - 66% of *charge*-model evaluation time, depending on
 - value of **FJUNQ**
 - model parameters
 - junction geometry

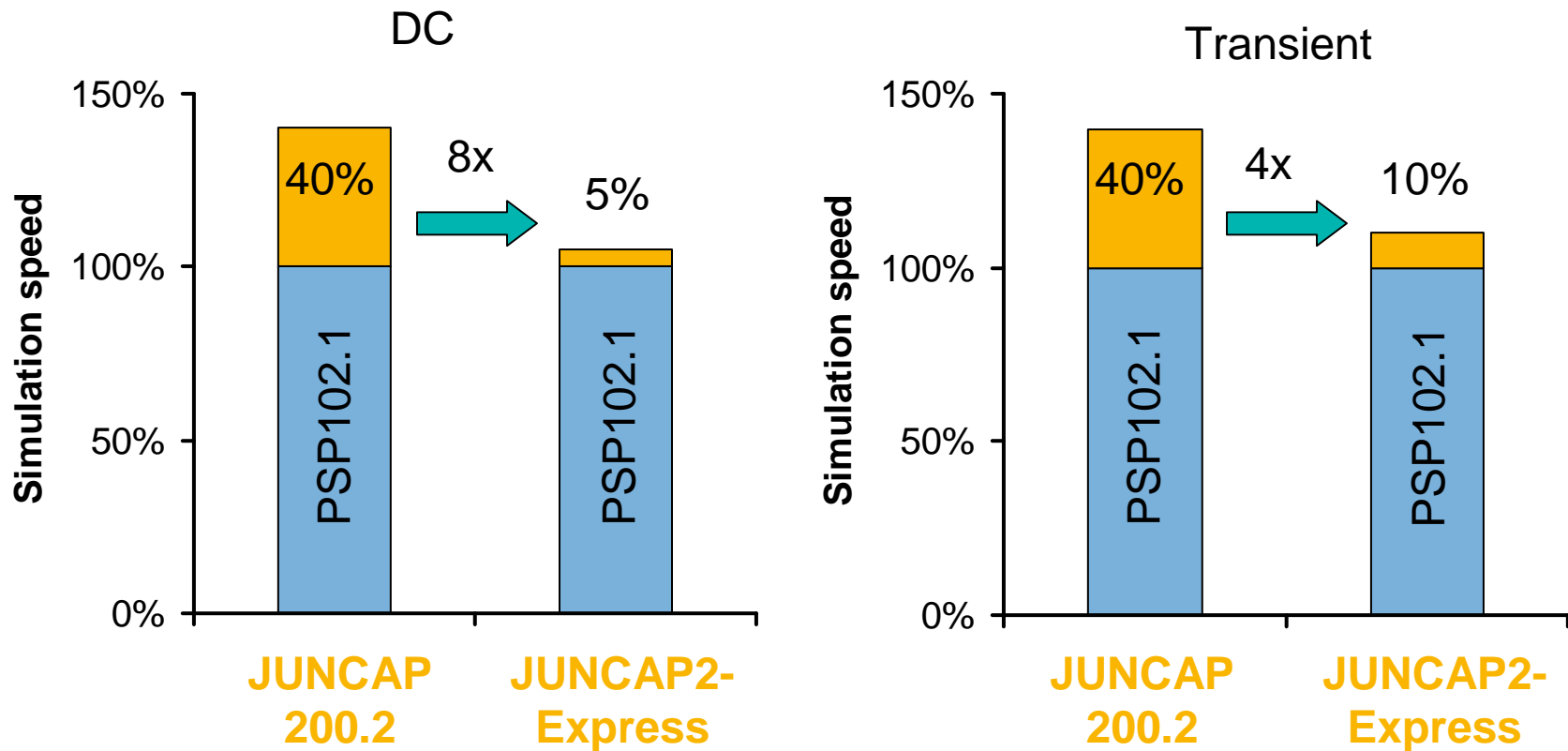
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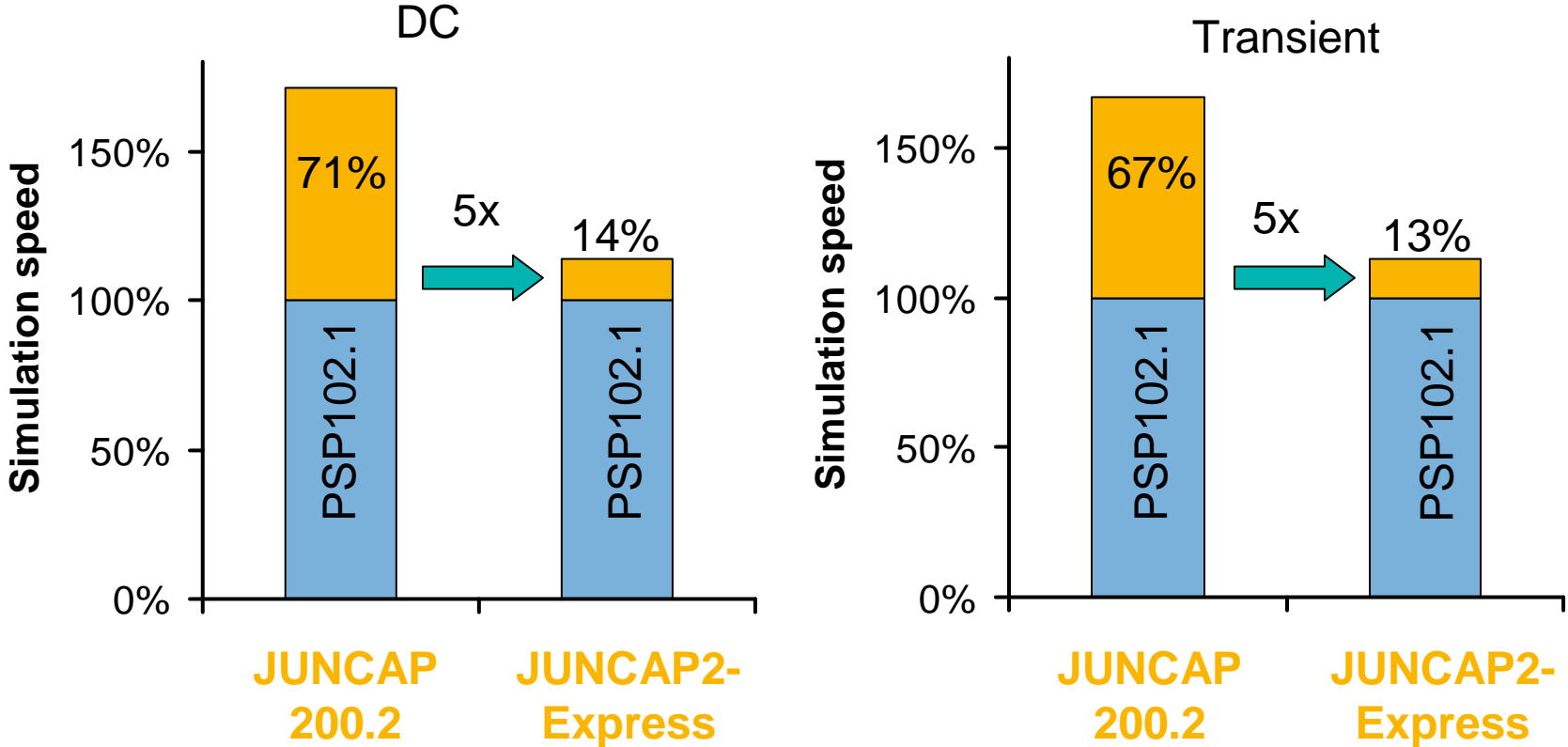
results: simulation speed

- ▶ JUNCAP2 Express simulation 4-8 times faster than full JUNCAP2
- ▶ numbers based on: vA-code / 50-MOST circuit



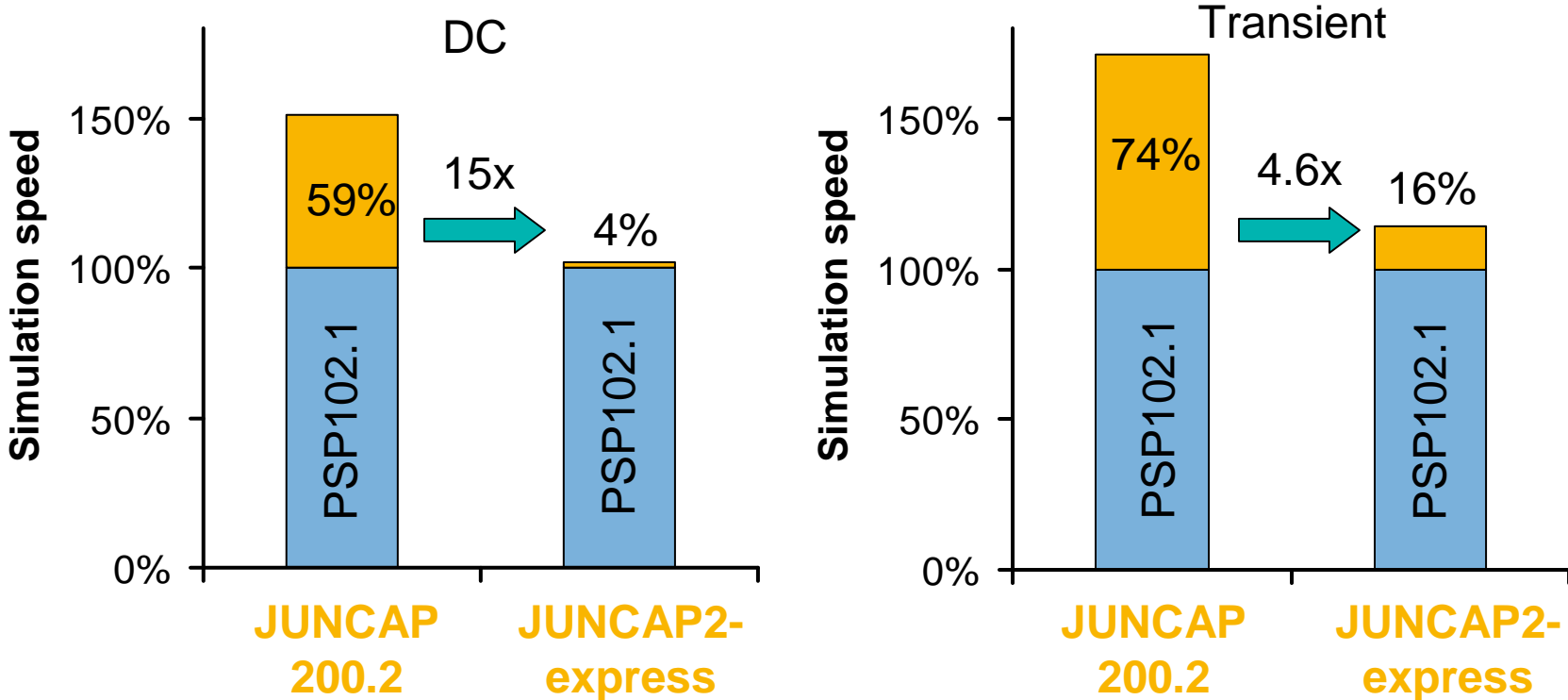
results: simulation speed

- ▶ JUNCAP2 Express about 5 times faster than full JUNCAP2
- ▶ numbers based on: Pstar + SiMKit 2.5_junexp / 50-MOST circuit



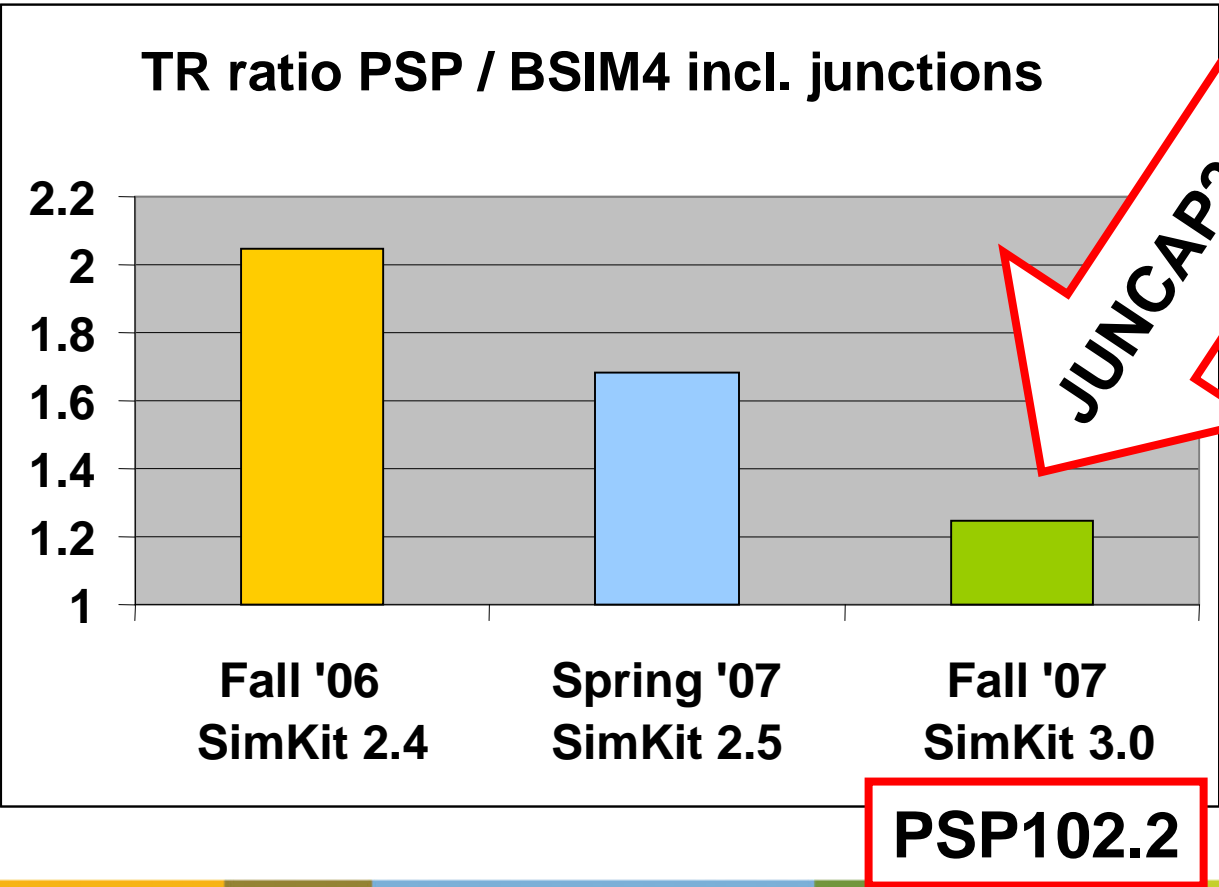
results: simulation speed

- ▶ JUNCAP2 Express about 5 times faster than full JUNCAP2
- ▶ numbers based on: Spectre 6.1.0.190 + SiMKit 2.5_junexp, 50-MOST circuit



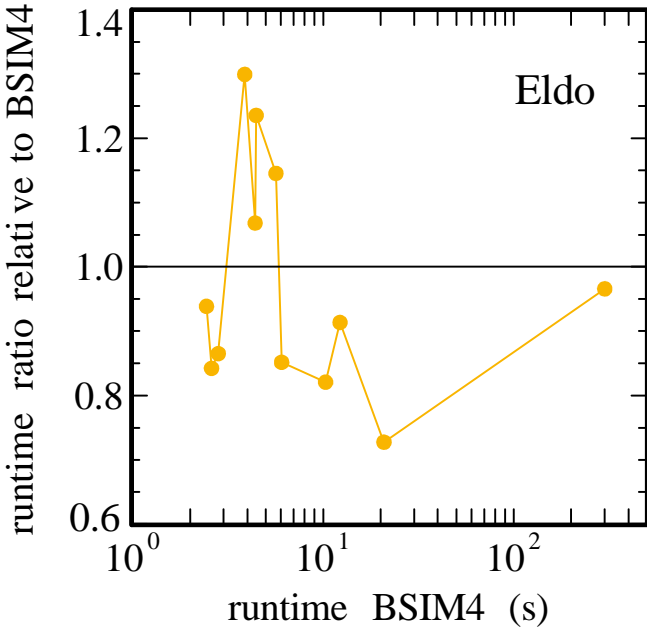
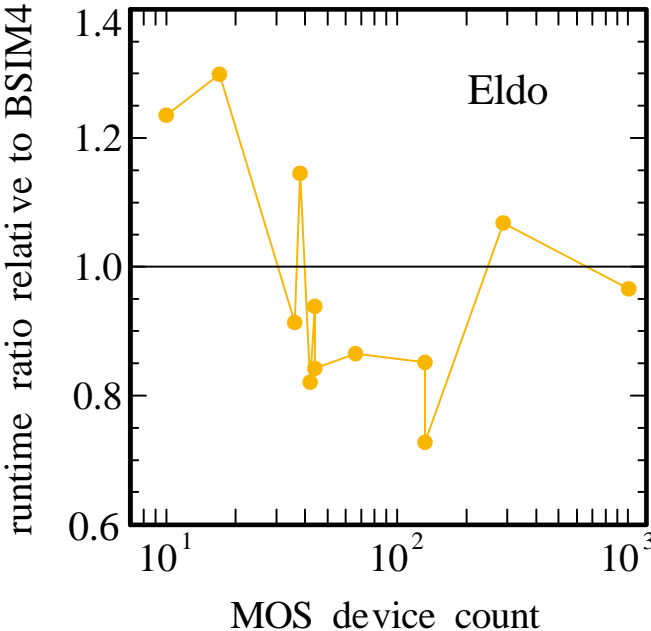
results: simulation speed

- ▶ simulation times of PSP relative to BSIM4



results: simulation speed

- ▶ results from STm (presented at CMC meeting, Boston, October 2007)
- ▶ 12 representative standard cells



circuit	#
Comprt	17
Fadd32	288
Inv	10
Nand1	44
Nand3	132
Nor1	44
Nor3	132
Ring3	66
Ring_rc	42
Ro19	38
Sram	1008
Ring	36

average ratio 0.97

PSP is suited for digital cell characterization



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conclusion

- ▶ much faster simulation speed (5x) than full JUNCAP2 model
- ▶ almost no loss in accuracy compared to full JUNCAP2 model
- ▶ still more accurate than junction models in any other compact MOS model

- ▶ no new or additional parameter extraction necessary
- ▶ verified on several process technologies
- ▶ JUNCAP2 Express is valuable addition to PSP
- ▶ JUNCAP2 Express is available starting with PSP 102.2 (released Fall 2007)



