INFLUENCE OF HALO IMPLANT ON LEAKAGE CURRENT AND SHEET RESISTANCE OF ULTRA-SHALLOW P-N JUNCTIONS

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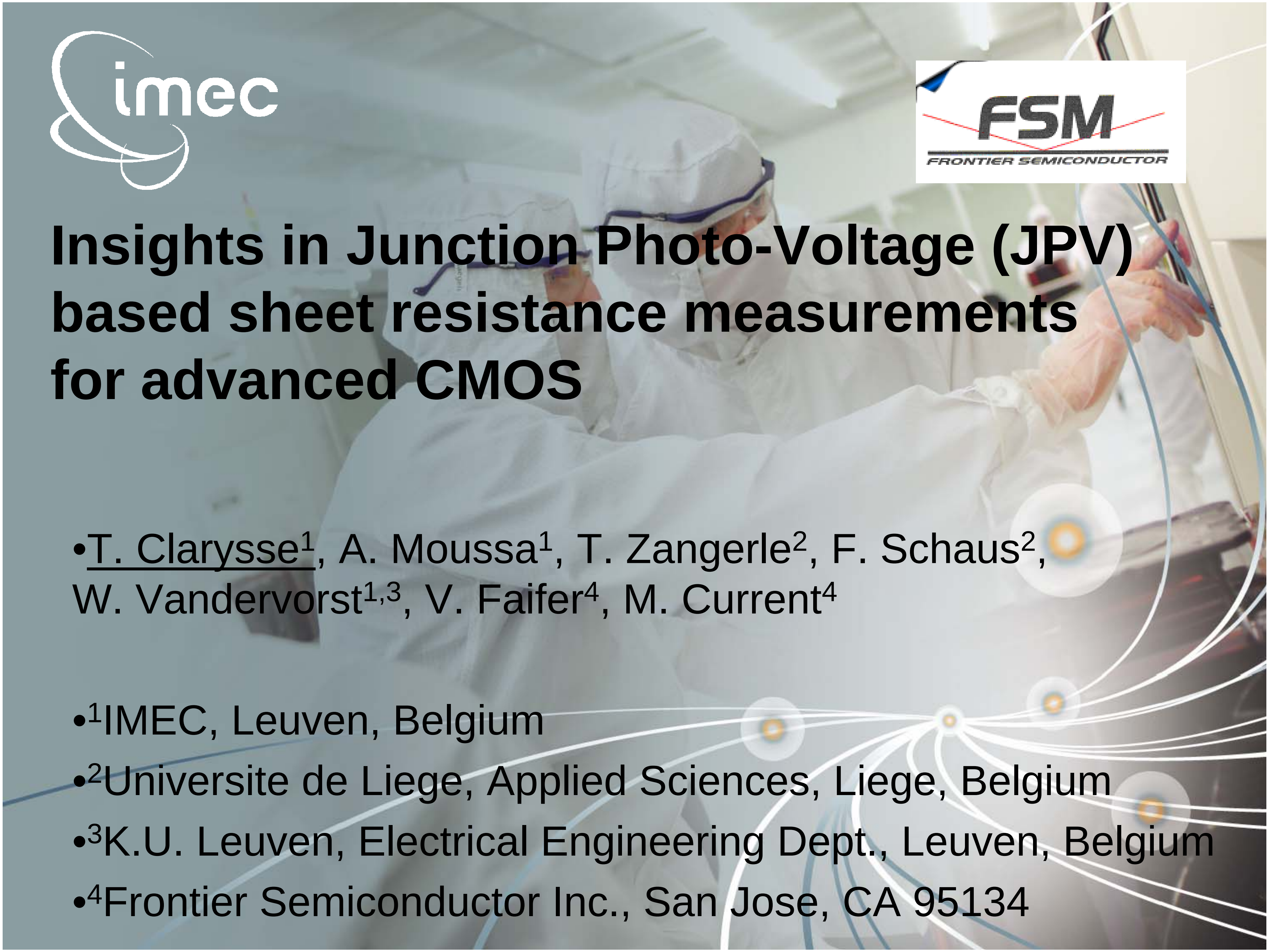

Insights in Junction Photo-Voltage (JPV) based sheet resistance measurements for advanced CMOS

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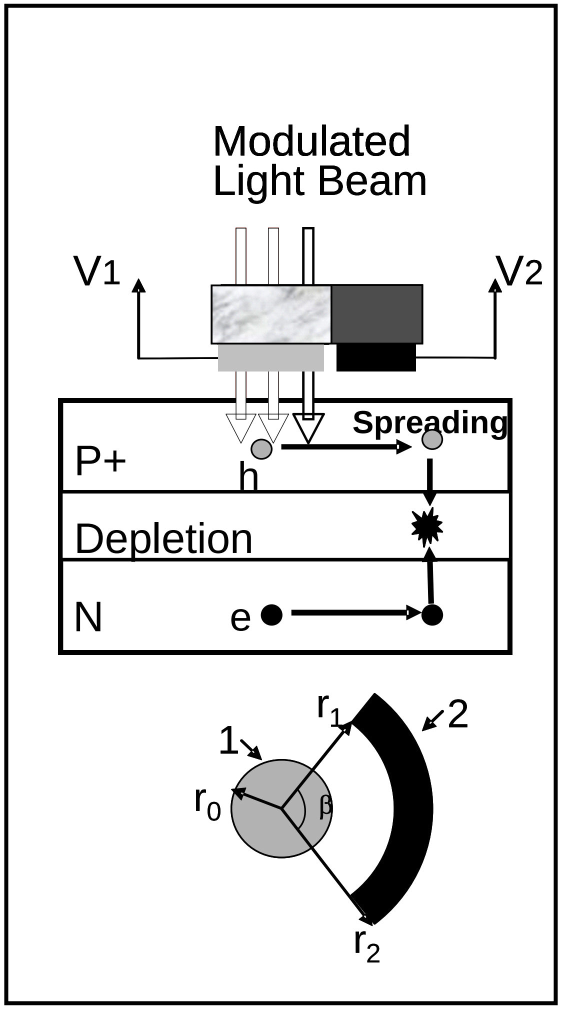
Outline:

- ***Junction photo-voltage methods for Rs and J_{leak}.***
- ***Comparison with contact probes.***
- ***Leakage current mechanisms.***
- ***Comparison of RsL and diode leakage current.***
- ***Effects of halo/epi doping on Rs and leakage for spike, ms-Anneals (flash RTP) and CVD grown USJs.***
- ***Conclusions.***

RsL Measurements: Junction Photo-voltage



$$V_1 = \frac{q\eta(1-R)\Phi_0 R_S}{k^2}\left[1-2I_1(kr_0)K_1(kr_0)\right]$$

$$V_2 = q\eta\frac{(1-R)\Phi_0\beta R_S}{\pi k^2 r_0} I_1(kr_0)\left[r_1K_1(kr_1)-r_2K_1(kr_2)\right]$$

$$k=\sqrt{R_S G_{p-n}+i2\pi f R_S C_{p-n}}$$

Rs=sheet resistance,

$C_{p\text{-}n}$= p-n junction capacitance

$G_{p\text{-}n}$=(q/kT)*J_{leak}=p-n conductance

V.N. Faifer, D.K. Schroder, M.I.Current, Appl.Phys.Let.89,151123,(2006)

T. Clarysse et al. (IMEC), INSIGHT, (2007).

Gerald Lucovsky, J. Appl. Physics 31, 1088 (1960)

Medici physical models IMEC

Poisson + continuity equations

$$\varepsilon \nabla^2 \psi = -q(p - n + N_D^+ - N_A^-) - \rho_S$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\vec{\nabla} \cdot \vec{J}_n - (U_n - G_n) = F_n(\psi, n, p)$$

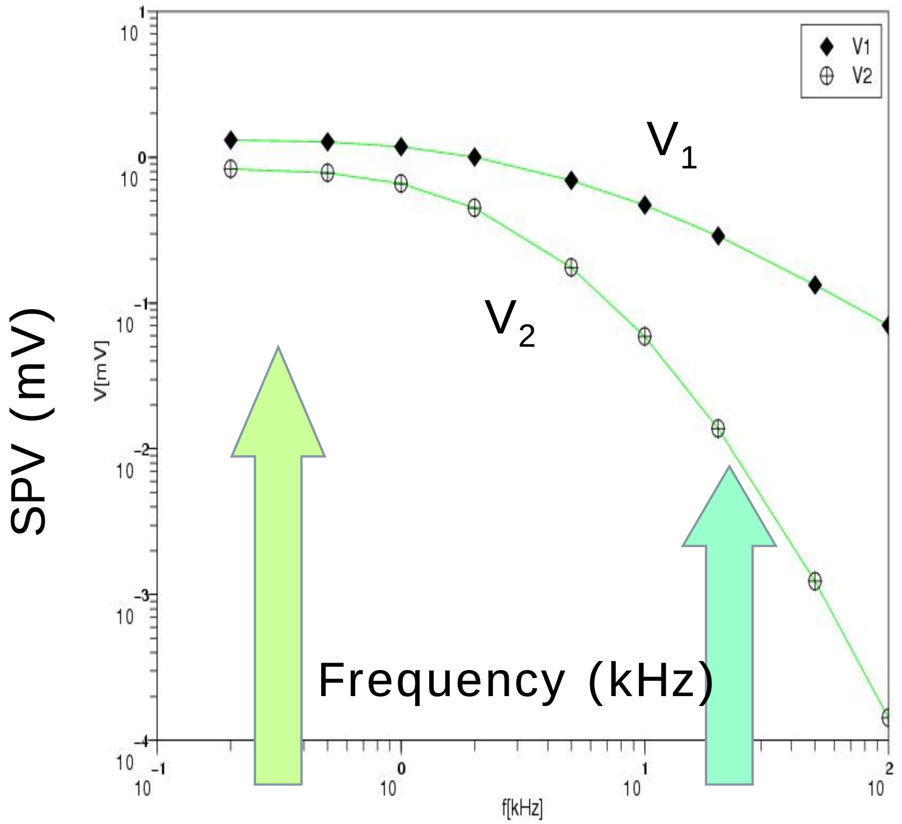
$$\frac{\partial p}{\partial t} = \frac{-1}{q}\vec{\nabla} \cdot \vec{J}_p - (U_p - G_p) = F_p(\psi, n, p)$$

$$\vec{J}_n = q\mu_n \vec{E}_n n + qD_n \vec{\nabla} n$$

$$\vec{J}_p = q\mu_p \vec{E}_p p - qD_p \vec{\nabla} p$$

- Fermi-Dirac statistics
- Band gap narrowing
- Philips concentration dependent mobility model
- Schokley-Read-Hall (SRH)
- Auger recombination

Modulation frequency dependence



Low frequency:
JPV dominated by
Product Rs*Gs

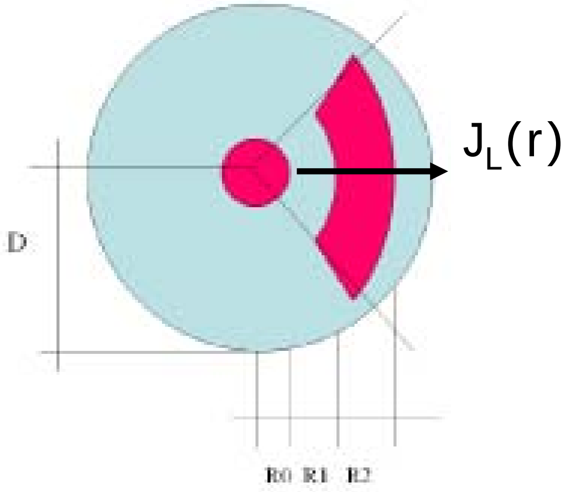
High frequency:
JPV dominated by
Product Rs*Cs

The ratio V_1/V_2 is measured for:

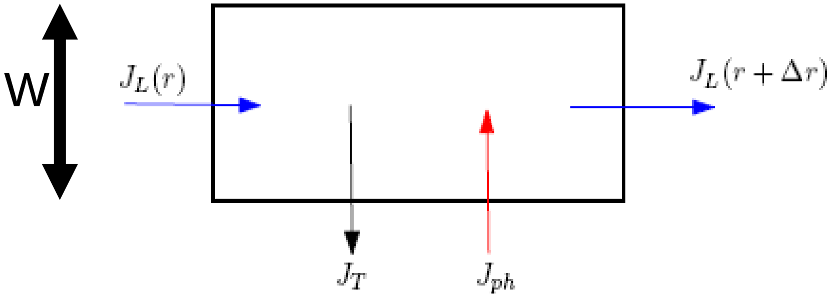
- a high modulation frequency
  ➔ $R_s.C_s$ (capacitance)
- a low modulation frequency
  ➔ $R_s.G_s$ (conductance)
- The value C_s can be determined through a special calibration procedure
- ➔ R_s and leakage (L)

Frontier Semiconductor

Lucovsky (1960): Constant illumination beam **IMEC**



Top view



Cross section view

$$J_{ph} = q.f$$

f = electron-hole separation rate

$$J_T = J_s(e^{\frac{q\varphi}{kT}} - 1)$$

J_s = saturation current
φ = potential

$$J_L(r) = -\frac{1}{\rho^*}\frac{d\varphi}{dr}$$

ρ^* = surface layer resistivity

$$(\nabla^2 - \alpha^2)\varphi(r) = -q R_s f(r)$$

$\alpha = \sqrt{R_s G_s}$, $R_s = \rho^*/W$, **$q.f/J_s << 1$**

Sinusoidal case: Theoretical solution

Same analytical solution but β replaces α:

$$\phi(r)=\begin{cases}\dfrac{qfR_s}{\beta^2}[1-\beta aK_1(\beta a)I_0(\beta r)] & \text{for } r<=a\\[2ex] \dfrac{qfR_s}{\beta^2}\beta aI_1(\beta a)K_0(\beta r) & \text{for } r>a\end{cases}$$

$$\beta=\sqrt{R_s\,G_s+i\omega\,R_s\,C_s}$$

$$V_1=\frac{1}{C_1}\int_{P_1}\phi(r)dS \qquad V_2=\frac{1}{C_2}\int_{P_2}\phi(r)dS$$

P_1, P_2 probe areas
$C_1=C_2=\pi.R_0^2$

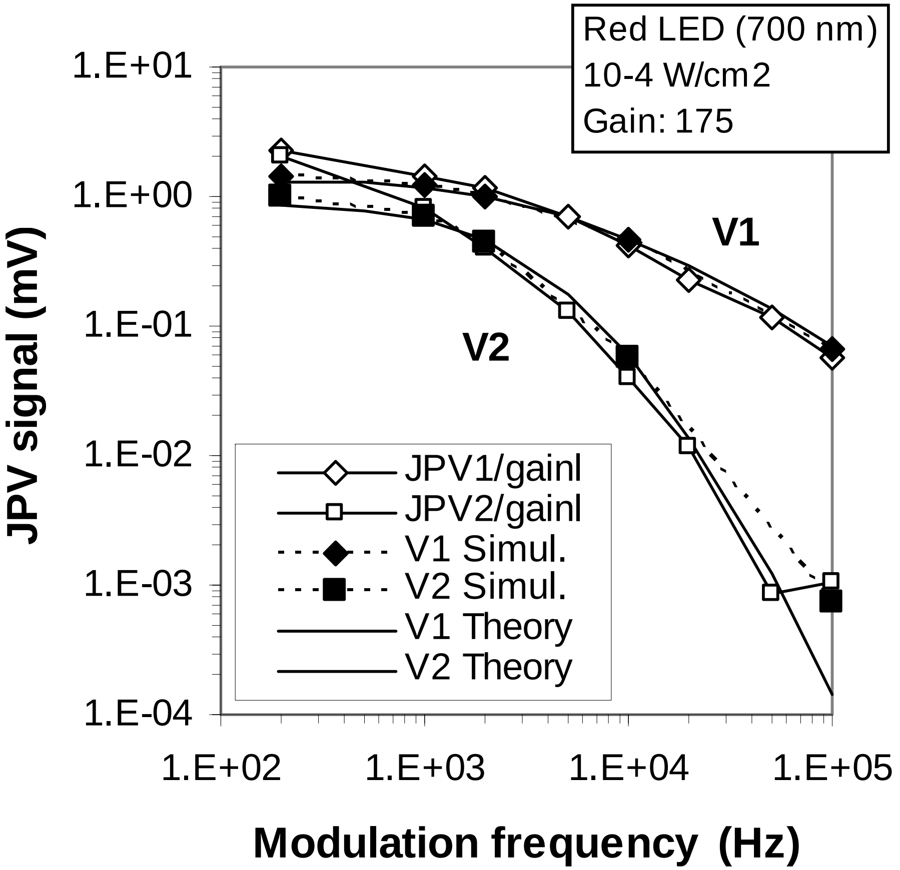
$$V_1=\frac{qFR_s}{\beta^2}[1-2I_1(\beta R_0)K_1(\beta R_0)]$$

$$V_2=\frac{\theta}{2\pi}\frac{2qFR_s}{\beta^2R_0}I_1(\beta R_0)[R_1K_1(\beta R_1)-R_2K_1(\beta R_2)]$$

θ= angle ...
R_i: radii defining probes

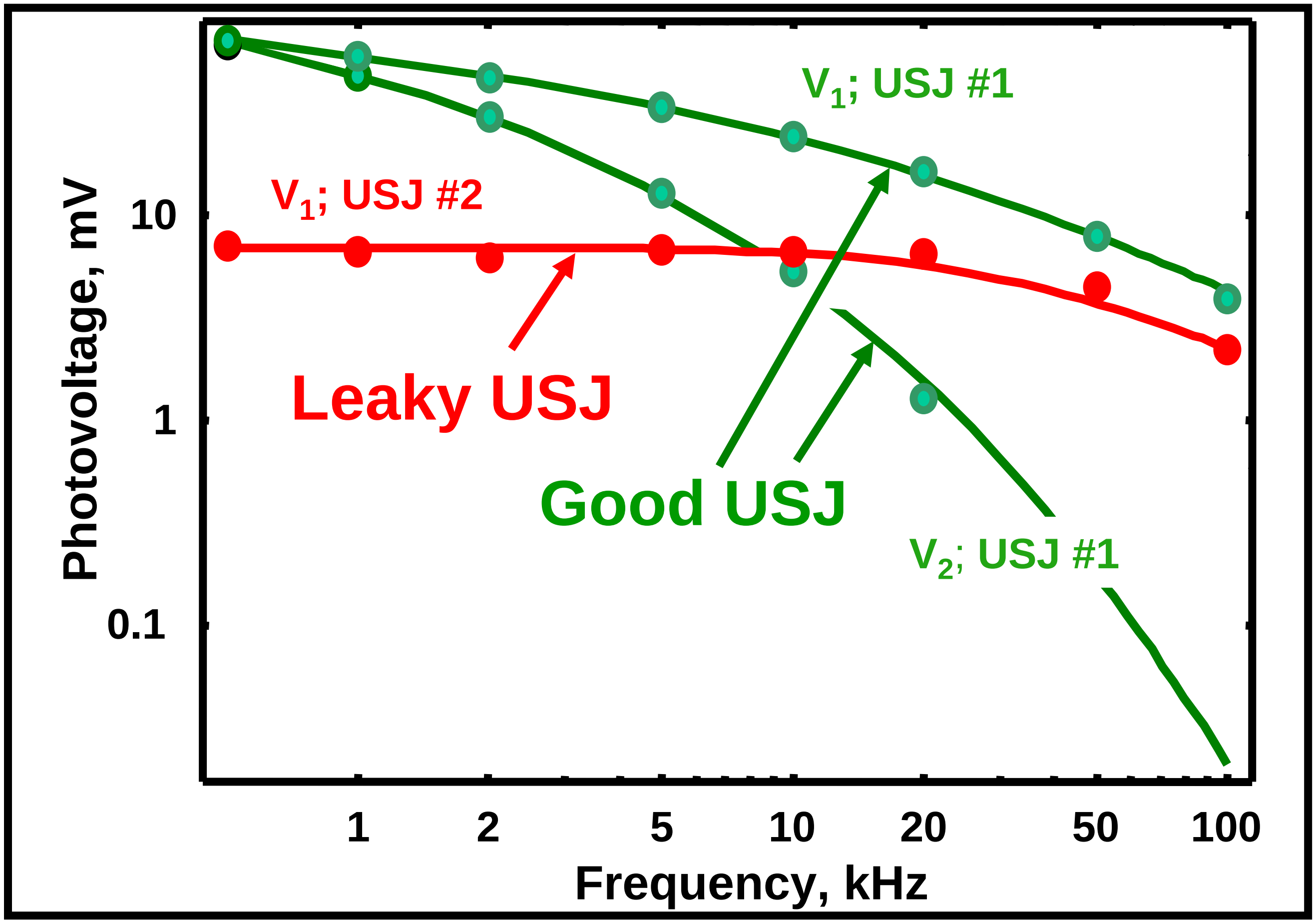
V_1 / V_2 independent of F,
Only depends on
R_s, G_s (Leakage), C_s,

IMEC Slide Simulated JPV frequency curves



- Good agreement between simulations, theory and experiments under standard conditions
- Availability of the simulator now also allows for studies of non standard cases

Good and Leaky p-n Junctions



Experiment (points)

Theory (lines)

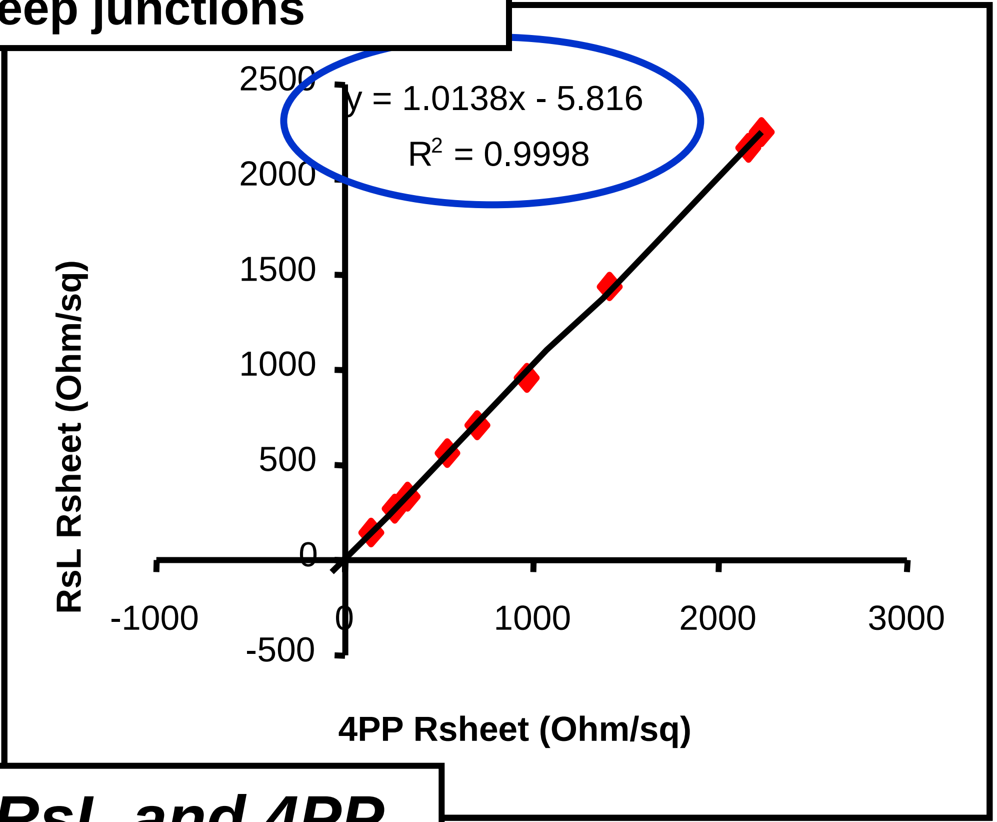
USJ#1: Rs=423 Ohm/sq
$J=10^{-6}A/cm^2$
USJ#2: $J=2.5x10^{-2}A/cm^2$

Leakage leads to decrease of photovoltages at low frequencies

Comparison of RsL with 4PP: IMEC data

Deep Junctions:

Low-doped substrates,
Deep junctions

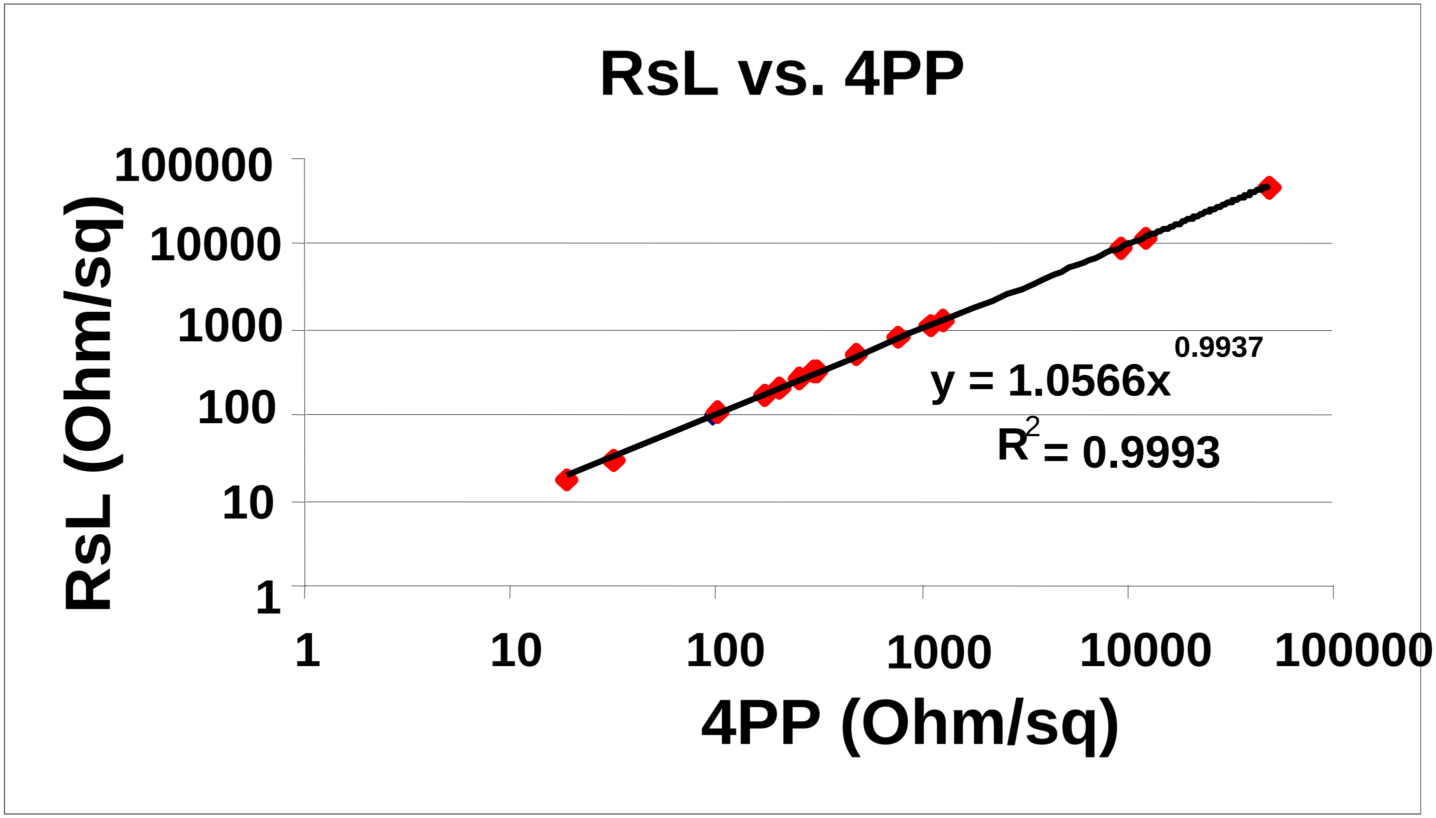


Deep (>50 nm) Junctions:

* no 4PP penetration
* no BTBT (for 10 Ohm-cm)
* no defect leakage

Good correlation between RsL and 4PP, Rs=100-2000 Ohm/sq

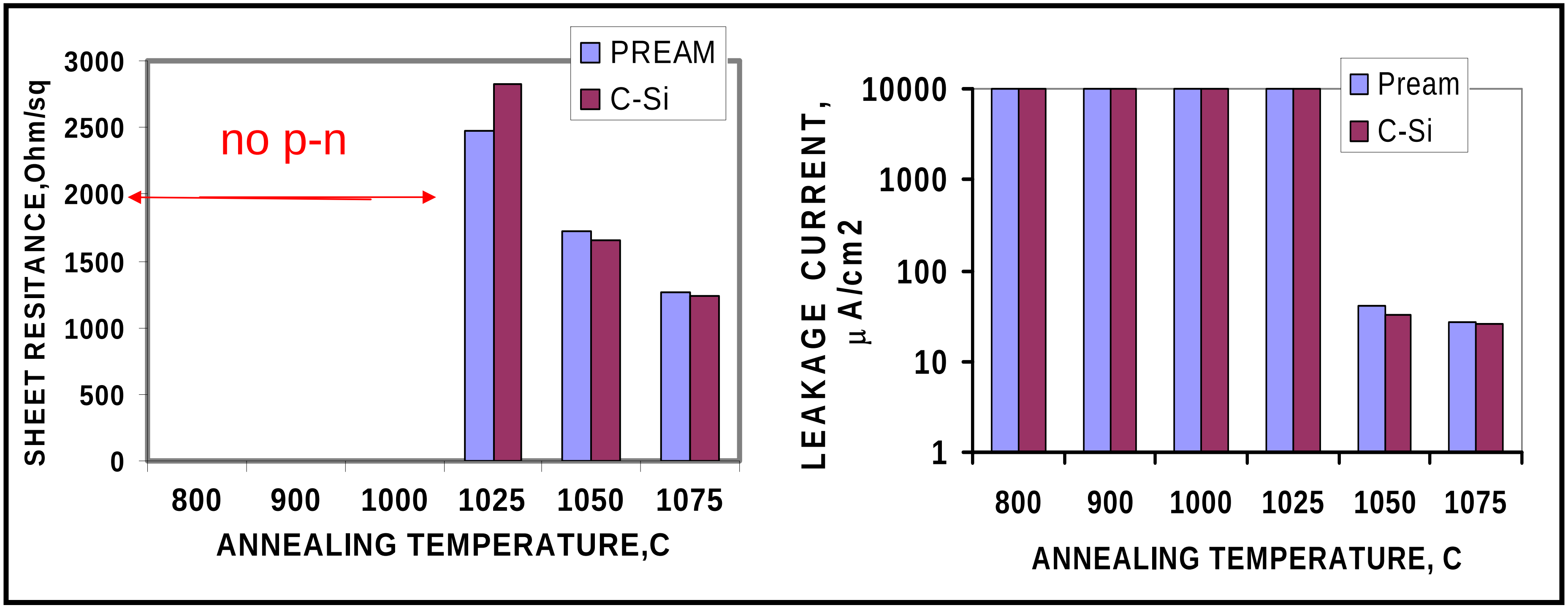
Comparison of RsL with 4PP: FSM data
Deep Junctions:



Close match of RsL and 4PP, Rs=20 – 50000 Ohm/sq

Sheet resistance and leakage current vs. RTP annealing temperature; USJs in halo/well profile

USJ: BF2, 4keV, 1E15cm-2 ; halo: As, 30keV, 5E13cm^{-2}; well: P, 300keV+500keV



Increase of annealing temperature leads to decrease of RsL sheet resistance and leakage current reduction.

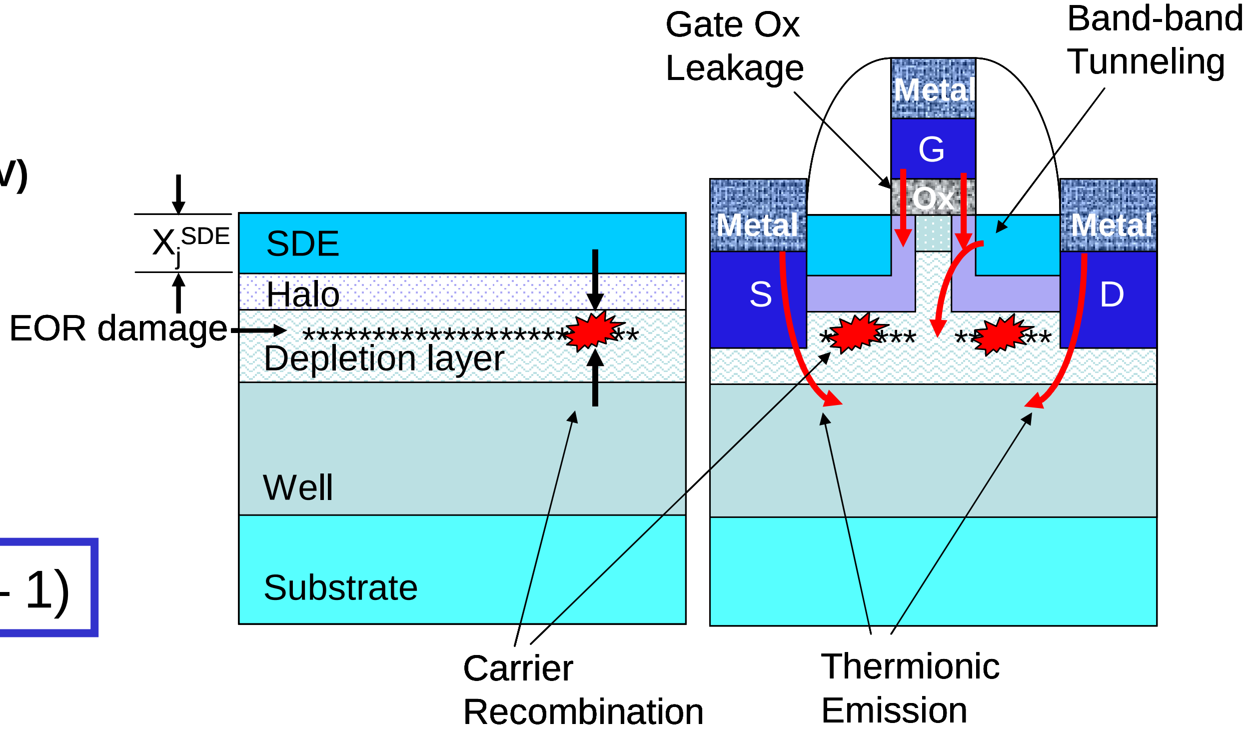
Leakage Currents in RsL and Transistors

RsL measures the "process dependent" (damage and doping) component of junction leakage, the recombination/ generation current amplitude, Io(A/cm²).

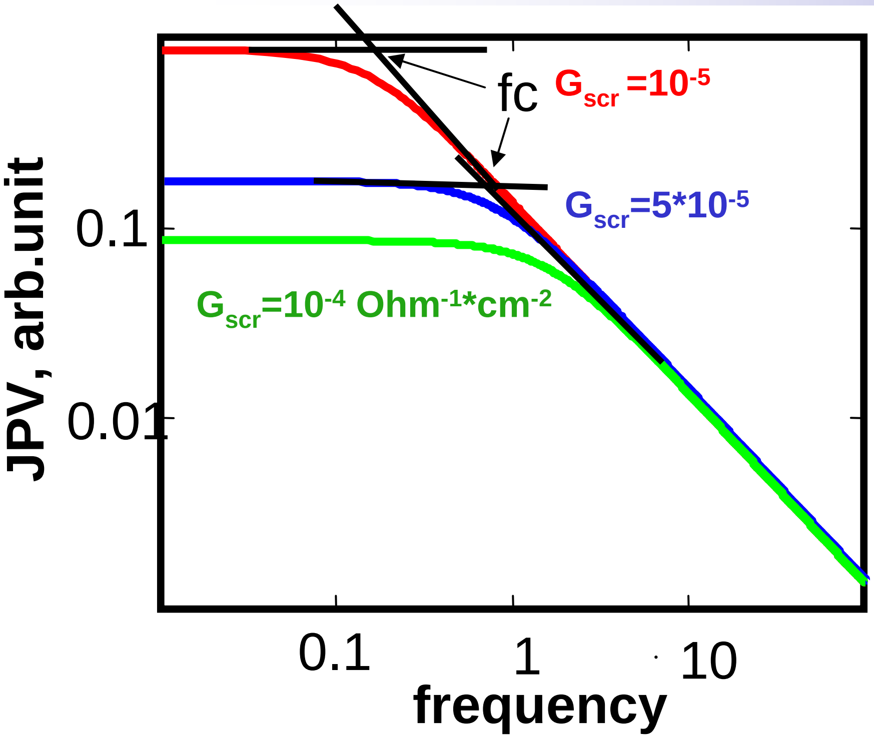
RsL (forward bias ~ +26 mV)
Recombination
Trap-assisted tunneling

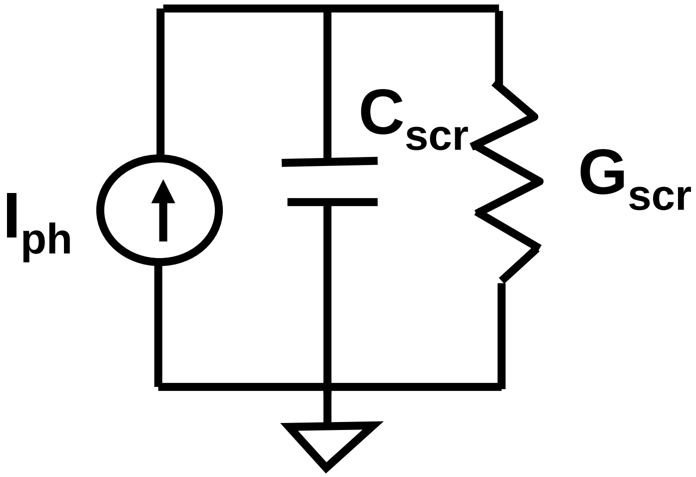
Transistors (reverse bias ~ -1 V)
Generation
Trap-assisted tunneling
Band tunneling
Contact emission
Gate leakage
Sub-threshold current

$$\boxed{J = \mathbf{I_o(A/cm^2)} * (e^{qV/kT} - 1)}$$



RsL Leakage Current (one dimensional)





$$Z = \frac{1}{G_{SCR} + i\omega C_{SCR}}$$

$$f_c = \frac{G_{SCR}}{2\pi C_{SCR}}$$

$$V_{JPV} = I_{ph} \cdot Z$$

$$J_{RsL}=(kT/q)G_{scr}=Io$$

G.E.Park, D.K. Schroder, *et al, J. Electrochem.Soc.148, G411 (2001).*

Leakage Current Mechanisms

$$J(V) = J_{diff} + J_S + J_{SCR} + J_{BTB} = \left(q\frac{n_i^2}{N_D}\sqrt{\frac{D_n}{\tau_n}} + qs\frac{n_i^2}{N_A} \right)\left[e^{qV/kT} + 1\right] + J_{SCR} + J_{BTBT}$$

$$J_{SCR} = q\int_{xj}^{xj+W} U dz$$

$$J_{BTBT}(V) = cqVE_m^{\sigma}\exp(-E_0/E_m)$$

$$U \approx q(1+\Gamma)\frac{v_{th}\sigma_n\sigma_p N_t(z)(pn - n_i^2)}{\sigma_n(n+n_1) + \sigma_p(p+p_1)}$$

$$\Gamma = 2\sqrt{3\pi}\,\frac{E_r}{E_\Gamma}\exp\left(\frac{E_r}{E_\Gamma}\right)$$

$$E_\Gamma = \frac{\sqrt{24m^*(kT)^3}}{q\hbar}$$

J_{SCR}=Generation/Recombination +Trap Assisted Tunneling (TAT)

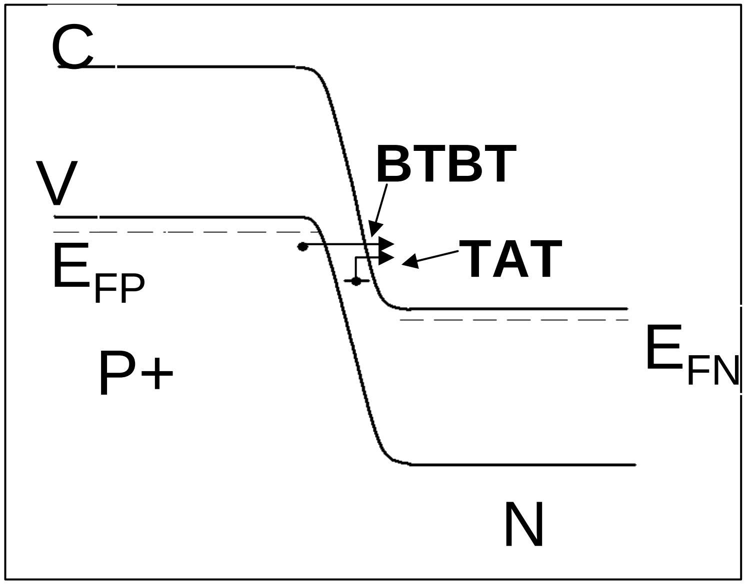
J_{BTB}=Band to Band Tunneling (BTBT)

G.A.M. Hurkx, et al., IEEE TRAN. on Electr. Dev., 39, 331(1992)

G.A.M. Hurkx, Solid-State Electron., 32, 665-668 (1989).

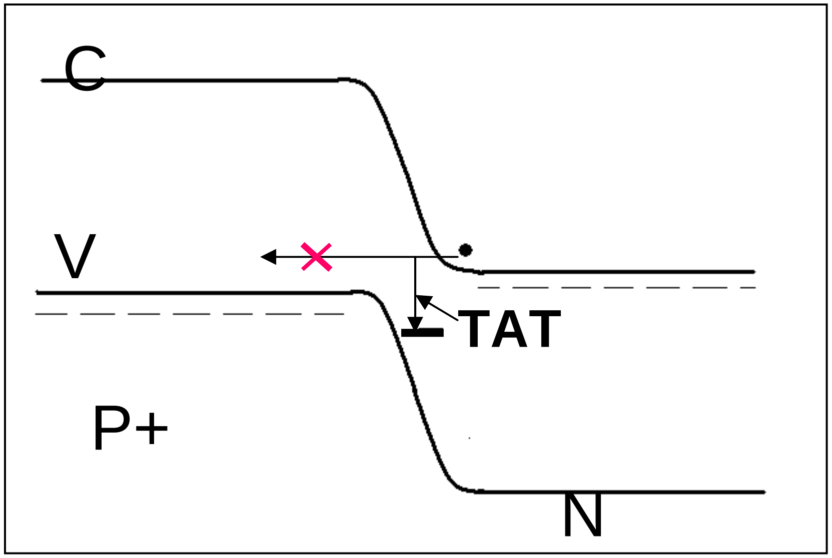
Band to Band (BTBT) and Trap-assisted Tunneling (TAT)

Reverse biased diode



$$\boxed{J_{REVBDIODE}=J_{SCR}+J_{BTBT}}$$

RsL (forward bias)

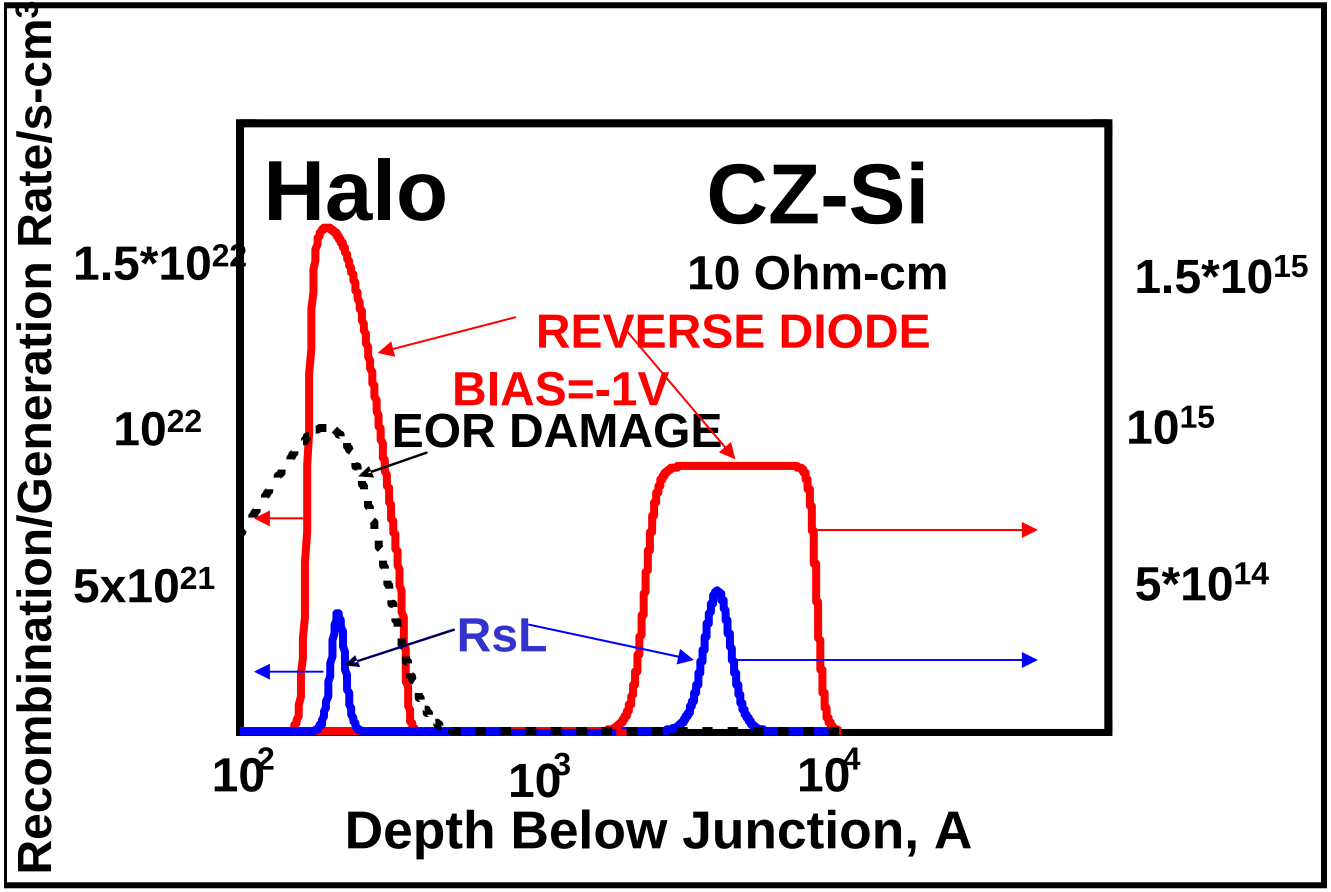


$$\boxed{J_{RsL}=\frac{kT}{q}\frac{dJ_{SCR}(V)}{dV}\Bigg|_{V\to+0}}$$

The relevant equations for the diode and RsL leakage currents

Recombination/Generation Rate Profiles

$$N_t(z) = N_{t\max}\exp\left(-\frac{q(z-z_{\max})^2}{\Delta^2}\right)+N_{tsub}$$ ***EOR, damage profiles***



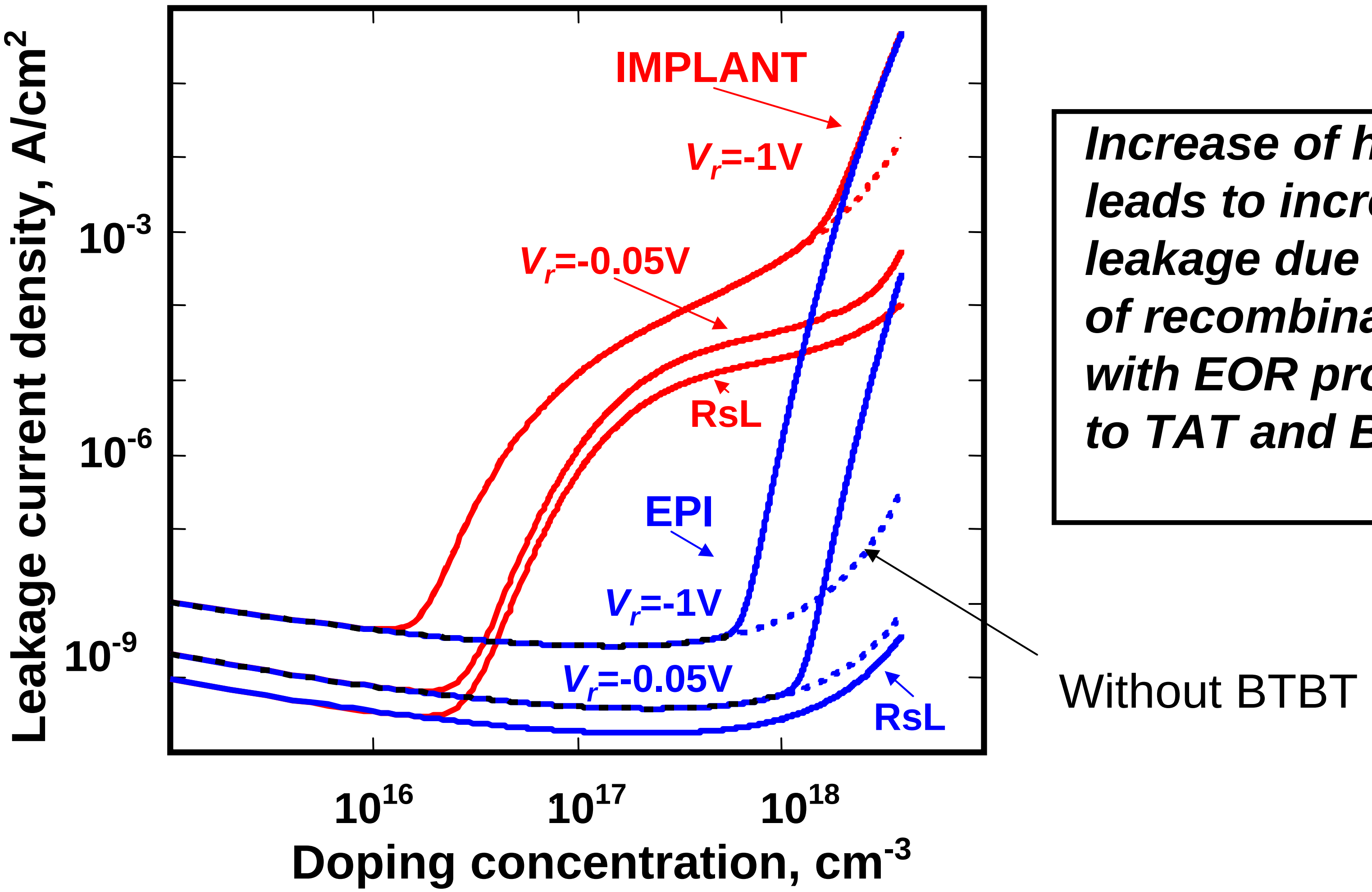
Halo, EOR
Nd=10^{18} cm^{-3}
N_{tmax}=10^{18}cm^{-3}
σ=10^{-14}cm^2
Z_m=20nm
N_{tsub}=10^{12} cm^{-3}

Δ=15 nm

CVD USJs,
Z_m=10nm

Δ=1 nm

Effect of Substrate & Halo Doping Level.

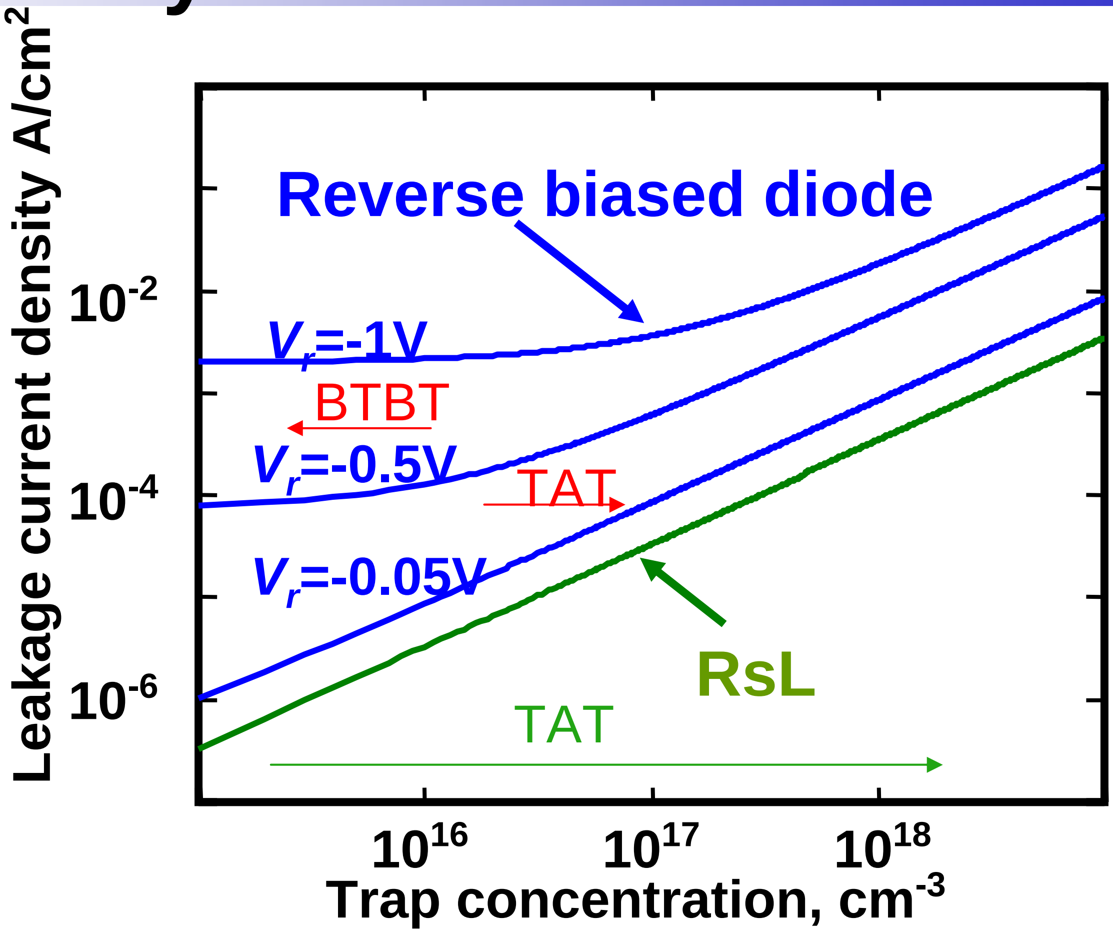


Increase of halo doping leads to increase of leakage due to overlap of recombination profile with EOR profile and due to TAT and BTBT

Effect of Trap Density

halo
$N_d=2*10^{18} cm^{-3}$

traps
$\sigma=10^{-14} cm^2$



Reverse-biased diode and non-contact RsL leakage currents are only similar for small reverse bias V~ kT/q.

Conclusions:

- FSM and IMEC analytical JPV formulas are similar.
- Good agreement between simulations, theory and experiments
- ***Close match of RsL and 4PP, Rs=20 – 50000 Ohm/sq***
- RsL measures leakage current density related with EOR damage in SCR *without* BTBT and is **similar to reverse biased diode** current density at V_r~25mV.
- Process monitors need to include all implants (PAI, Halo, SDE).