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CHRISTIAN SCHARF

FORWARD AND REVERSE CURRENT OF HIGHLY IRRADIATED SILICON PAD DIODES

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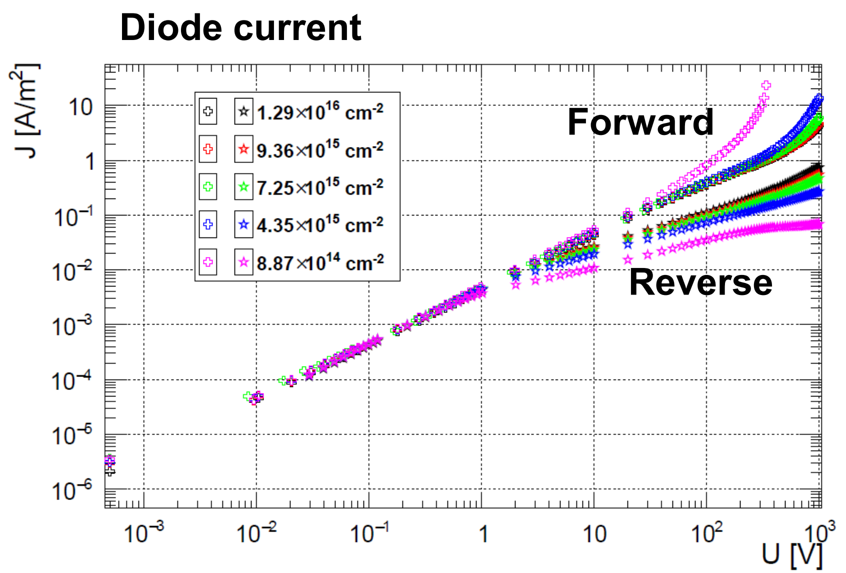
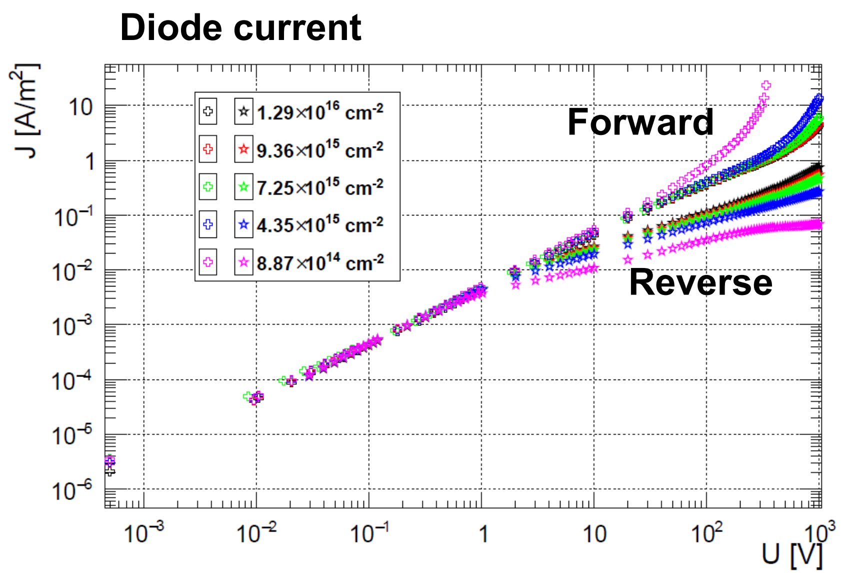
MOTIVATION



Is the current of highly irradiated silicon diodes understood?

MOTIVATION



Is the current of highly irradiated silicon diodes understood?

- Goals:
  - Develop models + extract parameters

SAMPLES

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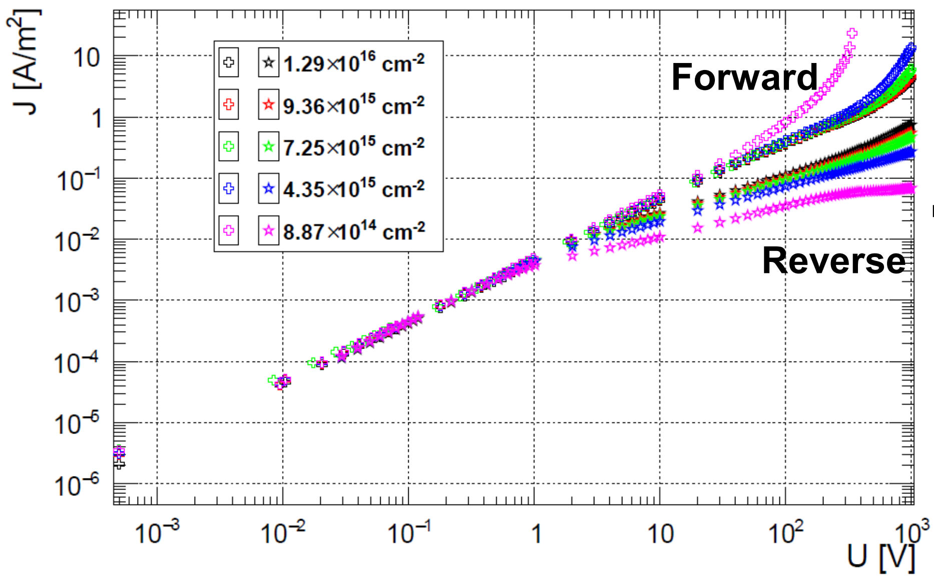
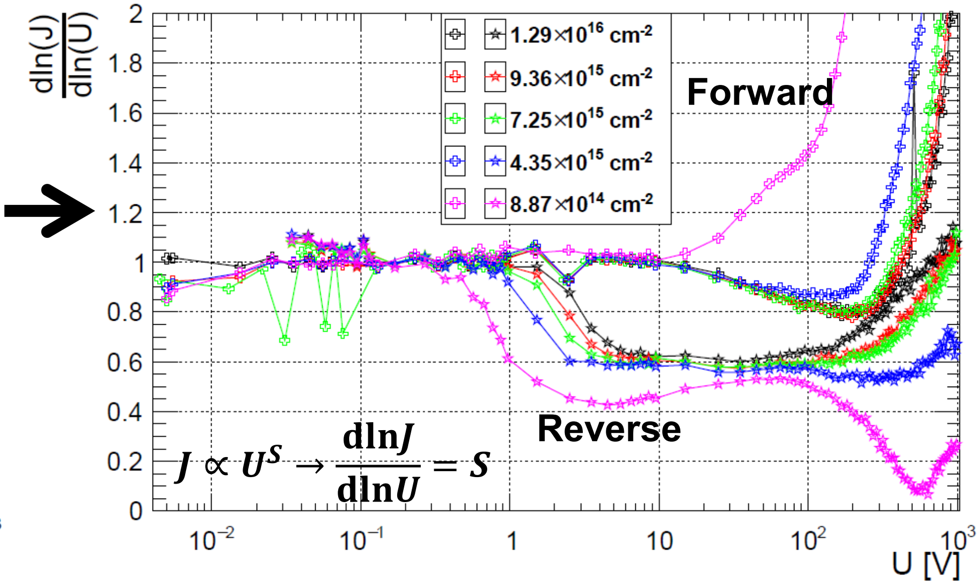
SAMPLES

- Diodes
  - Initial doping $\boldsymbol{N_D = 8 \cdot 10^{11} - 5 \cdot 10^{12}}$ cm^{-3}
  - N-type and p-type bulk, pad area 25 mm^2
  - Thickness 200 µm and 285 µm
- Irradiations
  - 24 GeV/c protons to $\boldsymbol{\Phi_{eq} = 9 \cdot 10^{14} - 1.3 \cdot 10^{16}}$ cm^{-2}
  - No annealing studies so far
- All measurements performed at 243 K

RESULTS

CURRENT OF HIGHLY IRRADIATED DIODES





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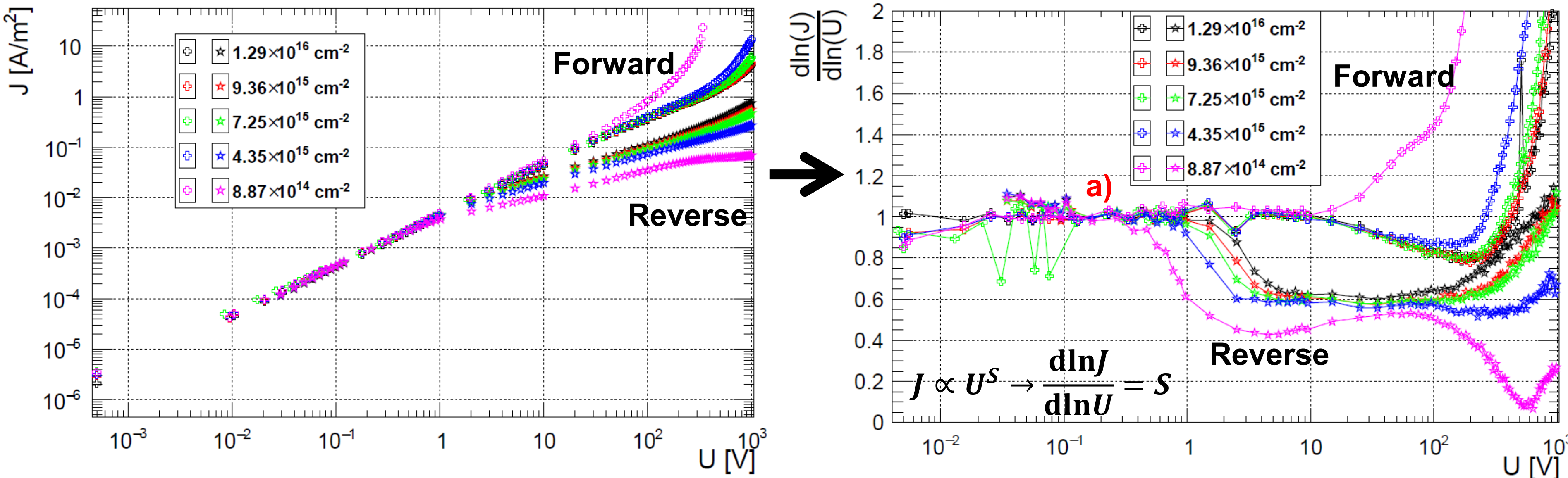
CURRENT OF HIGHLY IRRADIATED DIODES



a) Forward & reverse: Resistor: $I = {}^{U}/_{R},\ \rho = \left(e(n\mu_e + p\mu_h)\right)^{-1}$

CURRENT
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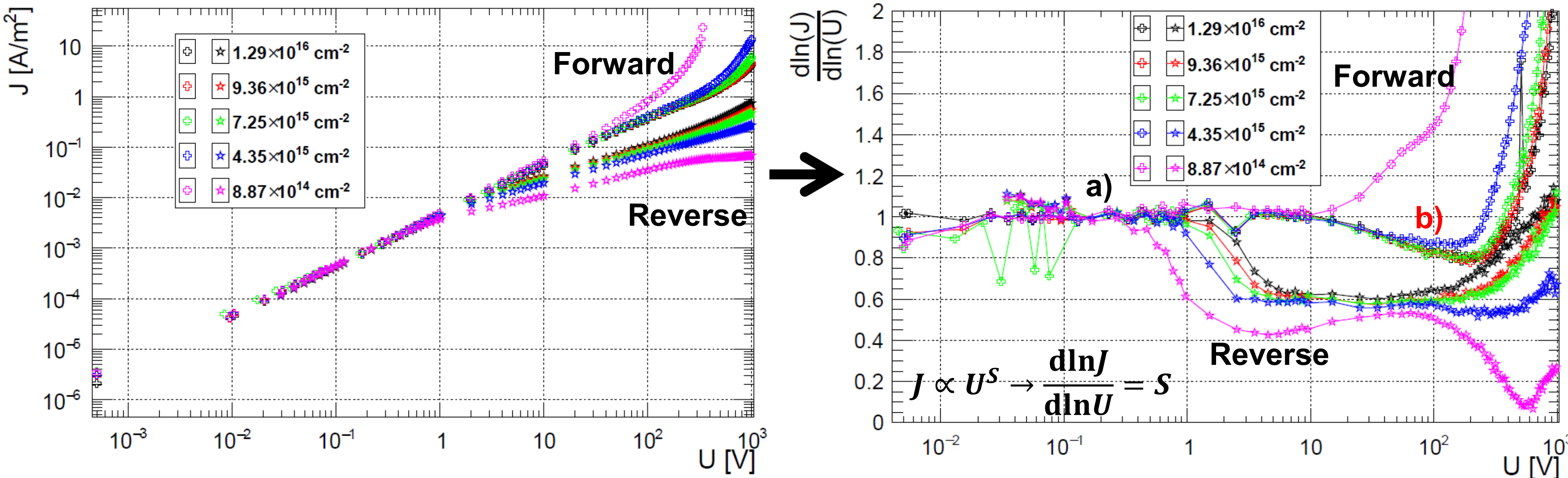

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b) Forward: Resistor: $\mu^0_{e,h} \rightarrow \mu_{e,h}(E)$

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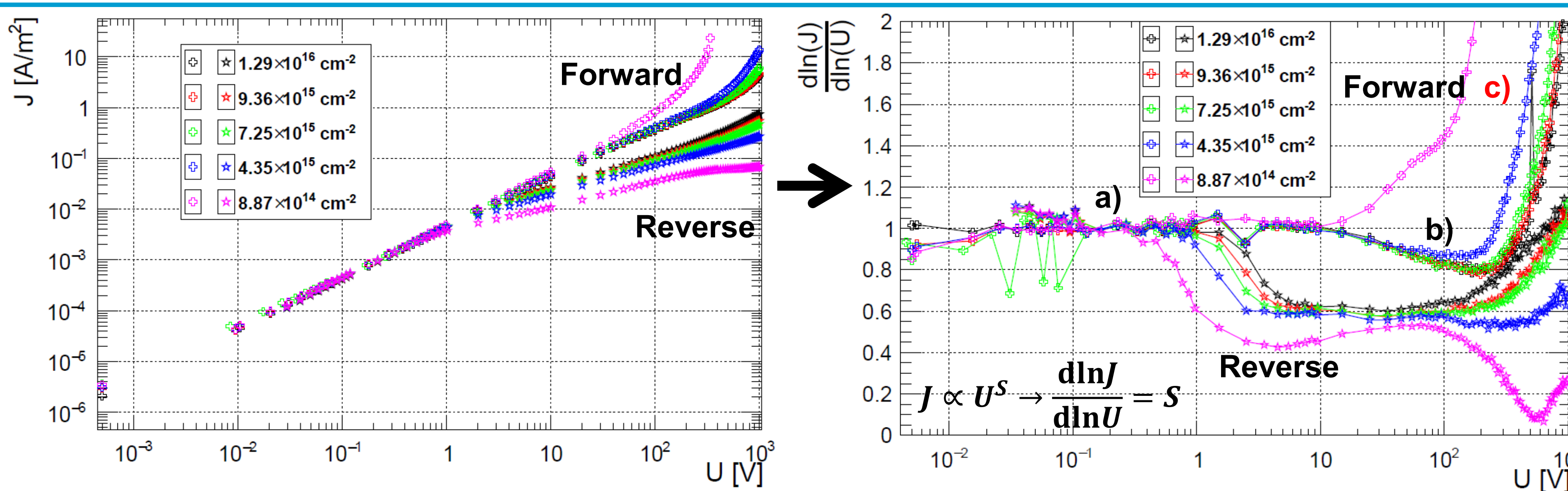

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c) Forward: Electron injection → Space-charge-limited currents

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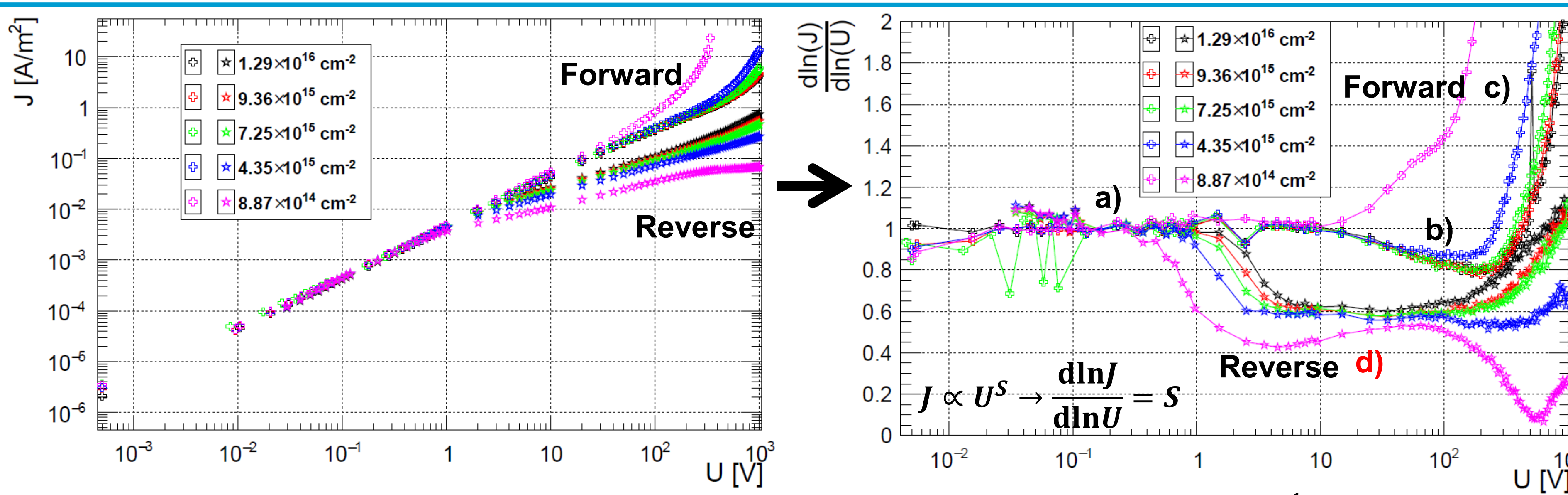

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d) Reverse: Space charge region SCR + bulk resistance

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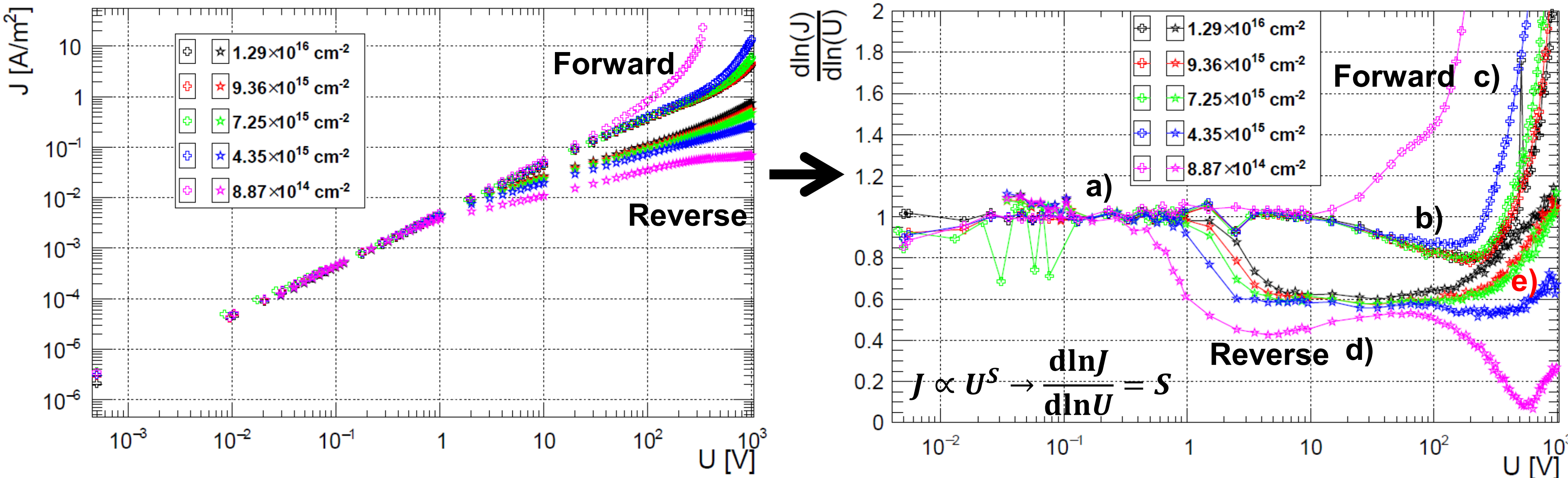

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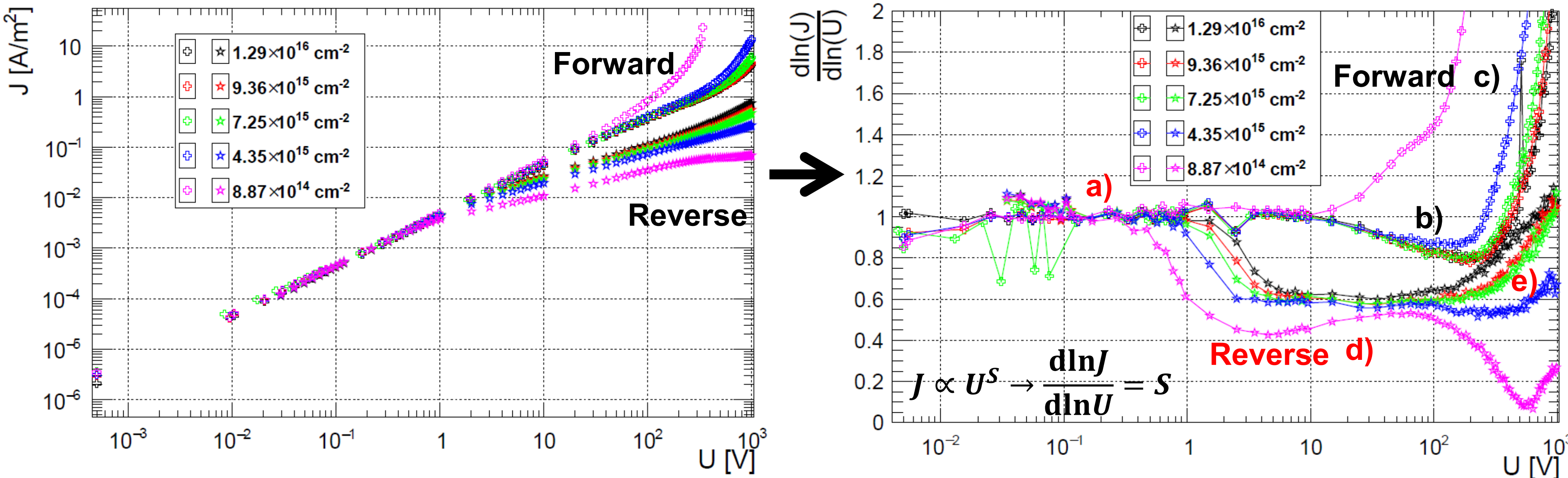

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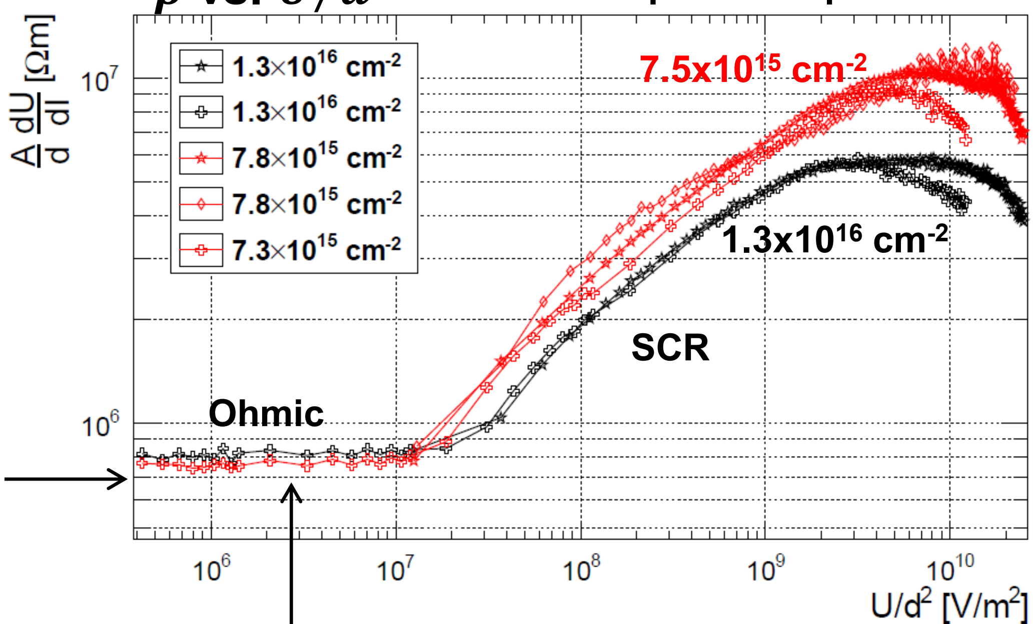
REVERSE CURRENT
OHMIC REGION – NEUTRAL BULK

ρ vs. U/d^2

200 µm & 285 µm diodes

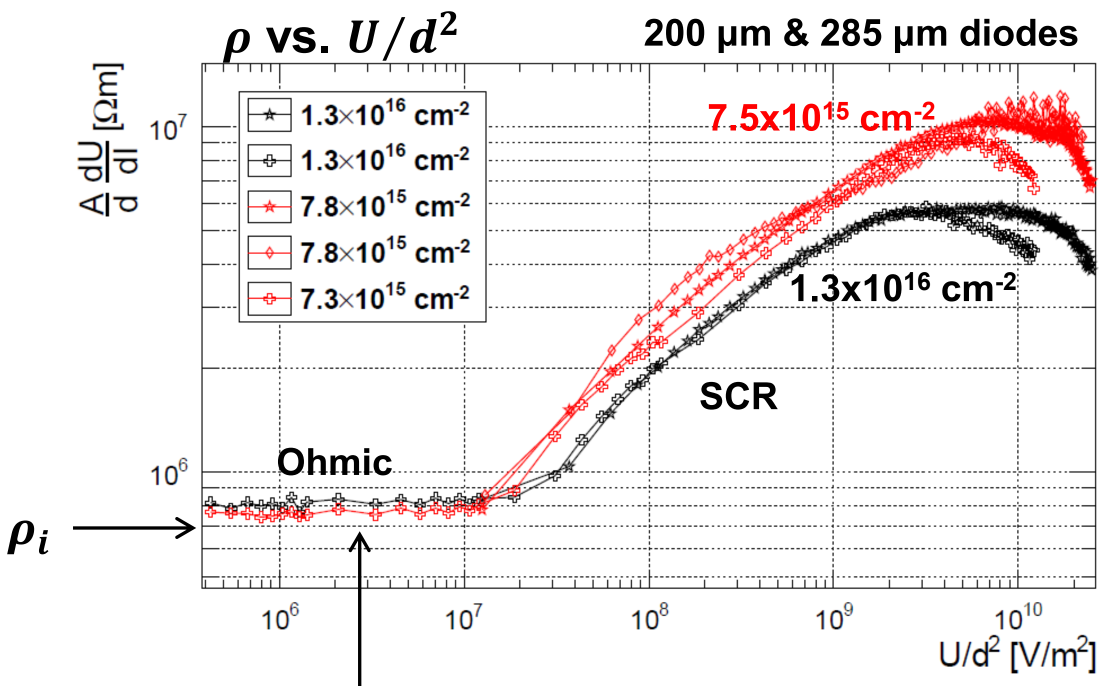


ρ_i

- High near-intrinsic $\rho_{ohm} \approx \rho_i$ at small bias voltages

$$\rho(\phi_{eq}) = \left(en_i(\mu_e(\phi_{eq}) + \mu_h(\phi_{eq}))\right)^{-1}$$

REVERSE CURRENT
OHMIC REGION – NEUTRAL BULK



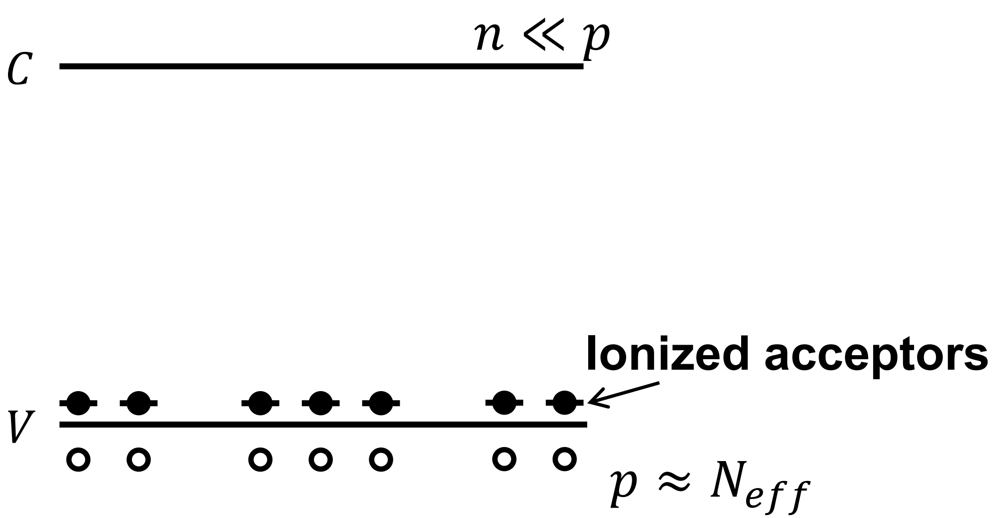
- High near-intrinsic $\rho_{ohm} \approx \rho_i$ at small bias voltages

$$\rho(\phi_{eq}) = \left(e n_i\left(\mu_e(\phi_{eq}) + \mu_h(\phi_{eq})\right)\right)^{-1}$$

→ Extract $(\mu_e + \mu_h)(\phi_{eq})$

REVERSE CURRENT
OHMIC REGION – NEUTRAL BULK

Non-irradiated



$$\boldsymbol{\rho = \left(e(n\mu_e + p\mu_h)\right)^{-1}}$$

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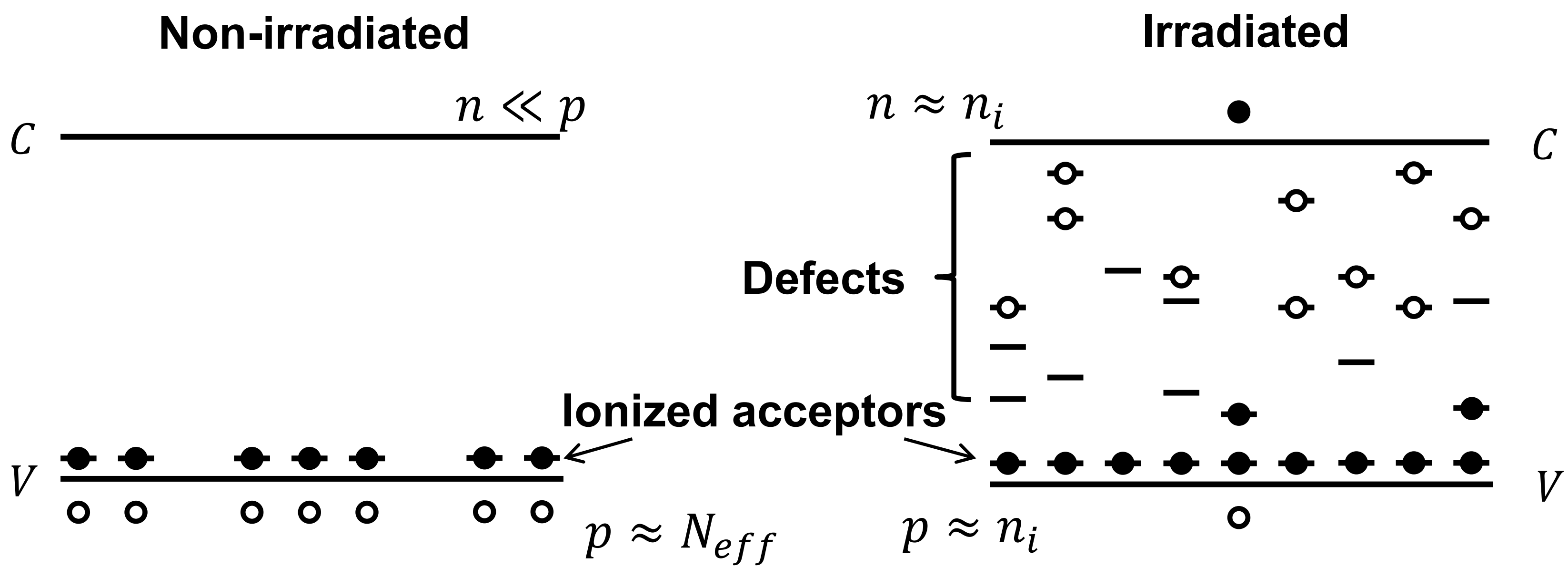
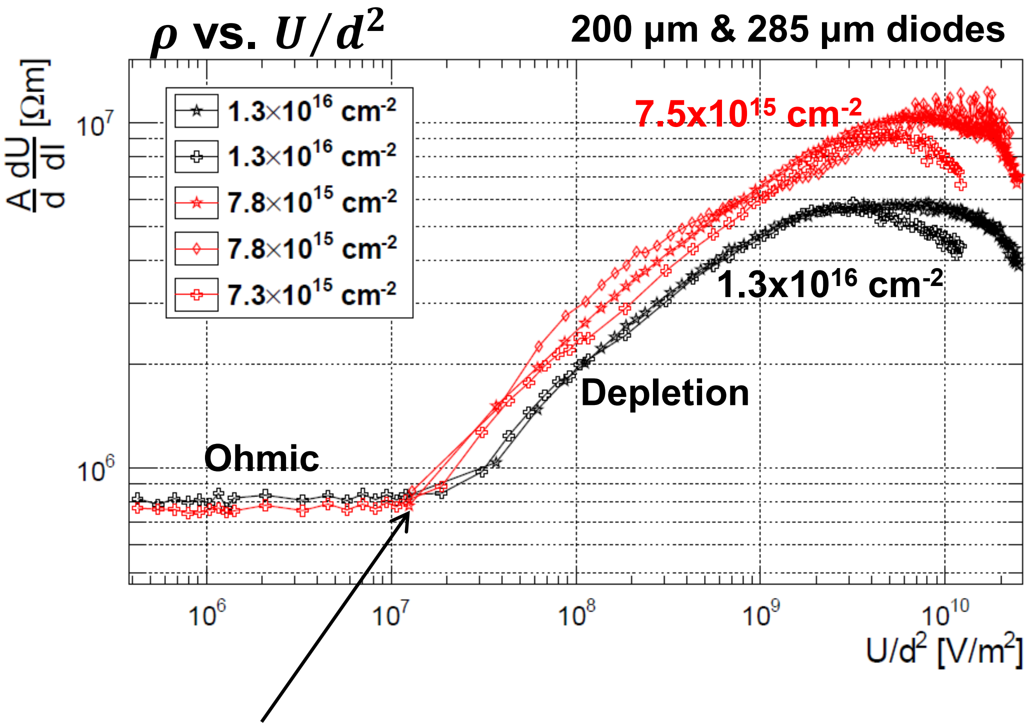
REVERSE CURRENT
OHMIC REGION – NEUTRAL BULK



- Carrier removal
  →W.M. Bullis. Solid-State Electronics. 9(2):143-168, 1966.
  →Z. Li. NIMA. 342(1):105-118, 1994.
  - Free carriers trapped at deep defects
  - $n \approx p \approx n_i$

$$\rho = \left(e(n\mu_e + p\mu_h)\right)^{-1}$$

REVERSE CURRENT
SPACE-CHARGE REGION

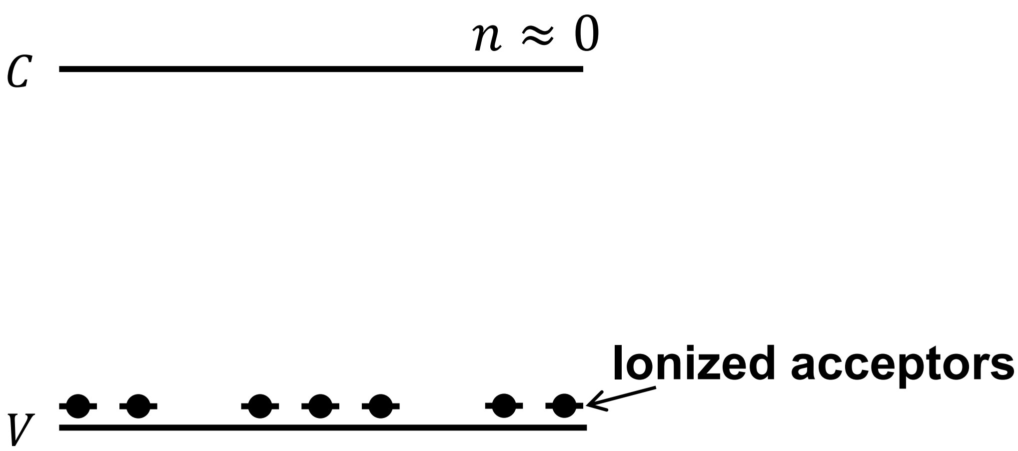


- Transition ohmic current to SCR generation current
  - Common threshold U_{th}/d^2

$$\boldsymbol{\rho = \left(e(n\mu_e + p\mu_h)\right)^{-1}}$$

REVERSE CURRENT
SPACE-CHARGE REGION

Non-irradiated



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REVERSE CURRENT
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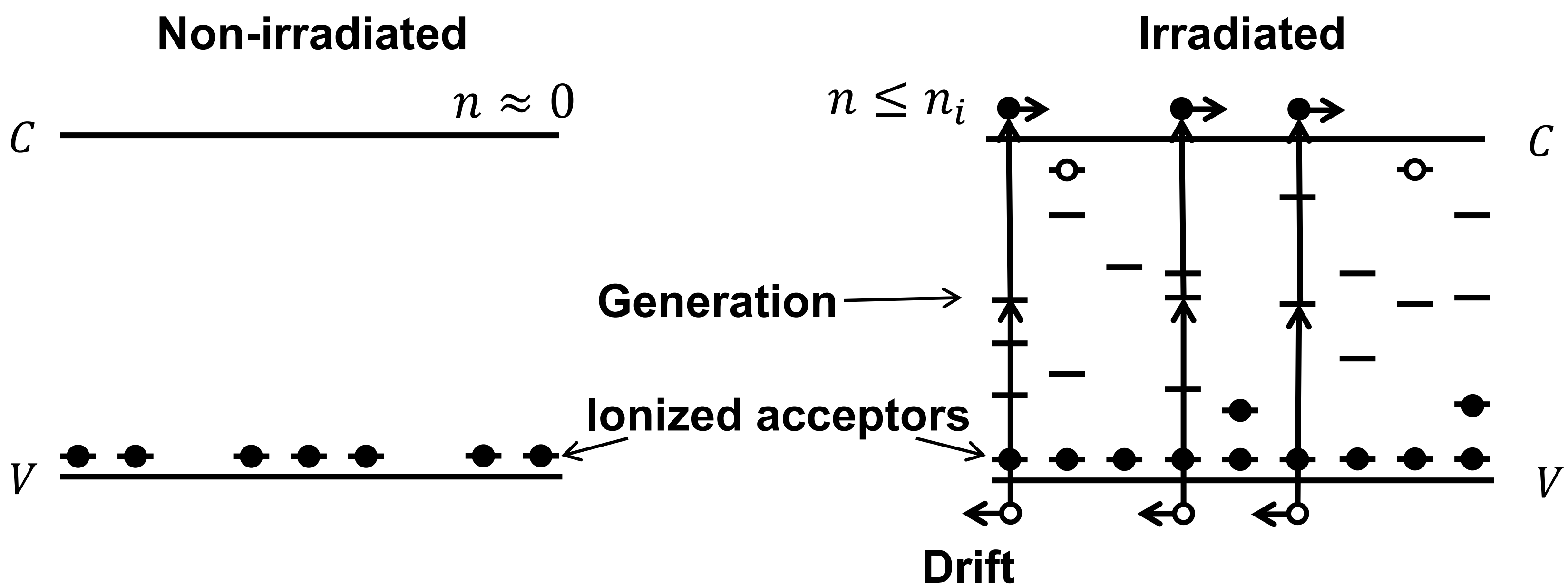
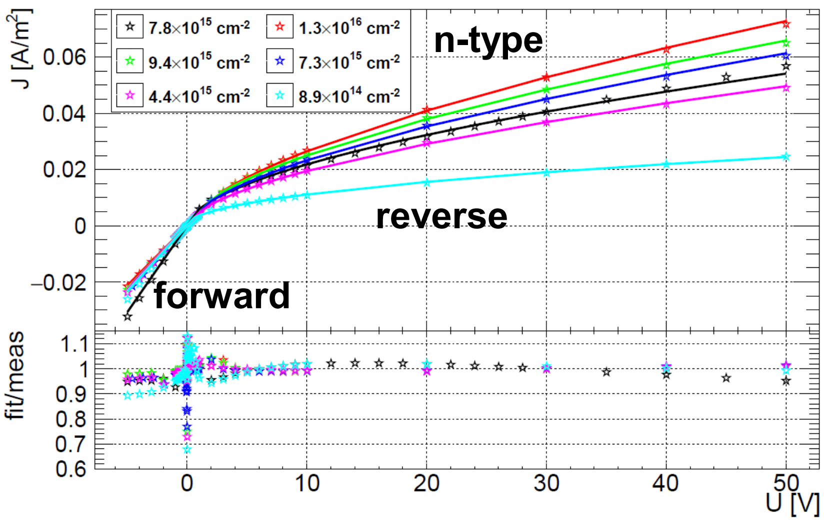
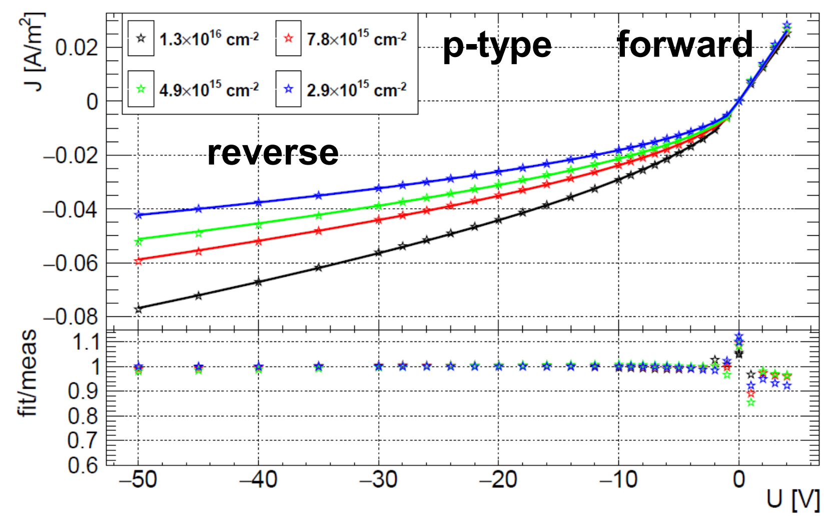


- Fast generation → High n, p in the SCR
  - Ohmic when $n, p \approx n_i$
  - U_{th}/d^2 when $n, p < n_i$ in the SCR due to drift

$$\boldsymbol{\rho = \left(e(n\mu_e + p\mu_h)\right)^{-1}}$$

REVERSE CURRENT
MODEL MEDIUM BIAS



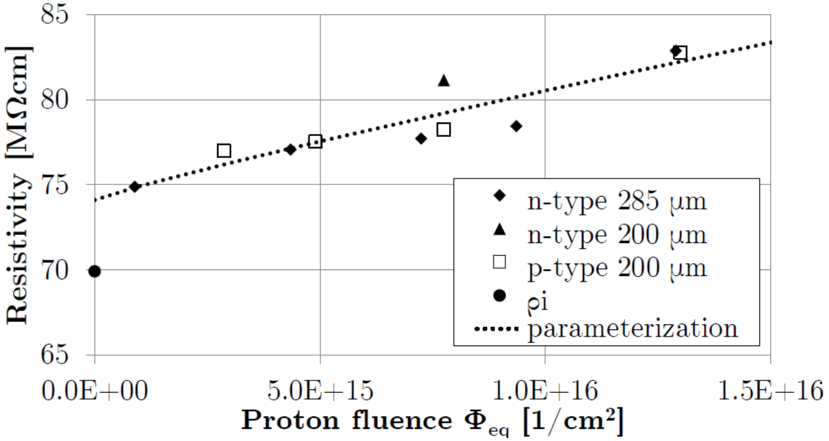


$$R(U) = \begin{cases} \rho_{ohm}(\Phi_{eq}) \cdot \frac{d}{A} & U \leq U_{th} \\ \widetilde{R}_{SCR}(\Phi_{eq}, A) \cdot U^{1-S(\Phi_{eq})} & U \geq U_{th} \end{cases}$$

$$\widetilde{R}_{SCR}(\Phi_{eq})^{-1} = \frac{A\left(d^2 \cdot \frac{U_{th}}{d^2}(\Phi_{eq})\right)^{1-S(\Phi_{eq})}}{d \cdot \rho_{ohm}(\Phi_{eq})}$$

- Simple model with three parameters
  - Fit 5 V forward to 50 V reverse describes measurements within few percent

REVERSE CURRENT MODEL MEDIUM BIAS



$$\rho_{ohm}(\Phi_{eq}) = 74.1\,\mathrm{M\Omega cm} \cdot \left(1 + \left(\frac{\Phi_{eq}}{\beta_{mob}}\right)^{0.9}\right)$$

- Parameters vs. fluence
  - ρ_{ohm} → Ionized impurity scattering

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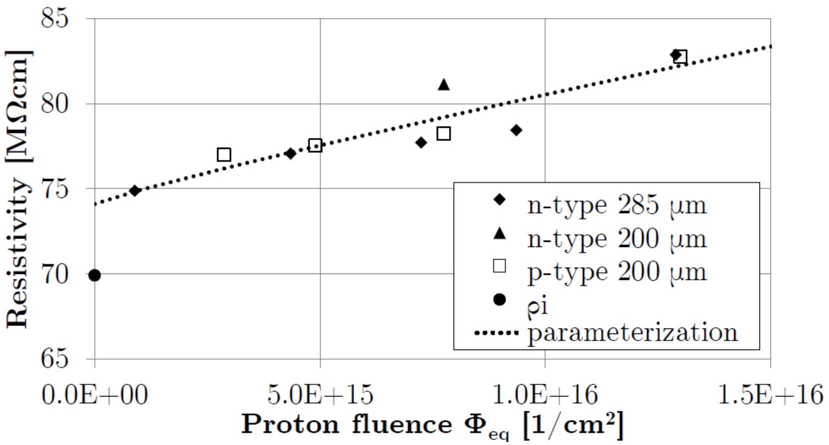
REVERSE CURRENT MODEL MEDIUM BIAS



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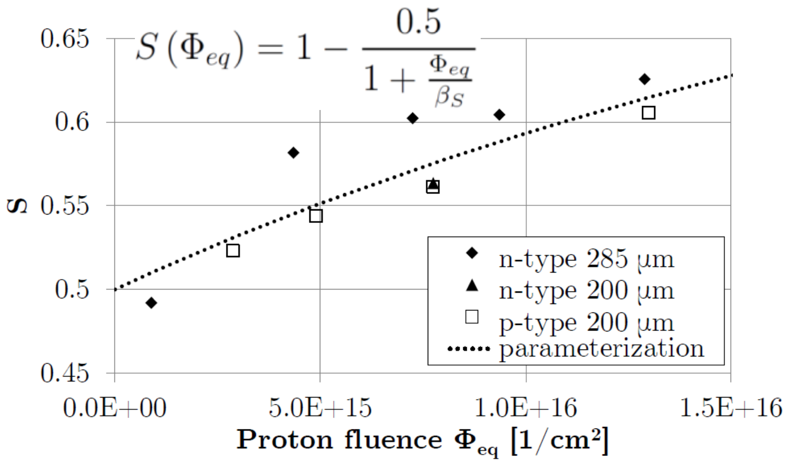
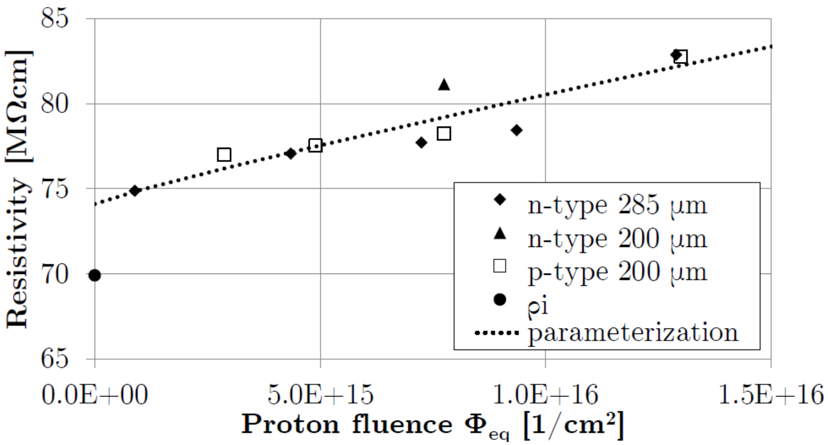


- Parameters vs. fluence
  - ρ_{ohm} → Ionized impurity scattering
  - S → $S(0) = 1/2$, $S\left(\phi_{eq} \to \infty\right) \to 1$

REVERSE CURRENT MODEL MEDIUM BIAS



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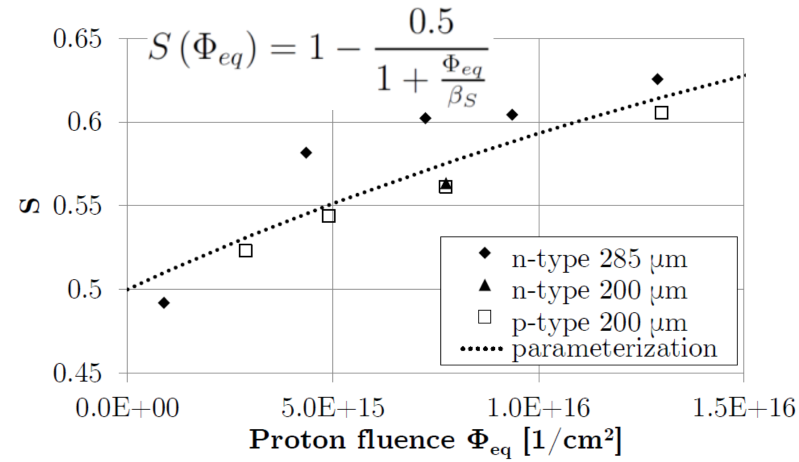
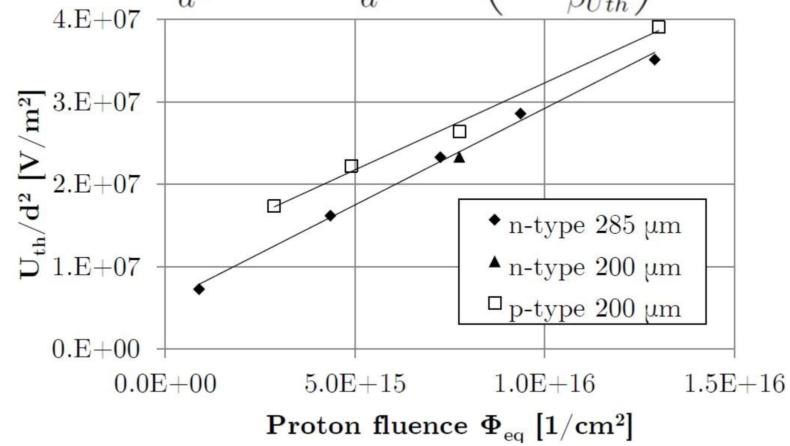
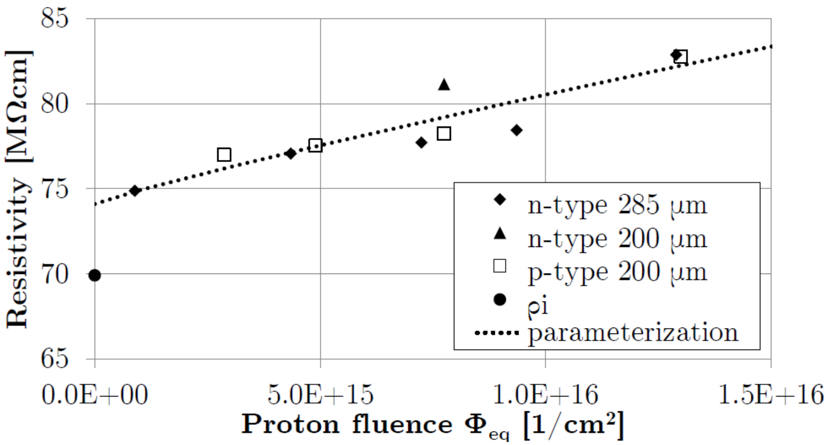


$$\frac{U_{th}}{d^2}\left(\Phi_{eq}\right) = \frac{U_{th}}{d^2}(0)\cdot\left(1+\frac{\Phi_{eq}}{\beta_{Uth}}\right)$$



- Parameters vs. fluence
  - ρ_{ohm} → Ionized impurity scattering
  - S → $S(0) = 1/2,\ S(\phi_{eq}\to\infty)\to 1$
  - $\frac{U_{th}}{d^2}$ → Linear with ϕ_{eq}

REVERSE CURRENT MODEL MEDIUM BIAS



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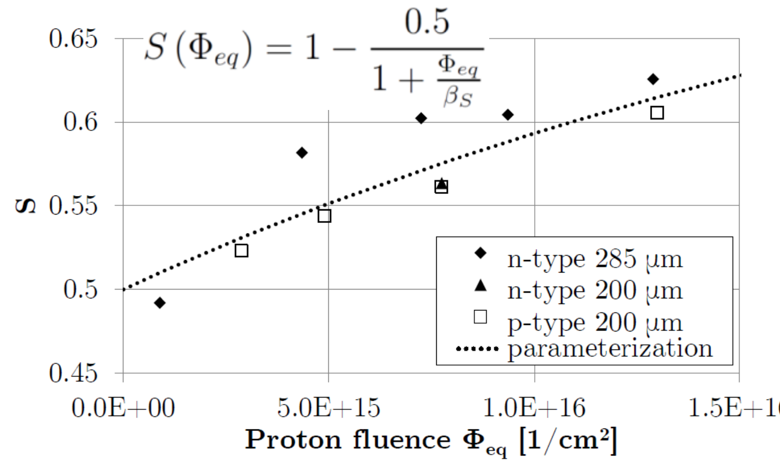

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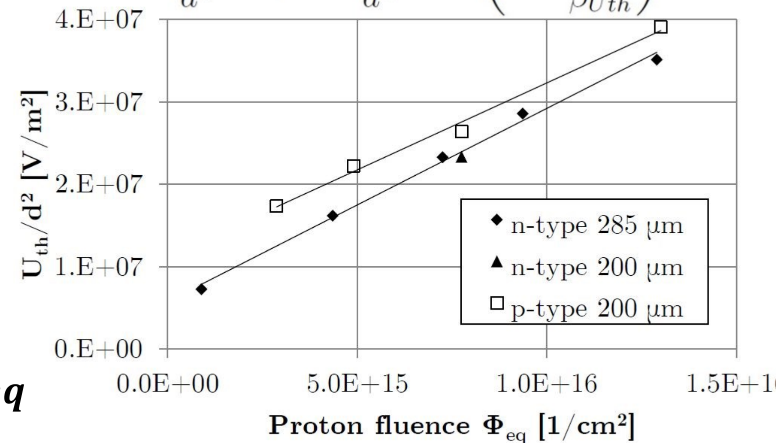

- Parameters vs. fluence
  - ρ_{ohm} → Ionized impurity scattering
  - S → $S(0) = 1/2$, $S(\phi_{eq} \to \infty) \to 1$
  - $\frac{U_{th}}{d^2}$ → Linear with ϕ_{eq} → Measure ϕ_{eq}

REVERSE CURRENT
OHMIC REGION – MOBILITY

- Assume ionized impurity scattering dominates at 243 K

$$\mu(N) = \mu_{min} + \frac{\mu_{max} - \mu_{min}}{1 + \left(\frac{N}{N_{ref}}\right)^{\varsigma}} \qquad N_{ref} \approx (0.5 - 2.4) \cdot 10^{17}\,\mathrm{cm}^{-3}$$

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Neglect μ_{min} → $\mu_0^e\left(\Phi_{eq}\right) + \mu_0^h\left(\Phi_{eq}\right) \approx \frac{\mu_0^e + \mu_0^h}{1 + \left(\frac{\Phi_{eq}}{\beta_{mob}}\right)^{\varsigma}}$

REVERSE CURRENT
OHMIC REGION – MOBILITY

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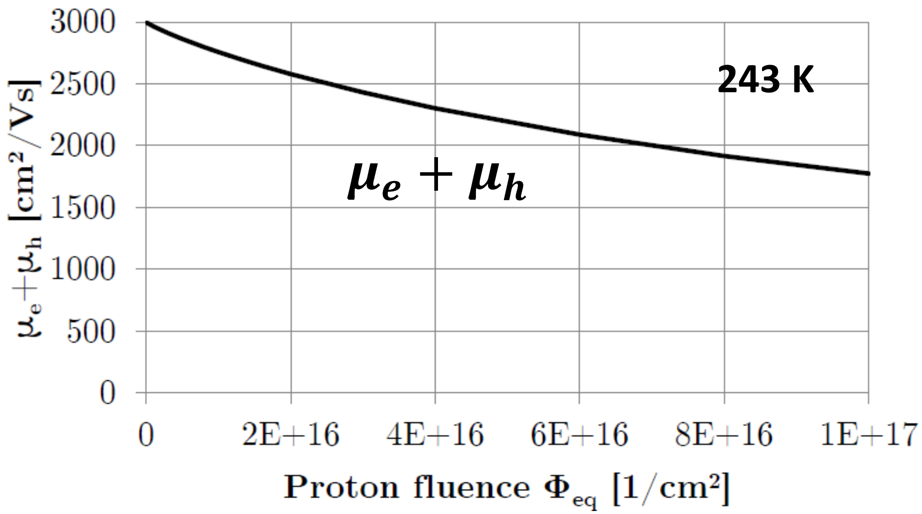

200 µm & 285 µm diodes

$$\rho = \left(en_i(\mu_e + \mu_h)\right)^{-1}$$

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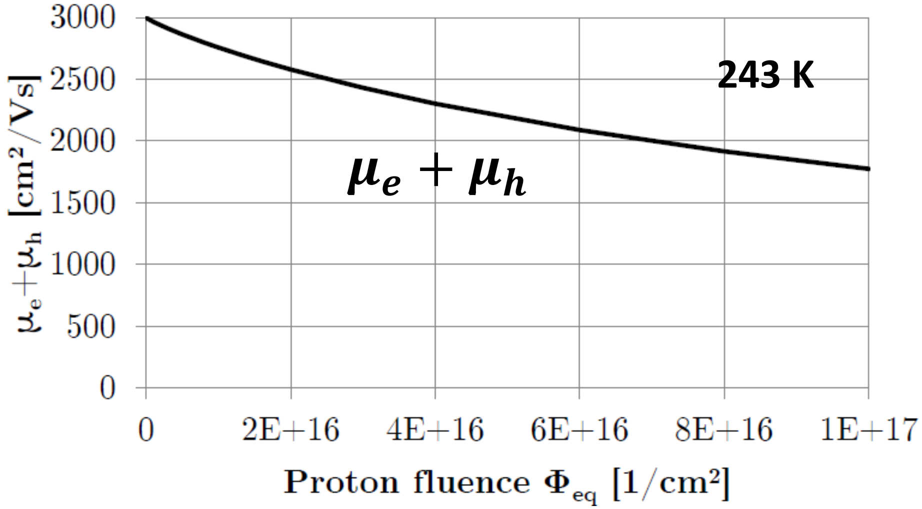
Neglect μ_{min} → $\mu_0^e(\Phi_{eq}) + \mu_0^h(\Phi_{eq}) \approx \frac{\mu_0^e + \mu_0^h}{1 + \left(\frac{\Phi_{eq}}{\beta_{mob}}\right)^{\varsigma}}$

$$\beta_{mob} = 1.52 \cdot 10^{17}\,\mathrm{cm}^{-2}$$
$$\beta_{mob} = N_{ref}/g_{eff}$$
$$g_{eff} \approx 1\,\mathrm{cm}^{-1}$$

REVERSE CURRENT
OHMIC REGION – MOBILITY



200 µm & 285 µm diodes

$$\rho = \left(e n_i (\mu_e + \mu_h)\right)^{-1}$$

Previous edge-TCT and Hall measurements show much larger decrease of $(\mu_e + \mu_h)(\phi_{eq})$ up to 50% at $\phi_{eq} = 10^{16}$ cm⁻² with $g_{eff} > 10$ cm⁻¹

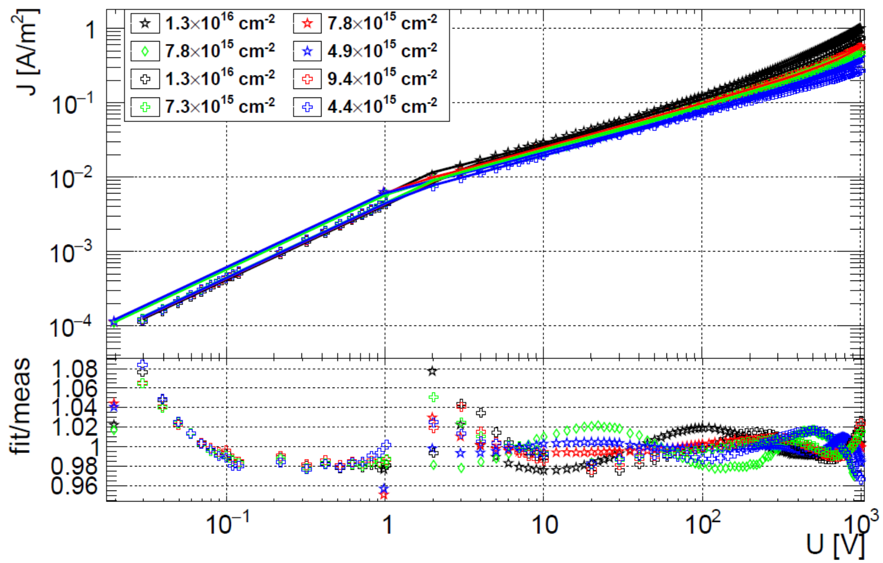
Neglect μ_{min} → $\mu_0^e(\Phi_{eq}) + \mu_0^h(\Phi_{eq}) \approx \frac{\mu_0^e + \mu_0^h}{1 + \left(\frac{\Phi_{eq}}{\beta_{mob}}\right)^{\varsigma}}$

$\beta_{mob} = 1.52 \cdot 10^{17}\,\mathrm{cm}^{-2}$

$\beta_{mob} = N_{ref}/g_{eff}$

$g_{eff} \approx 1\,\mathrm{cm}^{-1}$

REVERSE CURRENT MODEL HIGH BIAS



$$I = \frac{U}{R(U)} + I_{0,t} \cdot \left(\exp\left(\frac{U}{U_{0,t}} \right) - 1 \right)$$

$$R(U) = \begin{cases} \rho_{ohm}(\Phi_{eq}) \cdot \frac{d}{A} & U \leq U_{th} \\ \widetilde{R}_{SCR}(\Phi_{eq}, A) \cdot U^{1-S(\Phi_{eq})} & U \geq U_{th} \end{cases}$$

- Current increases exponentially for high reverse bias
  - Empirical model describes the measurements within a few percent

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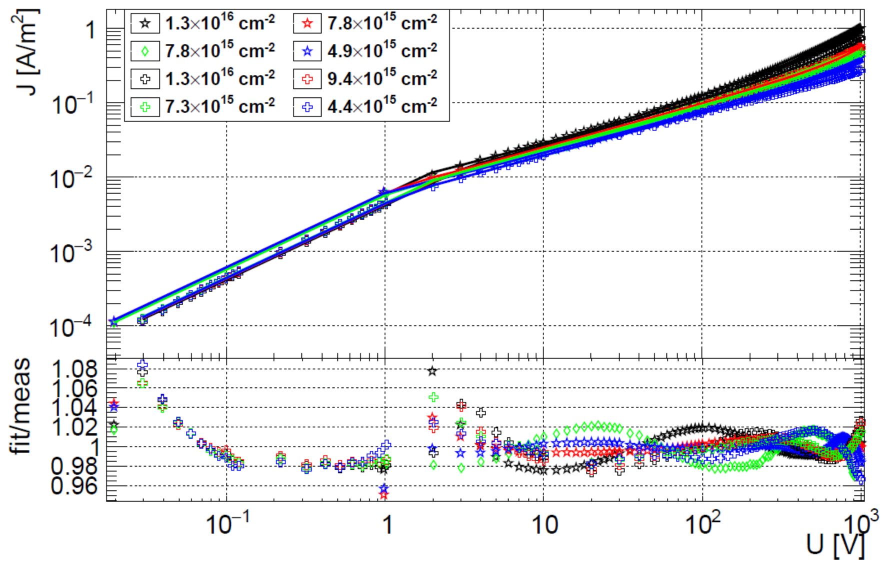
REVERSE CURRENT MODEL HIGH BIAS



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- Current increases exponentially for high reverse bias
  - Empirical model describes the measurements within a few percent
- Effects in the in high field of the SCR
  - Poole-Frenkel effect, trap-assited tunneling, and/or impact ionization

SUMMARY AND OUTLOOK

SUMMARY AND OUTLOOK

- Current model $\boldsymbol{I(U, A, d, \phi_{eq})}$
  - Carrier removal
  - Reverse: Threshold between ohmic and SCR-dominated current
    - Easy way to measure the mobility $\boldsymbol{\mu(T, \phi_{eq})}$
    - Replace $\boldsymbol{U_{dep}}$ + $\boldsymbol{\alpha}$ with $\boldsymbol{\frac{U_{th}}{d^2}}$ to determine $\boldsymbol{\phi_{eq}}$
  - Reverse: Exponential increase at high voltages
  - Forward: Space-charge-limited currents

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SUMMARY AND OUTLOOK

- Current model $I(U, A, d, \phi_{eq})$
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    - Easy way to measure the mobility $\mu(T, \phi_{eq})$
    - Replace $U_{dep} + \alpha$ with $\frac{U_{th}}{d^2}$ to determine ϕ_{eq}
  - Reverse: Exponential increase at high voltages
  - Forward: Space-charge-limited currents
- To-do
  - Extract more physical quantities
  - Temperature + annealing studies

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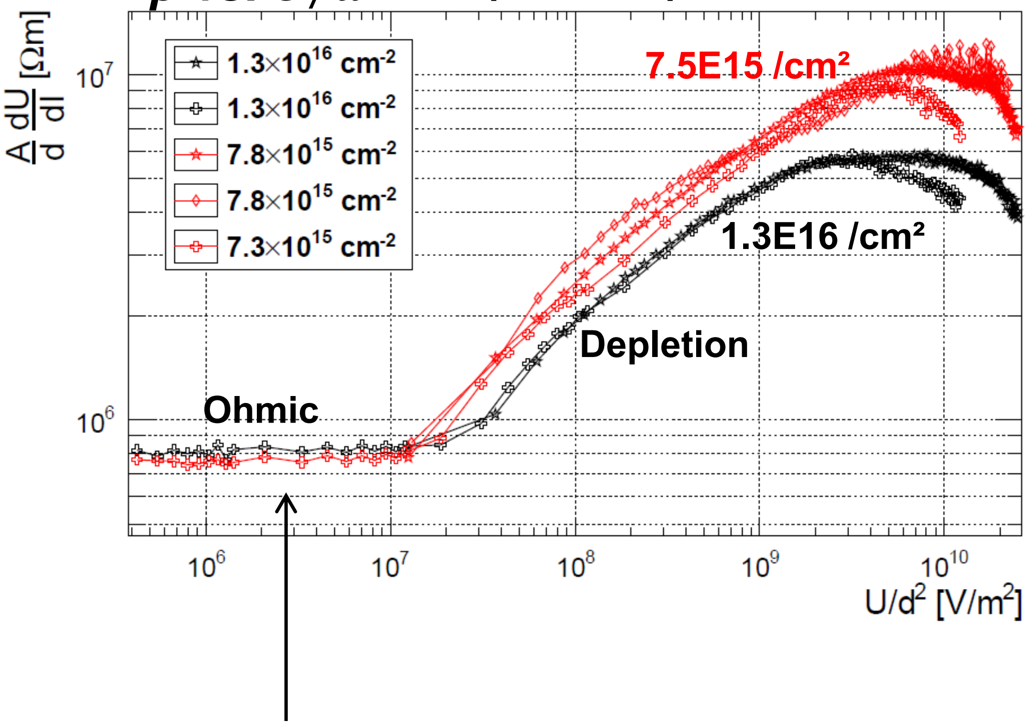
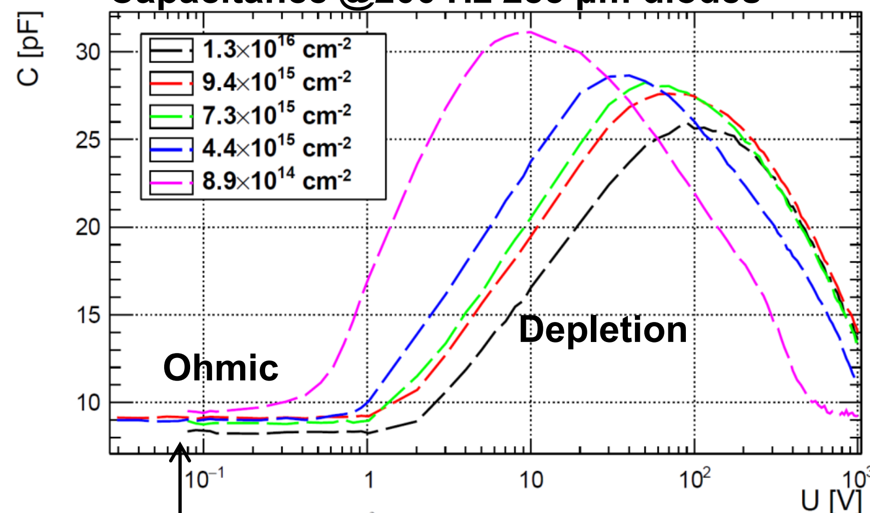
BACKUP

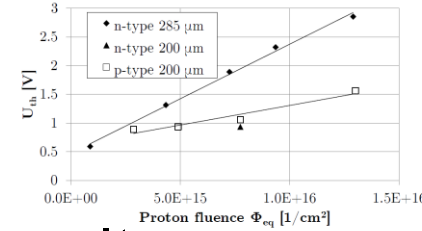
CURRENT
OHMIC REGION – NEUTRAL BULK

ρ vs. U/d^2 200 µm & 285 µm diodes



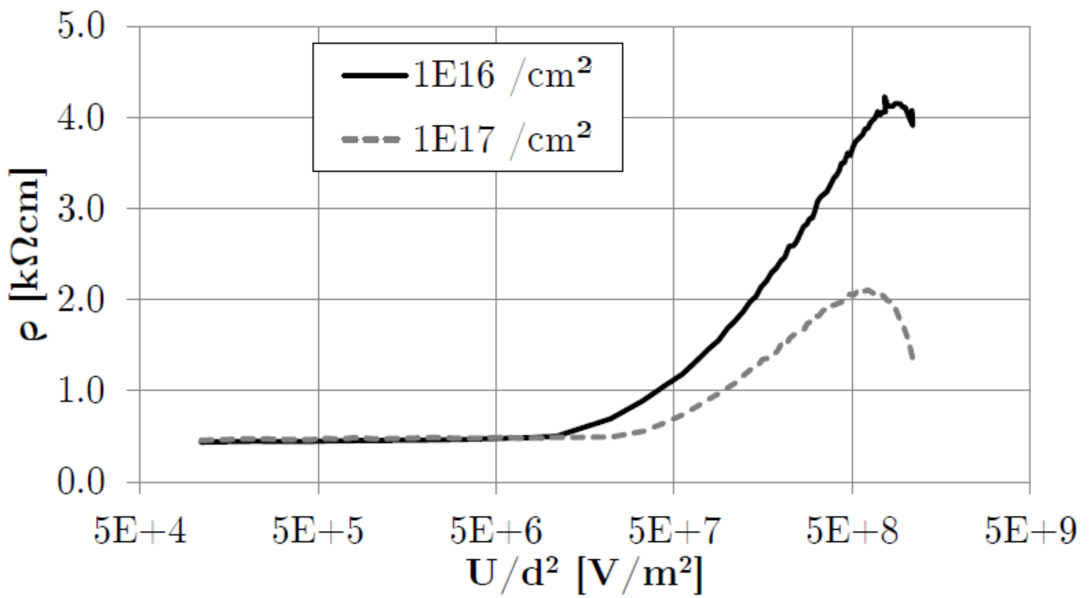
Capacitance @200 Hz 285 µm diodes





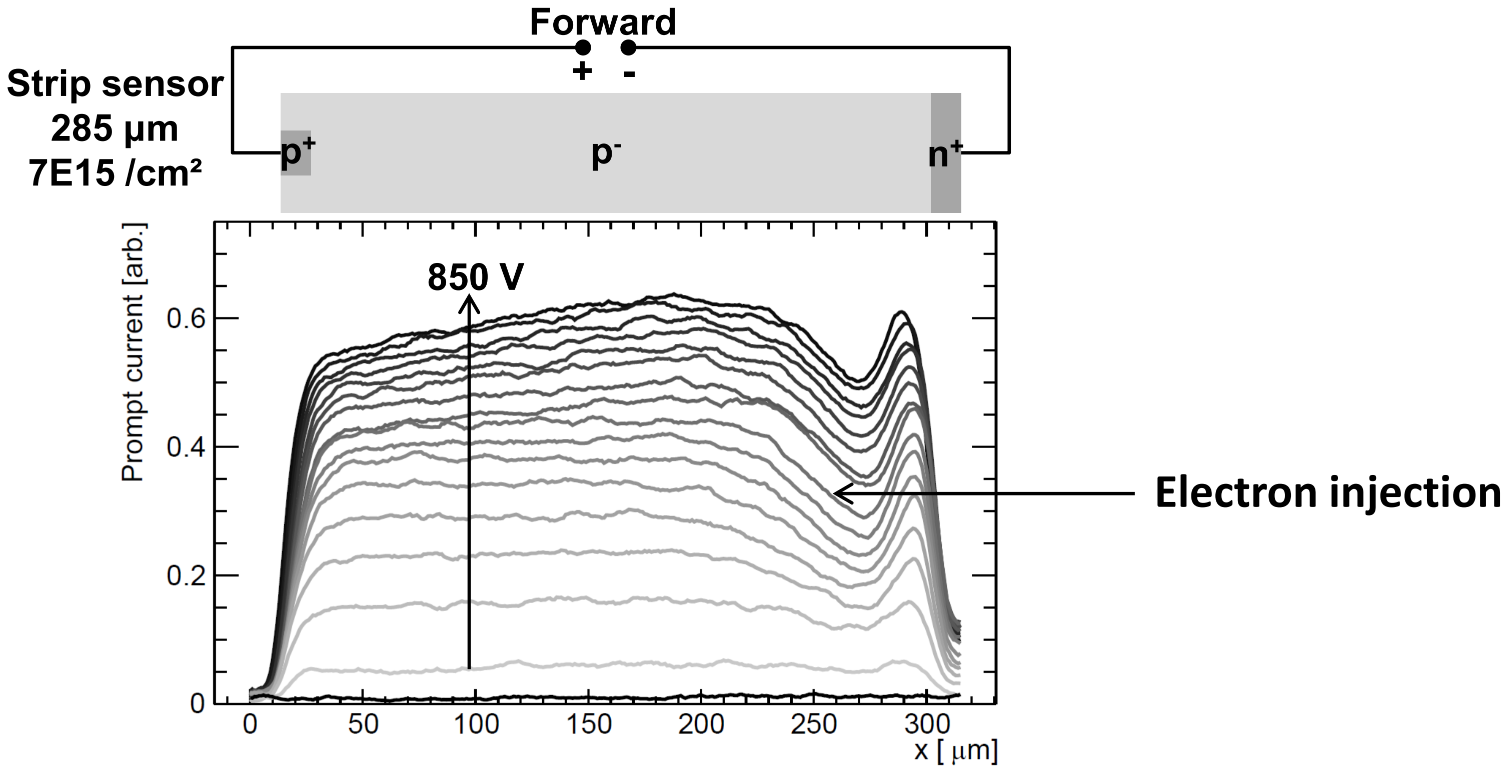
- High near-intrinsic $\rho_{ohm} \approx \rho_i$ at small bias voltages
  - Carrier removal: Free carriers trapped at deep defects, $n \approx p \approx n_i$

BACKUP



μ_0 changes little up to
$\phi_{eq} = 10^{17}$ cm^{-2} at 300 K
→ Phonon scattering dominating at 300 K

EDGE-TCT VELOCITY PROFILE FORWARD BIAS



- Edge-TCT $v_e + v_h \propto E$ gives an idea of electric field
  - Electron injection from junction
  - Ohmic bulk at low voltage, positive space-charge at high voltage

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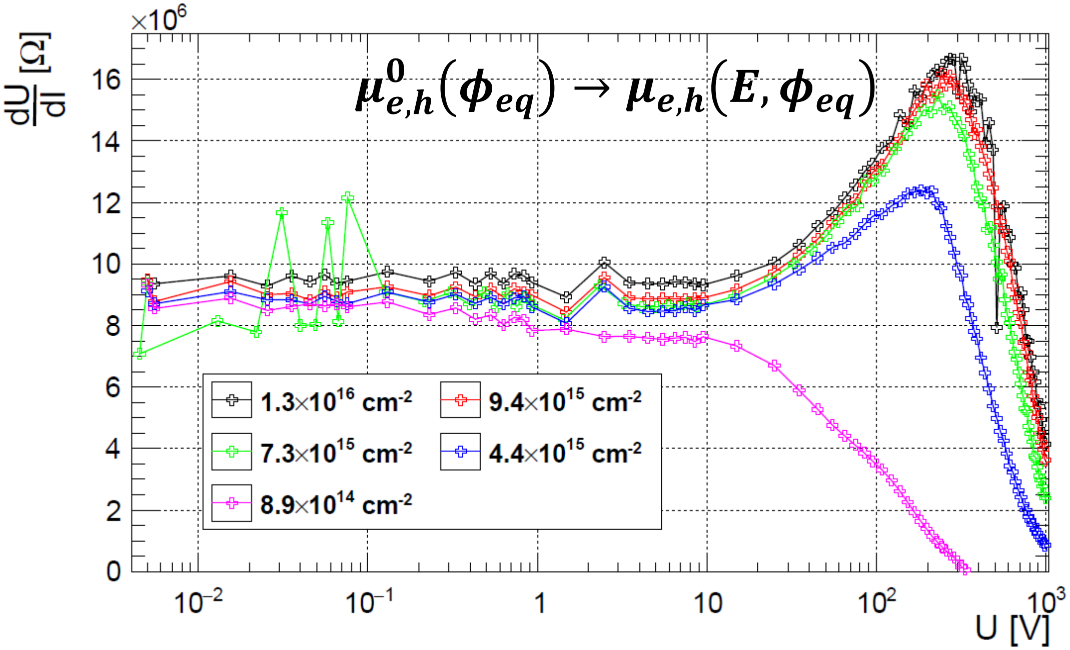
FORWARD CURRENT RESISTANCE



Space-charge-limited currents SCLC

- Forward current described by space-charge-limited currents
  - Ohmic up to high voltages $\mu^0_{e,h}(\phi_{eq}) \rightarrow \mu_{e,h}(E,\phi_{eq})$
  - Exponential increase at very high voltages

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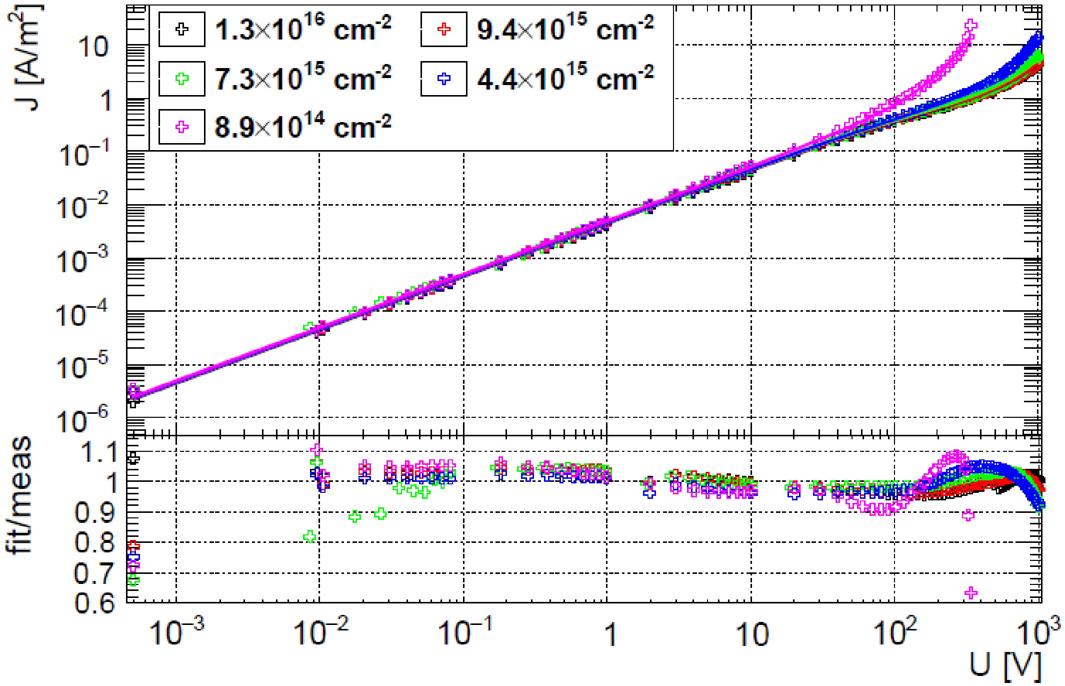
FORWARD CURRENT MODEL

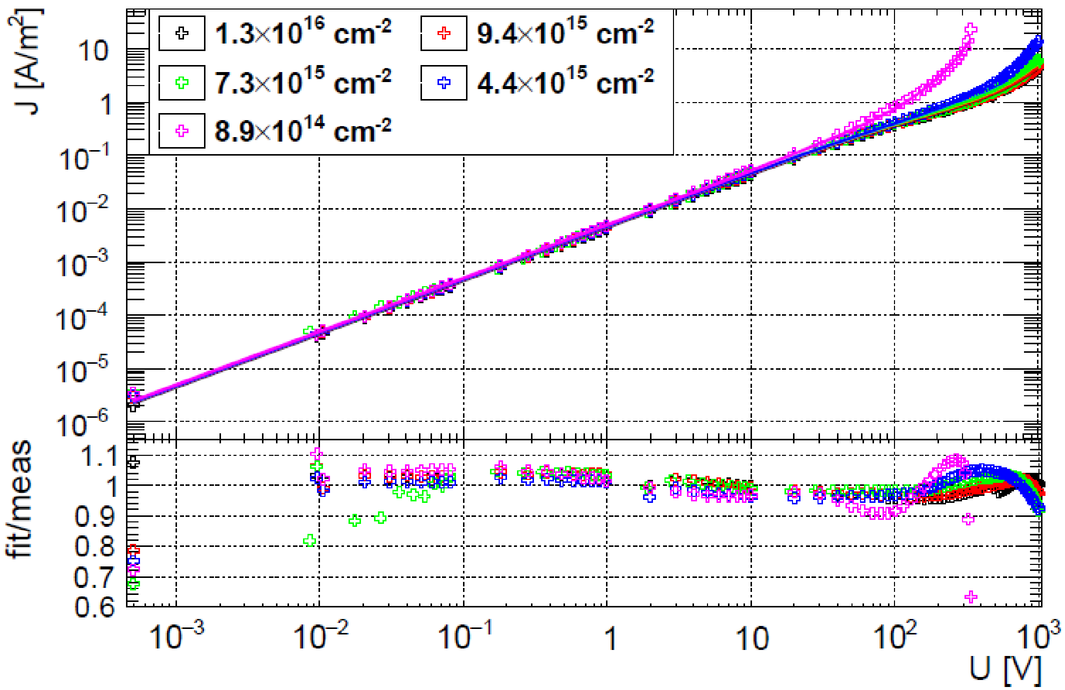


- Current described by SCLC within 10 %

$$I(U) = en_i \cdot A\frac{U}{d} \cdot \left(\mu_h(\Phi_{eq}, E) + \mu_e(\Phi_{eq}, E) \cdot \exp\left(\Xi\frac{U}{T \cdot d^2}\right)\right)$$

→ **A. Rose. Phys. Rev. 97(6):1538, 1955.**

FORWARD CURRENT MODEL



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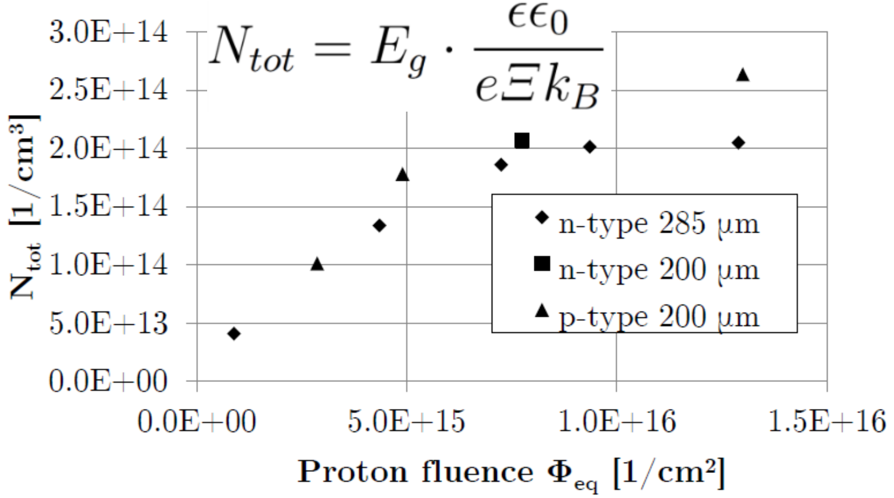
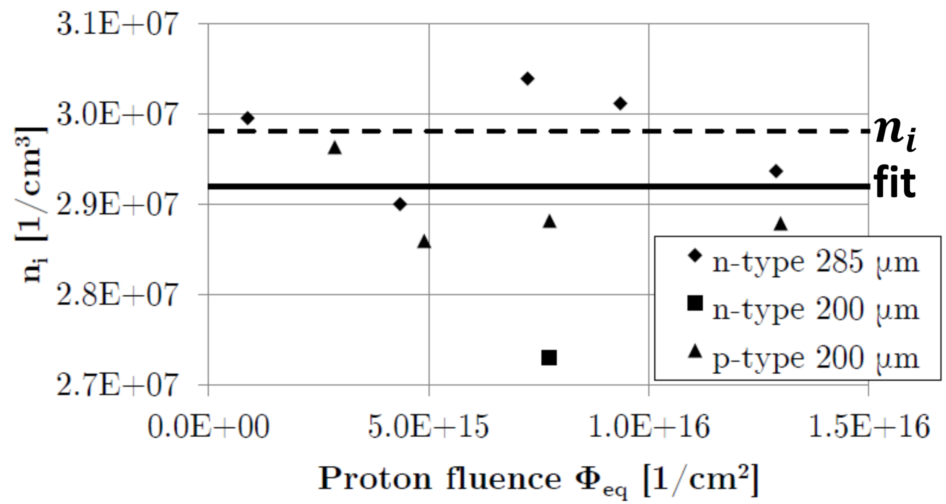
→ **A. Rose. Phys. Rev. 97(6):1538, 1955.**

FORWARD CURRENT MODEL PARAMETERS

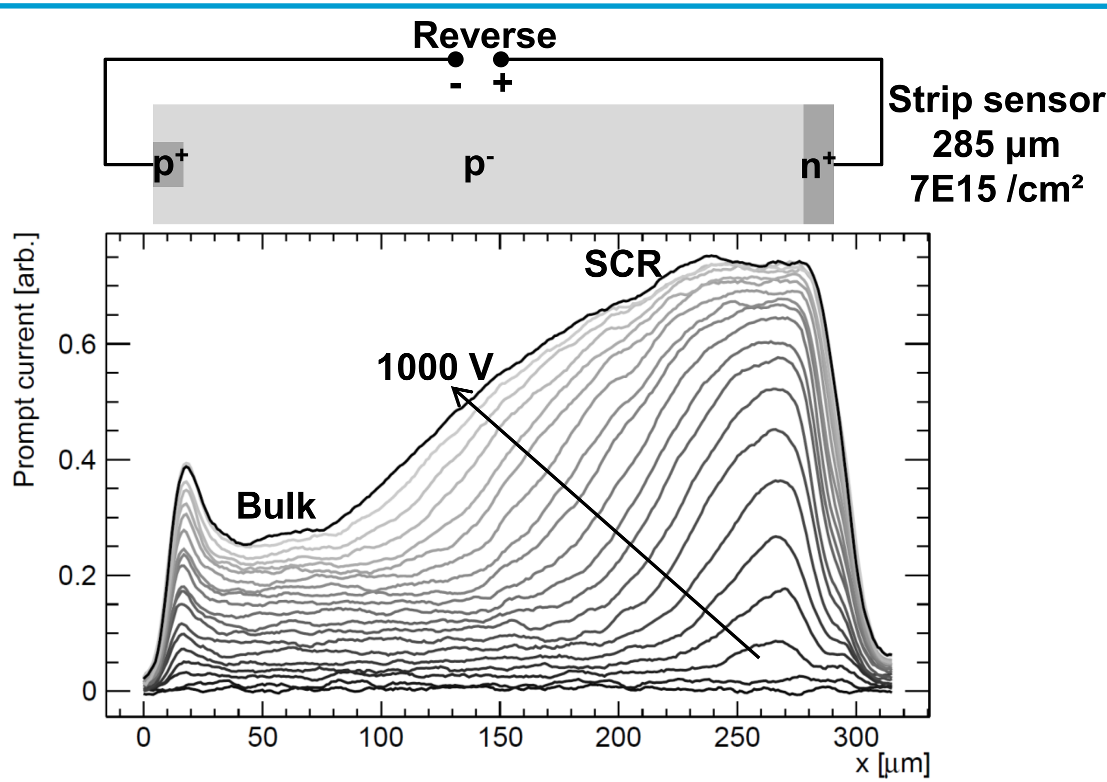




$$I(U) = en_i \cdot A\frac{U}{d} \cdot \left(\mu_h(\Phi_{eq}, E) + \mu_e(\Phi_{eq}, E) \cdot \exp\left(\Xi \frac{U}{T \cdot d^2}\right)\right)$$

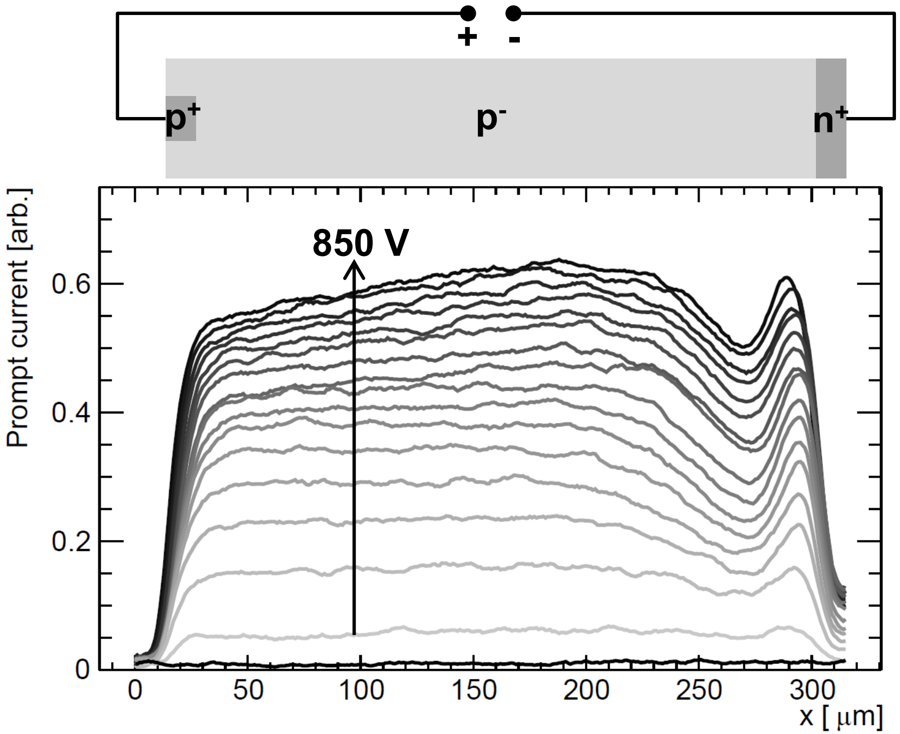
- Hypothetical trap concentration $\boldsymbol{N_{tot}}$ not linear with $\boldsymbol{\phi_{eq}}$
- $\boldsymbol{n_i}$ is reproduced to 2 %

EDGE-TCT VELOCITY PROFILE REVERSE BIAS

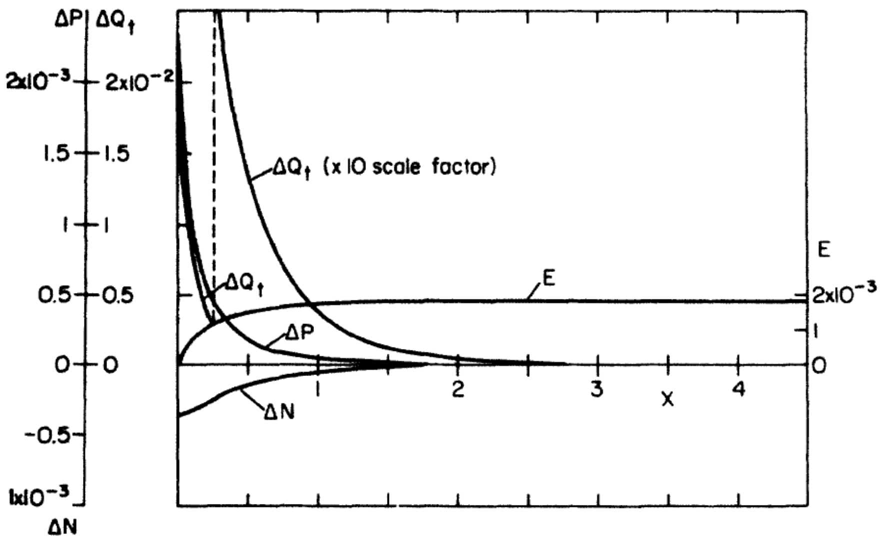


- Edge-TCT $v_e + v_h \propto E$ gives an idea of electric field
  - Near-constant field in the bulk
  - High field in the SCR

BACKUP



+
-
p+
p-
n+
850 V
Prompt current [arb.]
0.6
0.4
0.2
0
0
50
100
150
200
250
300
x [μm]



ΔP
ΔQt
2x10−3
2x10−2
1.5
1.5
1
1
0.5
0.5
0
0
−0.5
1x10−3
ΔN
ΔQt (x 10 scale factor)
ΔQt
E
ΔP
ΔN
E
2x10−3
1
0
1
2
3
x
4