Electrical Characterization of Irradiated Silicon Diodes at Different Temperature

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- Motivation
- DUT and measurements
- Scaling with temperature of:
  - Leakage current (IV)
  - Frequency (CV)
- Charge collection
- Summary

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Motivation

- For CV/IV characterization of irradiated silicon detectors a standard temperature of 20°C and frequency of 10 kHz are adopted
- However, cooling is very often necessary during measurements to decrease high leakage current for heavily irradiated samples
- To scale the data to the adopted standard, it is important to know:

What is the relationship between electrical parameters obtained at different temperatures?

Here we present our results of CV/IV measurements performed in wide temperature and frequency range, as well as CCE, for silicon diodes based on different material and irradiated with protons and neutrons in wide fluence range

Devices under test and measurement procedures

The following silicon pad diodes were irradiated and studied:

Type	Thickness [um]	Resistivity [kΩ·cm]	Irradiation particles	Φ_{eq} [10^{14} cm^{-2}]
p-MCz	280	3	24 GeV/c protons	1.4-5.8
n-MCz	280	0.7	24 GeV/c protons	1.4-5.8
n-MCz	280	0.7	reactor neutrons	2-10
n-Epi	150	0.5	24 GeV/c protons	1.4-66
n-Epi	150	0.5	reactor neutrons	2-100

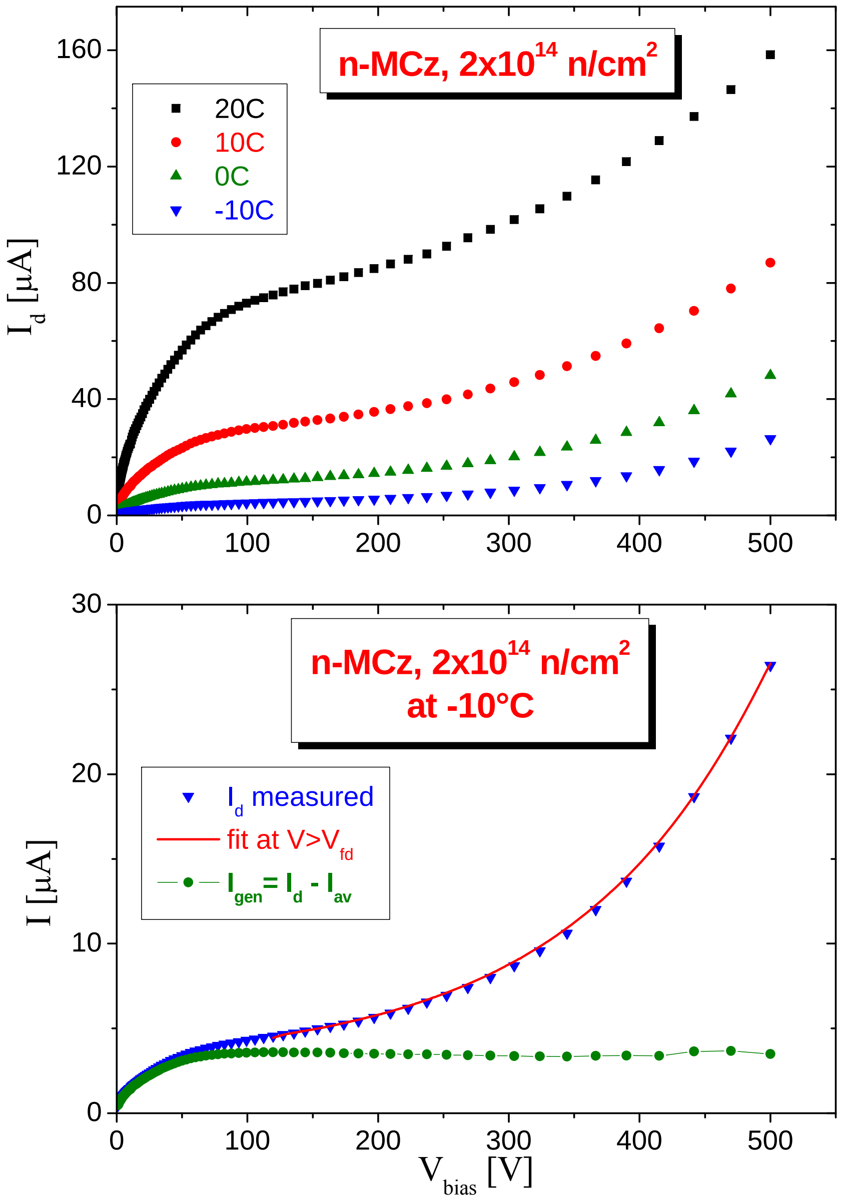
IV: at (20, 10, 0, -10)ºC;

CV:

t [ºC]	f [kHz]
20	0.8-100
10	0.2-30
0	0.2-30
-10	0.1-10

CCE: at -10ºC with Sr-90 β-particles

Leakage current components



Generally accepted:

- $I_d(V) = I_{gen}(V) = \begin{cases} I_{0gen} \cdot \sqrt{V/V_{fd}}, & V < V_{fd} \\ I_{0gen} = \mathbf{const}, & V \geq V_{fd} \end{cases}$
- $I(T) \propto T^2 \exp\left(-\frac{E_a}{kT}\right), \quad E_a \approx E_g/2 \rightarrow$

  $I(20^\circ C)/I(-10^\circ C) \approx$ **16**

Observed:

- strong increase at $V > V_{fd} \approx 120V$
- $I(20^\circ C)/I(-10^\circ C) \approx$ **6** (at 500V)

Proposed solution:

- $I_d(V) = I_{gen}(V) + I_{av}(V)$,

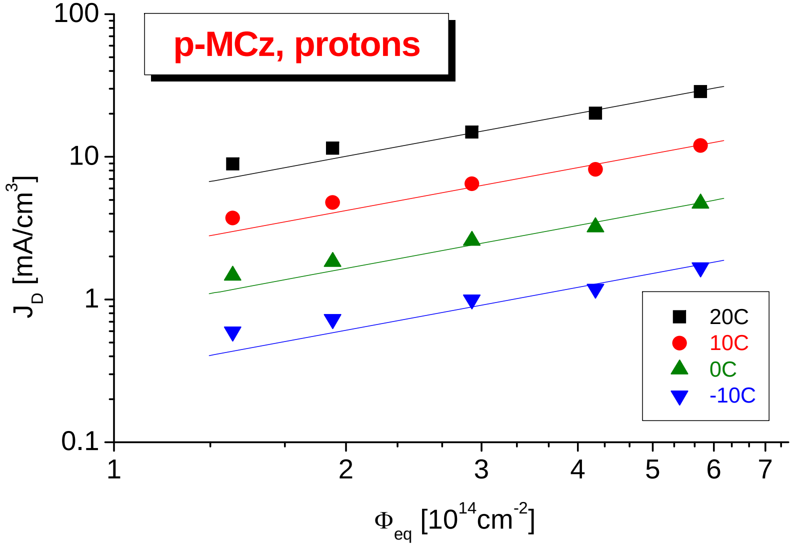
  (I_{av} – avalanche current)
- $I_{av}(V) = I_{0av} \cdot [\exp(V/V_0) - 1]$
- Fit $I_d(V)$ at $V > V_{fd} \Rightarrow$

  get I_{0gen}, I_{0av}, $V_0 \Rightarrow$

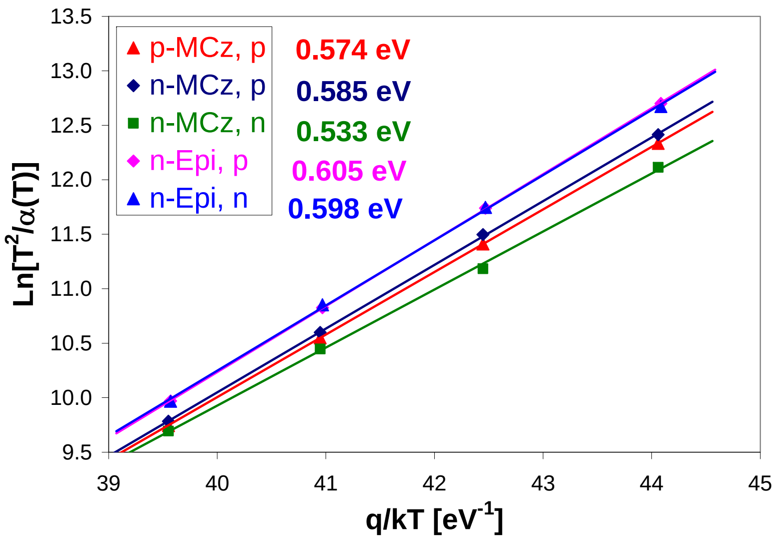
  $I_{gen}(V) = I_d(V) - I_{av}(V)$

Generation component scaling with temperature

Generation current density vs. Φ_{eq}



Arrhenius plot for α(T)



- ✓ Good linearity with fluence
- ✓ Good scalability with temperature

From linear fit: $\alpha = J_d / \Phi_{eq}$

α(20°C)=(4.8–5.3)·10^{-17}A/cm
(MCz, no annealing)

α(20°C)=4.0·10^{-17}A/cm
(Epi, after 4min@80C)

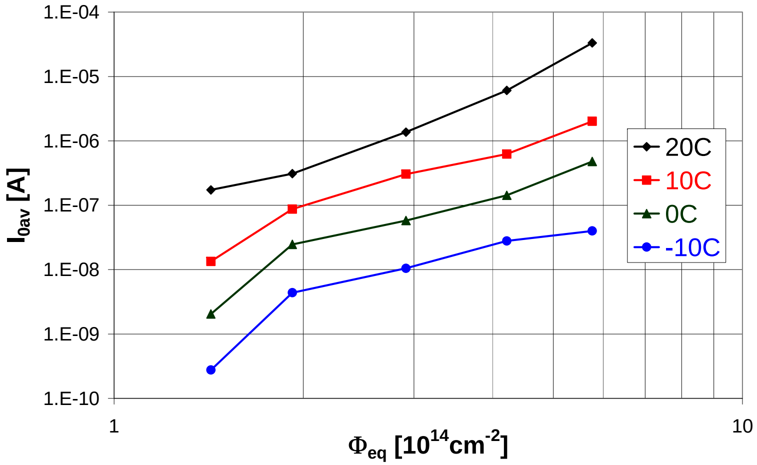
$$I_{gen}(T) \propto T^2 \exp\left(-\frac{E_a}{kT}\right) \Rightarrow Ln\left(\frac{T^2}{\alpha(T)}\right) = \frac{E_a}{kT} + const$$

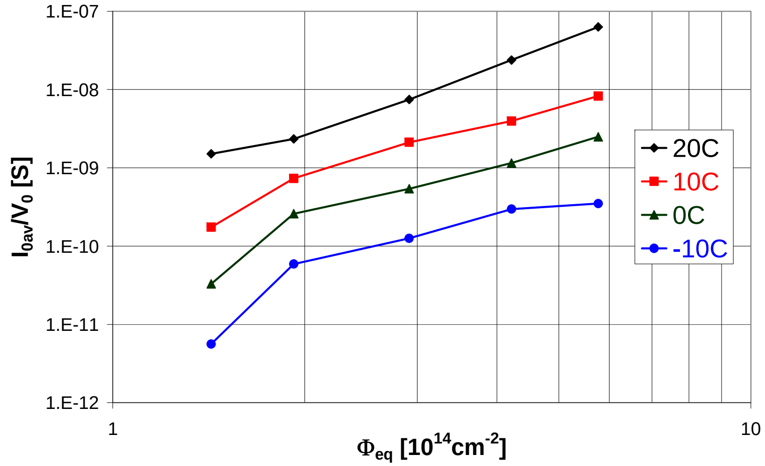
Average value E_a = **(0.58 ± 0.02) eV**

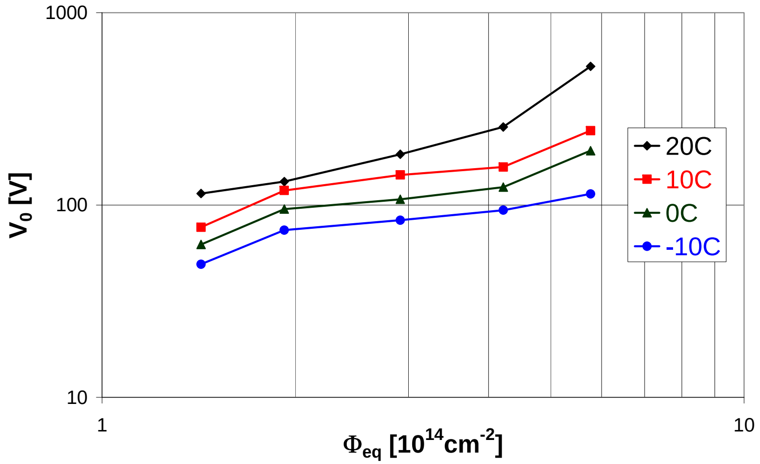
Sample/ Irradiation/ min@80°C	α [10^{-17} A/cm]				E_a [eV]
	20°C	10°C	0°C	-10°C	
p-MCz/protons/0	5.04	2.10	0.83	0.30	0.574
n-MCz/protons/0	4.84	2.00	0.76	0.28	0.585
n-MCz/neutrons/0	5.30	2.33	1.04	0.38	0.533
n-Epi/protons/4	4.02	1.59	0.59	0.21	0.605
n-Epi/neutrons/4	4.03	1.55	0.59	0.22	0.598

Avalanche component fit parameters vs. Φ and T

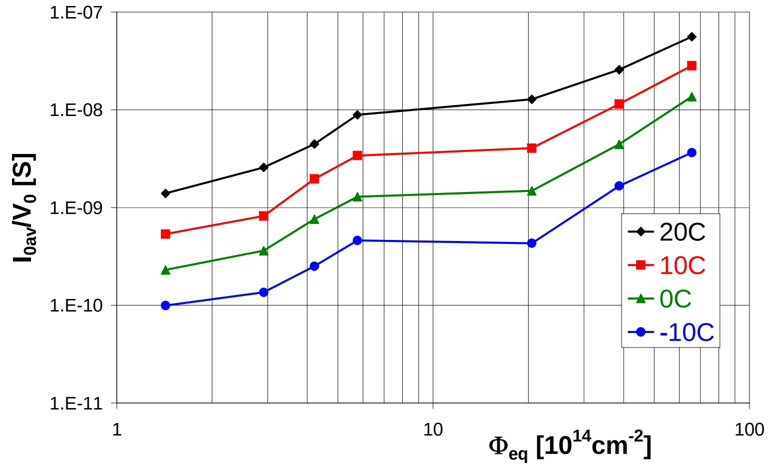
n-MCz, protons







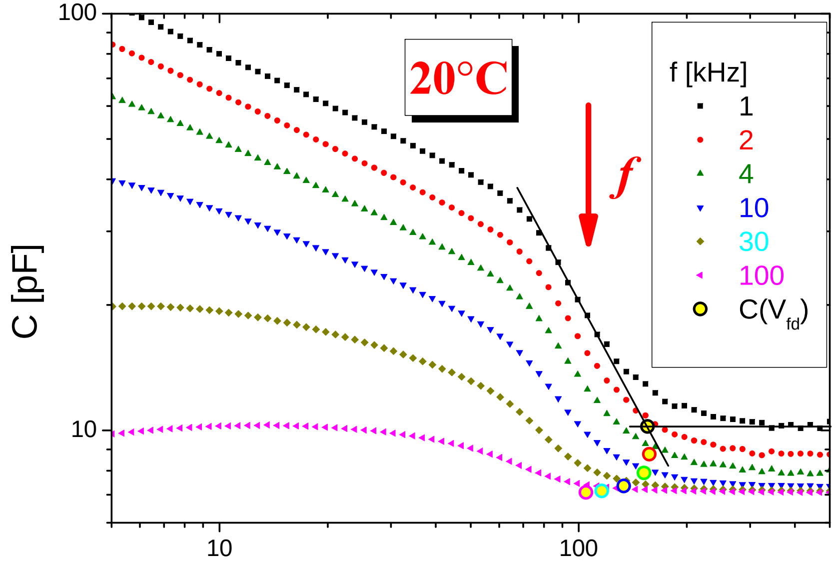
n-Epi, protons

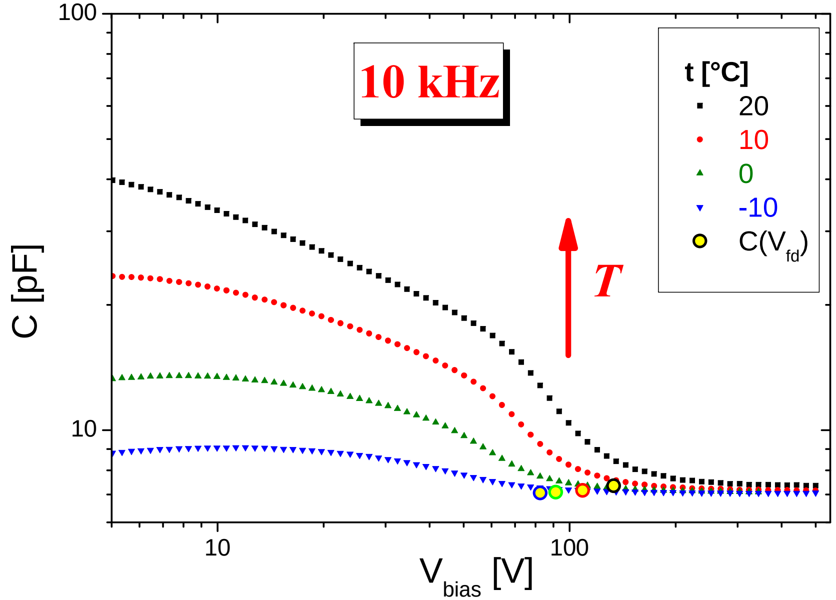


May we suggest that such an approach to IV fitting is justified?

CV: correlation between temperature and frequency

p-MCz, $3.1\cdot10^{14}$ p/cm^2





CV measurement:

$$V = V_{\mathrm{bias}} + V_{\mathrm{m}} e^{i\omega t}$$
$$C = dQ/dV$$

CV curves change in similar way either with frequency increase or temperature decrease:

- T=const, $f\uparrow$ – shorter half-period, dQ↓
- f=const, $T\downarrow$ – slower response, dQ↓

We need to find $f(T)$, for which

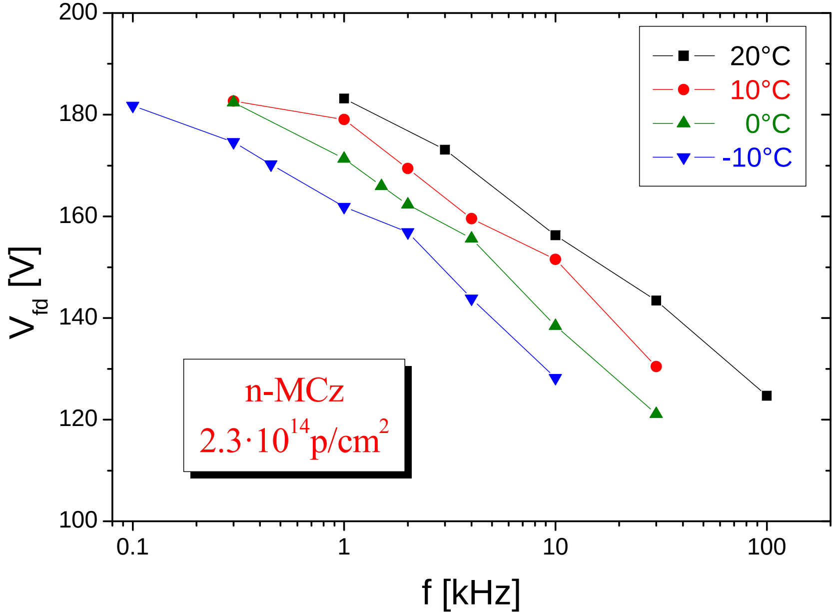
$$V_{fd}(T, f(T)) = V_{fd}(T_{ref}, f_{ref})$$

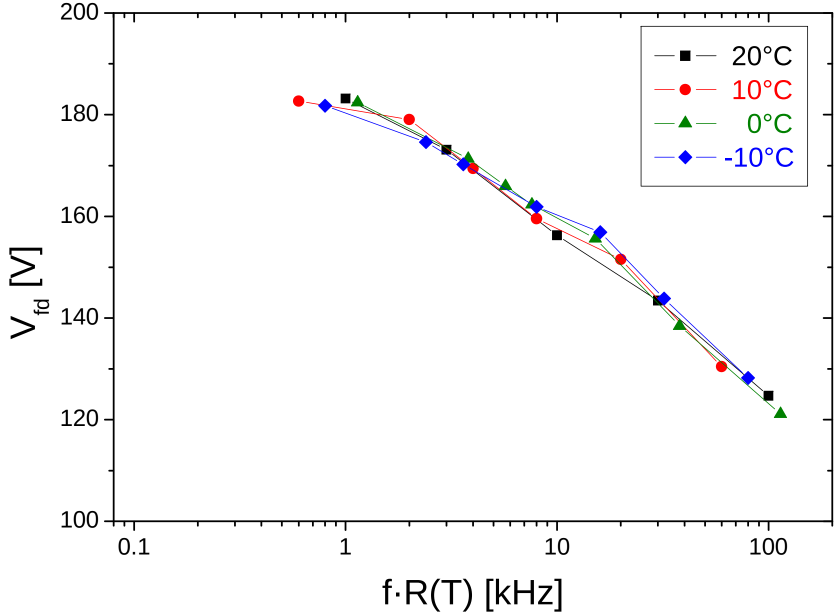
Petterson et al. (NIM A583):

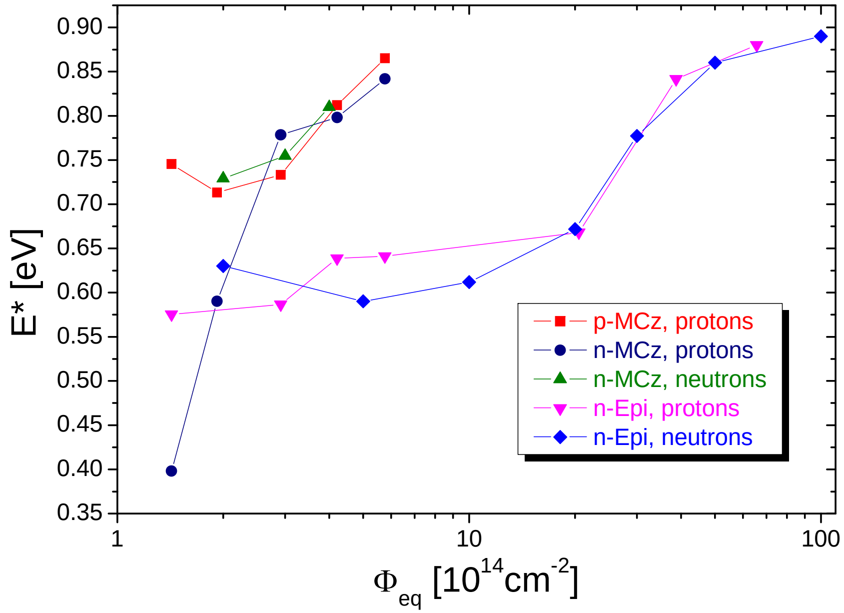
$$f(T) \propto T^2 \exp\left(-\frac{E^*}{kT}\right)$$

with $E^* \approx E_g/2$, like for $I(T)$

Results of f(T) scaling for CV measurements







$$V_{\mathrm{fd}}(T, f_T) = V_{\mathrm{fd}}(T_{\mathrm{REF}}, f_{\mathrm{REF}}) \Rightarrow R(T) = f_{\mathrm{REF}}/f_T;$$

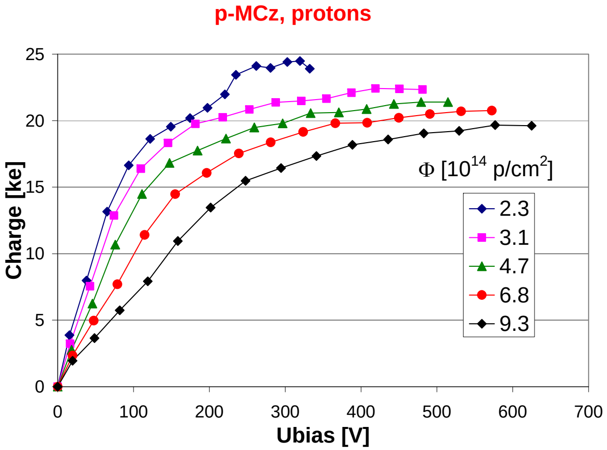
$$\ln\left(R(T) \cdot \left(\frac{T}{T_{REF}} \right)^2 \right) = E^* \left(\frac{1}{kT} - \frac{1}{kT_{REF}} \right)$$

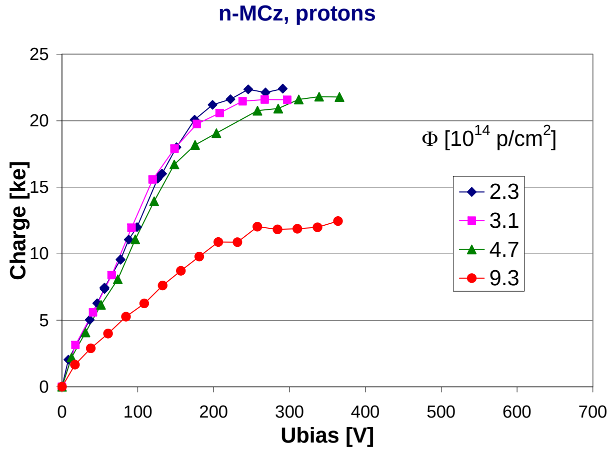
- E^* may depend on:
  material (thickness?)

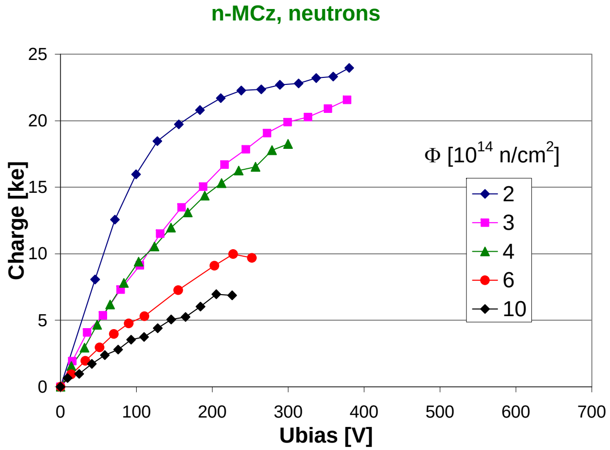
- Generally increase with fluence

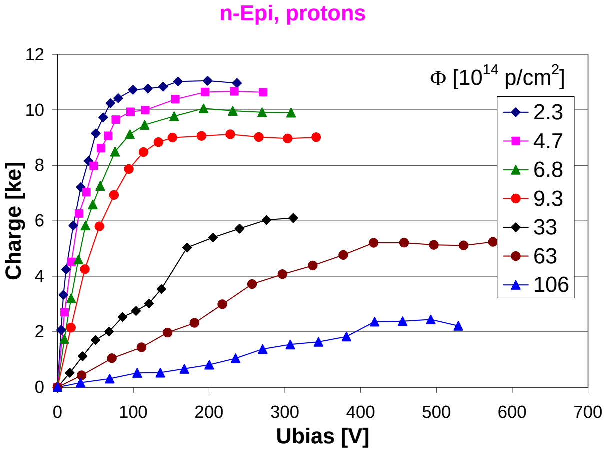
Charge collection with beta-particles

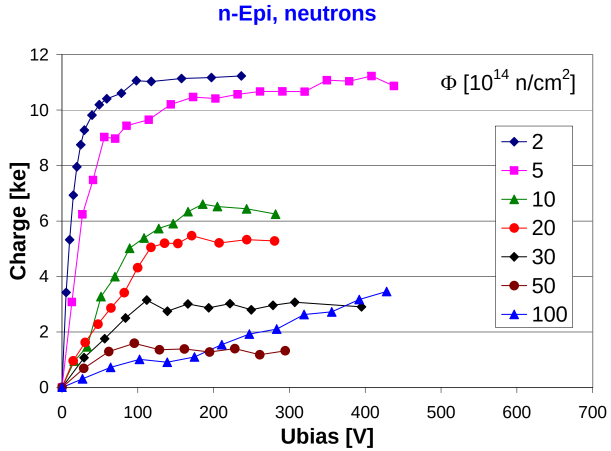
CCE was measured at -10°C in JSI (Ljubljana) (special thanks to Gregor and Vladimir!)



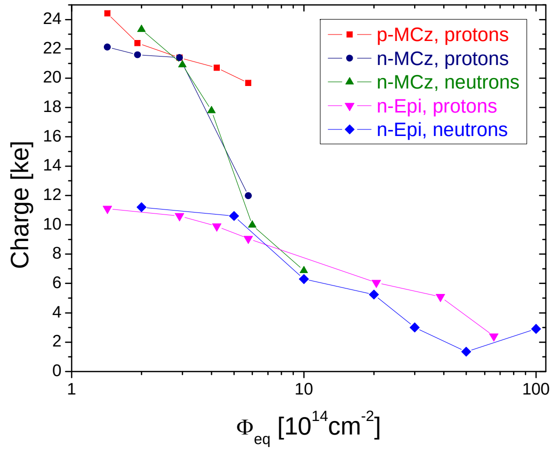






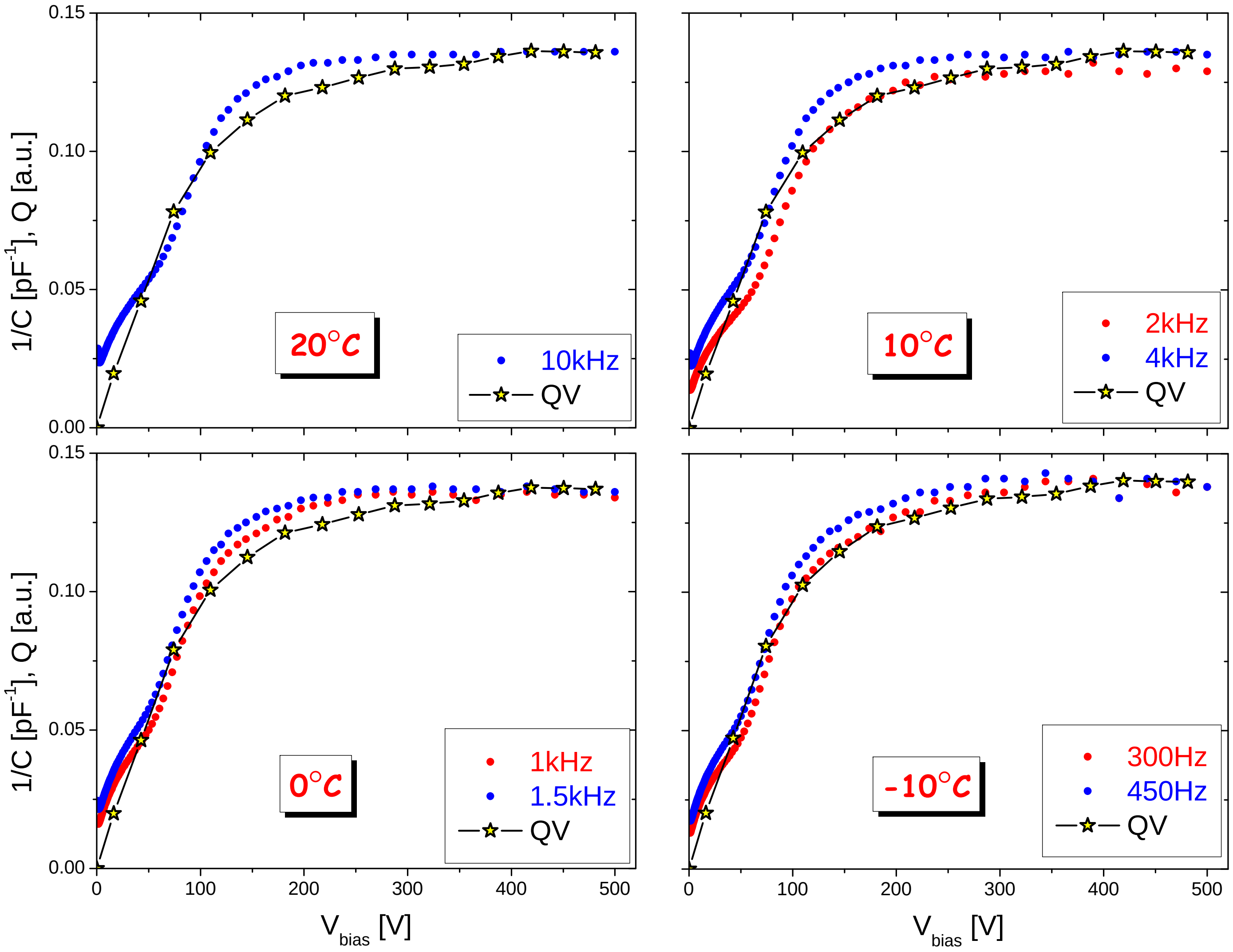


CCE degradation vs. Φ_{eq}



- CCE practically independent on type of irradiation;
- after 6×10^{14}cm^{-2} thick MCz are not better than thin Epi;
- MCz: n-on-p seems to be better than p-on-n;

Correlation between Q(V) and 1/C(V) measured at different T



p-MCz
$3.1\cdot10^{14}$ p/cm^2
E* = 0.79 eV

t[°C]	f1[kHz]	f2[kHz]
20	10	10
10	4	3.1
0	1.5	0.87
-10	0.45	0.22

f1 – Petterson et al. (NIM A583) E^* = 0.6 eV

f2 – for E^*=0.79 eV and

it fits better!

Summary:

- CV/IV were measured at 4 different temperatures for Epi- and MCz silicon diodes irradiated with protons and neutrons

- IV consists of generation (I_{gen}) and avalanche (I_{av}) component

    - o I_{gen} scales well with temperature using known dependence

      $$I_{gen}(T) \propto T^2 \exp\left(-\frac{E_a}{kT}\right), \qquad \text{with } E_a \approx E_g/2$$

    - o I_{av} increase exponentially with reverse bias, and fit parameters show some dependence fluence and temperature

- For CV correlation between frequency and temperature exists. Application of $I_{gen}(T)$ dependence to f(T) gives ambiguous results, fitted energy values depend at least on the material and fluence

- Nevertheless, 1/C(V) curves measured at different temperature and properly chosen frequency scale well with normalized Q(V)