Current and Capacitance Summary Tables

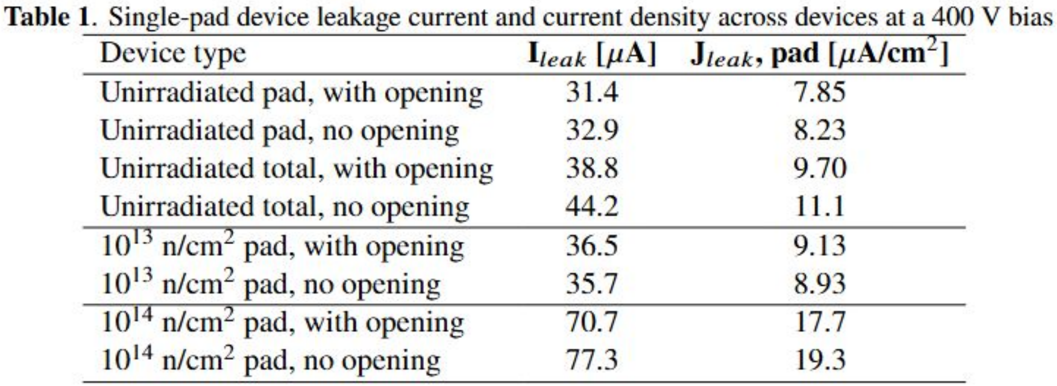


Table 1. Single-pad device leakage current and current density across devices at a 400 V bias

Device type	$\mathbf{I}_{leak}$ [μA]	$\mathbf{J}_{leak}$, **pad** [μA/cm^2]
Unirradiated pad, with opening	31.4	7.85
Unirradiated pad, no opening	32.9	8.23
Unirradiated total, with opening	38.8	9.70
Unirradiated total, no opening	44.2	11.1
10^{13} n/cm^2 pad, with opening	36.5	9.13
10^{13} n/cm^2 pad, no opening	35.7	8.93
10^{14} n/cm^2 pad, with opening	70.7	17.7
10^{14} n/cm^2 pad, no opening	77.3	19.3

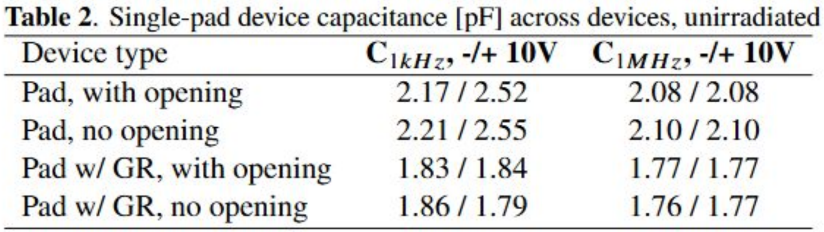
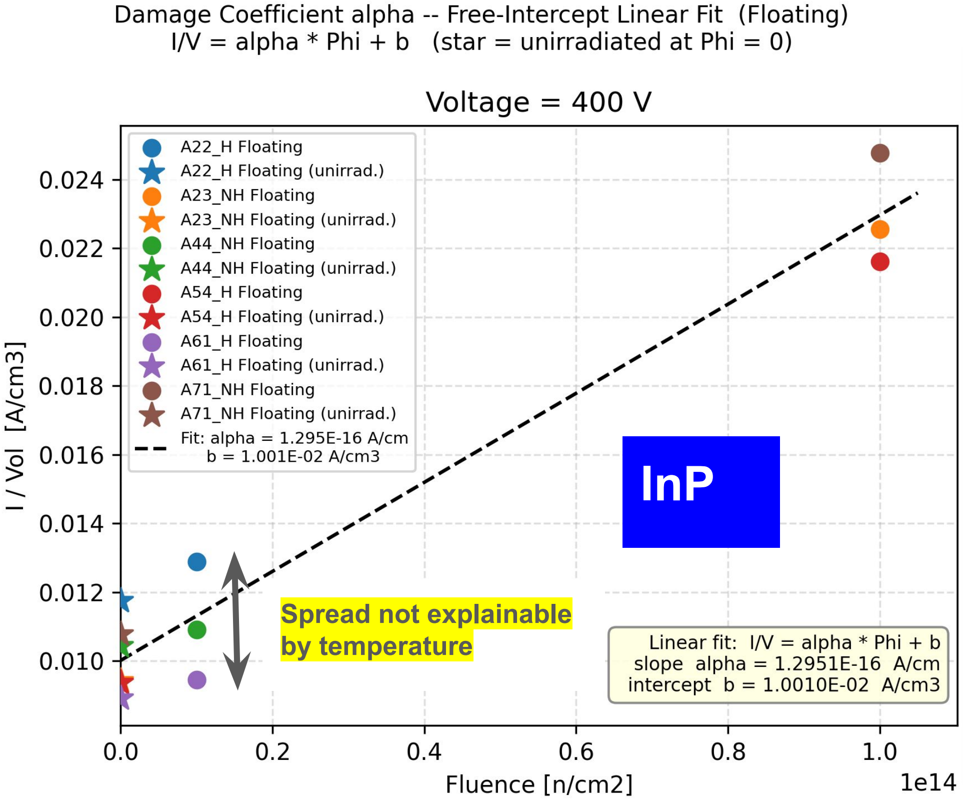


Table 2. Single-pad device capacitance [pF] across devices, unirradiated

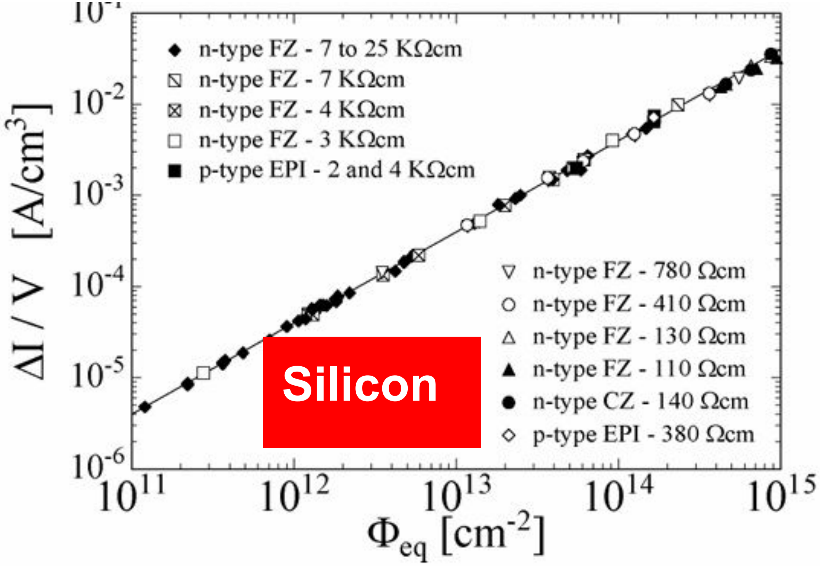
Device type	$\mathbf{C}_{1kHz}$, **-/+ 10V**	$\mathbf{C}_{1MHz}$, **-/+ 10V**
Pad, with opening	2.17 / 2.52	2.08 / 2.08
Pad, no opening	2.21 / 2.55	2.10 / 2.10
Pad w/ GR, with opening	1.83 / 1.84	1.77 / 1.77
Pad w/ GR, no opening	1.86 / 1.79	1.76 / 1.77

Alpha Parameter Results - Old



InP

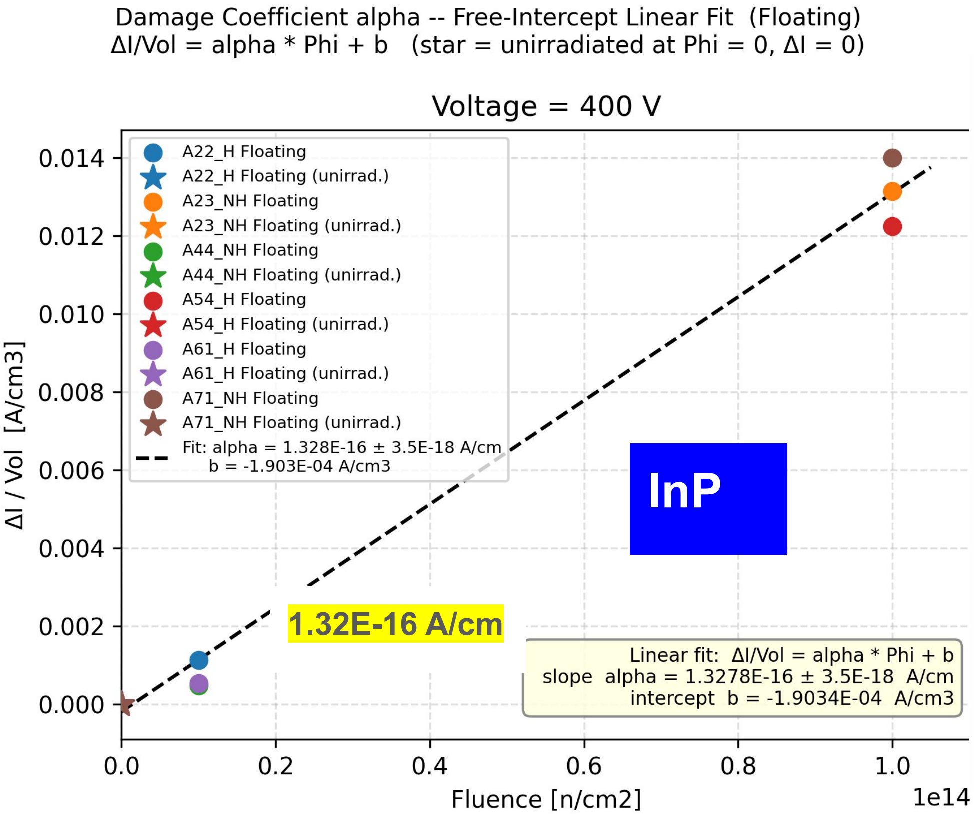
Spread not explainable by temperature



Silicon

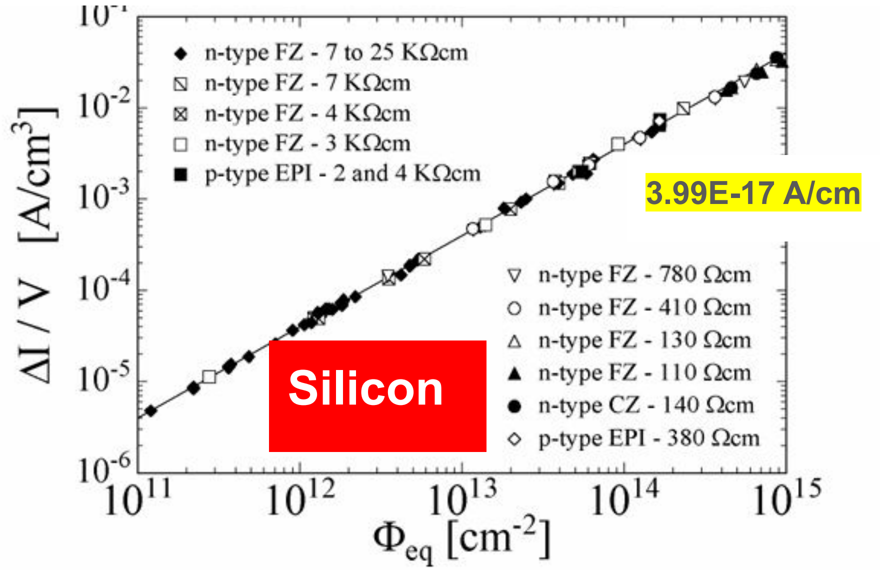
Figure 5.1: Fluence dependence of leakage current for silicon detectors produced by various process technologies from different silicon materials. The current was measured after a heat treatment for 80 min at 60°C $\{\alpha(80\,\mathrm{min}, 60°\mathrm{C}) = (3.99 \pm 0.03) \times 10^{-17}\,\mathrm{A/cm}$; for details see Fig. 5.6$\}$.

Alpha Parameter Results - Updated



InP

1.32E-16 A/cm

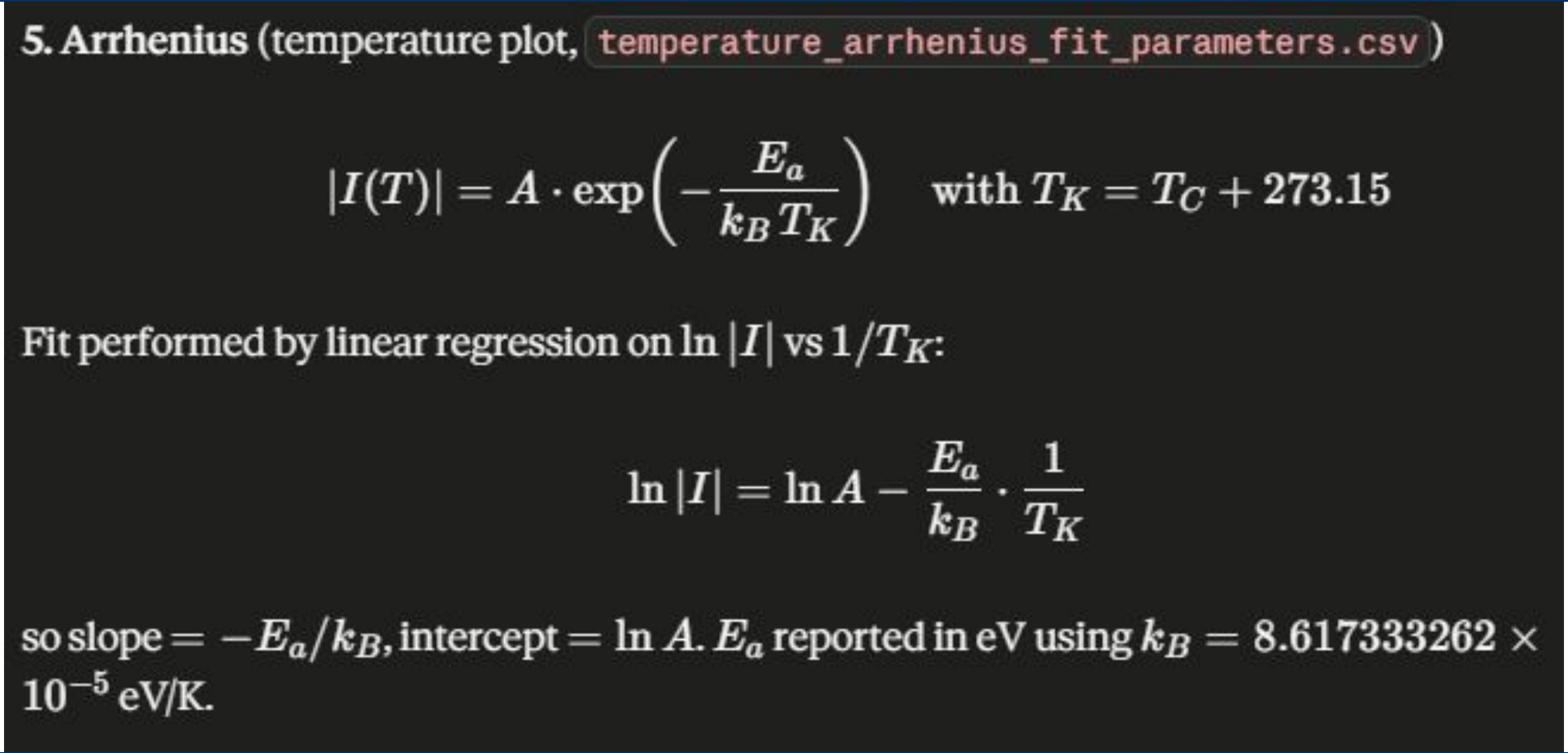


3.99E-17 A/cm

Silicon

Figure 5.1: Fluence dependence of leakage current for silicon detectors produced by various process technologies from different silicon materials. The current was measured after a heat treatment for 80 min at 60°C $\{\alpha(80\,\mathrm{min}, 60°\mathrm{C}) = (3.99 \pm 0.03) \times 10^{-17}\,\mathrm{A/cm}$; for details see Fig. 5.6}.

Arrhenius Equation



5. Arrhenius (temperature plot, `temperature_arrhenius_fit_parameters.csv`)

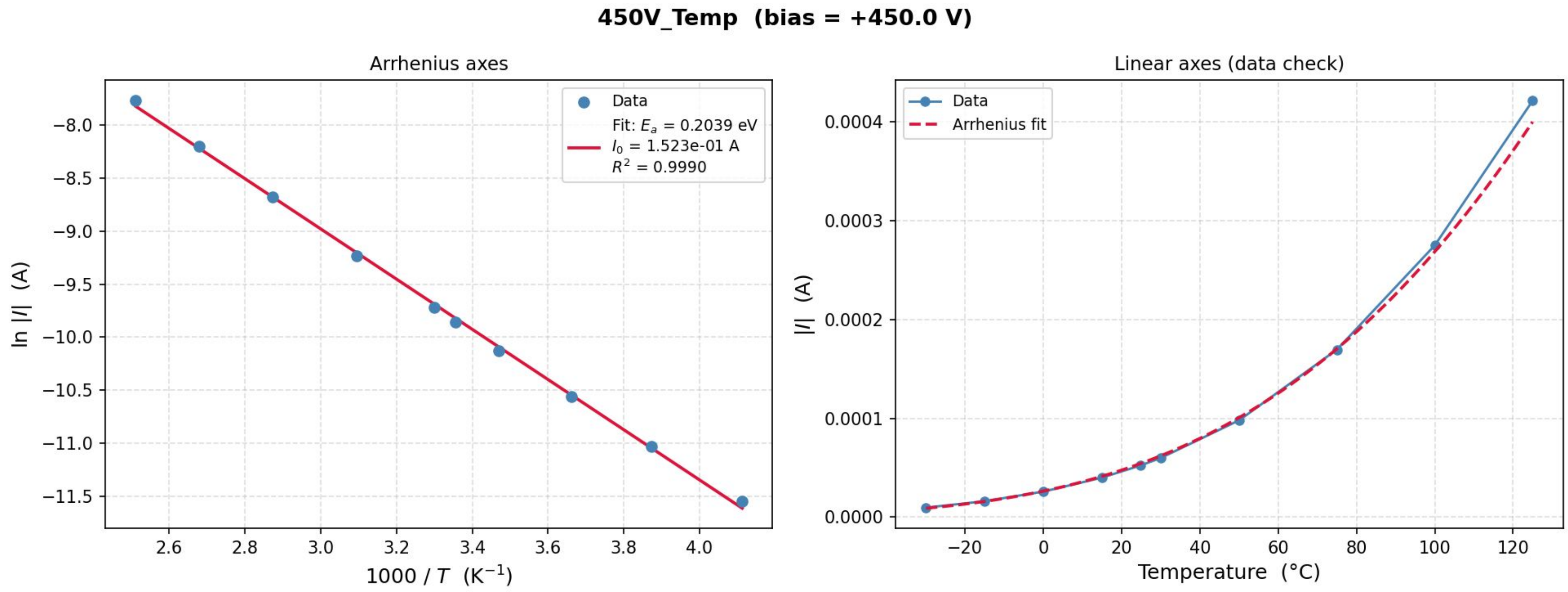
$$|I(T)| = A \cdot \exp\left(-\frac{E_a}{k_B T_K}\right) \quad \text{with } T_K = T_C + 273.15$$

Fit performed by linear regression on $\ln|I|$ vs $1/T_K$:

$$\ln|I| = \ln A - \frac{E_a}{k_B} \cdot \frac{1}{T_K}$$

so slope $= -E_a/k_B$, intercept $= \ln A$. E_a reported in eV using $k_B = 8.617333262 \times 10^{-5}$ eV/K.

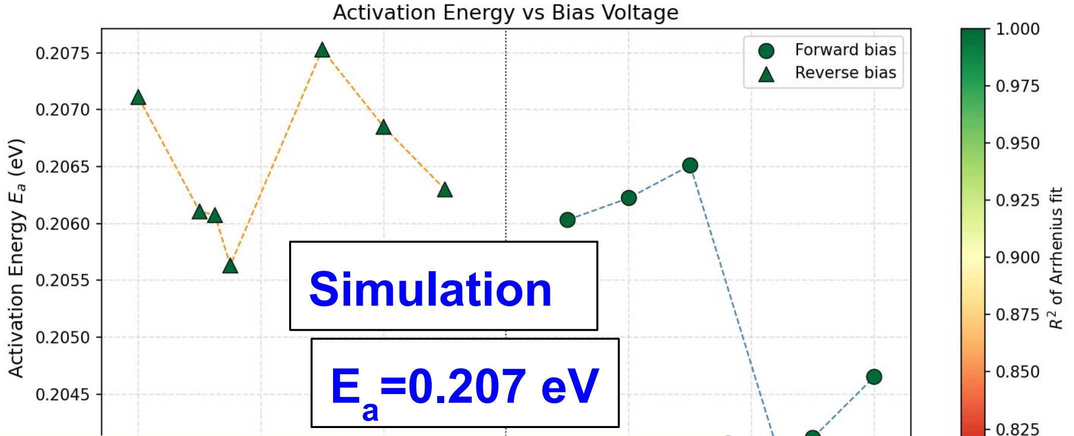
Simulation - Arrhenius Reconstruction - 450 V



Arrhenius plots from going over Richville’s simulations: Link

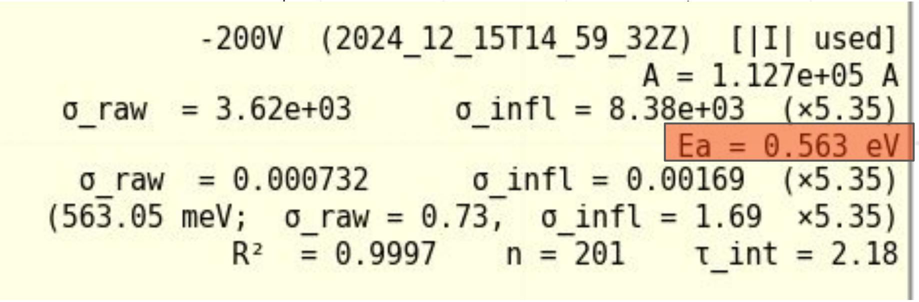
Simulation - Arrhenius Reconstruction

- Simulation Receonstructed E_a
  - Self-consistent within 2%
  - less than half of conduction -to-trap-center gap ?
  - E_a=/= gap to middle of trap state?
- Pure InP Bandgap: ~1.
  eV



Simulation

E_a=0.207 eV



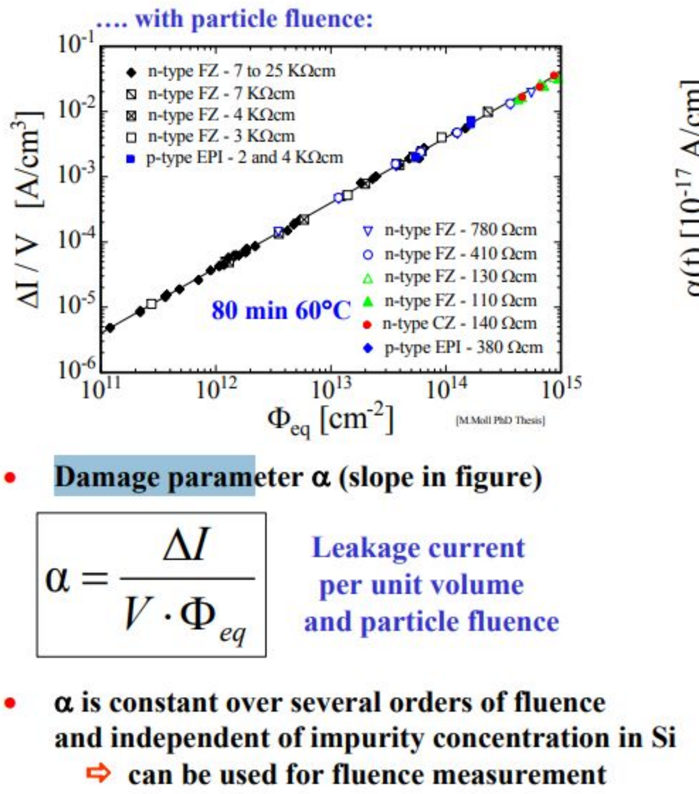
```
        -200V  (2024_12_15T14_59_32Z)  [|I| used]
                                A = 1.127e+05 A
σ_raw  = 3.62e+03      σ_infl = 8.38e+03  (×5.35)
                                Ea = 0.563 eV
 σ_raw  = 0.000732      σ_infl = 0.00169  (×5.35)
(563.05 meV;  σ_raw = 0.73,  σ_infl = 1.69  ×5.35)
        R²  = 0.9997     n = 201     τ_int = 2.18
```

Data Fit

Backup

Overview

- InP devices irradiated in Ljubljana:
    - 1E13-1E16 / 1 MeV n eq
- Radiation hardness of a material (to hadrons) can be summarized by the damage parameter **alpha**
    - aka **current related damage rate**
    - Invariant to doping, thickness, impurities
    - Proportional to fluence
- Accurate measurement requires two conditions
    - Constant ambient temperature
    - Known effective volume



- **Damage parameter α (slope in figure)**

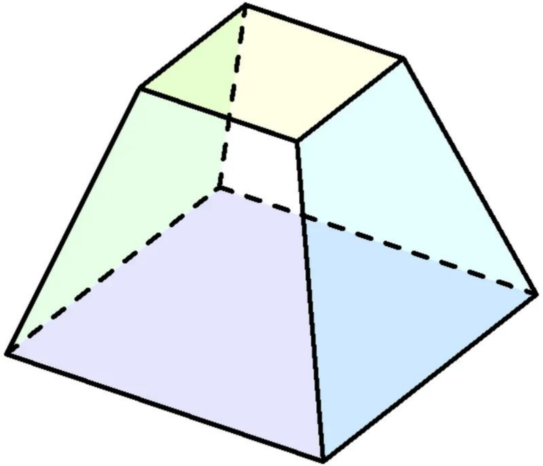
$$\boxed{\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}}$$

Leakage current per unit volume and particle fluence

- **α is constant over several orders of fluence and independent of impurity concentration in Si**
  ⇨ can be used for fluence measurement

https://indico.cern.ch/event/46820/attachments/951707/1350470/081202-Helsinki-Moll-final.pdf

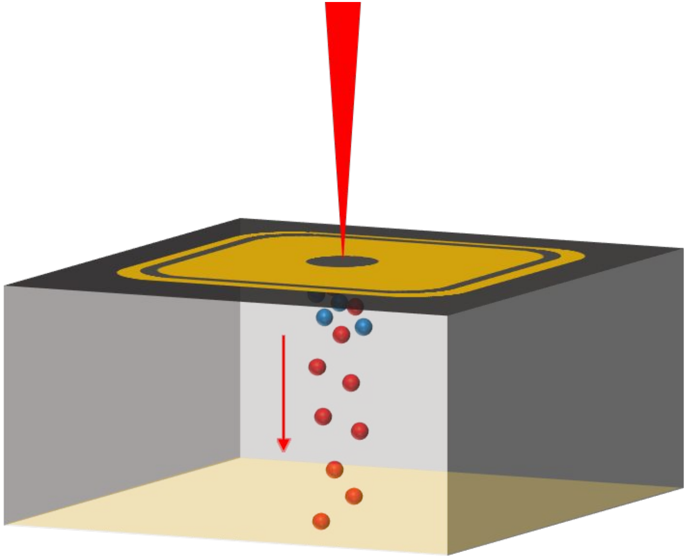
Caveat: Two Conditions Not Fulfilled



- Effective volume not constrained
  - **Floating guard ring**
    - Standard IV station does not have multiple channels to measure guard ring and central pad separately
  - Effective volume spreads beyond under central pad
  - Effective volume estimated as frustrum—-----------------------→
- Temperature not held constant
  - Temperature not held constant/measured + measurements taken on different days
  - Leakage current temperature dependence will spread values
- Presented will be preliminary estimation of alpha

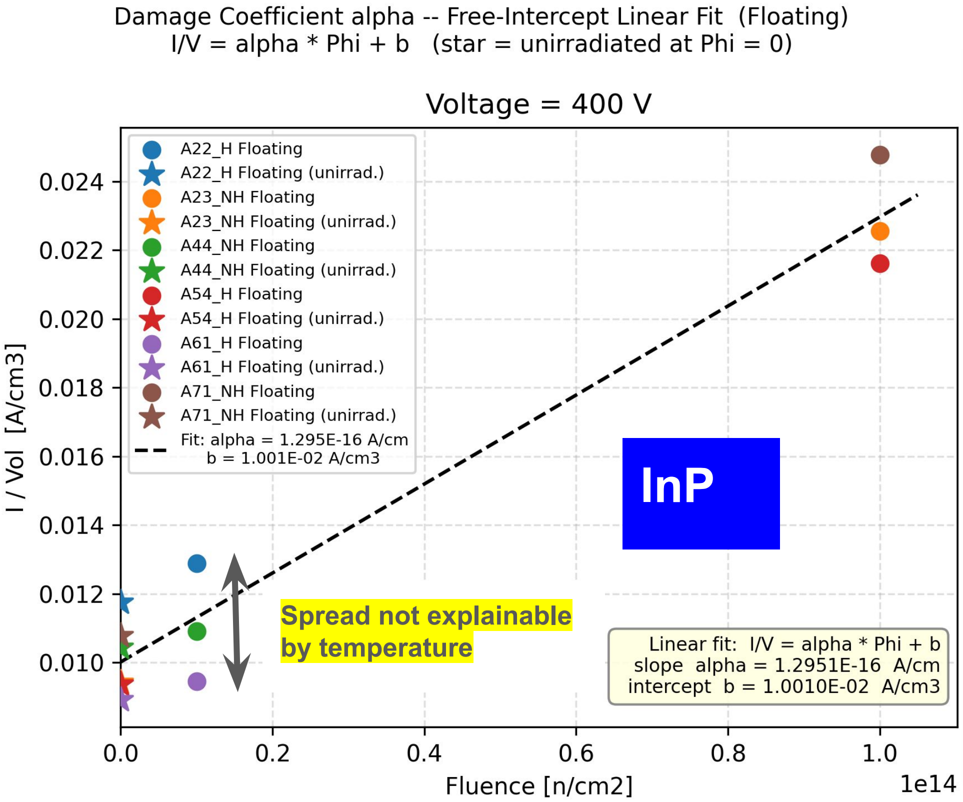
Caveat: No ‘Reverse Bias’ State

- Our devices are essentially asymmetric capacitors
    - Uniform doping
    - Single pad
    - No saturation current
- Alpha parameter assumes saturation current
    - Leakage current is dependent on choice of voltage for our devices
- Decision: choose characteristic voltage
    - Match to voltage shown in InP Paper
    - + 400 V on backside of device, central pad held at 0 V



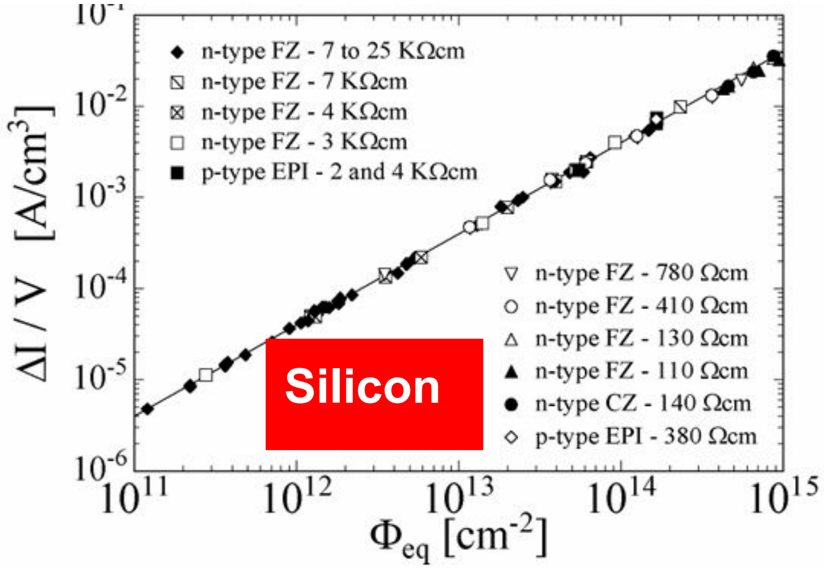
Schematic by Jennifer Ott

Results



InP

Spread not explainable by temperature



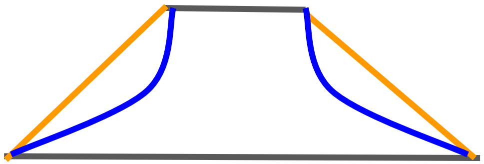
Silicon

Figure 5.1: Fluence dependence of leakage current for silicon detectors produced by various process technologies from different silicon materials. The current was measured after a heat treatment for 80 min at 60°C $\{\alpha(80\,\text{min}, 60°\text{C}) = (3.99 \pm 0.03) \times 10^{-17}\,\text{A/cm}$; for details see Fig. 5.6$\}$.

Comparison with Silicon

- InP: 1.30E-16 A/cm | Silicon: 3.99E-17 A/cm
- Why this InP alpha derivation is a lower bound estimate
    - Electric field simulations from here in Thin Films showed our device geometry shows **electric field lines** curve inward
        - **Frustrum** is overestimation of volume → alpha parameter is underestimation
- Follow-Up:
    - For an accurate measurement, we may need temperature controlled measurements using the parameter analyzer (multi-channel for GR separation)

Electric Field Simulation Pictures Here, if slides are on Indico (couldn't find them)

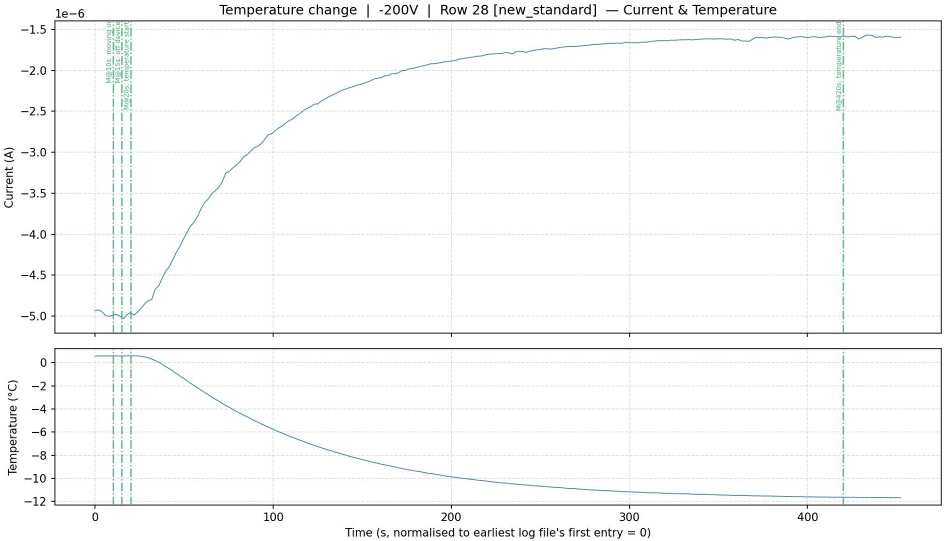


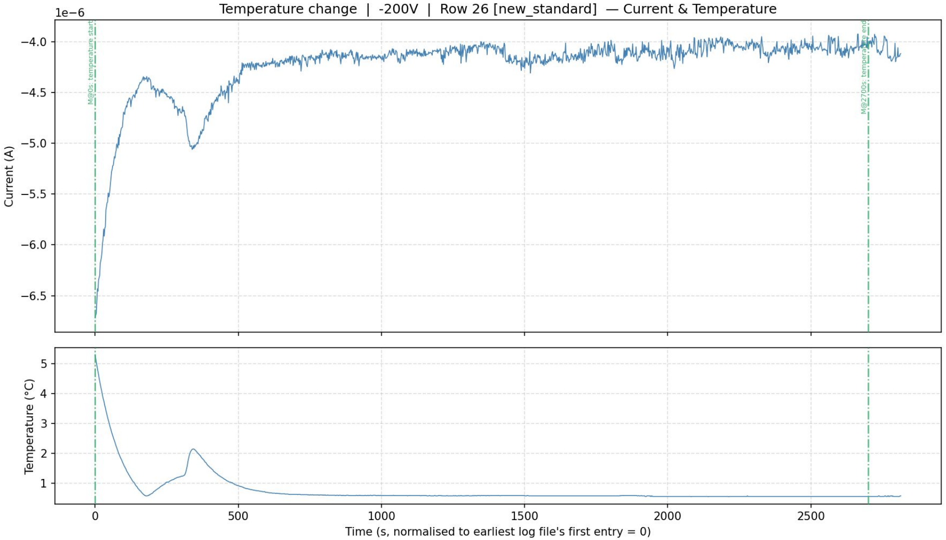
Long Scans - Temperature - 1

Record dark current as a function of temperature

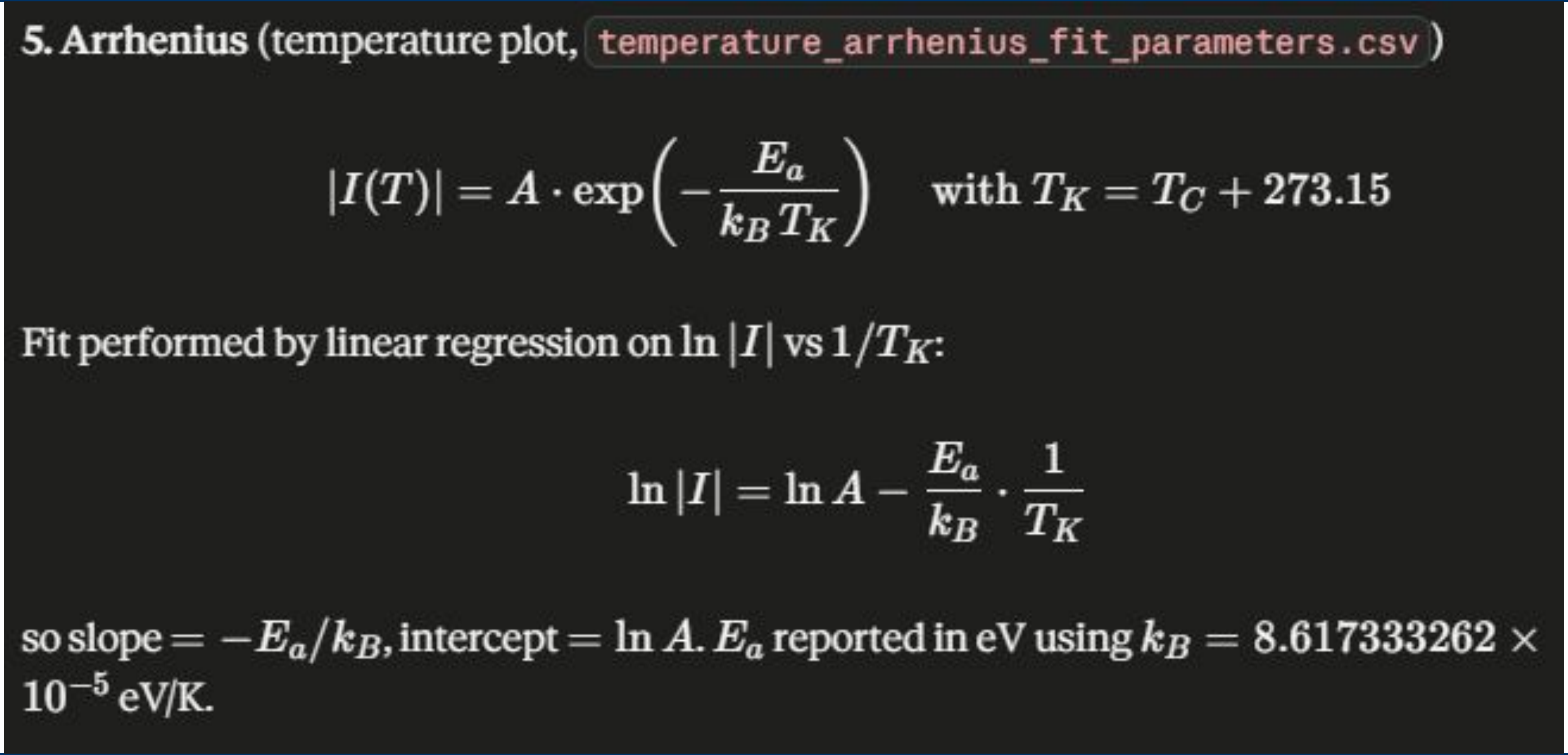
Get Arrhenius plot and derive activation energy

- Bandgap or deep Fe traps?





Long Scans - Temperature - 2



5. Arrhenius (temperature plot, `temperature_arrhenius_fit_parameters.csv`)

$$|I(T)| = A \cdot \exp\left(-\frac{E_a}{k_B T_K}\right) \quad \text{with } T_K = T_C + 273.15$$

Fit performed by linear regression on $\ln|I|$ vs $1/T_K$:

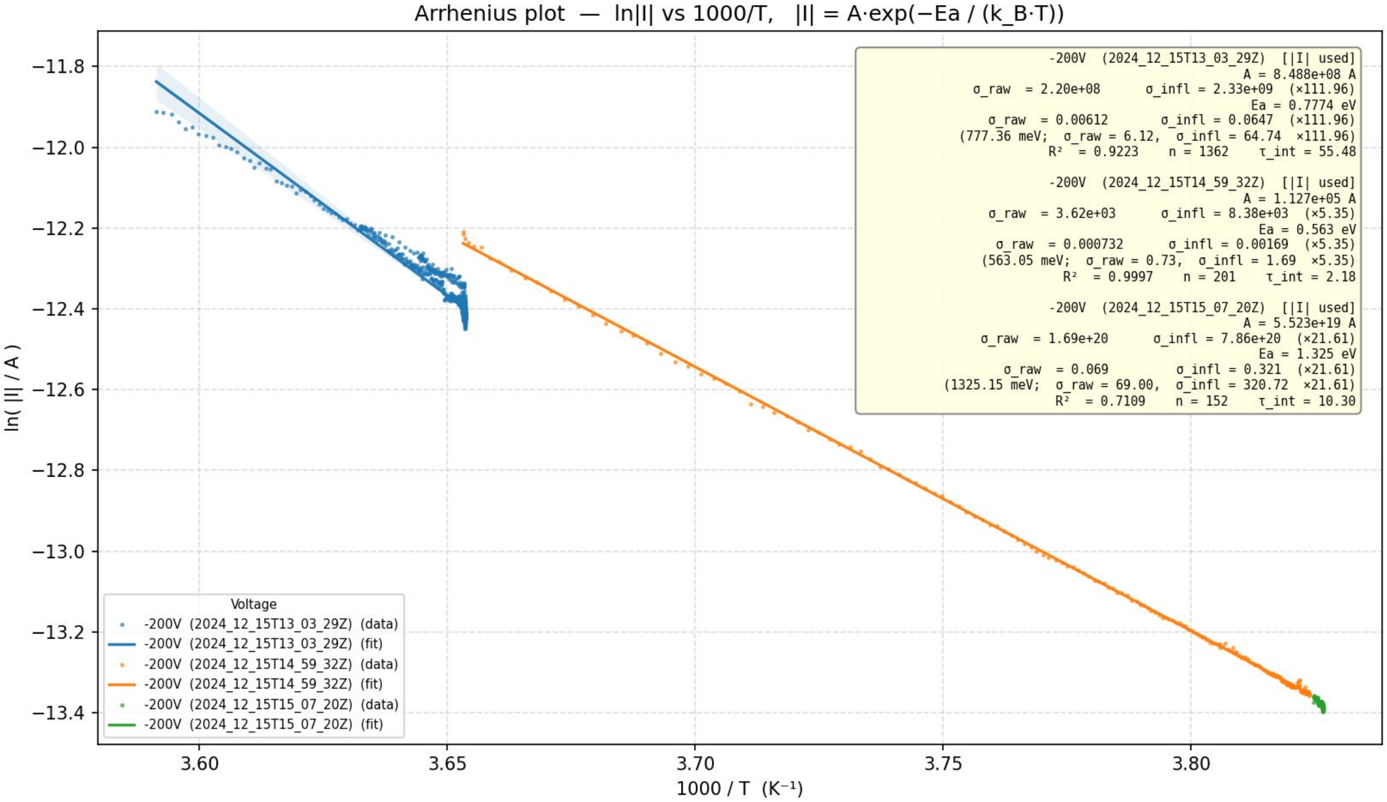
$$\ln|I| = \ln A - \frac{E_a}{k_B} \cdot \frac{1}{T_K}$$

so slope $= -E_a/k_B$, intercept $= \ln A$. E_a reported in eV using $k_B = 8.617333262 \times 10^{-5}$ eV/K.

Long Scans - Temperature - 3

Remap measured current + temp as functions of time into current vs temp, then fit to Arrhenius

Assume dark current from thermally-driven carrier exchange between energy levels

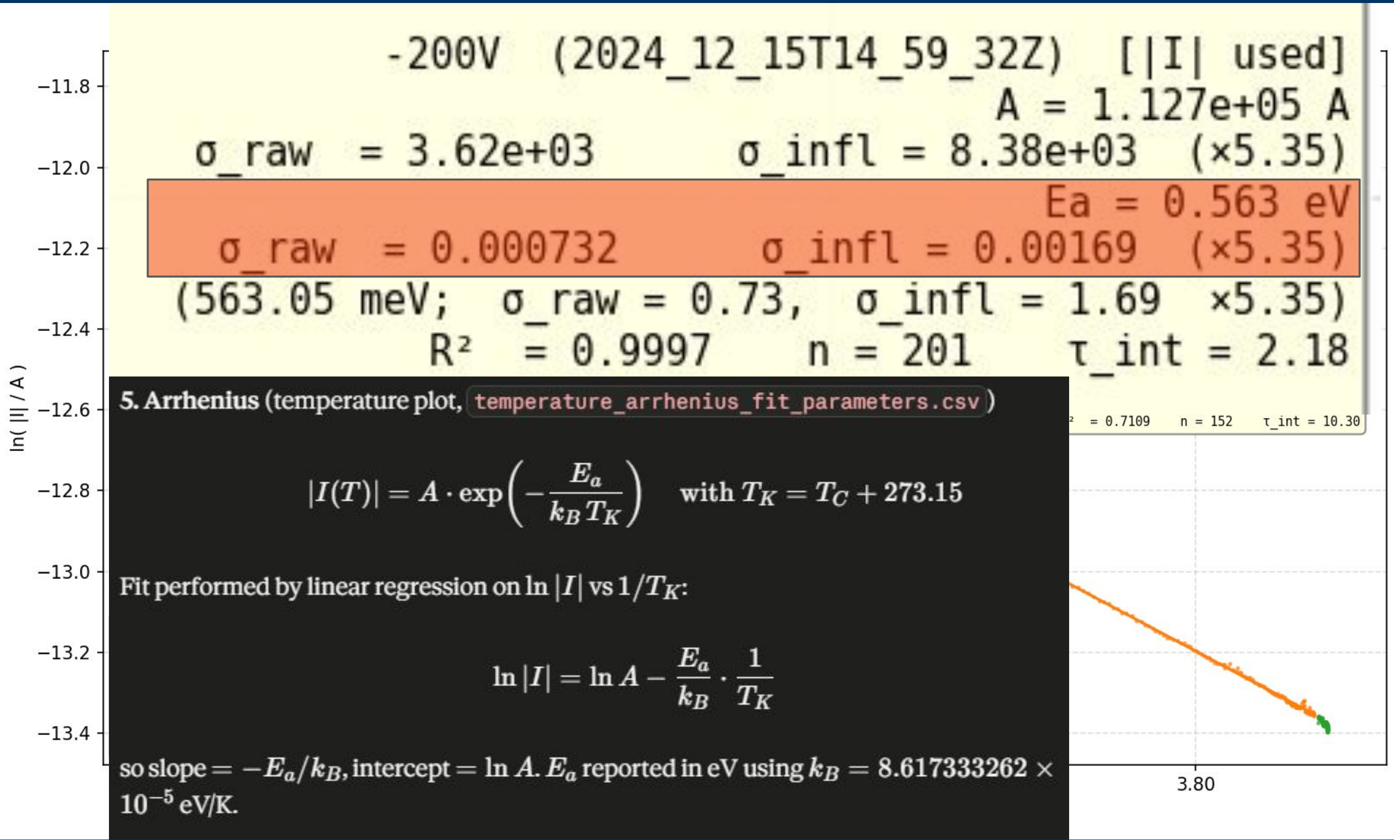

Arrhenius plot — ln|I| vs 1000/T, |I| = A·exp(−Ea / (k_B·T))

```
                    -200V  (2024_12_15T13_03_29Z)  [|I| used]
                                            A = 8.488e+08 A
      σ_raw  = 2.20e+08      σ_infl = 2.33e+09  (×111.96)
                                             Ea = 0.7774 eV
        σ_raw  = 0.00612       σ_infl = 0.0647  (×111.96)
    (777.36 meV;  σ_raw = 6.12,  σ_infl = 64.74  ×111.96)
                  R²  = 0.9223    n = 1362    τ_int = 55.48

                    -200V  (2024_12_15T14_59_32Z)  [|I| used]
                                            A = 1.127e+05 A
        σ_raw  = 3.62e+03      σ_infl = 8.38e+03  (×5.35)
                                               Ea = 0.563 eV
         σ_raw  = 0.000732      σ_infl = 0.00169  (×5.35)
       (563.05 meV;  σ_raw = 0.73,  σ_infl = 1.69  ×5.35)
                    R²  = 0.9997    n = 201    τ_int = 2.18

                    -200V  (2024_12_15T15_07_20Z)  [|I| used]
                                            A = 5.523e+19 A
       σ_raw  = 1.69e+20      σ_infl = 7.86e+20  (×21.61)
                                               Ea = 1.325 eV
          σ_raw  = 0.069          σ_infl = 0.321  (×21.61)
  (1325.15 meV;  σ_raw = 69.00,  σ_infl = 320.72  ×21.61)
                   R²  = 0.7109    n = 152    τ_int = 10.30
```

Long Scans - Temperature - 4

Activation energy ~trap-to-band gap → Dark current is driven by carrier exchange with the Fe traps, not bandgap

Low uncertainty from scipy fit



```
          -200V  (2024_12_15T14_59_32Z)  [|I| used]
                                   A = 1.127e+05 A
 σ_raw  = 3.62e+03      σ_infl = 8.38e+03  (×5.35)
                                      Ea = 0.563 eV
 σ_raw  = 0.000732      σ_infl = 0.00169  (×5.35)
(563.05 meV;  σ_raw = 0.73,  σ_infl = 1.69  ×5.35)
         R² = 0.9997      n = 201      τ_int = 2.18
```

5. Arrhenius (temperature plot, `temperature_arrhenius_fit_parameters.csv`)

$$|I(T)| = A \cdot \exp\left(-\frac{E_a}{k_B T_K}\right) \quad \text{with } T_K = T_C + 273.15$$

Fit performed by linear regression on $\ln|I|$ vs $1/T_K$:

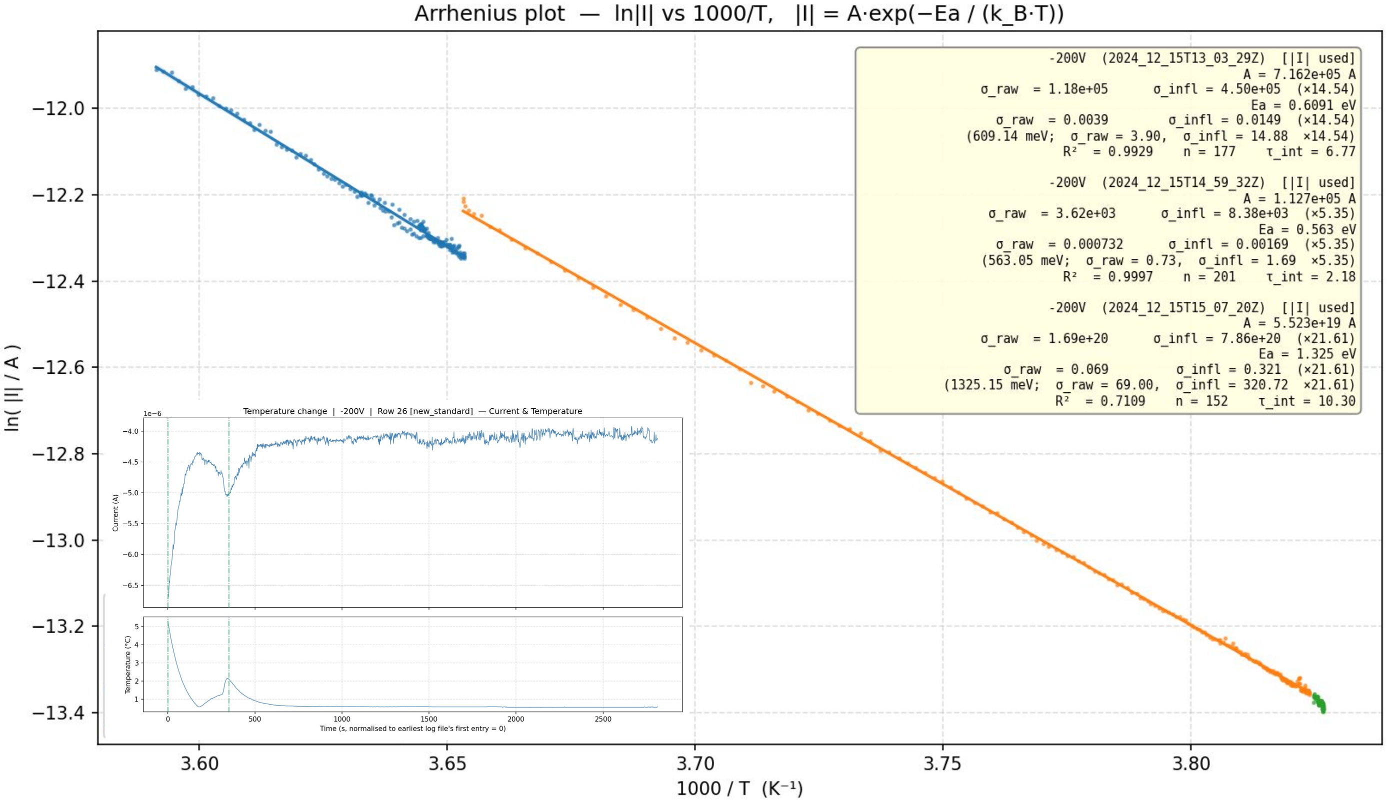
$$\ln|I| = \ln A - \frac{E_a}{k_B} \cdot \frac{1}{T_K}$$

so slope $= -E_a/k_B$, intercept $= \ln A$. E_a reported in eV using $k_B = 8.617333262 \times 10^{-5}$ eV/K.

Long Scans - Temperature - 5

Removing tail end of blue data / large cluster at high current leads to better matching E_a between runs.

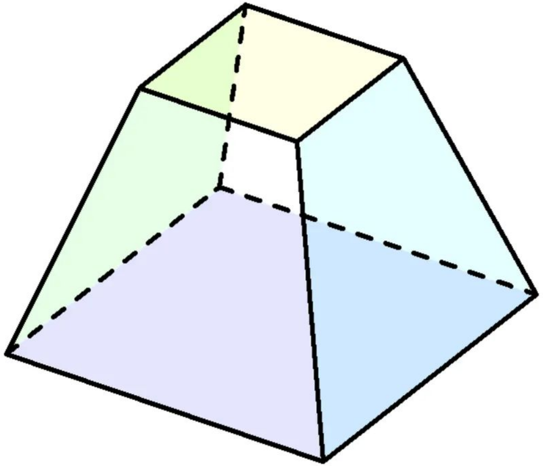
Later tail likely contains other processes not related to thermal exchange of carriers



```
                         -200V  (2024_12_15T13_03_29Z)  [|I| used]
                                                  A = 7.162e+05 A
       σ_raw  = 1.18e+05      σ_infl = 4.50e+05  (×14.54)
                                                   Ea = 0.6091 eV
         σ_raw  = 0.0039         σ_infl = 0.0149  (×14.54)
    (609.14 meV;  σ_raw = 3.90,  σ_infl = 14.88  ×14.54)
                   R²  = 0.9929    n = 177    τ_int = 6.77

                         -200V  (2024_12_15T14_59_32Z)  [|I| used]
                                                  A = 1.127e+05 A
        σ_raw  = 3.62e+03      σ_infl = 8.38e+03  (×5.35)
                                                    Ea = 0.563 eV
         σ_raw  = 0.000732      σ_infl = 0.00169  (×5.35)
      (563.05 meV;  σ_raw = 0.73,  σ_infl = 1.69  ×5.35)
                   R²  = 0.9997    n = 201    τ_int = 2.18

                         -200V  (2024_12_15T15_07_20Z)  [|I| used]
                                                  A = 5.523e+19 A
       σ_raw  = 1.69e+20      σ_infl = 7.86e+20  (×21.61)
                                                    Ea = 1.325 eV
          σ_raw  = 0.069          σ_infl = 0.321  (×21.61)
  (1325.15 meV;  σ_raw = 69.00,  σ_infl = 320.72  ×21.61)
                  R²  = 0.7109    n = 152    τ_int = 10.30
```

Caveat: Two Conditions Not Fulfilled

- Effective volume not constrained
  - **Floating guard ring**
    - Standard IV station does not have multiple channels to measure guard ring and central pad separately
  - Effective volume spreads beyond under central pad
  - Effective volume estimated as frustrum——————————————→



- Temperature not held constant
  - Temperature not held constant/measured + measurements taken on different days
  - Leakage current temperature dependence will spread values
- Presented will be preliminary estimation of alpha