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DESY.

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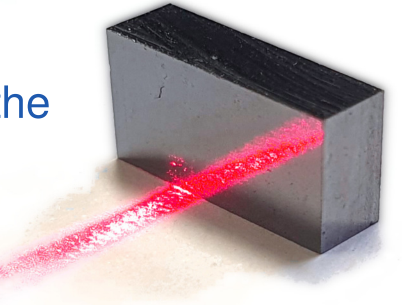


Radiation damage: influence on the absorption of near-infrared light in silicon

Eckhart Fretwurst, Robert Klanner,
Stephan Martens, Jörn Schwandt,
Annika Vauth

RD50

40th RD50 Workshop
CERN
June 21, 2022

Impact of Defects on Silicon Sensors

Increasing radiation load on detectors
→ Three main effects on the device performace:

Leakage current increase

increased noise, increased power consumption

Effective space charge

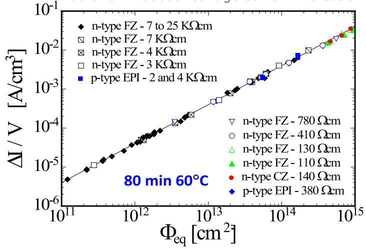
change in electric field distribution and depletion voltage
double junction effects, underdepleted operation

Trapping of charge carriers

by defect levels can reduce overall sensor signal
depends on trapping time and concentration of defects

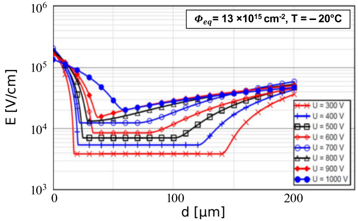
Sensor effects - but what about impact on silicon itself?

Radiation induced leakage current increase



[thesis M. Moll, UHH 1999]

Electric field in irradiated pad diodes



[arXiv:2111.11323]

Optical measurements of irradiated Silicon

Investigated Si samples:

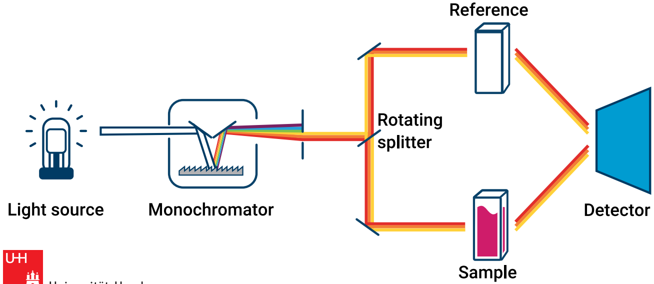
FZ n-type Si, $\approx 3.5\,\mathrm{k}\Omega\cdot\mathrm{cm}$,
$\langle 111\rangle$ crystal orientation,
Double-side polished

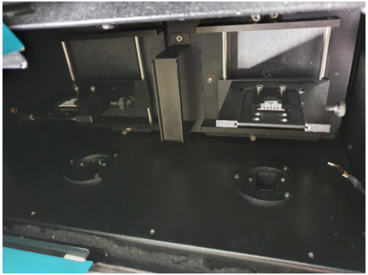
- Thickness d=280 µm,
  24 GeV/c proton irradiation to
  $\Phi_{eq} = (2.4, 6.1, 4.9, 8.6)\times 10^{15}\,\mathrm{cm}^{-2}$
  (CERN PS East Area)
- d=3000 µm, (2 samples per fluence)
  Reactor neutron irradiation to
  $\Phi_{eq} = (1, 5, 10, 30, 50, 100)\times 10^{15}\,\mathrm{cm}^{-2}$
  (JSI TRIGA reactor - thanks to the colleagues at the Jozef Stefan Institute!)

Measurement setup

Transmission measurements at room temperature with Cary 5000 spectrophotometer

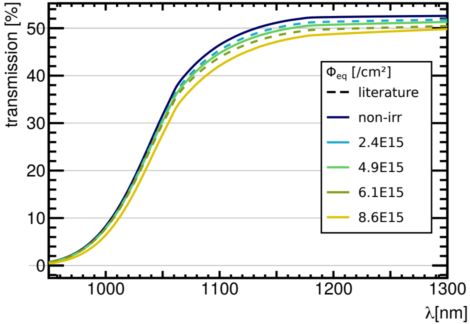
- For 280 µm samples (2019):
  $950\,\mathrm{nm} < \lambda < 1350\,\mathrm{nm}$ [j.nima.2020.163955]
- For 3000 µm samples (2021/22):
  $950\,\mathrm{nm} < \lambda < 2000\,\mathrm{nm}$



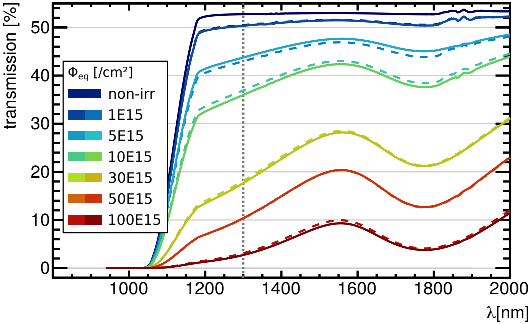


Transmission measurement

0.28mm, 24GeV/c p



3 mm, reactor n



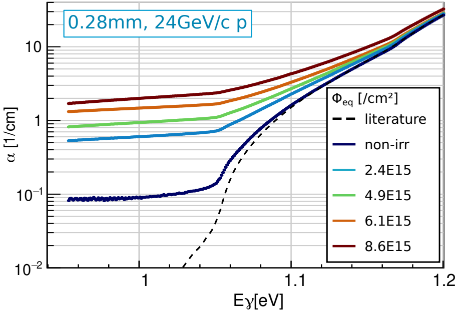
- Rapid decrease of transmission for $\lambda < 1.1\,\mu\text{m}$ ($E_{\text{gap}} = 1.124\,\text{eV} \rightarrow \lambda = 1.103\,\mu\text{m}$)
- Broad transmission minimum at $\lambda \approx 1.8\,\mu\text{m}$
- Steady decrease of transmission/increase of absorption with fluence

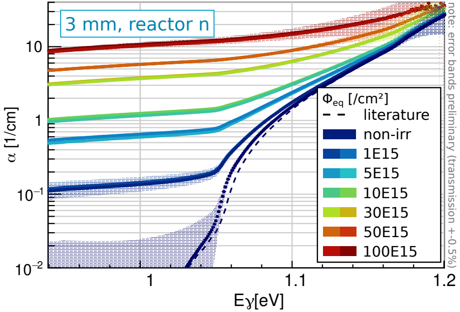
Absorption length

Fresnel equations (90°) $Ref = \frac{(n-1)^2}{(n+1)^2}$, $Tra = \frac{4\cdot n}{(n+1)^2}$ — n: from literature [M.A. Green]

Total transmission $Tr(n,\lambda,\lambda_{abs}) = \frac{Tra^2\cdot e^{-d/\lambda_{abs}}}{1-(Ref\cdot e^{-d/\lambda_{abs}})^2}$ — Tr: from measurement

Absorption $\alpha = \frac{1}{\lambda_{abs}} = \frac{\ln(Tra^2+\sqrt{(Tra^4+4\cdot Ref^2\cdot Tr^2)/(2\,Tr)})}{d}$ — d: sample thickness



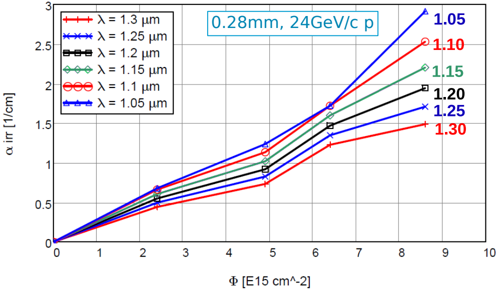


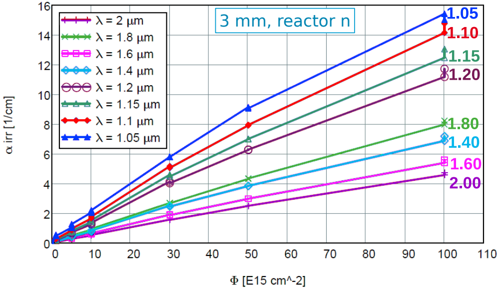
note: error bands preliminary (transmission +-0.5%)

Radiation-induced absorption

Define absorption contribution induced by radiation:

$$\alpha_{\text{irr}}(\lambda, \Phi) = \alpha(\lambda, \Phi) - \alpha(\lambda, \Phi = 0)$$

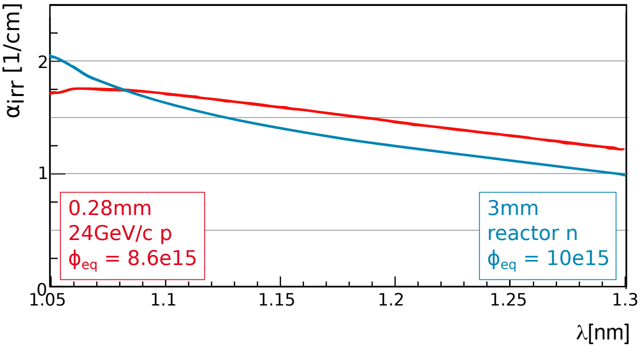




- α_{irr} proportional to Φ_{eq} up to $\Phi_{\text{eq}} \approx 4 \times 10^{16}\,\text{cm}^{-2}$, above indications of flattening
- α_{irr} decreases up to $\lambda \approx 1.6\,\mu\text{m}$, peak around $1.8\,\mu\text{m}$ (already seen in transmission)

24 GeV/c protons vs reactor neutrons

Radiation damage depends on particle type and energy (→ cluster defects vs point defects)



- Little difference in α_{irr} for reactor n and and 24 GeV/c p at similar fluence
- Difference in λ dependence?

Bandgap changes

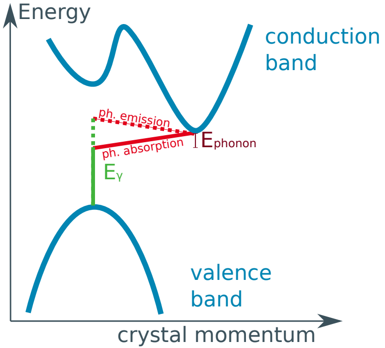
Energy needed to excite an electron
from valence band to conduction band:
Dependent on temperature and doping (decrease with N_d)

Also dependent on irradiation fluence?

Silicon = indirect semiconductor,
i.e. phonon absorption or emission needed

$$\alpha(E_\gamma) \propto (E_\gamma \pm E_{\text{phonon}} - E_{\text{gap}})^2 \quad \text{for } E_\gamma \geq E_{\text{gap}}$$

Change in E_{gap} → change in absorption edge

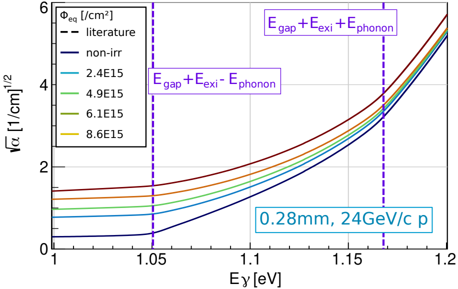


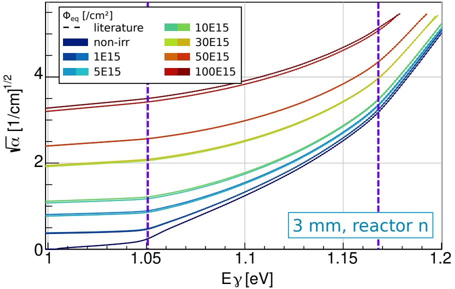
Bandgap dependence on fluence

Absorbance $\alpha(E_\gamma)$: phonon absorption + emission

$$\alpha(E_\gamma, T) \propto \left(\frac{(E_\gamma - E_\text{phonon} - E_\text{gap} + E_\text{exciton})^2}{exp(E_\text{phonon}/kT) - 1}\right) + \left(\frac{(E_\gamma + E_\text{phonon} - E_\text{gap} + E_\text{exciton})^2}{1 - exp(-E_\text{phonon}/kT)}\right)$$

[doi.org/10.1007/978-3-642-00710-1]





- Determine “kinks“ in $\sqrt{\alpha(E_\gamma)}$ → maxima in 2nd derivative
- Method: convolute with Gaussian to smooth, calculate numeric derivatives of graphs

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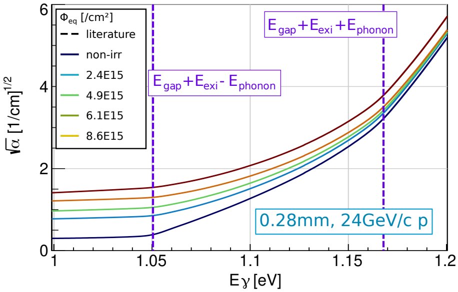

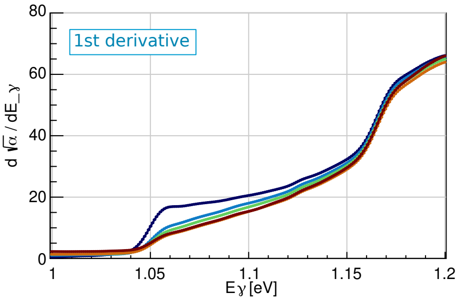

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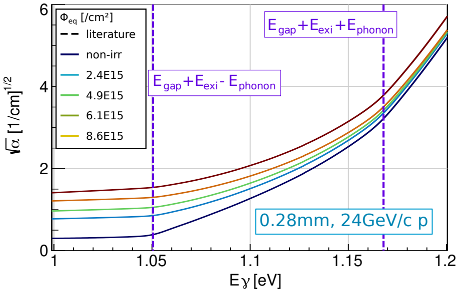

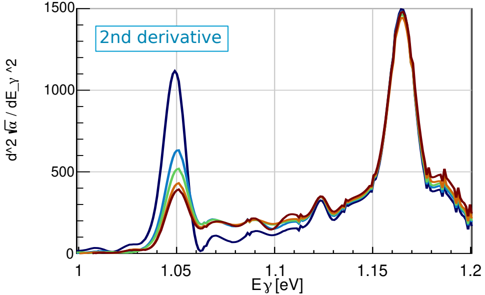

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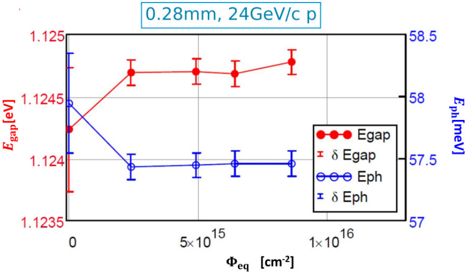
- Method: convolute with Gaussian to smooth, calculate numeric derivatives of graphs

[arXiv:2204.03288, submitted to NJP]

Bandgap dependence on fluence

Study Φ-dependence of “kinks“ in $\sqrt{\alpha(E_\gamma)}$
$\rightarrow$ Determine $E_{\text{gap}} = \frac{E_{\text{em}}+E_{\text{abs}}}{2} + E_{\text{exciton}}$ and $E_{\text{phonon}} = \frac{E_{\text{em}}-E_{\text{abs}}}{2}$

0.28mm, 24GeV/c p



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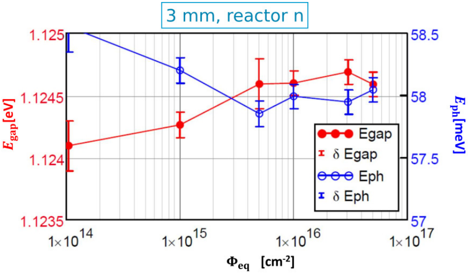


using $E_{\text{exciton}} = 15\,\text{meV}$

E_{gap} and $E_{\text{phonon}} \sim$ independent of fluence, agreement with literature$^{(*)}$

$^{(*)}$e.g. Alex *et al.*, J. Appl. Phys. 79, 6943 (1996): 295K: $1.124 \pm 0.002\,\text{eV}$, 293K: $1.125 \pm 0.002\,\text{eV}$

A look at $\lambda > 1.3\,\mu m$

Local peak in absorption around 1.8 µm → Silicon divacancy

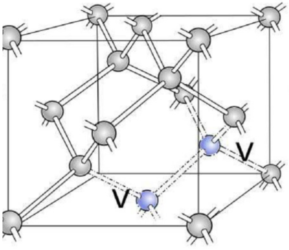
“Divacancy“ defect:
a) Agglomoration of two vacencies
b) Simultaneous displacement of two adjacent Si lattice atoms

Four charge states (+1, 0, -1, -2) → three deep energy levels

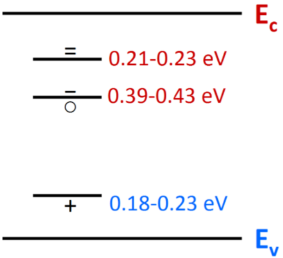
1.8 µm , 3.3 µm and 3.9 µm absorption bands
from excitation of the divacancy

Data agrees with literature:
Peak height [Cheng, Lori, 1968], shape [Fan, Ramdas, 1959]

Annealing studies to study “healing“ of this defect



[G. Herrero-Saboya. Defects in silicon. 2020]



[doi:10.1088/1748-0221/12/01/P01025]

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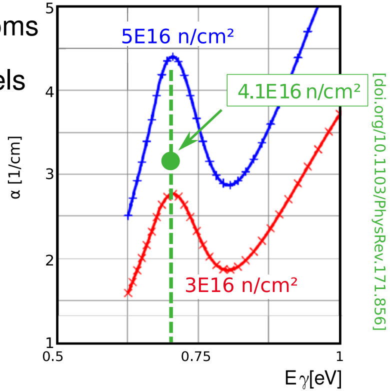
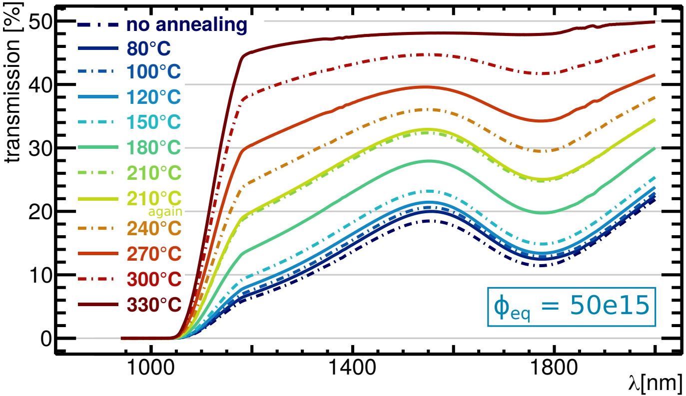


Annealing

Iso-chronal annealing, **15 min** per temperature at
80, 100, 120, 150, 180, 210, 240, 270, 300, 330 [°C]

Annealed four samples: $\Phi_{\text{eq}} = (0, 10, 50, 100) \times 10^{15}\,\text{cm}^{-2}$

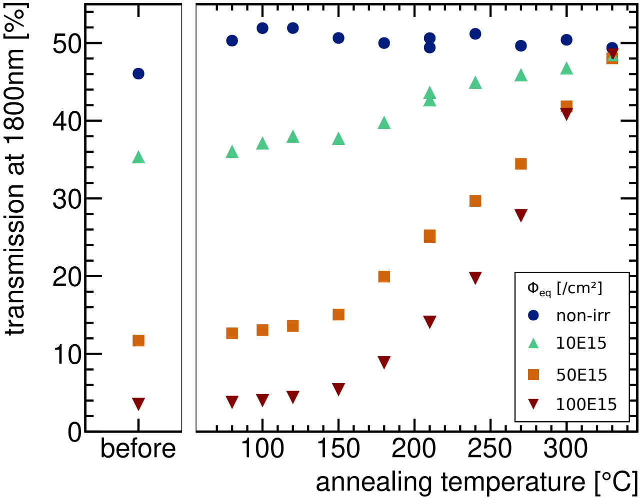


Annealing: Transmission recovery

- Clear impact of annealing for the three irreadiated samples studied here

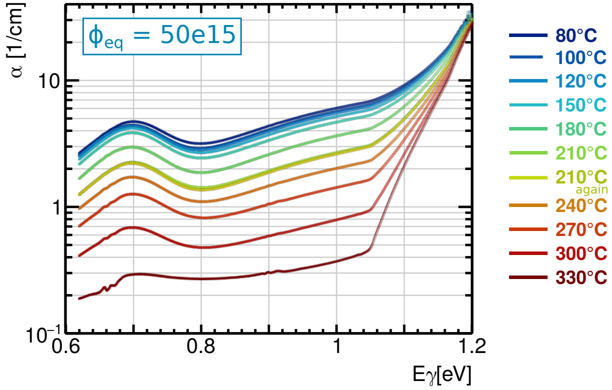
- Reduction of defect-induced optical absorption at 1.8 µm compatible with literature

  Cheng et.al, 1966



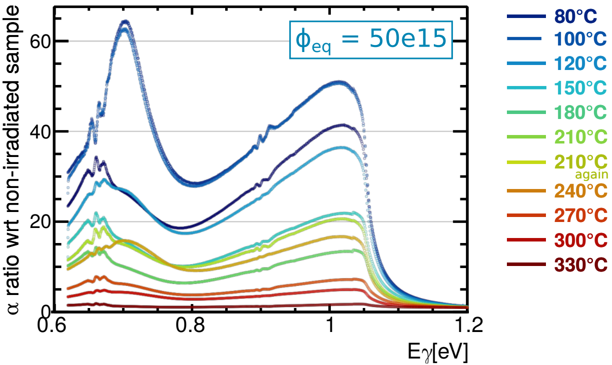
Absorption coefficient after annealing

- Calculate absorption



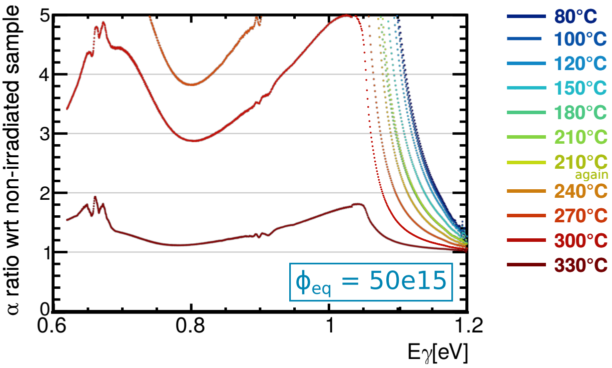
Absorption coefficient after annealing

- Calculate absorption
- Compare to non-irradiated sample measurement for each temperature step



Absorption coefficient after annealing

- Calculate absorption
- Compare to non-irradiated sample measurement for each temperature step
- Large fraction of optically active defects annealed after the last step (15 min at 330 °C)

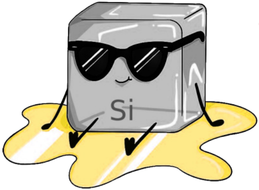


(plots for 10E15 and 100E15 in the backup slides)

Conclusions

Goal: understand behaviour of silion at high irradiations

Near-Infrared measurements to investigate silicon properties:



- Increase in absorption with fluence,
  Similar for p- and n-irradiation
- Can determine band gap / phonon energy:
  E_{gap} changes by $\lesssim$ 1 meV for $\Phi_{\text{eq}} = (0 \text{ to } 1) \times 10^{17}\,\text{cm}^{-2}$
- Observation of “1.8 µm“ absorption band
  from neutral di-vacancy
- Transmission largely restored after annealing at 330 °C

Backup slides

Principle spectro-photo-meter

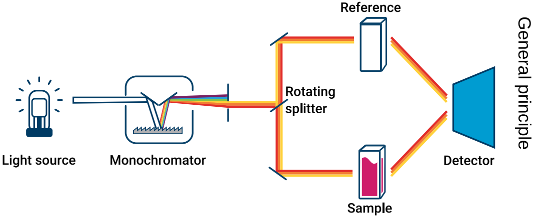
Single-beam and double beam systems exist

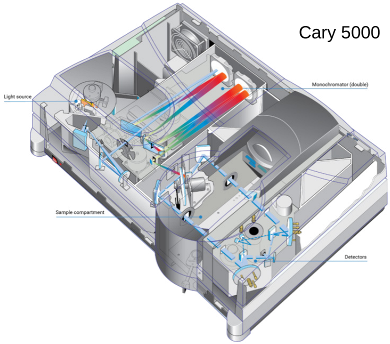
Double-beam system:

Monochromatic light is split
- in a reference beam
- and a sample beam
(passing the sample)
before hitting a detector.

Transmittance measurement:
- Ratio of sample to reference beam intensity
- Apply a baseline correction *(“blank”)*
(measurement without any sample)

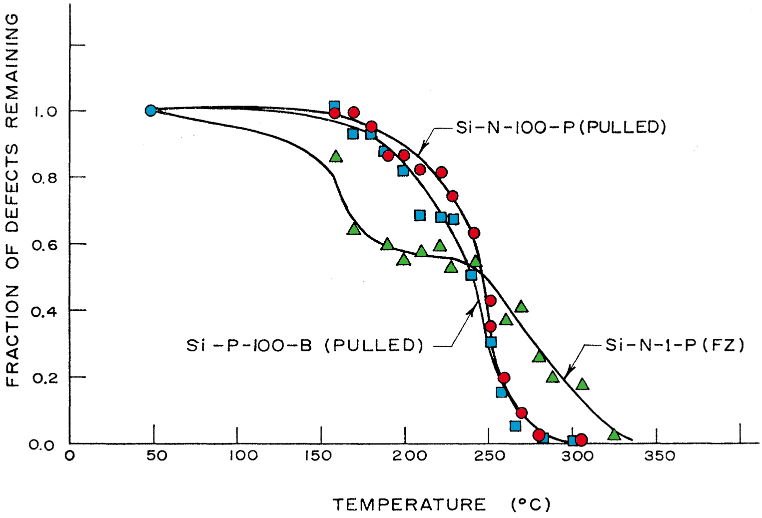
$$\%T = \frac{\frac{S_{Meas}}{R_{Meas}}}{\frac{S_{Blank}}{R_{Blank}}} \times 100$$





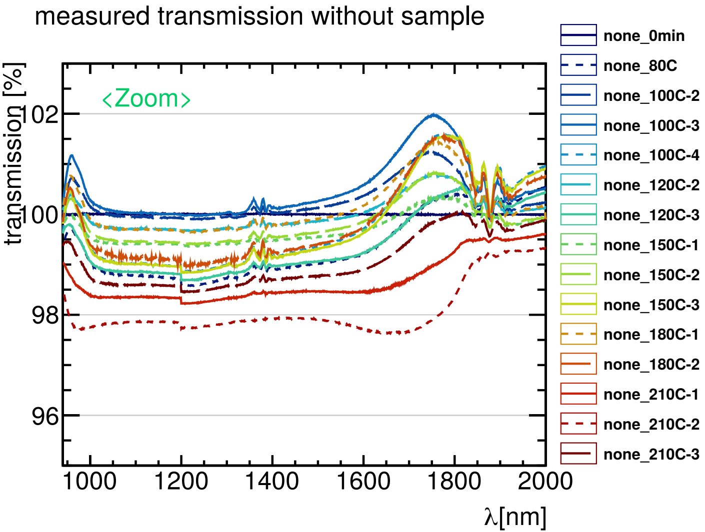
Cary 5000

Annealing of the 1.8 um line from literature:
(iso-chronal, 20 min)

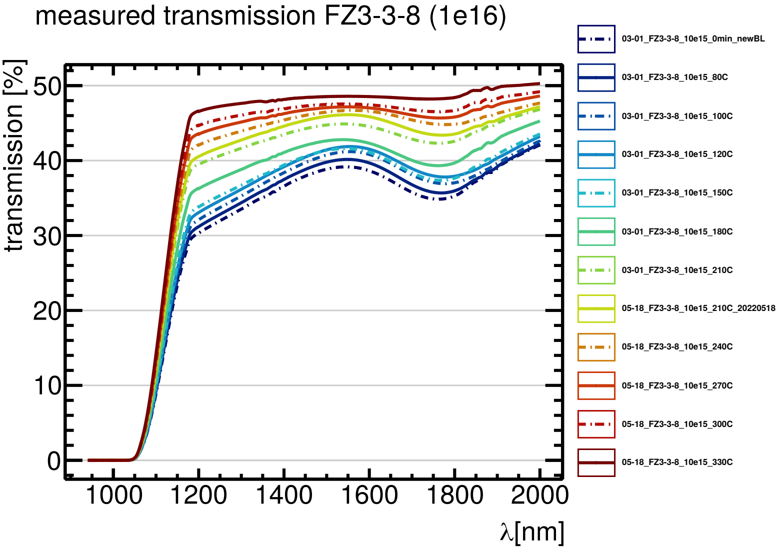


[doi.org/10.1103/PhysRev.152.761]

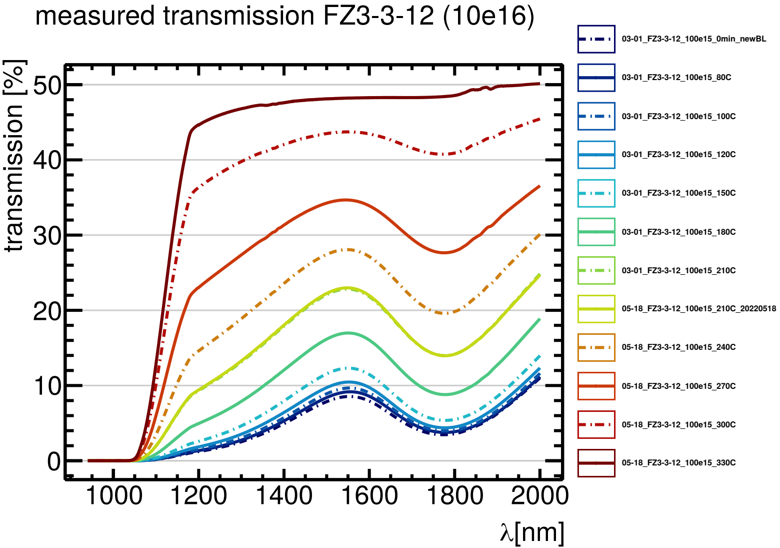
Transmission measurements with empty sample holder



Transmission measurements after annealing

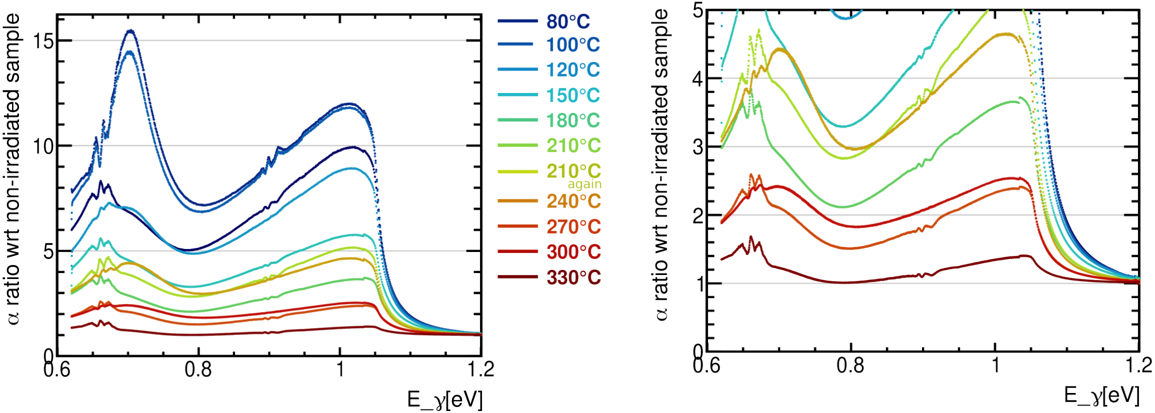


Transmission measurements after annealing



Absorption after annealing, compared to non-irradiated sample

FZ3-3-8_10e15



Absorption after annealing, compared to non-irradiated sample

FZ3-3-12_100e15