Experimental techniques - TSC and DLTS

Daniel Hynds

Disclaimer

I am definitely not an expert in this topic!

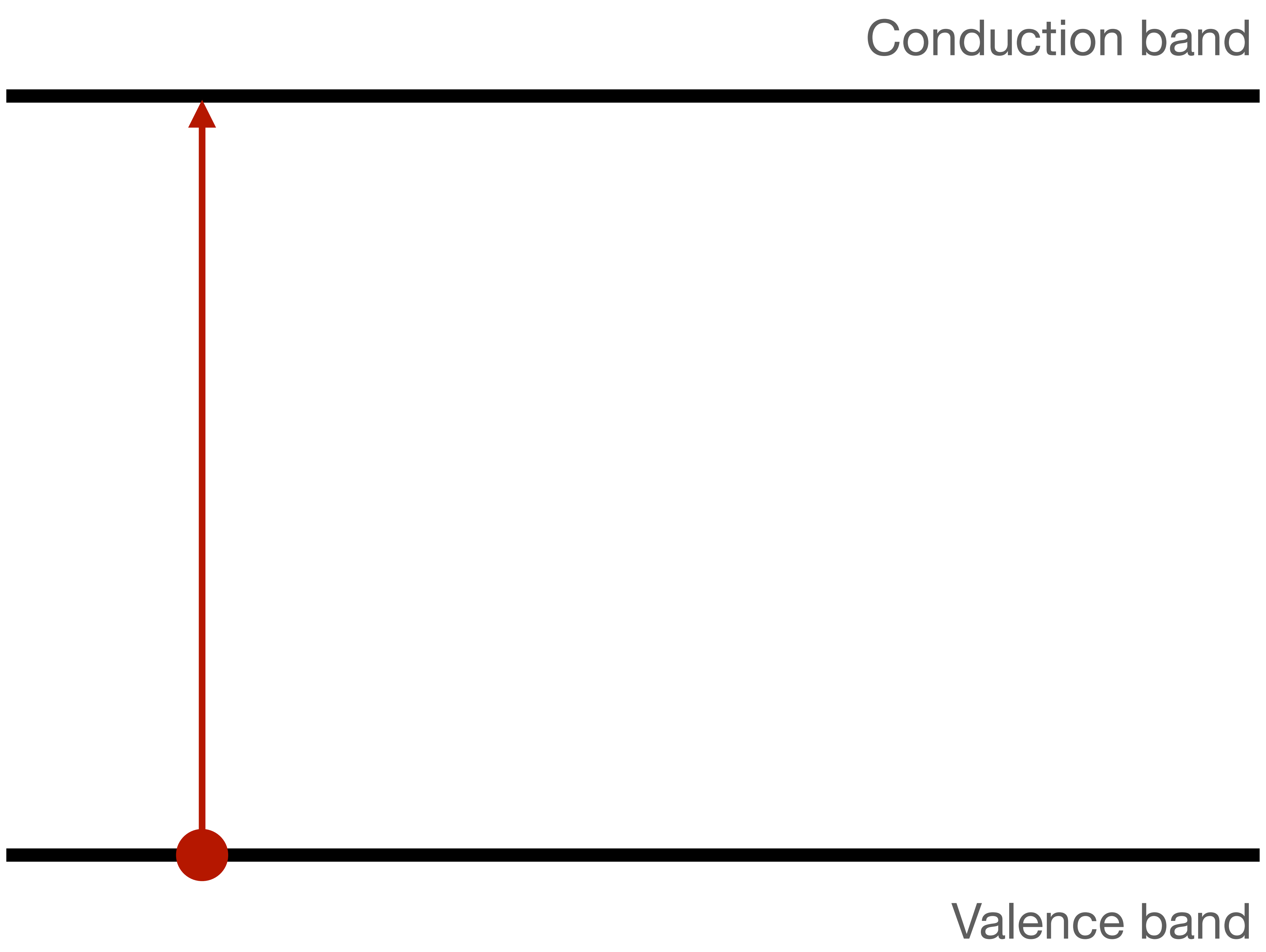
Defect characterisation is tricky - there is a lot of solid-state physics involved, a lot of caveats to the measurements, and a whole ton of different defects that can occur inside silicon (especially when recombining with oxygen, carbon, boron, phosphorous, vacancies… etc.)

This lecture is meant to illustrate some typical solid-state techniques and how they can be used to investigate such defects, not to describe all of the radiation-induced defects that exist

Energy levels in semiconductors

Charge carrier production in semiconductors relates to transitions from the valence to conduction band

- In depleted silicon detectors, this is the mechanism by which interacting particles are observed



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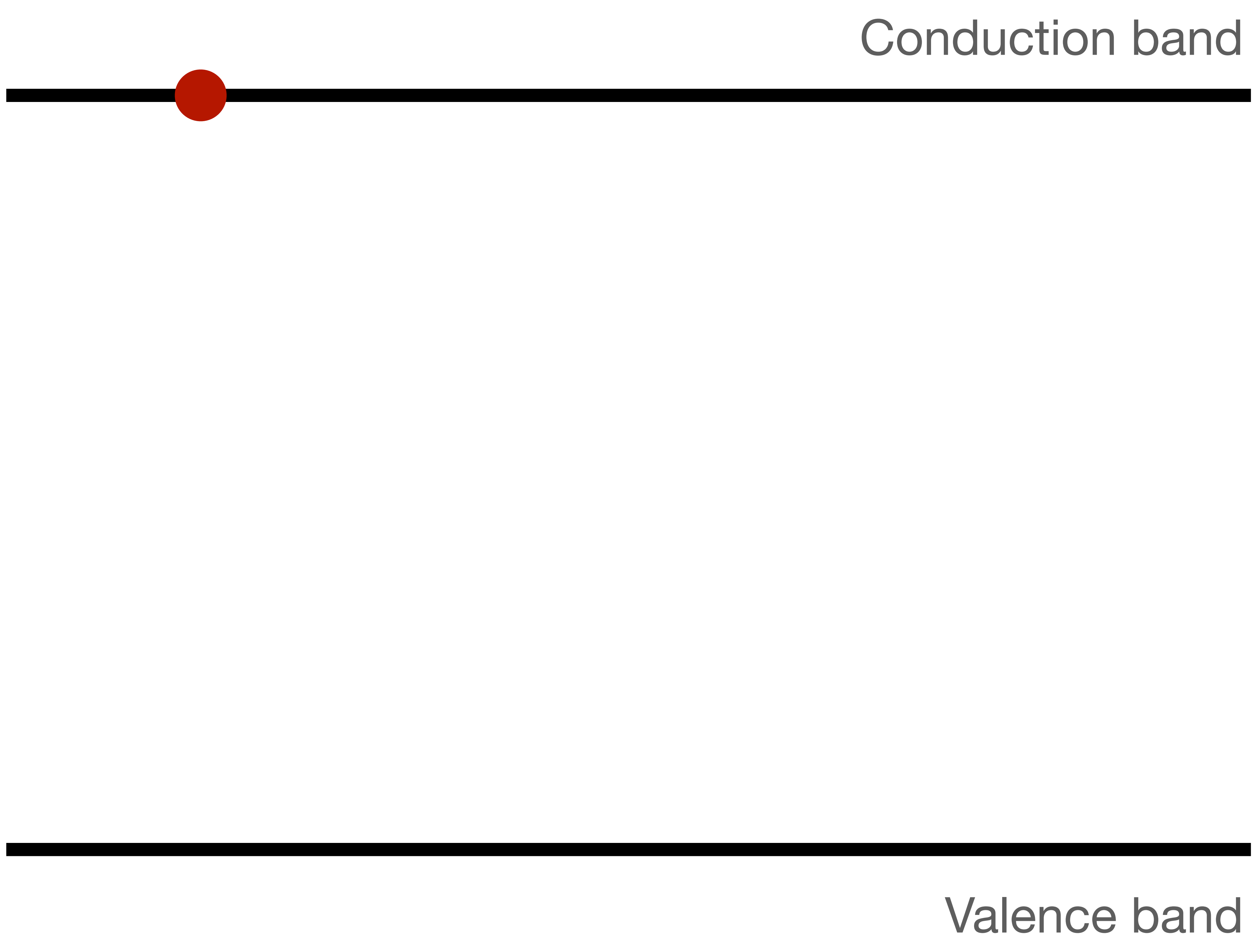
Where this goes wrong after irradiation damage is the introduction of additional energy levels in the band gap



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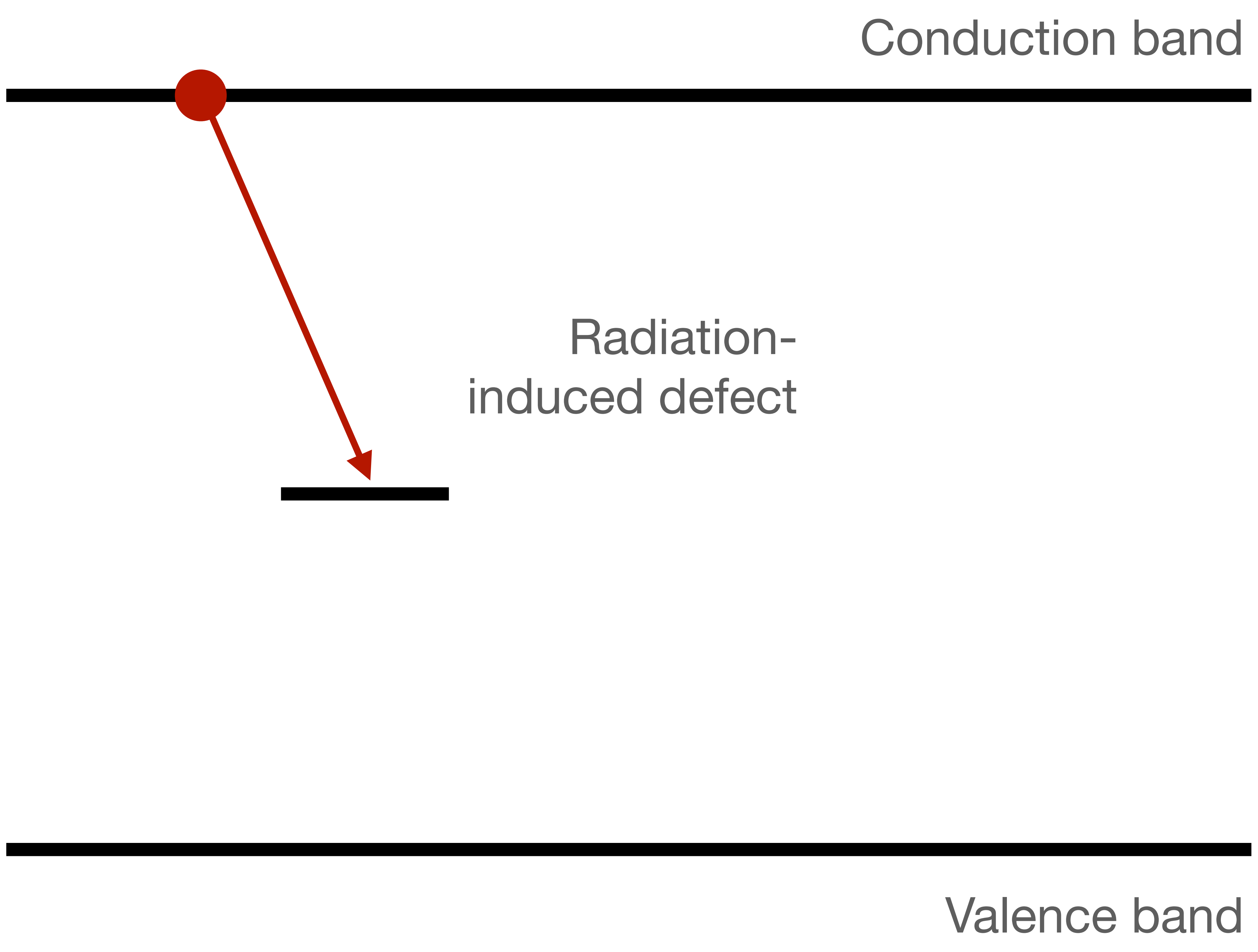

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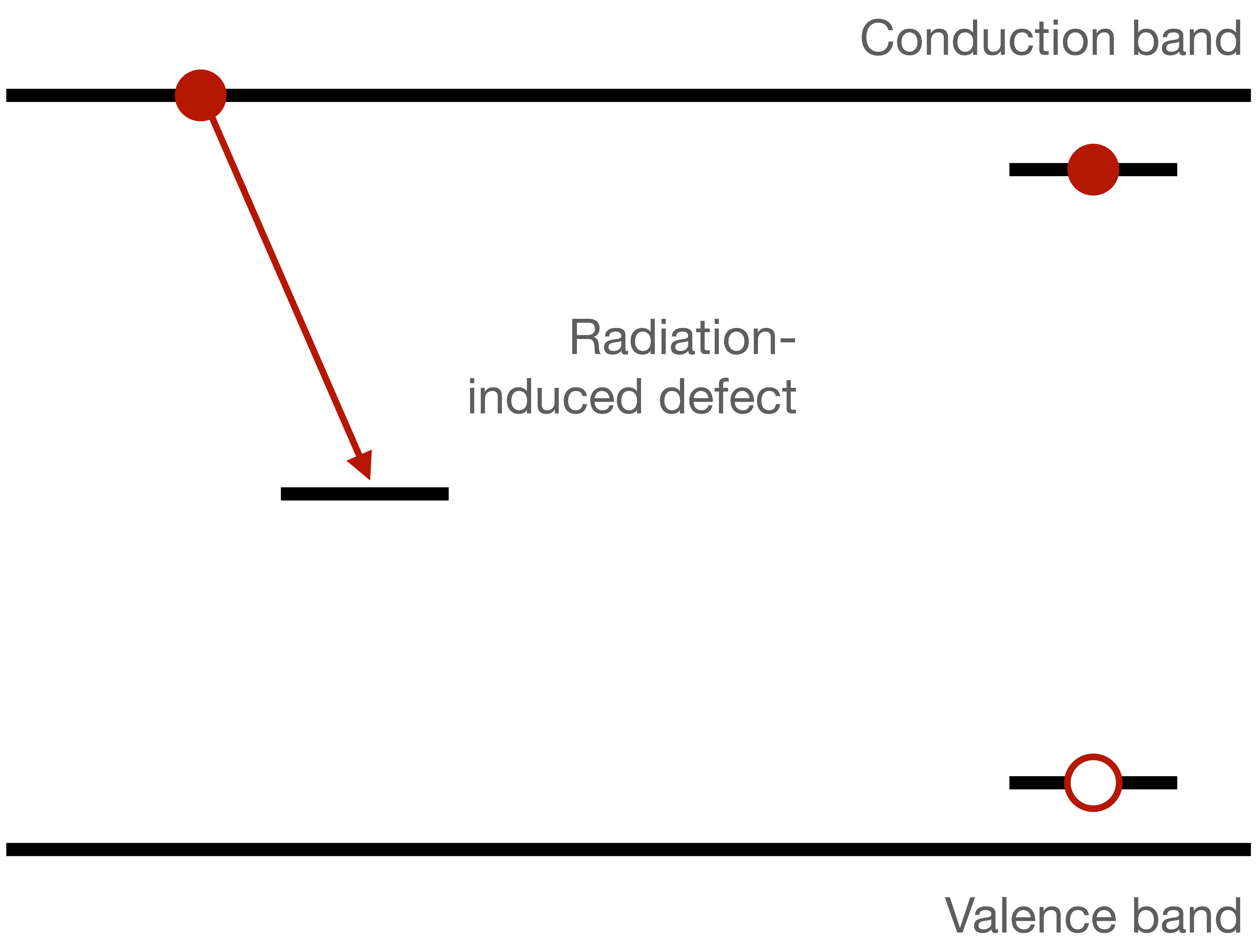

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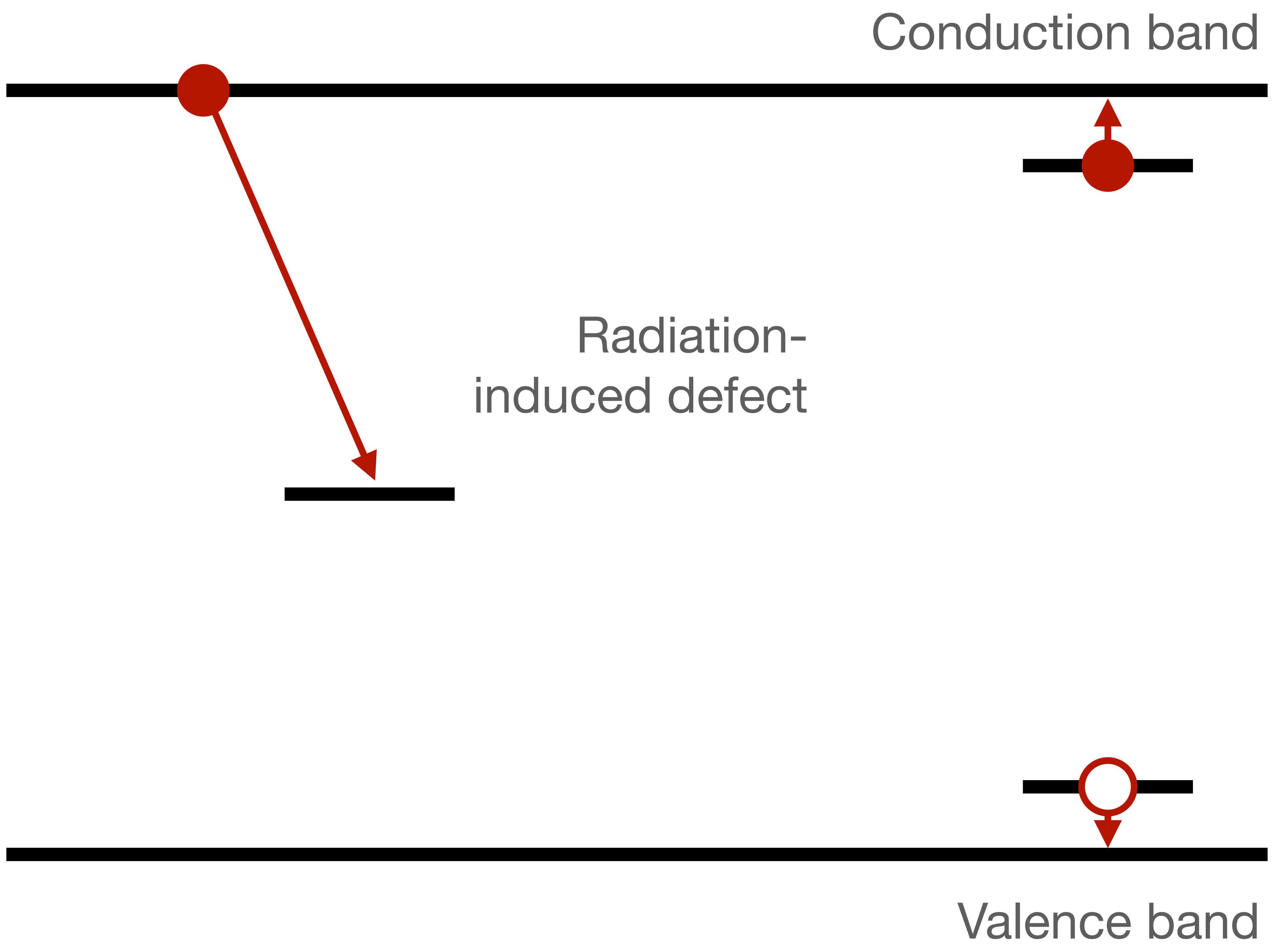

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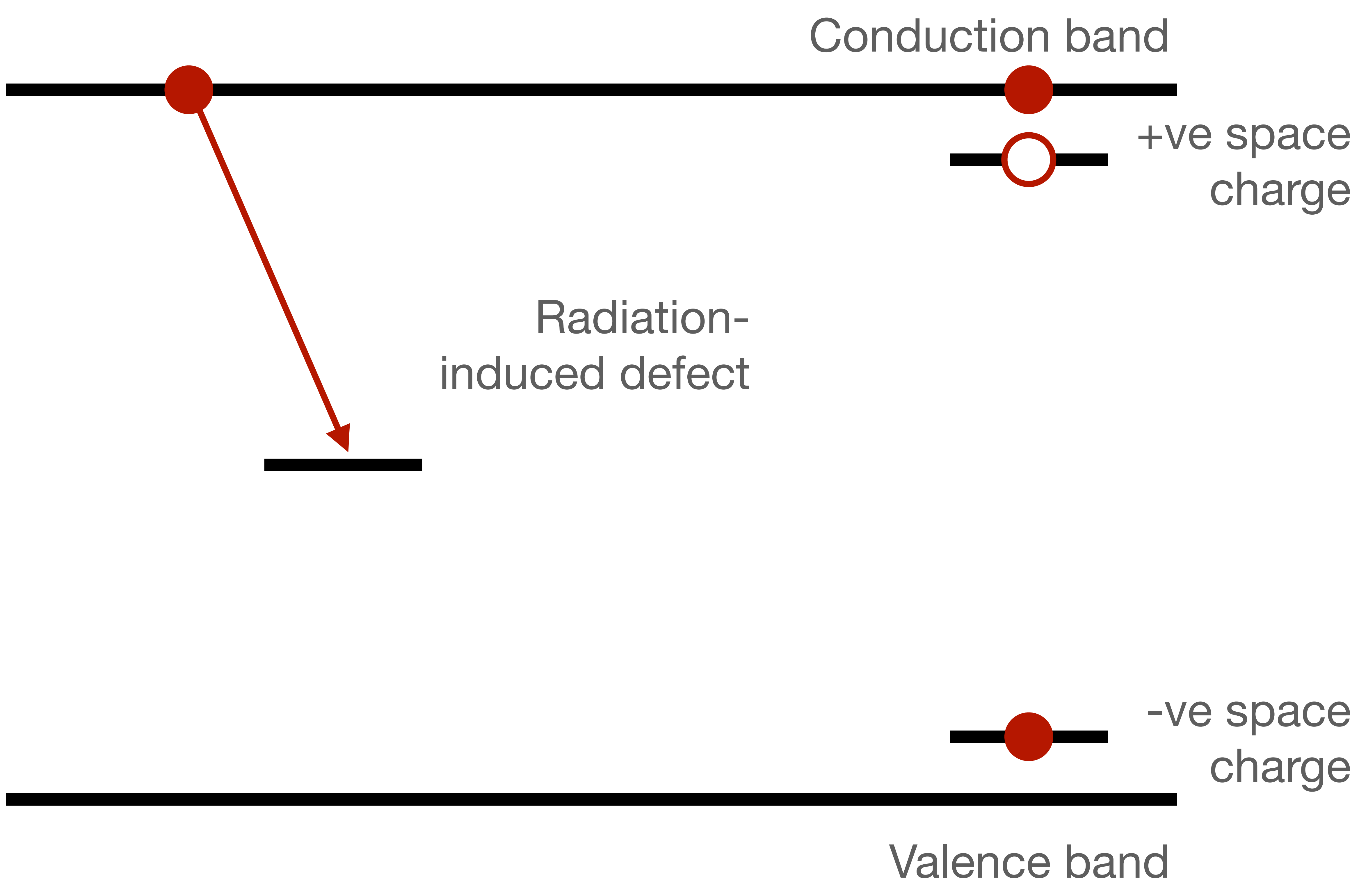
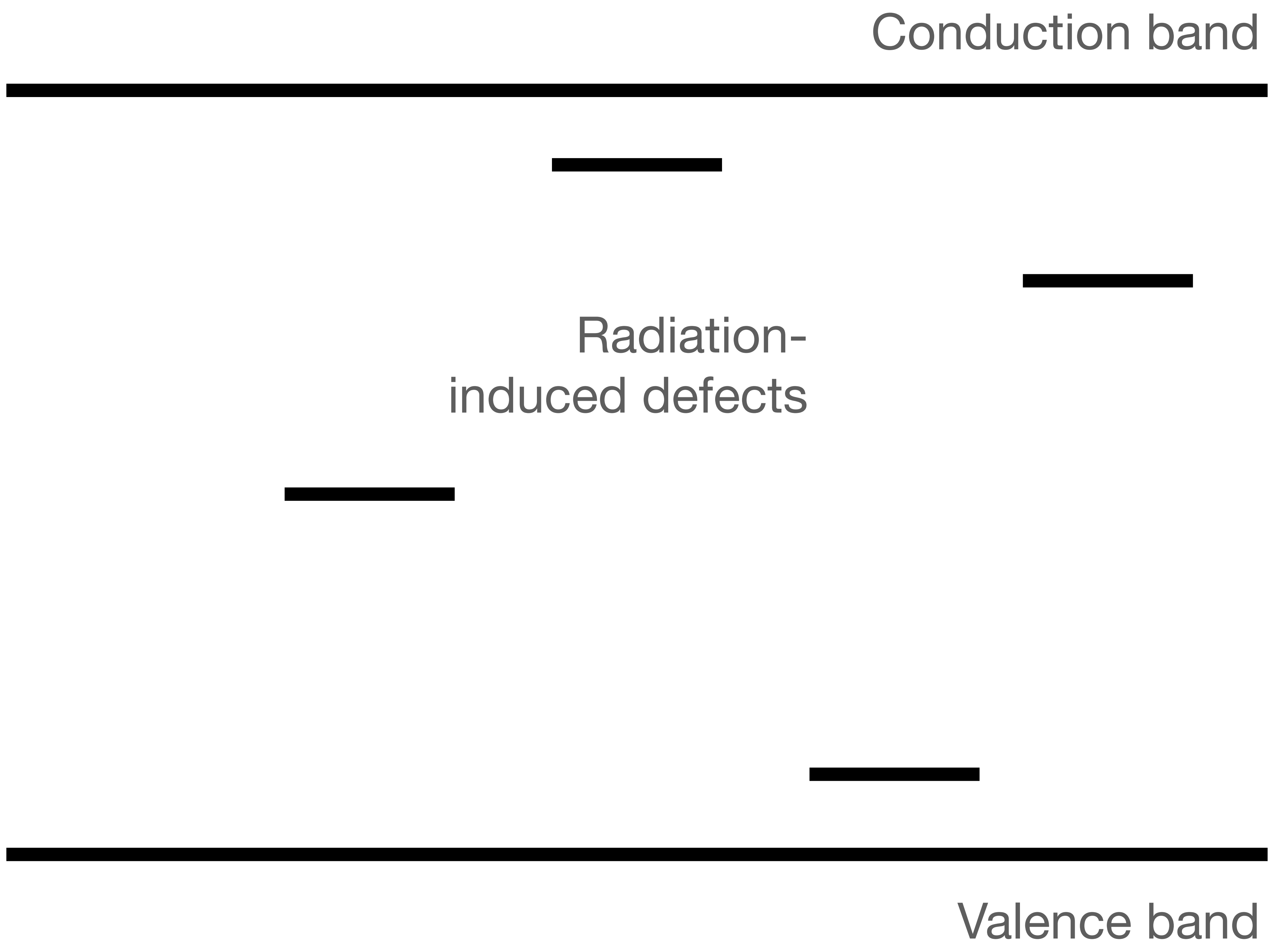


Energy levels in semiconductors

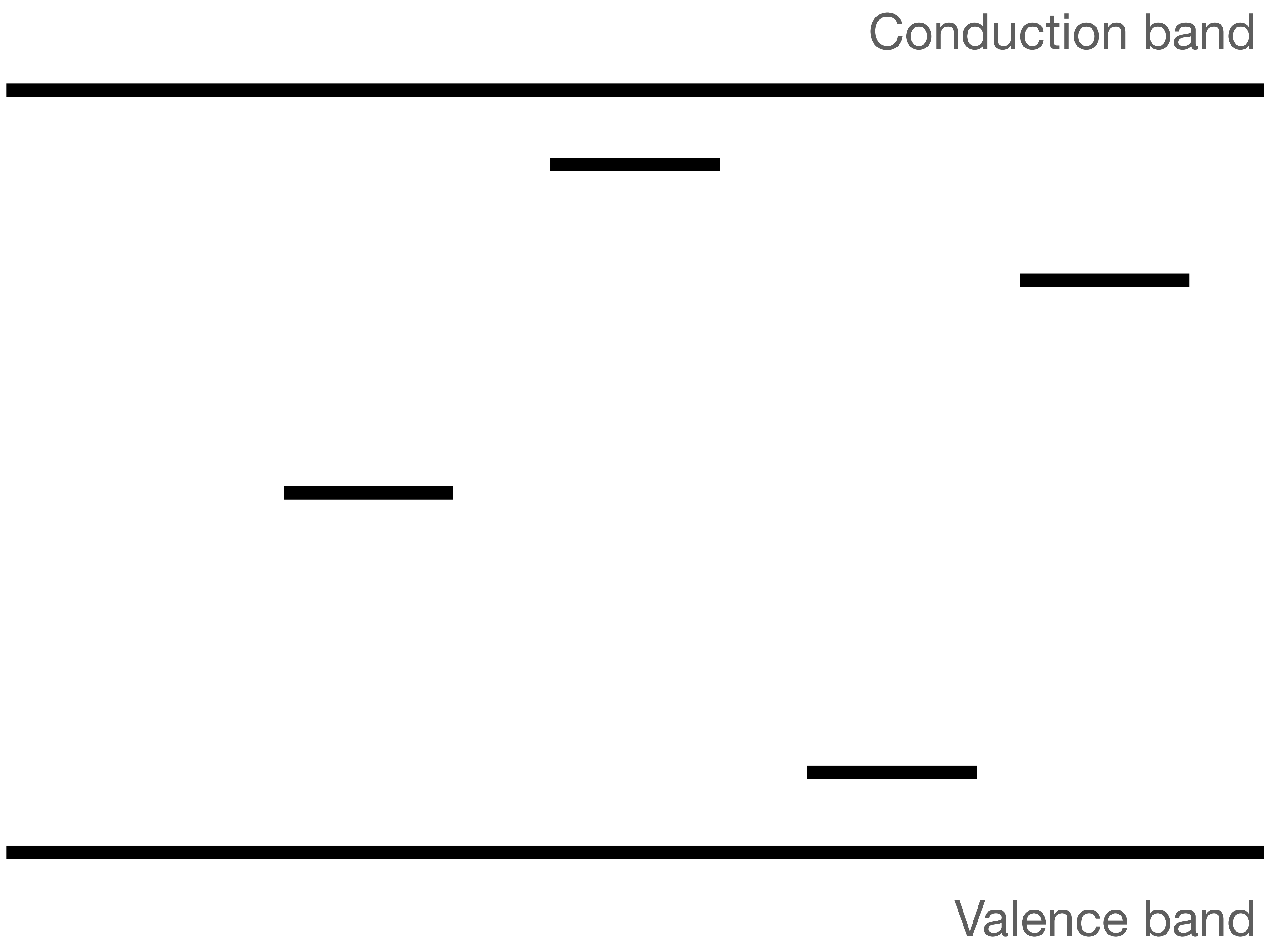
The question is, how do we study the various defects and understand what they are, where they come from, and how to mitigate their effects?



TSC - signal generation

We will start with the easier concept first - **Thermally Stimulated Current (TSC)**

- This technique is quite straightforward:
  - Cool down your silicon detector (let's say 10 K)



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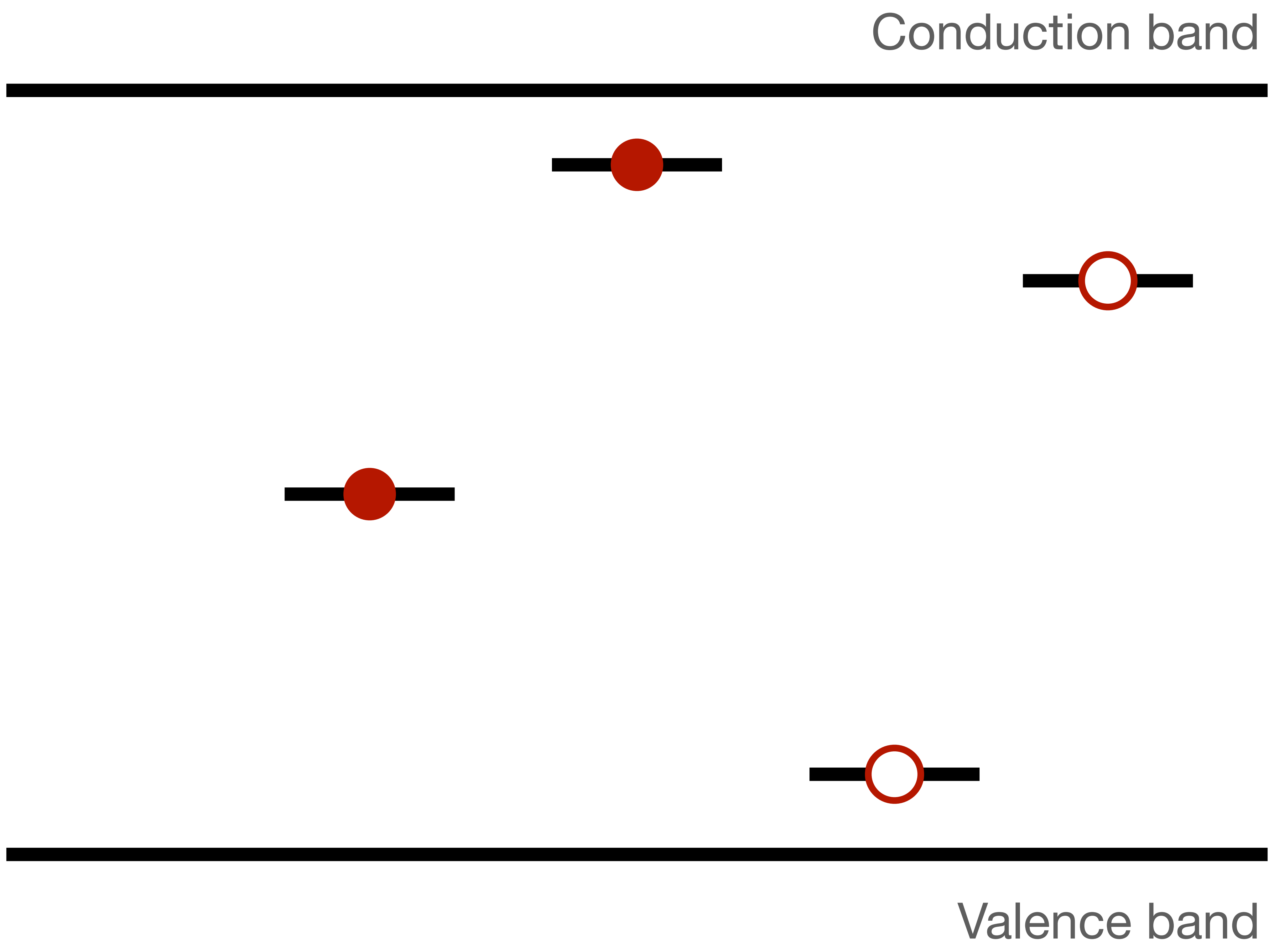

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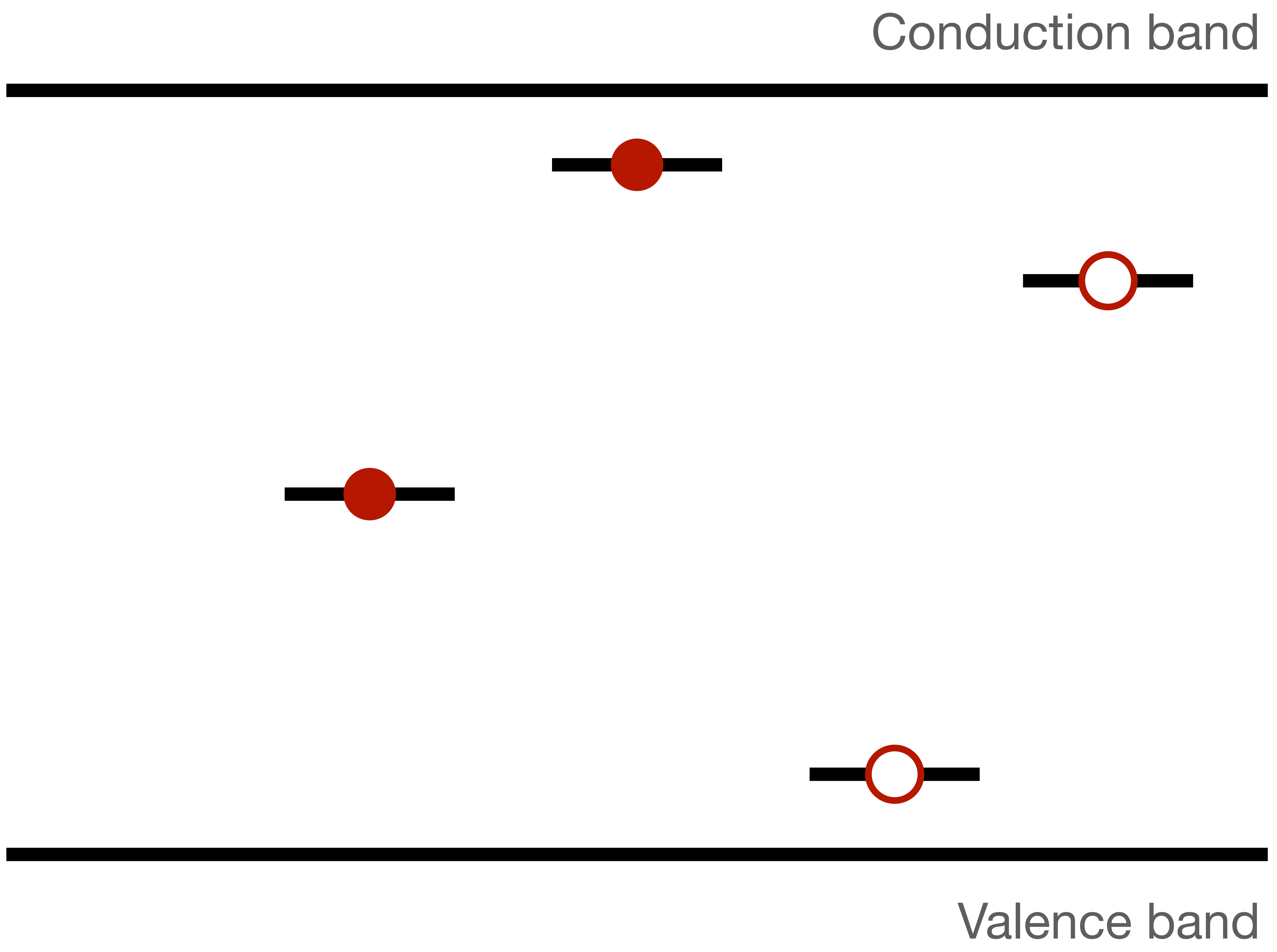

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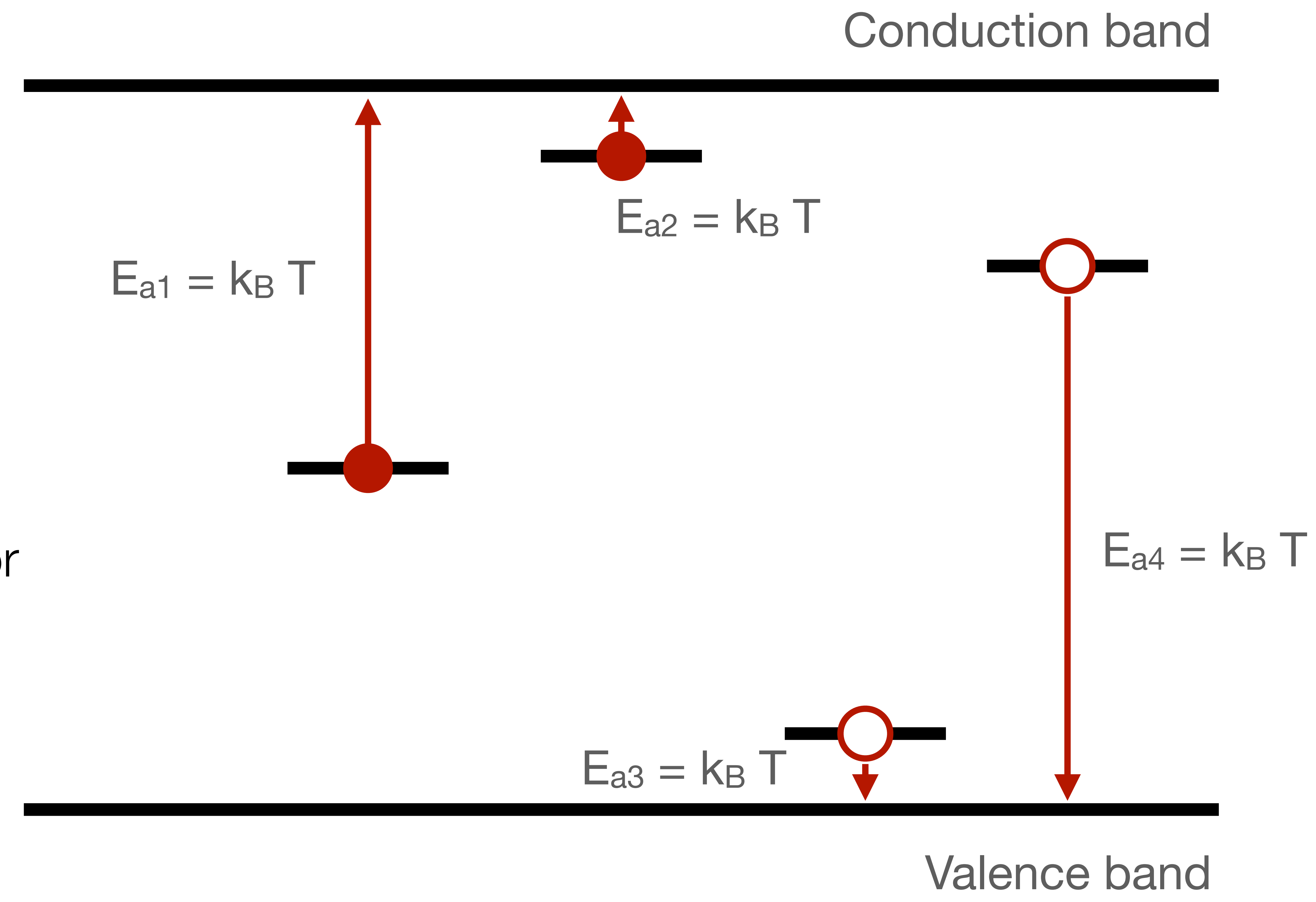
  - Apply a reverse bias to the sample
  - Increase the temperature at a fixed rate and look for current peaks



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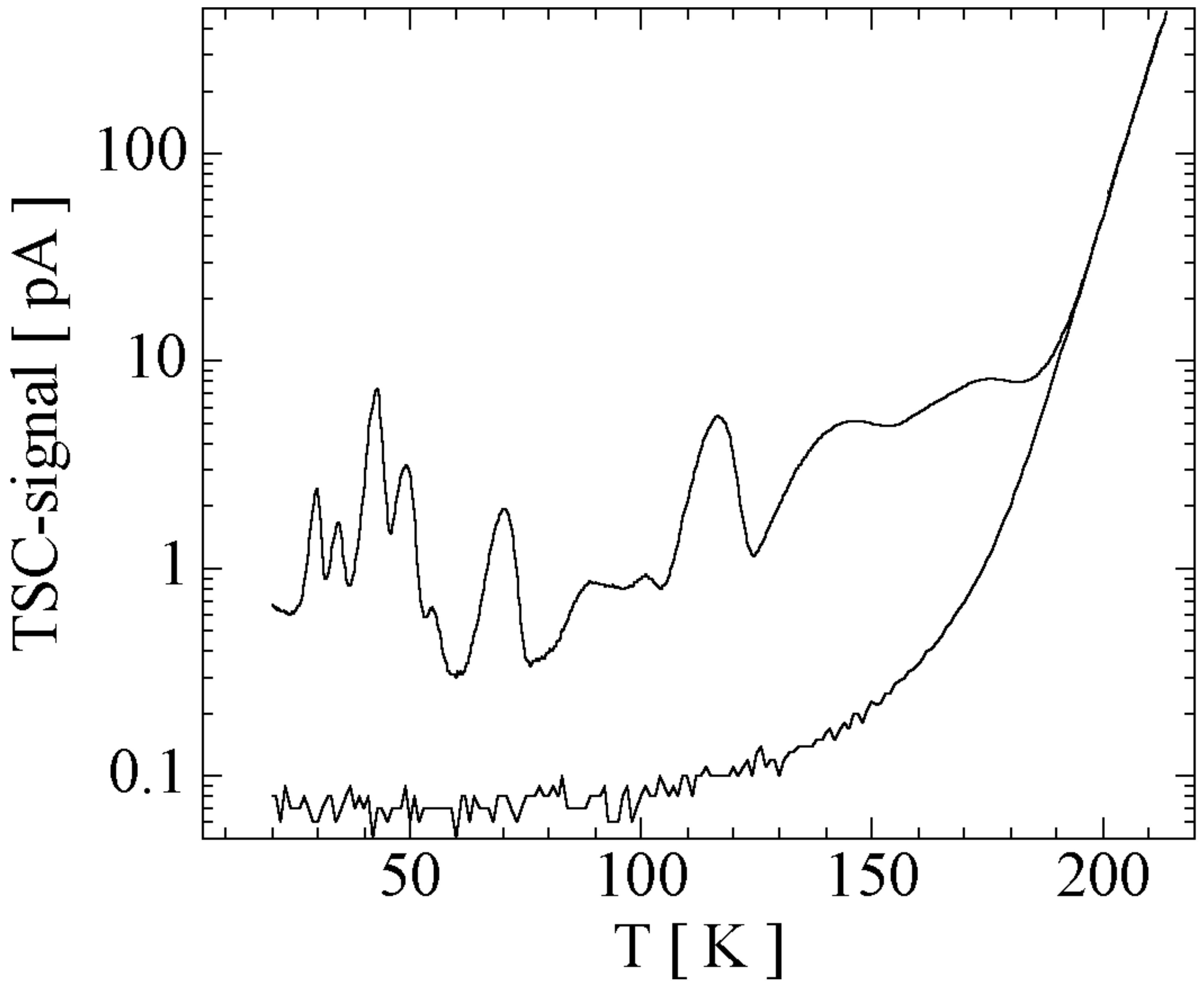
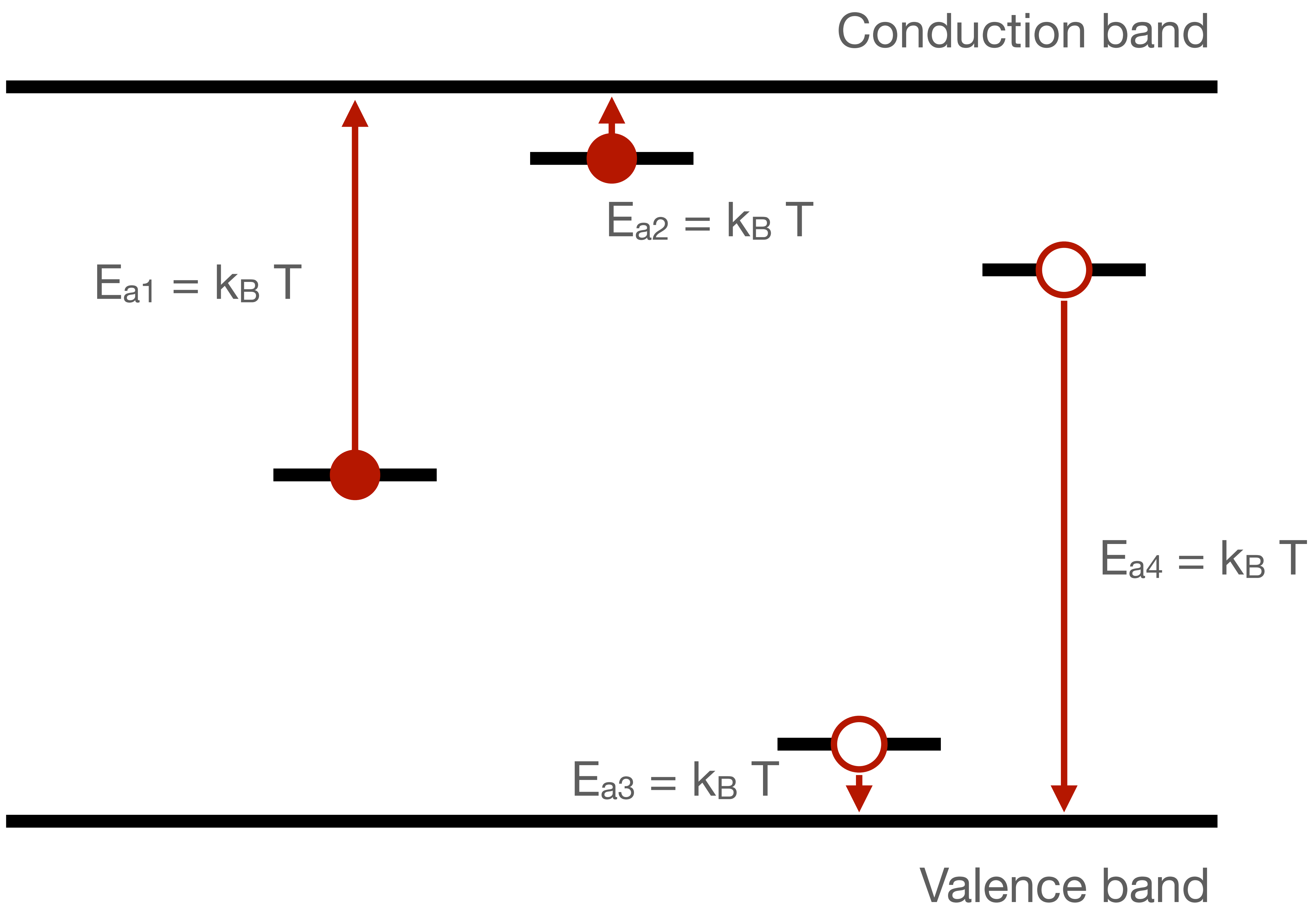
M.Moll, PhD thesis, 1999



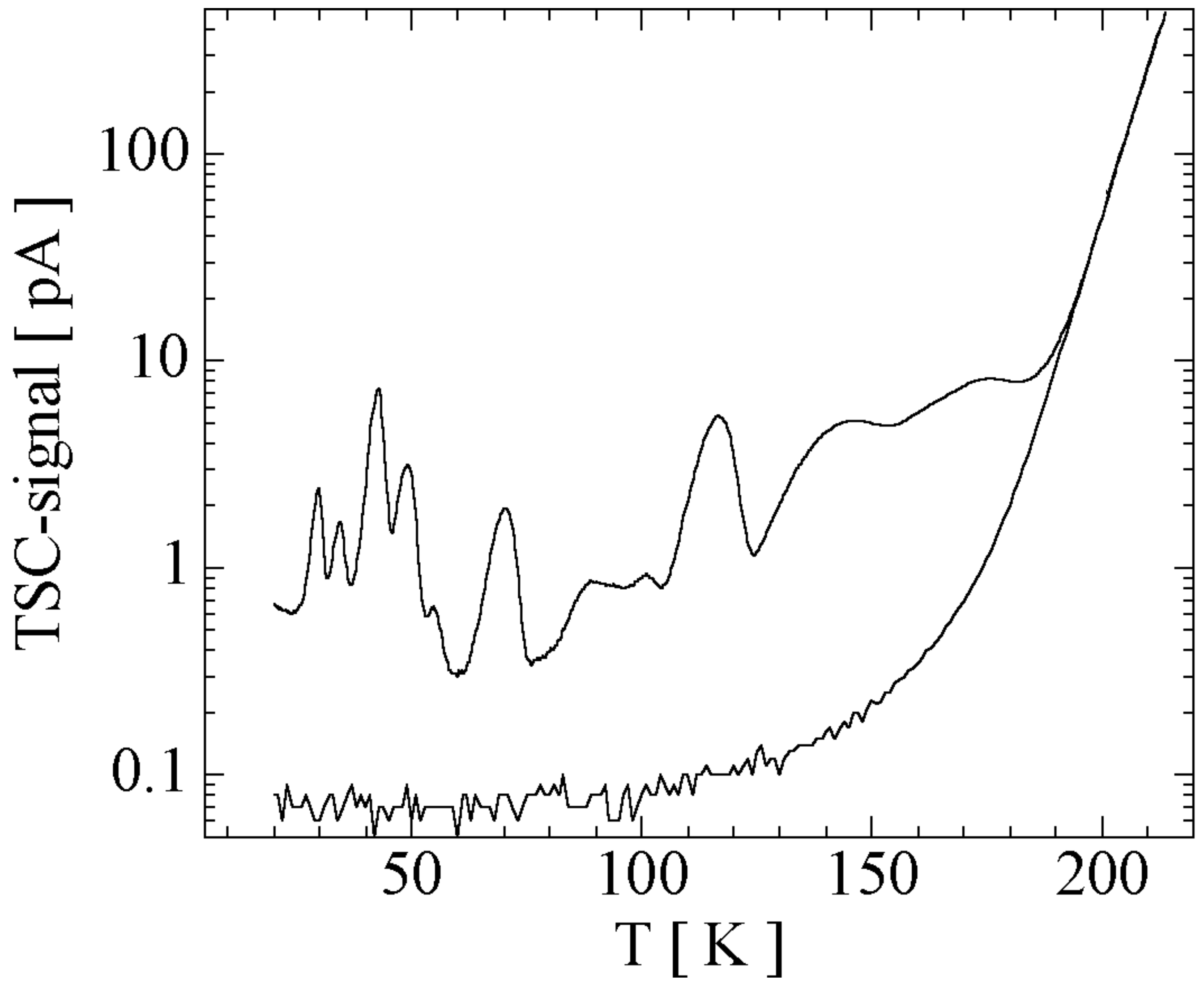


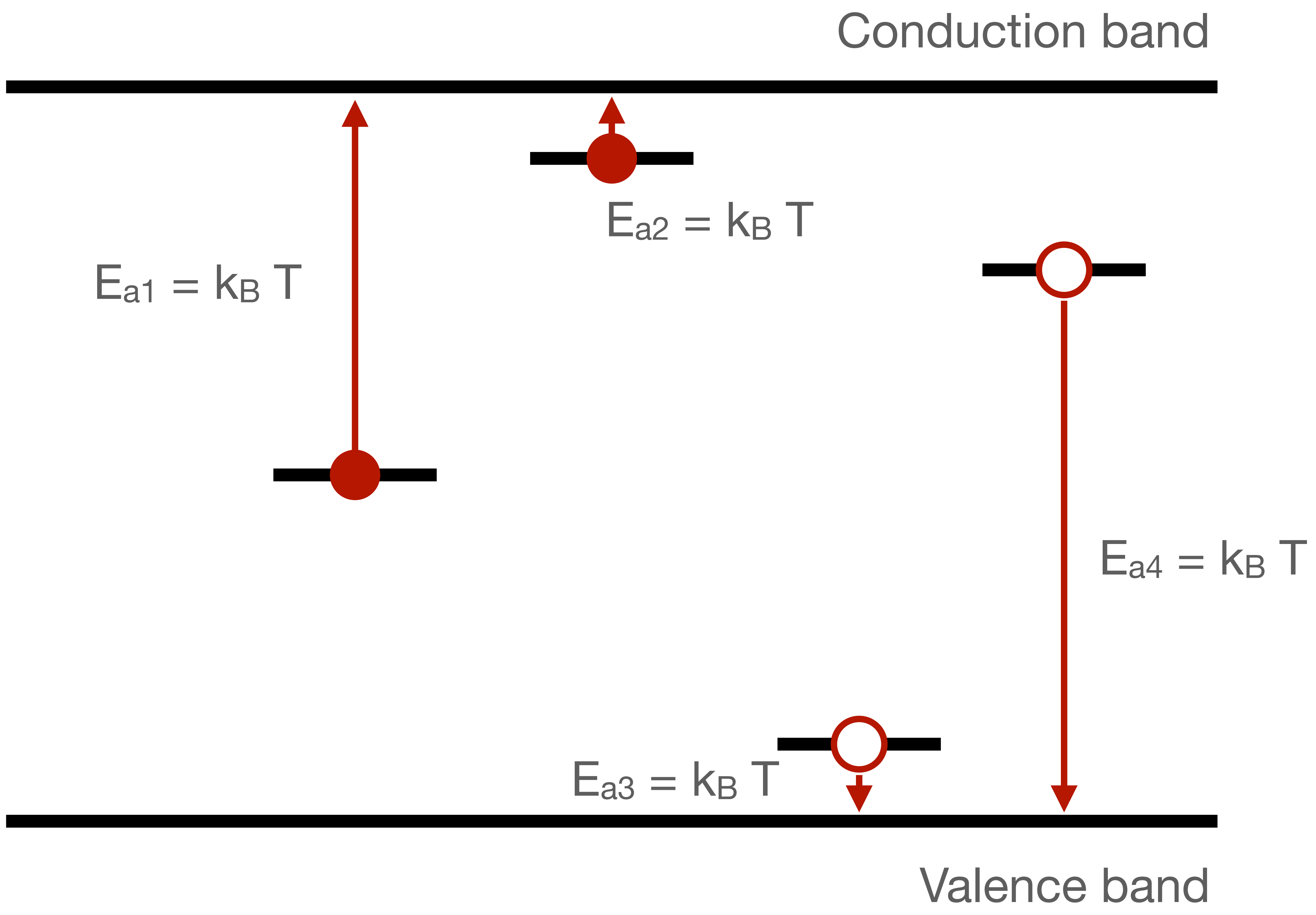
TSC - *nota bene*

M.Moll, PhD thesis, 1999

Something to note about TSC:

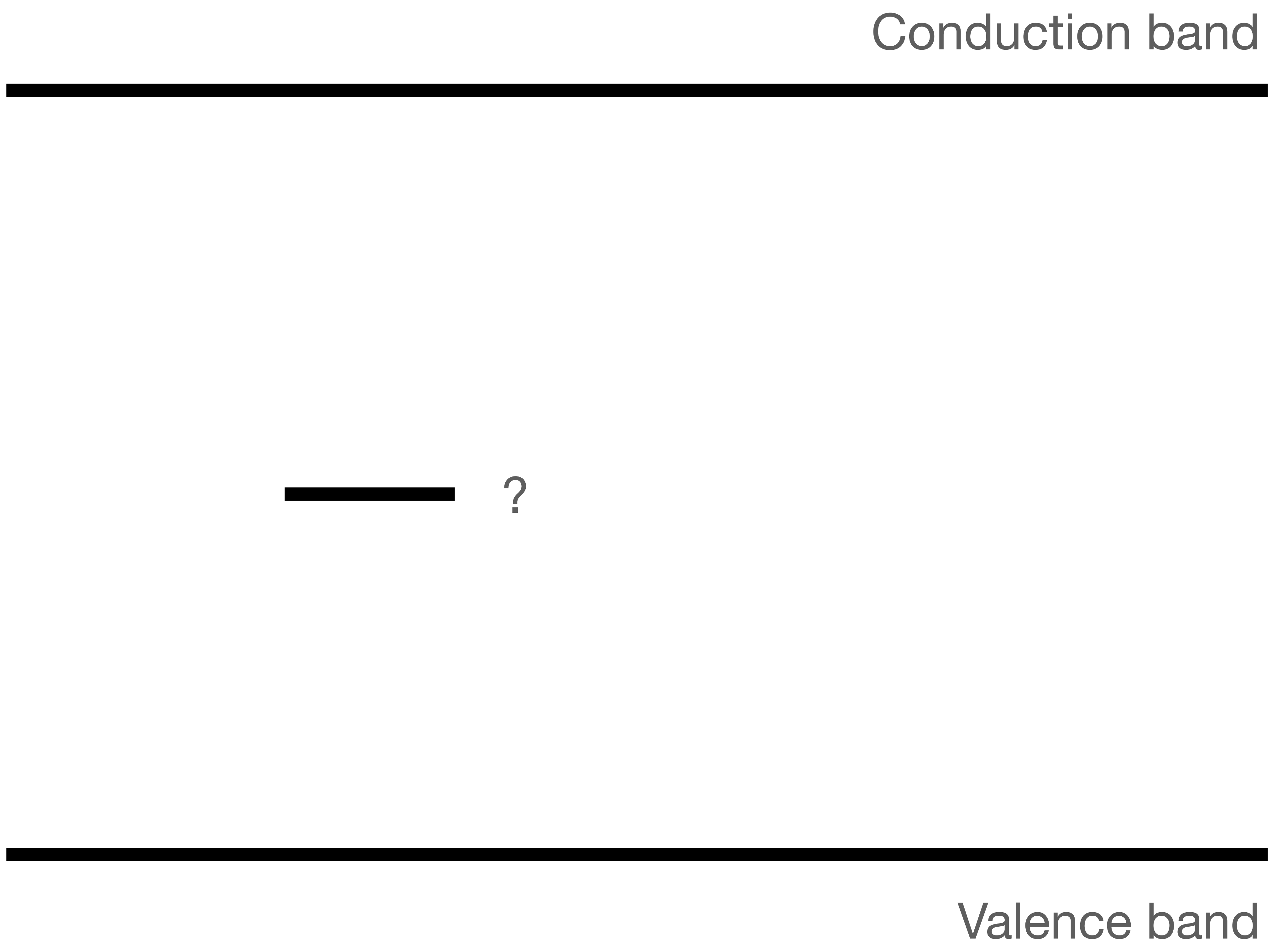
- We can measure the defect activation energy (roughly) and concentration, but we **do not know if they are electron or hole traps**; we only see the total current
- To investigate this we need more techniques (DLTS…)





Filling the traps

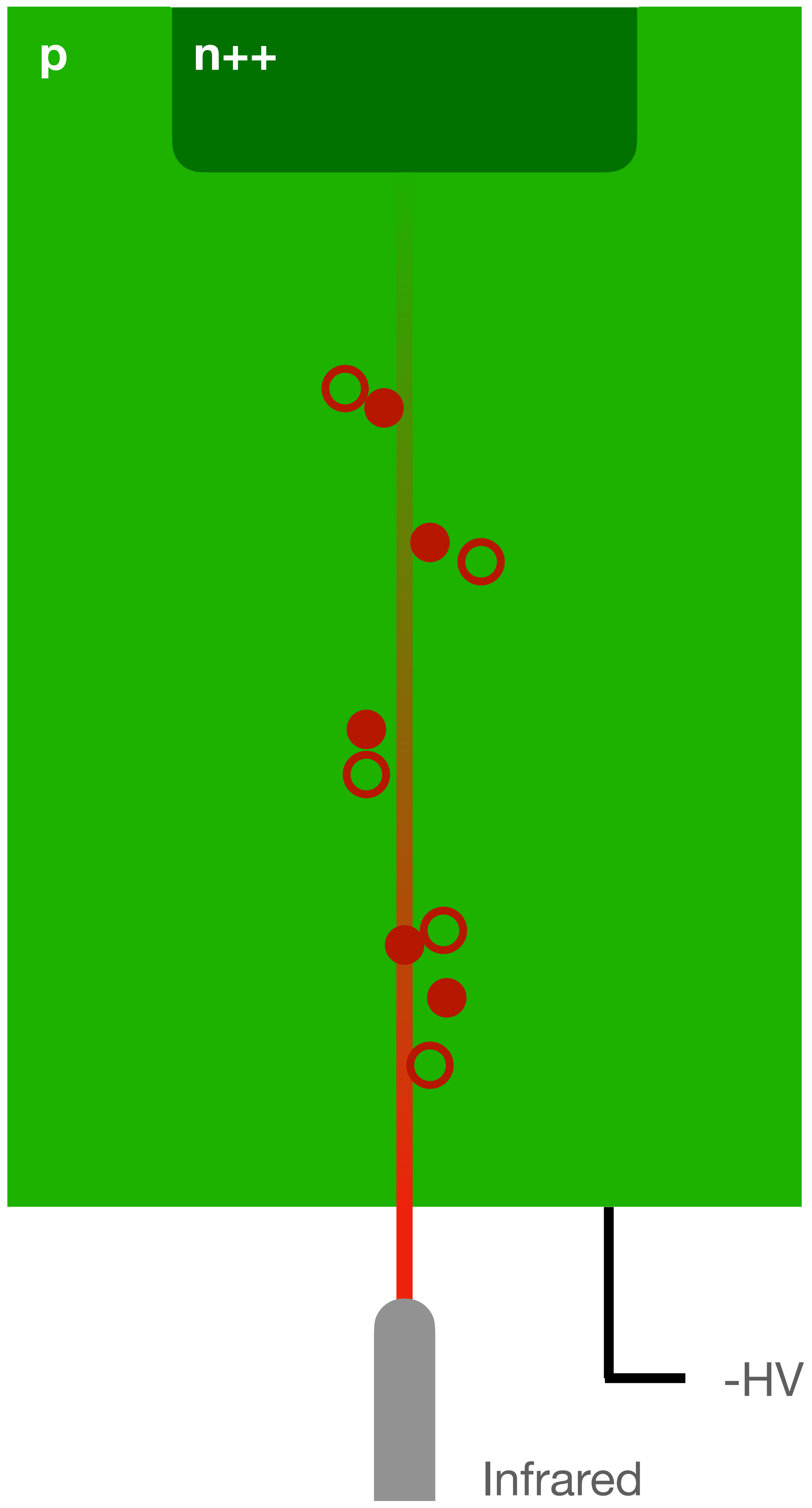
How do we fill the traps at low energy?



Filling the traps - optically

How do we fill the traps at low energy?

- One option is obviously to inject light on the sample
- Electron-hole pairs are generated along the path of the laser
- These charge carriers can be trapped by traps throughout the bulk (though some ambiguity if defects act as **both** donors and acceptors - filling will be by ratio of cross-sections)



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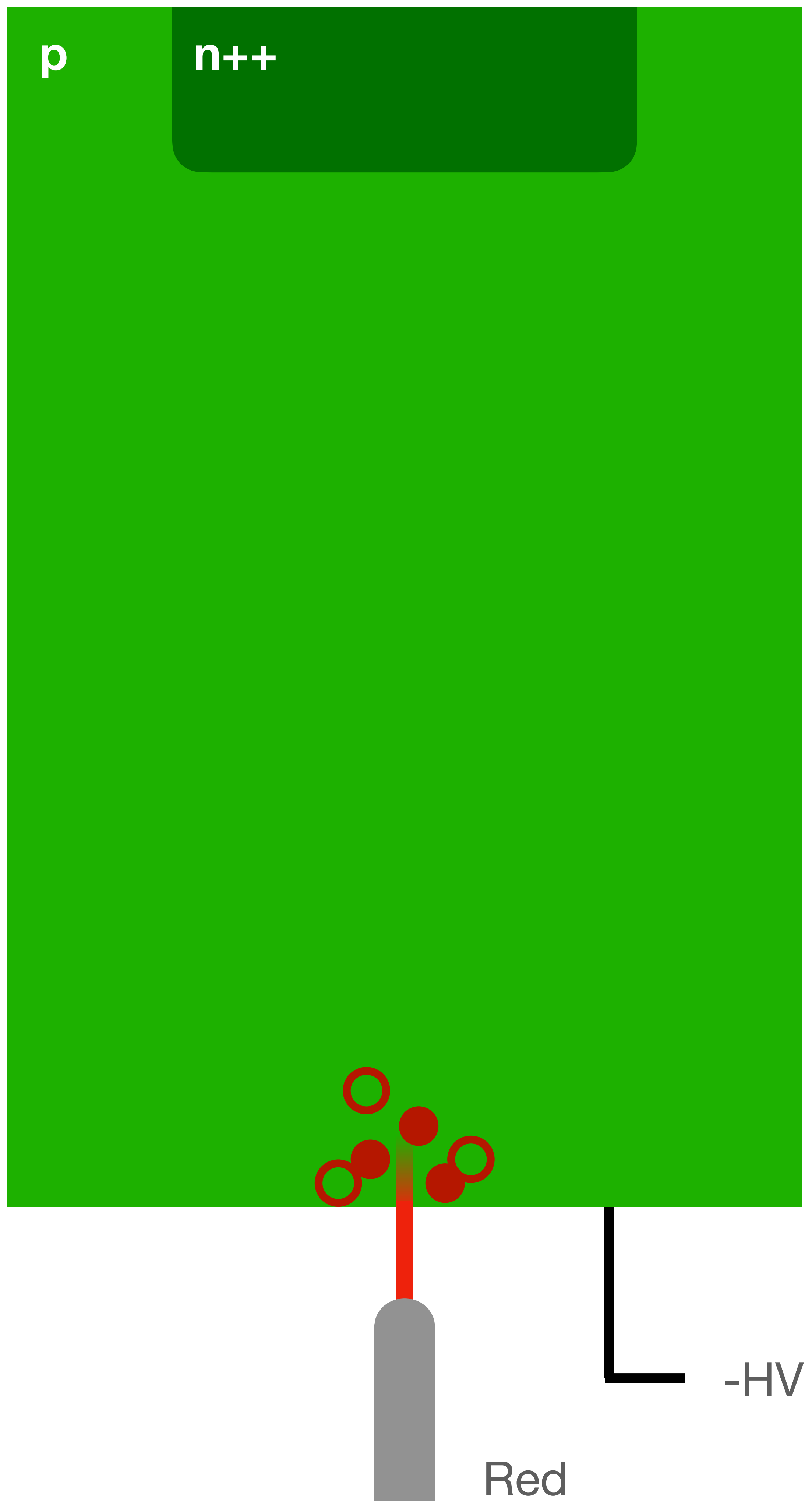
How do we fill the traps at low energy?

- Using a shorter wavelength laser with limited absorption depth can also be a very useful technique



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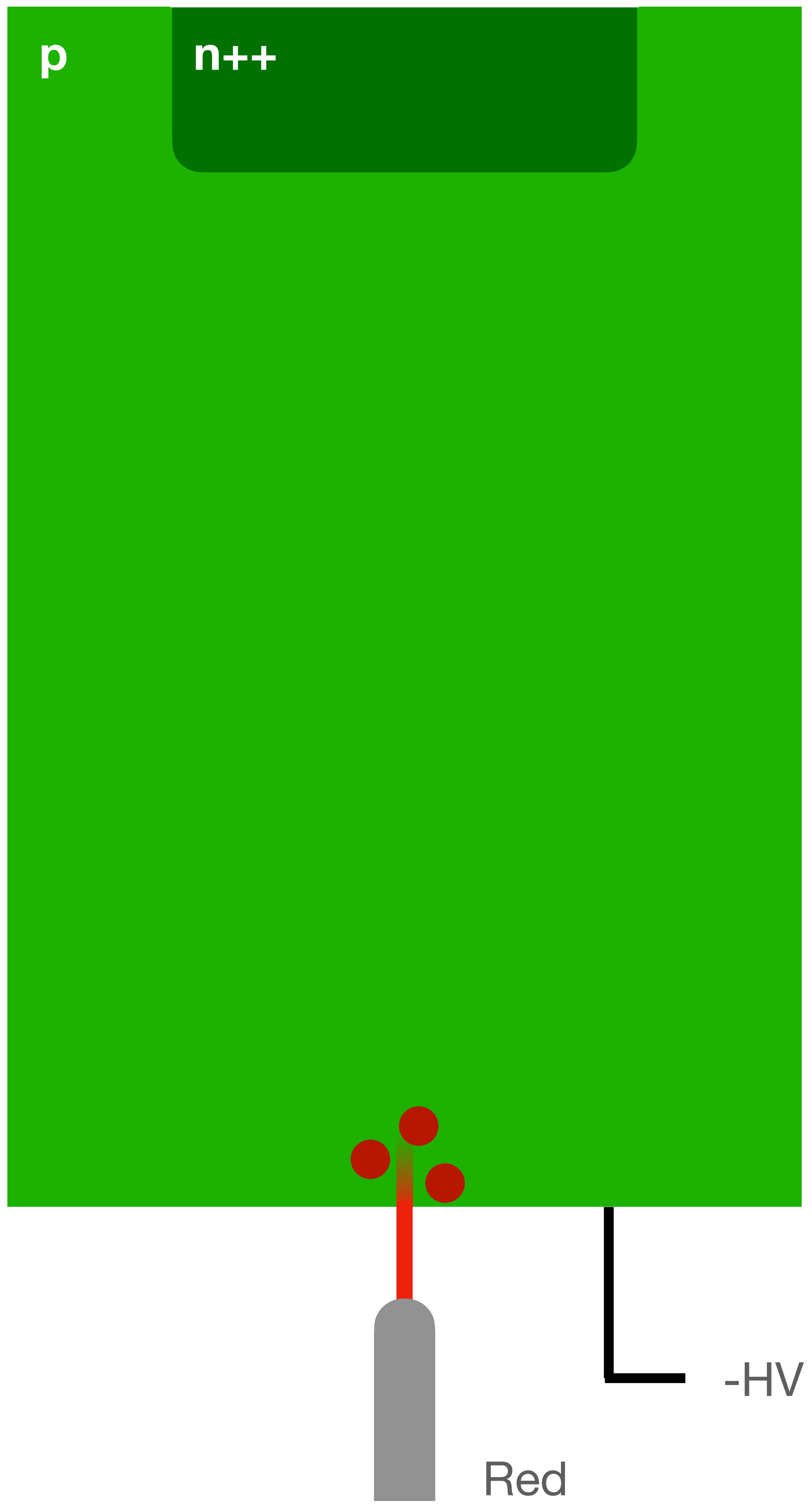

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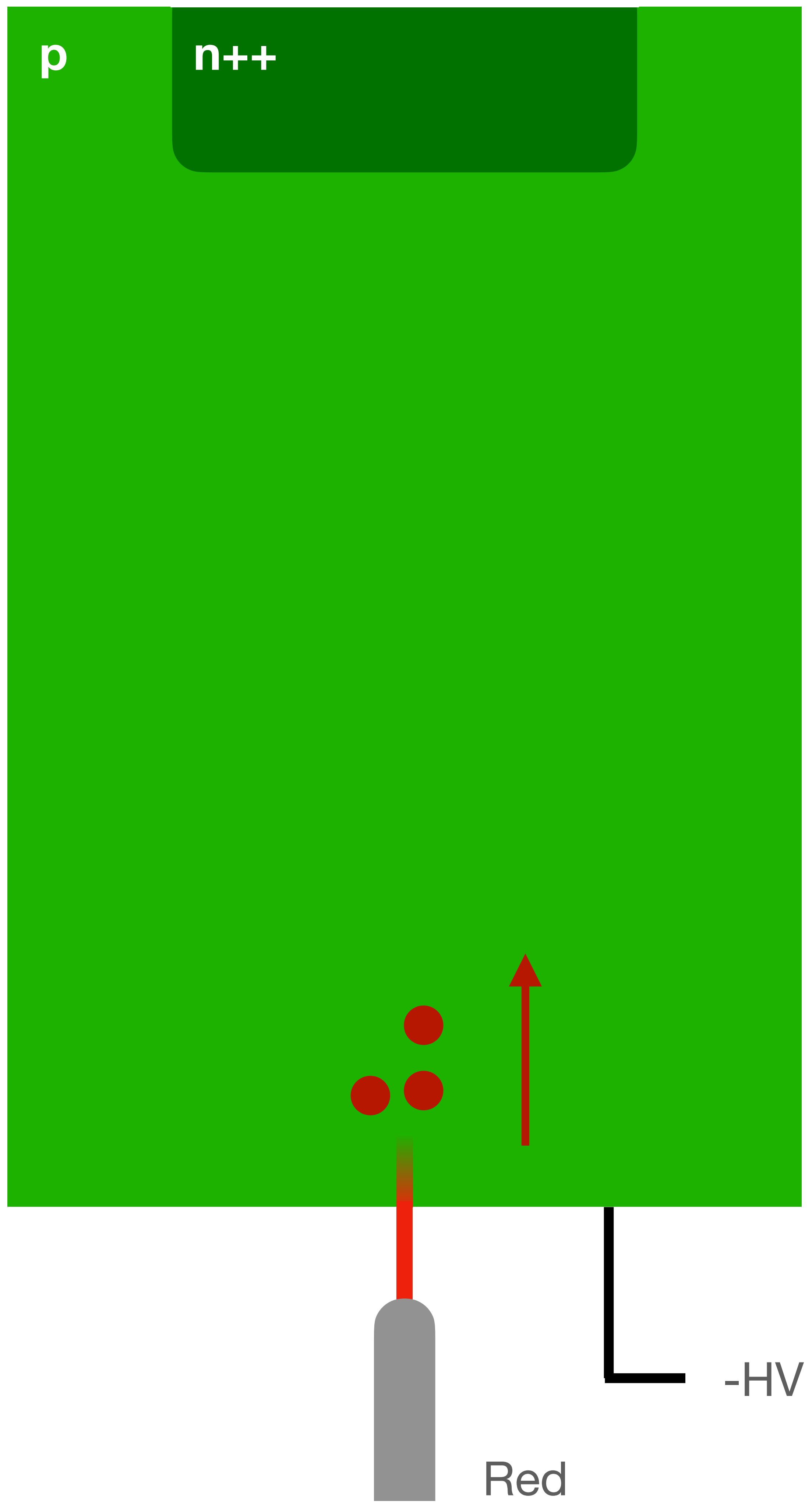

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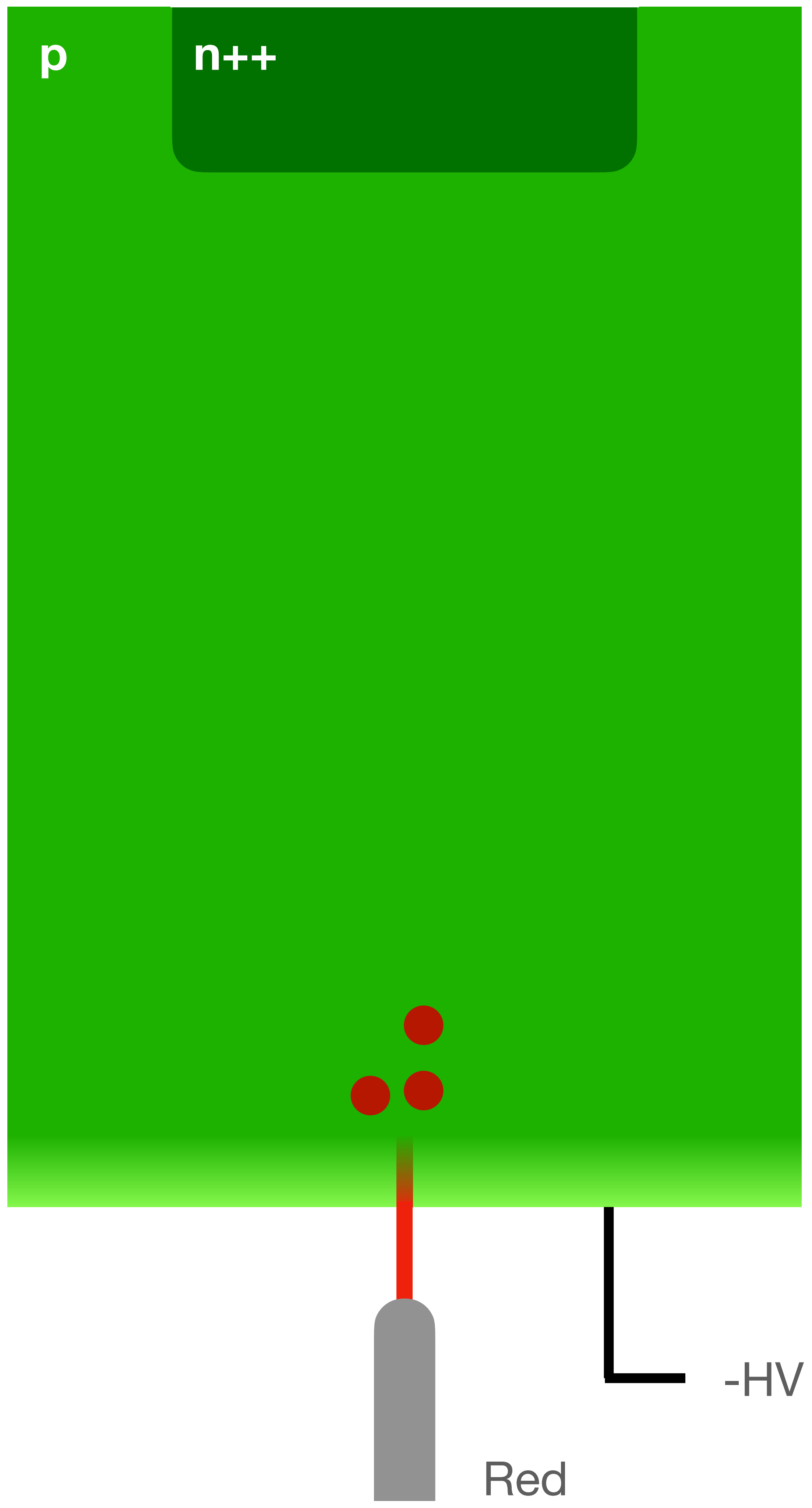
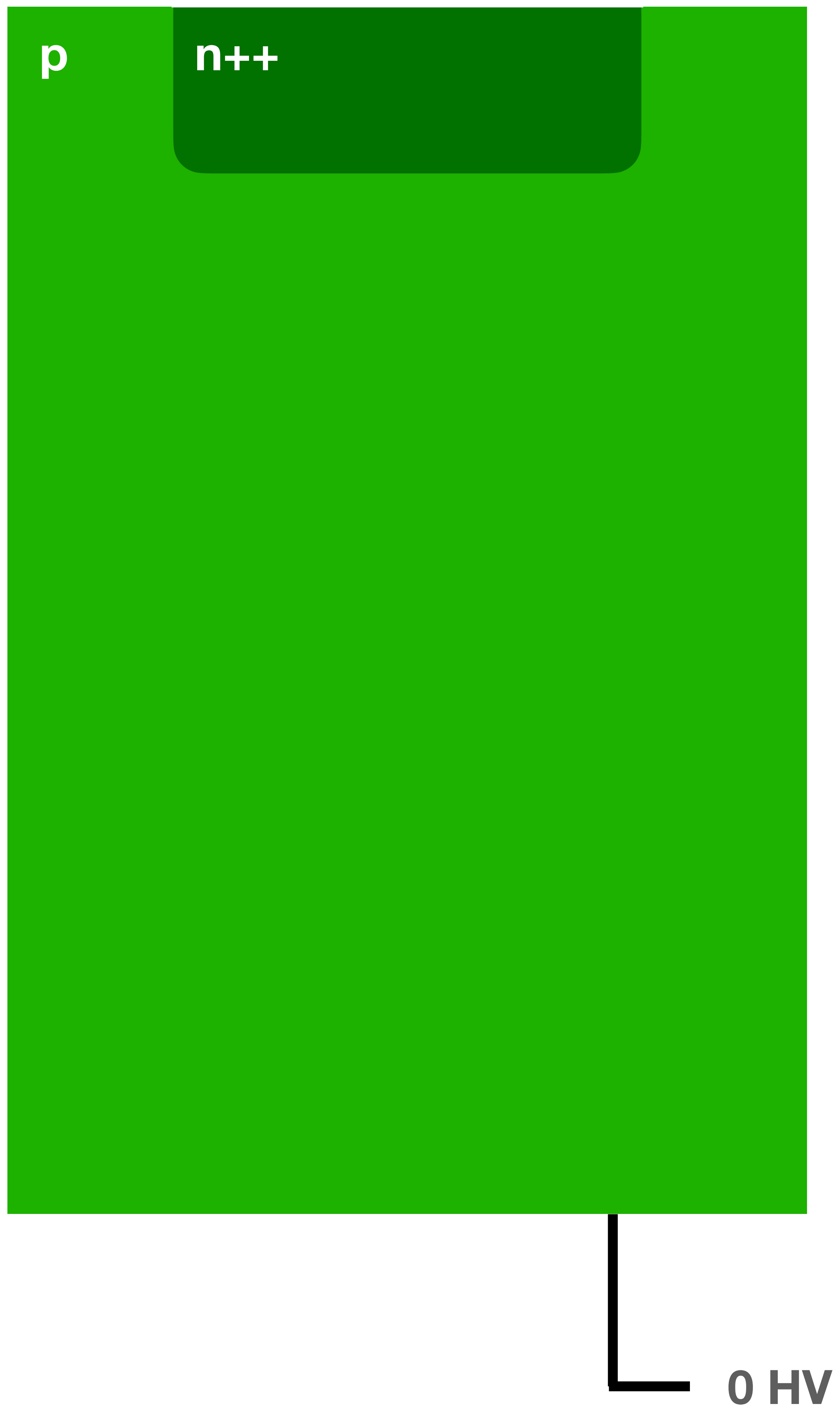
- Be aware that depending on the interaction length of the laser, you may be filling some of the opposing traps!



Filling the traps - zero bias

How do we fill the traps at low energy?

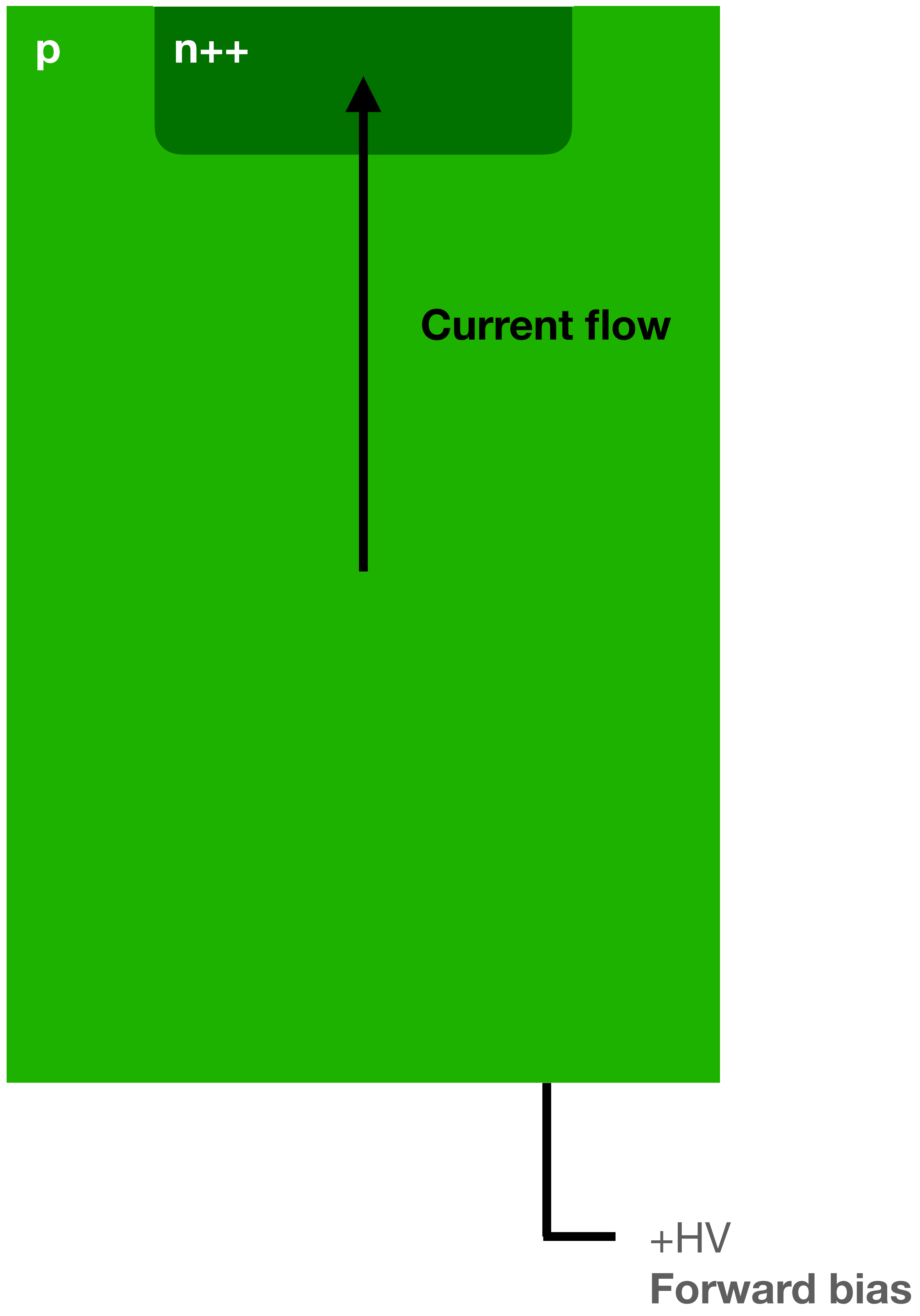
- We don't - fill them at high energy!
- If the device has 0 applied field and is cooled down, then the traps will be filled with majority carriers



Filling the traps - forward bias

How do we fill the traps at low energy?

- Forward bias the device!
- Carriers of both type will be injected through the sensor and occupy traps
- This has the same issue as penetrating laser illumination - defects that act as both donors and acceptors will be partially filled depending on their relative cross-sections for holes and electrons

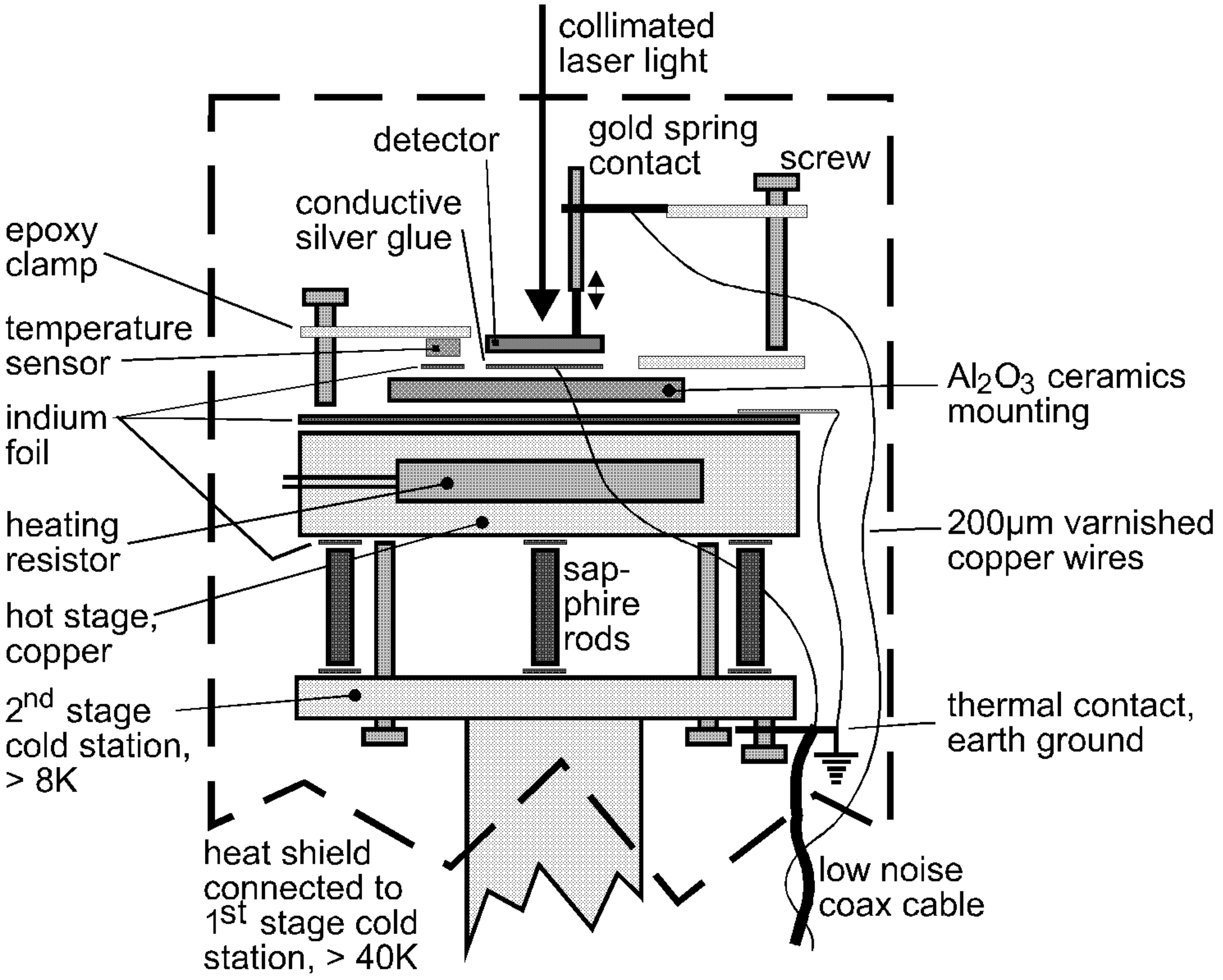


TSC/DLTS in the flesh

M.Moll, PhD thesis, 1999

What does the TSC setup look like in reality?

- "Simply" a controlled temperature chuck with contacts for connecting the sensor
- A hole for laser light injection (in the case of optical trap filling)
- Lots of low-noise electronics and isolation



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F.Hönniger, PhD thesis, 2007

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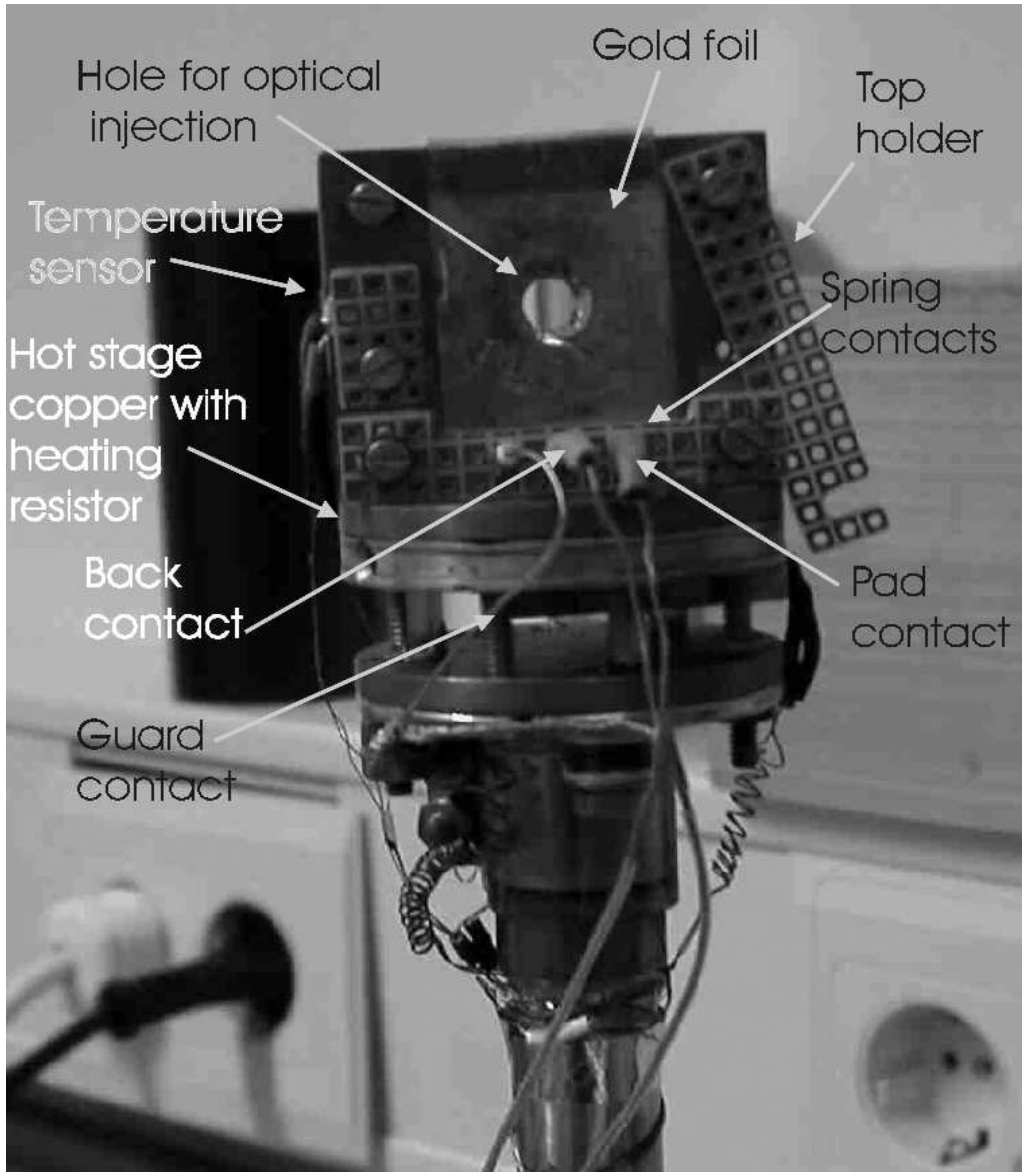
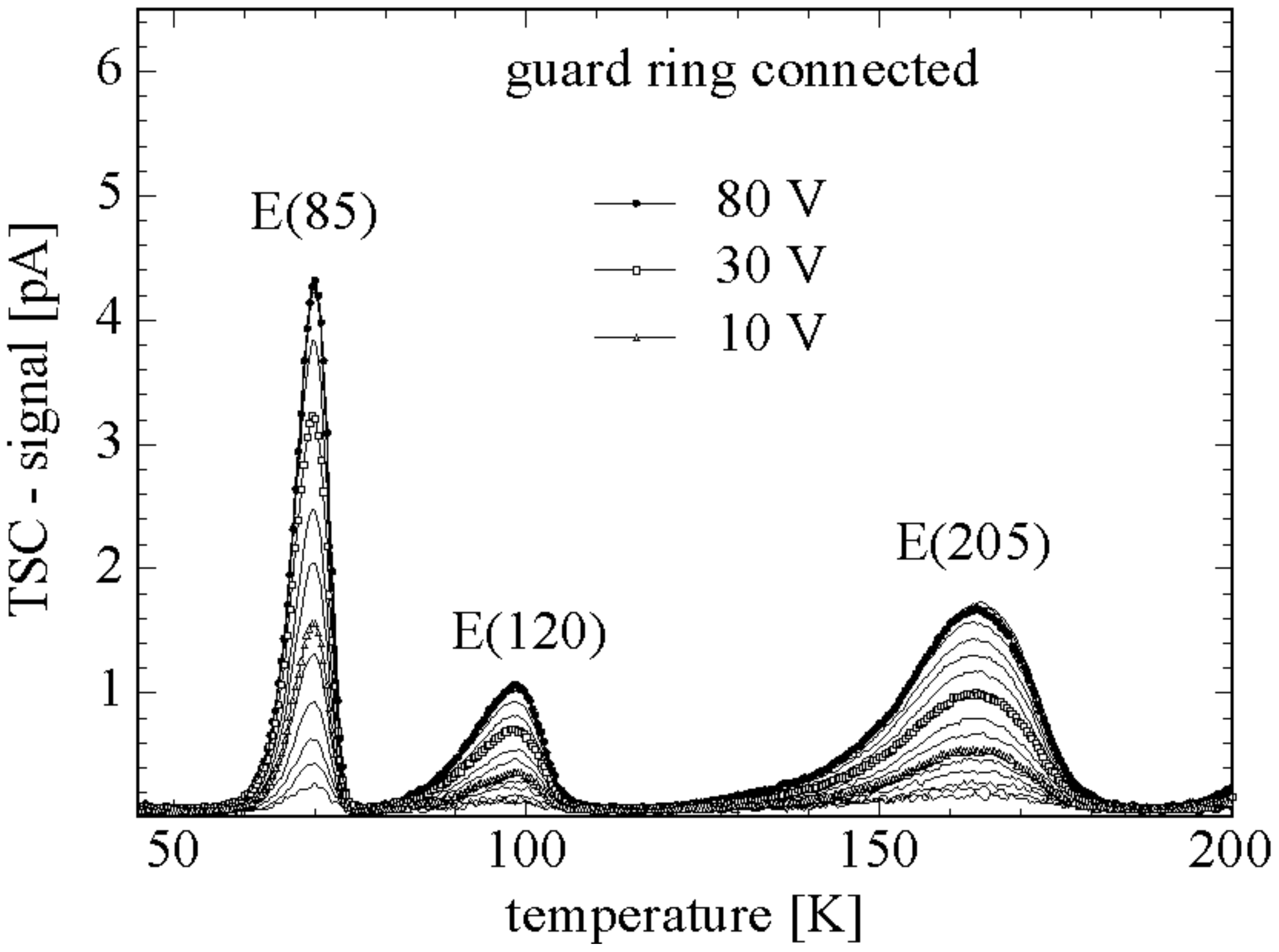


Typical TSC measurement

M.Moll, PhD thesis, 1999

Thesis from M.Moll is well worth reading (in general) - huge amount of detail on radiation damage and measurements of different defects

- Plot on the right shows a typical TSC measurement on an irradiated diode
- Sample was cooled with no bias voltage applied, so only electron traps are probed (n-type bulk material)
- **Shallow (phosphorous) bulk donor has higher concentration than electron traps for this fluence => all traps are occupied**



TSC - delayed heating

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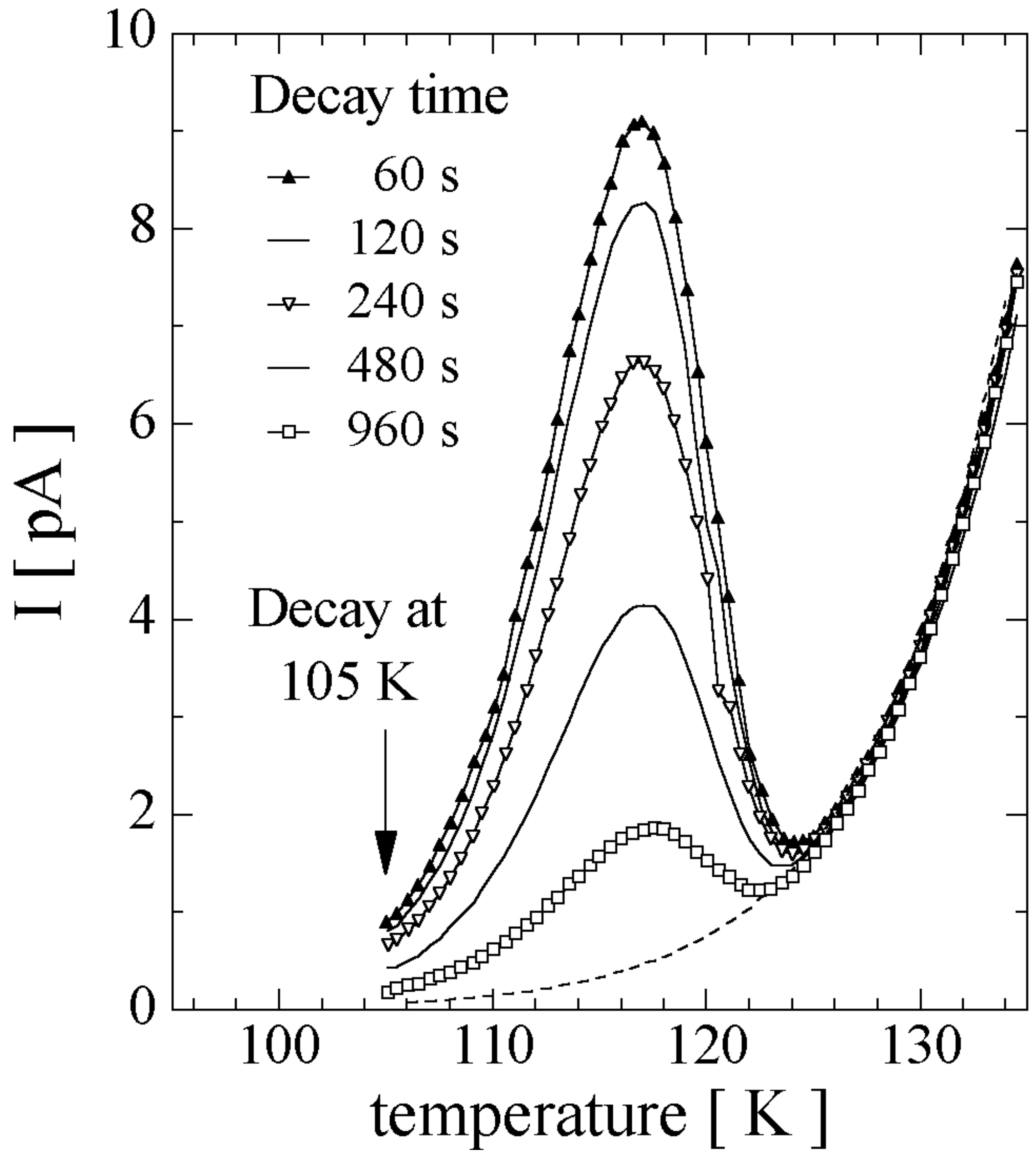

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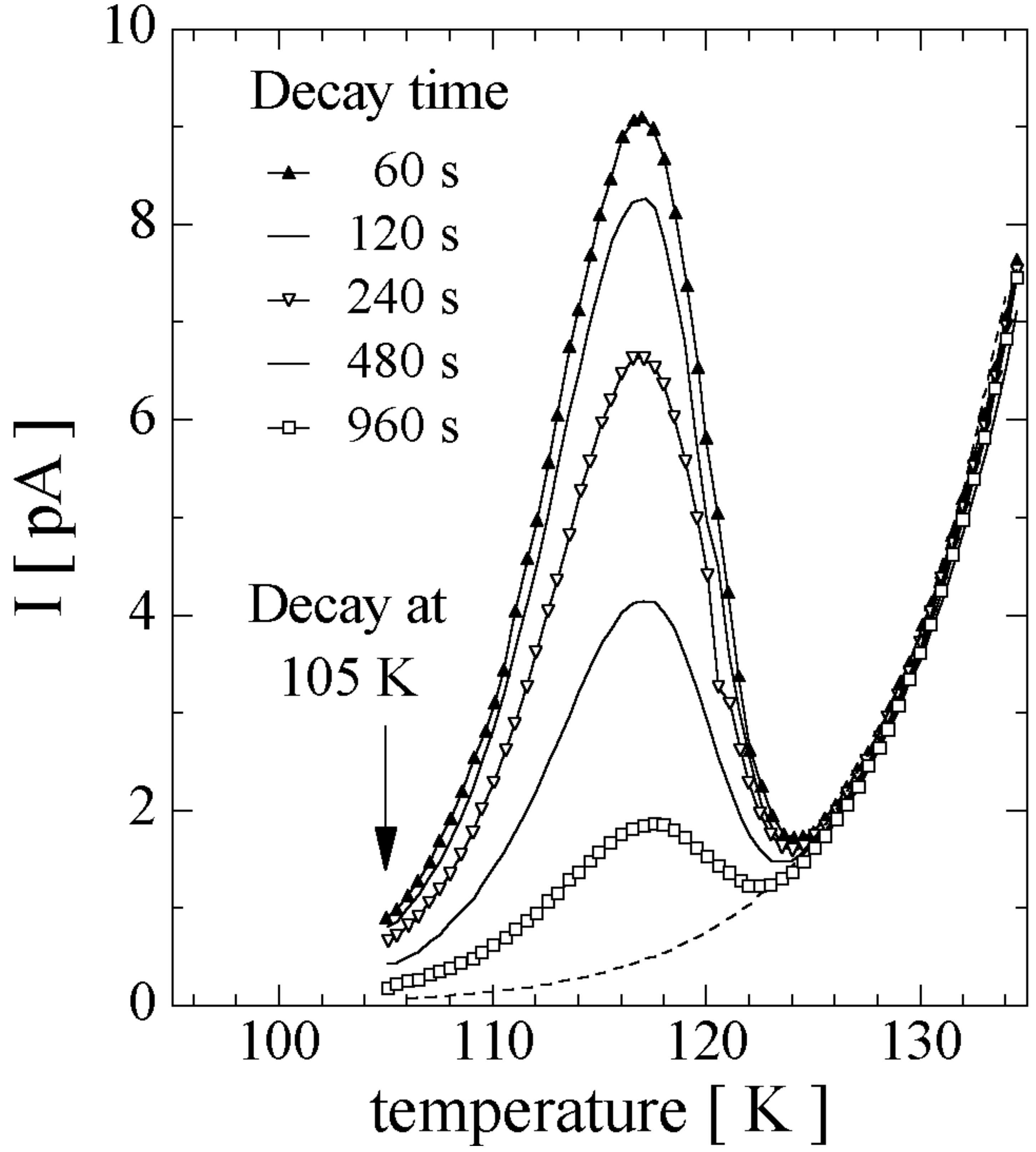

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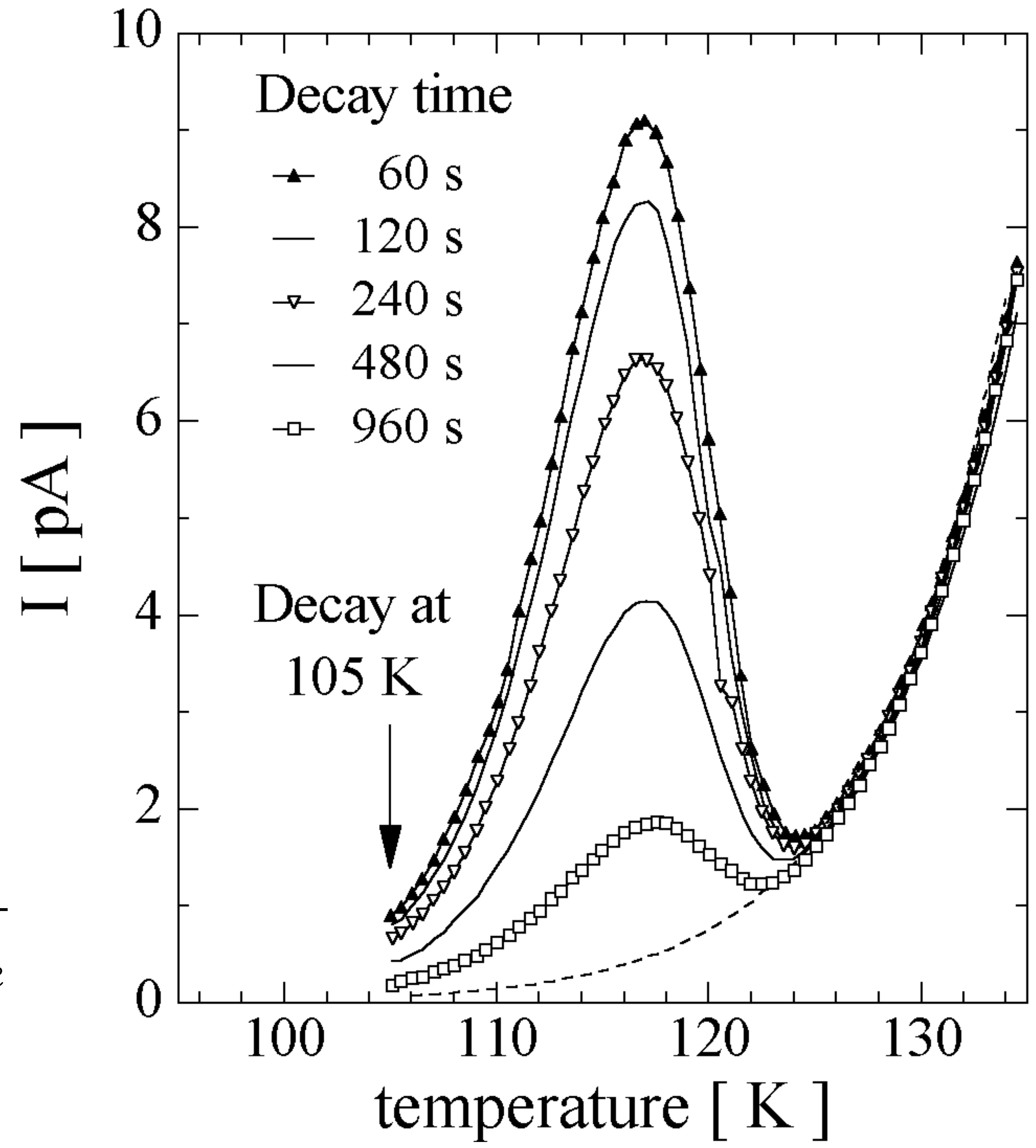

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- For a single filling temperature, perform measurements after different delays
- Extract the emission time

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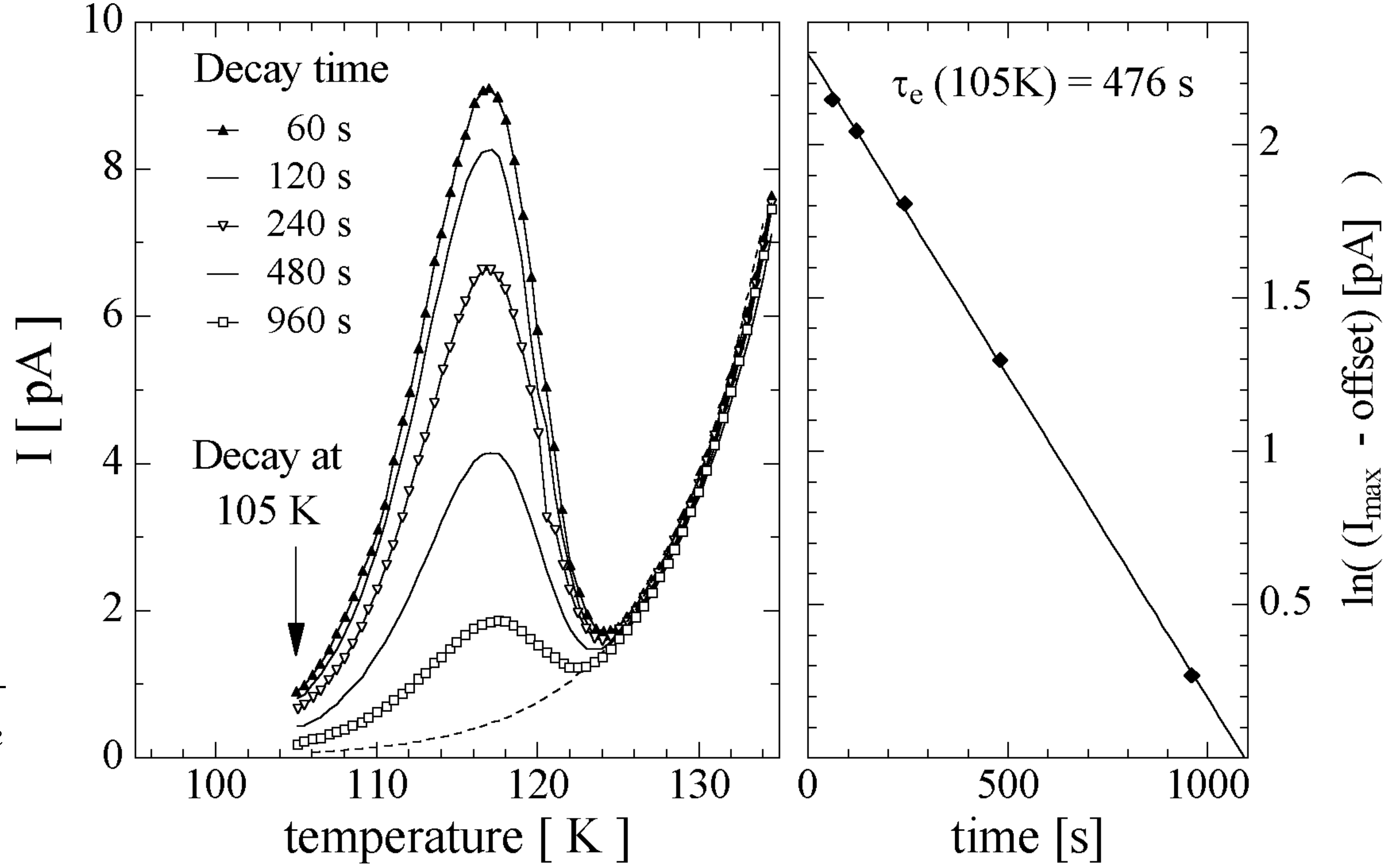
$$ln(N) = ln(N_0) - k_T t \qquad ln(N) = ln(N_0) - \frac{t}{\tau_e}$$



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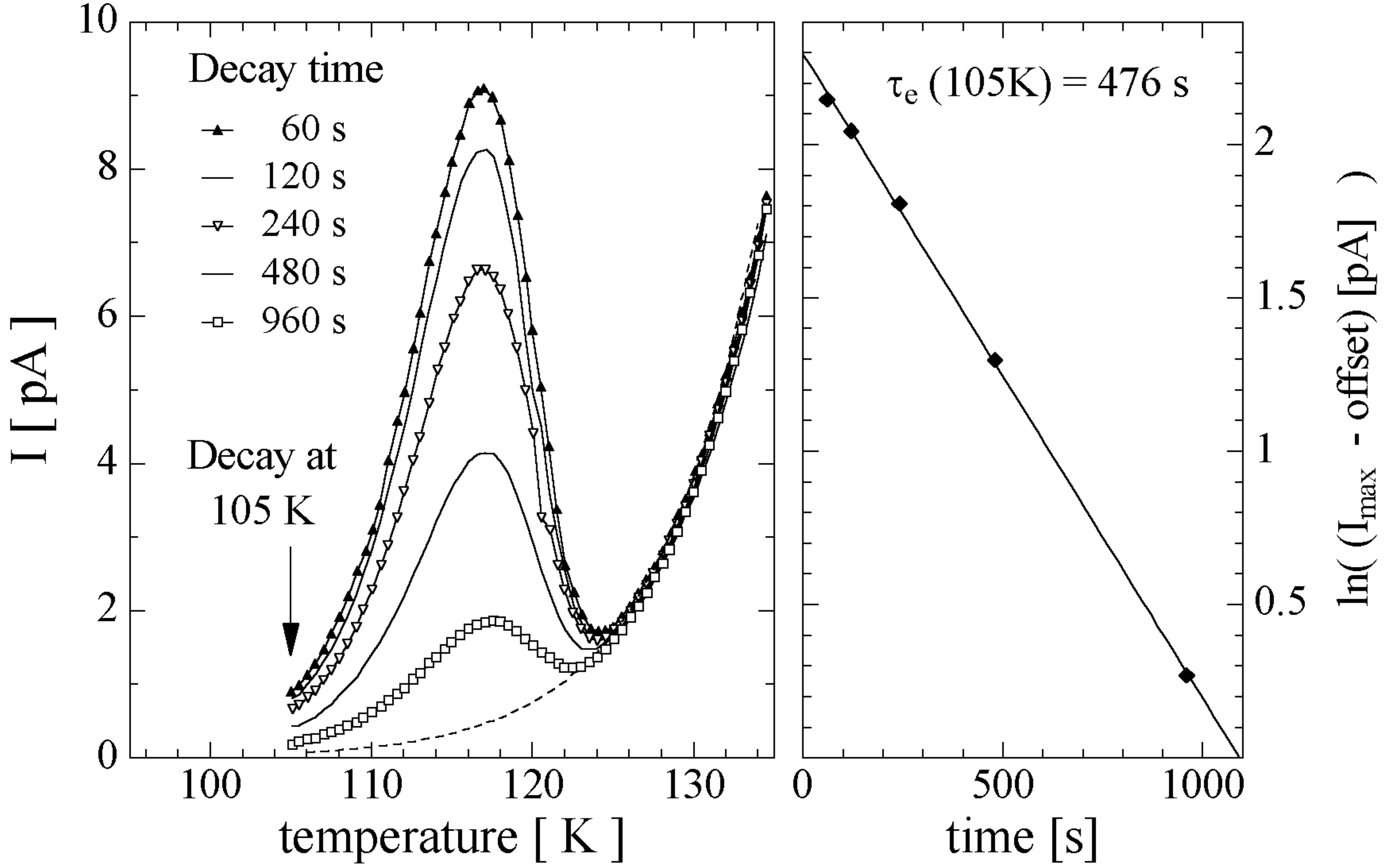

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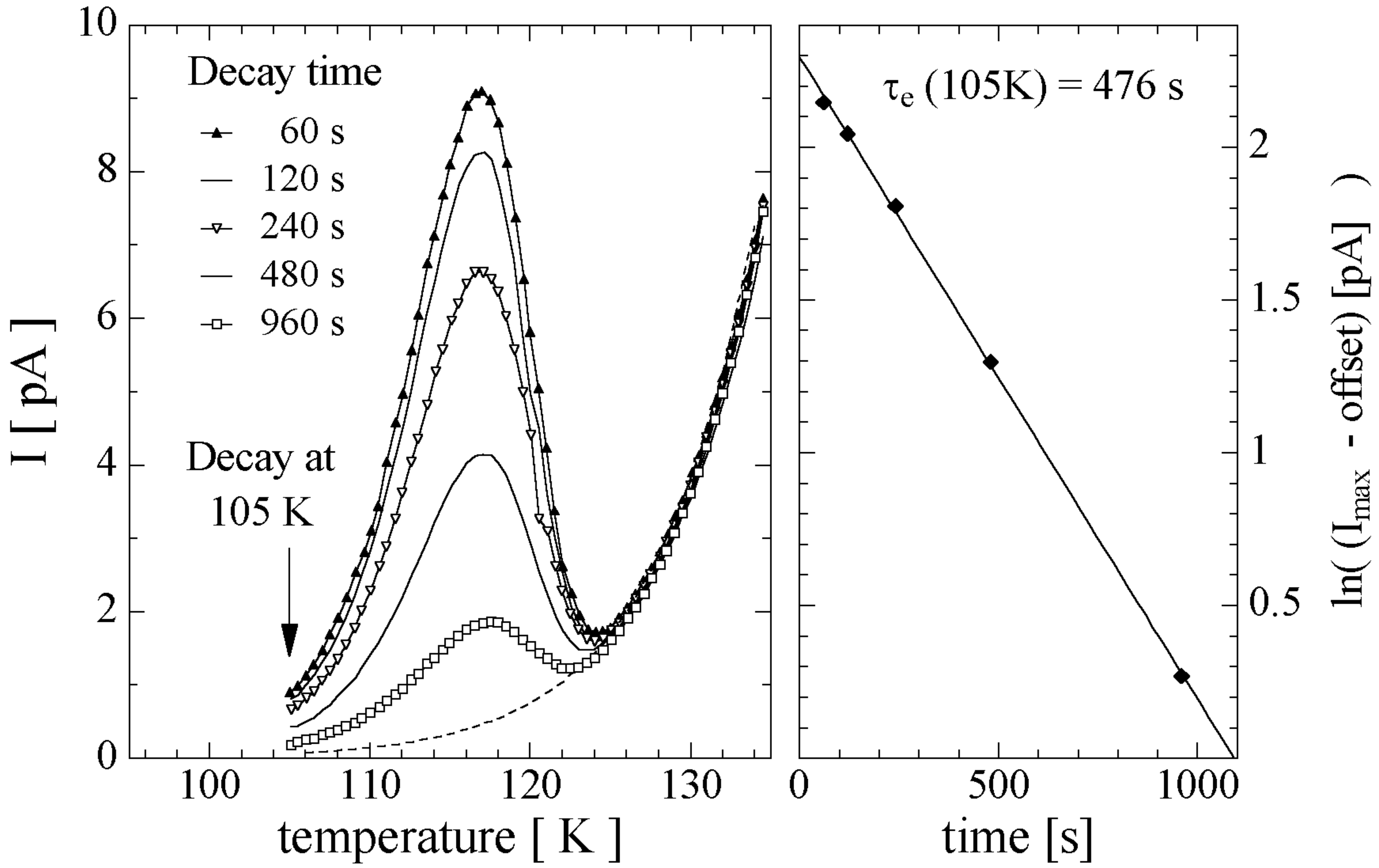

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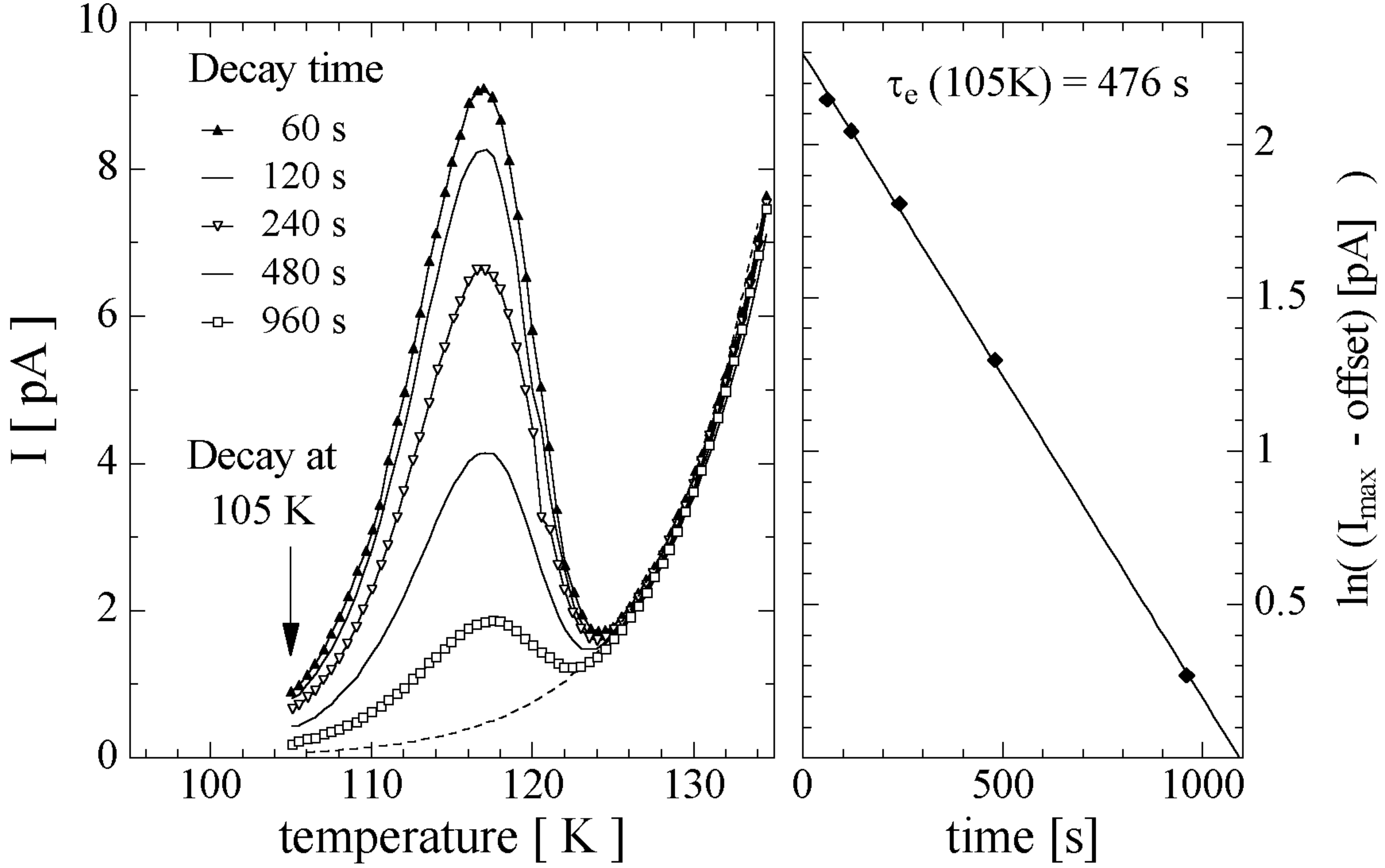
So measuring our emission time/rate constant at different temperatures allows us to extract the energy level of the trap:

$$ln(k_T) = ln(A) - \frac{E_a}{k_B}\frac{1}{T}$$



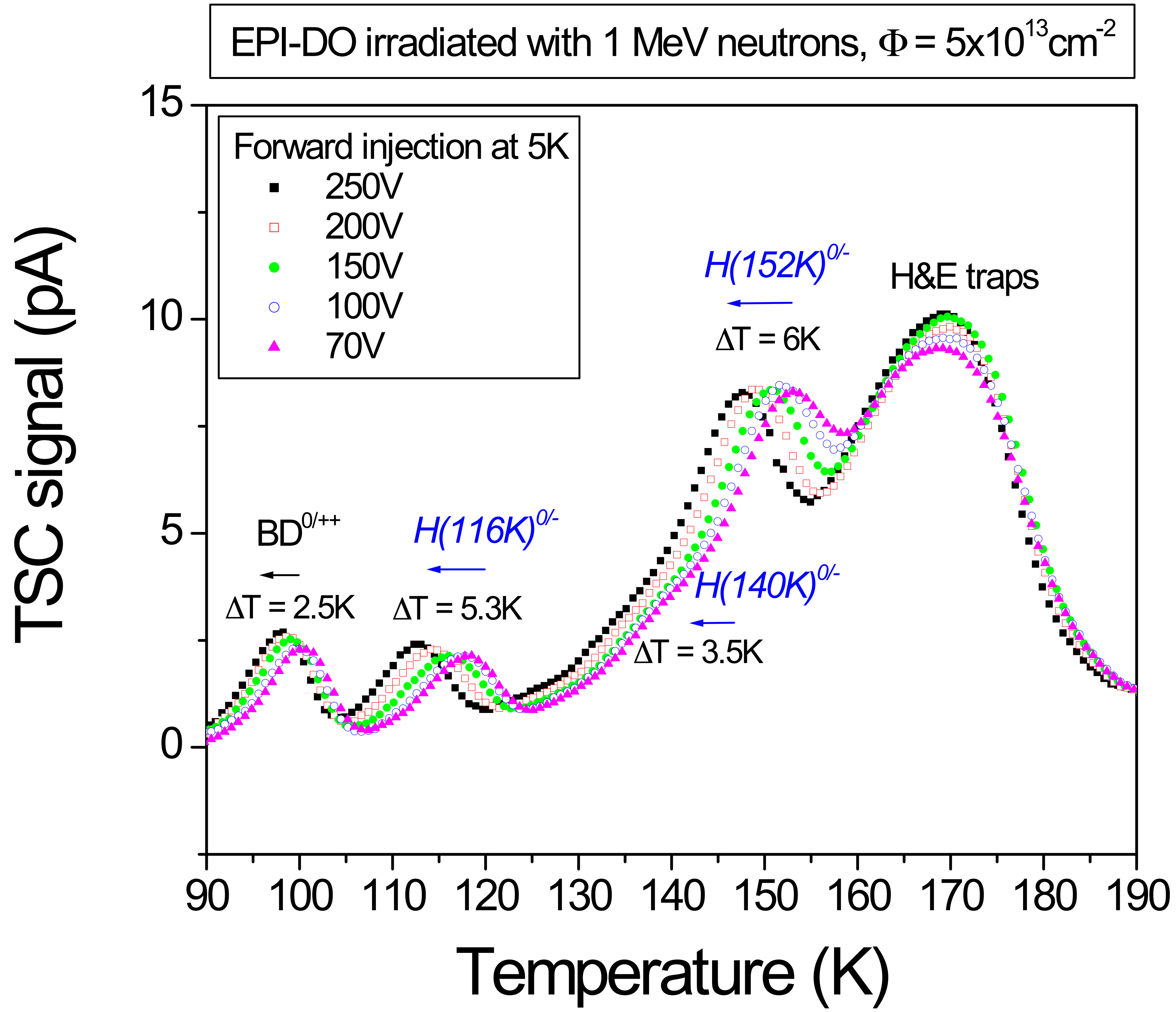
Field emission effect

Depending on the charge and type of the defect (and bulk), the departure of a charge carrier may be affected by the resulting space charge

- Eg. An electron emitted from a donor state in an n-type bulk leaves a positive charge

This energy barrier can be affected by the external bias: this is known as the **Poole-Frenkel effect**

- Measurements taken with different reverse biases can help to deduce the defect type, and extract the activation energy dependence on bias



TSC - electron/hole capture cross-section

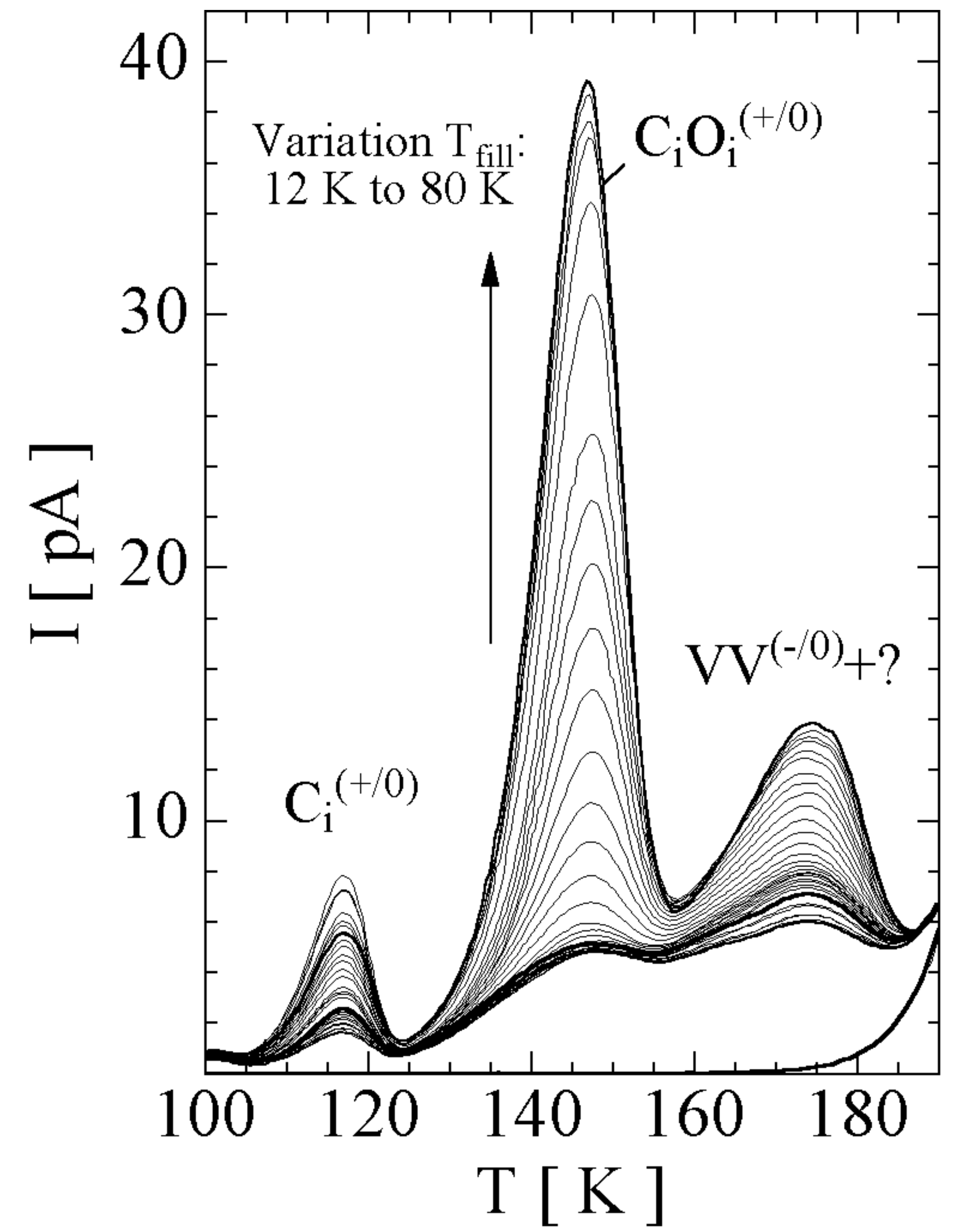
M.Moll, PhD thesis, 1999

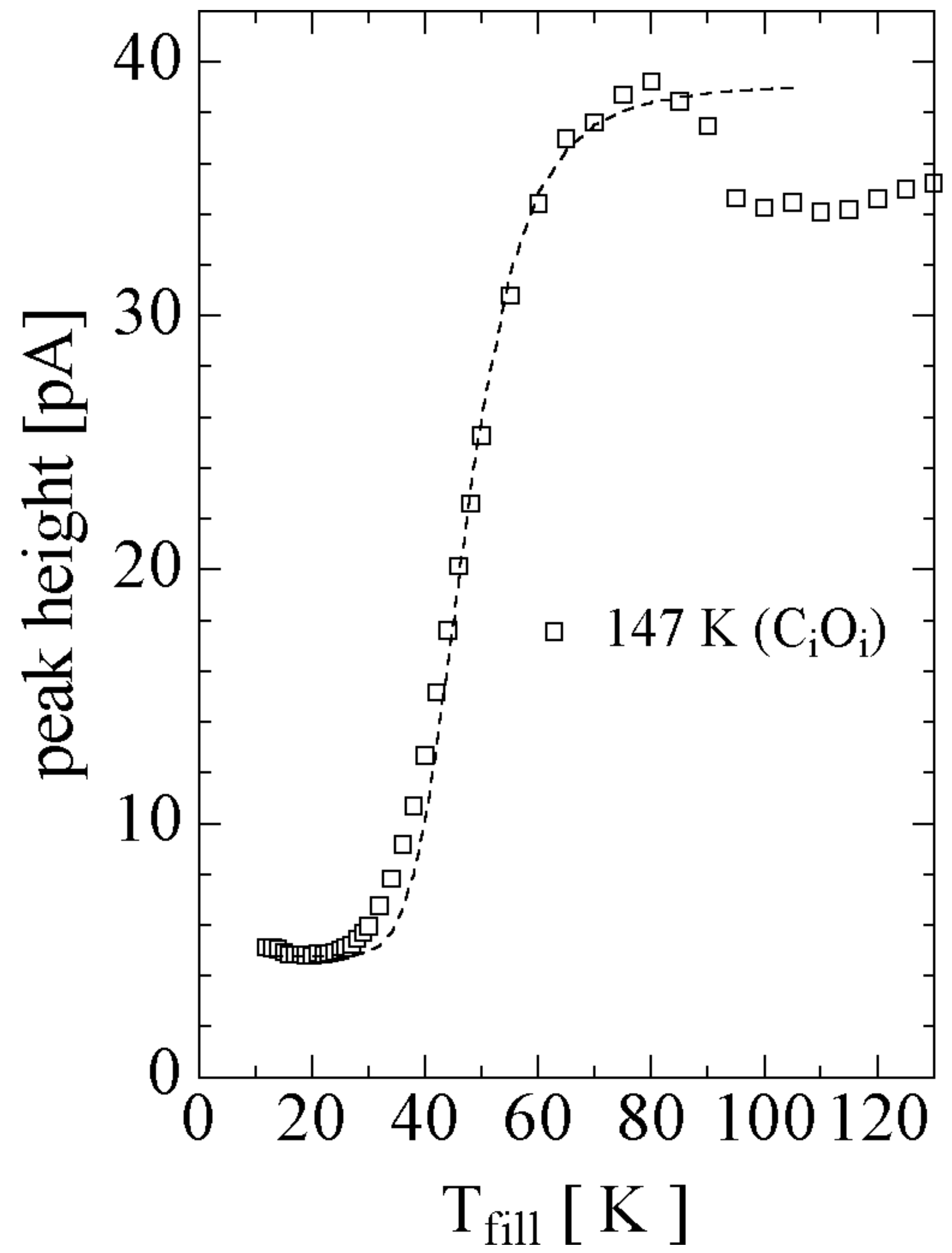
As mentioned earlier, for some filling techniques there is an injection of both electrons and holes

- Eg. Forward-biasing the sensor

For different filling temperatures, the ratio of electrons captured to holes captured will vary as the activation energies are different

- The peak height as a function of temperature gives an indication for the ratio between the electron and hole capture coefficient



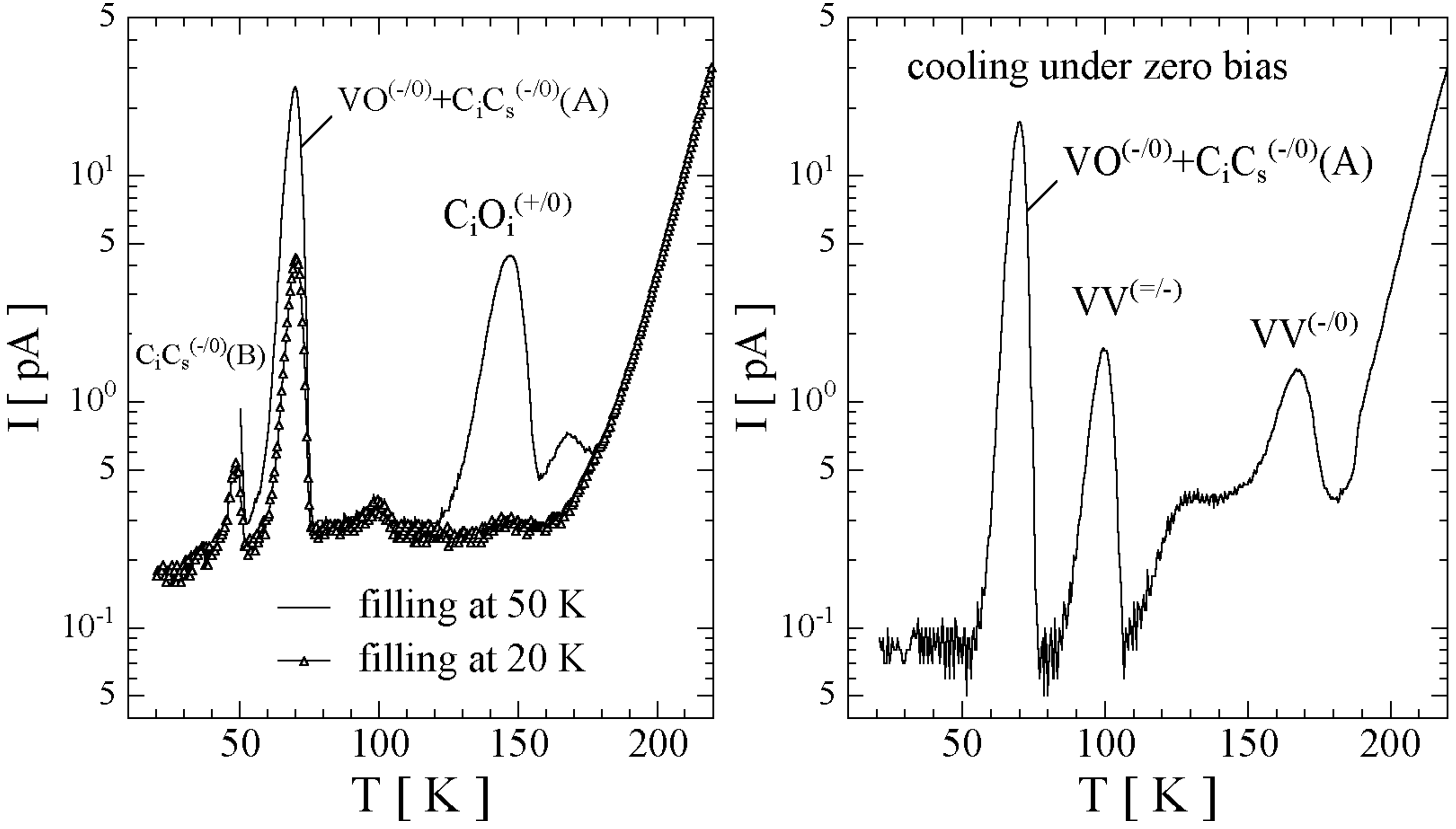


These measurements are not easy to interpret

M.Moll, PhD thesis, 1999

Can compare explicitly the difference in observed spectra for things like variation in the filling temperature, or the effect of cooling the sample with zero applied bias voltage

- On the left, the filling is via **forward biasing**; note that the C_iO_i dependence on temperature was shown on the previous slide
- On the right, traps were filled by cooling under zero bias (majority carriers, n-type bulk)



DLTS

For TSC, all that we could observe on heating was a current

- No indication of whether traps were acting on electrons or holes

A different technique for determining trap type and presence is **Deep Level Transient Spectroscopy (DLTS)**

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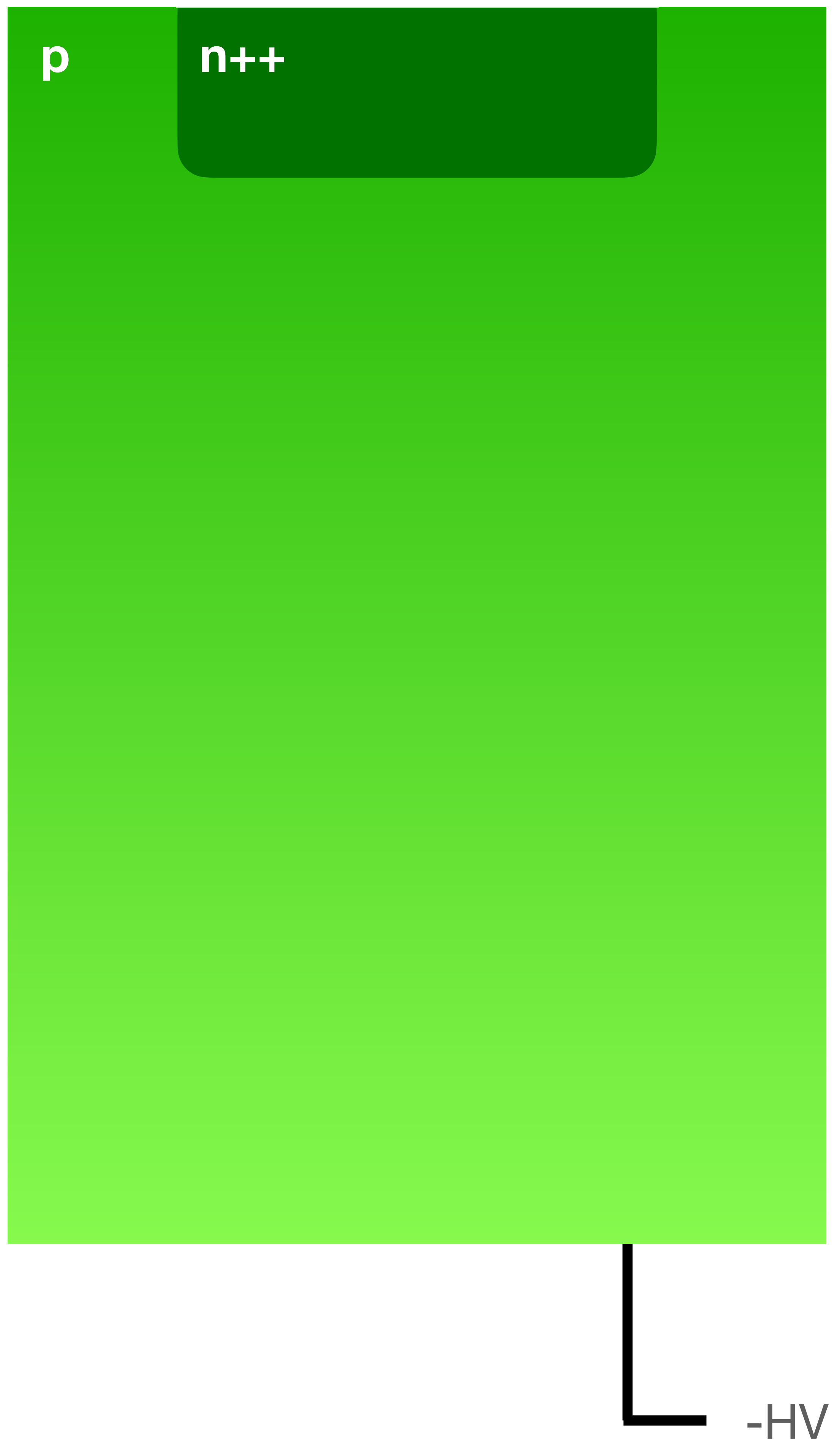
DLTS - signal generation

DLTS is based around transient measurements of occupied traps within the semiconductor

- The *transient* part relates to the relaxation of the system, which starts off under reverse bias



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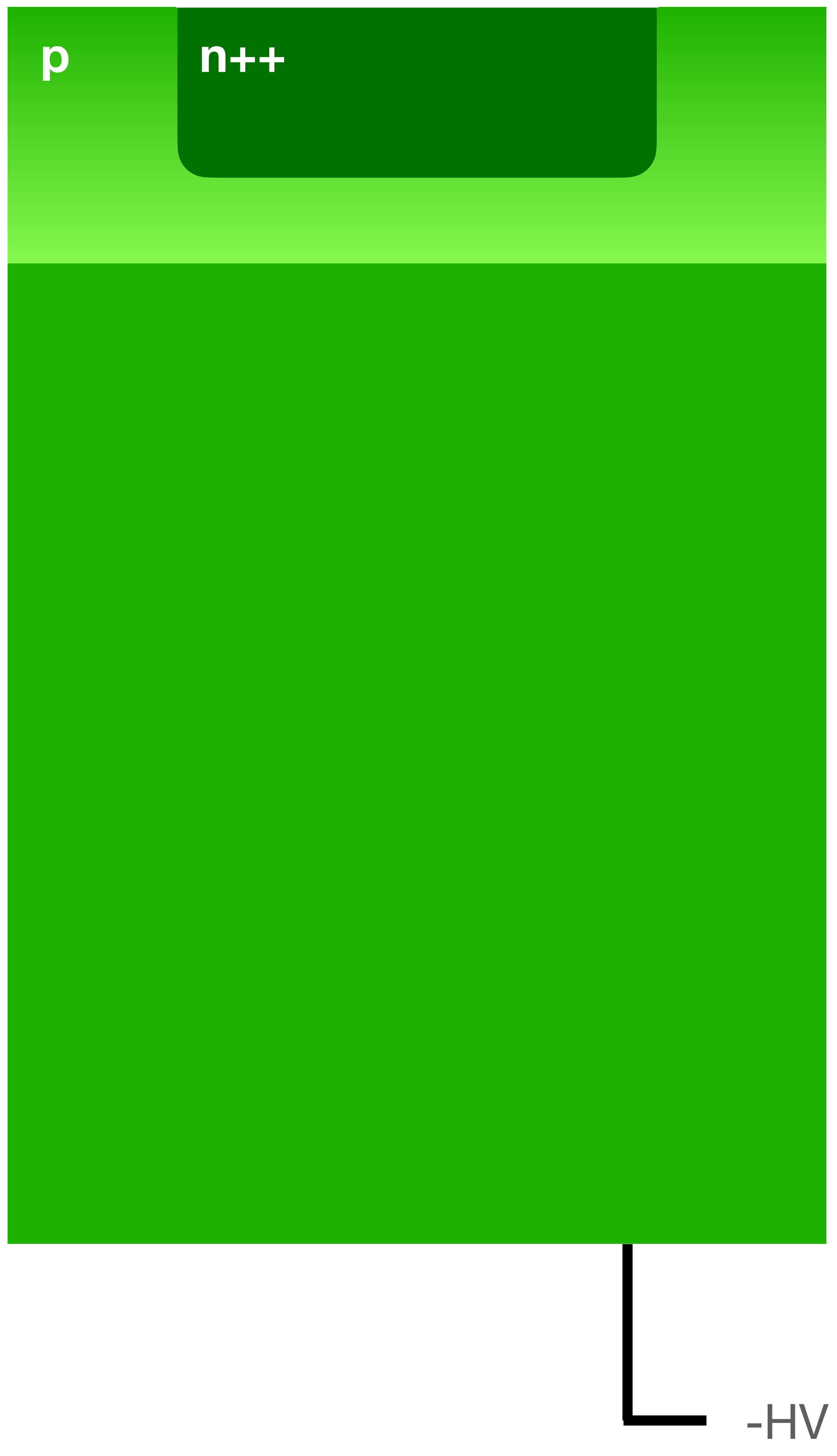

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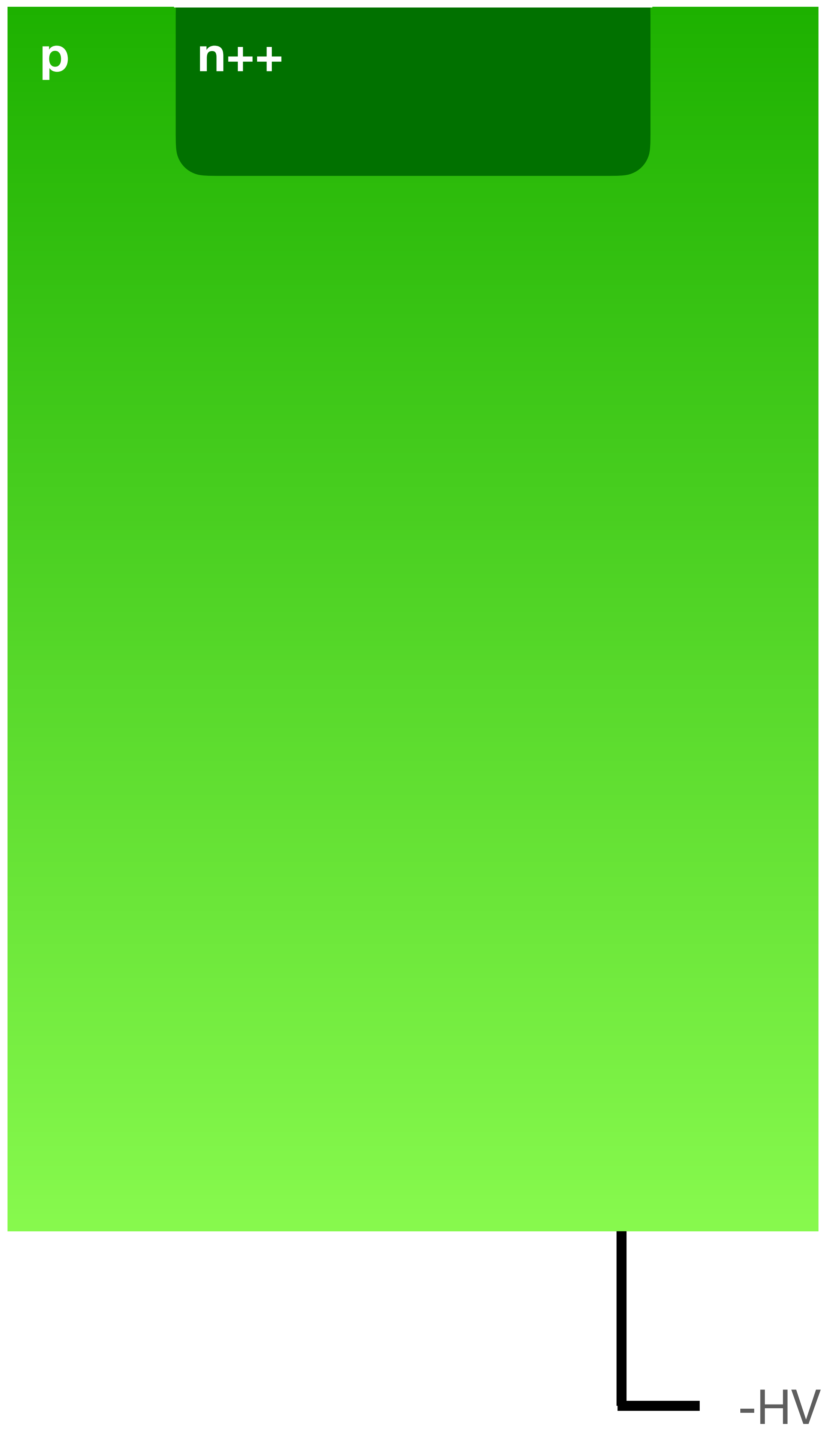

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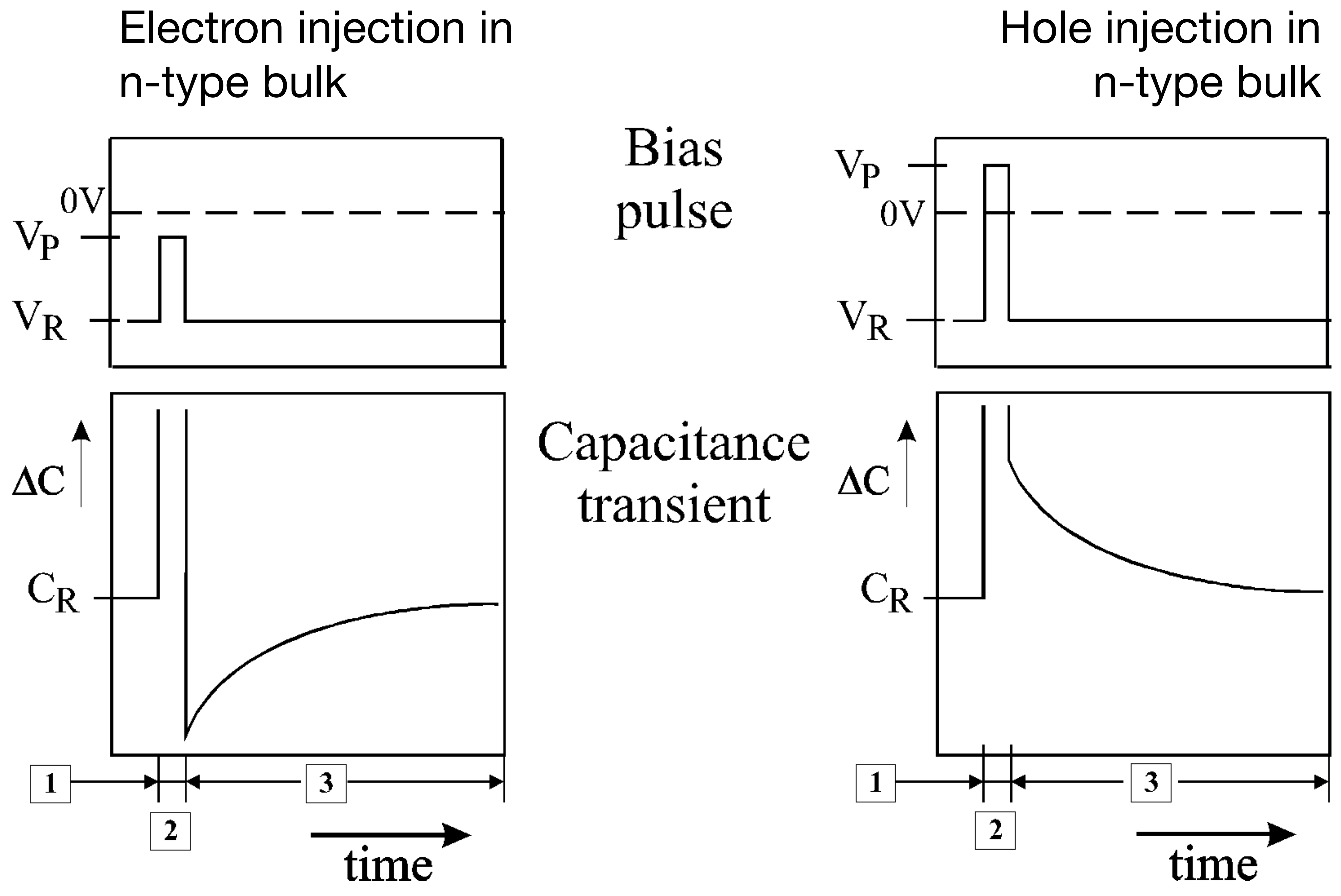
- The sensor is returned to full depletion and the change in capacitance measured **- the capacitance change tells us if the defects were hole or electron traps**

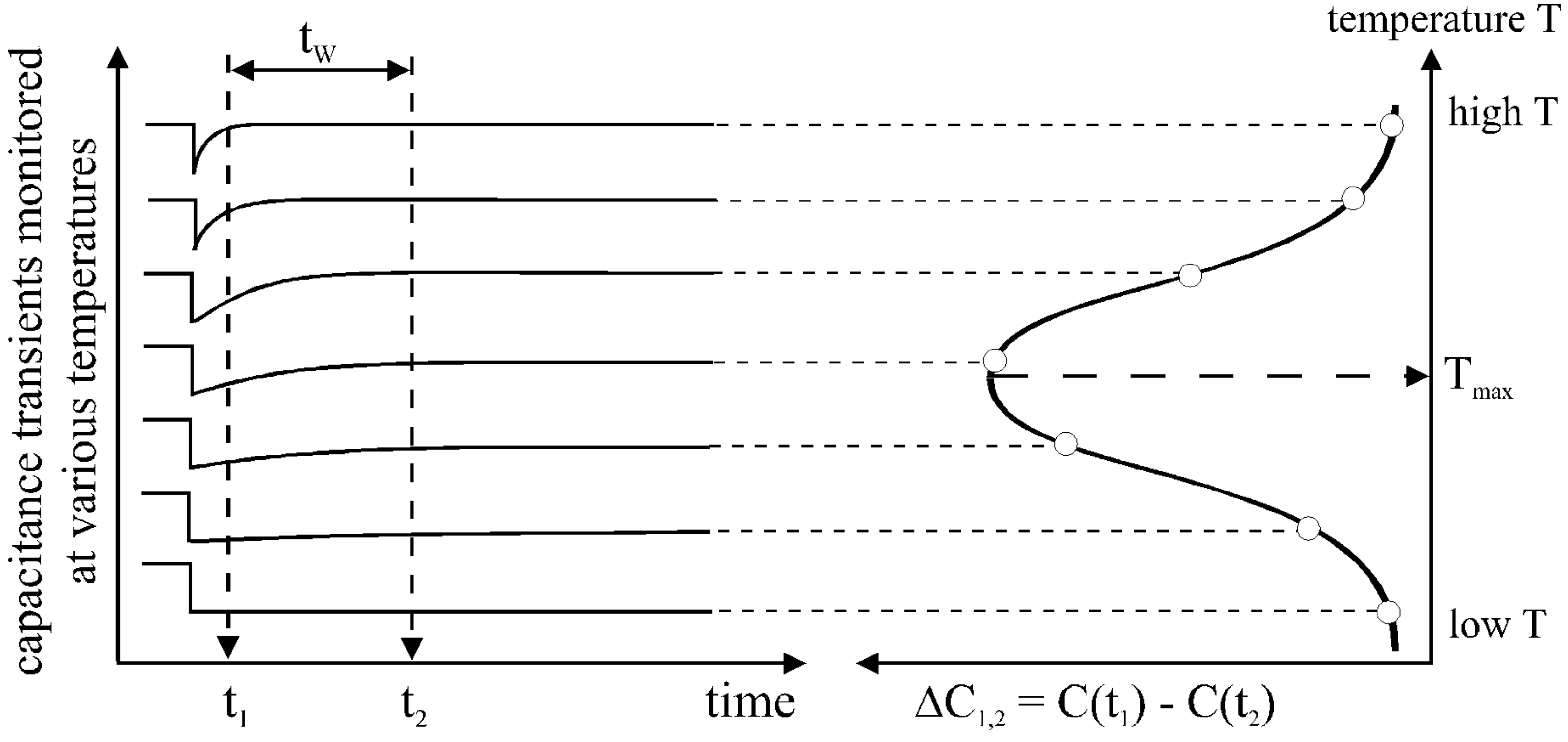


DLTS analysis - double boxcar

M.Moll, PhD thesis, 1999

Analysing the data from DLTS can be done in several ways

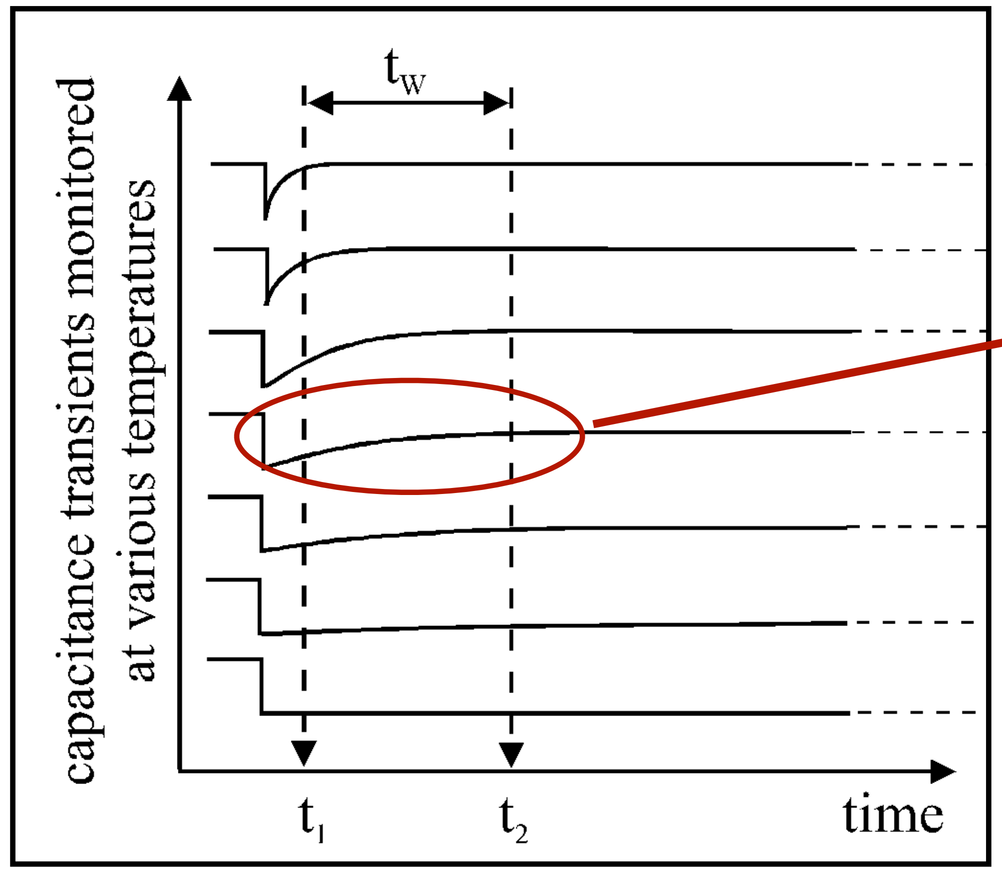
- One of the simplest/most straightforward is to basically compare the capacitance shortly after the end of the voltage pulse with the steady-state capacitance some time later
- This is usually called the *double boxcar* approach
- Comparing this value versus temperature gives similar peak formation as TSC, but with information on the trapped carrier type

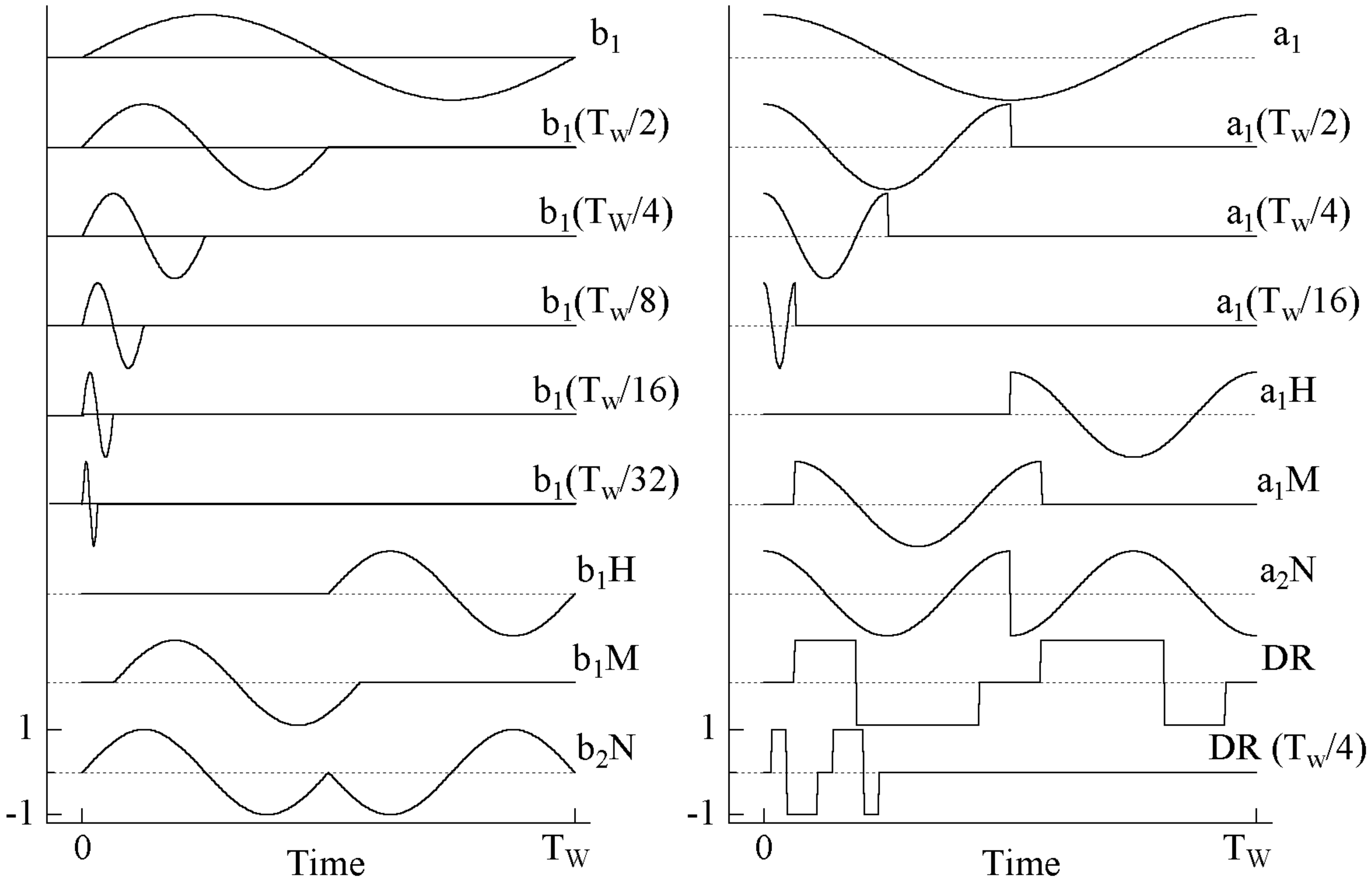


DLTS analysis - DL(Fourier)TS

An alternative to the double boxcar method is effectively Fourier analysis of the measured transient capacitance

- Correlator functions defined for the time window T_W of the measurement

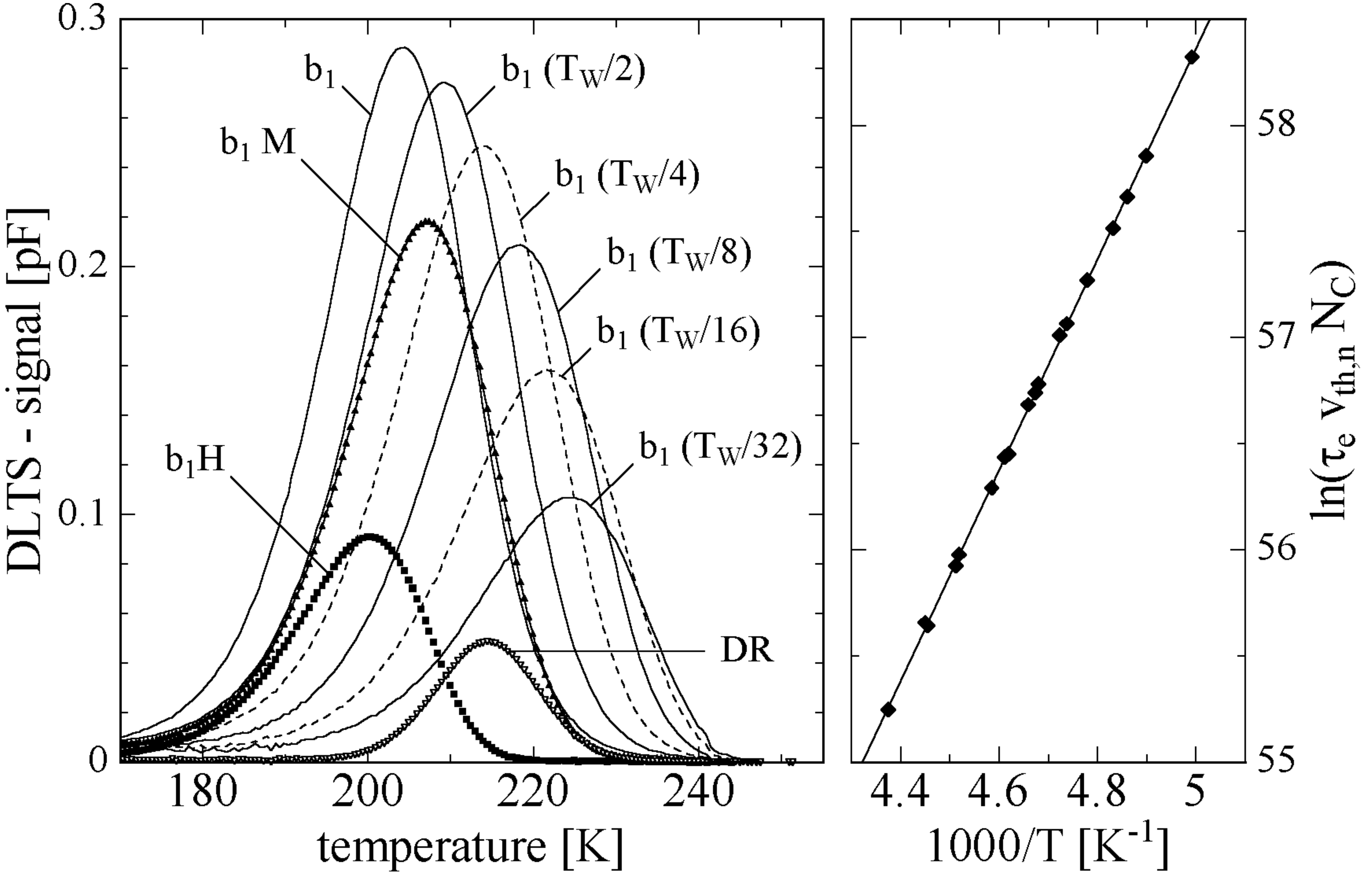




M.Moll, PhD thesis, 1999

An alternative to the double boxcar method is effectively Fourier analysis of the measured transient capacitance

- Correlator functions defined for the time window T_W of the measurement
- This gives (in the case on the right) 18 pairs of Temperature and emission rate for each time window, allowing an Arrhenius plot to be produced to extract the activation energy

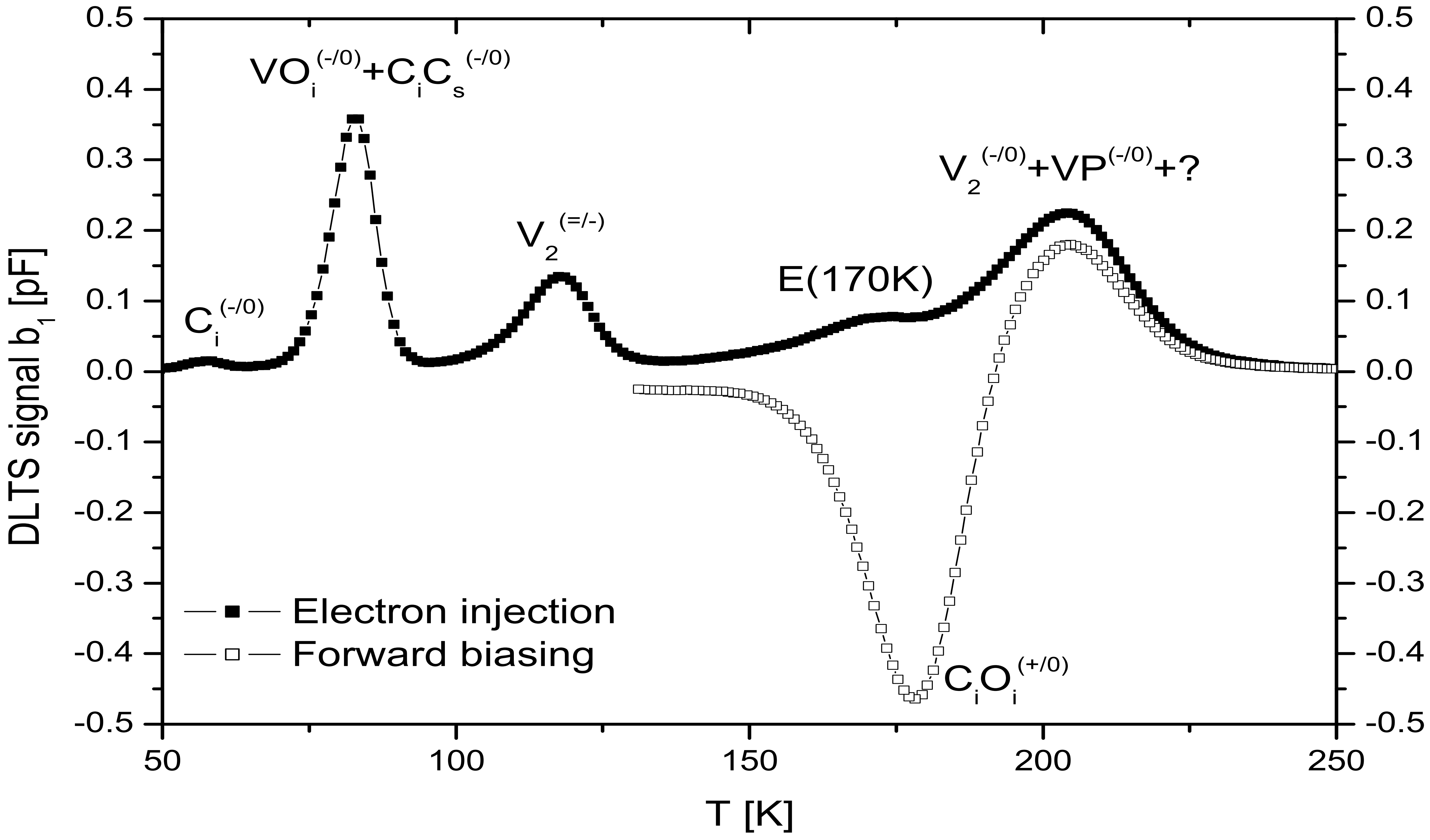


Typical DLTS plots

F.Hönniger, PhD thesis, 2007

Plotting a single of the extracted variables versus temperature gives us a typical DLTS plot

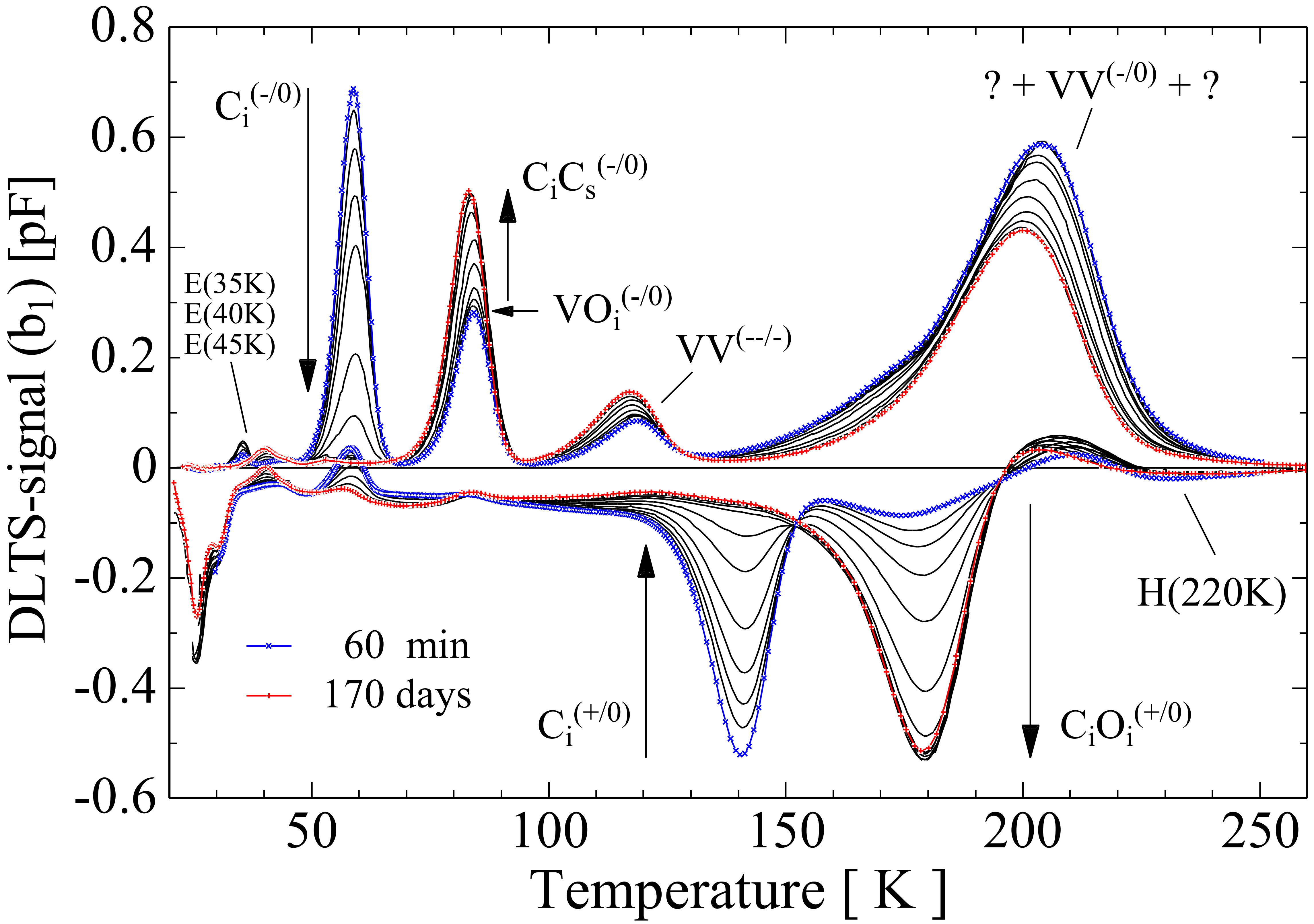
- As before, it is important to understand the bulk material, the injection method, the detector state during cooling, the analysis…



Typical DLTS plots

Plotting a single of the extracted variables versus temperature gives us a typical DLTS plot

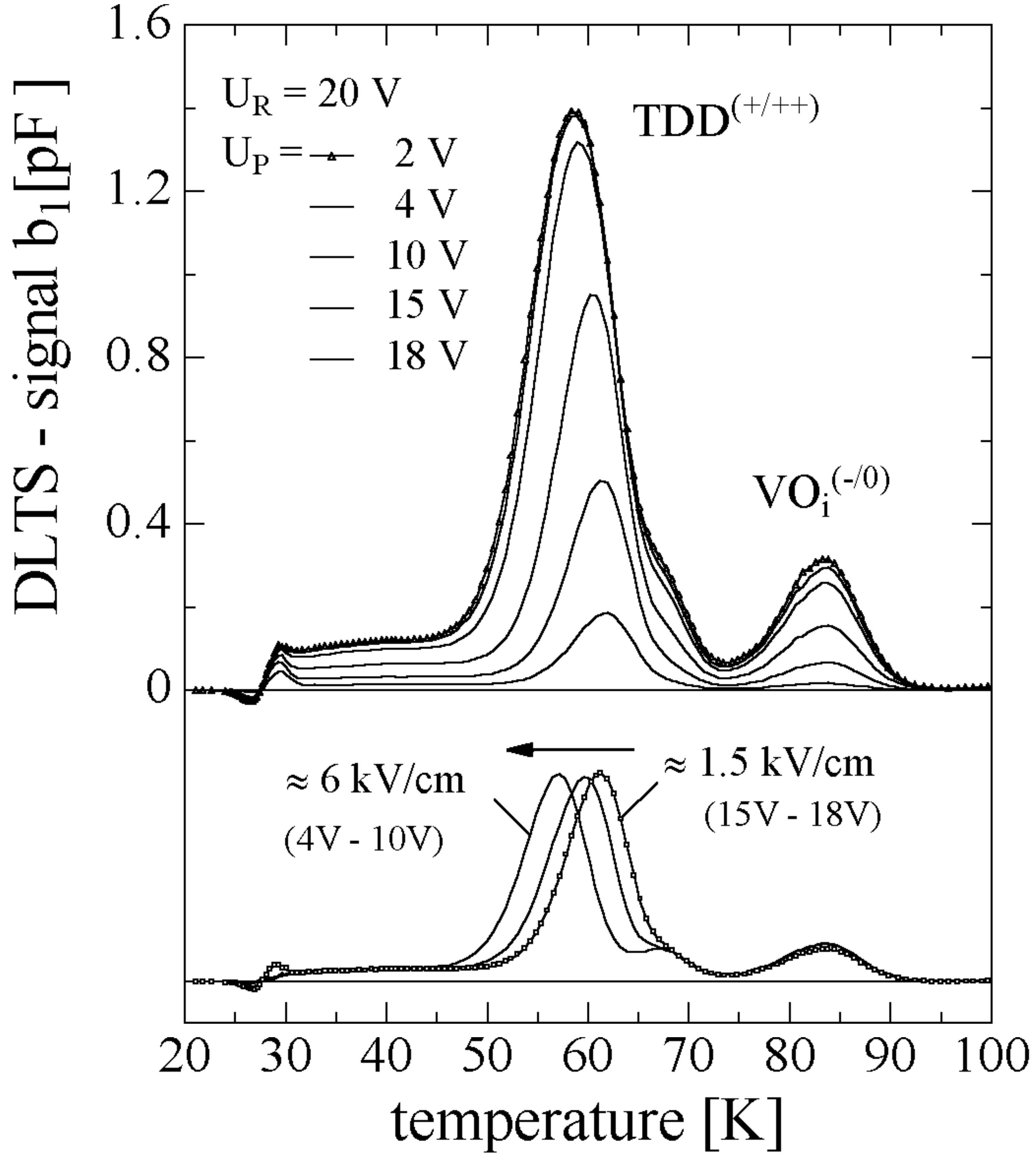
- As before, it is important to understand the bulk material, the injection method, the detector state during cooling, the analysis…
- All of this is before we start trying to analyse which defects are produced by radiation, how they develop with annealing/passivation/ whatever else we can think to do to them!

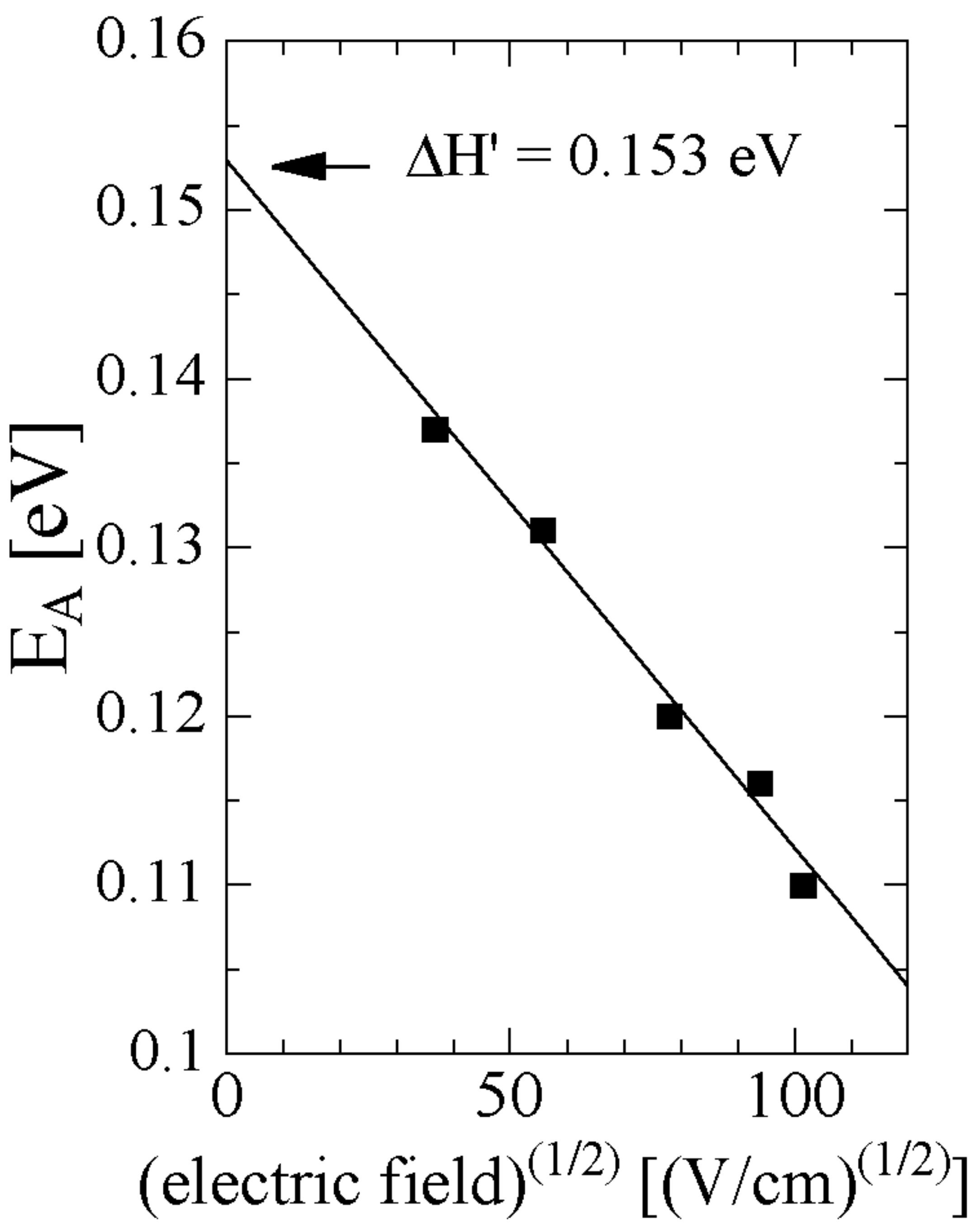


Poole-Frenkel effect in DLTS

M.Moll, PhD thesis, 1999

The same effect as was observed for TSC can be seen in DLTS - influence of the electric field on the energy barrier to escape from a trap

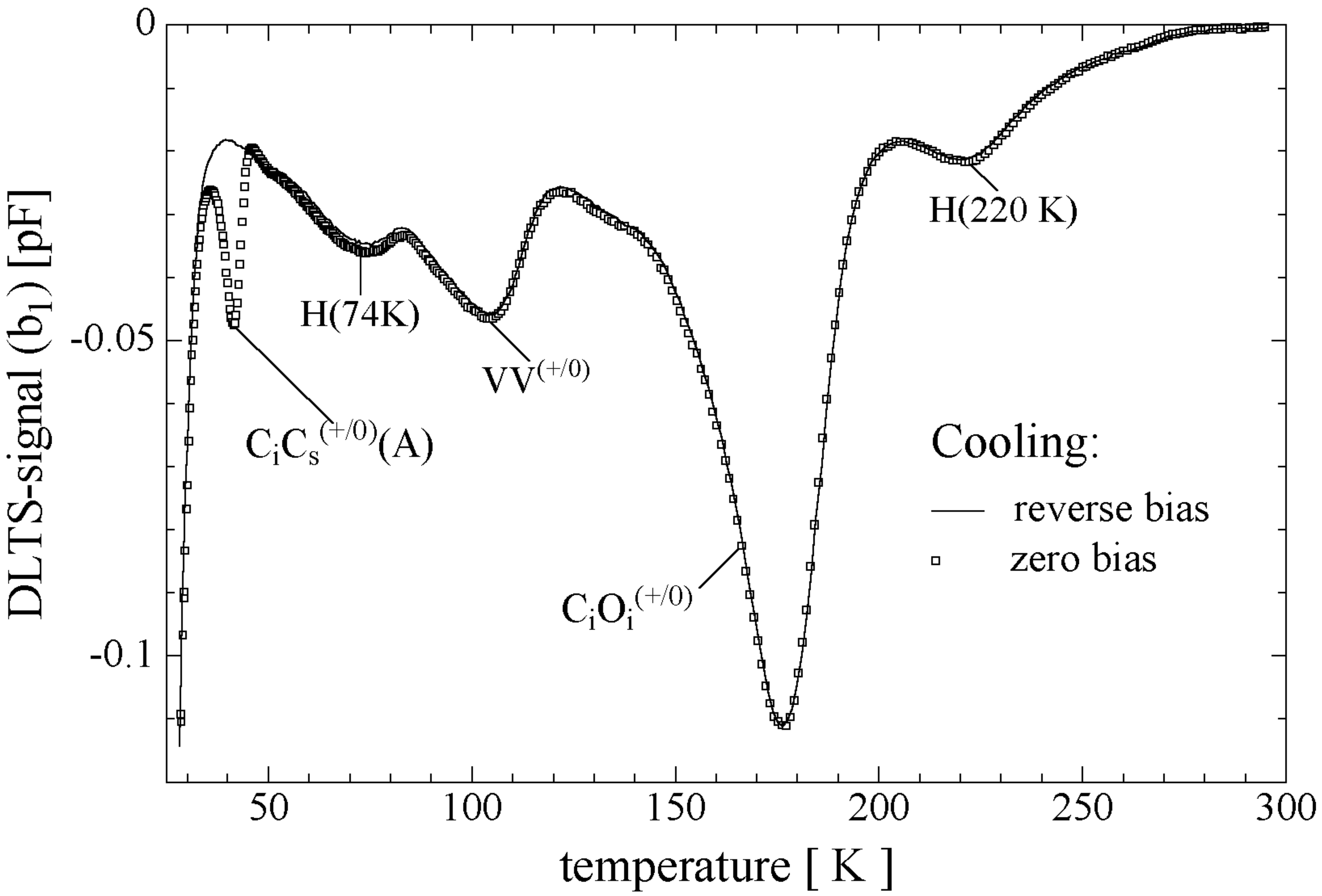




M.Moll, PhD thesis, 1999

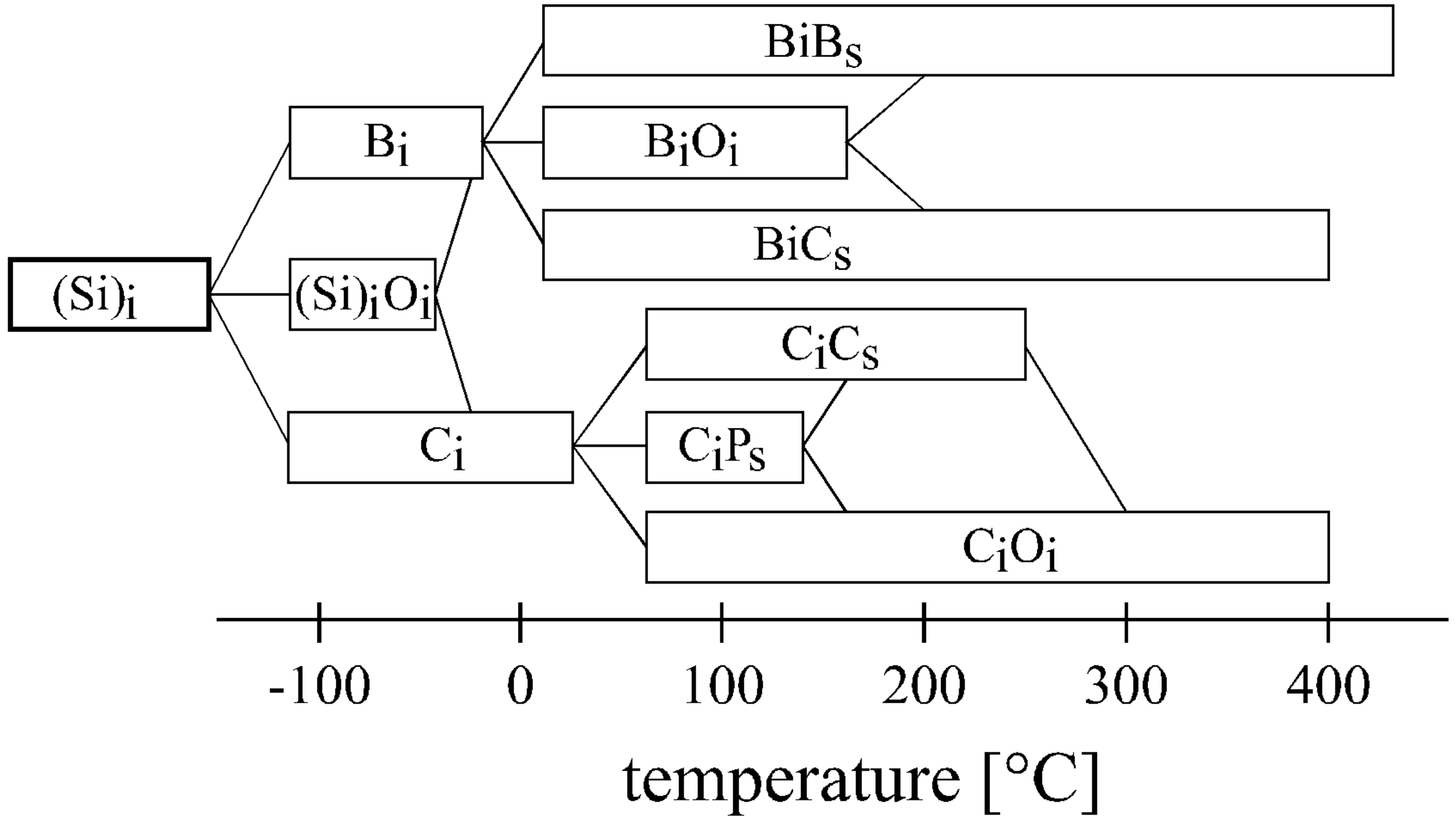
To make things more complicated, some defects exhibit quasi-stable behaviour

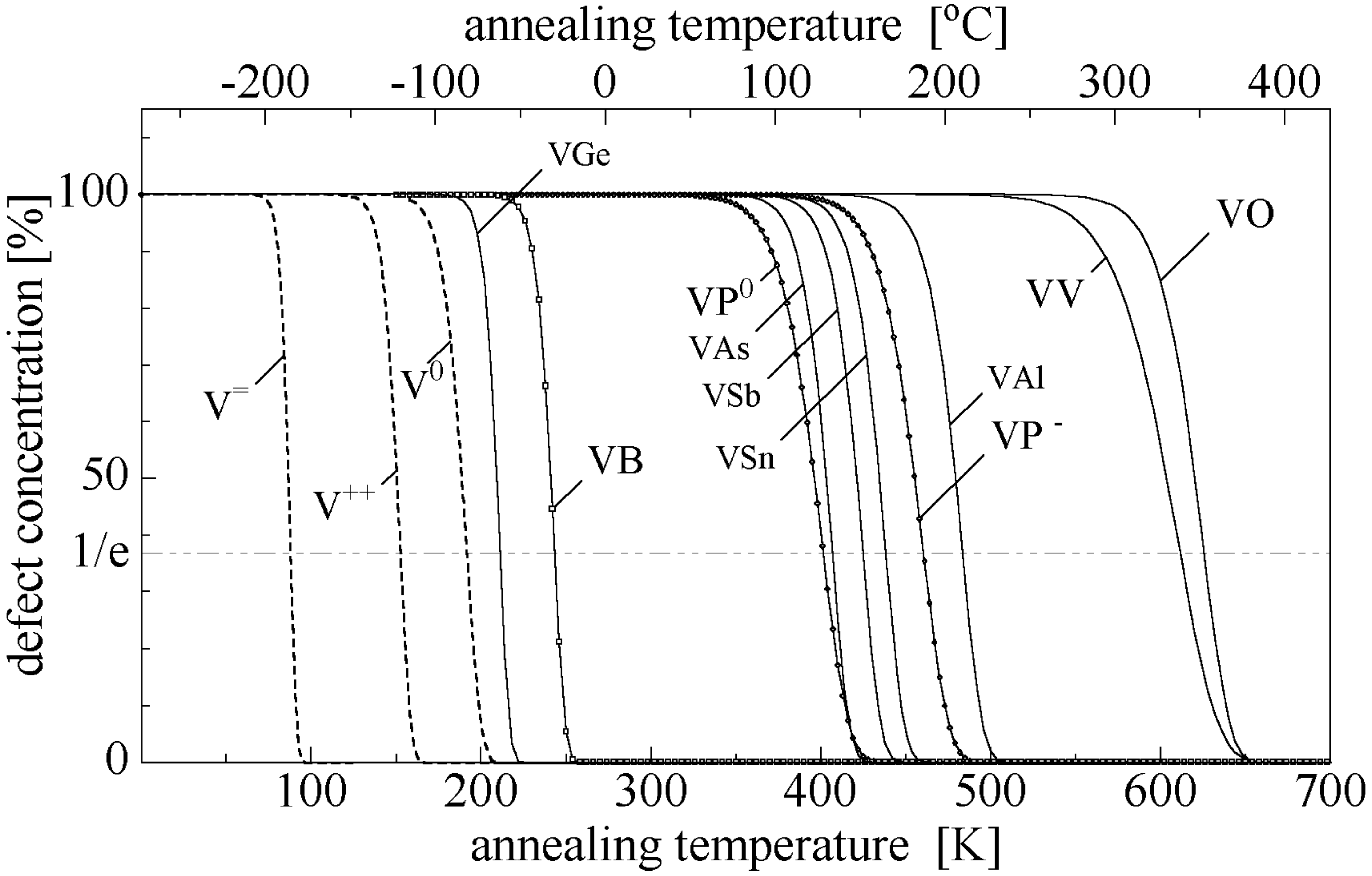
- CiCs defect has more than one role - can be an acceptor **or** a donor
- Two spectra shown on the right: minority carrier DLTS for an n-type bulk material (optical trap filling)
- Difference between the curves is the **presence of reverse bias during cooling**



Radiation damage is complicated…

M.Moll, PhD thesis, 1999





CC-DLTS, I-DLTS

DLTS is limited in the defect concentration that it can detect

- This must be lower than the effective doping of the unirradiated substrate

To counter this there are additional DLTS flavours, where the voltage applied to the junction is varied to keep the capacitance constant (CC-DLTS)

- The voltage pulse is then analysed to determine the defect concentration

A hybrid of TSC and DLTS also exists: current DLTS (I-DLTS)

- The DLTS method is followed, but it is the current transient that is measured
- This has the advantage that it can be applied to insulators and to samples with high defect concentrations

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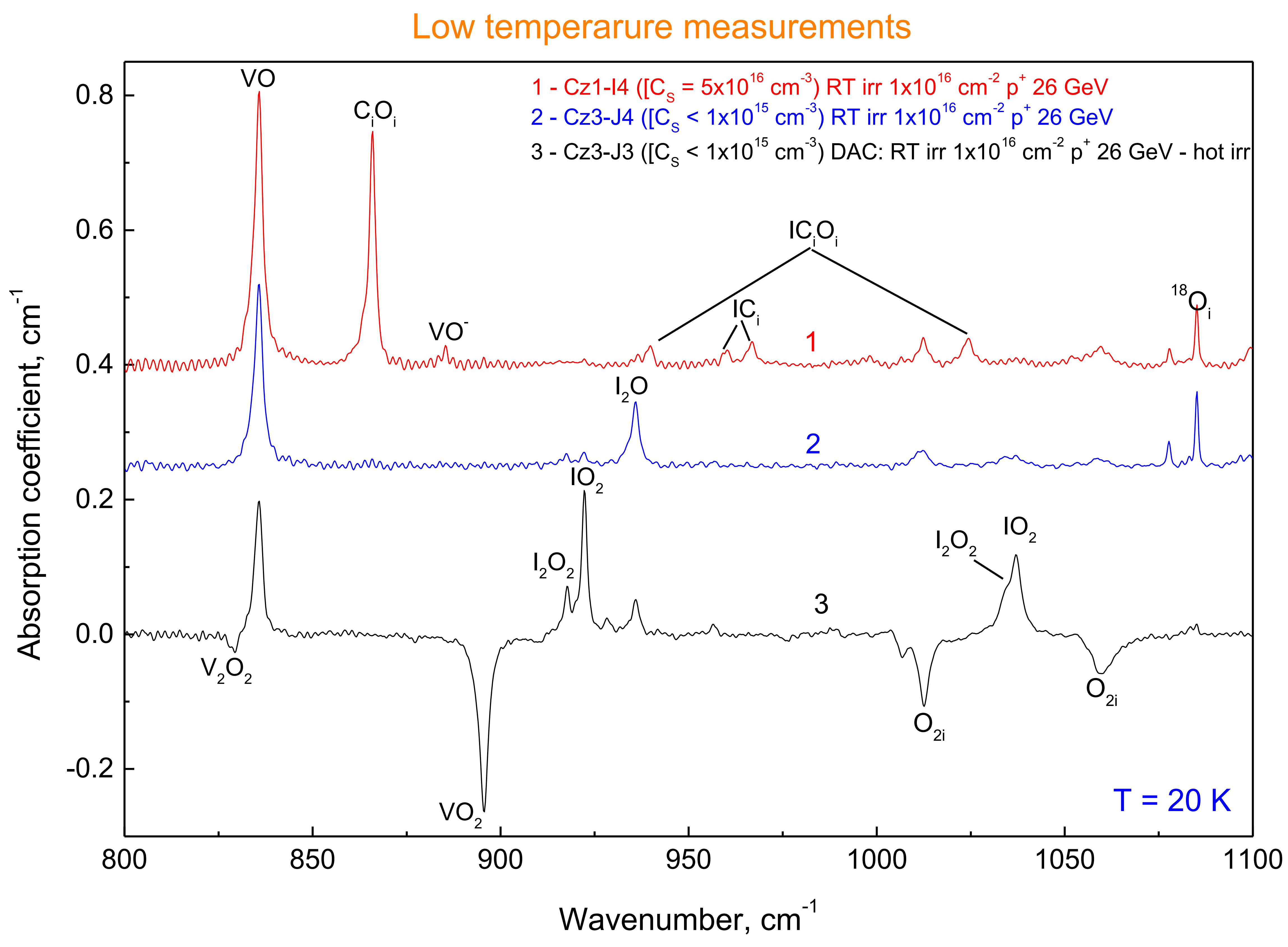
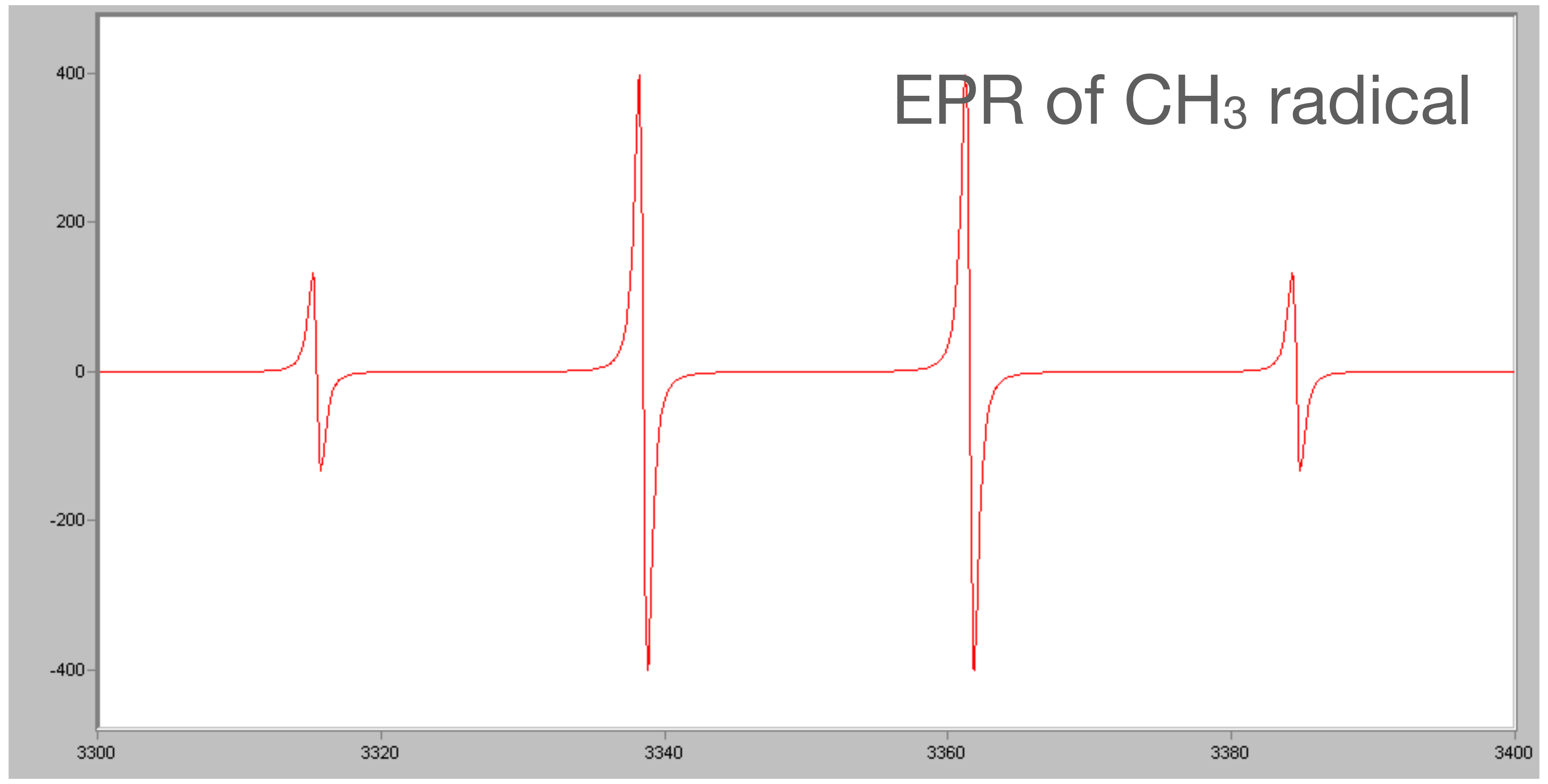
Infrared spectroscopy has long been used in chemistry to identify different interatomic bonds - can be similarly useful for defects in silicon

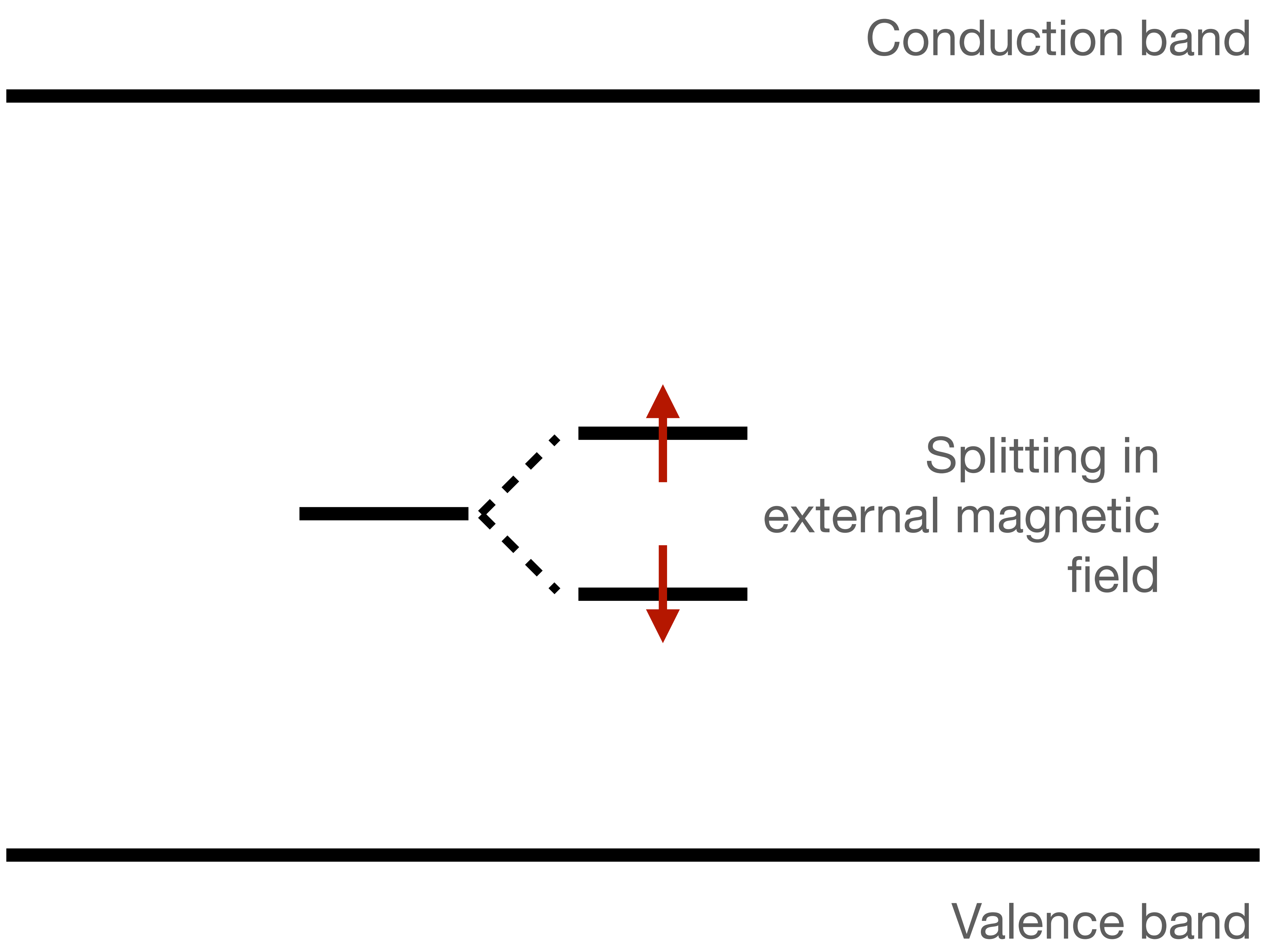
- Excitation of bonds by infrared illumination - need thin samples to do transmission measurements
- Measurements more easy to disentangle at **low temperature**
- Sensitive to defect concentrations from 10^{13} - 10^{15} cm^{-3}



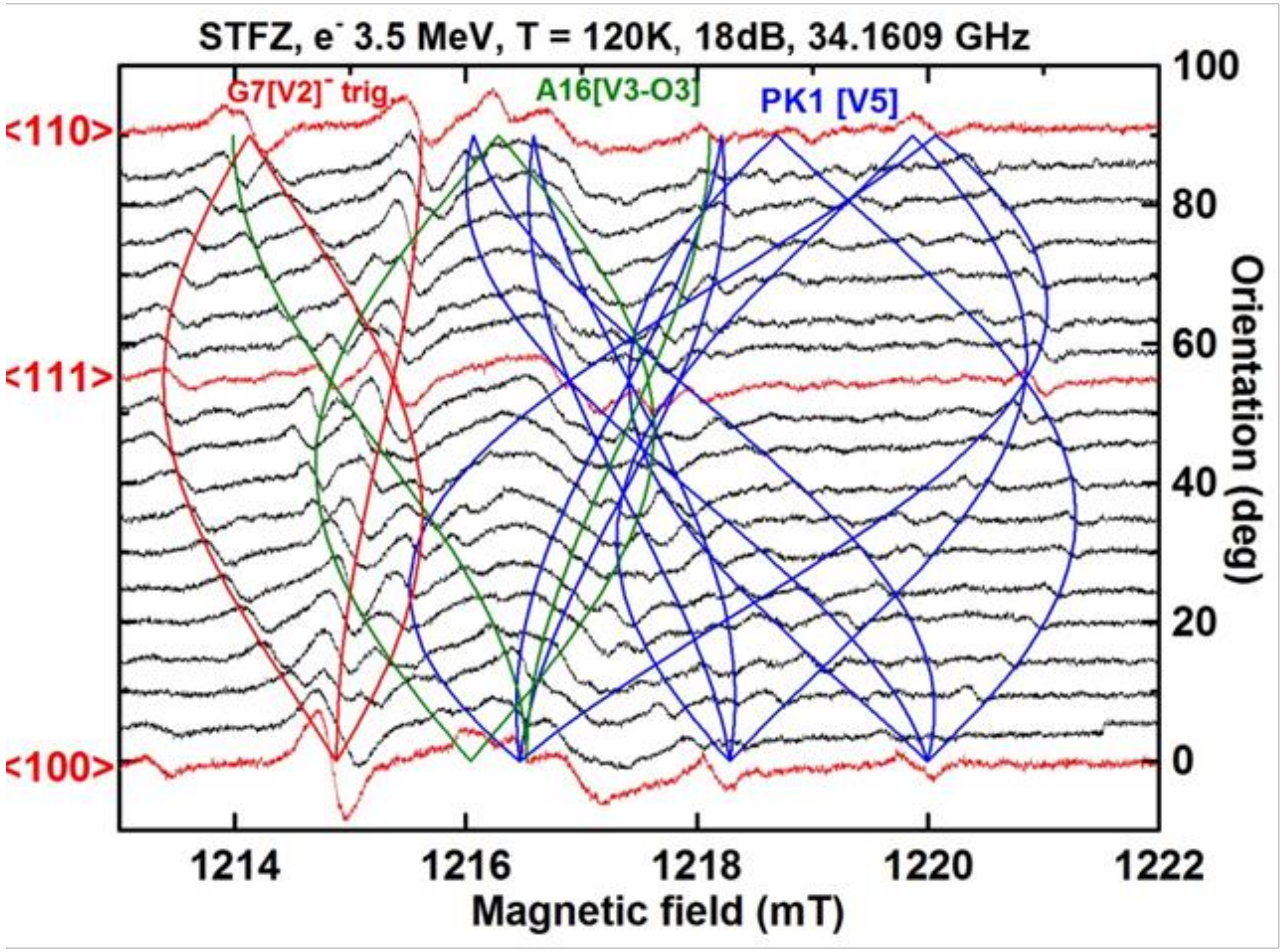
EPR is analogous to Nuclear Magnetic Resonance (NMR) but acts on electrons

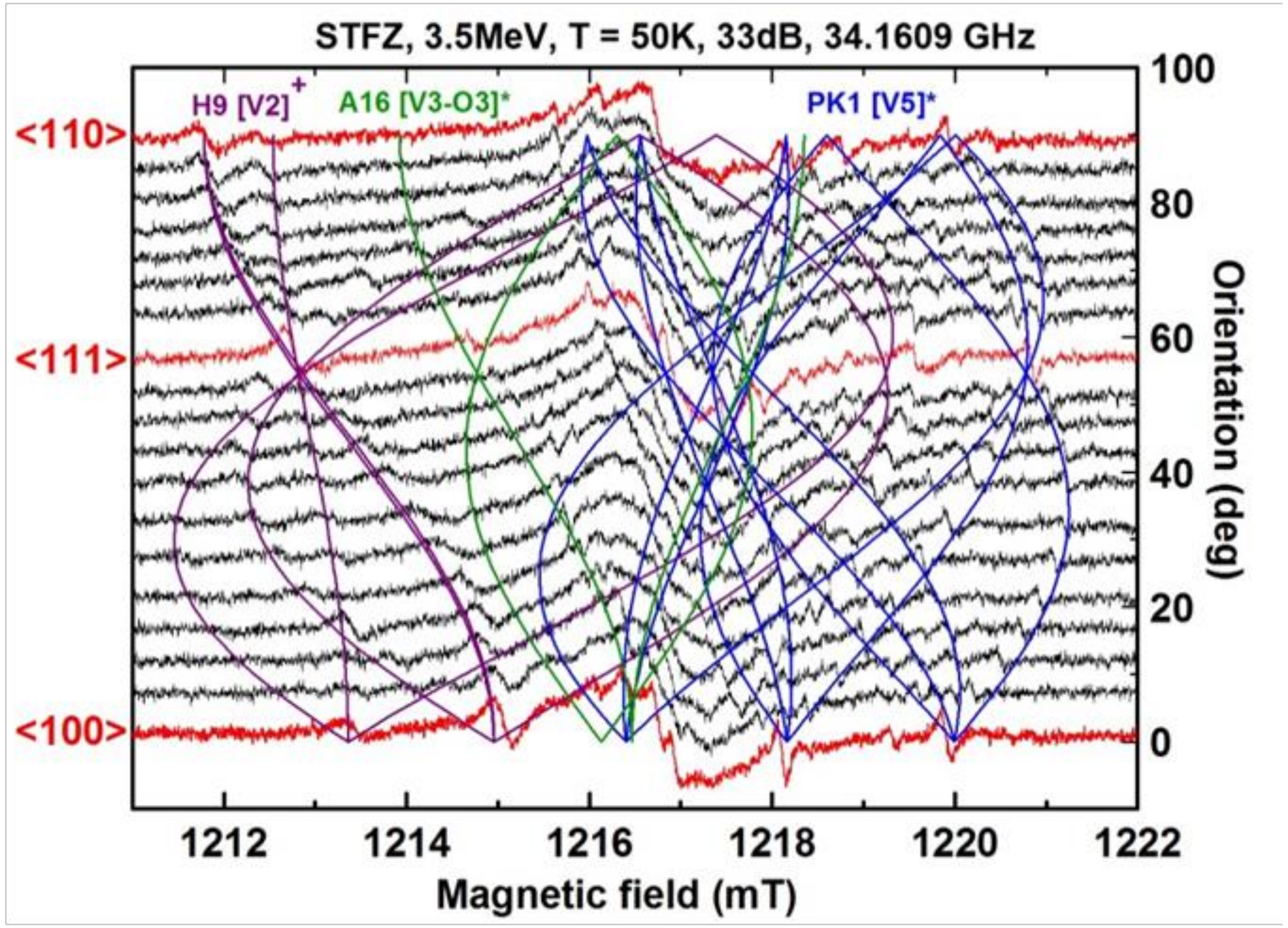
- Effective energy splitting due to presence of an external magnetic field - cf. Zeeman effect
- Can be used to study the presence of paramagnetic defects





Variation of ESR spectra with measuring temperature (120K) and (50 K).





Summary

Solid-state physics is messy and difficult…

TSC and DLTS (with many variations) form part of a myriad of probing techniques that can be used to investigate energy levels within the band structure of semiconductors

- TSC fills traps once, and heats at a constant rate to observe carriers escaping
- DLTS looks for transient observables at every temperature

There many other techniques which can be exploited, but interpretation is challenging!

- It is always important to understand the details of how the measurement was performed and how (and when) traps were filled, and by which carriers