NARODOWE CENTRUM NAUKI
UMO-2016/22/E/ST3/00553

# Electrical characterization of semiconductors and semiconductor based structures

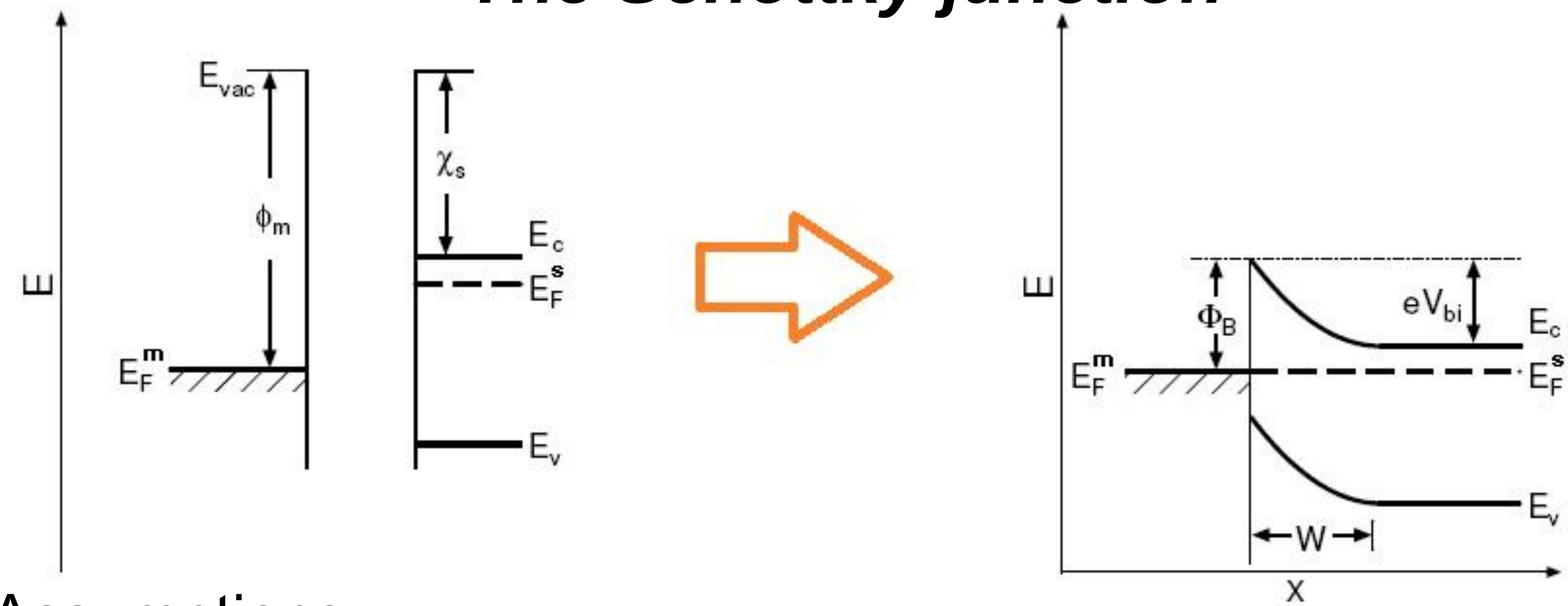
**Dr. Ramón Schifano**
**schifano@ifpan.edu.pl**

Institute of Physics, Polish Acad. of Sciences, Al. Lotnikow 32/46, 02-668 Warsaw, Poland

# *Outline pt.1*

1. Schottky junctions: Schottky-Mott limit and beyond.
2. Rectifying vs. Ohmic contacts and real structures.
3. Current vs Voltage and Capacitance vs Voltage characterization of rectifying structures and what can be extracted from them.

# *The Schottky junction*



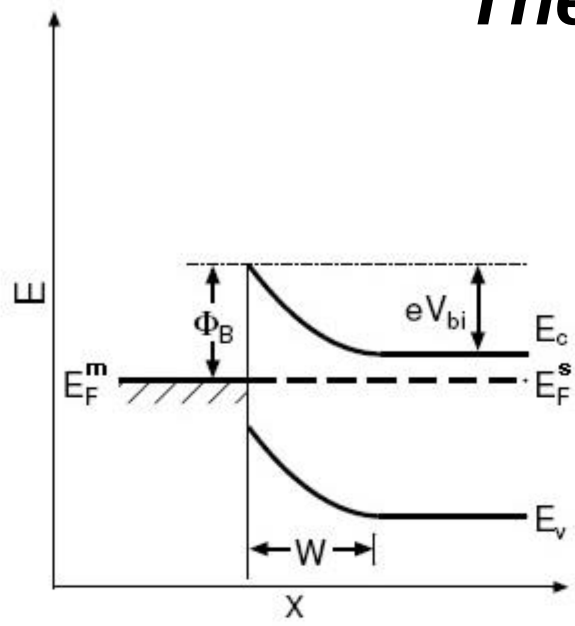

Assumptions:

1) No changes in $\phi_m$ and $X_S$ when brought in contact.

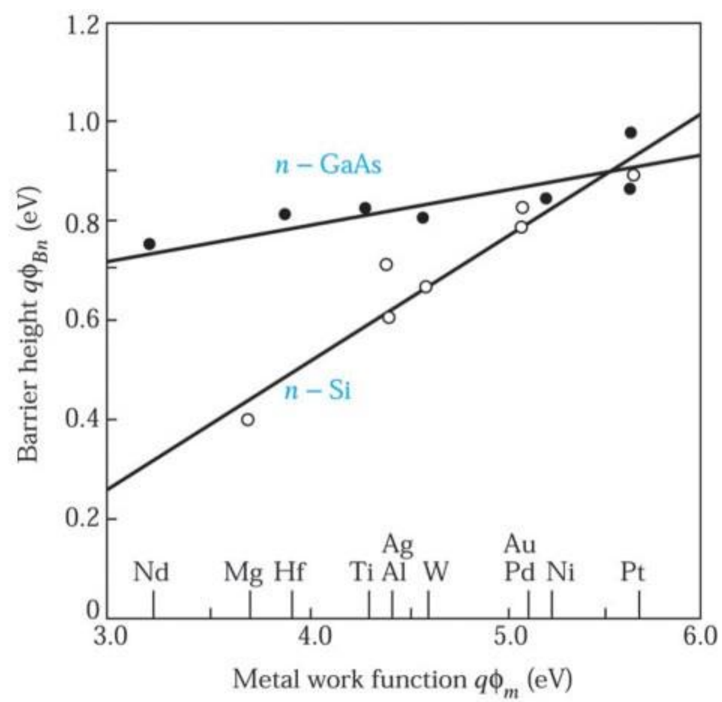
2) No electron states present on the semiconductor surface or metal-semiconductor interfaces.

3) No interfacial layer.

# *The Schottky-Mott limit*




$$\phi_B = \phi_m - \chi_S$$




- Case of n-Si the real dependence on $\Phi_m$ is sublinear (~ 0.25).
- Case of n-GaAs ~ 0.1 (0.07).

(*) After S. M. Sze and M. K. Lee, Semiconductor Devices John Wiley & Sons (2012)

# *Surface effects*

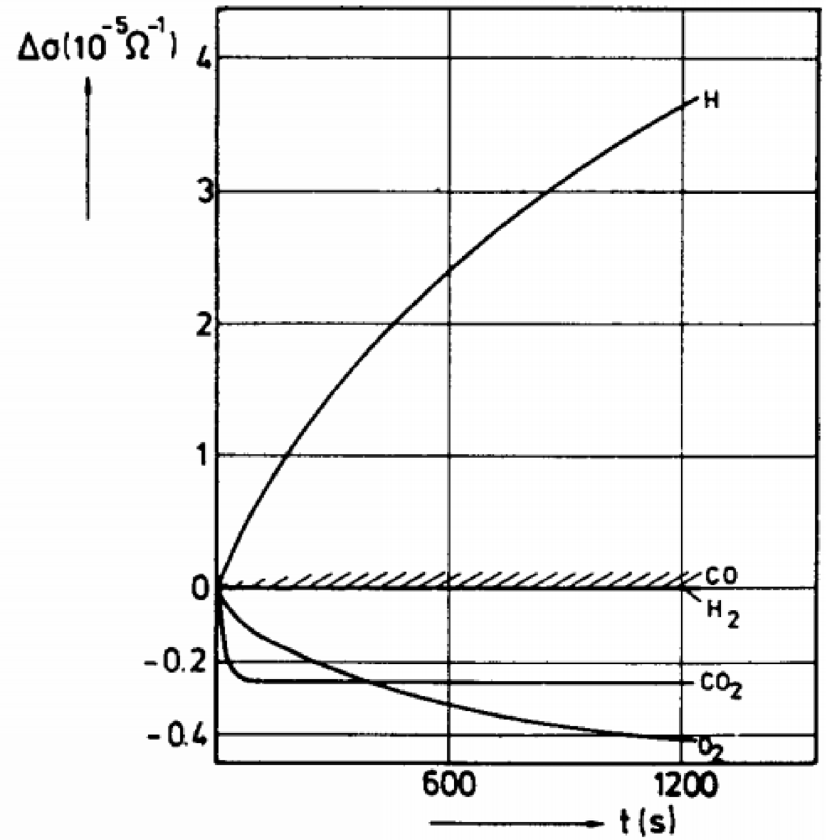
Examples of effects not considered:

1) Adsorbates (difficult to get rid of, like H).

2) Sub surface defects resulting from processing, piezo-electric field induced charge/defects.

3) Interfacial reactions.

4) Formation of surface/ interface states and surface reconstruction.

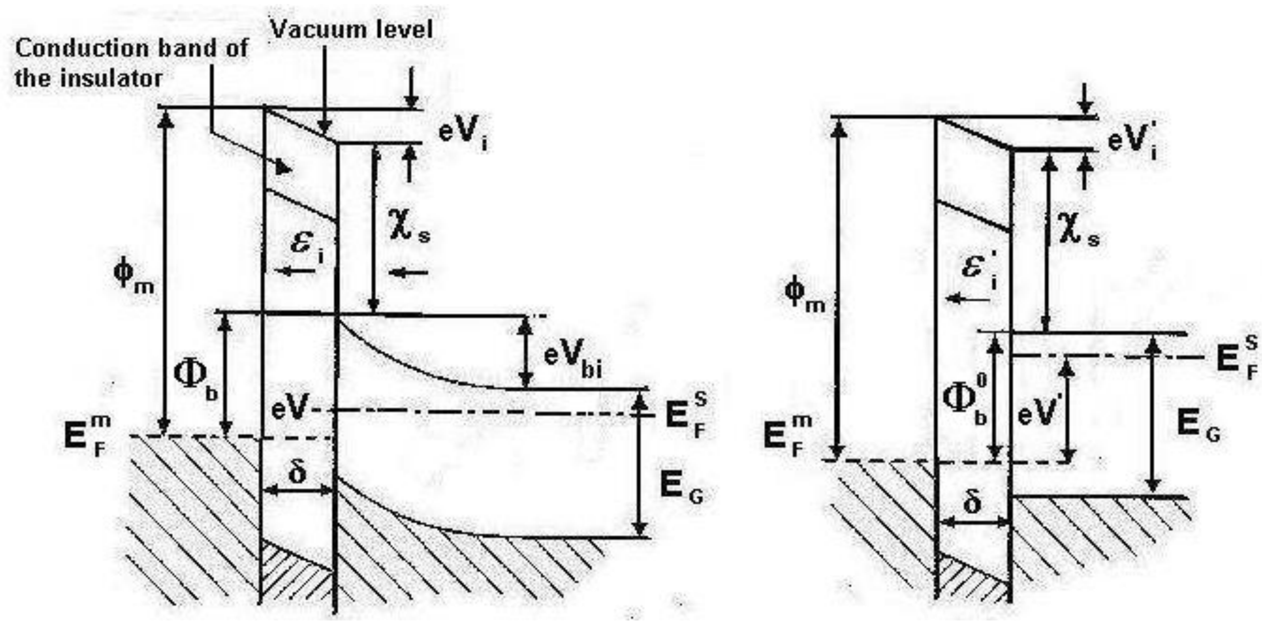



Changes in surface conductivity vs time after exposure of the ZnO (10.0) surface to various gases.*

(*) After V. E. Henrich and P. A. Cox The surface science of metal oxides, Cambridge University Press (1996).

# *Beyond the Schottky-Mott limit: Bardeen model*

Assumptions:




1) Interfacial layer of thickness δ.

2) Defects in the band-gap uniform $D_S$ (per surface unit and multiplied by *e*)

$$\Phi_b^0 = \gamma\,(\phi_m - \chi_S) + (1-\gamma\,)\,(E_G - \phi_0)$$

$$\gamma = \frac{\varepsilon_0 \varepsilon_r}{\varepsilon_0 \varepsilon_r + e\delta D_S}$$

with $\phi_0$ being the neutral level

$$D_S \to 0$$

$$\Phi_b^0 = (\phi_m - \chi_S)$$

$$D_S \to +\infty$$

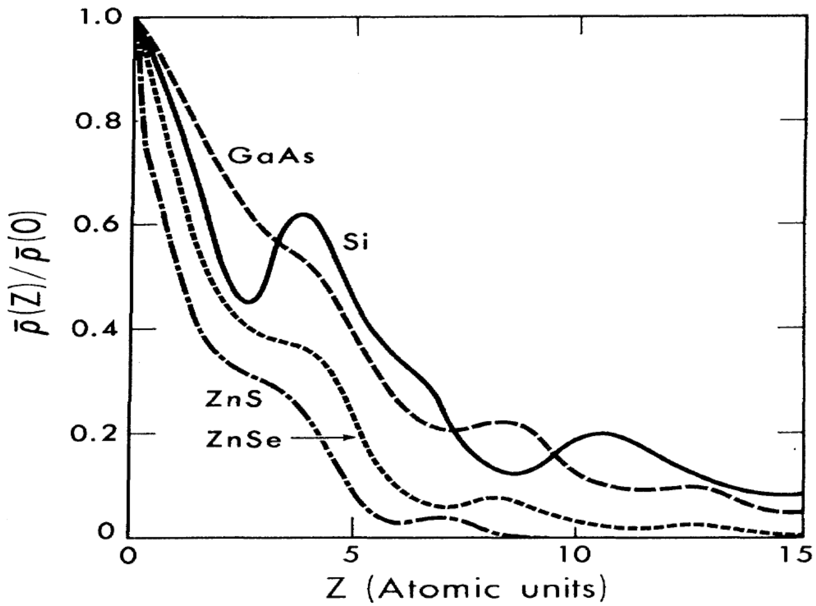
$$\Phi_b^0 = (E_G - \phi_0)$$

# *Beyond the Schottky-Mott limit: MIGS model*

Assumptions:

1) Metal in intimate contact with the semiconductor (i.e. no interfacial layer metal deposited in situ/cleavage.

2) Formation of interfacial states by contact with the metal (metal induced gap states-MIGS).

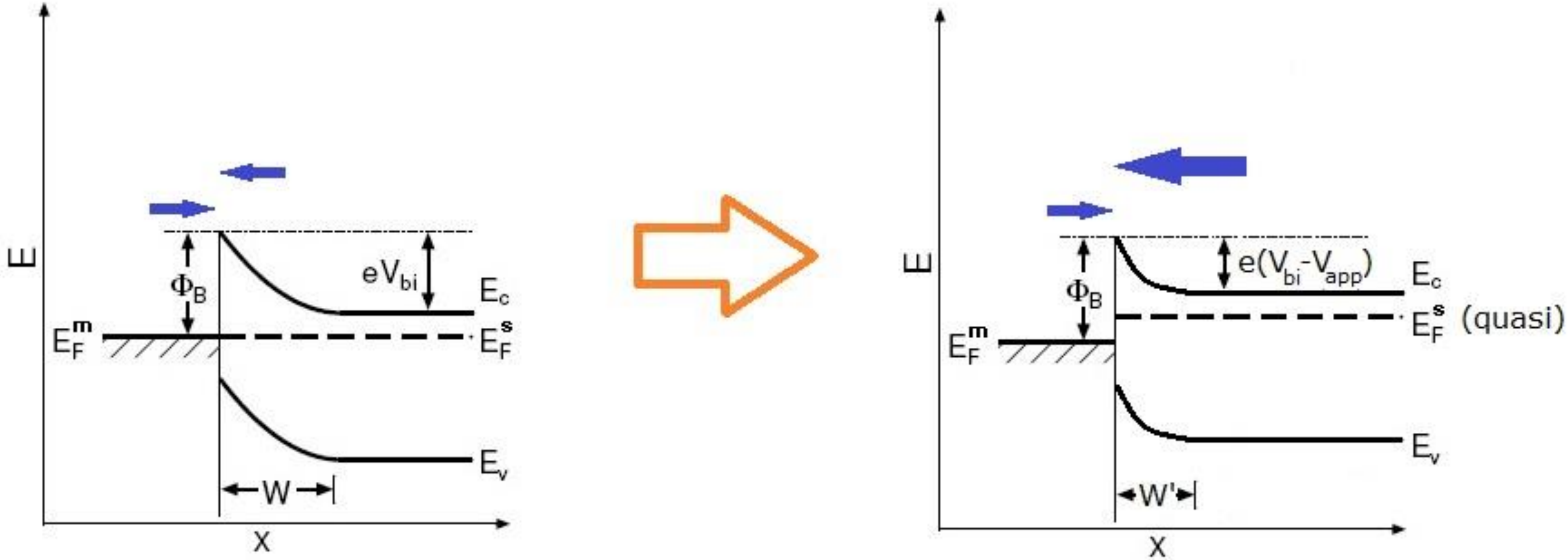



Relative charge distribution of the MIGS states as a function of the distance from the metal –semiconductor interface (z=0).Aluminium used as contact material.*

(*) After S. G. Louie et al. Phys. Rev. B 2154, 15 (1977).

Higher ionicity → less penetration → towards the Schottky-Mott limit

# *Current in Schottky junctions (thermionic case)*

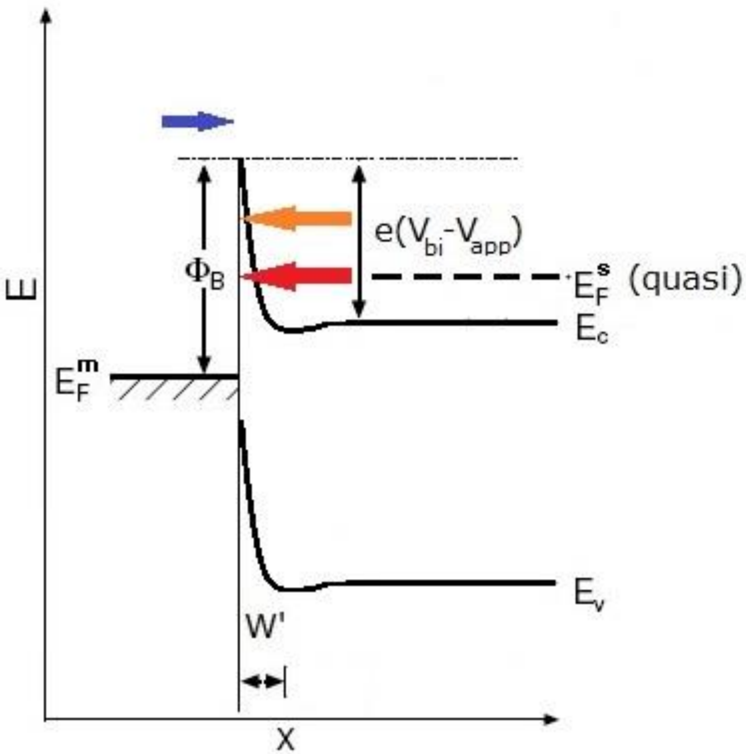



- Flow S→M increase of electrons able to overcome the barrier due to the applied V.

- Flow M→S no changes.

$$J = J_0\left[exp\left(\frac{eV}{k_B T}\right) - 1\right]$$ with: $$J_0 = A^* exp\left(\frac{-e\Phi_{b0}}{k_B T}\right) \quad A^* = \left(\frac{4\pi m^* e k_B^2}{h^3}\right)$$

# *Rectifying versus Ohmic contacts*



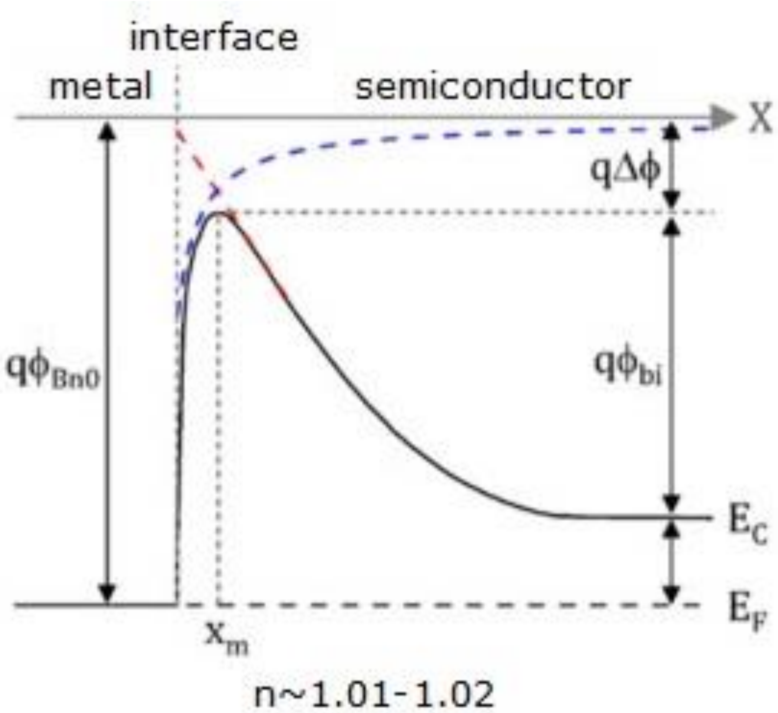

- Reducing the barrier thickness increases the probability of quantum mechanical tunneling.
- For $N_d \gtrsim 10^{17}$ cm$^{-3}$
  1) Thermionic field emission.
  2) Field emission.
- Essentially Ohmic contacts are obtained even though a barrier is present.

# ***Ideality factor n***

$$J = J_0 \left[ exp\left(\frac{qV}{k_B T}\right) - 1 \right] \quad \text{with} \quad J_0 = A^* exp\left(\frac{-e\Phi_{b0}}{k_B T}\right)$$

If the barrier height depends linearly on the applied voltage:

$$J = J_0 \; exp\left(\frac{eV}{nk_B T}\right)\left[1 - exp\left(\frac{-\,eV}{k_B T}\right)\right]$$



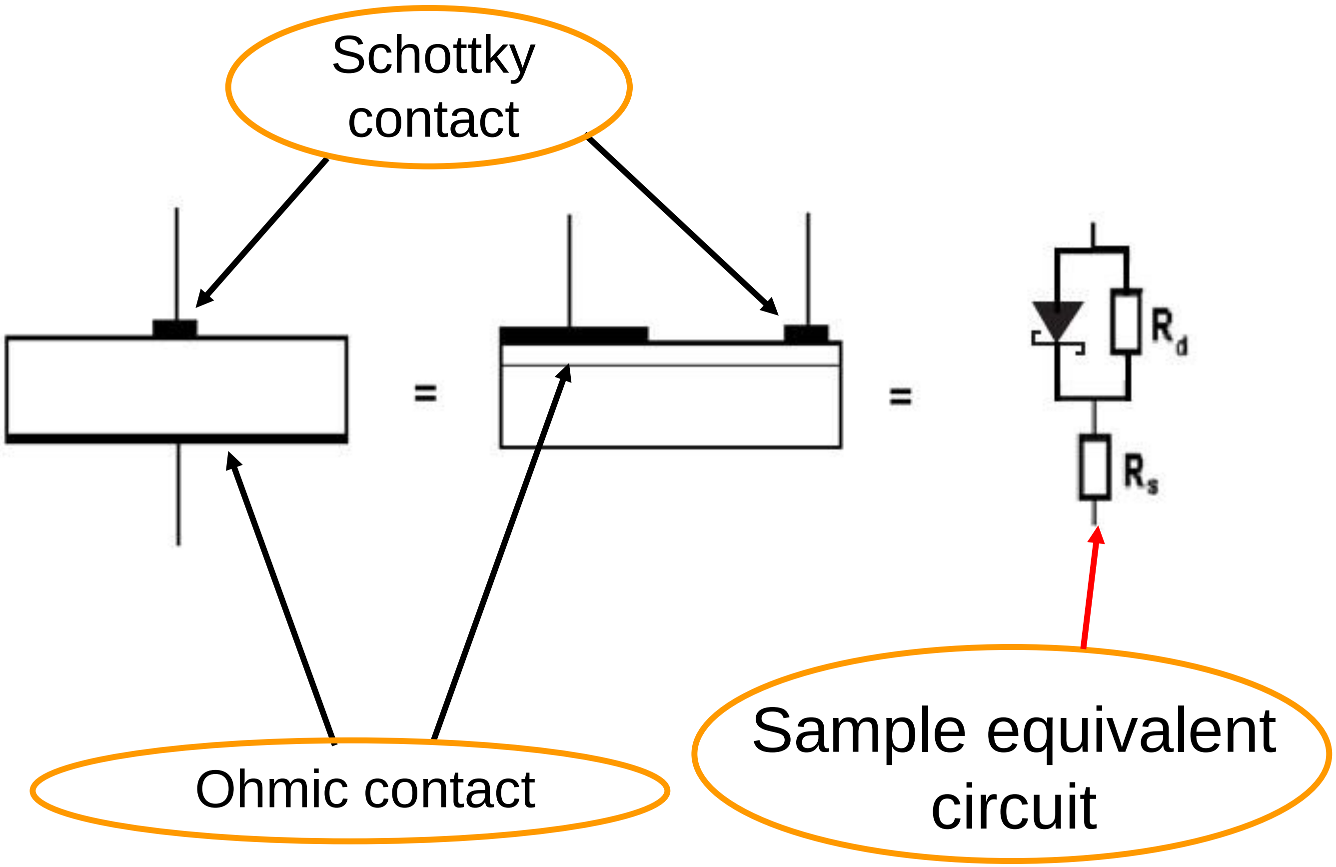

Other examples:

1) Interfacial layer.

2) Barrier height fluctuations.

3) Recombination in the depleted region W (n~2).

# *The real device: equivalent circuit*



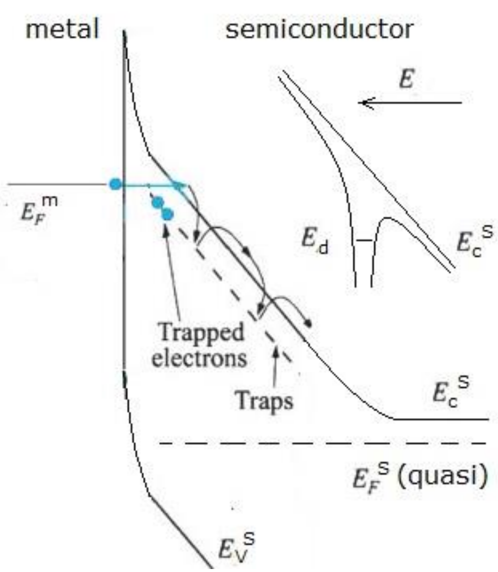

$$I = A\,J_0\,exp\left(\frac{e\,(V - IR_S)}{nk_BT}\right)\left[1 - exp\left(\frac{-q\,(V - IR_S)}{k_BT}\right)\right] + \frac{(V - IR_S)}{R_d}$$

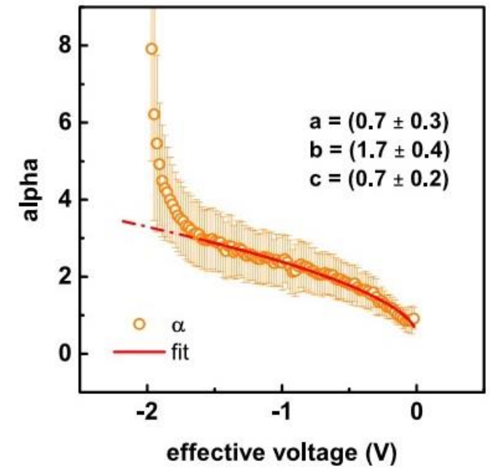
# *The leakage mechanism: $R_d$*

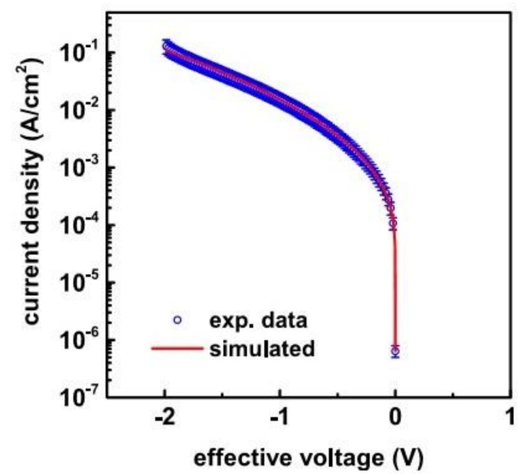
- Reverse current characteristics can be analyzed using a differential approach:[1]

$$\alpha(V) = \frac{V}{I}\frac{dI}{dV} \quad \text{if} \quad I \propto V^a exp(bV^c) \quad \text{then} \quad \alpha(V) = a + bcV^c$$

- a~0.5 points to defective channels conductions and b ~2 Frenkel-Poole enhancement.[2]



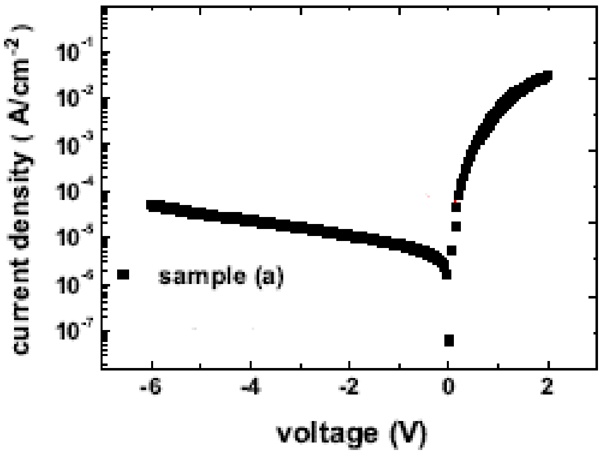

| a | b | c |
|---|---|---|
| 0.6 – 0.7 | 1.2 – 1.9 | 0.6 – 0.7 |

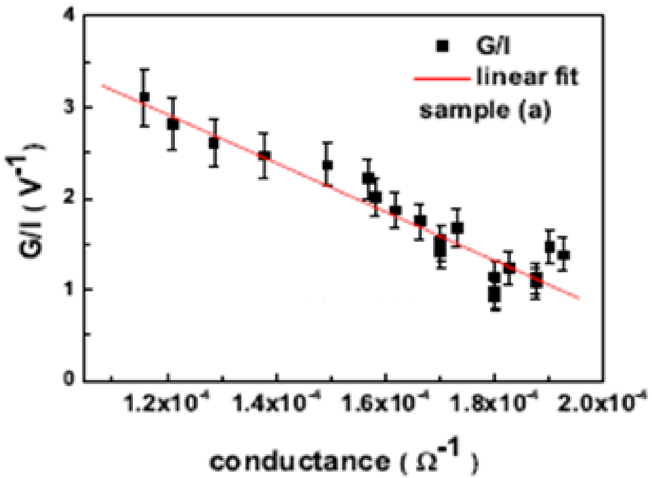
(*) After R. Schifano et a.l Appl. Surf. Science 149067, 552 (2021)).


[1] G.D. Bagratishviliet al. Phys. Status Solidi A 65, 701 (1981).

[2] P. Blood, and J.W. Orton, The Electrical Characterization of Semiconductors: Majority Carriers and Electron States, Academic Press, London, 1992.

# I-V to determine $R_S$ and n (Werner method)




Schottky contact in the thermionic emission regime current with reverse characteristics already analyzed:

$$I = I_0 \exp(e(V - IR_S)/nk_BT)$$

when $e(V - IR_S) \gg k_BT)$

$$\frac{G}{I} = (e/nk_BT)(1 - GR_S)$$

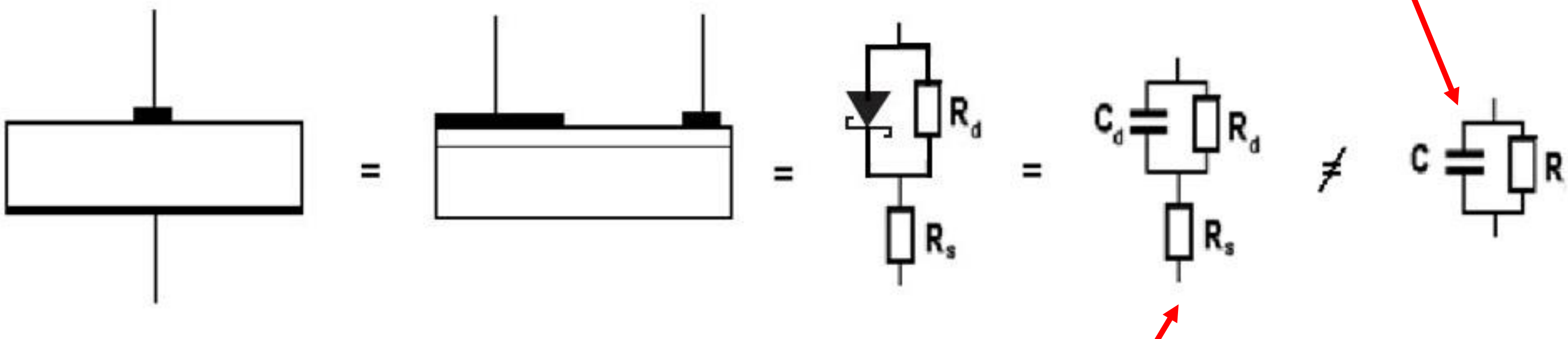
$n \approx 6$ $\qquad$ $R_S = (44\ \pm 6) \cdot 10^2$

[1] R. Schifano et al. phys. stat. sol. (a). **8**, 205 (2008).

[2] J. H. Werner, Appl. Phys. A **47**, 291 (1998)

# *The real device: equivalent circuit reverse bias case (details)*

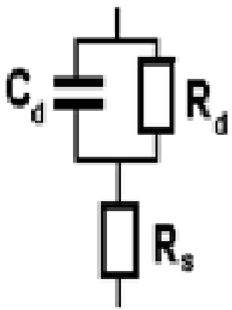
Instrument equivalent circuit



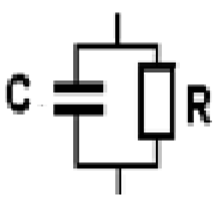

Sample equivalent circuit

$R_S$ has to be known prior to measure the capacitance.

# *Effect of $R_S$ on the capacitance measurements*




$$= Z^{-1} = \frac{\varpi^2 C_d{}^2 R_s + \frac{1}{R_d}\left(1+\frac{R_S}{R_d}\right)}{\left(1+\frac{R_S}{R_d}\right)^2 + \varpi^2 C_d{}^2 R_S^2} + j\frac{\varpi C_d}{\left(1+\frac{R_S}{R_d}\right)^2 + \varpi^2 C_d{}^2 R_S^2}$$




$$= Z^{-1} = \frac{1}{R} + j\varpi C$$

$$R_S << R_d \qquad \varpi C_d R_S << 1$$

$$C \rightarrow C_d$$

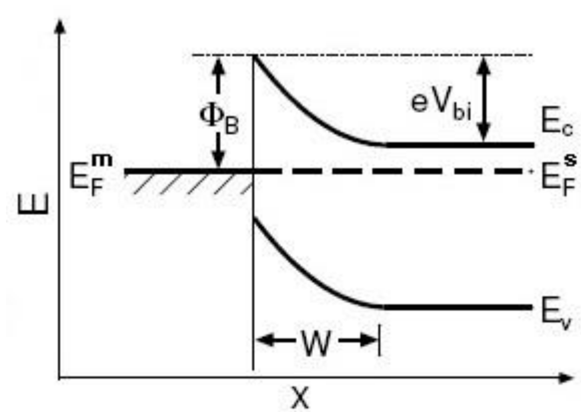
# *C-V measurement of a Schottky diode*

- The capacitance of a Schottky diode vs reverse bias ($V_R$) in case of constant effective doping ($N_D$ - $N_D$):[1]

$$C^{-2} = \left(\frac{2}{A^2 e\,(N_d - N_a)\varepsilon_0\varepsilon_r}\right)\left(V_{bi} + V_r - \frac{k_B T}{e}\right)$$

- Plotting $C^{-2}$ *vs* $V_R$ can be used to evaluate $V_{bi}$ .

Possibility to measure $\phi_B$ if ($E_c$ –$E_F$) can be determined.

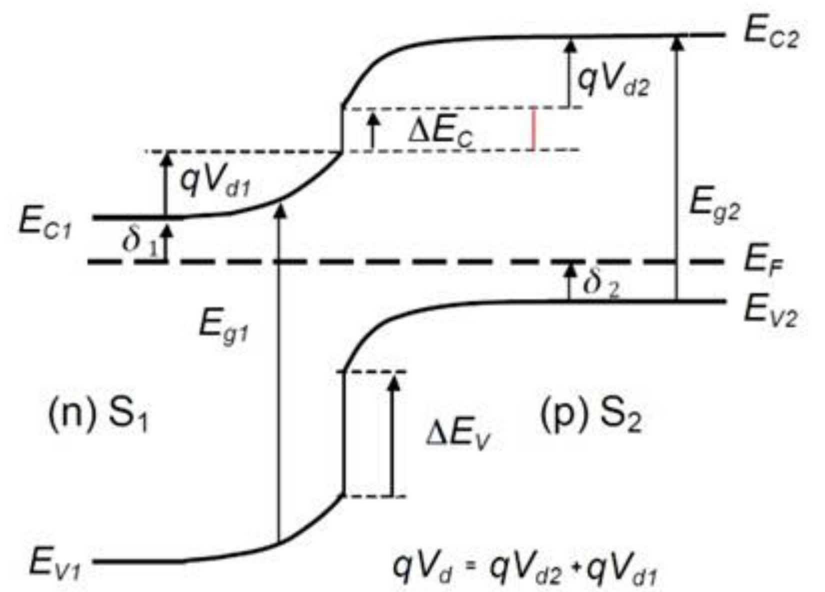



[1] E.H. Rhoderick, R.H. Williams, Metal-Semiconductor Contacts, Oxford University Press, 1988.

# C-V measurements to measure the conduction band misalignment

- Anderson model equivalent to the Schottky-Mott limit

- The conduction band offset $\Delta E_C$ is given by




$$\Delta E_C = E_{g2} - (qV_d + \delta_1 + \delta_2)$$

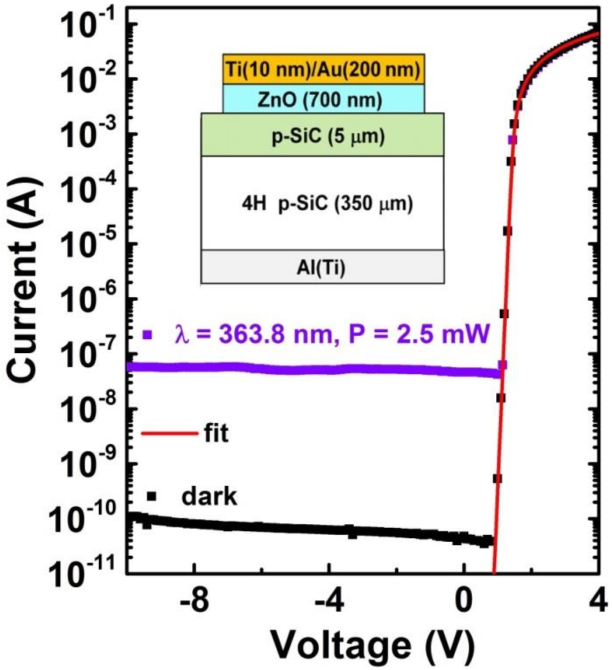
with $\delta_1/\delta_2$ equal to

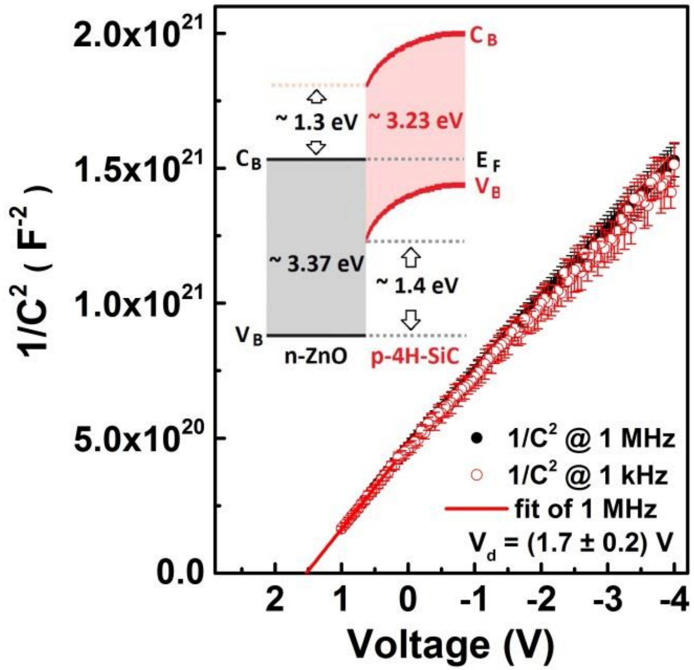
$$n_{S1} = \int_0^{+\infty} \sqrt{2E}\,\frac{{m_{S1}}^{3/2}}{\pi^2}\,\frac{1}{exp\big((E+\delta_{S1})/k_B T\big)+1} \qquad p_{S2} = \frac{1}{4}\left(\frac{2k_B T m_{S2}}{\hbar^2 \pi}\right)^{\frac{3}{2}} e^{\frac{-\delta_{S2}}{k_B T}}$$

and $qV_d$ that can be measured by C-V considering that:

$$C_d = A\sqrt{\frac{e\varepsilon_{S1}\varepsilon_{S2}n_{S1}p_{S2}}{2(\varepsilon_{S1}n_{S1}+\varepsilon_{S2}p_{S2})}}\frac{1}{\sqrt{V-V_d}} \Rightarrow \frac{1}{{C_d}^2} \propto (V - V_d)$$

# Example: the n-ZnO/p-4H-SiC heterostructure




(*) After M. Guziewicz, R. Schifano et al. Appl. Phys. Lett. **107,** 101105 (2015).

[1] H. B. Fan et al. Appl. Phys. Lett. **92**, 192107 (2008)

• Mesa structures with a semitransparent Al/Ti Ohmic back contact (~10% transmittance).

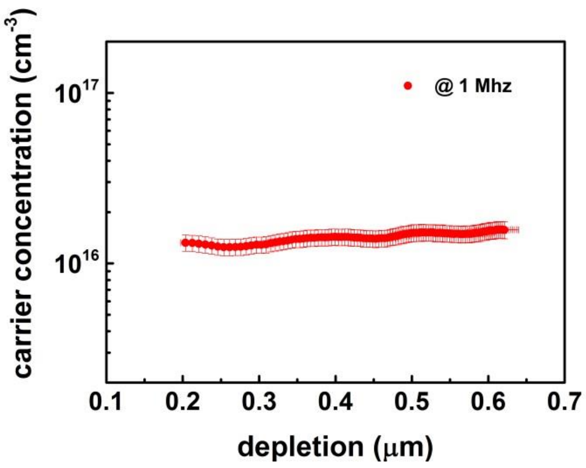
• High rectification ratios ($10^9$), ideality factor ~1 (1.17±0.04), leakage current density (~6 $10^{-8}$ A/cm$^2$), (~$10^3$) light to dark reverse current ratio.

• Type II band alignment, $\Delta E_c$=(1.3±0.2) eV in agreement with the values extracted from XPS measurements (1.5±0.2) eV.[1]

# *C-V measurement of a Schottky diode: effective donor profile (beyond the uniform approximation)*

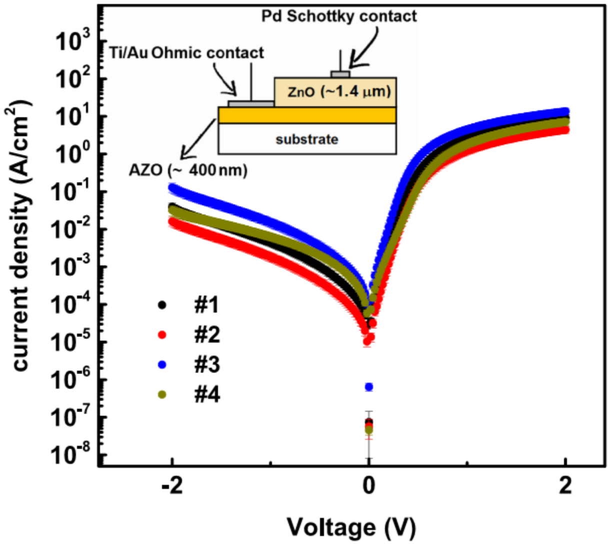
- The profile of the effective donor concentration $N_{eff}$ (electron responding to the probing signal).

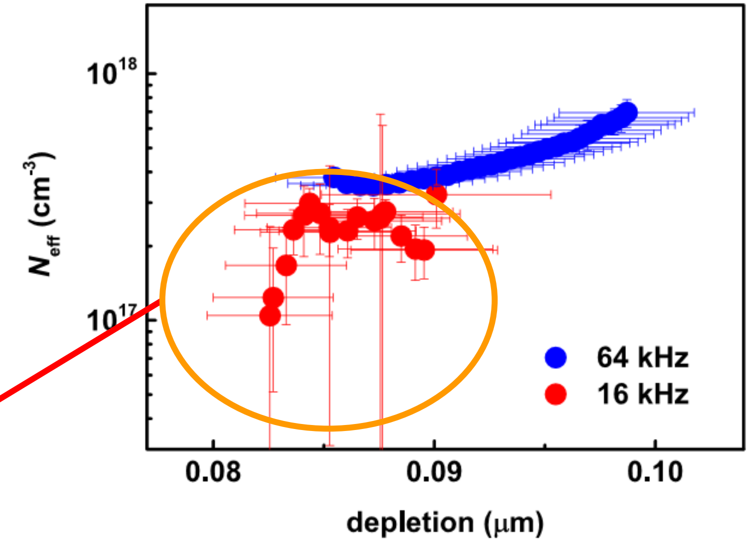
$$N_{eff}(W) = \frac{1}{e\,\varepsilon_0\,\varepsilon_r\,A^2}\frac{C^3}{\frac{\partial C}{\partial V}} \qquad \text{with} \qquad W = \frac{\varepsilon_0\,\varepsilon_r\,A}{C}$$

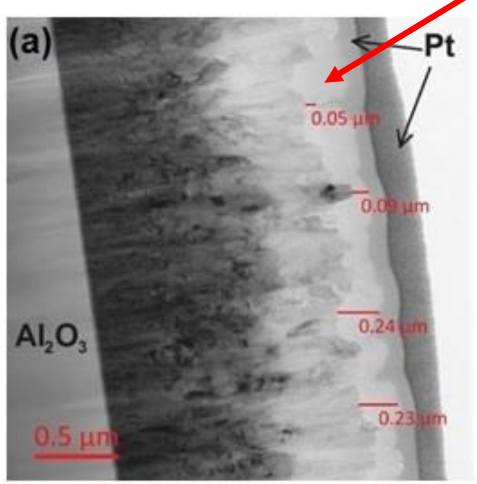



- The profile of the effective donor concentration $N_{eff}$ in the n-ZnO/p-4H-SiC heterostructure discussed in the previous slide.

# *Effective donor profile:example*




- TEM analysis evidenced presence of an O-rich polycristalline/amorphous region on the ZnO surface/interface.

- $O_i$(oct)/$V_{Zn}$ theoretically anticipated to be acceptor like defects consistent with the $N_{eff}$ profile.[1]

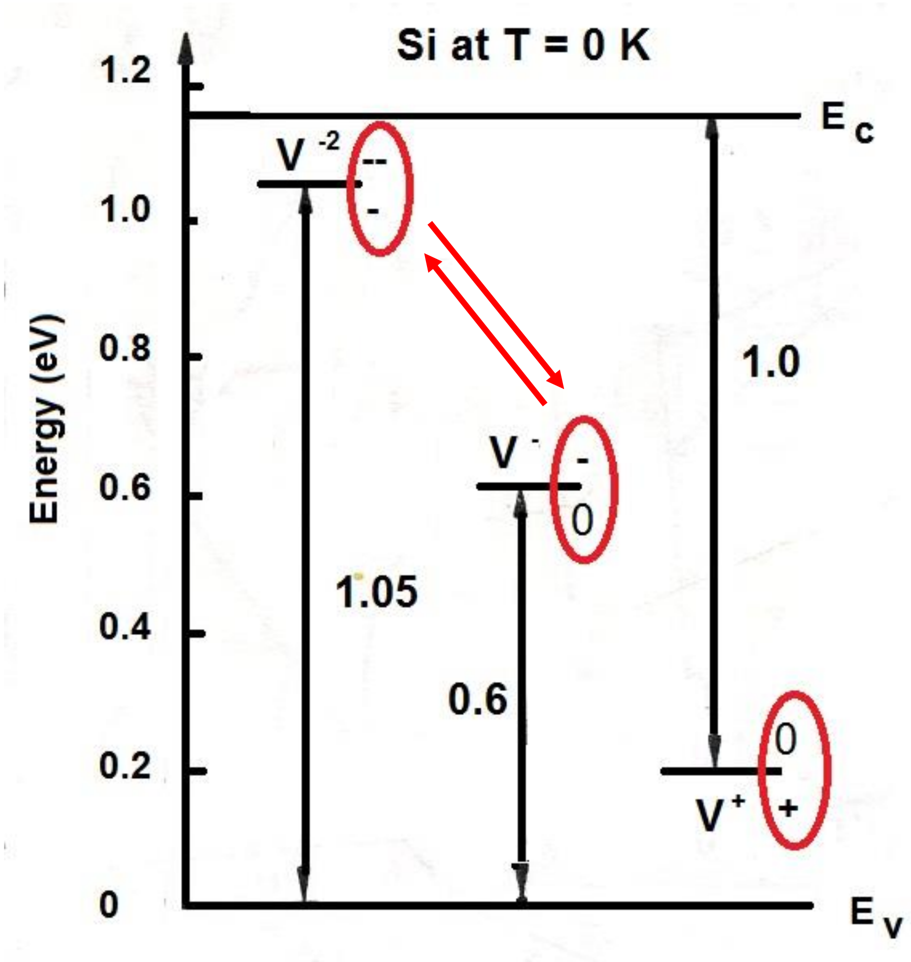
(*) After R. Schifano et a.l Appl. Surf. Science 149067, 552 (2021)).


[1] A. Janotti et al., Phys. Rev. B 76, 165202 (2007)

# *Outline pt.2*

1. Defects characteristics.
2. Deep level transient spectroscopy and Laplace deep level transient spectroscopy: how it is working and examples.
3. Thermal admittance spectroscopy: how it is working and examples.
4. Towards electrical defects assignment: examples.

# *Electrically active defects in a semiconductor (beyond shallow donors)*




- Deep levels strongly localized.

- The same defect can present several charge states (provide different levels).

- Adding an electron does not necessary means reducing the enthalpy-activation energy (negative-U).

## *Interaction of a defects with the bands*

- Capture of carriers occurs via a characteristics quantity, the capture cross section, via

$$c_n = \sigma_D \langle v \rangle n$$

- Emission towards the bands follows an exponential emission law

$$e_n^D = \sigma_{Di} T^2 \gamma \, exp\left(\frac{-E_D}{k_B T}\right) \quad \text{with} \quad \gamma = 2\sqrt{3}\,(2\pi)^{\frac{3}{2}} k^2 \frac{m\, m^*}{h^3}$$

$$e_n^D / c_n \simeq exp\left(\frac{E_D - E_F}{k_B T}\right)$$

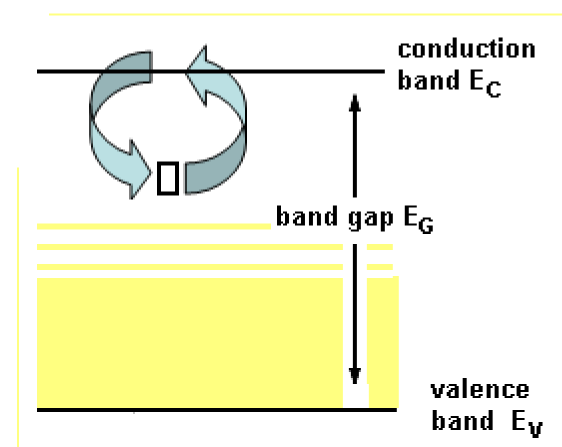
# *Defects: carrier emission/capture*

Shockley-Read-Hall statistics for majority carrier trap:

- the defect is emitting mainly towards the closest band.
- capture determined by the Fermi level position respect to the position of the defect related level into the bandgap

n-type semiconductor

majority carriers trap are defects with levels in the upper part of the band gap



## *TAS/DLTS what can they be used for?*

- Determining signatures (capture cross section/enthalpy-activation energy) of electrically active defects and their concentration.
- Based on capacitance measurements.

## *Requirements for TAS/DLTS*

- Relatively good rectifying junction.
- Depletion region extending mainly in the material to be studied i.e. Schottky contacts, $n^+$-p or $p^+$-n junctions/heterostructures .

# *Principle of TAS/DLTS measurements*

- Study of the changes in capacitance due to the emission/capture of majority carriers by electrically active defects present in the depleted region.

- Capacitance changes acquired at different temperatures either temperature scans or different fixed temperatures depending on the accuracy required.

# DLTS: how to get a transient (Schottky diode case)

1) Steady state: Schottky junction in reverse bias.

2) Filling pulse: charging of the defect.

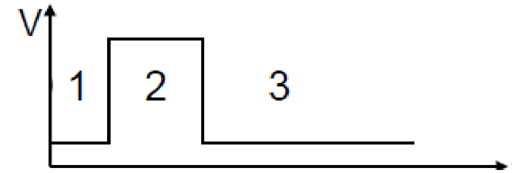
3) Back to the initial reverse bias: observing the defect decharging.

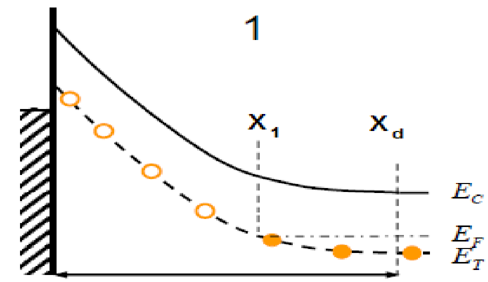
$$n_{filled} = N_T \exp(-e_D t) \propto \Delta C(t)$$

$$e_D = \beta T^2 \sigma_{app} \exp\left(\frac{-\Delta H}{k_B T}\right)$$

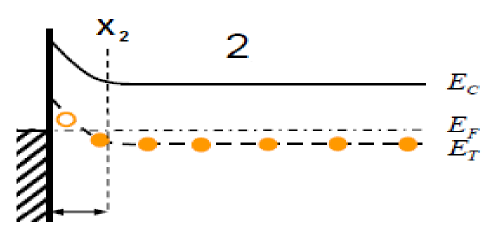
$$\Delta C(t) = \underbrace{C_\infty \frac{1}{2}\left(\frac{x_1^2 - x_2^2}{x_d^2}\right)\frac{N_T}{N_D}}_{\Delta C_0} \exp(-e_D t)$$

$$N_T \ll N_D$$

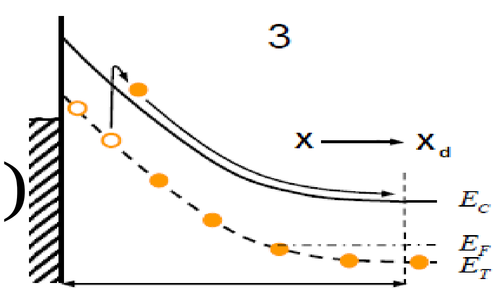



Reverse biased junction-steady

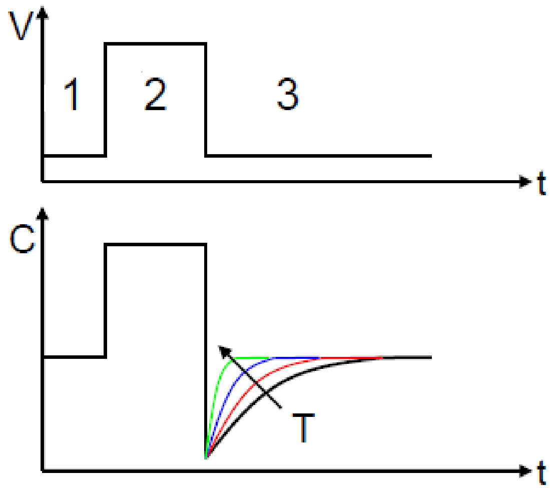



Filling pulse: filling of the defect




Emission from the defect: transient

# *DLTS principle how to analize the acquired data*

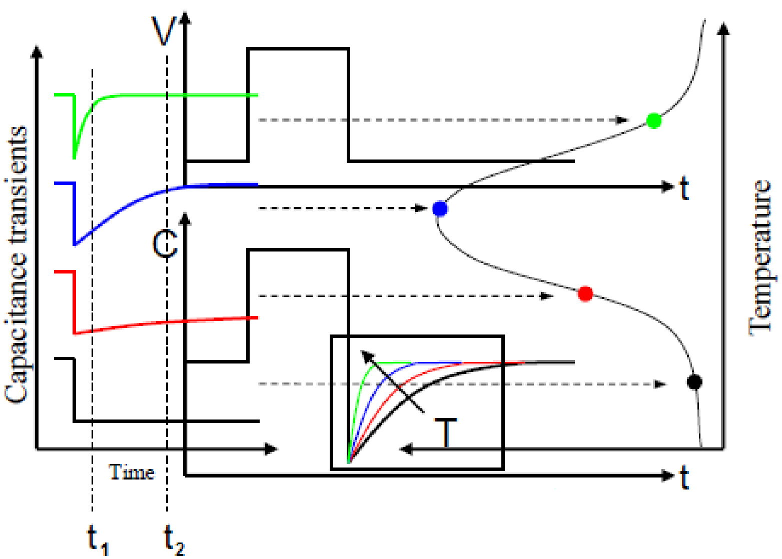



- Measuring the transients at different temperature.

- The DLTS spectra is the result of post measurement calculations.

- Transient is sampled at time $t_1$ and $t_2$ and substracted*.

- If $t_1$ fixed and $t_2$ varied the maximum will shift.




(*) After D. V. Lang J. Appl. Phys. **45,** 3023 (1974)

## *The DLTS spectra*

$$S_{DLTS}(T) = \frac{1}{t_i}\int_{t_p}^{t_p+t_i} \Delta C(t,T)\cdot w(t-t_p)\cdot dt =$$

$$= \frac{1}{t_i}\int_{t_p}^{t_p+t_i} \Delta C_0 \exp(-e(T)t)\cdot w(t-t_p)\cdot dt$$

the weighting function w is establishing the ***e(T)*** "window" for which ***e(T)*** is "resonant" with the weighting function ⇨ DLTS max.

Varying $t_i$ "window" changes the value of ***e(T)*** "resonant".

⇩

An Arrhenius plot for ***e(T)*** can be constructed

# *Possible weighting functions (among the others)*

1) Box-car method (original Lang approach see two slides above).

2) Lock-in based on

$$w(t-t_p) = \begin{cases} -1 & t_p \le t < t_p + t_W/2 \\ +1 & t_p + t_W/2 \le t \le t_p + t_W \end{cases}$$

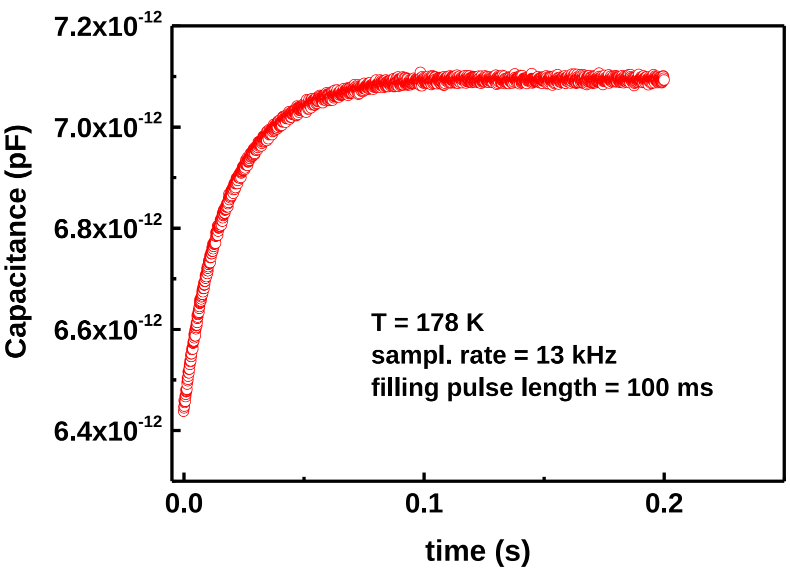
3) GS4 and following [1]

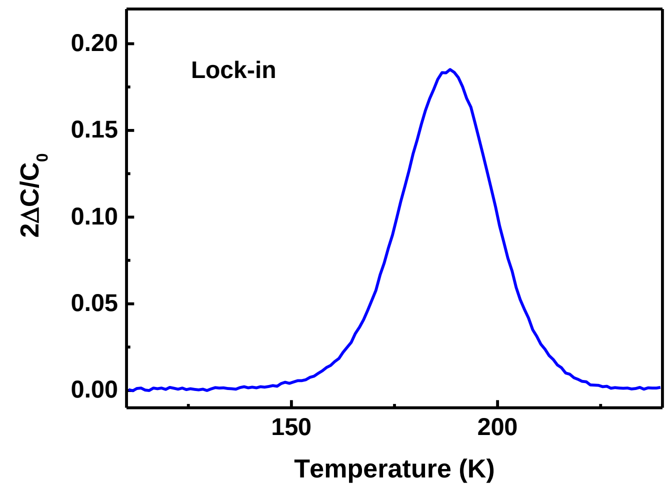
$$w(t-t_p) = \begin{cases} +2 & t_p \le t < t_p + t_W/4 \\ -26 & t_p + t_W/4 \le t < t_p + t_W/2 \\ 48 & t_p + t_W/2 \le t < t_p + 3t_W/4 \\ -24 & t_p + 3t_W/4 \le t \le t_p + t_W \end{cases}$$

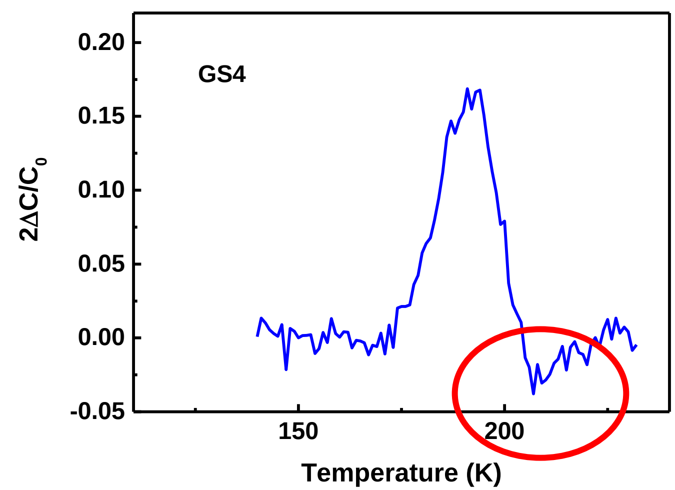
[1] A. A. Istratov J. Appl. Phys. **82** , 2965 (1997)

# *The choice of the weighting function w*

Measurements performed on
Pd Schottky contacts to ZnO




- $w_{\text{lock-in}}$ less selective than $w_{GS4}$.
- $w_{\text{lock-in}}$ more stable than $w_{GS4}$.
- Possible presence of false roots and intensity reduction.

# *Laplace DLTS*

Large instrumental broadening in ordinary DLTS spectra

Resolve time constant ratios larger than ~ 15-12 (5)

The spectral density of the transient *F(s)* can be determined by inverting

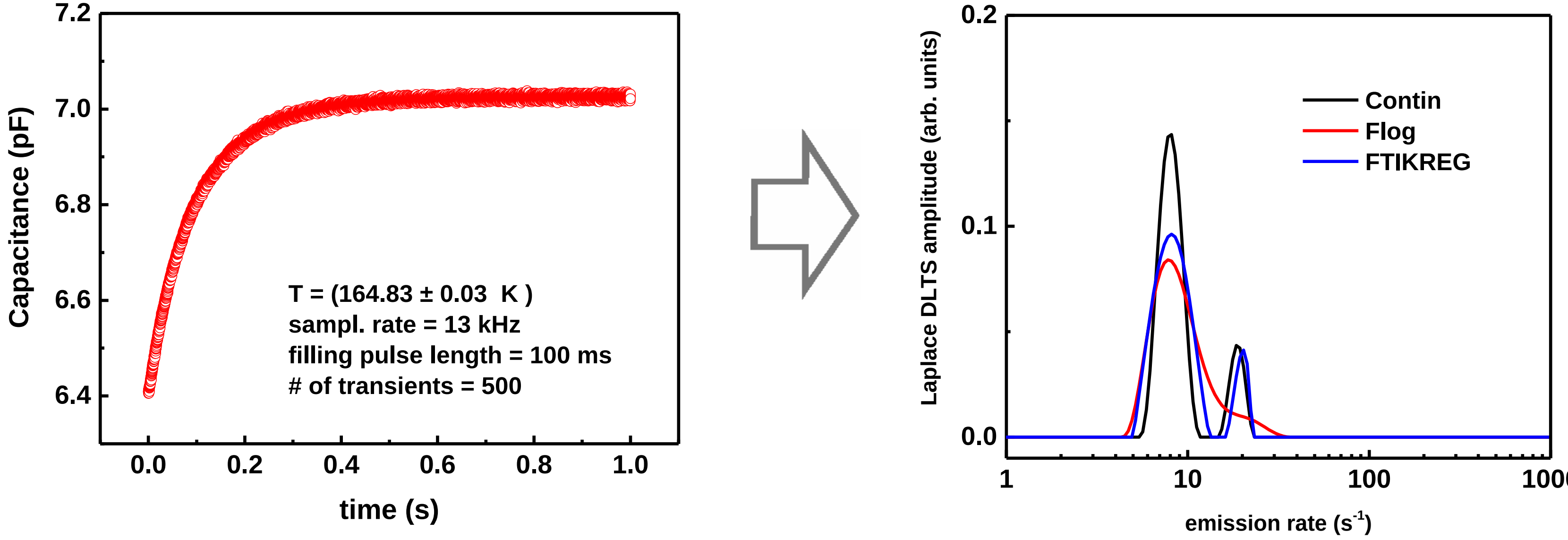
$$\Delta C(t) = \int F(s) \exp(-st)\, ds$$

Requires isothermal averaging to achieve a "good enough" signal to noise ratio

Possible to study the intrinsic broadening
Resolve time constant ratios larger than ~ 2

After L. Dobaczewski et al. J. Appl. Phys. **96**, 4689 (2004)

# *On the analysis of Laplace DLTS transients*

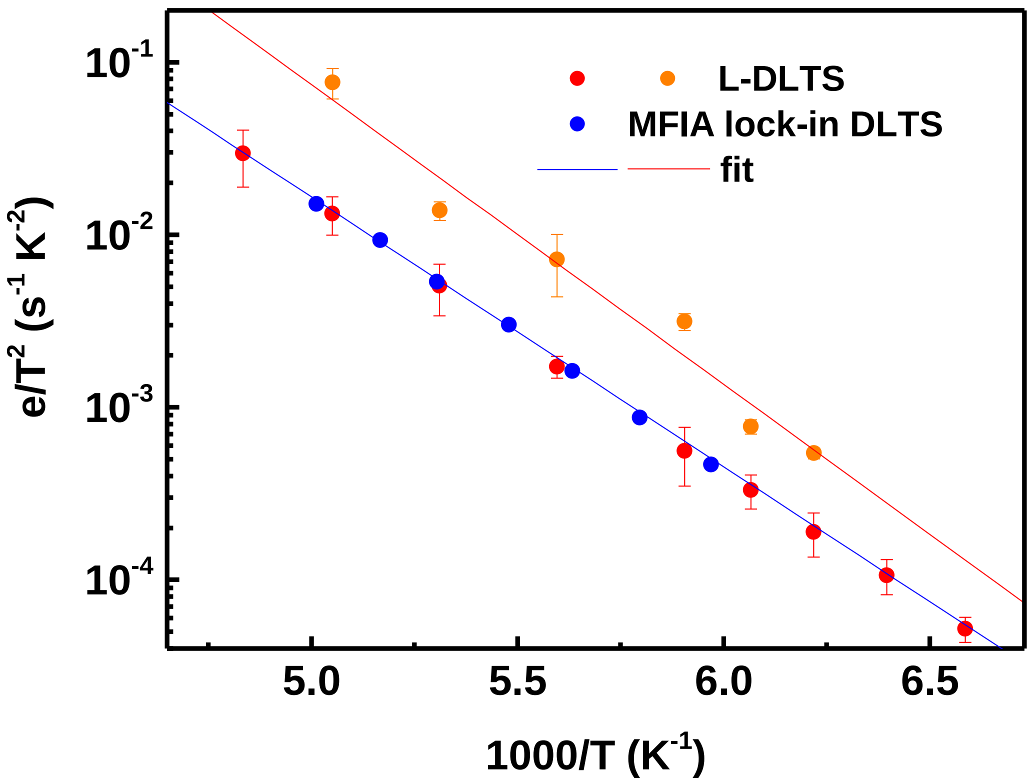



Measurements performed on the same sample as previously.

- Several inversion routines can be used.
- Clear evidence for the presence of two components with emission rate ratio ~2.

http://info.ifpan.edu.pl/Dodatki/WordPress/laplacedlts/?page_id=9#TPU

# Defect properties




- From the Arrhenius plot of $eT^{-2}$ vs $T^{-1}$ the defect enthalpy and the apparent capture cross section is extracted:

$$\Delta H \begin{cases} (0.31 \pm 0.1)\ eV \\ \sim 0.34\ eV \end{cases} \qquad \sigma_{app} \begin{cases} (1.2 \pm 0.4) \times 10^{-15} cm^2 \\ \sim 5 \times 10^{-14}\ cm^2 \end{cases}$$

# *The $E_3$ / $E'_3$ levels*

$$\Delta H \sim 0.3 \text{ eV} \qquad \sigma_{app} \sim 10^{-14} - 10^{-16}$$

- *Labelled as $E_3$ / $E'_3$ .*

- *Present in most samples independently on the growth techniques concentrations up to $\sim 10^{17}$ $cm^{-3}$ .*

- *Attributed both to $V_O$ [1] related defects and to Fe/Ni impurities[2] .*

$$e_D \sim 10^5 - 10^6 s^{-1} \quad at \quad 300K$$

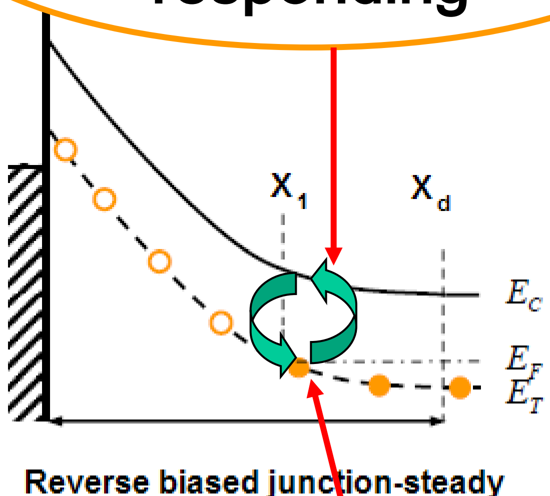
⇩

**Important!** It can be picked up during *C-V* measurements at 300 K

[1] J. Simpson et al. J. Appl. Phys. **63**, 1781 (1988)
[2] Y. Jiang, et al. J. Appl. Phys. **101**, 093706 (2007)

# *TAS principle of the measurement*

$f_T$ << $e_{D1}$(T) the centers in $x_1$ are **responding**




$f_T$ >> $e_{D1}$(T) the centers in $x_1$ are **not responding**

- Fixed reverse bias.
- Capacitance and conductance measured with probing frequency $f_T$ ($\omega_T = 2\pi f_T$).
- Temperature is scanned.
- Only majority carriers involved.
- Responding defects at the edge of the depletion region i.e. negligible electric field effects.

# *TAS spectra (not formal)*

- Pure capacitance = Schottky contact: *Q* and *V* in phase

- Capacitance for a Schottky contact/junction with defects:

$$Q = \mathrm{Re}\left(Q_0 e^{j(\omega t - \varphi(T))}\right) = Q_0 \cos\left(\omega t - \varphi(T)\right) =$$

$$= Q_0 \left(\cos \omega t \cos \varphi(T) + \sin \omega t \sin \varphi(T)\right)$$

Delayed defects response

By lowering the temperature it is observed:

1) a capacitance drop

2) a conductance increase.

# TAS spectra (more formal)

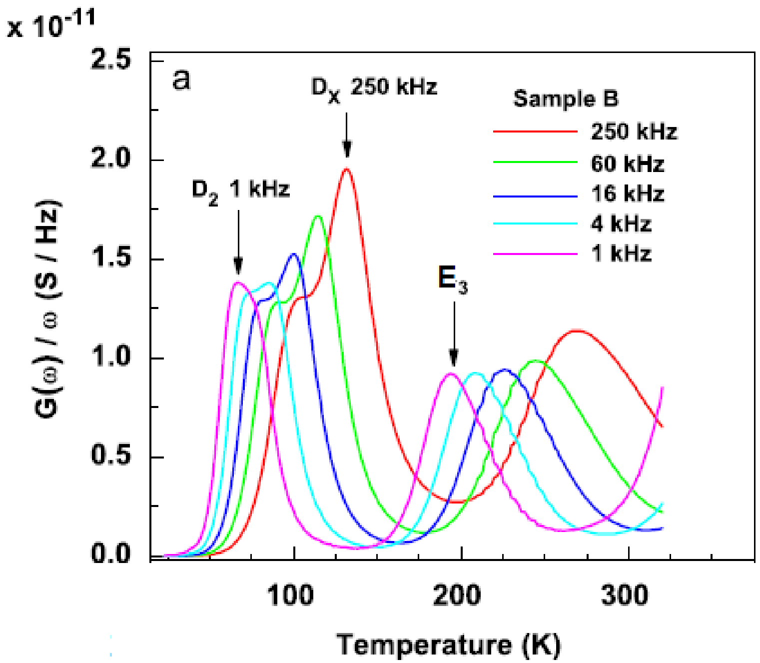
$$\Delta C = C_{HT} - C_{LT} \propto \frac{N_T}{N_D} \frac{(1 - x_1/x_d)}{(1 - (x_1 N_T)/(x_d N_D))}$$

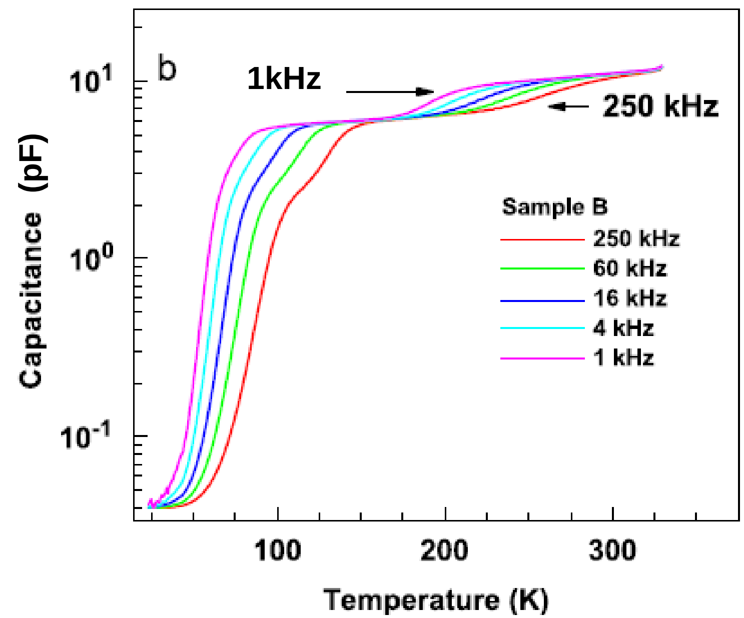
$$\frac{G(\omega_T)}{\omega_T} = \Delta C \frac{\frac{\omega_0}{\omega_T}}{1 + \left(\frac{\omega_0}{\omega_T}\right)^2}$$

$$\frac{\omega_0}{T_{max}{}^2} \propto exp\left(\frac{-\Delta H}{k_B T}\right)$$

- Cantilever effect i.e. $\Delta C \rightarrow 0$ for increasing reverse voltages.
- No limitation on the $N_T/N_D$ ratio.
- The probing frequencies have to be comparable to the emission rate ($\gtrsim 1/\pi$ times).

# *On the analysis of TAS spectra: an example (1)*



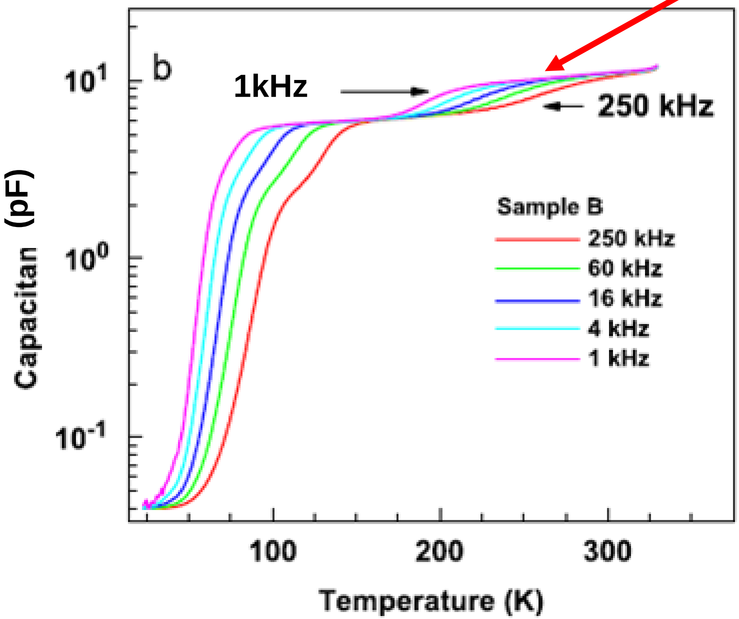

- Presence of leaking mechanisms may provide an increasing background in the conductance plot.

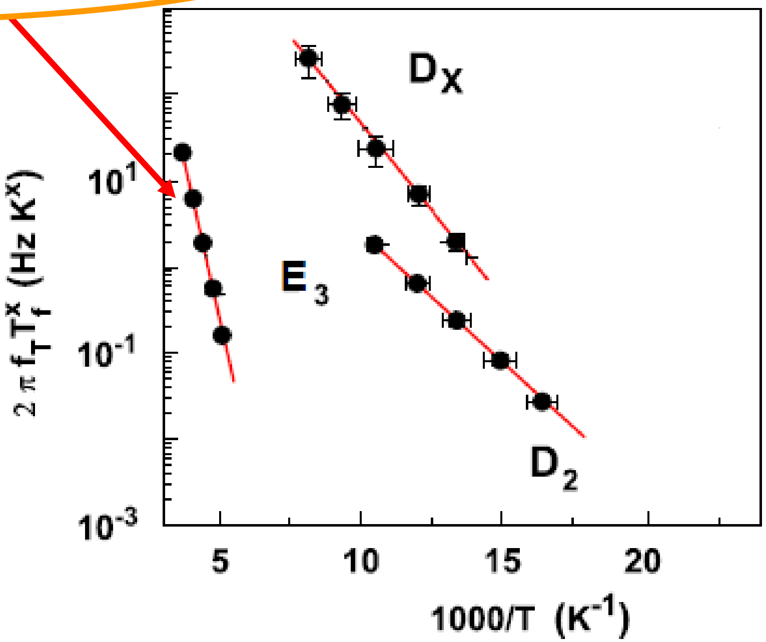
- Cantilever effect measurements particularly sensitive to the interfacial states.

(*) After R. Schifano et al. Physica B **404,** 4344 (2009)

# *On the analysis of TAS spectra: an example (2)*

$E_3$ is responding at 250 kHz



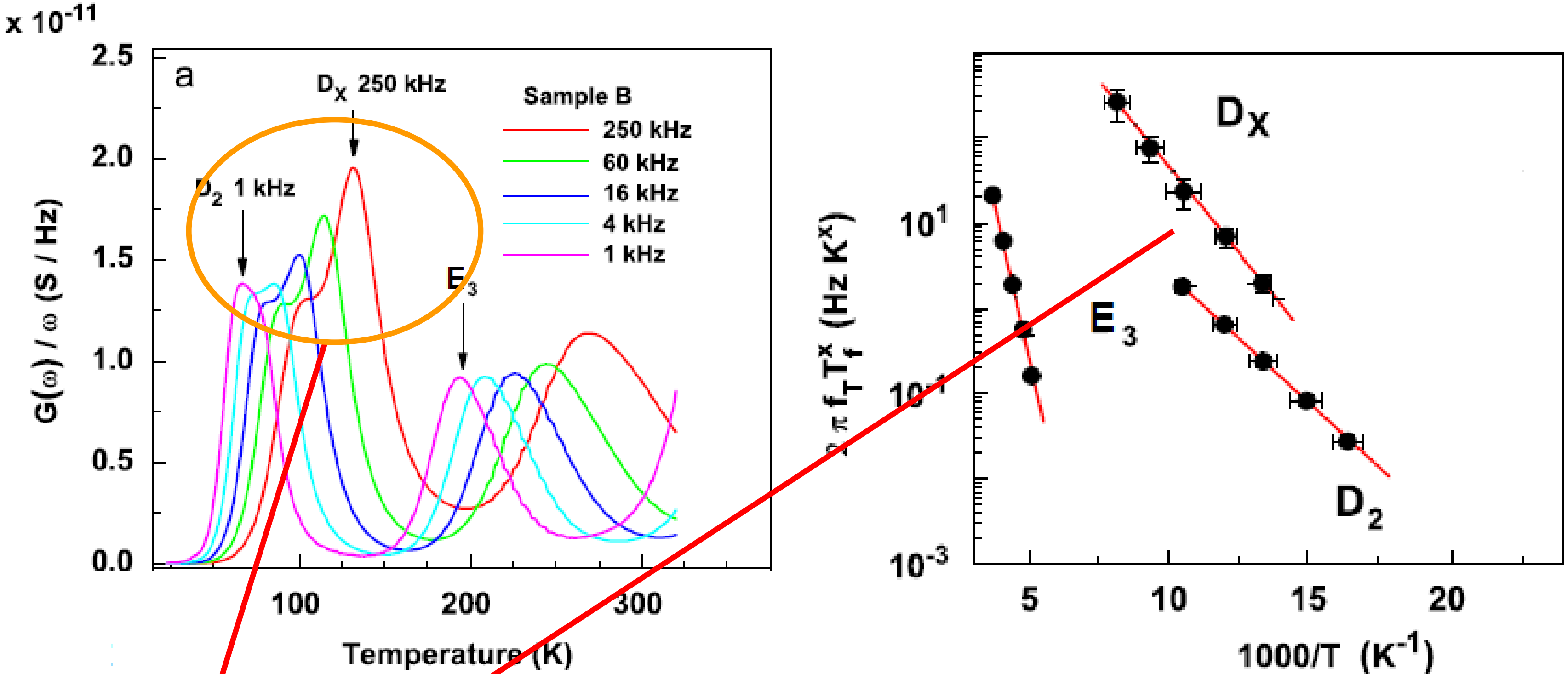




- From the Arrhenius plot of $\omega_0 T^{-2}$ vs $T^{-1}$ the defect enthalpy and apparent capture cross section is extracted (N.B. $\omega_0 \neq 2e$ in the general case).

$$\Delta H = (0.29\ \pm 0.03)\mathrm{eV} \qquad \sigma_{app} = (6 \pm 3) \times 10^{-16}\ cm^{-2}$$

(*) After R. Schifano et al. Physica B **404,** 4344 (2009)

# *On the analysis of TAS spectra: an example (3)*




- The $D_X$ temperature dependence points to a thermally activated process.

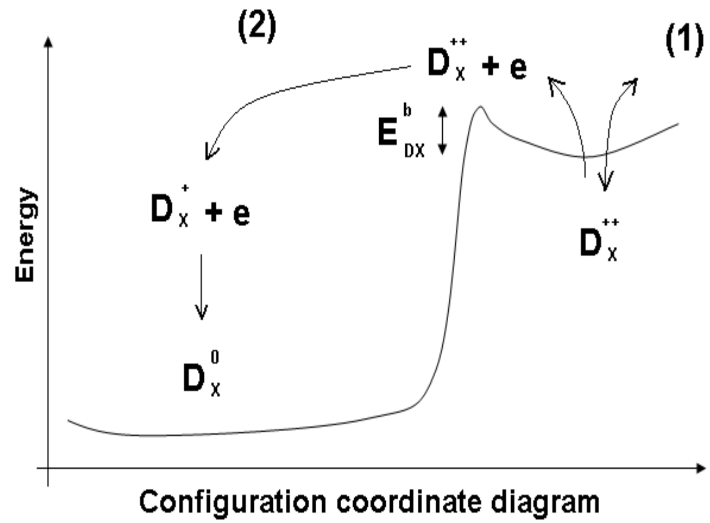
- Ordinary DLTS measurements do not reveal any signature corresponding to $D_X$.

(*) After R. Schifano et al. Physica B **404,** 4344 (2009)

# *The proposed model for $D_X$*

Two processes can occur:

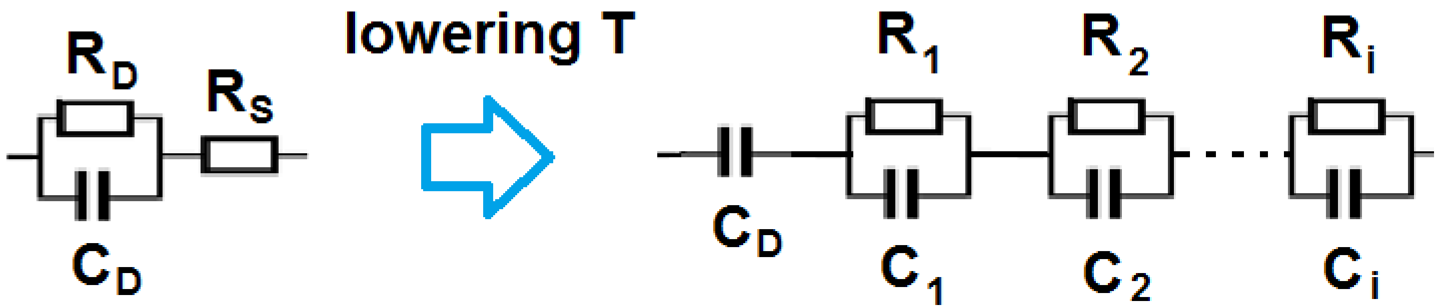
1) $D_X^{++}$ level probing → TAS peak.
2) Electron capture ($D_X^{++} \rightarrow D_X^{++}$ + e ) followed by the atomic reconfiguration and the capture of a second electron ($D_X^{+}$ + e→ $D_X^{0}$) → ordinary DLTS.




- $D_X$ negative-U defect possibly $V_O$.

- The high probing frequency permits to detect defects that are changing their configuration when charged (defects not so easy to detect with DLTS/L-DLTS).

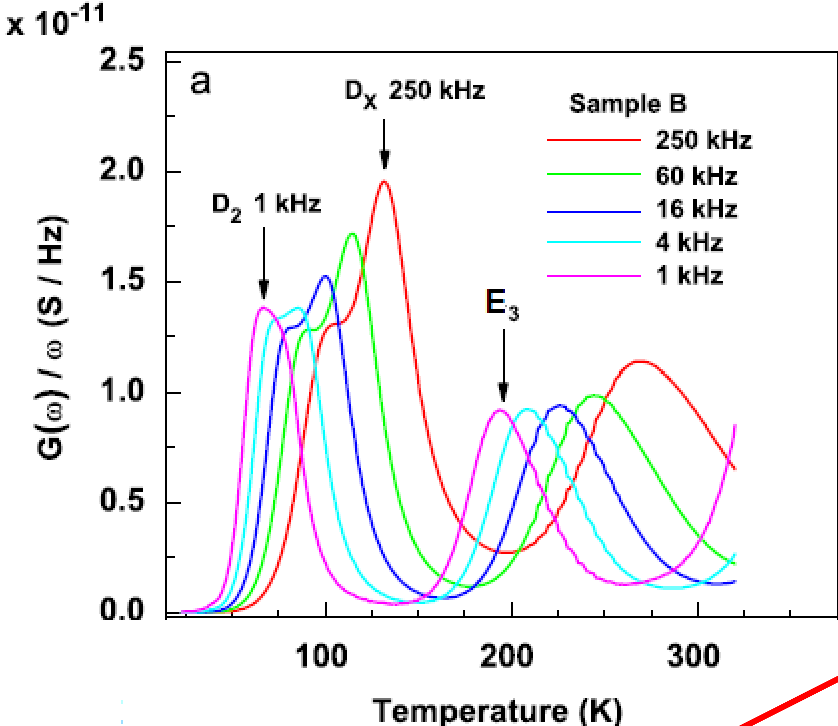
# *TAS spectra (freezing-out)*

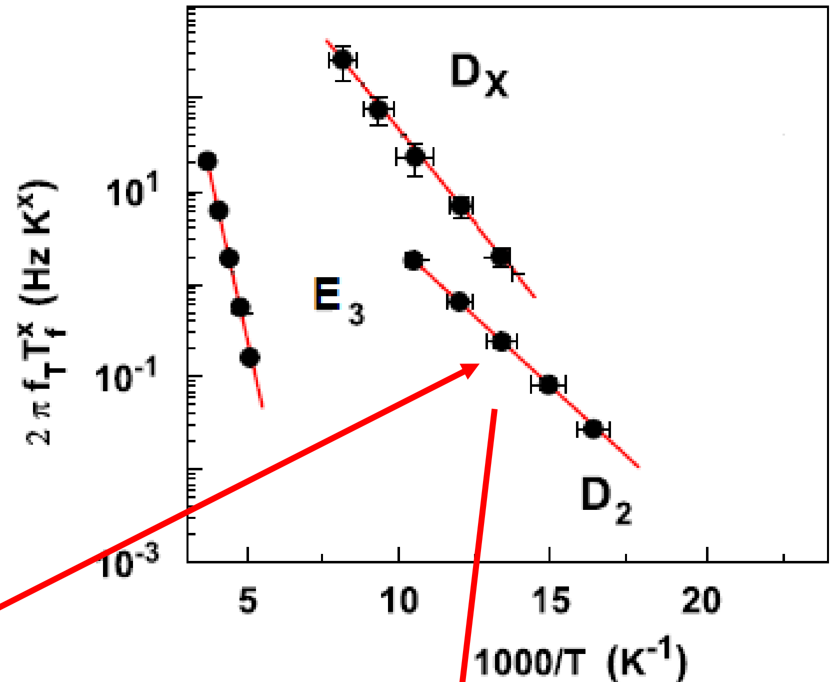



Similarly to ordinary TAS peaks the $\dfrac{G(\omega_T)}{\omega_T}$ freeze-out peak corresponds to $\dfrac{\Delta C}{2}$ and occurs for $C_D R_{tot} \omega_T = 1$

$$\left.\frac{2\pi f_T}{\mu(T)T^{3/2}}\right|_{\max} \propto \exp\left(\frac{-\Delta H}{k_B T}\right)$$

# *TAS: main donor parameters extractions*




- If $\mu(T)$ in the freezing-out temperature range is known $\Delta H$ can be evaluated.

$$\mu(T) \propto T^{\frac{3}{2}}$$

$$E_{D2} = (50 \pm 10)\, meV$$

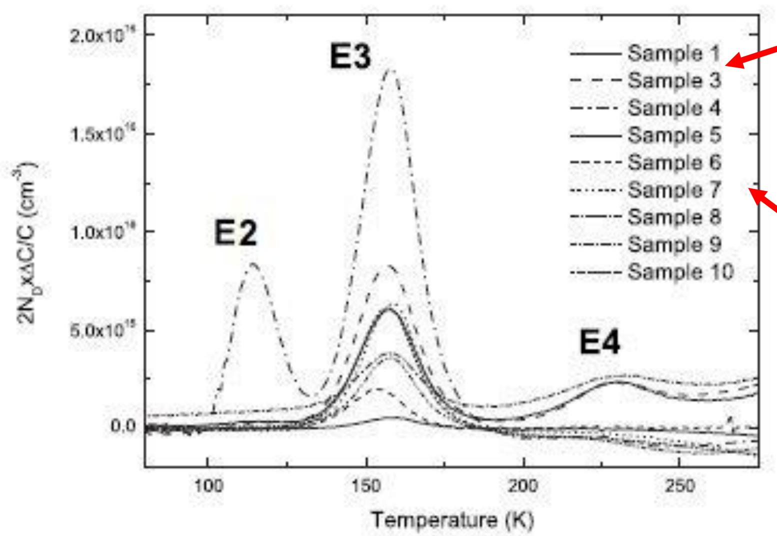
(*) After R. Schifano et al. Physica B **404,** 4344 (2009)

| DLTS | TAS |
|---|---|
| • Volume measurement → large reverse biasing preferred → good rectifying junction. | • $E_T - E_F$ cross region response → small reverse biasing preferred → not so good rectifying junction required. |
| • Diluition limit i.e. $N_D \gg N_T$. | • No diluition limit. No minority carriers injection. Negligible electric field in the probed region. |
| • Presence of electric field (Poole-Frenkel effect). | • Probing signal determining the investigated emission rates. Possible to detect defects with changing configurations. |
| • Possible minority carriers injection. | |
| • Rate window/transient time window limiting the range of investigated emission rates. | |

## *How to establish the nature of the defect*

- DLTS spectra is providing: $\sigma_{app}; \quad \Delta H; \quad N_T$

- Comparative studies are required: annealing, implantation, electron irradiation .... can be used to alter $N_T$ in establishing the chemical nature of the defect.

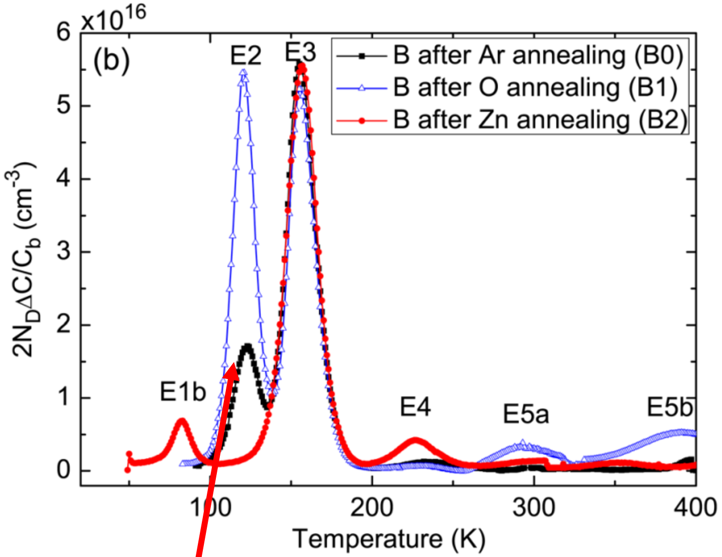


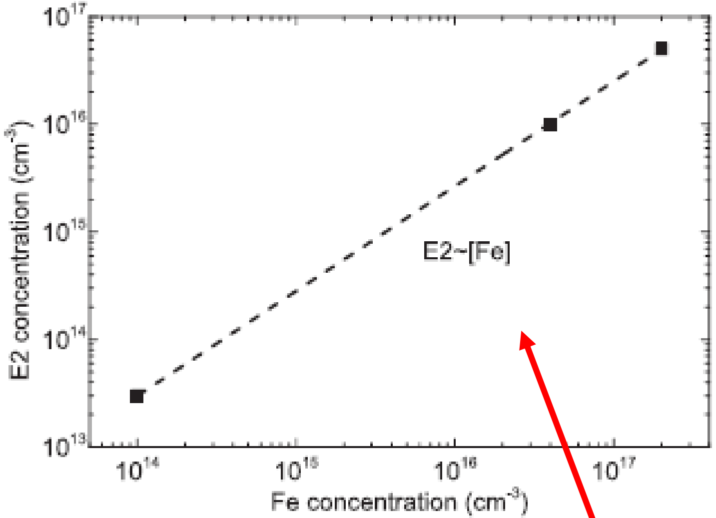

1,2 References

Annealed at 1100 - 1500 $^oC$ for 1 h in air

(*) After L. Vines E. Monakhov R. Schifano et al. J. Appl. Phys. **107**, 103707 (2010).

# *Example 1: an annealing study on ZnO*




Increases with annealing in $O_2$ at 1100 °C

$E_2$ accounts for ~ 30% of the total Fe concentration measured by SIMS

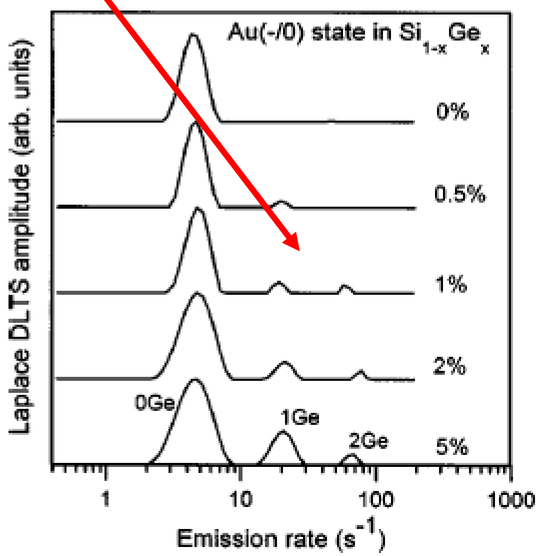
- $E_2$ involves Fe in a configuration enhanced by O-rich conditions such as Fe on Zn site

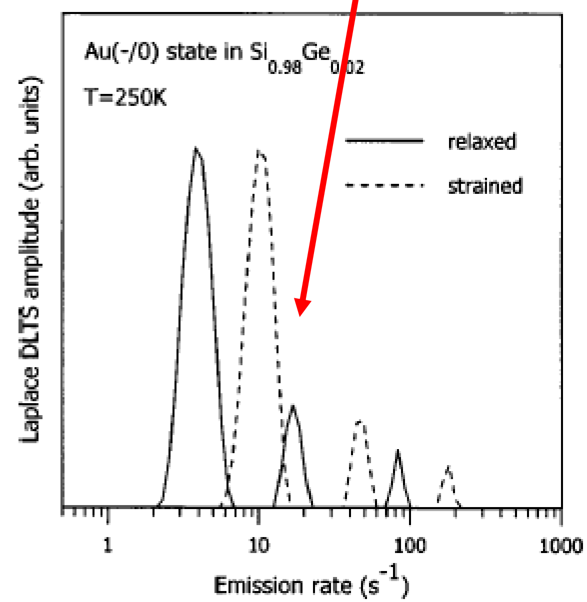
(*) After V. Quemener et al. Appl. Phys. Lett. **102, 232102** (2013).

# *An example: Laplace DLTS on SiGe*

Effect of the local enviroment on the Au acceptor in SiGe

Effect of the strain on the Au acceptor in SiGe




Laplace DLTS can be thought as a truly spectroscopic technique

(*) After L. Dobaczewski et al. J. Appl. Phys. 96 4689, 2004

NARODOWE CENTRUM NAUKI

UMO-2016/22/E/ST3/00553

# *Literature (books)*

1) S. M. Sze and M. K. Lee, **Semiconductor Devices,** John Wiley & Sons (2012).

2) E.H. Rhoderick, R.H. Williams, **Metal-Semiconductor Contacts,** Oxford University Press (1988).

3) P. Blood, J.W. Orton**The Electrical Characterization of Semiconductors: Majority Carriers and Electron States,** Academic Press, London (1992)**.**

NARODOWE CENTRUM NAUKI
UMO-2016/22/E/ST3/00553

# *Literature (articles)*

Alternative method to evaluate the series resistance

1) J. H. Werner, Appl. Phys. A **47**, 291 (1998)

DLTS/L-DLTS literature/links:

1) L. Dobaczewski, A. R. Peaker, and K. B. Nielsen, J. Appl. Phys. **96**, 4689 (2004)
2) http://info.ifpan.edu.pl/Dodatki/WordPress/laplacedlts/?page_id=9#TPU
3) Zurich Instruments Application Note

TAS literature:

1) J. L. Pautrat, B Katircioglu, N. Magnea, D. Bensahel, J. C. Phister and L Revoil, Solid State Electronics **23**, 1159 (1980)
2) R. Schifano, E. V. Monakhov, B. G. Svensson, W. Mtangi, P. Janse van Rensburg, and F. D. Auret, Physica B **404**, 4344 (2009)