DLTS with Boonton 7200

Deep Level Transient Spectroscopy

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7200 DLTS Users & Applications

Semiconductors

- Transistors
- Diodes
- ICs
- LEDs
- LCDs
- Optical Devices
- Fiber Components
- Thyristors
- Very high voltage devices
- Very high temperature devices

Material Research

Photovoltaic

Nanotechnology

Aerospace R&D

Medical R&D

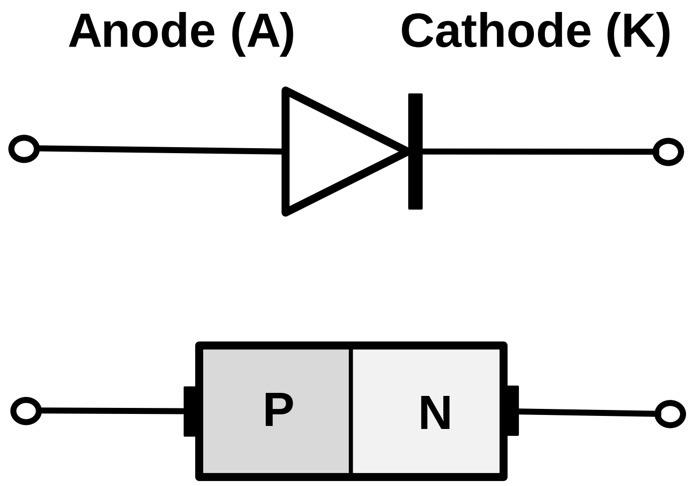
Military R&D

Automotive R&D

Webinar Overview

- Let’s Build a Diode
- Doping
- Semiconductors – Characteristics
- DLTS Measurements
- DLTS Measurement System
- Transient Data Analysis Software

Let’s Build a Diode



Periodic System of Elements (PSE)

- nonmetal
- metal
- transition metal
- metalloid

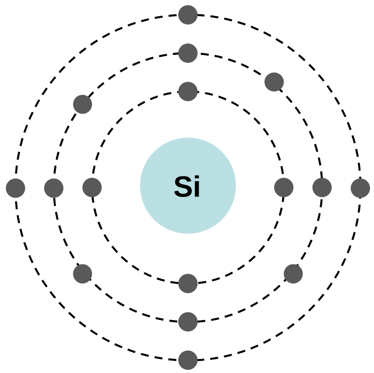
	1 1A	2 2A	3 3B	4 4B	5 5B	6 6B	7 7B	8 8B	9 8B	10 8B	11 1B	12 2B	13 3A	14 4A	15 5A	16 6A	17 7A	18 8A
1	1 **H** 1.008																	2 **He** 4.003
2	3 **Li** 6.941	4 **Be** 9.012											5 **B** 10.81	6 **C** 12.01	7 **N** 14.01	8 **O** 16.00	9 **F** 18.99	10 **Ne** 20.18
3	11 **Na** 22.99	12 **Mg** 24.30											13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.07	17 **Cl** 35.45	18 **Ar** 39.95
4	19 **K** 39.1	20 **Ca** 40.08	21 **Sc** 44.96	22 **Ti** 47.87	23 **V** 50.94	24 **Cr** 52.00	25 **Mn** 54.94	26 **Fe** 55.84	27 **Co** 58.99	28 **Ni** 58.34	29 **Cu** 63.55	30 **Zn** 65.39	31 **Ga** 69.72	32 **Ge** 73.61	33 **As** 74.92	34 **Se** 78.96	35 **Br** 79.90	36 **Kr** 83.8
5	37 **Rb** 85.47	38 **Sr** 87.62	39 **Y** 88.91	40 **Zr** 91.22	41 **Nb** 92.91	42 **Mo** 95.94	43 **Tc** 99	44 **Ru** 101.1	45 **Rh** 102.9	46 **Pd** 106.4	47 **Ag** 107.9	48 **Cd** 112.4	49 **In** 114.8	50 **Sn** 118.7	51 **Sb** 121.8	52 **Te** 127.6	53 **I** 126.9	54 **Xe** 131.3
6	55 **Cs** 132.9	56 **Ba** 137.3	57 **La** 138.9	72 **Hf** 138.9	73 **Ta** 181.0	74 **W** 183.8	75 **Re** 186.2	76 **Os** 190.2	77 **Ir** 192.2	78 **Pt** 195.1	79 **Au** 197.0	80 **Hg** 200.6	81 **Tl** 204.4	82 **Pb** 207.2	83 **Bi** 209.0	84 **Po** 209	85 **At** 210	86 **Rn** 222
7	87 **Fr** 223	88 **Ra** 226	89 **Ac** 227	104 **Rf** 261	105 **Db** 262	106 **Sg** 263	107 **Bh** 262	108 **Hs** 265	109 **Mt** 266	110	111	112						
			6	58 **Ce** 140	59 **Pr** 141	60 **Nd** 144	61 **Pm** 145	62 **Sm** 150	63 **Eu** 152.0	64 **Gd** 157	65 **Tb** 159	66 **Dy** 163	67 **Ho** 165	68 **Er** 167	69 **Tm** 169	70 **Yb** 173.0	71 **Lu** 175.0	
			7	90 **Th** 232	91 **Pa** 231.0	92 **U** 238.0	93 **Np** 237	94 **Pu** 244	95 **Am** 243	96 **Cu** 247	97 **Bk** 247	98 **Cf** 251	99 **Es** 252	100 **Fm** 257	101 **Md** 258	102 **No** 259	103 **Lr** 262	

Silicon Crystal

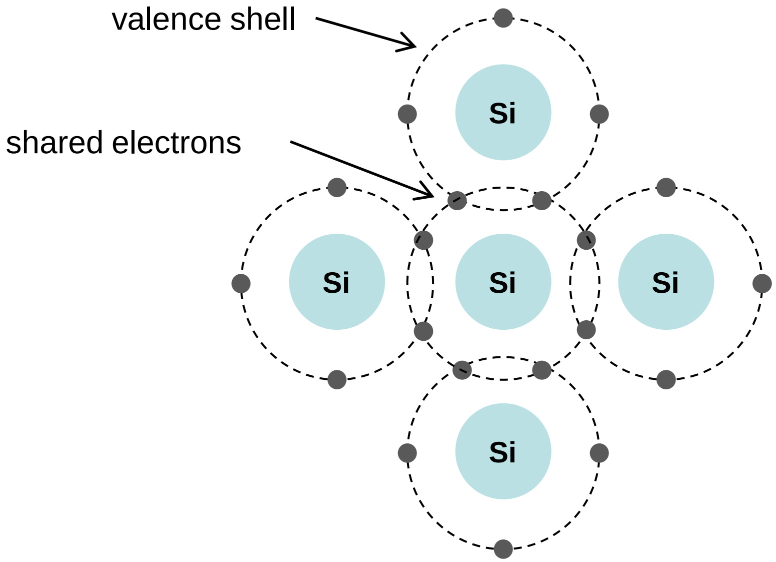
Silicon Atom

Atomic Number 14

Si $_{2,8,4}$



Silicon has 14 electrons,
4 of which are at the valence shell



Silicon Crystal Lattice

Doping

- Doping (semiconductors): Adding alien elements with a different amount of valence electrons into a crystal lattice that have 4 valence electrons

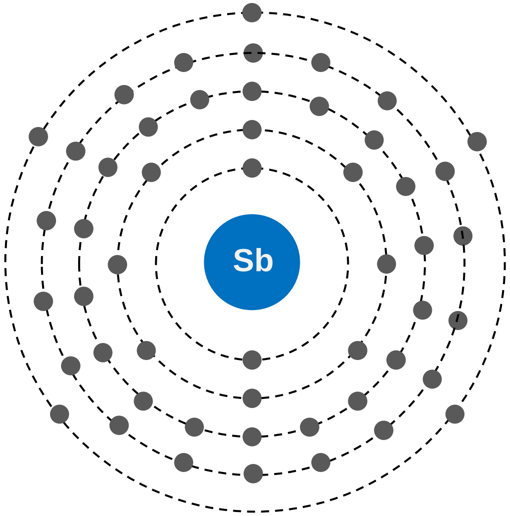
- Dope-elements with 5 valence electrons
  - One electron too much
  - little energy required to bring it into the conduction band
- Dope-elements with 3 valence electrons
  - one missing electron
  - material pulls electrons off the conductance band, and with that moves positive charge holes.

Antimony Doping

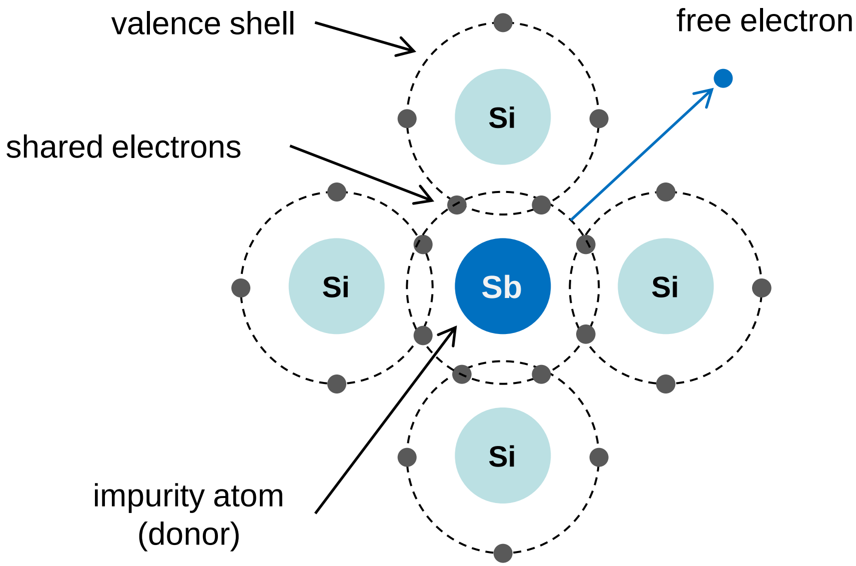
Antimony Atom

Atomic Number 51

$Sb_{2,8,18,18,5}$



Antimony has 51 electrons,
5 of which are at the valence shell



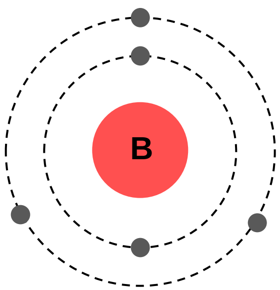
N-type Semiconductor

Boron Doping

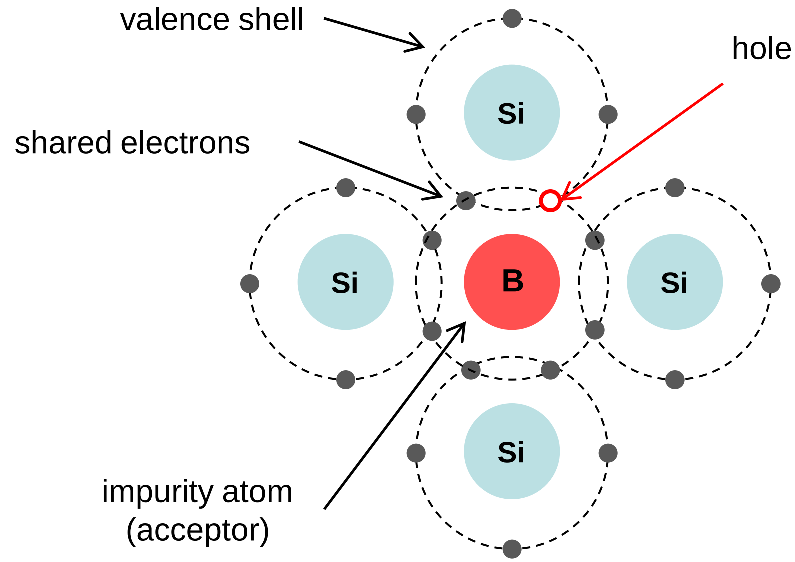
Boron Atom

Atomic Number 5

B $_{2,3}$



Boron has 5 electrons,
3 of which are in the valence shell

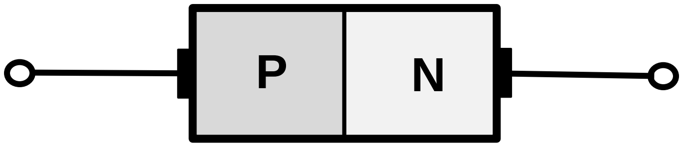


P-type Semiconductor

more on Boron

Let’s build a diode – Done.

- Combination of P-doped and N-doped material on a substrate works as a diode.



- A transistor is build by combining NPN doped or PNP doped elements.
- IC‘s are build by combining many transistors.

DLTS Measurements

Semiconductors

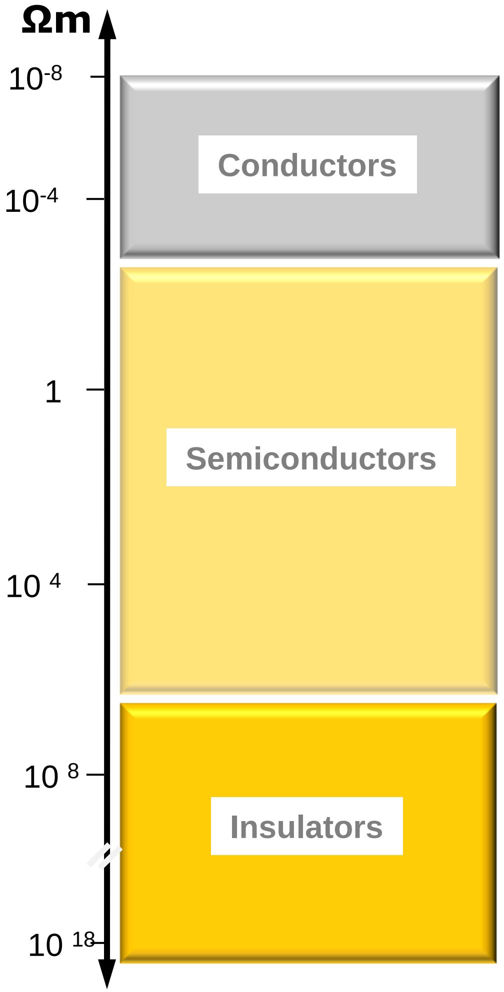
Semiconductor Characteristics

- Solid material
- Virtually no conductance at very low temperatures
- Conductance increases (often very quiclky) with higher temperature
- As higher the temperature as better the conductance
- At normal temperature (20° C) conductance can range from complete isolation to ranges comparable to metallic conductors.

- Mostly Germanium and Silicon based*.

* Both elements are in PSEs 4rth main group (they have 4 electrons at their valence shell).

Resistivity ρ (Rho)



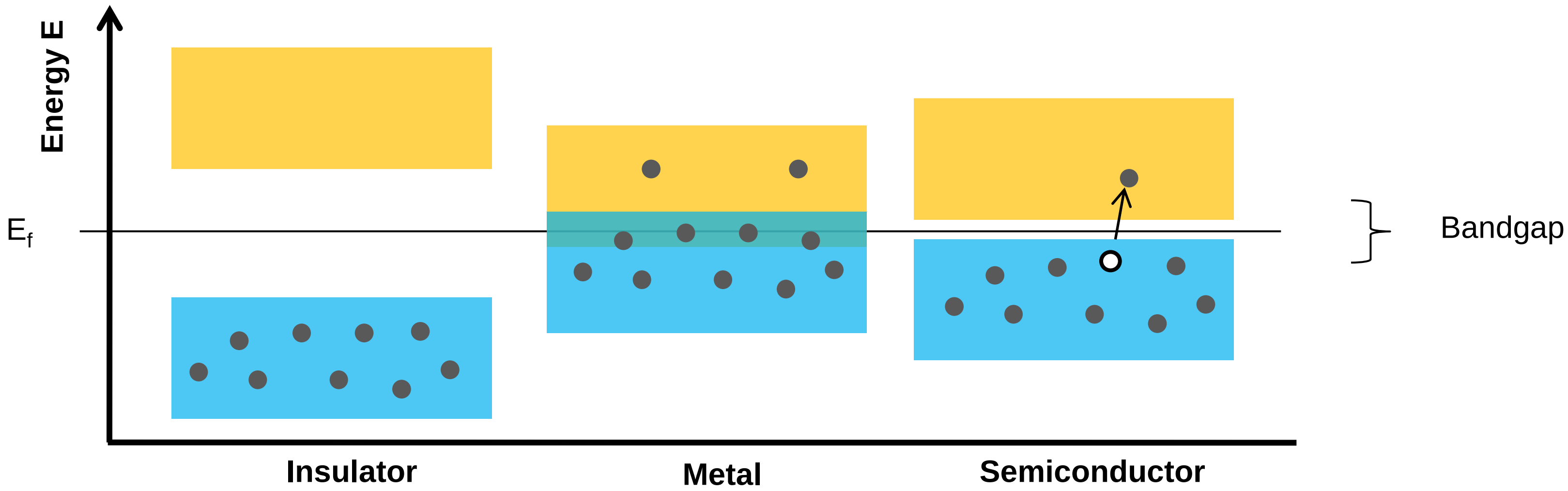
Resistivity ρ (Rho) @ 20° C

Silver (Ag)	1.6×10^{-8}
Copper (Cu)	1.7×10^{-8}
Aluminum (Al)	2.4×10^{-8}
Gold (Au)	2.9×10^{-8}
Carbon (C)	3.5×10^{-5}

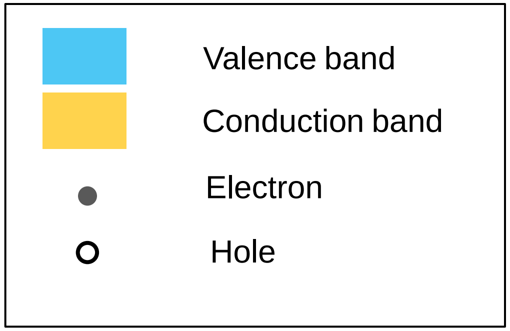
Sea water (var)	0.21
Germanium (Ge)	**0.46**
Drinking Water (var)	2.0×10^{2}
Silicon (Si)	**6.4×10^{2}**

Glass	1.0×10^{10}
Air (var)	1.8×10^{12}
Quartz	7.5×10^{18}

Valence Band / Conduction Band



- Valence electrons are bound to atoms
- Conduction electrons can move freely within the atomic lattice of the material



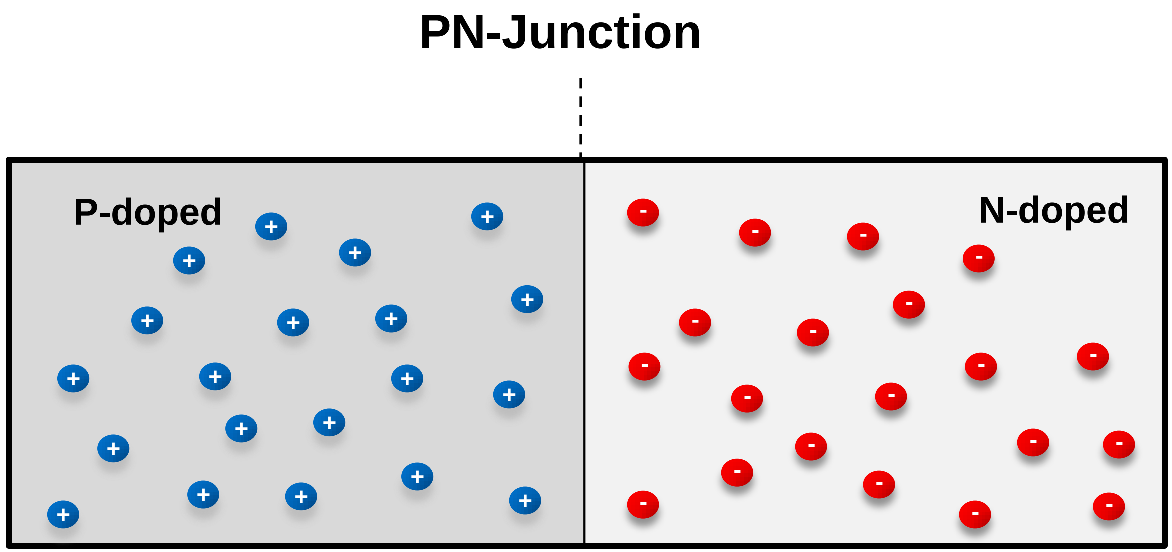
Bandgap Examples

Material	Symbol	Band gap (eV) @ 302K	used with technology
Silicon	Si	1.11	ICs, transistors, diodes
Germanium	Ge	0.67	Transistors, fiber optics, solar cells, IR optics, nanowires
Gallium(III) arsenide	GaAs	1.43	Microwave IC, Laser diodes, solar cells
Gallium antimonide	GaSb	0.7	IR Led, IR Laser, transistors, thermovoltaic systems
Zinc oxide	ZnO	3.37	LCDs, Transistors, LEDs
Lead (II) sulfide	PbS	0.37	IR receivers
Lead (II) selenide	PbSe	0.27	IR receivers, nanocrystal solar cells
Indium (III) nitride	InN	0.7	Solar cells, high speed electronics
Silicon Carbide	SiC	2.86	High temperature/ voltage semiconductor electronics, LED

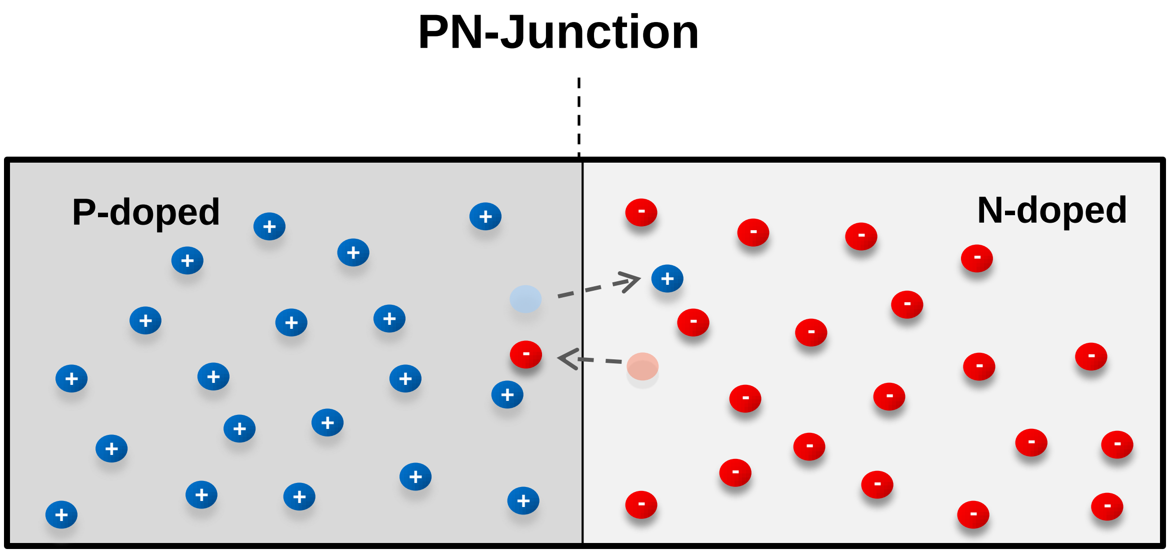
DLTS Measurements

How does DLTS work ?

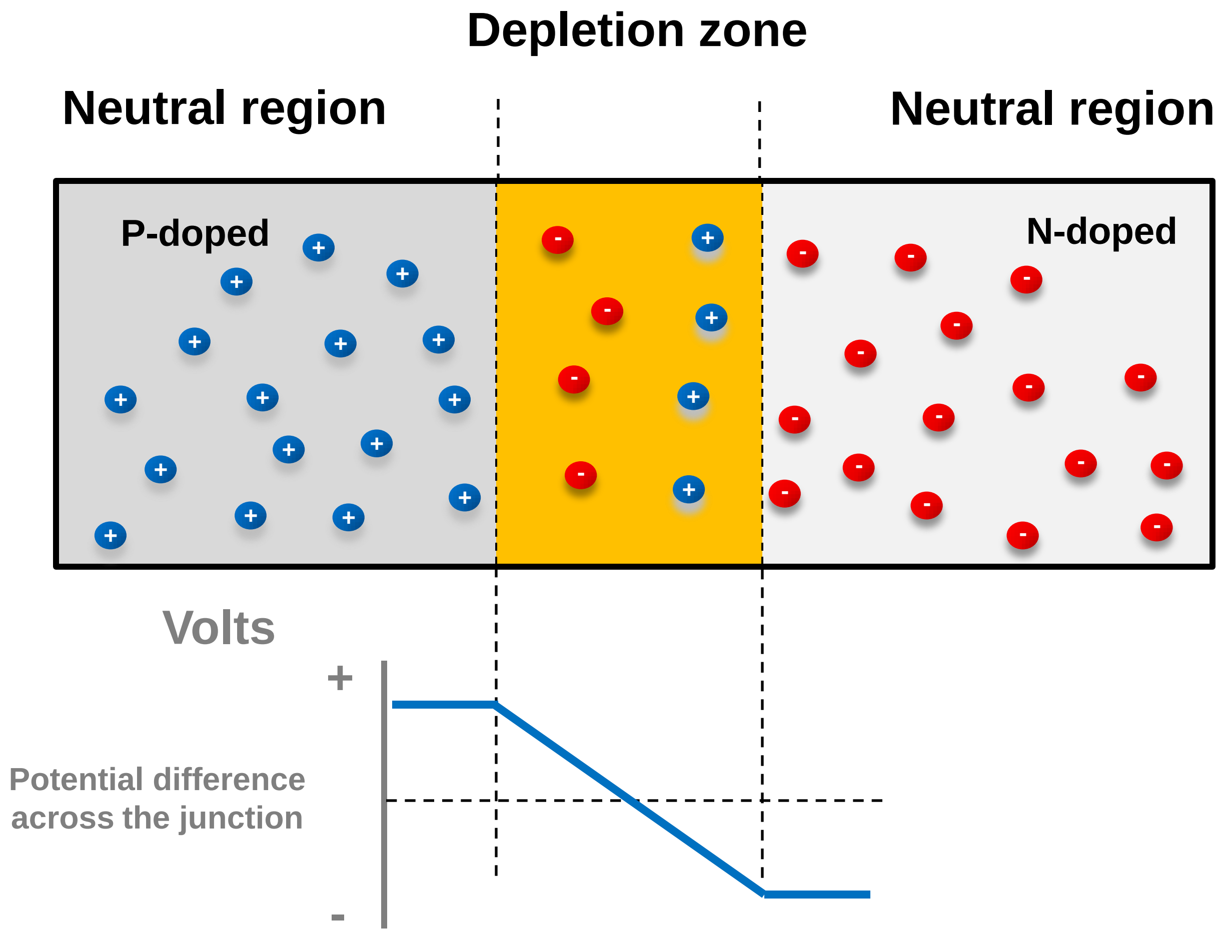
PN Semiconductor – Carrier Zones I



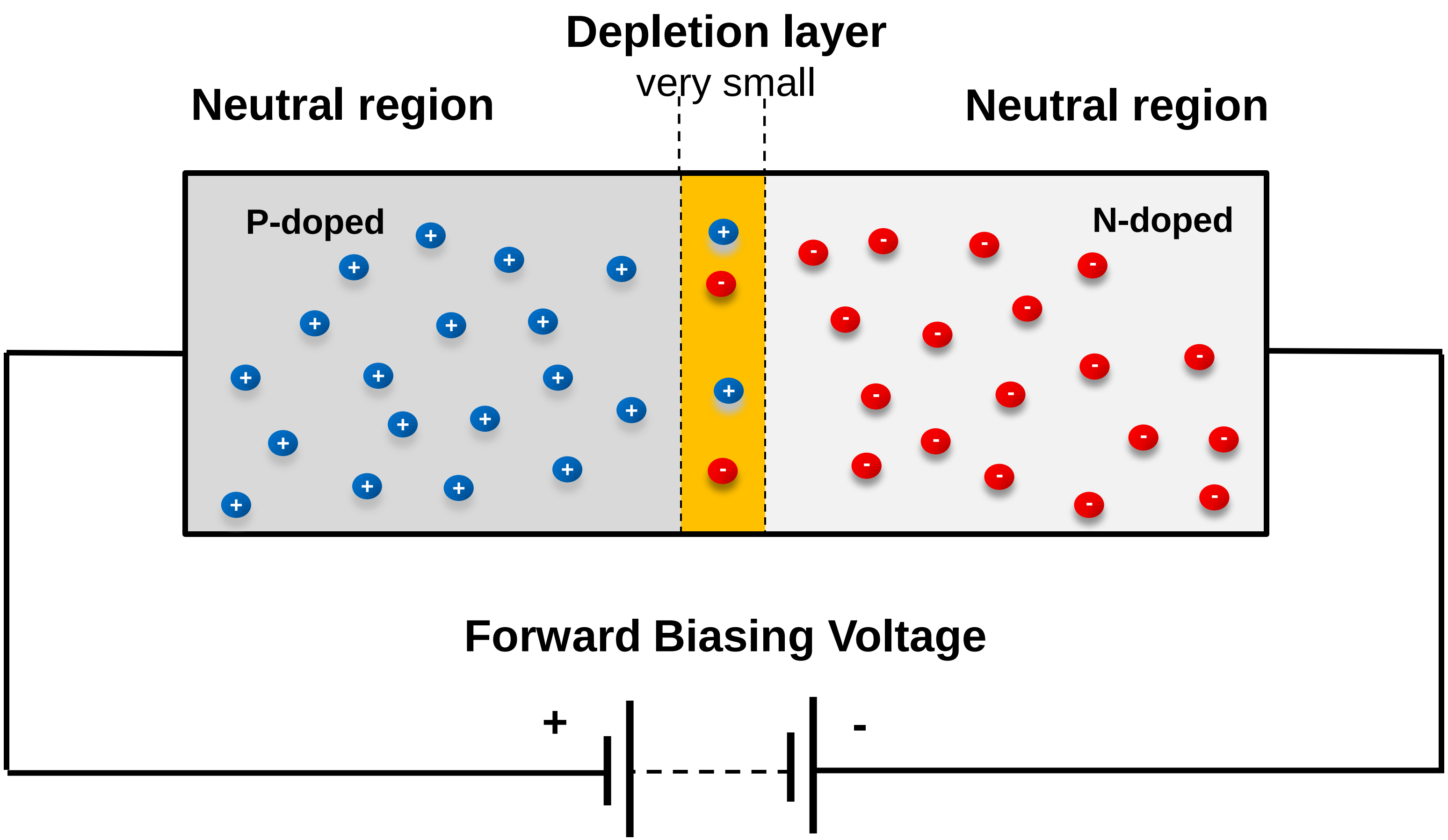
PN Semiconductor – Carrier Zones II



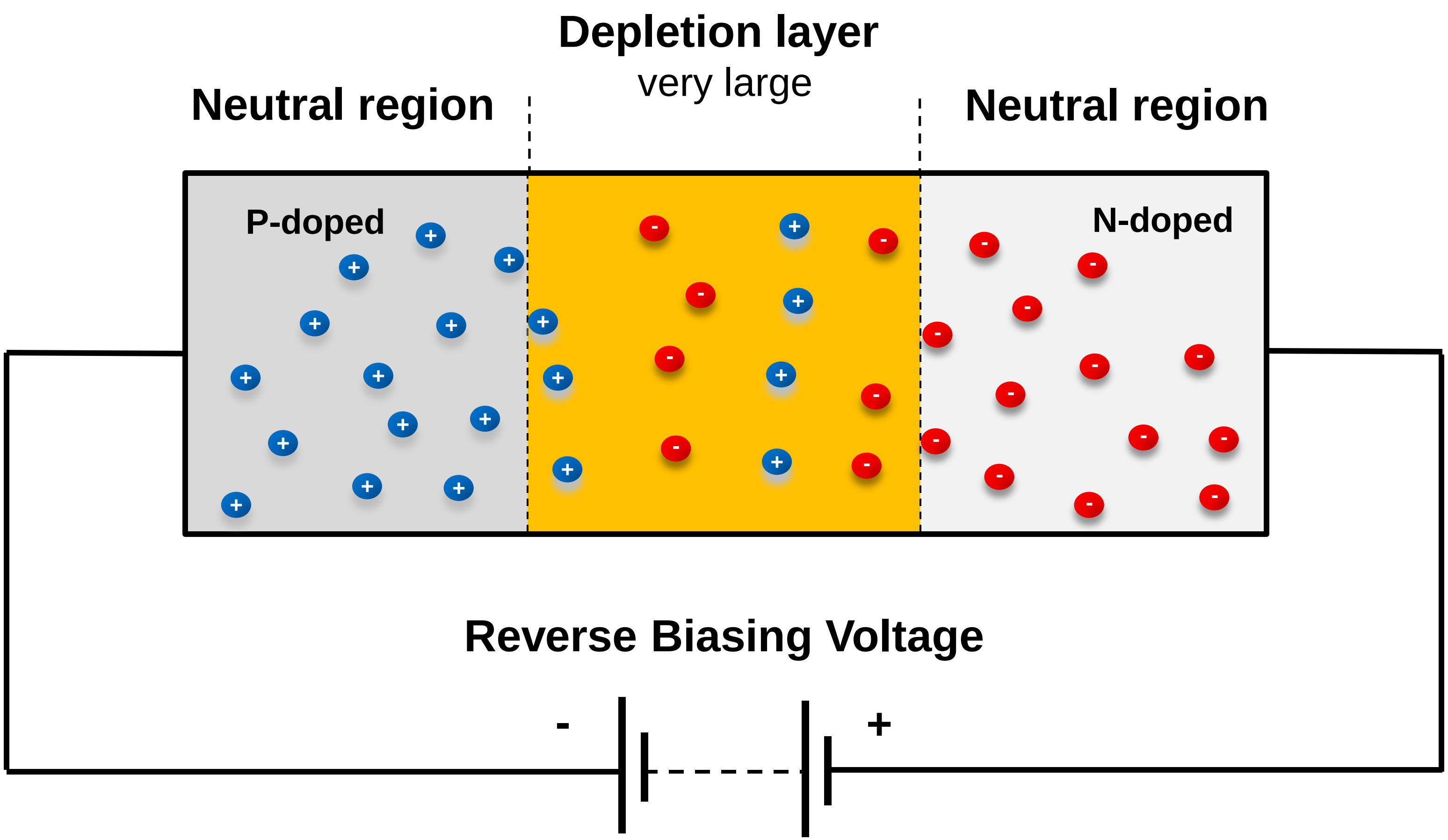
PN Semiconductor – Carrier Zones



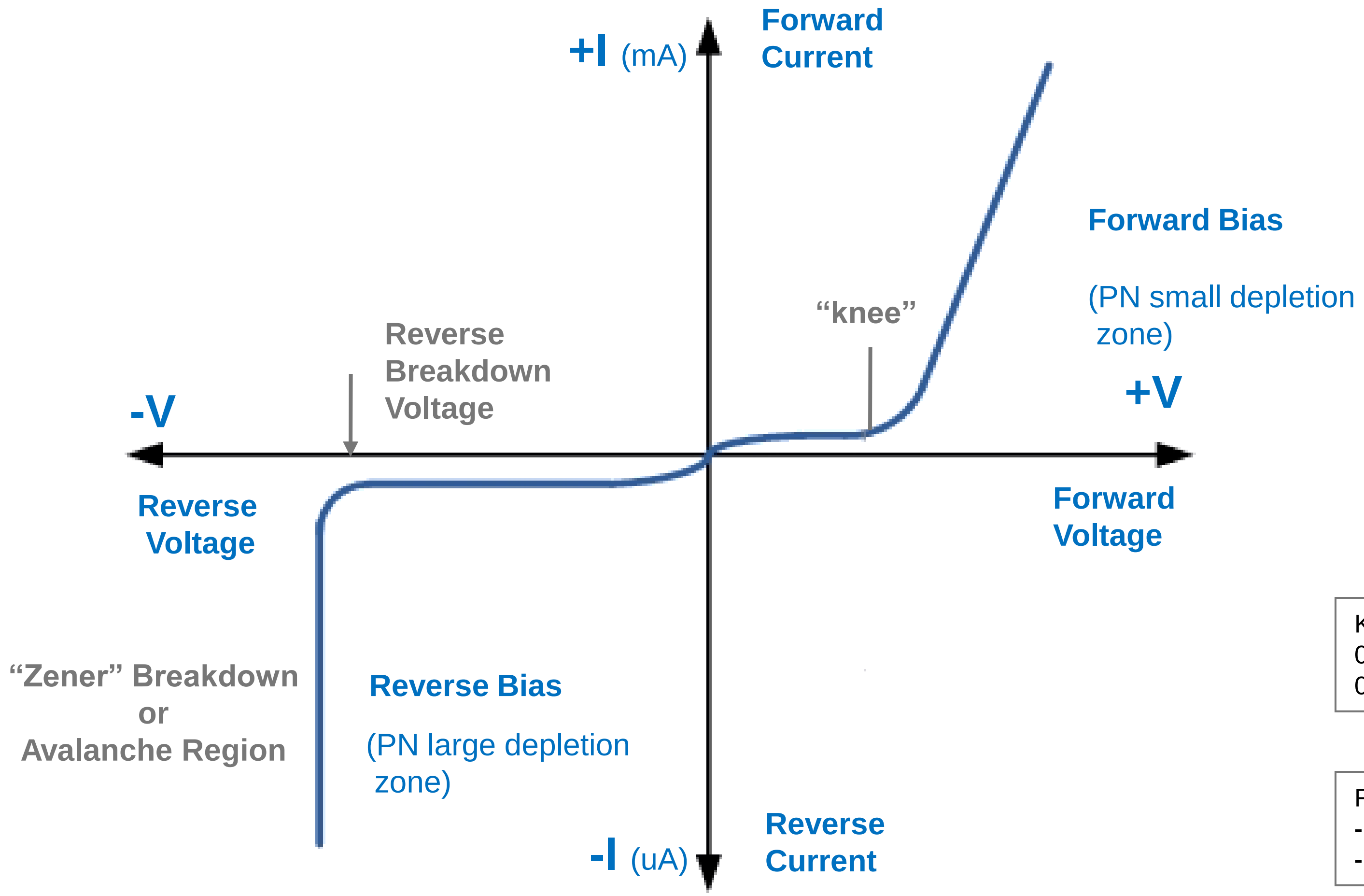
Forward Bias Voltage Applied



Reverse Bias Voltage Applied



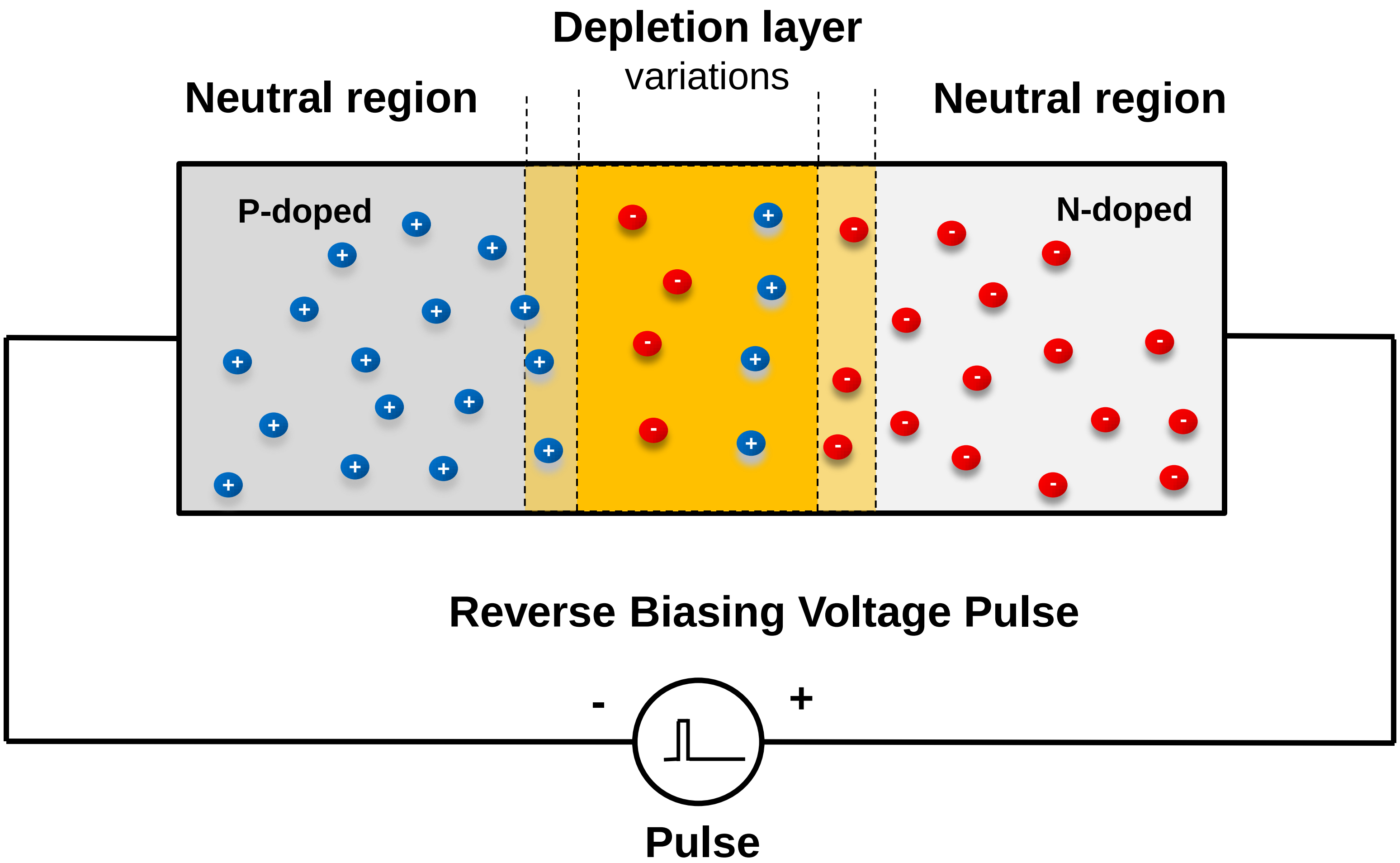
Diode Characteristics Curve



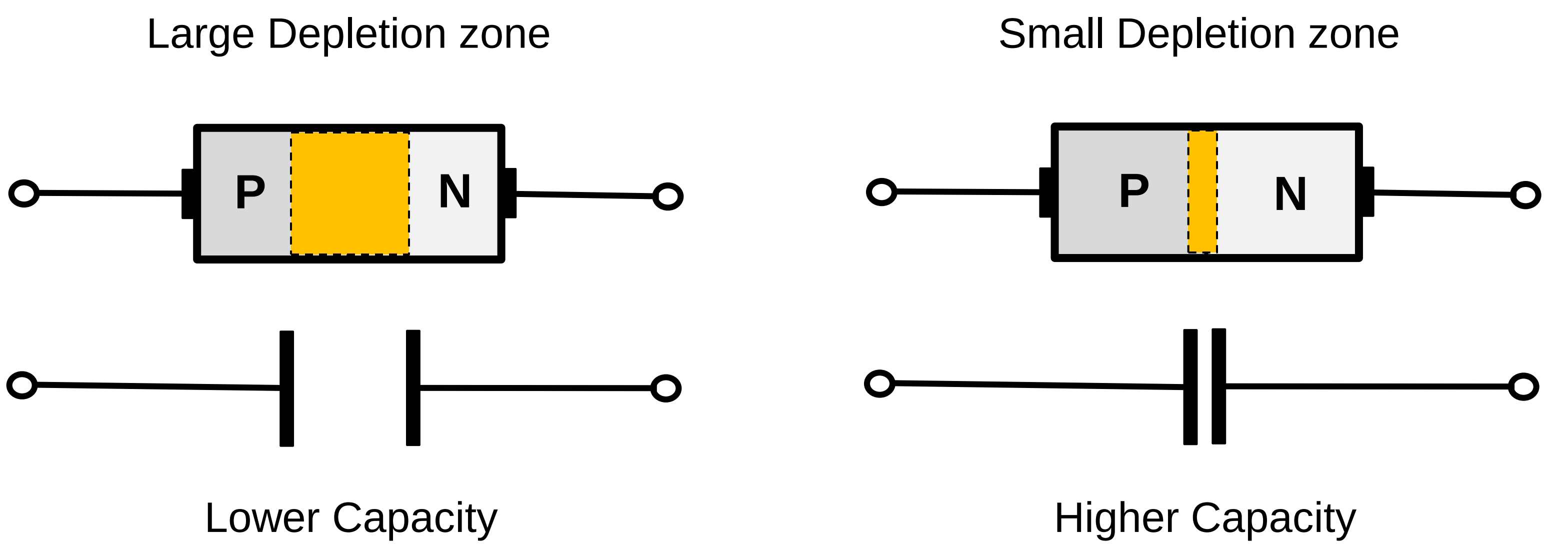
Knee:
0.7V Silicon
0.3V Germanium

Reverse Current:
-20uA Silicon
-50uA Germanium

Pulsed Bias Voltage

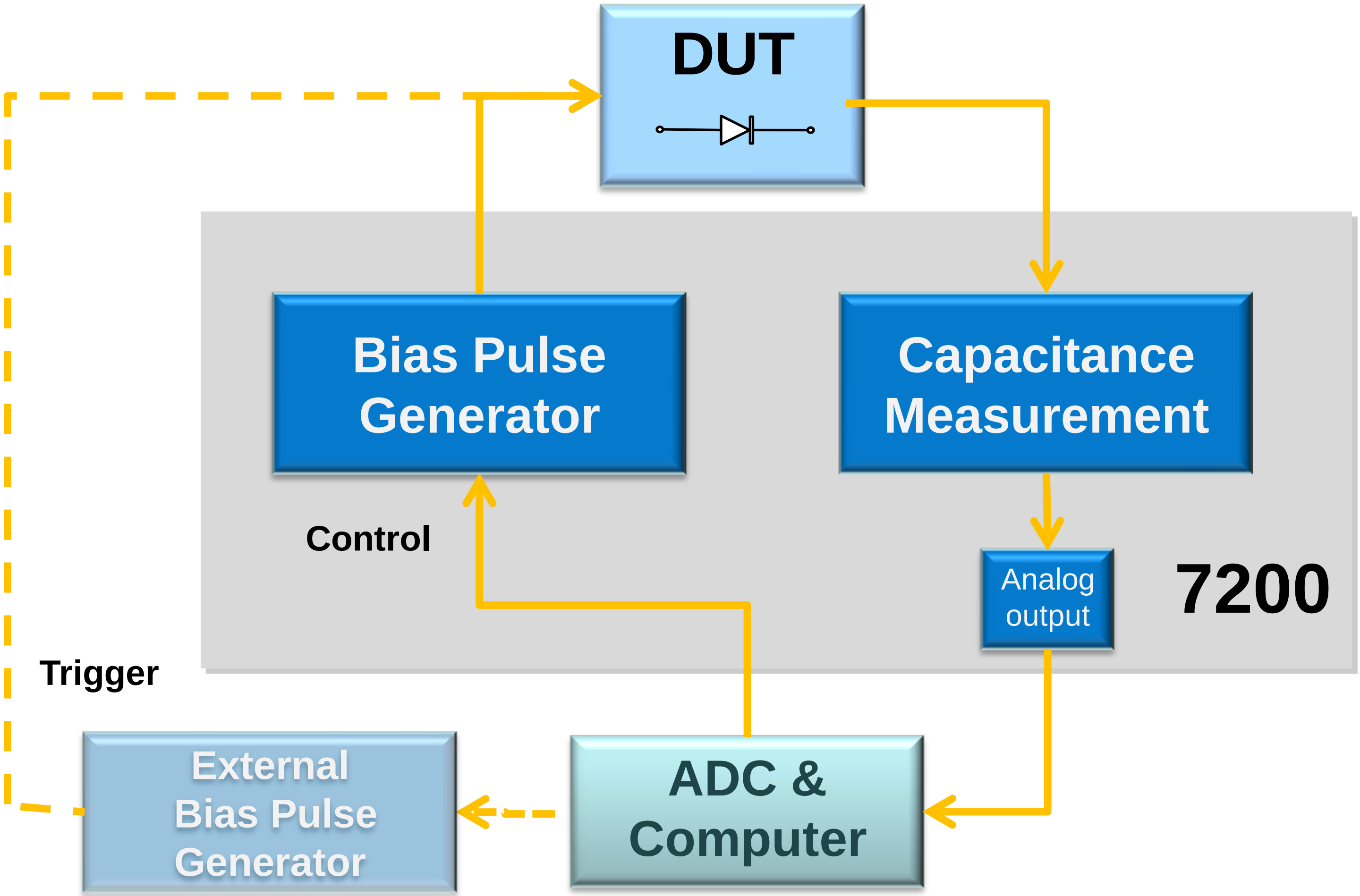


Correlation: Capacitance - Depletion Zone

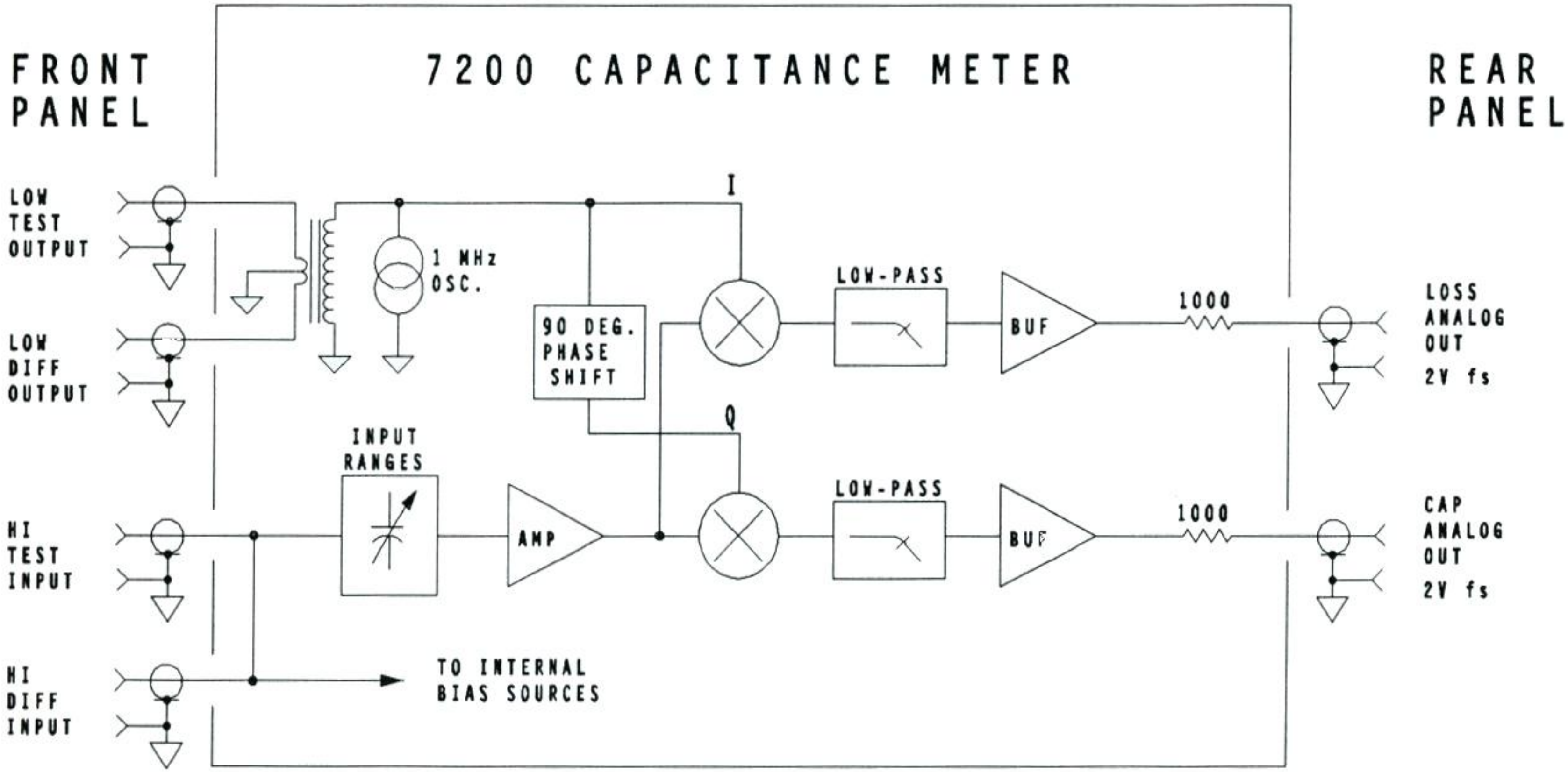


DLTS Measurements with 7200

7200 & DLTS

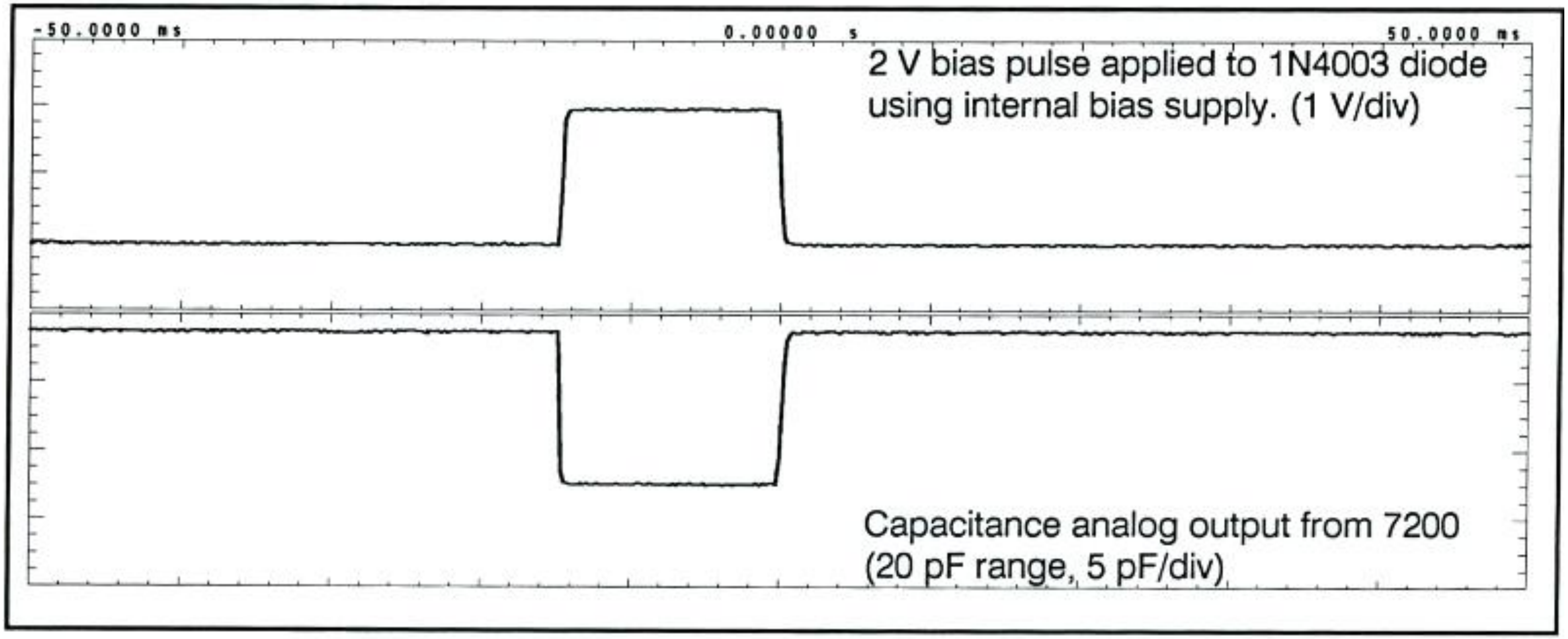

DUT
Bias Pulse Generator
Capacitance Measurement
Control
Analog output
7200
Trigger
External Bias Pulse Generator
ADC & Computer

7200 Block Diagram

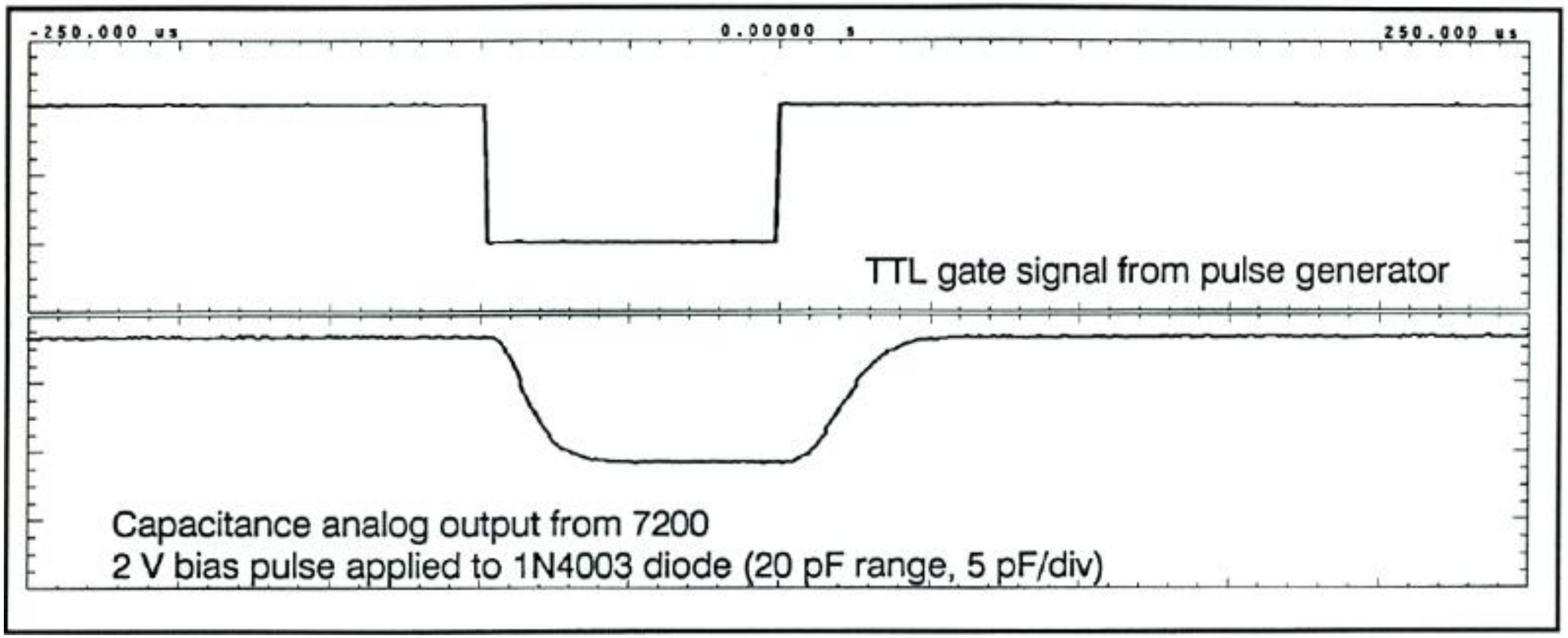


The measurement of parallel capacitance and conductance is achieved by using phase sensitive detectors.
Each Sensor extracts from the measurement signal the magnitude of the in-phase and quadrature components relative to the 1 MHz test level oscillator.

Capacitance Analog Output I

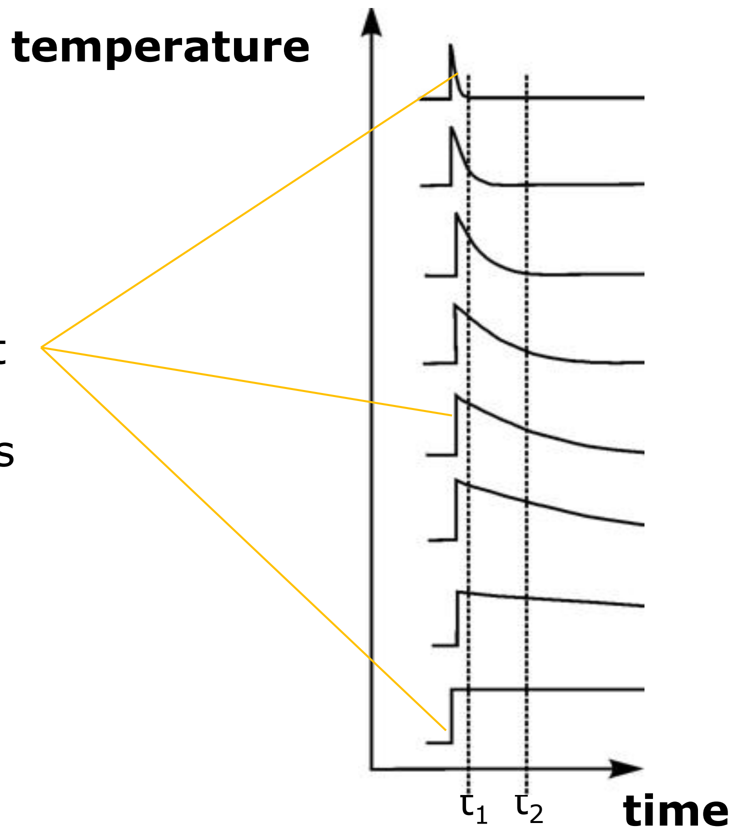


Capacitance Analog Output II

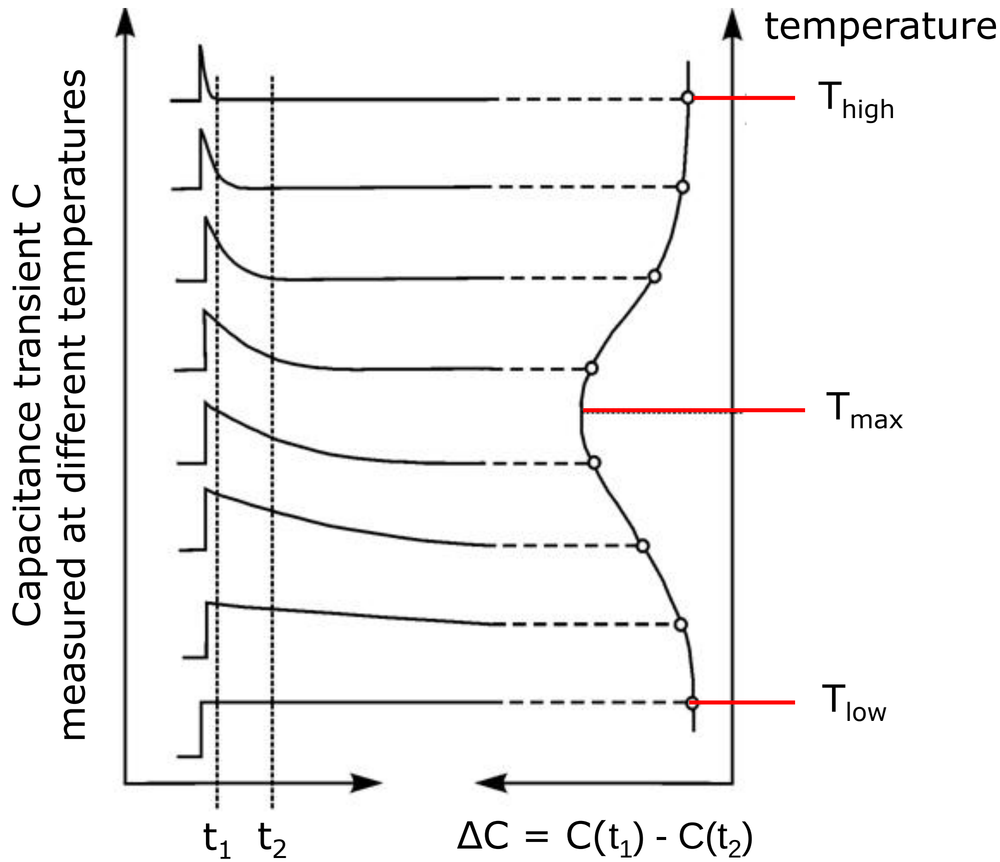


Capacitance Transient vs. Temperature

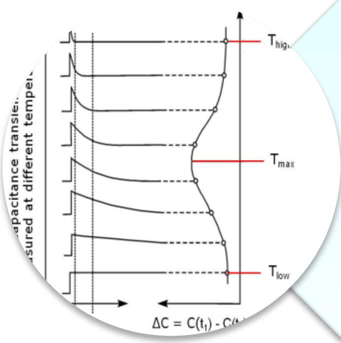
Capacitance transients C measured at different temperatures



Arrhenius plots



DLTS with 7200



Arrhenius plots are

"fingerprints"

of semiconductors

They provide indications about:

- **Doping quality amount (relative to base crystal)**
- **Expected performance of semiconductor**

DLTS Part 2

Semetrol DLTS Measurement Station

Deep Level Effects

- **Detectors**
  switching speed, dark current, resistivity
- **LED**
  reduced efficiency, long term degradation
- **LD**
  reduced efficiency and high threshold current for lasing, long term degradation
- **FETs**
  compensation, scattering, parasitic gating, defect mediated tunneling leakage currents

Deep Level Transient Spectroscopy

- Collapse depletion region of p-n or Schottky diode to fill traps
- Apply reverse bias
- Measure capacitance decay
- Determine energy and capture cross section from temperature dependence of emission rate trap concentration from capacitance transient amplitude.

Digital DLTS

Collect full transient at temperature steps

- Rate window analysis
- Alternatively –fit for multi-exponential components – extracts signature of overlapping traps

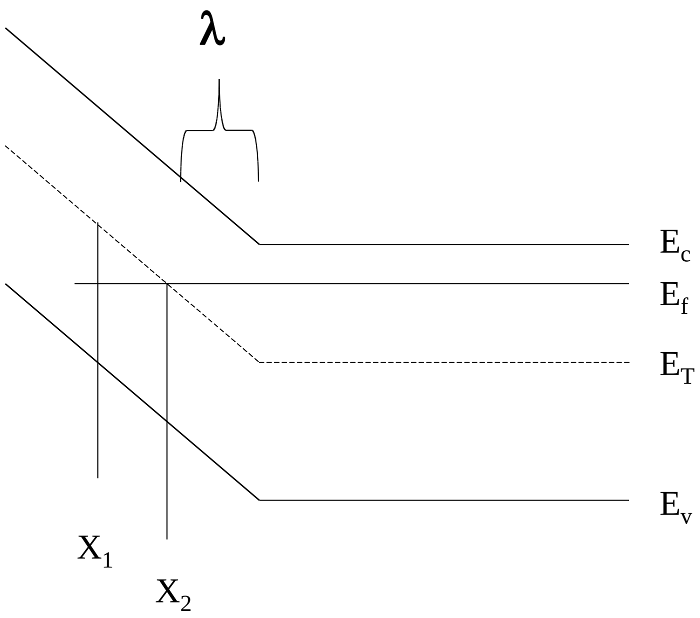
Other methods - boxcar integrator, correlator, lock-in amplifier.

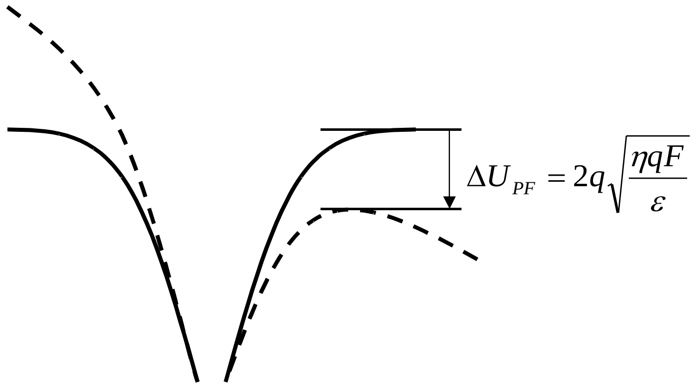
- May not get the whole picture

Double Pulse DLTS

Uses difference in signal resulting from incremental steps in either filling pulse voltage or measurement voltage

- **Deep level profiling** – e.g. defects diffusing from substrate, surface effects, dopant related traps.
- Poole-Frenkel Effect
  Reduction in emission energy at increased electric field. Can be used to determine **charge state**, donor or acceptor nature.



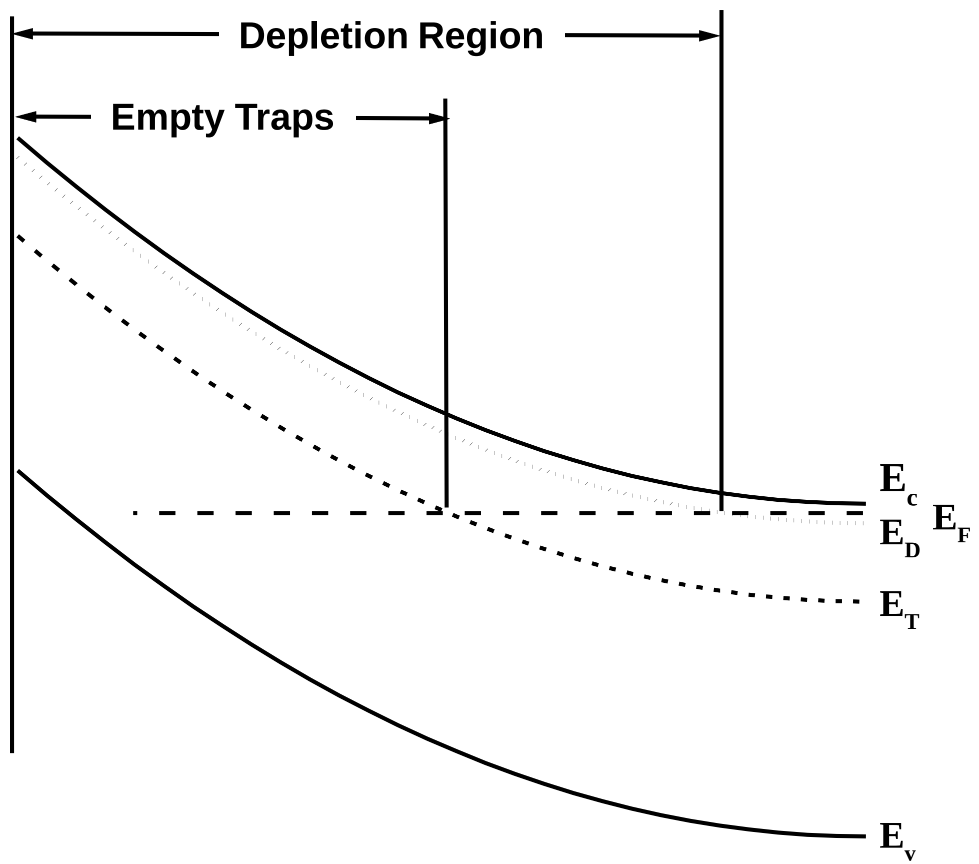


Optical DLTS

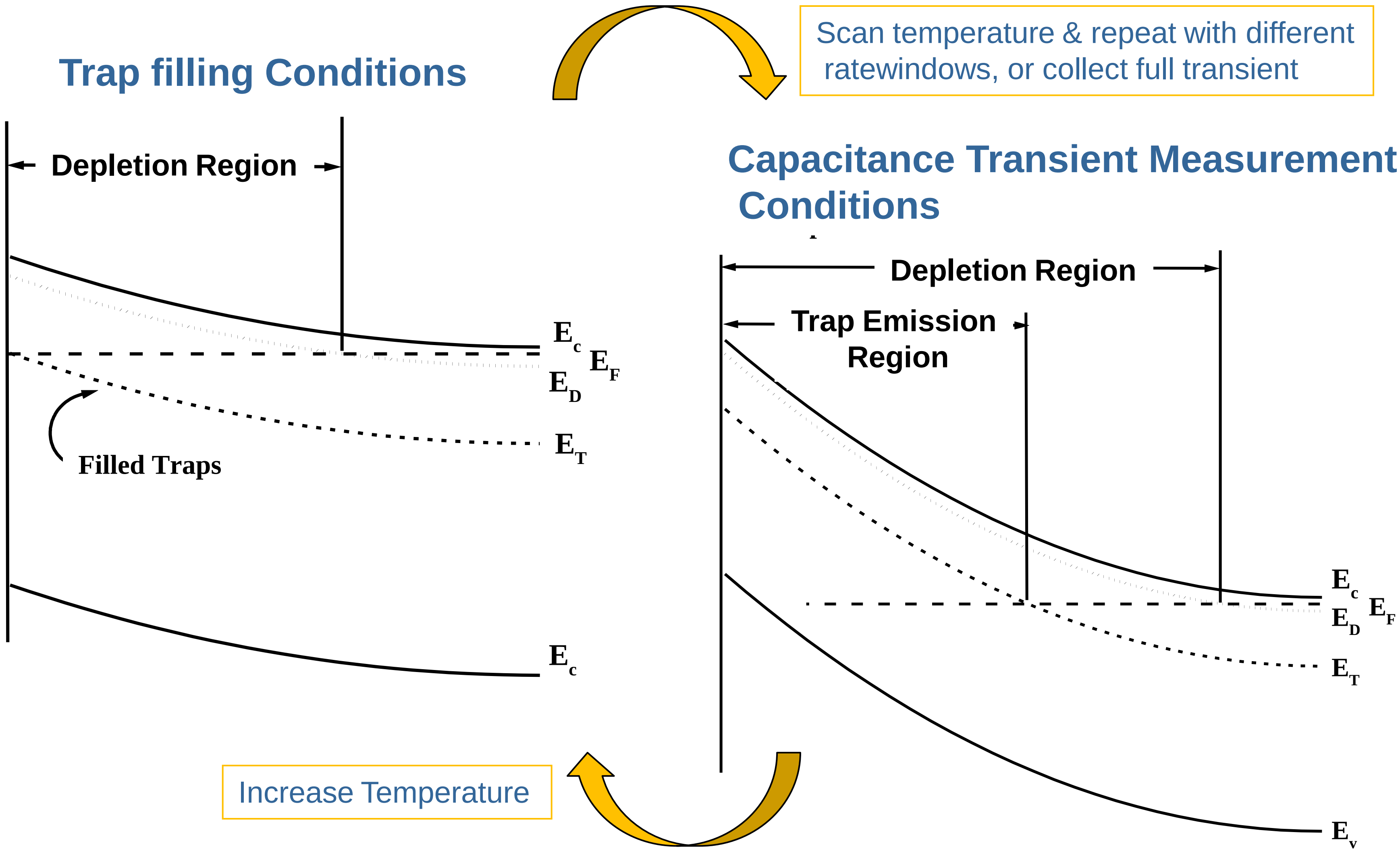
Optical filling pulse and/or illumination during emission.

Used for material with low carrier concentration.

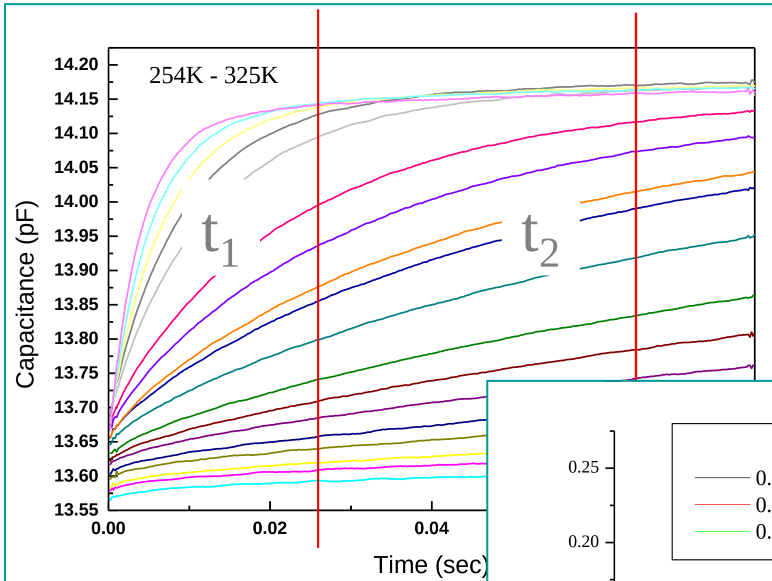
DLTS Measurement Concept - I



DLTS Measurement Concept - II



DLTS Measurement Concept - III



$$\Delta C = C_\infty\left(\exp(-e_n t_2) - \exp(-e_n t_1)\right)$$

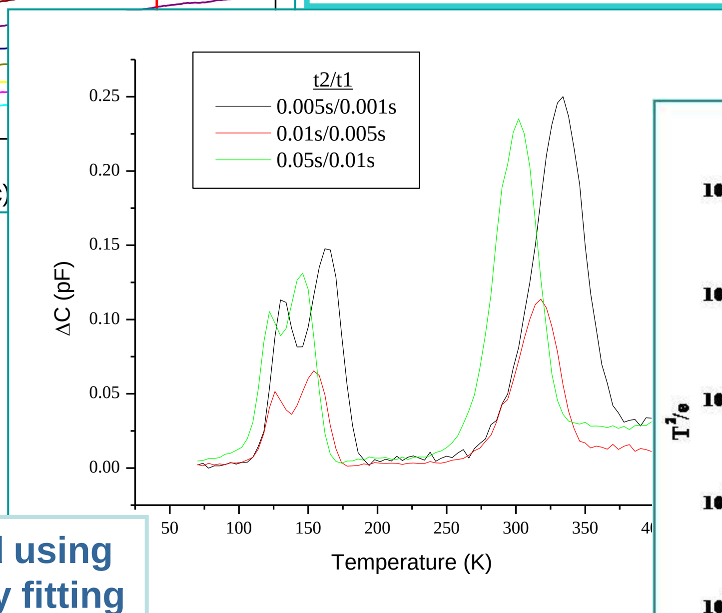
$$\text{max at} \quad e_n = \frac{\ln\left(\frac{t_2}{t_1}\right)}{t_2 - t_1}$$

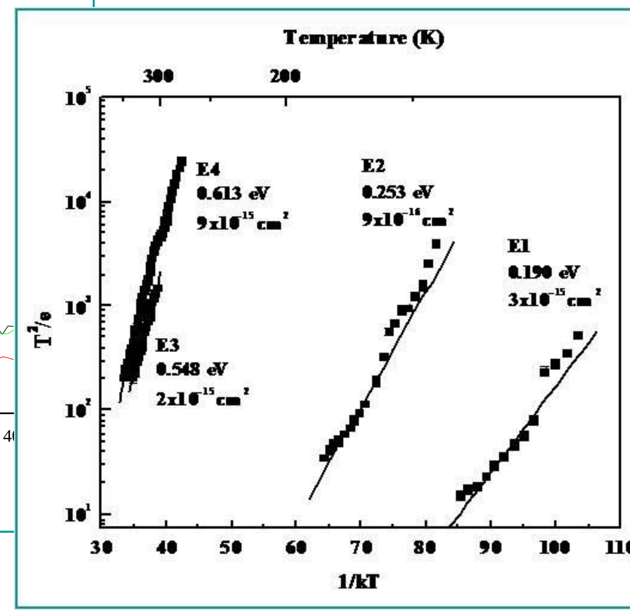
$$e_n = \sigma_n v_{th} N_c \exp\left(\frac{-E_T}{kT}\right)$$

$$N_c = 2M_c\left(\frac{2\pi m^* kT}{h^2}\right)^{3/2}$$

$$v_{th} = \sqrt{\frac{8kT}{\pi m^*}}$$

$$C^2 = C_0^2 - \frac{C_0^2}{N_s}\sum_i N_{Ti}(t)$$

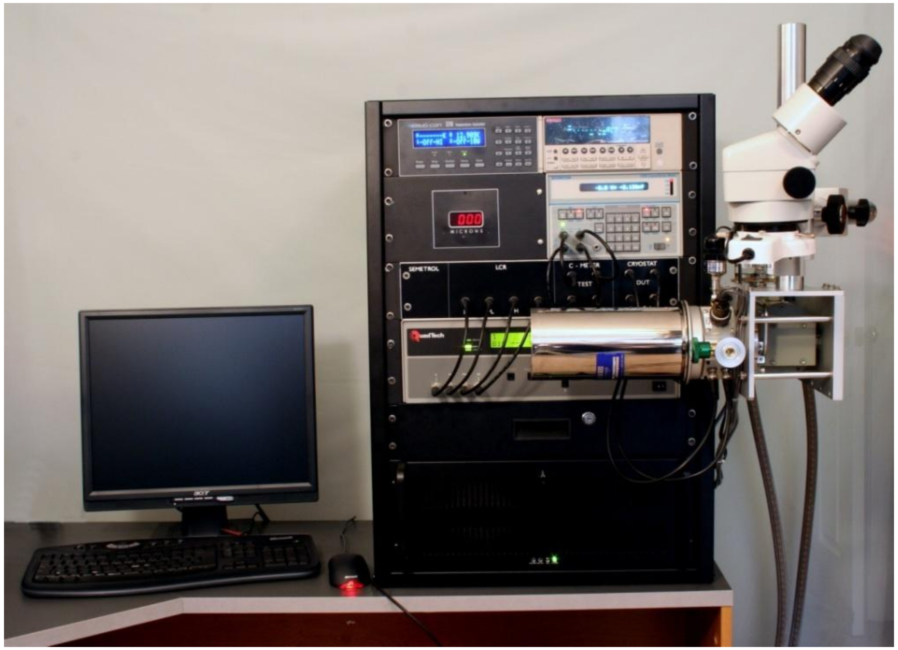




Energy can be determined using ratewindow analysis, or by fitting each transient.

DLTS Equipment

- **Fast capacitance meter**
  - Conversion time less than 50 microseconds, low noise.
  - Analog output.
- **Cryostat**
  - Sample stage with temperature sensor
  - Probes or connections for packaged devices
  - Heaters, temperature sensor, mass configuration for fast stabilization, e.g. <1 min. for temperature increase of 5K.
- **Temperature controller**
  - GPIB control
- **Vacuum pump**
  - <10 microns (10 mTorr)
  - Vacuum gauge on cryostat – avoids excessive pump down time.



Combined DLTS, Current-Voltage-Temperature, Thermal Admittance Spectroscopy system. Cryostat covers temperature range of 20-700K.

DLTS Data Acquisition & Analysis Process

- **Measure CV profile, IV relationship.**
  - **CV profile provides the correspondence between applied voltage and resulting depletion. Shows where there may be features of interest, such as quantum well or heterointerface.**
  - **IV is used to determine overall quality of the diode, and limits where leakage current may interfere with emission process.**
- **DLTS data acquisition.**
  - **Adjust measurement conditions for optimum signal at room temperature or where a peak is expected.**
  - **Set the temperature range, steps, stabilization conditions.**
  - **Collect the data.**
- **DLTS data analysis.**
  - **Plot the deep level spectrum.**
  - **Determine trap signatures from ratewindow analysis.**
  - **Check against simulation.**
  - **Determine trap signatures from a fit of the transients.**

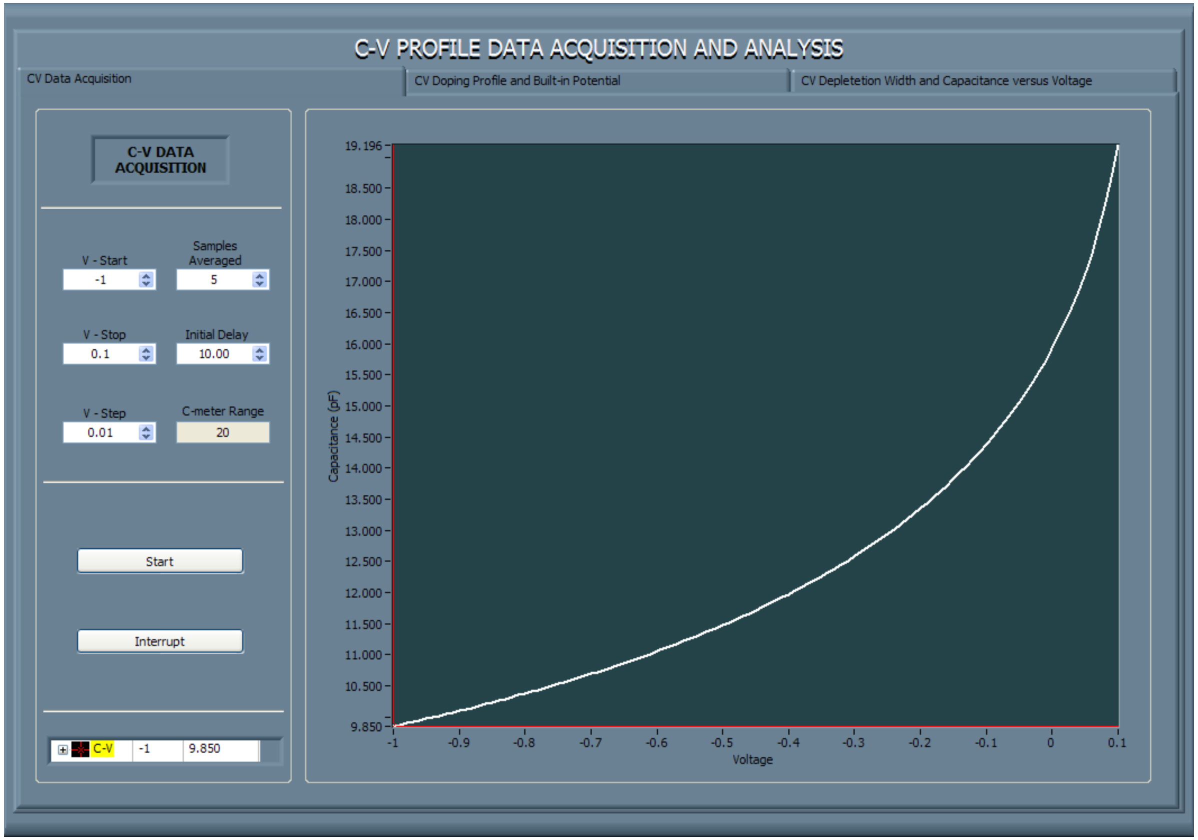
CV Profile for DLTS Setup

CV profile is used to determine accessible regions for filling pulse and measurement voltages.

Analysis of the CV profile is performed for the impurity profile and built in potential.

Plots of C(V) and V(W) are also provided. Useful for setting the bias in DLTS.

The data is saved in the format CVWN (capacitance, voltage, depletion width, and dopant concentration) and may be re-loaded for later analysis.



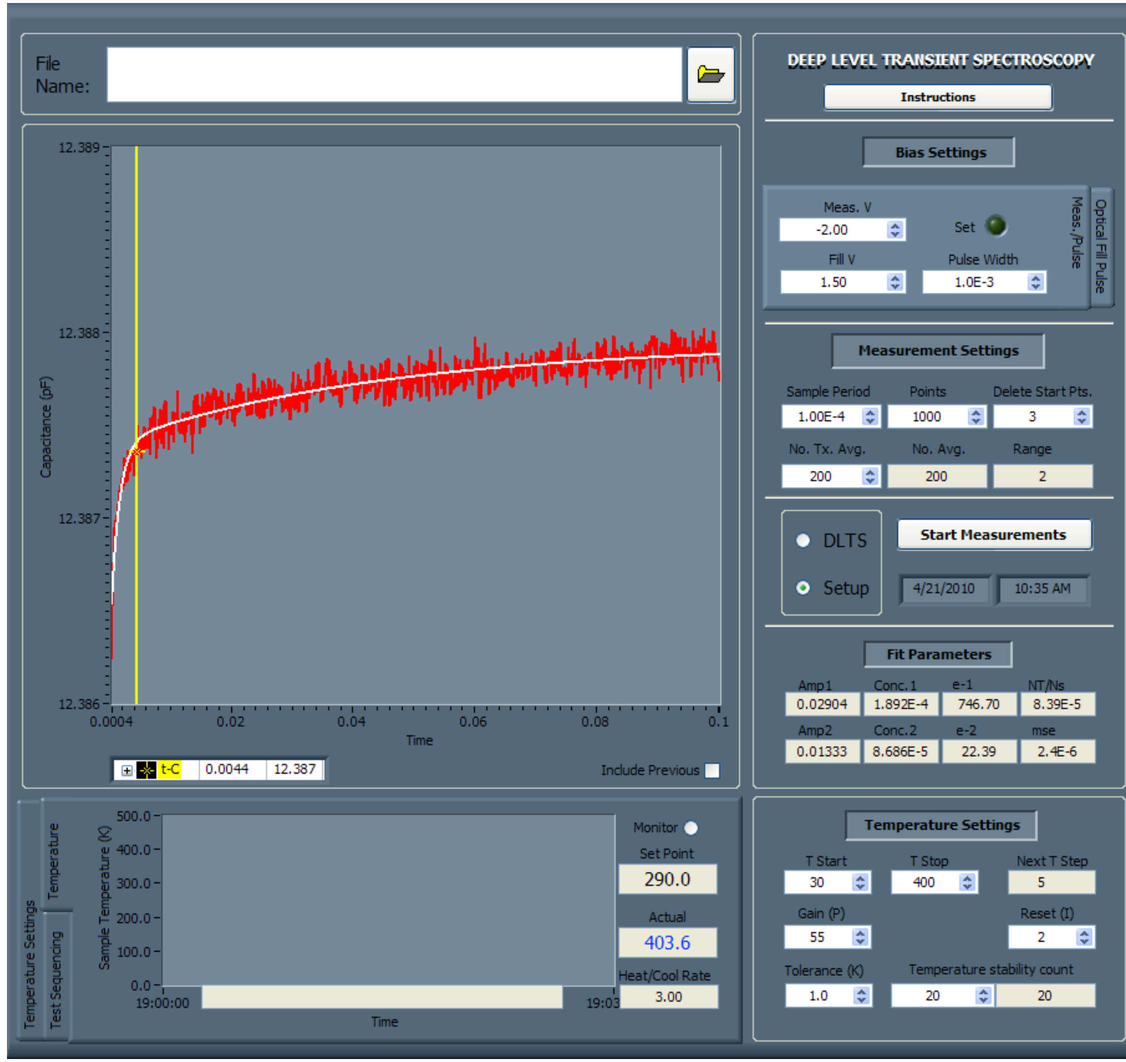
User Interface for DLTS Data Acquisition

User interface to control all experimental conditions for DLTS data acquisition.

Data analysis is performed separately. The values from fitting can be used to adjust the fill/measure settings for the best transient signal.

Capacitance meter is nulled automatically for highest sensitivity scale.

Sensitivity is on the order of 0.2fF for ~30sec of averaging.

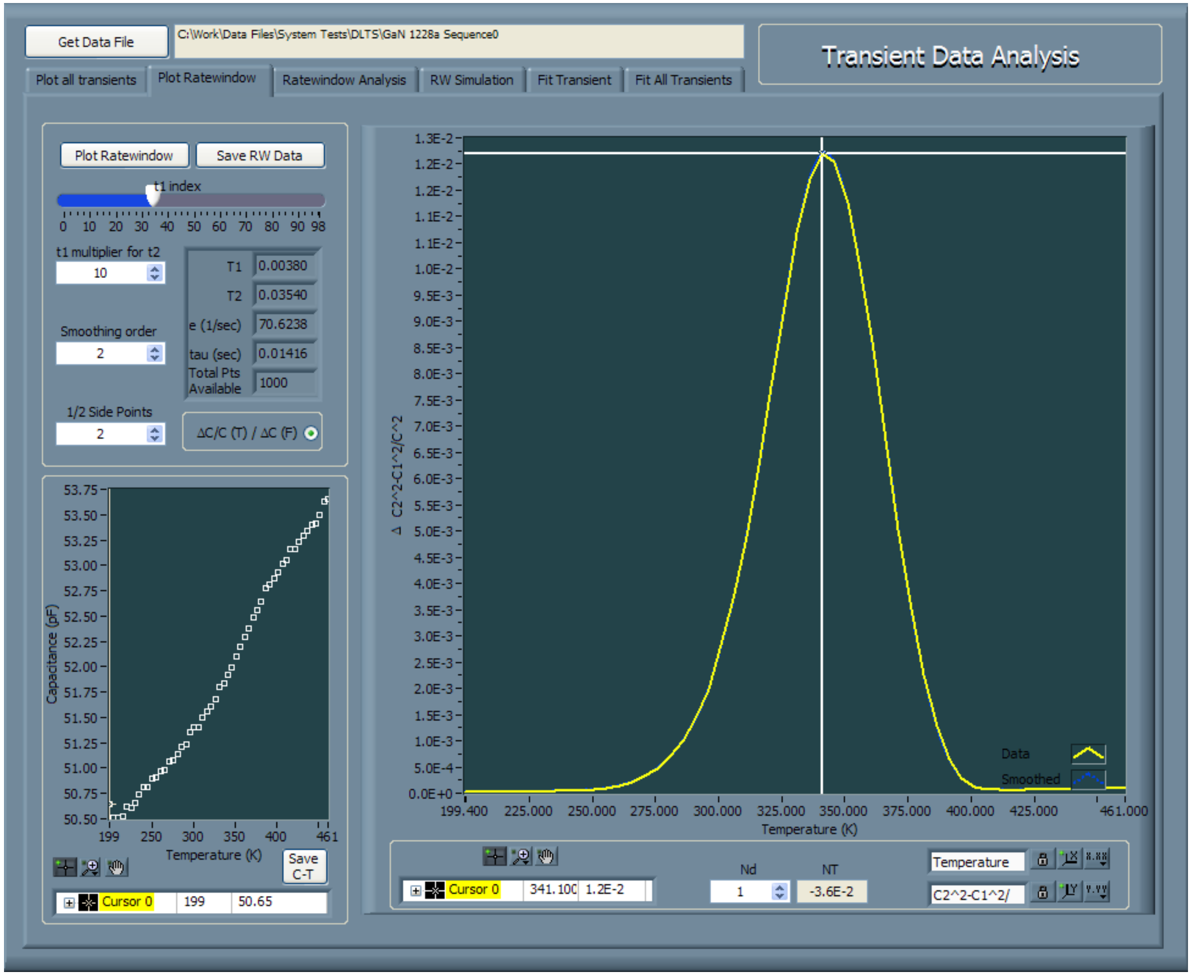


UI DLTS Data Analysis: Ratewindow Plot

Data analysis program allows the user to view the deep level spectra in a ratewindow plot.

The sample times, t_1 and t_2, can be selected to match emission rates used in literature reports, for comparison.

Plot of C, taken from the end of each transient, versus T is useful to confirm valid data, e.g. steps correspond to traps, discontinuities correspond to invalid data from diode breakdown.



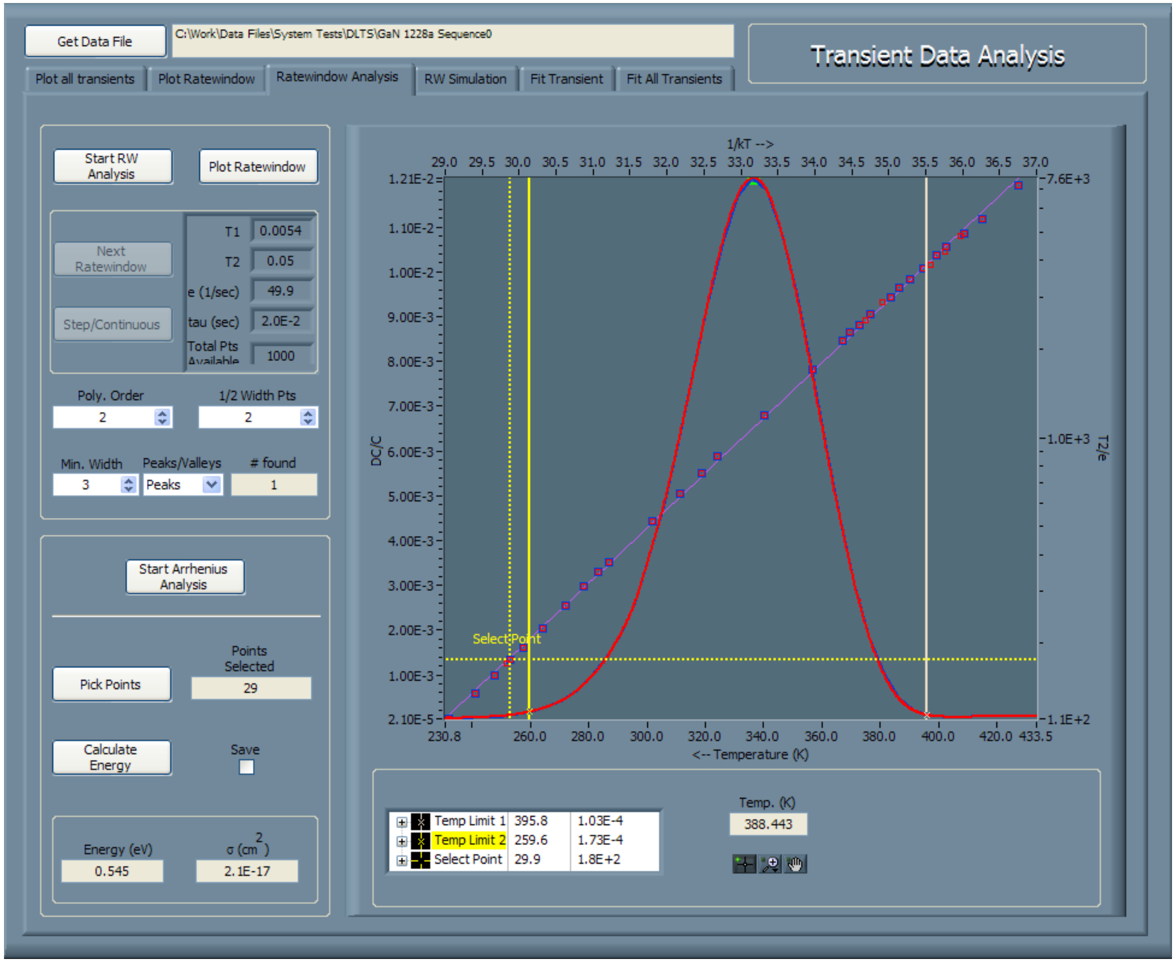
UI DLTS Data Analysis: Ratewindow Analysis

Select temperature range with cursors.

Automatically select peaks (or valleys) using automatically generated ratewindows.

Select points for Arrhenius plot
High sensitivity

Next, compare simulation generated from measured characteristics, to actual data.

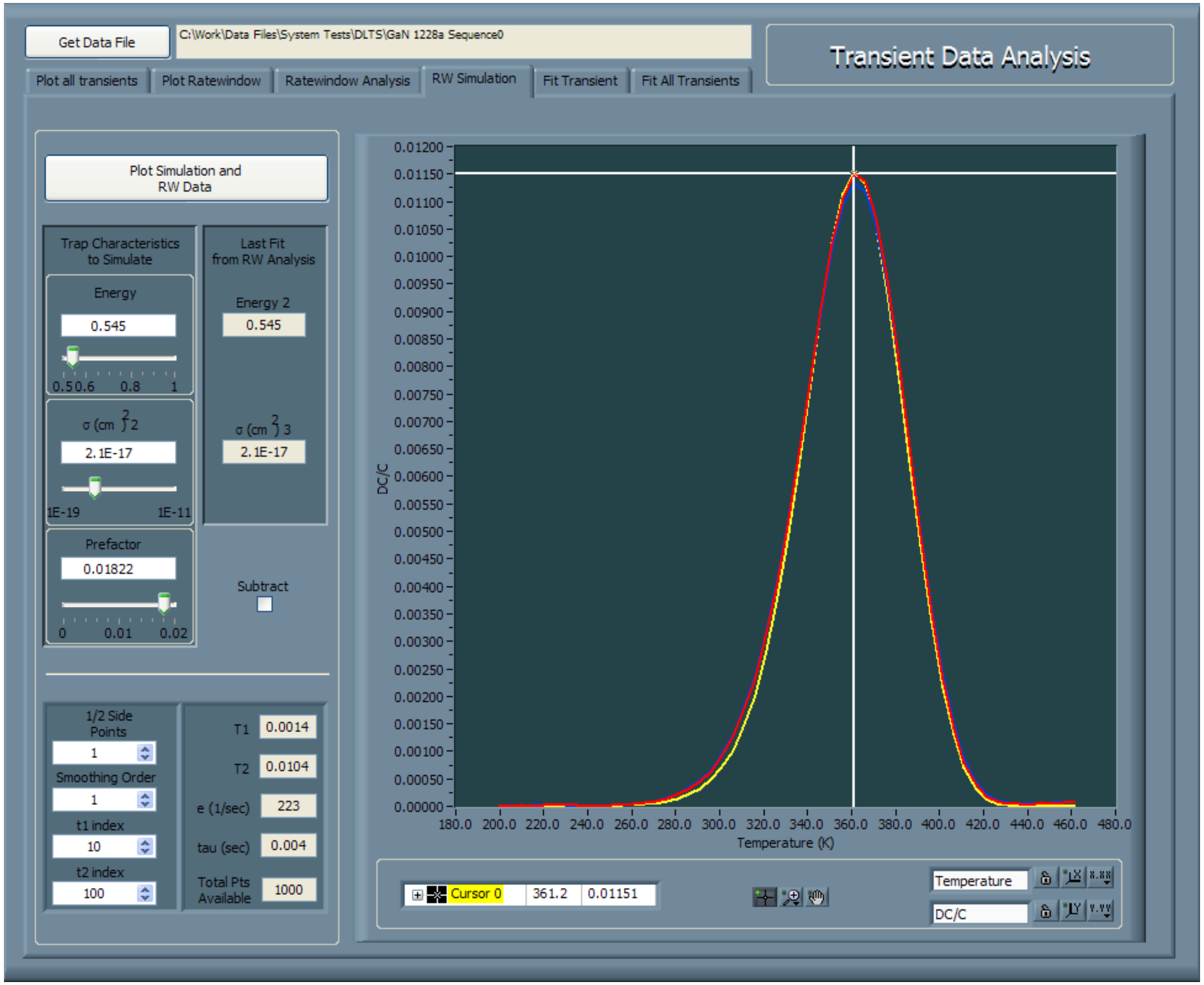


UI DLTS Data Analysis: Simulation

Simulate trap characteristics for comparison to data, or check against reported characteristics.

In this example, the fit from ratewindow analysis is good except a portion at low temperature.

Next, fit transients to see if more than one trap is present in the peak.

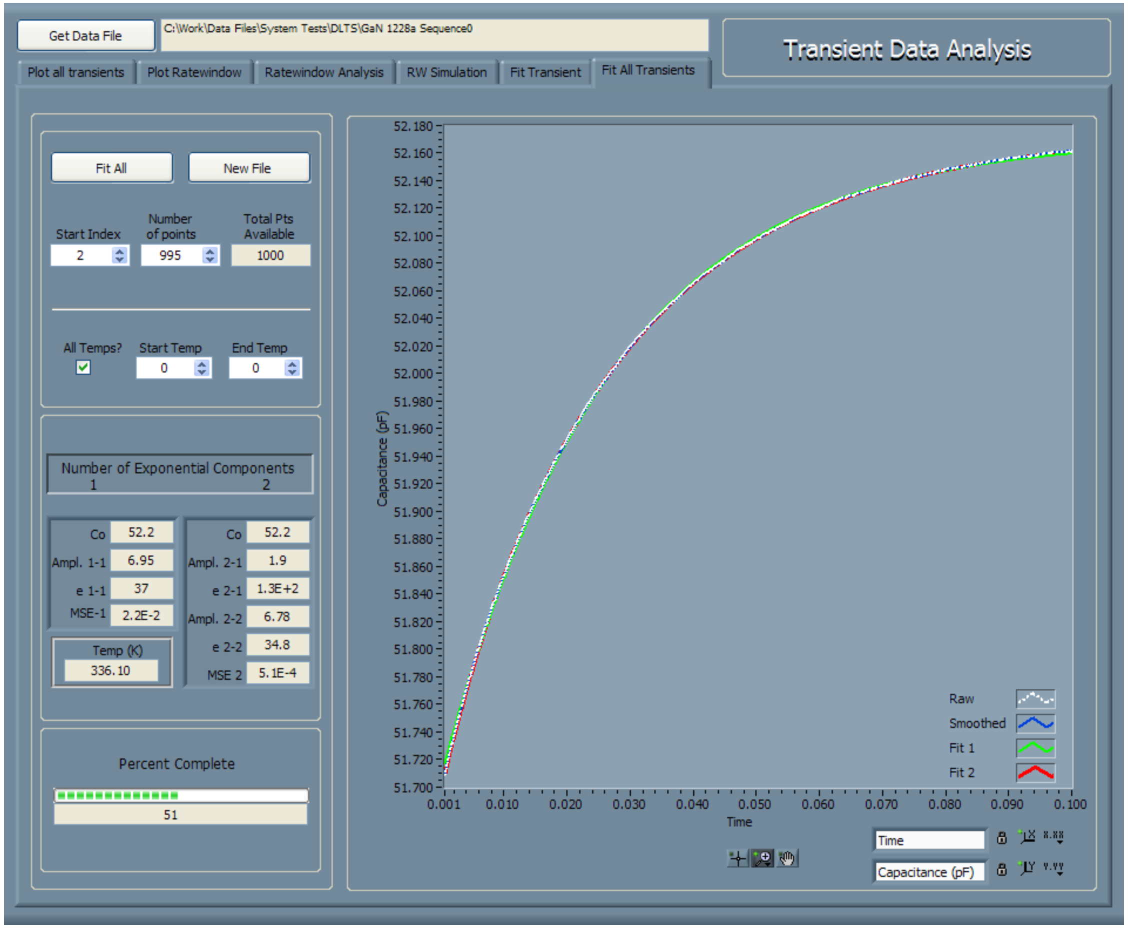


UI Data Analysis: Capacitance Transient Fitting

"Fit All Transients" tab is used to fit all the the collected capacitance transient data.

In this case, the mean square error for the fit for 2 exponential components was more that an order of magnitude better than the fit for a single exponential component. The fit for 2 (red) overlaps the experimental data (white).

Regions of the transient can be selected in order to extend the range of fit emission rates. For example, if more than two components are present over the recording time, a smaller region can be selected.



UI Data Analysis: Arrhenius Plot

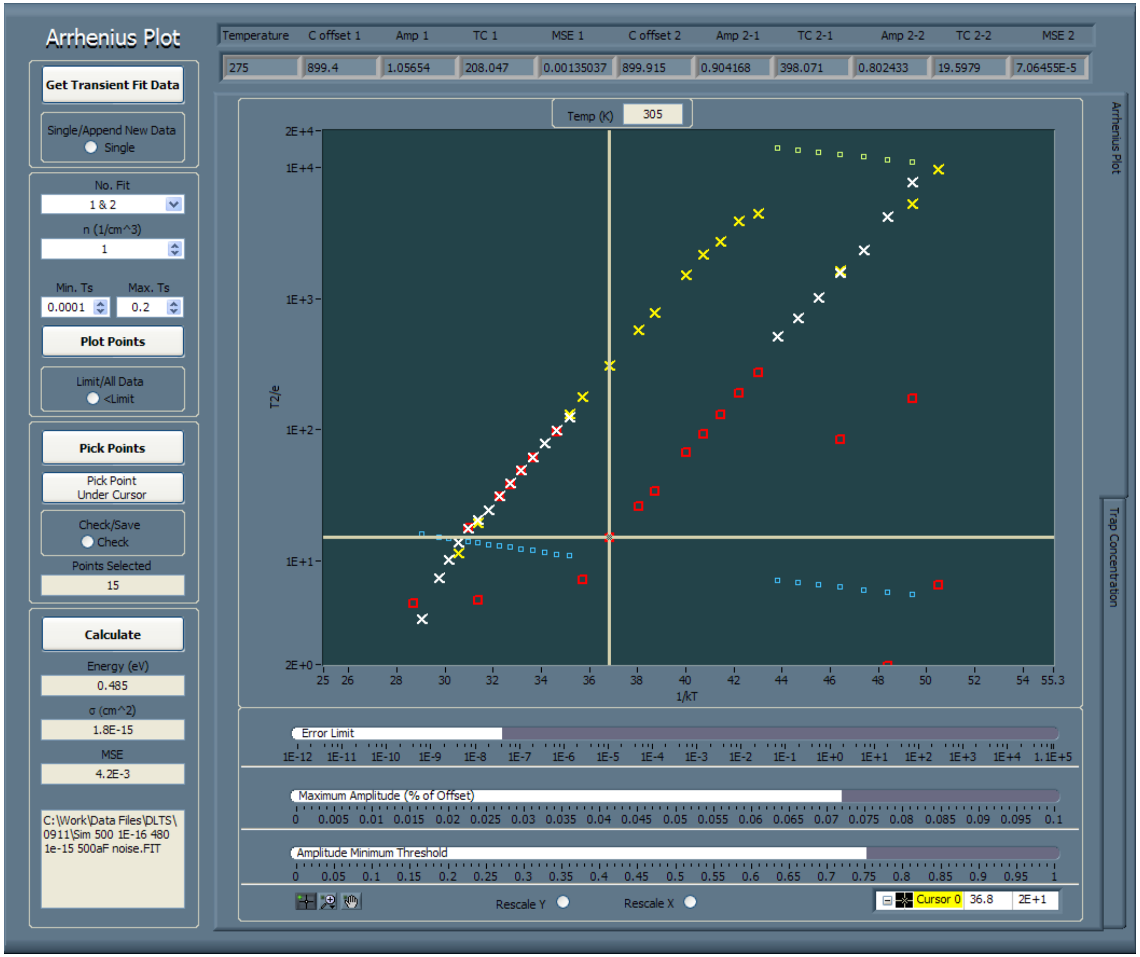
Read and plot Arrhenius data from the fitting program.

The data shown is from a simulation of two closely spaced traps.

The mean square error is used to filter out points that were not fit as well, or points that correspond to negligible transient amplitude.

Points can be plotted for fits from 1 or 2 components, or both.

The cursor is used to select points to be included in the fitting for the energy and capture cross section.



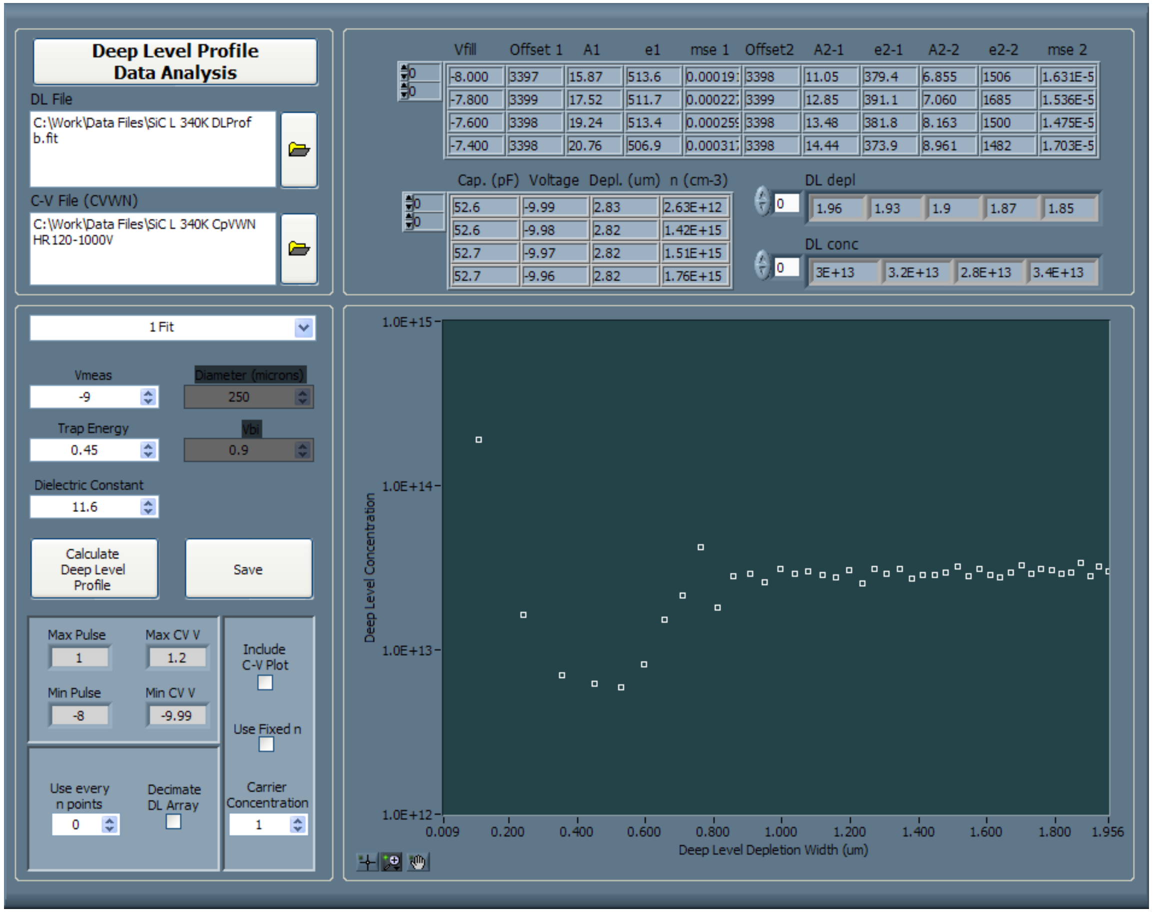
UI Data Analysis: DDLTS Deep Level Profile

Load deep level profile data from transient fitting program

Programmed to account for λ(x), important for variations in N_s. Load CV profile taken at the same temperature. Enter measurement bias, trap energy.

Calculate deep level profile from fit for 1 or 2 exponential component fits.

Other methods of profiling deep levels simply runs several DLTS scans with different filling pulses or measurement biases. This method uses fixed temperature, incremental filling pulses providing finer detail, and qualitative results.



Conclusion

- Let's Build a Diode
- Doping
- Semiconductors – Characteristics
- DLTS Measurements
- DLTS Measurement System
- Transient Data Analysis Software

Thank You

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