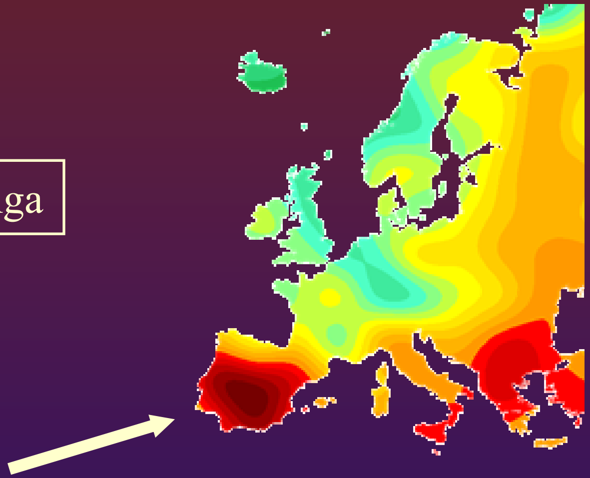
Electrical Characterization of Semiconductors

"Don't be ridiculous. How could there possibly be other life in the universe more intelligent than us?"

Peter Stallinga



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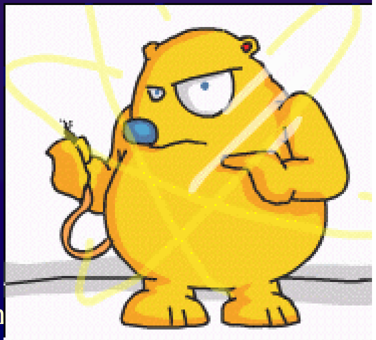
OptoElectronics

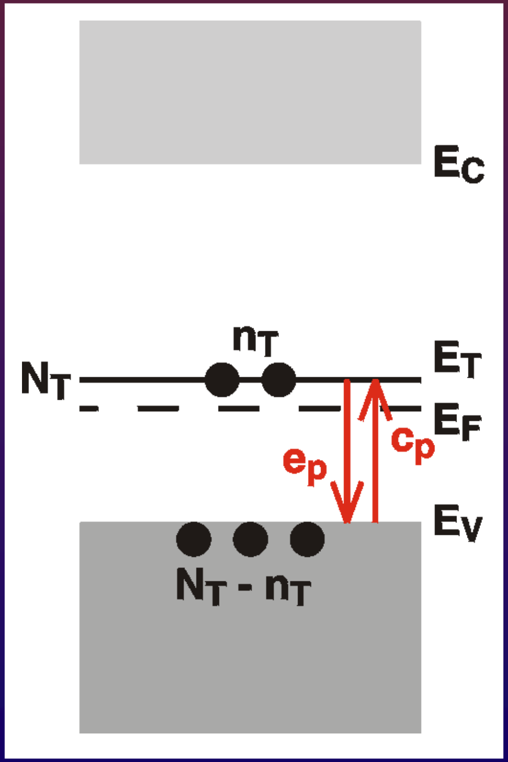
Overview

- Relaxation: trap filling and emptying times
- Transient (spectroscopy)



Basic Kinetics

A “trap” is a deep level, localized in space. Difficult to get the charge out of there   long relaxation time



Trap “thermalization time” is increasing with

- E_T (level depth, E_a)
- T (temperature)

mid-gap levels in silicon are already slow, so in polymers …… forget fast electronics!

$$\boxed{1/\tau = e_p = \gamma T^2 \sigma \exp(-E_a/kT)}$$

Capacitance Transients

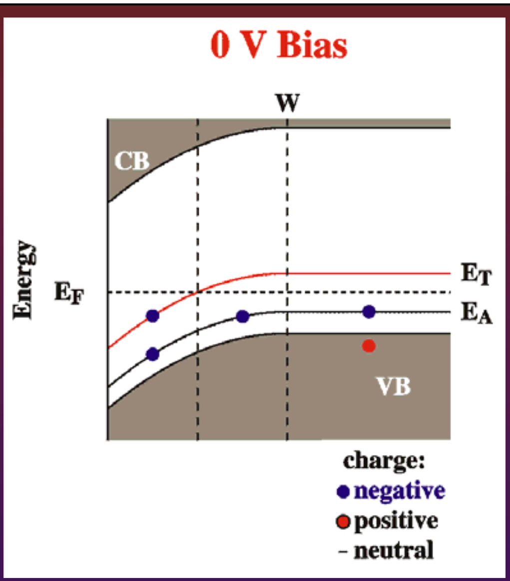
“Change the bias and let’s look how the capacitance evolves over time”

- Capacitance depends on bias (remember, something like $C \sim 1/V^{1/2}$)
- A new depletion width has to be reached. At the end:

$$C = \varepsilon A / W$$

- For shallow levels: response is immediate. Limited only by speed at which free carriers can move out (μ_p).
- For deep levels: the charges have to come off there first.

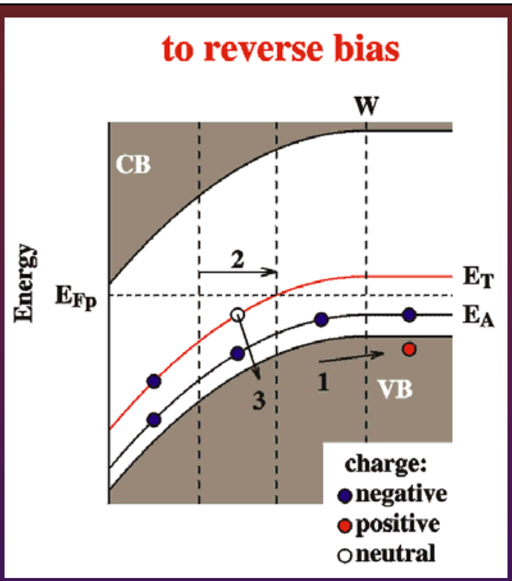
Example: deep acceptor



0 V Bias

Change

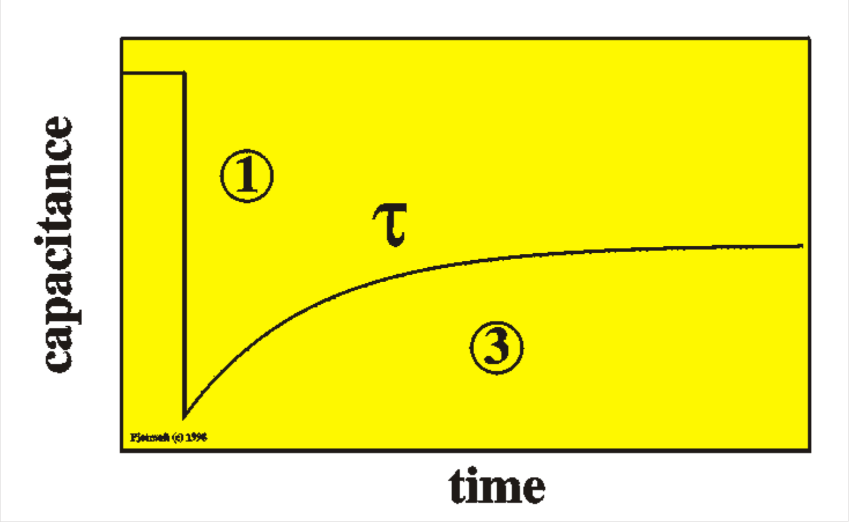
bias



to reverse bias

1. Free holes move out of interface region. Immediate increase of W (C↓)
2. This creates a region where the deep levels are off-equilibrium
3. Charges are slowly emitted from the deep levels there
   - higher space-charge density
   - less depletion width is needed to reach condition $\int\int_0^W \rho(x) d^2x = V_{bb}$
4. W slowly shrinks again a little. Increased capacitance

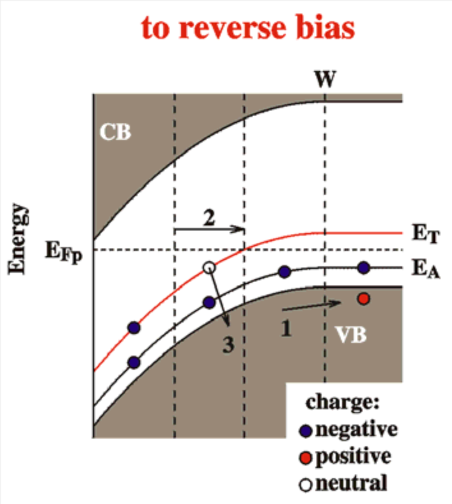
Transient



Summary:

1) Free carriers move out
2) Region off-equilibrium
3) Deep levels empty

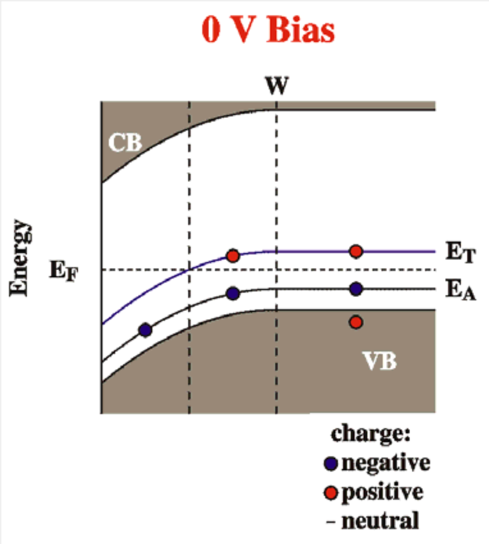
$$1/\tau = e_\mathrm{p} = \gamma T^{2}\sigma \exp(-E_\mathrm{a}/kT)$$

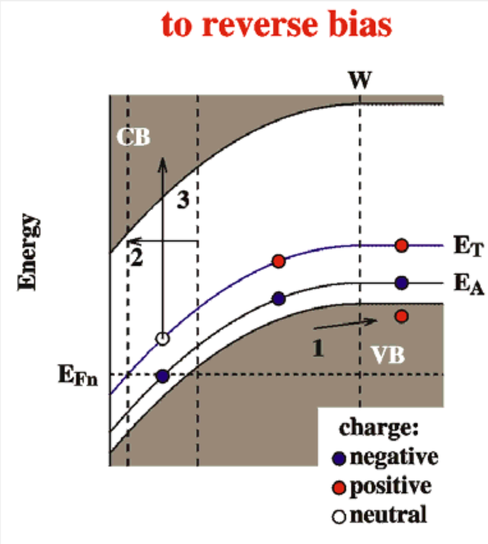


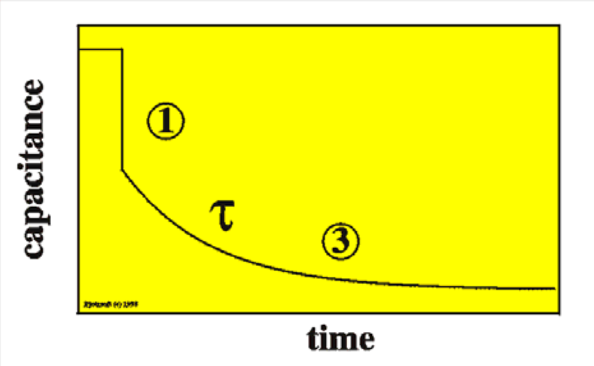
Monitoring τ over temperature will give us E_a

Very sensitive and very accurate!

Minority Traps

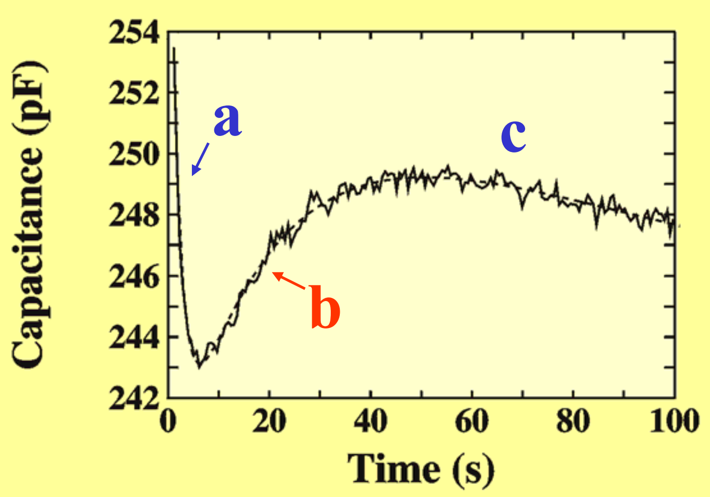






- A "minority trap" communicates with the minority band
- Under bias, the minority Fermi level moves in opposite direction
- This time electrons are emitted and the space charge decreases
- Slowly increasing W and decreasing C over time

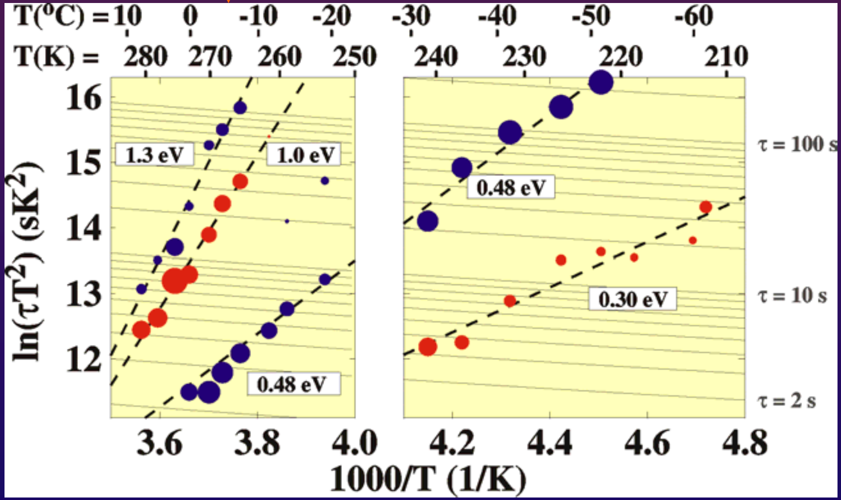
Example of C-transients:



MEH-PPV on Silicon

- 2 minority traps: a, c
- 1 majority trap: b

$$1/\tau = e_p = \gamma T^2 \sigma \exp(-E_a/kT)$$



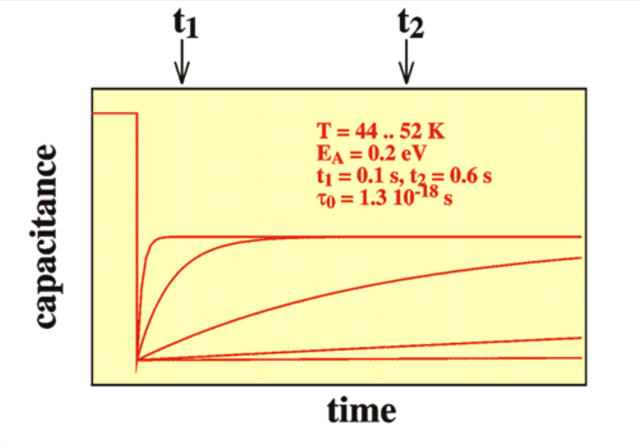
DLTS (deep-level transient-spectroscopy)

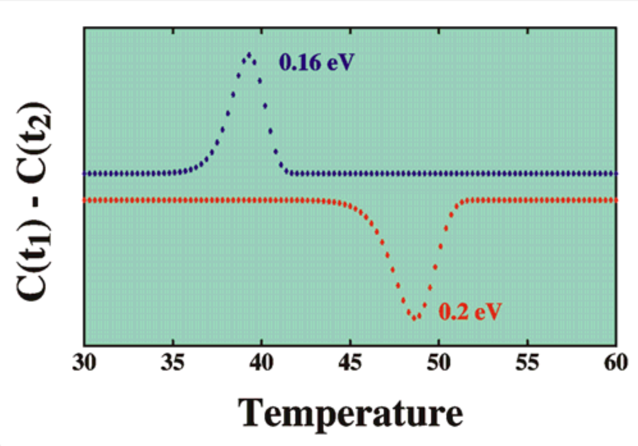
- Of the entire set of data, take only two points, at t_1 and t_2
- The DLTS signal is then $S = C(t_1) - C(t_2)$

For low-T: $\tau = \infty$, $C(t_1) = C(t_2)$: $S = 0$

For high-T: $\tau = 0$, $C(t_1) = C(t_2)$: $S = 0$

Maximum when: $\tau_0 T^{-2} \exp(E_a/kT) = (t_2 - t_1)/[\ln(t_1/t_2)]$





Two scans, with different time window (t_1, t_2) will yield E_a

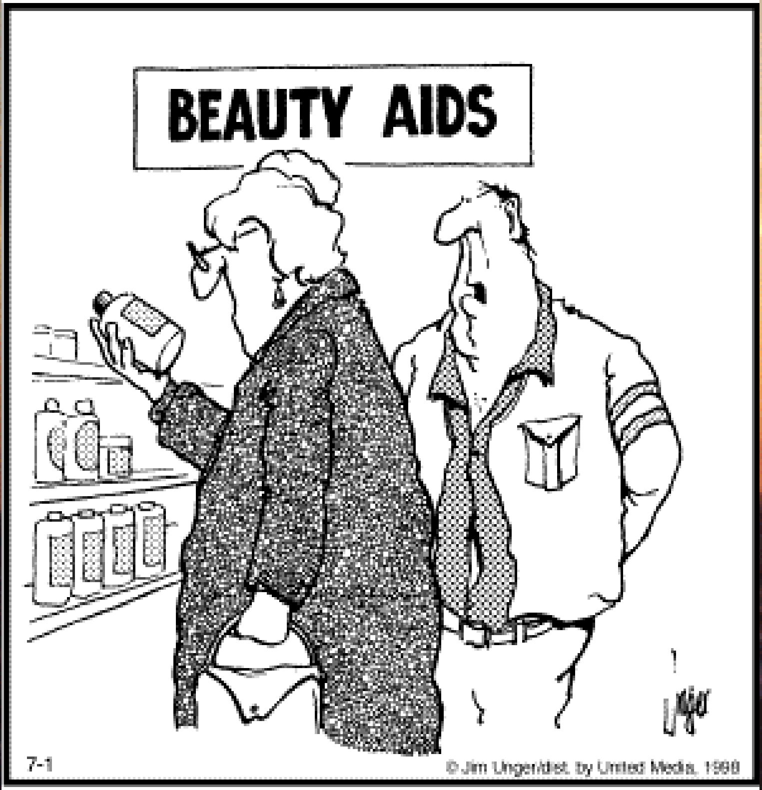
DLTS summary

DLTS is

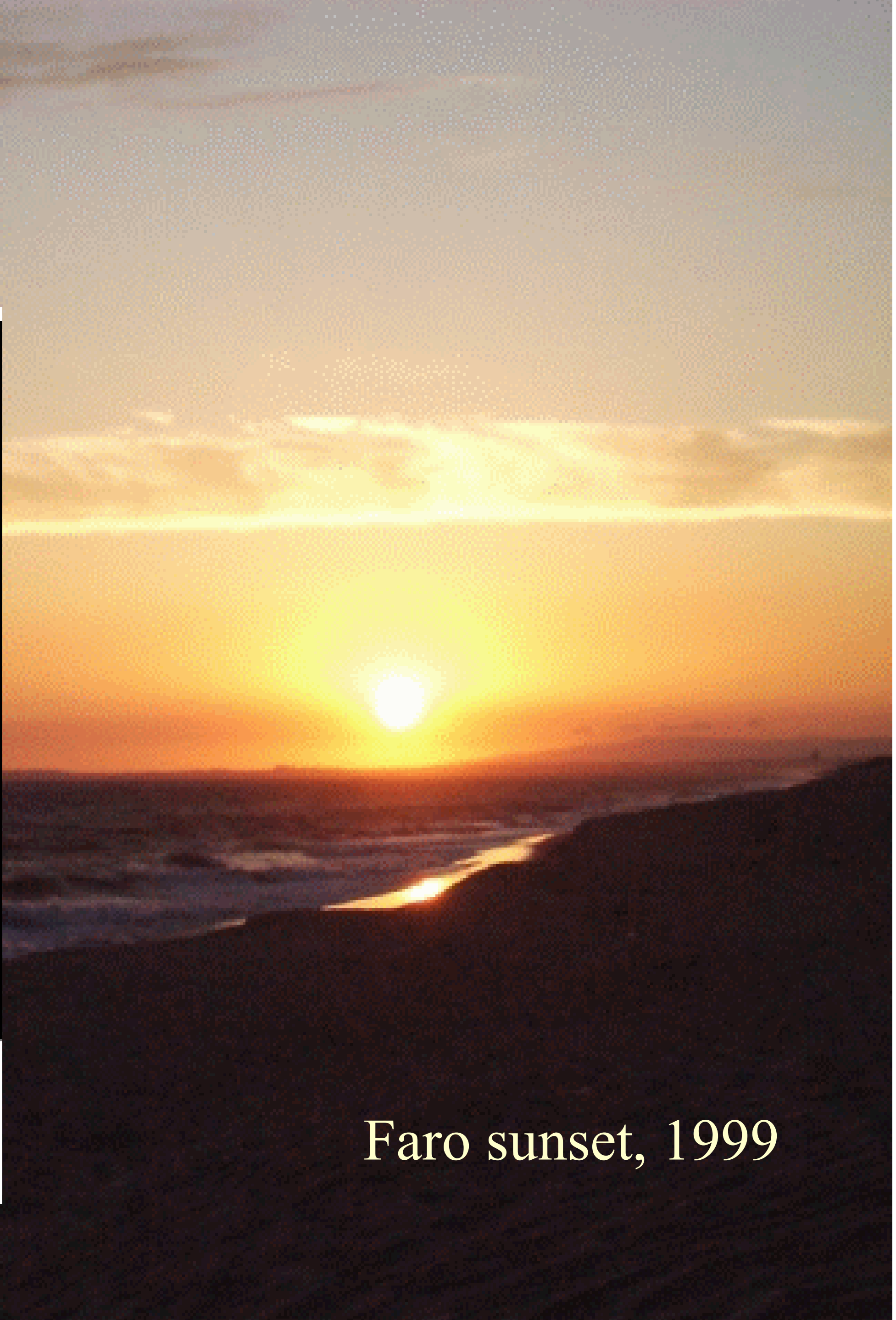
- Very easy to perform. “Walk-away” measurements
- Sensitive
- Reliable data with acurate energy determination
- “Fingerprint” spectra of defects
- Can determine density of defects. $\Delta C/C = N_T/2(N_A\text{-}N_D)$

Modern improvement Laplace DLTS :

- Use entire transient in analysis
  - Higher sensitivity
  - Higher resolution
- Made possible by abundance of cheap computing power (can be done even on-line)



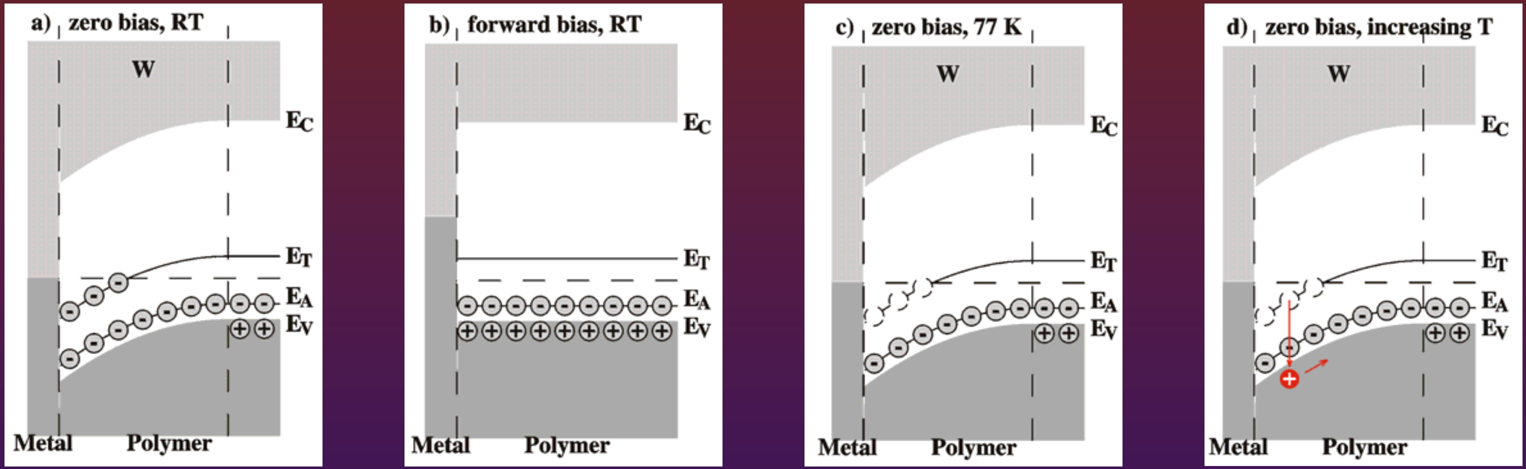
“Want me to get you a shopping cart?”



Faro sunset, 1999

TSC (thermally stimulated current)

“Cool down the sample under (forward) bias and warm up without”



a) 0V, RT, thermal equilibrium
b) Forward bias, RT, thermal equilibrium
cool down, remove bias
c) Zero bias, 77 K, no-equilibrium
d) Warm up, charges are emitted; external current
until all levels are empty. *I* back to 0 . We see a peak in I

$$1/\tau = e_p = \gamma T^2 \sigma \exp(-E_a/kT)$$

TSC (2)

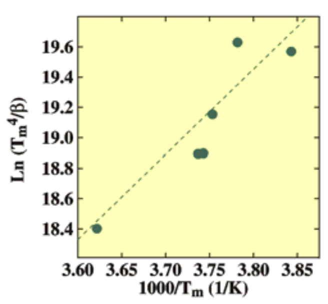
Position of the peak T_m depends on the scanning speed $\beta = dT/dt$:

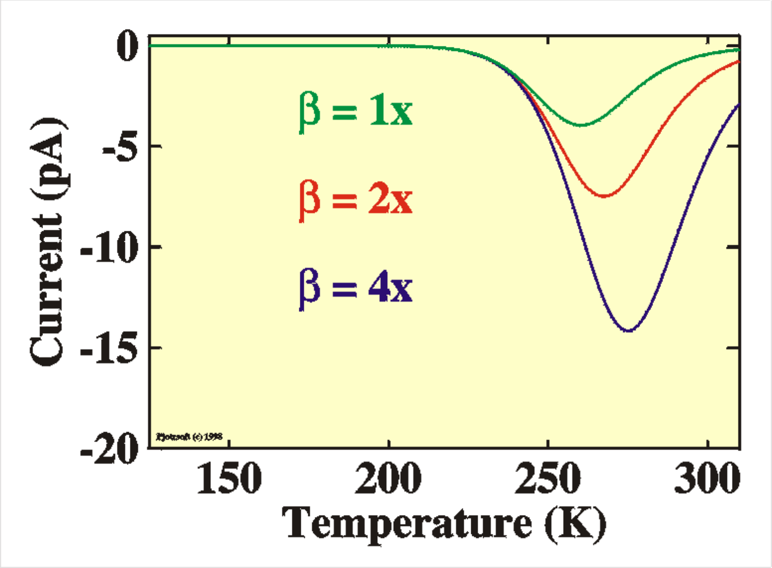
fast scan: the levels have no time to empty. high T_m

slow scan: low T_m

$$\ln (T_m^4/\beta) = E_a/kT_m + C$$

Example:





I is negative:

holes move towards p-side of junction which is equivalent to reverse current

Integral $\int I\, dt$ is constant

is independent of scanning speed and reveals the deep level density

Experimental Set-up

Measurement of capacitance and conductance:
Apply a sign-voltage and observe what current results

- Everything “in-phase” is conductance, “out-of-phase” is capacitance

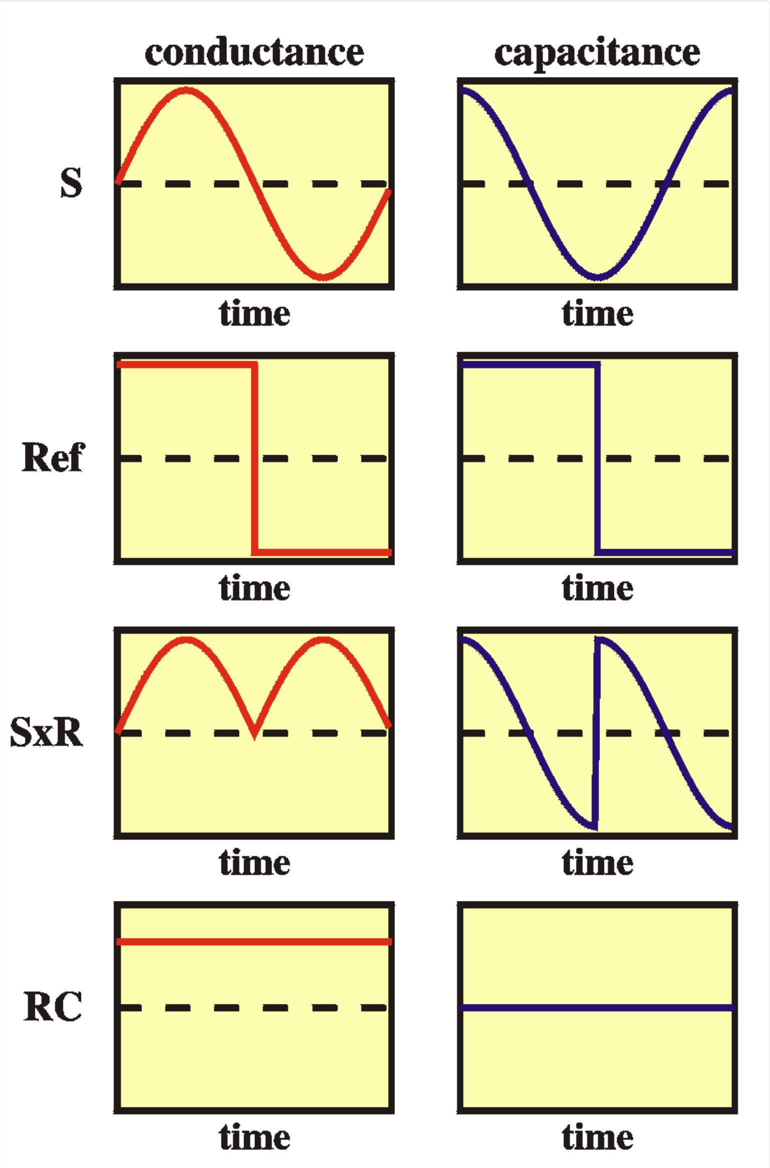
$$\mathrm{V} = V\,\sin(\omega t)$$

$$I = G\;V\,\mathbf{sin}(\omega t) \qquad \text{(R)}$$

$$I = \omega\;C\;V\,\mathbf{cos}(\omega t) \qquad \text{(C)}$$

Lock-in detection (or phase-sensitive detection) to decompose the current into in-phase and out-of phase parts

Phase-sensitive Detection



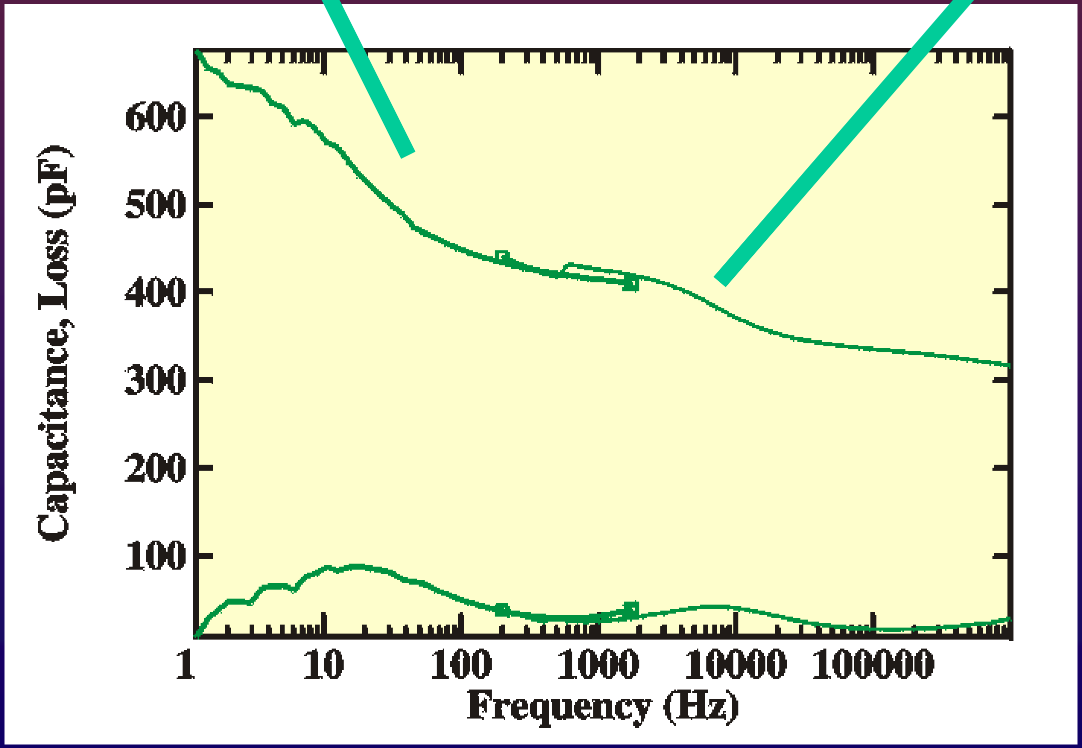
- Signal
- Reference signal
- Product contains
  - DC (ω=0)
  - 2ω, 4ω ..
- After (LP) filter only DC ~ *G*

- out-of-phase signal
- ω, 3ω ..
- no output!

PSD example

Home-built RCL bridge
Based on Stanford SR830
1 mHz - 3 kHz

Commercial
RCL bridge
Fluke 6306
100 Hz - 1 MHz



Summary of Electrical Measurements

	Device Structure	Shallow Level position	Shallow Lelvel density	Deep level position	Deep level density	Free carrier mobility	Conduc-tion Model	Interface states	Difficulty cost
IV	Schoottky Bulk	+	+				++		**1**
CV	Schottky p-n		++					+	**3**
Admittance Spectroscopy	Schottky P-n	++							**4**
IV	FET					++			**2**
Hall	Bulk					++			**8**
TSC	Schottky P-n			+	++			+	**3**
DLTS	Schottky P-n			++	+			+	**5**
ToF	bulk					++			**8**