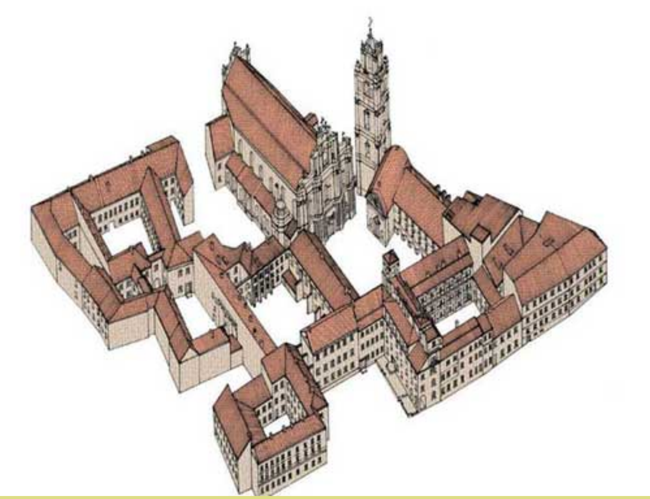


# “Non-traditional methods of material properties and defect parameters measurement

**Juozas Vaitkus on behalf of a few Vilnius groups**

Vilnius University, Lithuania

# Outline:

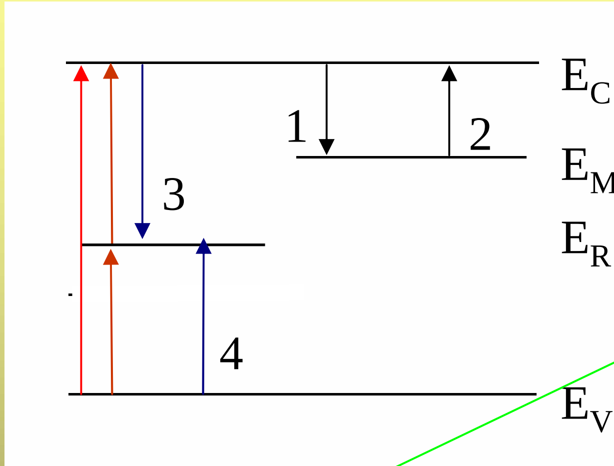
- Definition of aims
- Photoconductivity kinetics
- Free carrier diffusion and capture process measurement
- Photo-Hall and magnetoresistance
- Photo-ionization spectroscopy

# A few general words:

- Profile of our group "self-formed" 40 years ago as: "measurement of properties of high resistivity and wide bandgap materials".
- These materials have many different type of local levels and, usually, different non-uniformities.
- Therefore it was developed or modified a few of methods for exclusion or activation of a  definite level or non-uniformity.
- The modification of methods was oriented on:
  - Exclusion of an origins of nonlinearities;
  - Avoiding an influence of contacts;
  - Creation of scenario that allows to understand the process.

# Free carrier kinetics

# Direct measurement of trapping and recombination:
# photoconductivity decay (short pulse excitation)




1 $\tau_M = 1/\gamma_{nM}(M-m)$

2 $\tau_N = 1/\gamma_{nM} N_{CM}$

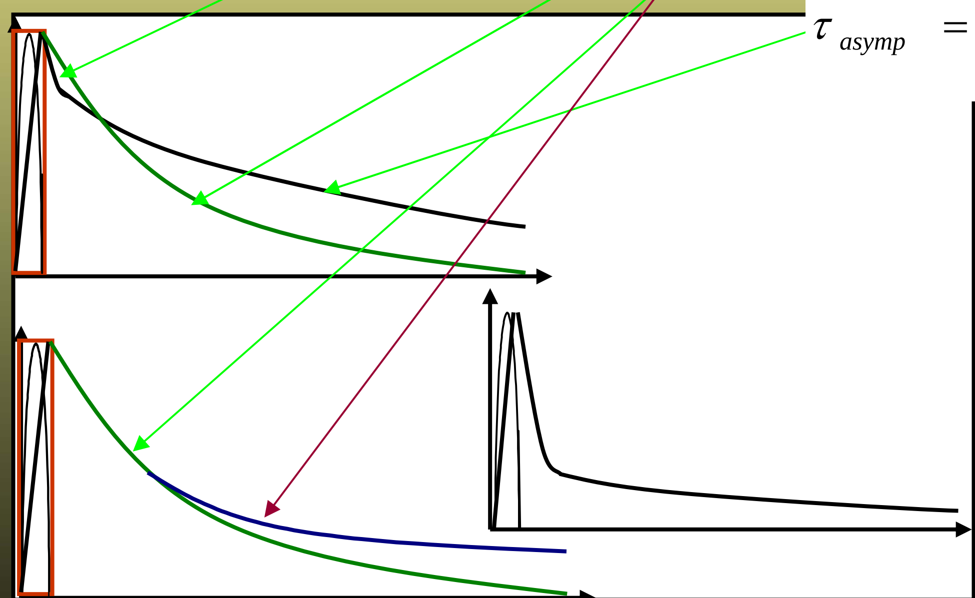
$\Theta_I = 1/[\gamma_{nM} N_{CM} + \gamma_{nM}(M-m)]$

$\Theta_{II} = 1/[\gamma_{nM} N_{CM}]$

3 $\tau_R = 1/\gamma_{nR}(R-r)$

4 $\tau_P = 1/\gamma_{pR}\, r$

$$\tau_{asymp} = \tau_R \left(1 + \frac{M - m_0}{(N_{CM} + n_0)^2}\right)$$



**Measurement of this dependence:**
**E.Gaubas talk!**

# Limitations and possibilities

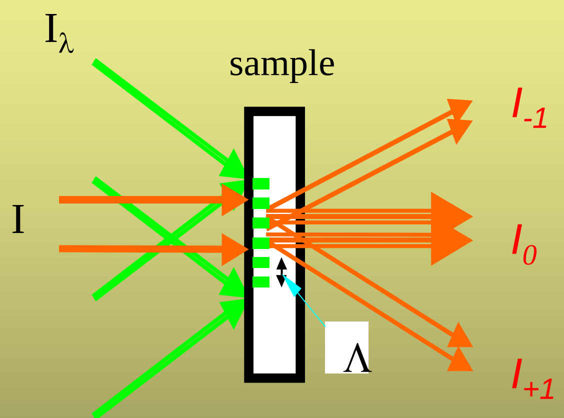
- Excitation pulse duration: ~10 ps, ~10 ns and longer pulses or mosulated dc light.
- Generation of carriers – direct band-band or extrinsic (via deep levels or from/to deep level)
- Problems appears in high quality samples due to influence of the recombination at the surface (if the diffusion is significant)

# Transient gratings

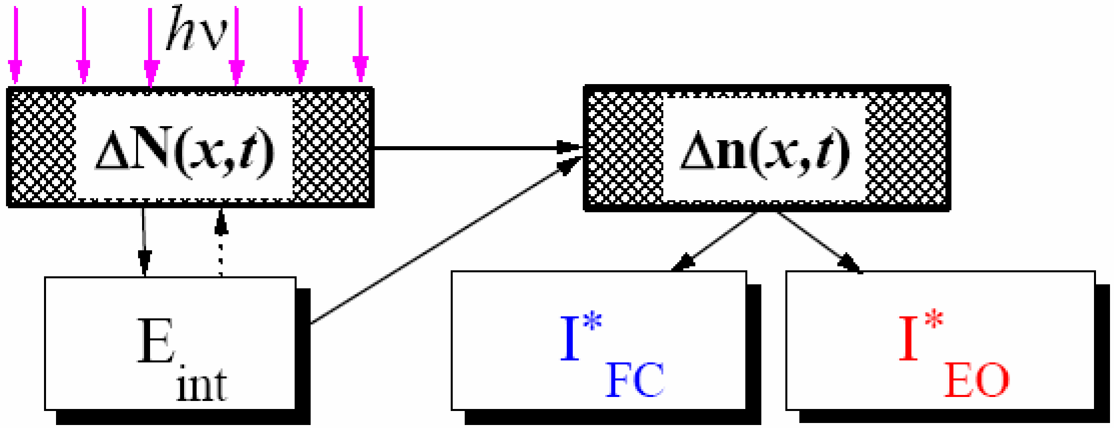
- Free carriers change the refractive index of semiconductor, therefore if the excitation is by the light interference pattern, then semiconductor become as a periodical grating.

- The incident or probe beam pulse will diffract in it.

Transient gratings - contactless, non-destructive semiconductor **homogeneity control** **parameters** (D, S, $\tau$ *and etc.*) **measurement method**




## *Refractive index modulation mechanisms*




$$\Delta n_{FC} = -(e^2/2n_0\omega^2\varepsilon_0)[\Delta N/m_n^* + \Delta P/m_p^*]\omega_g^2/(\omega_g^2-\omega^2)$$

**The Linear Electro-Optic (Pockels) effect:**

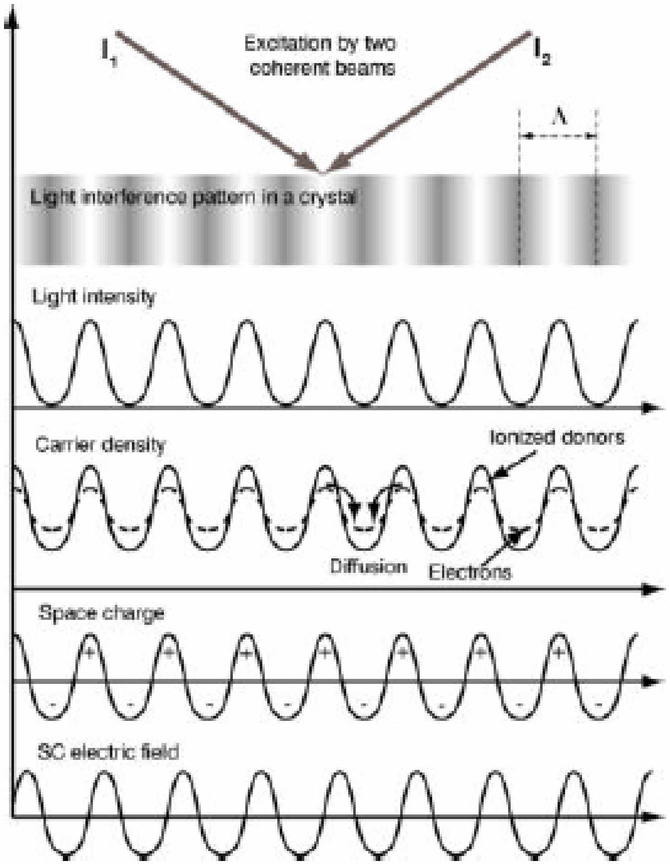
$$\Delta n_{EO} = -n^3 r_{eff} E_{int}/2, \quad r_{eff} = e_i[RK_g]e_d$$

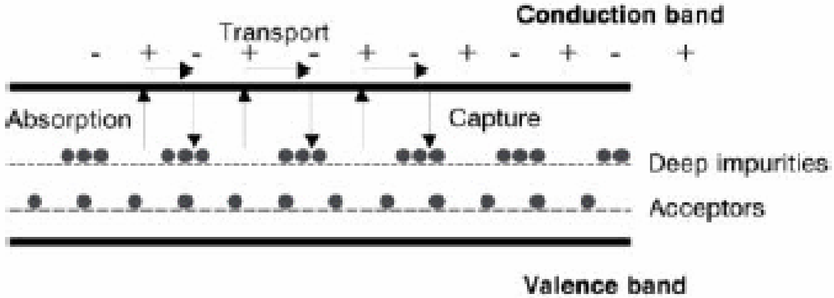
**The Quadratic Electro-Optic (Kerr) effect:**

$$\Delta n_{EO} = -n^3 g(\varepsilon - 1)^2 \varepsilon_0^2 E_{int}^2 = A E_{int}^2$$

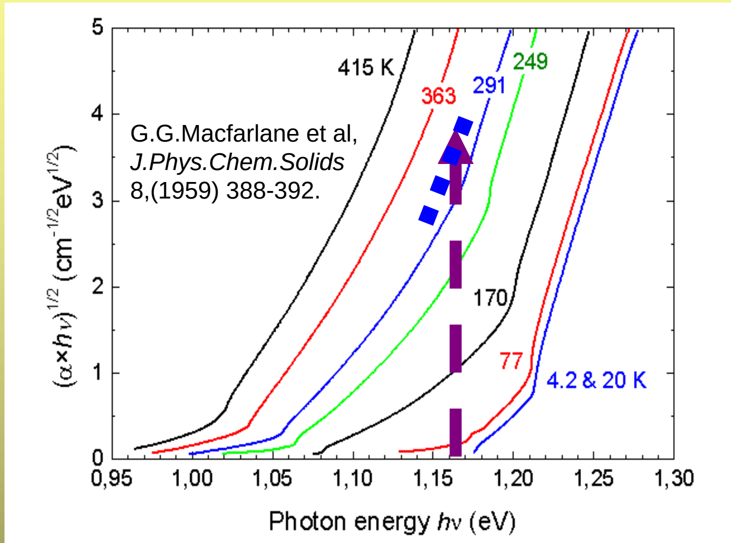
Also allows to indicate the internal electric field related to impurities if the optical symmetry allows the effect.

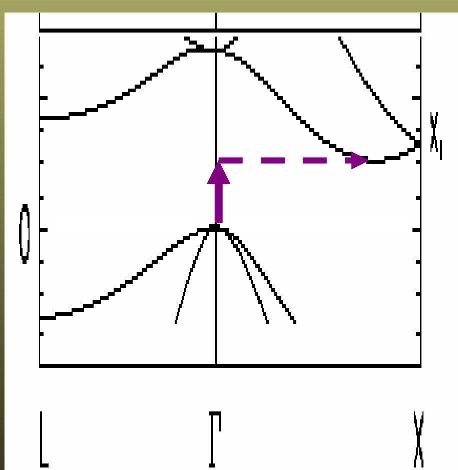
# *Carrier transport governed formation of space charge field*

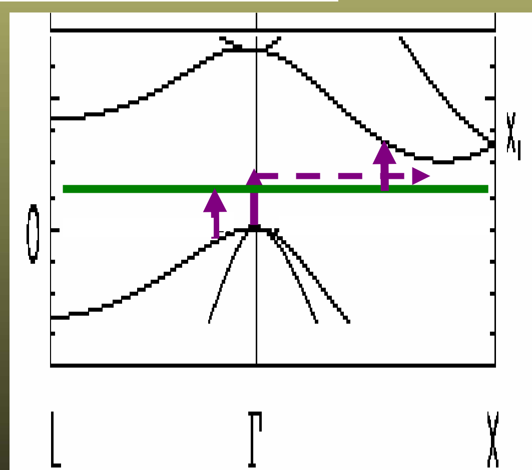


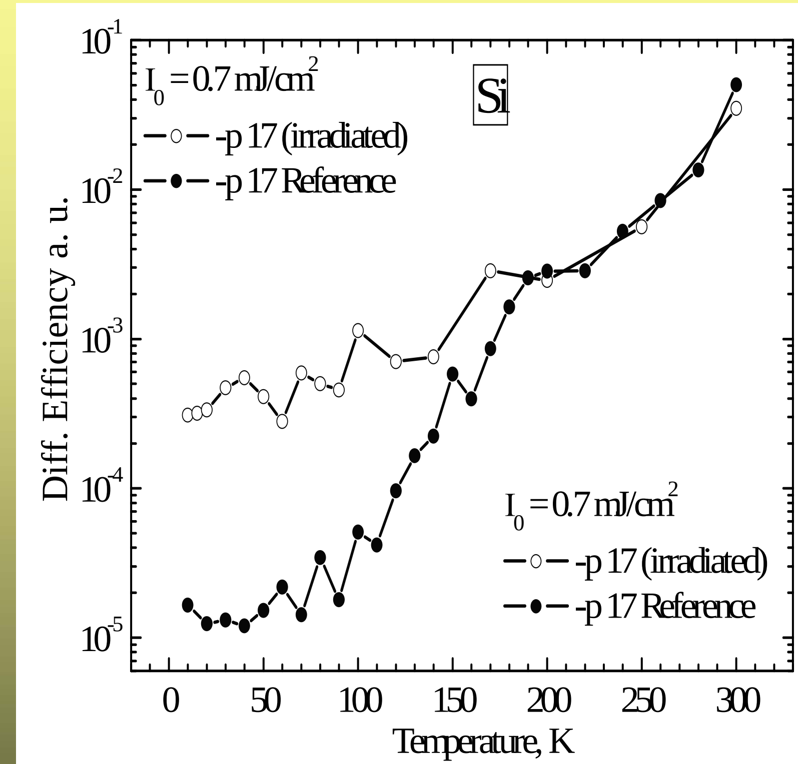



# Two step excitation spectroscopy: generation of carriers via deep centers



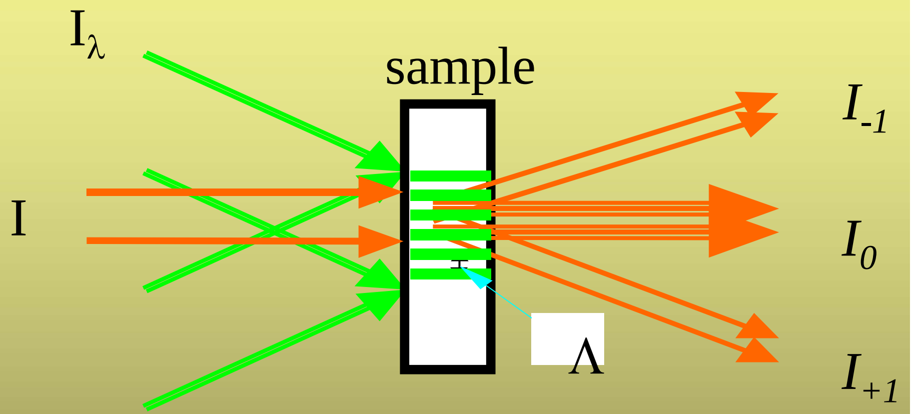



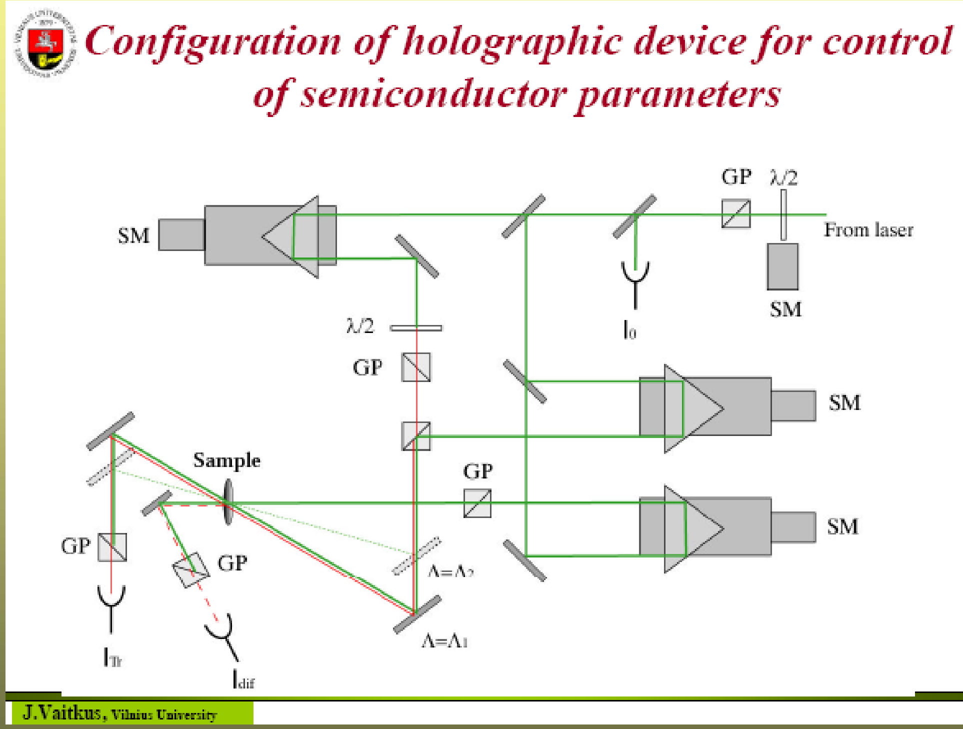



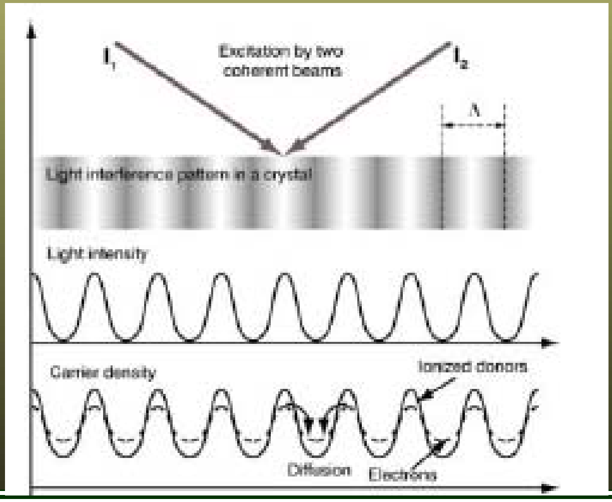




Identification if the centre is localized or Hydrogen-type

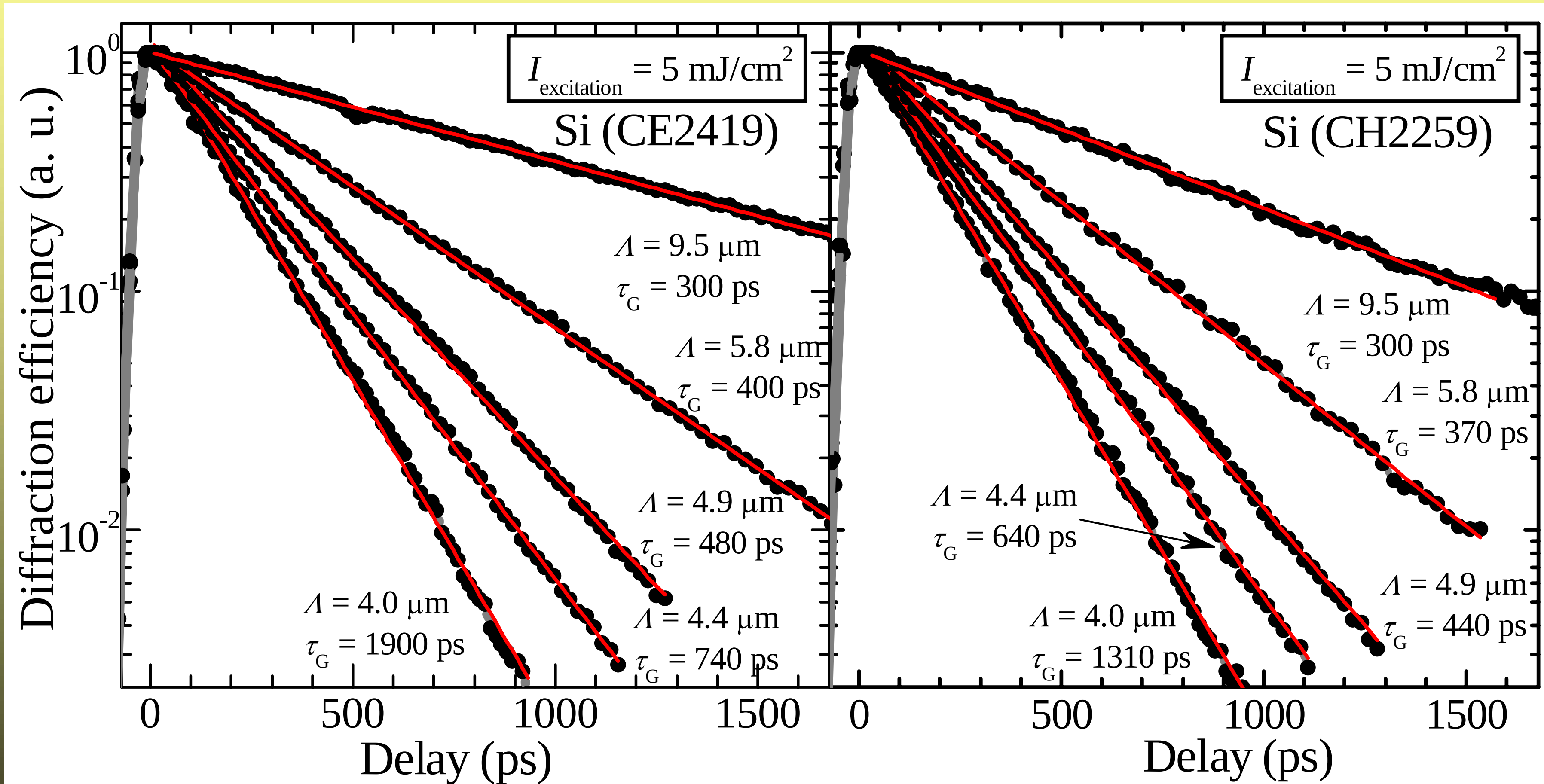
# Free carrier lifetime (trapping time and diffusion) measurement by transient grating method



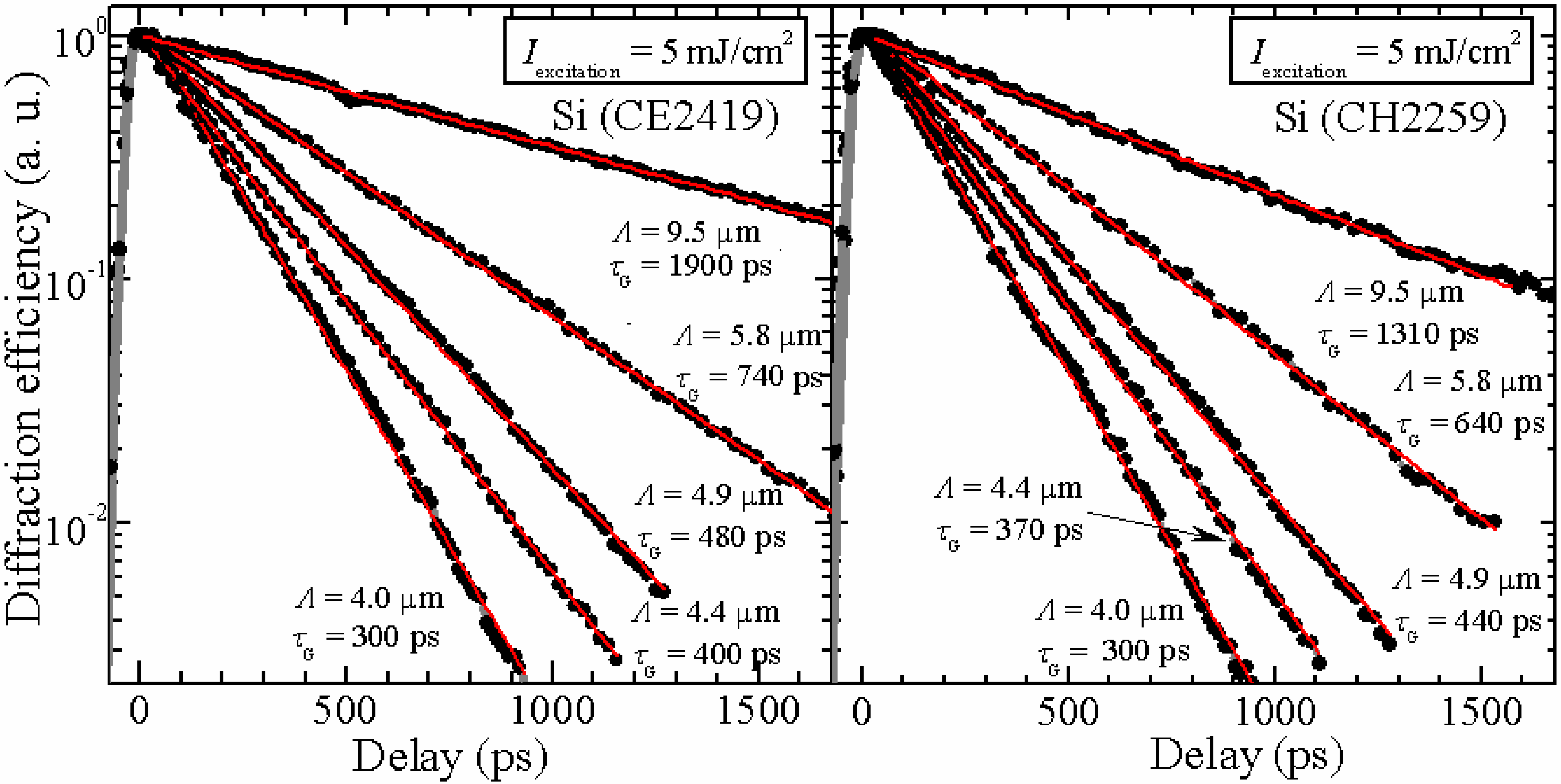




$$\frac{1}{\tau_G} = \frac{1}{\tau_R} + \frac{4 \cdot \pi^2}{\Lambda^2} \cdot D$$



Diffraction efficiency (a. u.)
10^0
10^-1
10^-2
I excitation = 5 mJ/cm^2
Si (CE2419)
Λ = 9.5 µm
τG = 300 ps
Λ = 5.8 µm
τG = 400 ps
Λ = 4.9 µm
τG = 480 ps
Λ = 4.4 µm
τG = 740 ps
Λ = 4.0 µm
τG = 1900 ps
0
500
1000
1500
Delay (ps)
I excitation = 5 mJ/cm^2
Si (CH2259)
Λ = 9.5 µm
τG = 300 ps
Λ = 5.8 µm
τG = 370 ps
Λ = 4.4 µm
τG = 640 ps
Λ = 4.9 µm
τG = 440 ps
Λ = 4.0 µm
τG = 1310 ps
0
500
1000
1500
Delay (ps)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Λ = 4.0 μm
$\tau_G$ = 300 ps
Delay (ps)
$I_{excitation}$ = 5 mJ/cm$^2$
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Λ = 9.5 μm
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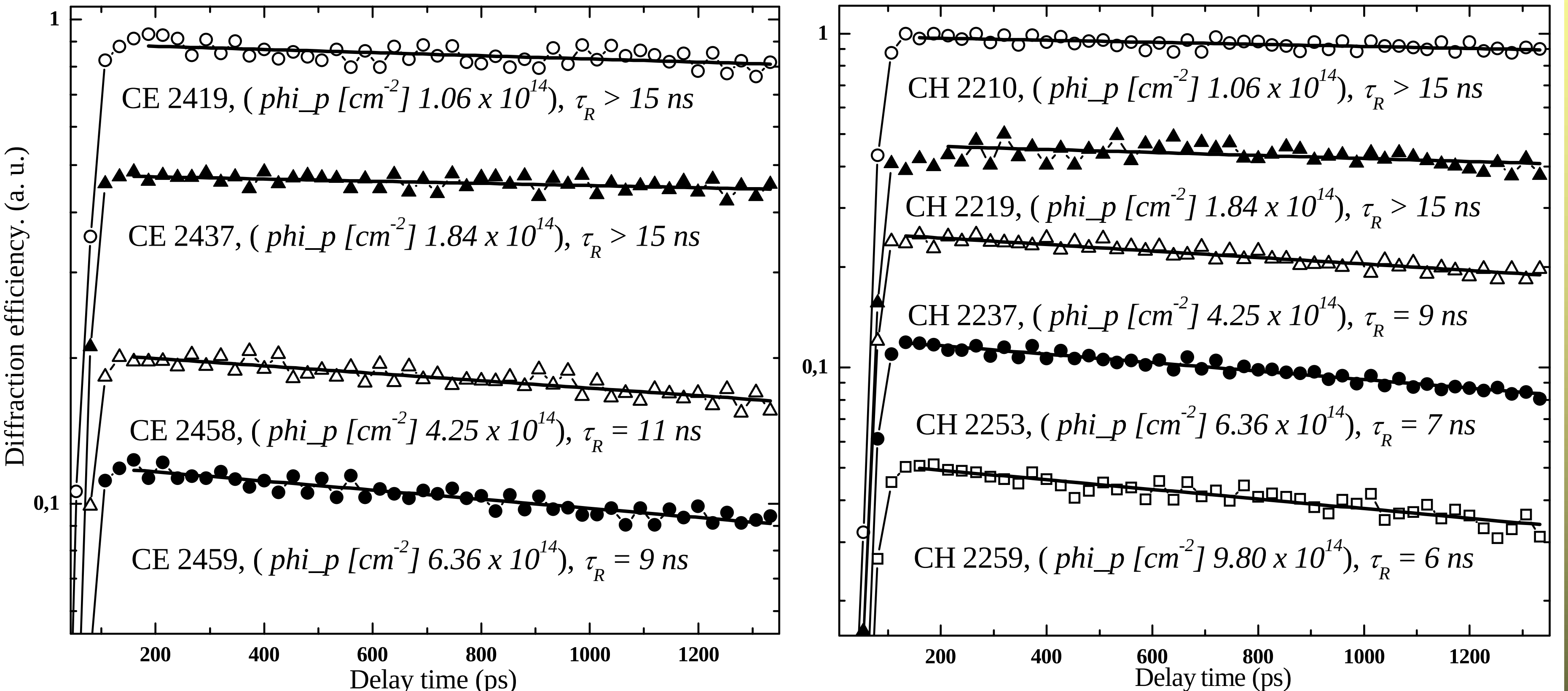
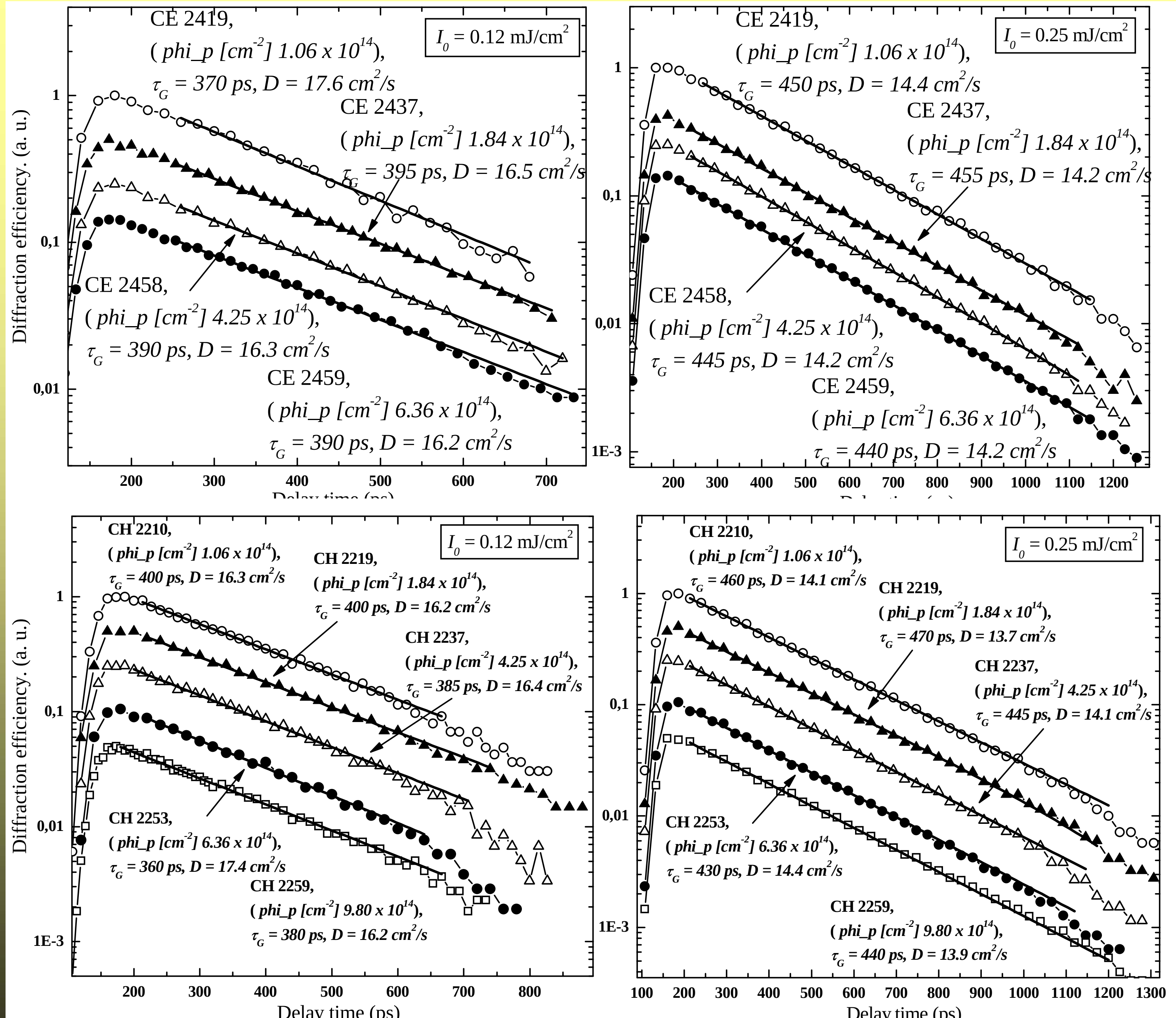
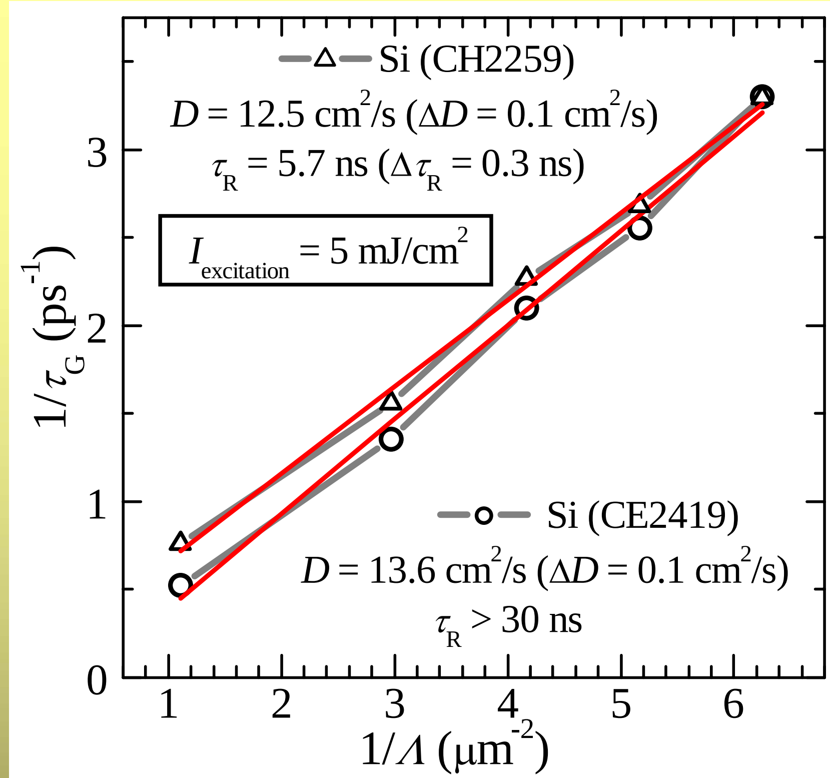
$\tau_G$ = 640 ps
Λ = 4.9 μm
$\tau_G$ = 440 ps
Λ = 4.4 μm
$\tau_G$ = 370 ps
Λ = 4.0 μm
$\tau_G$ = 300 ps
Delay (ps)




$I_0$ = 0.2 mJ/cm$^2$, grating period $\Lambda = 60$ $\mu$m (decay time ~ recombination (trapping) time)



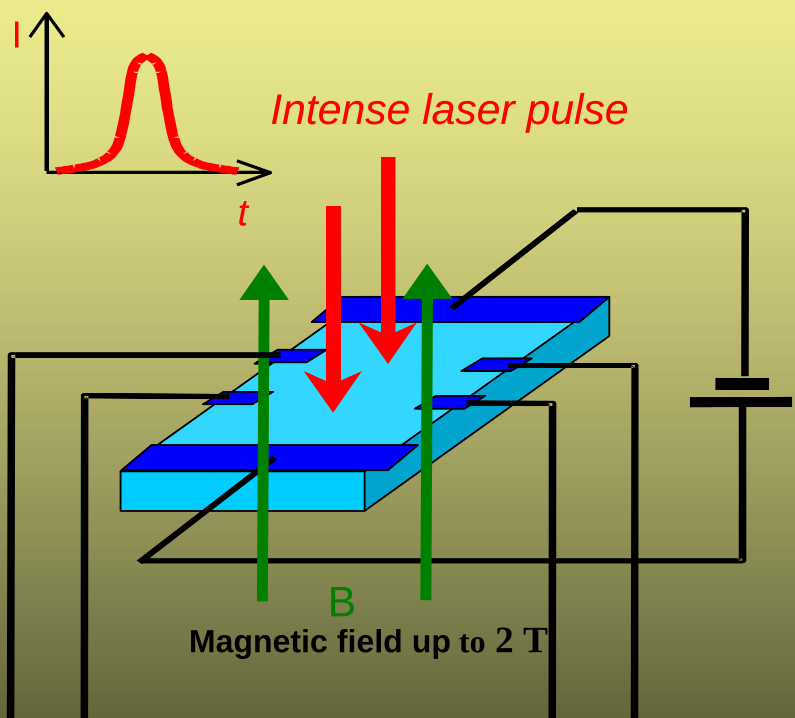

Grating period Λ = 5 µm (diffusion influence)




| **Excitation ($mJ/cm^2$)** | | **Si (CE2419)** **$1.06\ 10^{14} cm^{-2}$** | **Si (CE2459)** **$6.36\ 10^{14} cm^{-2}$** | **Si (CH2259)** **$9.80\ 10^{14} cm^{-2}$** |
|---|---|---|---|---|
| 0.7 | ***D*** **($cm^2/s$)** | 16 (± 0.1) | 15.7 (± 0.1) | 17.2 (± 0.1) |
| | **$\tau_R$ (ns)** | > 30 | >30 | 20 (± 2) |
| 5.0 | ***D*** **($cm^2/s$)** | 13.6 (± 0.1) | 13.1 (± 0.1) | 12.5 (± 0.3) |
| | **$\tau_R$ (ns)** | > 30 | > 30 | 5.7 (± 0.3) |

# Photo-Hall effect

- An influence of impurities on free carrier mobility.
- The indications of scattering on impurities, clusters and etc.:
  - According the scattering coefficient value
  - According the different dependence on temperature




**Digital processing:**

High input impedance, small capacitance !

(2) An increase in Hall mobility, corresponding to an increase in microscopic mobility, can be caused by photoexcitation if the charge on inhomogeneously distributed ionized centers is removed as the result of the capture of photoexcited carriers. This case is similar to the first except that here the scattering is associated with space-charge regions surrounding volumes in the crystal with differing Fermi level. Weisberg[24] has shown how such an inhomogeneous distribution of charged imperfections can lead to apparently huge scattering cross sections if the observations are interpreted in terms of point-defect scatterers.

[24] L. R. Weisberg, J. Appl. Phys. 33, 1817 (1962).

# Transient Photo-Hall and photo-magnetoresistance effects

## 1. Basic relationships:

$$\mu = \frac{e < \tau_m >}{m_{eff}} \quad (1)$$

$$E_H(t) = \frac{\sum_i (-1) e_i n_i(t) A_i \mu_i^2(t)}{\sum_i |e_i| n_i(t) \mu_i(t)} B E_x \quad (2)$$

$$\frac{\Delta\rho_B}{\rho_B}(t) = T_M (\mu B)^2 \quad (5)$$

$$|\Delta U_H(t)| = w[E_{H0} - E_H(t)]B = r_H \Delta\mu \cdot wEB \quad (3)$$

$$T_M = \frac{< \tau_m^3 >< \tau_m > - < \tau_m^2 >^2}{< \tau_m >^4} \quad (6)$$

$$r_H = \frac{< \tau_m^2 >}{< \tau >^2} \quad (4)$$

$$< \frac{1}{\tau_m} > = \sum_i \frac{1}{< \tau_m >_i} \quad (7)$$

$$\frac{1}{\mu_H(t)} = \frac{1}{\mu_0} + \beta v S(t) N(t) \quad (8)$$

Matthiessen's rule

# Transient Photo-Hall and photo-magnetoresistance effects

## 2. Practical considerations:

$$\frac{1}{\mu_H(t)} = \frac{1}{\mu_0} + \beta v S(t) N(t) \qquad (8)$$

$$\Delta(SN) = S_0 N_0 - SN = \frac{1}{\beta v}\Delta\left(\frac{1}{\mu_0} - \frac{1}{\mu(t)}\right) = \frac{wBE}{\beta v U_{H0}}\left(1 + \frac{U_{H0}}{\pm \Delta U_H}\right)^{-1} \qquad (9)\ (10)$$

$$Y(t) = \left(1 + \frac{U_{H0}}{\Delta U_H}\right)^{-1} \qquad (11)$$

$$\Delta[S(t)N(t)] = const \cdot Y(t) \qquad (12)$$

$$\mu_{ion.i.} \sim T^{3/2}$$

$$\mu_s = e\left[N_s \left(2m^* kT\right)^{1/2} S\right]^{-1}$$

$$\mu_{barr.} \sim T^{-1}$$

Further analyze depends on the model and a number of re-chargeable centers

(1) An increase in Hall mobility, corresponding to an increase in microscopic mobility, can be caused by photoexcitation if the charge on ionized scattering centers is removed as a result of the capture of photoexcited carriers. If $\Delta(1/\mu)$ is the magnitude of the mobility change, $m_e^*$ is the effective carrier mass involved in the conductivity process, $N$ is the density of scattering centers, and $\Delta S$ is the change in scattering cross section caused by photoexcitation,[3]

$$\Delta(1/\mu) = 10^4 m_e^{*\frac{1}{2}} T^{\frac{1}{2}} N \Delta S. \tag{2}$$

If the scattering centers involved are point defects with Coulombic scattering cross section, then $\Delta S$ is given to within a factor of order unity by

$$\Delta S = (10^{-10}/K^2)\ \mathrm{cm}^2 \tag{3}$$

at room temperature, for the change from a singly charged to a neutral center, where $K$ is the dielectric constant.

# Photo-Hall effect

- If the sample has micro/nano non-uniformities, then the signal is more complex dependent on parameters.

    (That should be in a case of change of conductivity type)

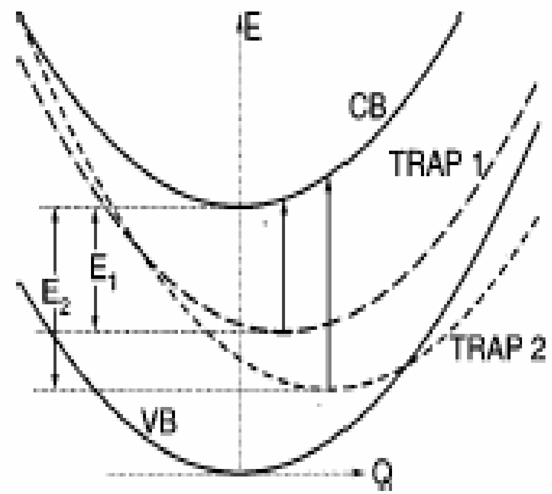
- It changes an effective active volume therefore changes the effective Hall-mobility (a lot of models, quite complicated expressions)

# Photo-ionization spectrum

Measurement of photoconductivity (possible effect also: quenching of photoconductivity, if additional excitation is used), photo-voltage, short circuit current.

Possible regime of constant signal: varying of excitation. It excludes different non-linearities.

Determination of defect optical ionization energy.




Sketch of a configuration coordinate diagram showing the relationship of the deep traps and the band edge. $E_1$ and $E_2$ represent the thermal trap depths, while the optical transition energies indicate the photoionization thresholds

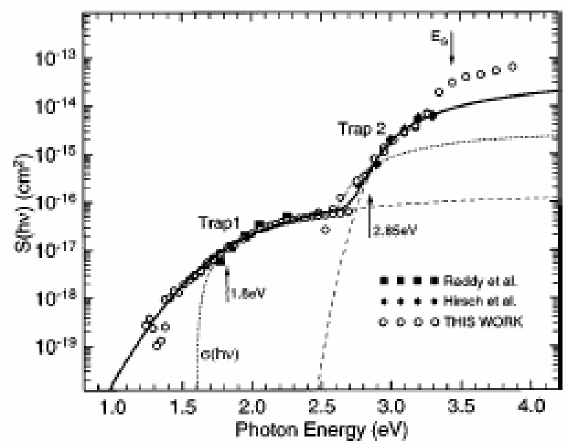



FIG. 2. Spectral dependence of the current collapse response function $S(h\nu)$. The open circles are the experimental data, and the solid symbols represent recent (scaled) PPC data. The dotted line is an unsuccessful fit of the data to a standard deep-level photoionization cross section $\sigma(h\nu)$, while the heavy solid line is a fit of the data following the approach in Ref. 12, which is essentially a convolution of the photoionization cross section with a Gaussian broadening function.

[12] P. M. Mooney, G. A. Northrup, T. N. Morgan, and H. G. Grimmeiss, Phys. Rev. B 37, 8298 (1988).

# Si photoconductivity spectrum

Example of data from literature:

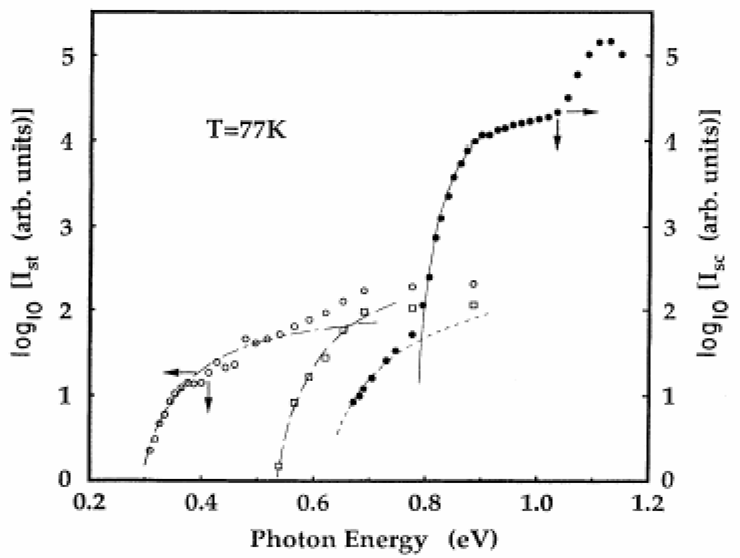
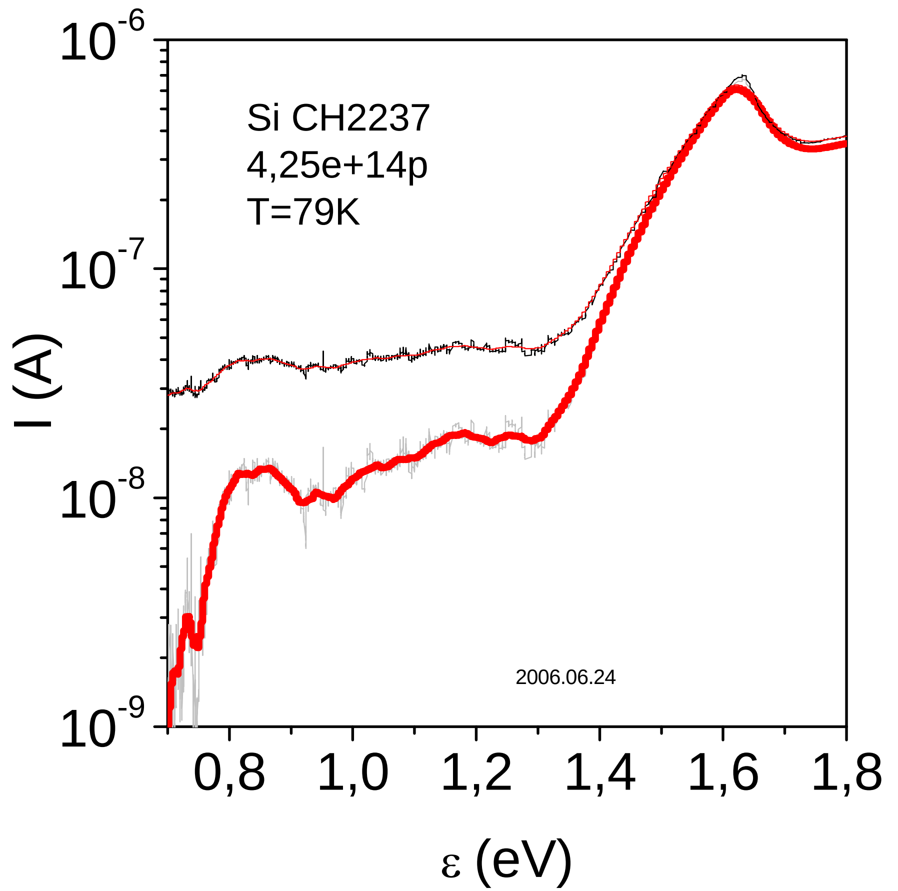



FIG. 5. Spectral distribution of the short-circuit current $I_{sc}$ (solid circles) and the photocurrent storage effect $I_{st}$ (open circles and squares) measured for holes in $n^+$-$p$ Si:Ti diodes at 77 K. The open squares have been obtained by subtracting the dash-dotted curve from the open circles.

Sample from Hamburg:



# Conclusions:

1. It exists additional (time consuming) methods for carrier capture processes and defect parameters measurement.
2. It is most important to have the samples, that are interesting for supplier.

Thank You for Your attention!