Peculiarities of defect type recognition by non-equilibrium conductivity investigation in different semiconductors

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This contribution presents a possibility of defect analysis at Vilnius University by methods based on effects:

a) thermally stimulated current and polarisation;

b) photo-Hall effect (including transient behaviour after excitation by light pulse);

c) carrier trapping and recombination extracted from light pulse induced microwave absorption;

d) photoconductivity extrinsic spectra and quenching;

e) light induced transient gratings on free and localised carriers.
“The real” contact and semiconductor

Model of metal-semiconductor junction with defect levels and inhomogeneous potential relief of the conductivity band bottom
Thermally stimulated currents in SiC at different applied voltages in forward (solid lines) and reverse (dashed curves) directions as indicated on the Figure.
Multiple annealing in TSC measurement

Temperature dependence on time in a multiple heating regime

TSC in a multiple heating regime
TSC in the multiple heating regime after the excitation for 900 s by 1.08 eV light. The numbers nearby curves indicate their thermal activation energy values.
Activation energy from multiple annealing TSC in SI-GaAs

![Graph showing thermal activation energy vs. 1/T of previous annealing](image)

- Thermal activation energy (eV)
- 1/T of previous annealing (1000/K)

Values for TSC (A) and 1/T (1000/K) are indicated on the graph.
Thermal depolarization current spectra measured after short excitation with 1.08 eV light (normal state of the EL2 level - solid line), and after long excitation with the same light (metastable state the EL2 level - dashed curve)
Transient carrier transport in SI-GaAs

Photoconductive decay after short laser excitation

Photocurrent kinetics at two different excitation wavelengths
Transient Photo-Hall effect

Principle of the transient Photo-Hall effect technique

Digital processing:
High input impedance, small capacitance!
Transient photo-Hall mobility in SI-GaAs:In after laser pulse excitation at 300 K (a), 350 (b) and 420 K (c).

TABLE I. The determined [according to Eqs. (2)–(4) and Ref. 5] values of the recombination barrier height \(E_{\text{rec}}\), effective radius of the space charge region \(R_Z\), and its charge \(Z\) of the samples 1–3.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Indium doping (\text{(cm}^{-3})</th>
<th>Recombination barrier height, (E_{\text{rec}}) (eV)</th>
<th>Effective radius of the space charge region, (R_Z) (cm)</th>
<th>Effective charge, (Z) (electrons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>undoped</td>
<td>0.19</td>
<td>(6.5 \times 10^{-7})</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>(6 \times 10^{19})</td>
<td>0.18</td>
<td>(6.3 \times 10^{-7})</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>(2 \times 10^{20})</td>
<td>0.14</td>
<td>(5.6 \times 10^{-7})</td>
<td>7</td>
</tr>
</tbody>
</table>
Photoconductivity $= f ( T, I )$ dependences

Dark current and photocurrent dependence on temperature

Photocurrent dependence on temperature at different excitation intensity
I measurement - yellow (1f) - increase of $h\nu$ (constant number of quanta); black (1b) - decrease of $h\nu$, II - red (2f), green (2r); III - blue (3f), I(excitation lamp)=29Å (145) =const, T = 100 K.

The low energy part of the photoconductivity spectral dependence. The arrows indicates the direction of measurement and the number indicates the number of the measurement cycle.
Photoconductivity kinetics

After a short pulse excitation – decay of photoconductivity, that depends on:

carrier trapping, recombination and diffusion (and mobility)

Via analyze of the decay: time constant allow to measure,
i.e. parameters of local levels, surface recombination can be found.

Measurements (light induced conductivity, absorption, refraction):
dc, high frequency, microwave, IR
Principles of determination of recombination parameters

bulk & surface recombination

recombination & trapping

non-linear recombination

excess carriers domain

$g(x,t)$

$\tau_s$

$\tau_b$

$t$ (µs)

$10^{-2}$

$10^{-1}$

$10^0$
Experimental arrangements MWA/R to implement cross-sectional scans

Microwave absorption technique modification using perpendicular excitation by broad light spot and probe by slot resonant MW antenna.

Probing provides the product of mobility and concentration

$$\mu^* n_{exc} \propto <\tau>$$
Principles of determination of recombination parameters

Si substrate d=420 µm
sample B3

n/n₀ vs. t (µs)

1 - bulk excitation
2 - face side
3 - rare side
near surface excitation

A² vs. S=sd/D

A² vs. S=sd/D

αd=1
αd=10
αd=10²

Velocity of surface recombination (cm/s)

Processing
Results of simulations of the excess carrier profiles

Reconstruction of excess carrier concentration profile through the analysis of the decay shape and normalised amplitude variation with excitation spot position

\[ s_0 = s_d = 10^3 \text{ cm/s}, \ \Phi = 50 \ \mu\text{m}, \ d = 280 \ \mu\text{m}, \]

\[ Y_1 = 0 \ \mu\text{m} \]

\[ Y_1 = 100 \ \mu\text{m} \]
Transients

Excess carrier concentration decays measured by extended broad laser beam excitation / IR 120 µm probe

Excess carrier concentration decays measured by fiber excitation/ MW slot probe in NTD oxidized Si d= 280 µm
Recombination characteristics of the starting material modified by stratification of micro-defects

Correlation of carrier effective lifetime lateral scan with etching revealed strata of micro-defects in Si wafer

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The fast components

Photoconductivity decay in different samples. The grey lines are a fit. The sample and fitting parameters given in Table 1.

\[ I(t) = I(0)[A_1 \exp\left(-\frac{t}{\tau_1}\right) + A_2 \exp\left(-\frac{t}{\tau_2}\right)] \]

Table 1: A fit of the data in Fig. to a sum of exponential functions. \(A_i\) is the partial amplitude, \(\tau_i\) the corresponding time constant and \(n^0\) the total amplitude of the slower components.

<table>
<thead>
<tr>
<th>Sample growth T, 0°C; TMG flow rate</th>
<th>(A_1), rel.u.</th>
<th>(\tau_1), µs</th>
<th>(A_2), rel.u.</th>
<th>(\tau_2), µs</th>
<th>(n^0), rel.u.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100 g1</td>
<td>35</td>
<td>163</td>
<td>200</td>
<td>1700</td>
<td>13.5</td>
</tr>
<tr>
<td>950 g1</td>
<td>14</td>
<td>278</td>
<td>28</td>
<td>1800</td>
<td>4</td>
</tr>
<tr>
<td>900 g1</td>
<td>5.4</td>
<td>8</td>
<td>17</td>
<td>409</td>
<td>5.5</td>
</tr>
<tr>
<td>925 g2</td>
<td>&lt;4</td>
<td>&lt;5</td>
<td>15</td>
<td>660</td>
<td>&lt;1</td>
</tr>
<tr>
<td>925 g4</td>
<td>16</td>
<td>&lt;0.3</td>
<td>3</td>
<td>&gt;3</td>
<td>10.7</td>
</tr>
</tbody>
</table>
Variation of recombination characteristics influenced by irradiation (Pb ions)

The normalized decay amplitude variation within irradiated diode thickness
“Excite-probe” configurations for nonlinear optical experiments
Refractive index modulation mechanisms

\[ \Delta n_{\text{FC}} = - \frac{e^2}{2n_0 \omega^2 \varepsilon_0} [\Delta N/m_n^* + \Delta P/m_p^*] \frac{\omega^2}{(\omega^2 - \omega_0^2)} \]

The Linear Electro-Optic (Pockels) effect:

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

The Quadratic Electro-Optic (Kerr) effect:

\[ \Delta n_{\text{EO}} = - n^3 g(\varepsilon - 1)^2 \varepsilon_0^2 E_{\text{int}}^2 = AE_{\text{int}}^2 \]
Carrier transport governed formation of space charge field
Number of defect-related characteristics can be obtained:

- Defect spatial distribution (dislocations, clusters, etc.);
- Carrier generation rate from deep traps;
- Compensation ratio of deep traps by shallow impurities;
- Spatial variation of carrier lifetimes;
Carrier dynamics in proton-irradiated SI InGaAs/GaAs MQWS and GaAs:Cr substrate

\[ \Upsilon = 23 \text{ \mu m}, \ T_G = 570 \text{ ps} \]
\[ \Upsilon = 8.3 \text{ \mu m}, \ T_G = 350 \text{ ps} \]
\[ \Upsilon = 6 \text{ \mu m}, \ T_G = 255 \text{ ps} \]
\[ \Upsilon = 5 \text{ \mu m}, \ T_G = 190 \text{ ps} \]

\[ \frac{1}{T_G} (\text{GHz}) \]
\[ \frac{1}{\Upsilon^2} (\text{cm}^{-2}) \]

\[ D = 23 \text{ cm}^2/\text{s}, \ \tau_R = 650 \text{ ps} \]

Bulk carrier lifetime (ps)

Proton dose (cm$^{-2}$)

as grown

annealed

non-annealed
Configuration of holographic device for control of semiconductor parameters
Prototype of the holographic device HOLO-1 for control of semiconductor parameters

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Alpha particle detection

Equipment:
• a standard multi-channel analyser,
• comprising pre-amp, shaper,
• comparator and scalar, with a shaping time of 1 µs, a gain of 50 and a live time of 300 s (corrected for the system dead time).

The α-particle spectrum was well resolved even if the detector was not biased, showing the existence of material polarization. The weak dependence of the signal on bias voltage show evidence of full depletion in the detector but also the existence of high field effects that change the shape of the resolved α-particle spectrum. It shows the large difference of the peak shape from the Gaussian profile that fits the spectrum at low bias.
Thank you for attention