Using Kramers-Kronig compatibility for analysis of photoconductivity kinetics in InSe layered crystals



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Photoconductivity kinetics in the frequency and time domains



Fig. 1. Spectra of real (in-phase) and imaginary (quadrature) components of light-beam intensity modulated photoconductivity of InSe layered crystals (spectra corresponding different temperatures are shifted along ordinate axis by two orders of magnitude) Photoconductivity decay in semiconductors may be presented either in the form of time dependence characteristic or frequency dependence spectra. In the first case photoconductivity kinetics is measured after abrupt termination of light illumination of the sample as time dependence. In the second case the sample under study is illuminated by light beam ac component of intensity of which is changed according to sinusoidal law with time. Measuring at different frequencies allows to get frequency dependencies of in-phase (real) and quadrature (imaginary) components of photoconductivity. Both time and frequency characteristics describe kinetics of the same process been interconnected via integral Fourier transform. Analysis of frequency spectra have the same advantages in comparison with time-domain technique, e.g. allow to observe kinetics on wider frequency range, a few orders on magnitude, what is difficult to realize in time-domain because of fast decreasing of photoconductivity with increasing time especially by orders of magnitude and presence of static term.

$$i_1(\omega) - 1 = \frac{2}{\pi} \int_0^\infty \frac{\omega_0 i_2(\omega_0)}{\omega_0^2 - \omega^2} d\omega_0$$
$$i_2(\omega) = \frac{2\omega}{\pi} \int_0^\infty \frac{i_1(\omega_0)}{\omega_0^2 - \omega^2} d\omega_0$$

Importance of Kramers-Kronig compatibility of the spectra is very useful method to approve validity and correctness of the experimental data measured within a linear response region.

Light beam intensity modulated photoconductivity of InSe in the frequency domain

The spectra of in-phase and quadrature components of modulated photoconductivity of layered InSe crystals at different temperatures are shown on fig. 1 in log-log scale. On the frequency dependence of imaginary part of modulated conductivity the wide maximum at frequency of about 4 kHz (40 μ s) could be observed. The maximum position coincides with the onset of strong dispersion on the spectra of real part with increasing frequency. The weaker dispersion process could be observed on frequencies below 100 Hz, appearing as a result of deviation of the shape of the left side of the large maxima from a linear dependence in log-log scale. This process is accompanied by weak step on the spectra of real part of modulated photoconductivity. Complex structure of high frequency dispersion process becomes more clearly visible at low temperature.

Height of maximum on spectra of imaginary part of modulated

photoconductivity decreases with increasing temperature. Maximum width also

decreases with decreasing temperature. Complex diagrams of the spectra at

different temperatures shown on fig. 2 have shape of the circles with shifted

Fig. 2. Complex diagram of light-beam intensity modulated photo-

conductivity of InSe layered crystals at different temperatures

down below abscissa axis centers

 Table 1 – Averaged photoconductivity kinetic parameters of InSe crystals obtained from complex diagram of modulated photoconductivity

 photoconductivity

 T, K
 293
 268
 242
 214

 n
 0.36
 0.39
 0.38
 0.56





Time-domain kinetics of photoconductivity of InSe layered crystals



Fig. 3. Impulse characteristics of modulated photoconductivity of InSe layered crystals at different temperatures



Fig. 4. Localized energy levels in the forbidden gap of InSe layered crystal

$$i_1(\omega) = \int_0^\infty h(t) \cos(\omega t) dt , \quad i_2(\omega) = \int_0^\infty h(t) \sin(\omega t) dt \quad (2)$$

These relations mean that frequency and time domains responses describe kinetic properties of the same dynamic system. Thereby h(t) response obtained as from spectra of real so imaginary parts of modulated photoconductivity should be the same. That property reflects K-K compatibility of modulated spectra. Therefore, the time domain response could be obtained from the spectra as of real so imaginary part of modulated photoconductivity:

$$h(t) = \frac{2}{\pi} \int_{0}^{\infty} i_{1}(\omega) \cos(\omega t) d\omega \quad h(t) = \frac{2}{\pi} \int_{0}^{\infty} i_{2}(\omega) \sin(\omega t) d\omega$$
(3)

These two equations can be used for checking K-K compatibility of $i_1(\omega)$ and $i_2(\omega)$ spectra comparing of the pulse characteristic in time domain obtained from the spectra of real and imaginary components.

Conclusion

Obtained spectra of light beam intensity modulated photoconductivity of InSe layered crystals characterizing kinetics of photoconductivity in the frequency domain show significant deviation from a Debye law. Using double sequential sine and cosine integral Fourier transform from the spectra of imaginary part of modulated photoconductivity it has been shown their compatibility to integral Kramers-Kronig transform that confirms validity of the spectra. Position of large maximum on the spectra of imaginary part of photoconductivity weakly depends on temperature of crystal indicating dominating of not thermally activated recombination processes. Thereby it could be concluded that recombination of nonequilibrium excess charge carriers in InSe crystals mainly occurs via deep recombination centers without significant delaying by trapping on shallow traps.