Referee report

on the doctoral thesis

"Ultrafast carrier dynamics in semiconductors studied by time-resolved terahertz spectroscopy",

written by Ph.D. candidate Ladislav Fekete

Doctoral thesis is devoted to the study of interaction between terahertz radiation and free carriers in the semiconductor materials excited optically. The author is using the time-resolved terahertz time-domain spectroscopic technique that allows to access time dependent conductivity of the excited material on picosecond and sub-picosecond time scales. Free carrier parameters such as carrier lifetime and mobility can be extracted from the measurement results, and can be therefore applied to study important emerging materials.

The scientific contribution of Ph.D. candidate Ladislav Fekete can be seen in two areas. First, studied carrier dynamics (lifetime and mobility) in the two types of the semiconductor materials – ion bombarded Indium Phosphide and micro-crystalline Silicon. Second, he has exploited the optically induced transient conductivity for the novel fast modulation of the terahertz beam intensity.

Understanding of electrically active native defects in the semiconductor material is very important from several points of view. Such defects can strongly influence the free carrier density, lifetime and mobility. Since native defects in the semiconductor are incorporated during the material processing, due to material irradiation in the harsh environment, or they are produced intentionally, knowledge of the carrier dynamics influenced by them is a key information for semiconductor device development. In this view, results obtained by author in collaboration with his colleagues on the Br-ion irradiated InP are part of the knowledge base of the defects in this semiconductor material. In the analysis of the transient photoconductivity of irradiated InP the author is demonstrating the real strength of the used experimental technique – time-resolved terahertz spectroscopy. Unfortunately, he is not taking opportunity to fully exploit the obtained results, since no attempt to identify the possible candidates for observed traps has been made.

The second material studied by time-resolved terahertz spectroscopy was microcrystalline Silicon. This technologically important material exhibits a large variety of the properties due to a very flexible crystalline structure. The grain size and the degree of crystallinity are strongly dependent on the technology of preparation, and they have impact on the electrical properties of the final material. Knowledge of correlation between the carrier dynamics and crystalline structure (or technological condition of the material preparation) is important for improving the performance devices based on the micro-crystalline Silicon such as photovoltaic cell or a thin-film display. The transient photoconductivity measurement is convenient tool for the assessment of carrier dynamics in such material. Using terahertz time-resolved spectroscopy the Ph.D. candidate has obtained unique insight into the processes, in which the carriers in microcrystalline Silicon are involved. Namely, except of the expected Drude contribution he identified two different relaxation dynamics. They are connected to the presence of the grain boundaries in the microcrystalline silicon and are completely
missing in the either monocrystal or amorphous Silicon. Such findings help to better understand this technologically important material.

Another new result presented by the author is a modulator of terahertz beam based on the optically controlled by the Drude absorption. The author verified basic principle of the modulator experimentally on the optically excited semiconductor. To fully exploit this principle of operation, he has developed the idea of the modulator further by implementing an optical cavity. The author put together complex theoretical description of optical properties of the modulator and he provides extended proof of the modulator functionality. The demonstrated optical device can be seen a precursor of the wide range of possible terahertz beam manipulating optical components after the issue of the optical control beam power is addressed properly.

Regarding the formal aspects of the doctoral thesis, the thesis structure is conceived and logic. First part contains introduction to the terahertz radiation with convenient overview of available terahertz sources and detection principles. Second section of the thesis is focused on the time-domain terahertz spectroscopy with detailed description of the technique. This section is supplemented with a description of models of the conductivity dynamics, which are later used by the author for an evaluation of the time-resolved measurement of different semiconductor systems. The last, third, section of the thesis, which occupies about one third of the thesis page space, presents the work of the author himself. While the previous sections are written in the usual format of the doctoral thesis, this last section is written in the form of the comments on results obtained by the author. The section contains only a brief description of the studied semiconductor systems, optical devices and results with reference to the published papers. Usually, printed publications provide only limited space for expressing ideas and results and, therefore, the thesis provides more convenient platform for thorough description and discussion of author achievements. Although author missed this opportunity, the referenced publications are integral part of the doctoral thesis, so this unusual form of thesis is accepted.

Finally, to provide some input for the discussion I am proposing several topics that should be addresses by Ph.D. candidate Ladislav Fekete:

a/ Ph.D. candidate field of expertise is the terahertz time-domain spectroscopy. Could Ph.D. candidate specify advantages and disadvantages of the terahertz time-domain spectroscopy in the comparison to standard Fourier transform based spectroscopy and spectroscopic systems using tuneable CW laser sources (heterodyne detection)? What would be “user guidelines” for selecting those different systems for measurement?

b/ For the sake of completeness, in Section 2 of the thesis is missing description for the conductivity contribution of the confined carrier systems such as 2-dimensional electron/hole gas and associated plasmons. Although this is not the case of the semiconductor systems studied by author, could he complete the theoretical background of the time-resolved terahertz spectroscopy considering those phenomena?

c/ Could the Ph.D. candidate comment on the fact that the terahertz spectroscopy is probing very high frequency mobility of free carriers?
d/ One of the excellent achievements of Ph.D. candidate is the optical modulation of broadband terahertz pulses. For future applications, however, the energy of the control beam is important. Could Ph.D. candidate evaluate the used principle for the terahertz transmission control from a viewpoint of the energy efficiency? Could be specified some more energy efficient methods for the terahertz beam control?

e/ Particular method used for the terahertz beam control is based on the Drude absorption and the optical resonator and it exhibits very good sensitivity. Could Ph.D. candidate explain in details the physics behind the improved sensitivity? What are implications for the future optical devices based on such principle?

In summary, the work presented in the doctoral thesis proves the ability of Ph.D. candidate Ladislav Fekete for the creative work in the research and development.

In Vienna, 06.02.2009

Juraj Darmo