# Supervisor report

on doctoral thesis entitled

## Charge transport in semiconductor nanostructures investigated by time resolved multi terahertz spectroscopy

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The submitted thesis is focused on the investigation of both linear and non-linear terahertz response of charges confined in semiconductor nanostructures. On the one hand, terahertz conductivity spectra encode charge motion on nanometer distances and their measurement and interpretation thus provides information on short-distance charge transport which is a fundamental process in many applications. On the other hand, the design of nanostructures can be used to control the terahertz response.

The thesis is rather extensive and full of original results presented in a clear and graphically appealing way:

- Semi-classical calculations of the linear response of model nanostructures (chapter 5) explained that the universal character of terahertz conductivity spectra observed experimentally in almost all semiconductor nanostructures stems from the broad distribution of thermal velocities in a non-degenerate electron gas. Rich spectral features (geometrical resonances) were predicted for confined degenerate electron gas, together with dimensionality-dependent coupling with the plasmon resonance.
- Combined experimental and theoretical investigation of terahertz conductivity spectra of charges in $TiO_2$ nanotube layers (chapter 8) enabled non-contact determination of electron mobility inside the nanotube walls; they also revealed that charges are confined into volumes smaller than the nanotube wall geometrical extent.
- Non-linear terahertz response of confined charges is a completely new topic and the author had to investigate many physical processes to construct a link between microscopic material properties and measurable signal. The core of the calculations is based on the semi-classical Monte-Carlo approach (section 2.2) which the author implemented and adapted for intense probing terahertz electric fields. Analysis of these calculations cannot be done using the simple formalism commonly employed in nonlinear optics; a generalization reflecting the broad spectrum of terahertz pulses was thus developed (section 1.2). The resulting generalized mobilities and non-linear current densities (chapter 6) then revealed a strongly non-perturbative response, permitting high harmonics generation even for moderately strong terahertz waves. It was also discovered that the confinement-induced third-order nonlinearity per charge carrier is 20× stronger than that of graphene, which has been considered as one of the most nonlinear terahertz materials. The complex distribution of the electric field inside the structures induced by freely propagating terahertz pulses was accounted for using a combination of effective medium approximation and solution of wave propagation in nonlinear media (chapter 4). It was shown that the high dielectric contrast encountered in common nanostructures practically discards any nonlinear effective response. To fully profit from the unprecedented nonlinearity strength, a metallic nanoslit structure concentrating the electric field into the semiconductor was proposed and investigated in detail (chapter 7). The resulting nanostructure may easily produce a nonlinear signal comparable with the linear one.

The results on the linear terahertz response were published in four impacted papers. The breakthrough work on the non-linear response is very extensive; the most important results were just submitted to Phys. Rev. Lett. for publication while a longer detailed manuscript is under the preparation.

The author undoubtedly proved his competence and scientific independence. I highly appreciate his earnest approach and his strong devotement which made it possible to successfully conclude the complex and demanding calculations. I strongly recommend accepting the present work for the defence.

In Prague, August 30, 2019

Hynek Němec