UKF „Gaining Experience“ Grant 2A

Duration of the project: 6 months (May 30. 2011. – November 30. 2011.)

Funds awarded: 72.000,00 HRK

Project leader: Marinko Jablan, Faculty of Science, University of Zagreb, Croatia

Project co-leader: Prof. Marin Soljačić, Massachusetts Institute of Technology, USA

Project title:

Exploiting opto-mechanical properties of graphene for novel nano-technologies

Project summary:

Ever since the stone age new materials meant new technologies and graphene is unlike any material we encountered so far. Being just one atom thick it has exceptional mechanical, electrical and optical properties which we wish to explore from two different aspects. On one side we are interested in generating a coherent phonon source (“sound laser”) by optical forces while on the other side we want to use strain engineering to observe quantum effects in graphene at room temperature conditions. Finally we wish to explore interplay between these two phenomena.

For the past four years we have been working with prof. Marin Soljačić from Massachusetts Institute of Technology on the problem of plasmonics in graphene and trough this UKF grant we are continuing our collaboration. I plan to stay at MIT for six months which will allow me to interact with some of the best researchers in the world and to gain skills and ideas that will greatly benefit Croatian scientific community upon my return to Croatia.

Proposed communication and outreach of results:

I gave two lectures at Department of Physics, University of Zagreb for the group of dr. sc. Petar Pervan and dr. sc. Marko Kralj from Institute of Physics and the rest of Croatian scientific community on the results of research done at MIT. The last of these talks was also my PhD thesis defense where I included all the results done as a part of this project. Title of the talk was „Electrodynamic properties of graphene and their technological applications“, and the talk was extremely well attended.

I will also give a public talk in my home town Zadar. In that respect I gave an interview for the newspaper *Slobodna Dalmacija* anouncing the talk. The article can be found on the following web address:

http://www.slobodnadalmacija.hr/Zadar/tabid/73/articleType/ArticleView/articleId/159842/Default.aspx

Project Results:

During my stay Massachusetts Institute of Technology I participated in research on several different subjects related to opto-mechanical properties of graphene, and on graphene as a potential material for technological applications. The following three projects were the main focus of our research:

1. Coherent phonon generation by optical forces
2. Strain engineering and room temperature Quantum Hall effect

3. Near-field heat transfer and thermo-photo-voltaics

We have achieved important progress in all three points, however priority was given to the last point (on near field heat transfer) which was the hottest and needed to be addressed first due to competition with other groups. As a result we have finished two papers on near field thermo-photo-voltaics which are both published in prestigious scientific magazines.

1. O. Ilic, M. Jablan, J.D. Joannopoulos, I. Celanovic, H. Buljan, and M. Soljačić, "Near-field thermal radiation transfer controlled by plasmons in graphene", Phys. Rev. B **85**, 155422 (2012)
2. O. Ilic, M. Jablan, J.D. Joannopoulos, I. Celanovic, and M. Soljačić, "Overcoming the black body limit in plasmonic and graphene near-field thermophotovoltaic systems", Optics Express **20**, A366 (2012)

In the first paper we analyze the near field heat transfer between two graphene sheets mediated by thermally excited plasmon modes. In general, heat transfer between two bodies can be greatly enhanced in the near field, i.e. by bringing the surfaces close together to allow tunneling of evanescent photon modes. This happens because near field radiation transfer involves thermal excitation of various surface modes which can have much greater wave vectors (and density of states) than the freely propagating modes (limited by the light line). Since each wave vector corresponds to a heat channel, vacuum becomes better heat conductor in the near field. However, due to their localization and evanescent nature, it is only a sub-wavelength separation that these modes become relevant. In our paper we show that thermally excited plasmon-polariton modes can strongly mediate, enhance and tune the near-field radiation transfer between two closely separated graphene sheets. The dependence of near-field heat exchange on doping and electron relaxation time is analyzed in the near infra-red within the framework of fluctuational electrodynamics. The dominant contribution to heat transfer can be controlled to arise from either interband or intraband processes. We predict maximum transfer at low doping and for plasmons in two graphene sheets in resonance, with orders-of-magnitude enhancement (e.g. 100 to 1000 for separations between 100nm to 10nm) over the Stefan-Boltzman law, known as the far field limit. Strong, tunable, near-field transfer offers the promise of an externally controllable thermal switch as well as a novel hybrid graphene-graphene thermoelectric/thermophotovoltaic energy conversion platform.

In the second paper we study near field thermophotovoltaic (TPV) systems and present a detailed theoretical study of implementing several different plasmonic and graphene thermal emitters resulting in high device efficiencies and power densities. With the current world energy demand and large environmental impact of fossil fuels there is a worldwide shift towards renewable energy sources. In that respect, TPV are a promising class of heat to electricity conversion devices where sun can heat up an emitter that selectively re-radiates frequencies matched to the band gap of the photovoltaic cell thus minimizing the loss. TPV are not limited by the sun source and can use any hot (terrestrial) object like a factory furnace or various hot car parts as a heat source. From the perspective of future energy crisis there is a large demand for more efficient energy management where TPV can play an important role by turning wasted heat into electricity. Near field TPV further offer greater power densities since the near field heat transfer can be orders of magnitude larger than the far field limit. Finally, due to evanescent nature of electromagnetic modes, one does not need to worry about losing energy through modes with frequencies below the photovoltaic band gap, resulting in even greater device efficiencies. In our paper we find that optimal improvements over the black body limit are achieved for low band gap semiconductors and properly matched plasmonic frequencies. In addition we study plasmons in graphene and show that doping can be used to tune the plasmonic dispersion relation to match the photovoltaic cell band gap. These near field TPV systems with carefully tailored emitter-photovoltaic properties show large promise for a new temperature range (600K-1200K) solid state energy conversion, where conventional thermoelectric devices can not operate due to high temperatures and far field TPV schemes suffer from low efficiency and power density.

Regarding the issue of coherent phonon generation by optical forces we have achieved important progress. I have benefited a great deal from a discussion with Dr. Zheng Wang (which was collaborator on this project) and various seminars from his group members on nanoscale optical forces. Our preliminary calculations suggest several interesting paths to follow in the near future. We are currently intensively working on these problems however there are several issues to resolve before we can start writing the paper.

Regarding the strain engineering and room temperature Quantum Hall effect (QHE) we had numerous fruitful discussions with MIT prof. Tomas Palacious. We plan to continue working on this subject in our future research.