Fundamentals of carrier diffusion waves in electronic solids

Andreas Mandelis[1,2]*, Qiming Sun[1,2], Alexander Melnikov[1]

[1]Center for Advanced Diffusion-Wave and Photoacoustic Technologies (CADIPT), University of Toronto, Toronto, Canada
[2]School of Optoelectronic Information, University of Electronic Science and Technology of China, Chengdu, China
*mandelis@mie.utoronto.ca

Photocarriers in semiconductors excited by modulated laser sources give rise to charge diffusion waves that can be used to study and characterize the electronic transport properties of materials and devices. In this talk the concept of carrier diffusion waves (CDW) will be introduced for continuous-band semiconductors (e.g. Si); and of hopping diffusion waves in nanolayers (e.g. colloidal quantum dot (CQD) excitonic ensembles). The fundamental transport equations describing these coherent oscillations will be presented with focus on the key CDW parameters: wavenumber, diffusivity, drift velocity, mobility, diffusion length and surface/interface diffusion currents determined by recombination velocities and flux transfer coefficients [1,2].

In continuous-band materials CDW transport is limited by band-to-band recombination and band-to-defect state decays with relaxation times controlled by bandgap defect and impurity state trap densities interacting with the free carrier bandedges through thermal emission and capture rates. The CDW concept has given rise to new material and device diagnostic methodologies, specifically photocarrier radiometry (PCR) [3] and its imaging analog, lock-in carrierography (LIC) [4]. Examples of PCR and LIC applications to the measurement and imaging of diffusion-wave parameters in micro- and opto-electronic materials and devices will be discussed.

In discrete-particle nanolayers (CQD ensembles, in particular), very recent formulations of the hopping CDW theory leading to physical insights into diffusion and drift mechanisms in band-energy-equivalent structures consisting of CQD will be presented with focus on how excitonic and/or dissociated carrier hopping diffusion determines anomalous S-shaped current-voltage characteristics of state-of-the-art nanolayered solar cells. The effects of the presence of electrodes in device quality will be identified by means of ultra-high-frequency LIC images revealing compromises in carrier diffusivities and diffusion lengths at the contract-nanolayer interface.

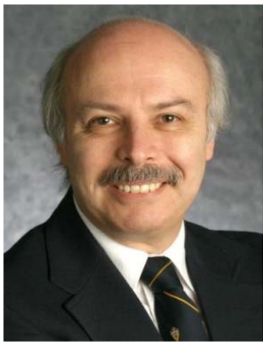
References

[1] A. Mandelis: *Diffusion-Wave Fields*, Springer, New York 2001, Chap. 9.

[2] A. Mandelis, L. Hu, J. Wang: *Quantitative measurements of charge carrier hopping transport properties in depleted heterojunction PbS colloidal quantum dot solar cells from temperature dependent current–voltage characteristics.* RSC Adv. **6**, 93180 (2016).

[3] A. Mandelis, J. Batista, D. Shaughnessy, *Infrared photo-carrier radiometry of semiconductors: Physical principles, quantitative depth profilometry and scanning imaging of deep sub-surface electronic defects*. Phys. Rev. B **67**, 205208 (2003).

[4] A. Melnikov, A. Mandelis, J. Tolev, P. Chen, S. Huq, *Infrared lock-in carrierography (photocarrier radiometric imaging) of Si solar cells.* J. Appl. Phys. **107**, 114513 (2010).



Andreas Mandelis is a Full Professor of Mechanical and Industrial Engineering; Electrical and Computer Engineering; and the Institute ofBiomaterials and Biomedical Engineering, University of Toronto. He is the Canada Research Chair in Diffusion-Wave and Photoacoustic Sciences and Technologies and Director of the Center for Advanced Diffusion-Wave and Photoacoustic Technologies (CADIPT) at the University of Toronto. He received his BS degree (Magna cum Laude) in physics from Yale University, and MA, MSE, and Ph.D. degrees from the Applied Physics and Materials Laboratory, Princeton University. He is the author and co-author of 415 scientific papers in refereed journals and 190+ scientific and technical proceedings papers. He is Editor-in-Chief of the Springer International Journal of Thermophysics, an Associate Editor of the AIP Journals Review of Scientific Instruments, Journal of Applied Physics, Topical Editor of the OSA Journal Optics Letters, and he is on the editorial board of the SPIE Journal of Biomedical Optics. He is Consulting Editor of the AIP flagship magazine *Physics Today*. He has several inventions, 38 patents and patents pending in the areas of photothermal tomographic imaging, signal processing and measurement, hydrogen sensors, dental laser diagnostics (biothermophotonics), semiconductor laser infrared photothermal radiometry, laser photo-carrier radiometry and laser biophotoacoustic tissue imaging. He holds the Canada Research Chair (Tier 1) in Diffusion-Wave and Photoacoustic Sciences and Technologies at the University of Toronto. He is also a National 1000-Talents Professor at the University of Electronic Science and Technology of China in Chengdu.

Professor Mandelis has received numerous national and international prizes and awards including the APS Keithley Award in Instrumentation Science, the Discovery Award in Science and Engineering (the Ontario Premier's Innovation Award), the ASME 2009 Yeram Touloukian Award (and Medal) in Thermophysics, the Senior Prize of the International Photoacoustic and Photothermal Association, the Canadian Association of Physicists (CAP) Medal for Outstanding Achievement in Industrial and Applied Physics and the CAP-INO Medal for Outstanding Achievement in Applied Photonics. In 2014 he was elected Killam laureate, recipient of the Killam Prize in Engineering, one of Canada's highest academic prizes awarded annually by the Governor General of Canada.