Nanoscale transport phenomena in silicon-based materials

Transport phenomena describe the exchange of physical quantities (e.g. heat, charge, momentum, mass, spin, etc.) between different locations of the system. While classical theories well describe these processes in condensed matter at macroscopic (*continuum*) scales, the understanding of transport phenomena below the µm length-scale is poor. On the other hand, the significant developments in nanotechnology occurred in the last few decades is calling for a more comprehensive understanding of nanoscale transport processes, since the realization of many nanotechnology-based devices requires the implementation of nanoscience discoveries into micro- and nano-scale design. For instance, the characteristic time for heat transport in silicon, the most common material for electronics, at a few µm length-scales has been determined by means of optical transient grating (TG) experiments; despite such a relatively long length-scale it was found to be sizably longer (by ≈ 20 %) than what expected by the classical Fourier law of heat diffusion [1].

Experimental measurements at shorter (sub-µm) distances relies upon using fabricated nanostructures [2-4], which complicates the data interpretation and often leads to contrasting results. The recent development of the extreme ultraviolet transient grating (EUV TG) approach at the FERMI free electron laser (FEL) can fill this lack of experimental capabilities [5-7]. Indeed, in the EUV TG method the effective heat transfer distance is determined by the spatial periodicity of the excitation pattern, with no need for nanofabrication. The use of short wavelength radiation allows for periodicities as short as a few 10s on nm (with the mid-term outlook of exploiting single-digit nm TGs). This permits to study nanoscale transport processes, with the benefits of the contactless approach and down to length-scales even beyond what currently possible with nanostructures. For instance, in a recent EUV TG experiment we have showed that the heat transport timescale in silicon at ≈35 nm length-scales is more than one order of magnitude longer than the predictions of classical heat transport theory, while in amorphous silicon nitride the thermal transport process is still classical [7]. Such kind of information are clearly of the highest relevance, e.g., for nanoelectronics, since the thermal management of nanoscale devices is one of the major technological issues. The EUV TG technique can be also applied for studying nanoscale magnetic phenomena [8,9], since it will allow studying the dynamics of spin transport and the ultrafast magnetization switching process on a few nm length-scales. In this context we have recently developed at FERMI a dedicated setup (in collaboration with other institutions) and conducted the first successful experiments. On the other hand, we are planning to realize an optical TG setup in the laser laboratories available at FERMI, for fully characterizing the thermal and elastic properties (plus the magnetic and magnetoelastic ones if needed [10]) of the samples in the long wavelength limit, prior to be investigated by EUV TG. Such complementary measurements would be extremely relevant for the interpretation of the EUV TG results. Indeed, the samples are often designed for addressing specific scientific questions and, therefore, some of the parameters needed for interpreting the EUV TG data are either poorly known and/or present large variations from sample to sample. An accurate characterized of the specific sample in the long wavelength limit is therefore necessary in most applications.

The PhD project will be developed in two phases. In the first one he/she will realize the optical TG setup in the FERMI laser laboratory. This setup will be featured by excitation pulses with a tunable photon energy across the band-gap of common semiconductors (1-5 eV) and will allow generating, for a given photon energy, transient grating with variable spatial periodicity, e.g. a few values in the 1-10 µm range. The TG response will be detected either in transmission or in reflection geometry (in order to also allow probing optically opaque samples) via real time sampling of the transient diffraction of a CW laser, the options of detecting the ultrafast TG response with a pulses probe and the time-dependent Faraday rotation (for determining the magnetic and magnetoelastic properties [10]) will be evaluated as well. This system will be used to carry out a systematic study on membranes of silicon-based materials with relevant application in nanoelectronics and nanosensing (i.e. silicon, silicon nitride, silicon carbide and silicon oxide) as a function of the thickness (from the bulk limit to a few 10s of nm), composition and temperature. The outcome of this study will allow determining the thermal and mechanical properties at macroscopic scale, which are needed to interpret the EUV TG data, as well as in understanding the role of the finite dimension in the direction orthogonal to the TG modulation (i.e. the thickness). The latter task has a more general relevance, since can be also regarded as a critical test of the one dimensional approximation commonly used to interpret TG data (preliminary indications from EUV TG measurements somehow challenge this assumption). This comprehensive work will be the basis for proposing dedicated EUV TG experiments on such materials, which will be carried out at the TIMER beamline and/or at the mini-TIMER setup (DiProI beamline) at the FERMI FEL in the second stage of the project. Dedicated in-house beamtime may be reserved at TIMER if necessary. In these experiments two further developments of present EUV TG capabilities are foreseen, whose practical implementation will be in charge of the PhD student, namely: (i) the generation of TGs with single-digit nm spatial periodicities, in order to probe a wavelength range where also amorphous samples might show sizable deviations from conventional thermal transport, and (ii) the devising of a dedicated setup for detecting the EUV TG signal in reflection geometry, for permitting to study samples opaque to the EUV radiation, e.g. any solid samples thicker than the EUV absorption length (typically < 1 µm).

People involved

Filippo Bencivenga, Flavio Capotondi, Federico Cilento and Claudio Masciovecchio (Elettra-FERMI)
Riccardo Cucini (CNR-IOM)

References

[1] J. A. Johnson et al., Phys. Rev. Lett. **110**, 025901 (2013)
[2] K. M. Hoogeboom-Pot et al., PNAS **112**, 4846–4851 (2015)
[3] Y. Hu et al., Nat. Nanotechnol. **10**, 701–706 (2015)
[4] M. E. Siemens et al., Nat. Mater. **9**, 26–30 (2010)
[5] F. Bencivenga et al., Nature **520**, 205–208 (2015)
[6] A. A. Maznev et al., Appl. Phys. Lett. **113**, 221905 (2018)
[7] F. Bencivenga et al., Science Advances (accepted)
[8] A. Eschenlohr et al., Nat. Mater. **12**, 332–336 (2013)
[9] A. Kirilyuk, A. V. Kimel amd T. Rasing, Rev. Mod. Phys. **82**, 2731–2784 (2010)
[10] J. Janušonis et al., Phys. Rev. B **94**, 024415 (2016)