Electrical and optical techniques to observe phonon hydrodynamic transport in 2D materials

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In the past decades, the increasing demand for effective thermal management of microelectronic devices and efficient thermoelectrics has raised the need for new materials with extremely high thermal conductivity. In the last century, a new phenomenon of heat transport emerged that resemble wave propagation in liquids, known as heat hydrodynamic. This effect arises when normal phonon scattering dominates over Umklapp scattering, thus implying that the phonon momentum is mainly conserved and consequently, temperature fluctuations can be observed. This is known as Second Sound and it was experimentally discovered in superfluidic helium in 1944 [1], NaF [2] and graphite samples [3], [4]. A timescale in between the normal and the Umklapp phonon scattering time ($\tau N < \tau exp < \tau U$) is needed to investigate second sound phenomena. Theoretical studies have predicted for graphene [5] a nanosecond timescale to observe second sound. Therefore, pump-probe spectroscopy experiments are well suited for measuring the thermal response at this timescale.
Figure 1 shows the schematic of our pump-probe setup which can be used to realize both time-resolved Raman spectroscopy (TRRS) or transient reflectivity (TR) experiments. TRRS is an inelastic light scattering and non-destructive technique that allows the investigation of the phonon dynamics in nanostructures [6]. This technique is able to track the temporal evolution of specific phonon modes, moreover we directly measure the effective lattice temperature. This makes TRRS a unique technique to study ultrafast lattice dynamics of materials. TR technique is widely applied to examine the thermal properties of materials. It monitors the change in reflectance as a function of time on a sub-picosecond scale [7]. This change in reflectance, induced by the change in the material's dielectric constant generated by the heat pulse, can then be used to understand light matter interaction and extract transport properties, such as the electron-phonon coupling as well as the thermal conductivity[8]. Using TRRS we are able to map the temperature profile of a phonon mode over time, and reconstruct the wave-like propagation of the heat which is a fingerprint of hydrodynamic heat transport[4]. Instead, TR gives us information about the decay channels of electrons into phonons and how both systems relax towards equilibrium. Therefore, it provides access to the average phonon behaviour in the materials.
Probing a deviation of heat flow from the Fourier's law requires a highly sensitive device and good isolation from the environment. A suspended four terminal device, with thermometer coils placed on top of a bridged silicon nitride (SiNx) membranes, is fabricated. This device enables to simultaneously perform electrical and thermal measurement by the means of Joule effect and Raman thermometry. It provides optimal isolation from the environment while assessing the thermal conductivity of the specimen under investigation. The four coils are made of platinum and are placed on top of SiNx membranes, which are bridged to the surrounding by SiNx beams. The beams provide mechanical stability and loose thermal conductance to the environment. By electrically heating one coil is possible to generate an heat pulse that raises the temperature in the membrane, therefore it heats one side of the sample. The remaining membranes can be used as sensors to probe the change in temperature in their respective sides. Since in our newly designed devices there are four coils, it is possible to probe temperature in several points of the sample or swap the heating sides with the sensor side.

References

[1] R. D. Maurer and M. A. Herlin, Physical Review 76, 948 (1949), URL https://journals.aps.org/pr/abstract/ 10.1103/PhysRev.76.948.
[2] T. F. McNelly, S. J. Rogers, D. J. Channin, R. J. Rollefson, W. M. Goubau, G. E. Schmidt, J. A. Krumhansl, and R. O. Pohl, Heat Pulses in NaF, Physical Review Letters 24, 100 (1970), URL https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.24.100.
[3] Y. Machida, N. Matsumoto, T. Isono, and K. Behnia, Science 367, 309 (2020), ISSN 10959203, URL http://science.sciencemag.org/.
[4] S. Huberman, R. A. Duncan, K. Chen, B. Song, V. Chiloyan, Z. Ding, A. A. Maznev, G. Chen, and K. A. Nelson, Science (2019).
[5] S. Lee, D. Broido, K. Esfarjani, and G. Chen, Nature Communications 6 (2015), ISSN 20411723.
[6] R. B. Versteeg, J. Zhu, P. Padmanabhan, C. Boguschewski, R. German, M. Goedecke, P. Becker, and P. H. V. Loosdrecht, Structural Dynamics 5 (2018), ISSN 23297778.
[7] S. Sandell, E. Ch´avez- ´Angel, A. E. Sachat, J. He, C. M. S. Torres, and J. Maire, , Journal of Applied Physics 128 (2020), ISSN 10897550.
[8] M. Segovia and X. Xu, Nano Letters p. acs. nanolett.1c02210 (2021), ISSN 1530-6984, URL https://pubs.acs.org/doi/10.1021/acs.nanolett.1c02210.

Figures

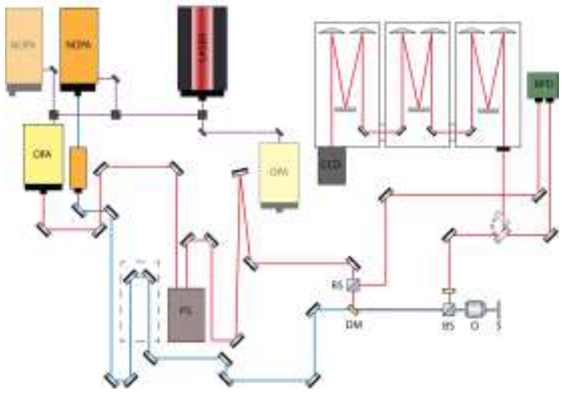

Figure 1: femtosecond pulsed laser is split into two beams. The probe, goes through an optical parametric amplifier (OPA), the pump, goes through a non-collinear optical parametric amplifier (NOPA). A mechanical delay line in the pump path produces a variable time delay between pump and probe. Two different detection systems are used to realize either TRRS or TR. A pulse shaper (PS) is used to tune the pulse duration and increase frequency resolution, and a triple spectrometer is used to realize Raman spectroscopy. Instead in TR, a balanced photodiode (BPD) is used to reconstruct the changes in reflectivity of the sample.

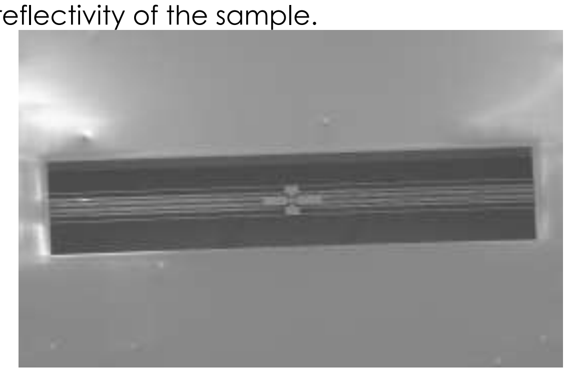

Figure 2: Tilted view of the suspended thermometer taken in the SEM after the second wet etching of silicon. In the centre there are visible four suspended membrane of SiNx with the platinum meanders on top. Not visible in the image, there are the gold pads, on the extreme sides of the image, for electrical connection, those are linked to the meanders in the center through gold lines on top of the beams.