Thermal response of materials to extreme temperature gradients and the role of the spatial frequency

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The thermal response of materials to extreme temperature gradients has recently become of intense interest both scientifically and for applications. Prior work has established that if thermal gradients occur over length scales comparable to phonon mean free paths (MFPs), the apparent thermal properties of materials depend both on intrinsic mechanisms as well as the characteristics of the applied thermal gradient. However, a deep understanding of transport in this regime remains lacking. Here, we probe the thermal response of crystals to large thermal gradients generated by optical heating of nanoline arrays. Our experiments reveal the key role of the spatial frequencies and Fourier series amplitudes of the heating profile for thermal transport in the quasiballistic regime, in contrast to the conventional picture that focuses on the geometric dimensions of the individual heaters. Using this insight, we demonstrate that the ballistic thermal resistance associated with nanoscale heat sources can be nearly eliminated by rationally engineering the spatial arrangement of individual heaters, a finding that could impact strategies for heat dissipation in electronics and other applications.

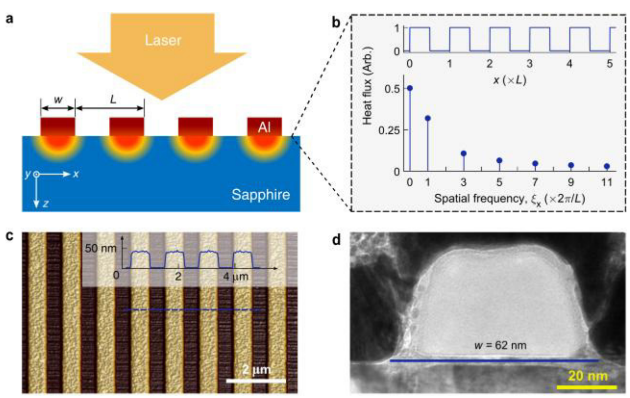

Fig. 1: (a) Schematic of sample geometry and (b) the generated spatial heating profile on the substrate. Representative (c) AFM topography and (d) TEM cross-section profile of line arrays.

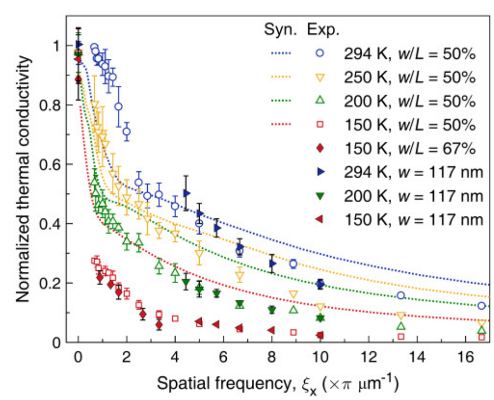

Fig. 2: Thermal conductivity versus spatial frequency from TDTR measurements and synthetic TDTR data.