# Out-of-plane heat transfer in Van der Waals stacks

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Van der Waals stacks (heterostructures of different 2D materials such as graphene, BN, $WSe_2$ and $MoS_2$) have highly promising applications in thermal management, photodetection, data communication, light emission and more. In many cases it is essential to understand – and control – heat flow in van der Waals devices. In this talk, I will discuss our recent results [1] on carrier cooling in one of the most promising device architectures: graphene encapsulated by hexagonal BN (hBN). We find that out-of-plane cooling of graphene electrons is highly efficient, owing to the special hyperbolic nature [2-6] of the hBN encapsulant: hyperbolic phonon polaritons carry high momenta, enabling near-field energy transfer that is orders of magnitude more efficient than Planckian emission into free space. This super-Planckian, near-field energy transfer into hyperbolic hBN phonons leads to a surprisingly short cooling time scale of a few picoseconds (at RT).

Our experiments are based on ultrafast, time-resolved photocurrent microscopy of hBN-encapsulated graphene devices, where two local gates allow the formation of a *pn*-junction. This allows us to extract the cooling time of hot graphene carriers, while controlling carrier density, lattice temperature and initial hot carrier temperature. Comparing the experimental results with microscopic calculations of hot graphene carrier cooling by near-field emission into hyperbolic phonon polaritons in hBN, we find agreement without any fit parameters. Our results open up an interesting avenue for controlling out-of-plane heat transfer by adapting the encapsulating material.

## References

[1] Tielrooij et al, submitted (2106)
[2] Caldwell et al. Nature Comm. 5 (2014) 5221
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[4] Basov et al. Science 354 (2016) 1992
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[6] Principi et al, Arxiv, 1608.01516 (2016)

## Figures

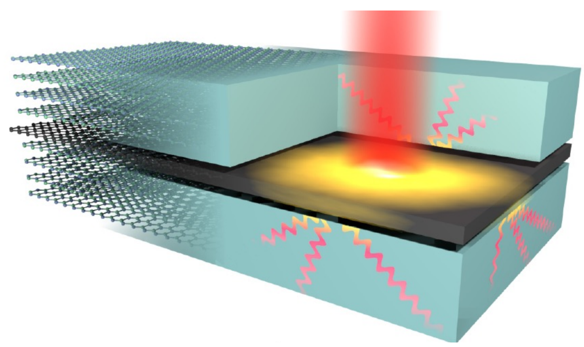

**Figure 1:** Out-of-plane heat transfer in encapsulated graphene: absorbed light (vertical red beam) creates hot carriers in graphene (yellow area), which are cooled by ultrafast emission into hyperbolic phonon polaritons (wiggly lines) in the encapsulating 2D material.