Heat dissipation in few-layer MoS$_2$ and MoS$_2$/hBN heterostructure

Alois Arrighi$^{1,2,4}$, Elena del Corro$^1$, Daniel Navarro Urrios$^1$, Marius V Costache$^1$, Juan F Sierra$^1$, Kenji Watanabe$^3$, Takashi Taniguchi$^3$, J A Garrido$^4,5$, Sergio O Valenzuela$^{4,5}$, Clivia M Sotomayor Torres$^{4,5}$ and Marianna Sledzinska$^3$

$^1$ Catalan Institute of Nanoscience and Nanotechnology (ICN2), CSIC and BIST, Campus UAB, Bellaterra, 08193 Barcelona, Spain
$^2$ Departamento de Física, Universidad Autónoma de Barcelona, Bellaterra E-08193 Barcelona, Spain
$^3$ MIND-IN2UB, Departament d’Enginyeria Electrònica i Biomèdica, Facultat de Física, Universitat de Barcelona, Martí i Franquès 1, 08028 Barcelona, Spain
$^4$ Research Center for Functional Materials, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan
$^5$ International Center for Materials Nanoarchitectonics, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan
$^6$ ICREA, Pg Lluís Companys 23, 08010 Barcelona, Spain
$^*$ Authors to whom any correspondence should be addressed.

E-mail: alois.arrighi@gmail.com, SOV@icrea.cat and marianna.sledzinska@icn2.cat

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Abstract

State-of-the-art fabrication and characterisation techniques have been employed to measure the thermal conductivity of suspended, single-crystalline MoS$_2$ and MoS$_2$/hBN heterostructures. Two-laser Raman scattering thermometry was used combined with real time measurements of the absorbed laser power. Measurements on MoS$_2$ layers with thicknesses of 5 and 14 nm exhibit thermal conductivity in the range between 12 Wm$^{-1}$ K$^{-1}$ and 24 Wm$^{-1}$ K$^{-1}$. Additionally, after determining the thermal conductivity of the latter MoS$_2$ sample, an hBN flake was transferred onto it and the effective thermal conductivity of the heterostructure was subsequently measured. Remarkably, despite that the thickness of the hBN layer was less than a hal of the thickness of the MoS$_2$ layer, the heterostructure showed an almost eight-fold increase in the thermal conductivity, being able to dissipate more than ten times the laser power without any visible sign of damage. These results are consistent with a high thermal interface conductance $G$ between MoS$_2$ and hBN and an efficient in-plane heat spreading driven by hBN. Indeed, we estimate $G$ $\sim$ 70 MW m$^{-2}$ K$^{-1}$ for hBN layer thermal conductivity of 450 Wm$^{-1}$ K$^{-1}$ which is significantly higher than previously reported values. Our work therefore demonstrates that the insertion of hBN layers in potential MoS$_2$-based devices holds the promise for efficient thermal management.

1. Introduction

Molybdenum disulfide, MoS$_2$, arguably the most studied 2D material (2DM) after graphene, has attracted much interest due to its semiconducting nature, high carrier mobility and tunable bandgap, which are highly relevant for potential electronic and optoelectronic devices [1, 2]. However, as high-performance devices have been demonstrated in research laboratories, it remains to be addressed how they would respond in industrial implementations, for which thermal dissipation plays a key role. In this context, MoS$_2$ thermal conductivity measurements have yielded relatively small values, scattered over $k_{\text{MoS}_2}$ $\sim$ 15–100 Wm$^{-1}$ K$^{-1}$ [3–9]. These results have two important implications. First, they highlight the relevance of proper thermal management as the low $k_{\text{MoS}_2}$ can impair the performance of MoS$_2$ in, for instance, field effect transistors (FETs). Because the heat cannot be efficiently dissipated from the device active area solely by MoS$_2$, the thermal interface conductance $G$ between MoS$_2$ and its surroundings acquires special relevance. Second, it is necessary to implement techniques to accurately determine the thermal conductivity of 2DMs and establish the origin of the discrepancies observed in the literature. The spreading in reported results is not only limited to MoS$_2$ as thermal conductivity measurements of 2DMs are challenging from the perspectives of material growth and device fabrication. However,
while the spread could partly be attributed to different sample preparation methods and thickness, it has been argued that a more plausible reason is measurement errors [10]. Raman scattering-based methods have been widely used to determine the thermal conductivity of 2DMs [3, 4, 6, 7, 11, 12]. In one-laser Raman thermometry (1LRT), a laser is used both as a heater and temperature probe (figure 1(a)) and the thermal conductivity is obtained from the temperature rise and the power absorbed [3, 4, 6, 11]. The main drawback of this method is that only the temperature at the centre of the sample is known with information neither on the temperature decay along the sample nor at its edges, in contact with the heatsink. In fact, in the specific case of the sample being in thermal equilibrium, there are several sources of error, including the interaction between the 2DMs and the substrate, the role of the substrate as heat-sink, the temperature-dependent Raman scattering frequency shift calibration, the environment (e.g. air, vacuum) and the determination of the absorbed laser power, which can vary with temperature [10]. Such limitations are even more critical in multilayer heterostructures, where the power, partially absorbed in each layer, has to be assumed, leading to additional uncertainty in the results.

Here, we overcome these limitations by implementing 2LRT to determine the thermal conductivity of suspended, single-crystalline MoS₂ layers and a MoS₂/hBN heterostructure. As the 2D layers are free-standing, errors deriving from thermal interface effects with the substrate are eliminated, thus simplifying data analysis. In contrast to 1LRT, in 2LRT one laser creates a hotspot at the centre of the sample, whereas the other laser directly probes the generated temperature profile (figure 1(b)). In this way, the thermal conductivity of the material can be extracted without any assumptions. The 2LRT technique has been successfully used to study silicon nanomembranes [13], phononic crystals [14–16], thermal diodes [17] and polycrystalline MoS₂ [18]. However, no results have yet been reported using this technique for crystalline 2DMs, perhaps due to the inherent difficulty of fabricating large enough suspended samples. For the heterostructure, we chose hBN because it has been shown to dramatically increase the MoS₂ carrier mobility. Furthermore, hBN is an excellent 2D dielectric material with a high reported thermal conductivity (k_{hBN} ~ 200–800 Wm⁻¹ K⁻¹ [19–21]). The use of hBN as a thermal interface material in 2D devices can thus improve thermal management and overall lead to increased device performance, with higher carrier mobility and thermal dissipation in FETs [22, 23].

In order to disentangle G from the thermal conductivities of each layer in the MoS₂/hBN heterostructure, k_{MoS₂} and k_{hBN}, we have implemented a singular experimental protocol. We first determine k_{MoS₂} on a suspended MoS₂ flake using 2LRT. Then a thin hBN layer is selected and transferred onto the already characterized MoS₂. By measuring the thermal conductivity of the bilayer with 2LRT, we can estimate k_{hBN} and the thermal interface conductance G. As hBN is transparent at the wavelength of the used laser, the laser power is mainly absorbed by MoS₂. Therefore, the MoS₂ temperature rise for a given laser power can be demonstrated to be largely determined by G, which is estimated to be ~70 MW m⁻² K⁻¹, depending on the assumed k_{hBN}. This result is significantly larger than previously reported values and opens the way for thermal management using van der Waals heterostructures.

2. Experimental details

In order to support the free-standing 2DM layers, silicon membranes with a thickness of 3 µm were fabricated from a silicon-on-insulator wafer using standard microfabrication techniques. Holes with diameters of 20 µm were then patterned on the membranes using a focused ion beam. The hole-size was selected to be large enough to obtain sufficiently detailed...
temperature maps of the suspended layers. The 2DMs were mechanically exfoliated using viscoelastic polydimethylsiloxane films. Selected flakes were located with an optical microscope and then transferred onto the holey membranes using all dry transfer methods to avoid contamination [24].

As the Raman-active mode frequency is used as a temperature probe, it is crucial to calibrate its dependence as a function of temperature ($\chi$). During calibration, the entire sample is heated uniformly in vacuum and spectra are recorded at low enough laser power to avoid inducing extra heating. The coefficient $\chi$, known as the 1st-order temperature coefficient of a given mode, was measured directly in the suspended samples for both $A_{1g}$ and $E_{2g}$ modes (see supplementary information (available online at stacks.iop.org/2DM/9/015005/mmedia)).

Two single crystalline MoS$_2$ samples with thickness of 5 and 14 nm have been characterized, which roughly corresponds to 7 and 20 monolayers, respectively (see supporting information). These samples were used to establish the implementation of 2LRT in single crystalline 2DM. After obtaining $k_{\text{MoS}_2}$ for the 14 nm sample, an 8 nm thick layer of hBN was transferred onto it to study heat transport in the heterostructure, from which $G$ was extracted. All measurements were carried out in vacuum to prevent heat dissipation in air (or surrounding environment), which would be a source of error, leading to an overestimation of the heat conductivity of the suspended layers.

### 3. Results

The 5 nm MoS$_2$ sample suspended over a 20 $\mu$m diameter hole and its corresponding Raman spectrum are shown in figure 2(a). For the 2LRT measurements, the heat was applied at the centre of the sample, while the Raman spectra were recorded at several points along the sample diameter. The change in the Raman $A_{1g}$ mode frequency was consequently converted to temperature, using $\chi$ as described previously; the resulting linescan, is shown in figure 2(b). The data provides information on the temperature rise at the centre of the sample ($x = 0$), the temperature decay along the sample and the temperature at the edges. It should also be noted that samples reach close to room temperature at the edges, confirming a good thermal contact and a high quality heat transfer process to the substrate.

In order to extract the $k_{\text{MoS}_2}$ the spatial distribution of the temperature rise induced by the laser beam, the problem is reduced to a one-dimensional integral, which is evaluated numerically using the finite elements method (FEM) in COMSOL software. The solution for an arbitrary laser intensity distribution is specified for the case of a Gaussian beam (see section 6) [25]. The numerical solution is directly fitted to the experimental points shown in figure 2(b) for $P_{\text{abs}} = 40 \mu W$ to obtain $k_{\text{MoS}_2}$.

Here $P_{\text{abs}}$ is determined experimentally by measuring the incident, reflected and transmitted power across the suspended layer. In this case, the best fit corresponds to $k_{\text{MoS}_2} = 12 \pm 5 \text{ Wm}^{-1} \text{ K}^{-1}$. We believe that the slight deviation of the fitting with respect to the experimental data near the edges is mainly due to a decreasing intensity of the Raman signal of supported flakes, which increases the uncertainty of the temperature estimation. Another possibility is the temperature-induced strain which becomes apparent during the heating scans, especially for the thinnest samples.

The same experimental procedure was applied to the 14 nm thick MoS$_2$ sample suspended over 20 $\mu$m hole, as shown in figure 2(c). The temperature linescan in figure 2(d) shows temperature distribution on the sample and a uniform thermal boundary where the sample was in contact with the substrate. Slight asymmetry on the right side of the linescan is attributed to the drift of the sample position during measurement (see section 6). The best fit to figure 2(d) for $P_{\text{abs}} = 0.425 \text{ mW}$ yields a thermal conductivity $k_{\text{MoS}_2} = 24 \pm 5 \text{ Wm}^{-1} \text{ K}^{-1}$.

Finally, an 11-layer hBN flake was transferred onto the suspended MoS$_2$ using the dry transfer method (see inset in figure 3(a)). The uniformity of both suspended layers is evidenced by Raman spectroscopy measurements, which highlight a uniform value of the frequency of the $A_{1g}$ mode and a constant difference between the frequencies of the $A_{1g}$ and $E_{2g}$ modes (figure S2). Because the intensity of the Raman peaks in the few-layer h-BN sample is weak compared to that in MoS$_2$, they are unsuitable for Raman thermometry techniques [19]. Indeed, it was not possible to obtain the temperature distribution in the hBN layer and the temperature could only be probed in the MoS$_2$, which we further used to calculate the effective $k$ of the heterostructure.

The temperature profile was obtained using the procedure implemented for the isolated MoS$_2$. Similar to the isolated MoS$_2$, the fit was obtained by introducing an effective $k$ for the MoS$_2$/hBN heterostructure. From the temperature profile in figure 3(b), the $k$ was calculated to be $185 \pm 20 \text{ Wm}^{-1} \text{ K}^{-1}$. This value shows an almost eight-fold increase with respect to the isolated MoS$_2$ layer. Furthermore, up to 7.078 mW heating power was applied to the heterostructure, leading to a temperature increase of 550 K without any visible damage. In the case of isolated MoS$_2$, a laser power of just 0.425 mW leads to a temperature increase of 350 K. A temperature mapping for this sample was also performed showing a symmetric temperature distribution (figure S3(b)). These observations confirm that the hBN layer serves as an efficient in-plane heat spreader in the heterostructure.
4. Discussion

While the 1LRT is experimentally less challenging, it provides limited information on the thermal transport in the samples. In contrast, 2LRT provides a deeper picture of the different thermal transport processes in the system, in particular, it allows us to determine the spatial temperature distribution with high accuracy, which can provide information on the boundary thermal contact, the presence of hotspots and further resolve thermal anisotropy in the samples investigated. 1LRT is also not sensitive to sample quality, as Raman spectra are only taken at the centre of the sample. The need of high-quality and clean samples becomes evident in 2LRT, as the polymer residues are visible in the linescans and maps. The temperature profile of an example MoS$_2$ layer transferred using PLLA polymer, and containing various residues, is shown in figure S4. Such an inhomogeneity in less than ideal samples could easily be overlooked by 1LRT.

In figure 3(c) the thermal conductivity values obtained in this and previous works on crystalline MoS$_2$ are compared. Apart from the three samples described above a fourth one, a 3 nm thick MoS$_2$ layer suspended over the 10 µm hole was measured using 1LRT. Following the formalism developed previously [3, 11] we obtain $k_{\text{MoS}_2} = 23 \pm 5$ Wm$^{-1}$K$^{-1}$ (see supplementary information). In our work, both 1LRT and 2LRT show consistent values of $k_{\text{MoS}_2}$ between 12 and 24 Wm$^{-1}$K$^{-1}$. However, these values appear to be slightly lower than many of the previously reported, which we attribute to differences in the experimental methods. For instance, the higher values reported in [4] are likely due to the fact that the measurements were performed in air. As explained in section 2, all of the measurements in this work were performed in vacuum, which is crucial to extract the intrinsic $k$ of the 2DMs, as the heat conduction to air constitutes a significant dissipation channel and can be treated as a source of systematic error [15]. Even though we would expect some temperature dependence of $k_{\text{MoS}_2}$, very good fits to the experimental data are obtained for constant $k_{\text{MoS}_2}$. This assumption is shown to be valid within the quoted $k_{\text{MoS}_2}$ uncertainty, as shown in figures 2(b) and (d), where the expected temperature profiles are plotted for selected $k_{\text{MoS}_2}$.

In order to extract $G$ between the MoS$_2$ and hBN we refer to the literature for the values of
$k_{\text{hBN}}$. The bulk $k_{\text{hBN}}$ was previously measured to be of approximately 400 W m$^{-1}$ K$^{-1}$ and strongly dependent on the crystalline quality of the samples [26]. For single- and few-layer hBN, same as for the other 2DMs, the large disparity of $k$ values can be found in the literature. The thermal conductivity in single-crystalline hBN was reported as 751 ± 340 W m$^{-1}$ K$^{-1}$, 646 ± 242 W m$^{-1}$ K$^{-1}$, and 602 ± 247 W m$^{-1}$ K$^{-1}$ at room temperature for one, two and three layers, respectively using 1LRT [21]. There, the absorption coefficient was directly measured using optical microscopy in transmission mode. The absorbance of the single hBN layer was ∼0.5% for the 514 nm wavelength. Taking into account the large bandgap (∼6 eV) of high-quality hBN very weak absorption is expected, however, defect states can significantly increase the absorption in the visible range. The $k_{\text{hBN}}$ of the 5- and 11-layer sample was determined to be 250 W m$^{-1}$ K$^{-1}$ and 360 W m$^{-1}$ K$^{-1}$, respectively, using a microbridge device with built-in resistance thermometers [19]. However, in that work the presence of polymer residues on the sample surface was found to strongly affect the thermal conductivity, especially for the five-layer sample.

Assuming an (infinitely) large $G$ between the MoS$_2$ and hBN, the temperature of MoS$_2$ and hBN would be approximately equal and the obtained $k$ from figure 3(b) would derive from the contributions of MoS$_2$ and hBN in a parallel configuration. Using the latter approximation, and knowing $k_{\text{MoS}_2} = 24$ W m$^{-1}$ K$^{-1}$, we can estimate $k_{\text{hBN}} \approx 460$ W m$^{-1}$ K$^{-1}$, which sets the lower limit of the possible $k_{\text{hBN}}$ values. The relation between $G$ and $k_{\text{hBN}}$ was further studied using COMSOL (see section 6). For this purpose, we simulated the temperature rise at the hotspot with $P_{\text{abs}} = 7.078$ mW, probed at the MoS$_2$. The value of $k_{\text{hBN}}$ was varied between 300 W m$^{-1}$ K$^{-1}$ and 600 W m$^{-1}$ K$^{-1}$, while $k_{\text{MoS}_2}$ was again set to our experimental result, i.e. $k_{\text{MoS}_2} = 24$ W m$^{-1}$ K$^{-1}$. For 14 nm thick MoS$_2$ we do not expect any significant change in $k_{\text{MoS}_2}$ due to the interactions with the hBN layer [8, 27]. As observed in figure 3(d), for $k_{\text{hBN}} < 460$ W m$^{-1}$ K$^{-1}$ there are no possible solutions for $G$ (i.e. $G \to \infty$), in agreement with our simple parallel resistance approximation. $G > 70$ MW m$^{-2}$ K$^{-1}$ is obtained for $k_{\text{hBN}} \sim 460$ W m$^{-1}$ K$^{-1}$. If we assume higher values of $k_{\text{hBN}} > 500$ W m$^{-1}$ K$^{-1}$ it results in $G < 35$ MW m$^{-2}$ K$^{-1}$, however such large $k_{\text{hBN}}$ is not expected and have been only reported in very thin layers of hBN.
This represents a considerable increase in $G$ compared to previous reports with hBN and other interfaces. For MoS$_2$ layers on the typical CMOS substrates, such as SiO$_2$ or AlN, $G \approx 2-15$ MW m$^{-2}$ K$^{-1}$ was measured [28, 29]. These very low values mean that heat dissipation to the substrate might not be sufficient to assure correct device operation. Early measurements of thermal conductance of the MoS$_2$–hBN interface with 1LRT on a supported sample yielded the room-temperature value of $17.0 \pm 0.4$ MW m$^{-2}$ K$^{-1}$. Also, a maximum theoretical limit of $26.4$ MW m$^{-2}$ K$^{-1}$ was predicted using non-equilibrium Green’s function, a value that is significantly lower than the one obtained in our work. For comparison, $G$ between graphene and hBN was reported to have a value of $52.2 \pm 2.1$ MW m$^{-2}$ K$^{-1}$ [22].

Finally, a recent work reported $G \approx 70$ MW m$^{-2}$ K$^{-1}$ in MoS$_2$ fully-encapsulated with hBN (i.e. hBN/MoS$_2$/hBN) in both supported and suspended samples using 1LRT [30]. For the hBN/MoS$_2$ heterostructure, the estimated thermal conductance was only $23.8$ MW m$^{-2}$ K$^{-1}$. Surprisingly, the absorbance $10.6$ and $16.8$ nm thick hBN was measured to be $16.7\%$ and $25\%$, respectively, indicating the presence of either defects or contamination or both. This might represent a hint why the full encapsulation was needed in order to evacuate heat efficiently.

In conclusion, both of these prior works used Raman spectroscopy to study similar systems, but their contradictory results confirm the pitfalls of thermal measurements in 2DMs and how the quality of the samples and the experimental conditions may influence the estimated values of the thermal conductivity. Our results point to significantly higher interfacial thermal conductance between the MoS$_2$ and hBN than any other substrate. The superior heat dissipation can be achieved with only one few-layer heterostructure, the estimated thermal conductance was only $23.8$ MW m$^{-2}$ K$^{-1}$. For the few-layer samples, in agreement with previous studies.

We showed that using mechanical exfoliation and dry transfer, is feasible to fabricate high-quality, suspended samples. The high quality of the suspended heterostructure is confirmed by the determination of its effective $k$. In particular, we show an eight-fold increase in $k$, and more importantly, that it is possible to dissipate in the heterostructure a laser power that is at least ten times higher than in isolated MoS$_2$ with no damage to the material. The systematic measurements of the MoS$_2$/hBN heterostructure have proved the concept of this material combination is excellent to dissipate heat efficiently. It opens the possibility to measure other types of 2D layered materials and heterostructures, and to determine with high accuracy their $k$, eliminating the error arising from the presence of a bulk substrate. These results prove the potential of integrating few-layer hBN onto MoS$_2$-based devices for efficient in-plane heat spreading.

6. Materials and methods

6.1. Raman characterisation

Spectra shown in figures 3(d), S2 and S3 were obtained using a Witec Alpha300 R confocal Raman spectrometer and the 488 nm laser line.

All the other spectra were taken using a Horiba T64000 Raman spectrometer and the 532 nm laser line.

6.2. Raman thermometry

All the Raman thermometry measurements were performed in a Linkam temperature-controlled vacuum stage (THMS350V) under vacuum ($5 \times 10^{-3}$ mbar) at room temperature. Horiba T64000 Raman spectrometer and a 532 nm laser (cobalt) were used to obtain the spectra.

In 1LRT the laser beam was focused on the sample with the microscope objective ($50 \times$ and NA = 0.55) acting as a Gaussian heat source with a waist size of about $1 \mu$m. The absorbed power, $P_{abs}$, was measured for each sample as the difference between the incident and the transmitted plus reflected laser power. The powers were measured with a calibrated system based on cube nonpolarizing beam splitters, i.e. no assumptions are made of the sample optical absorption. The error of absorbed power measurements was of $\Delta P_{abs} = 5\%$.

In the 2LRT experiments light emitted by the fibre-coupled continuous wave laser operating at 405 nm (cobalt) was focused onto the sample from the bottom by a long working distance microscope objective ($50 \times$ and NA = 0.55) acting as a Gaussian heat source with a waist size of about $1 \mu$m. The absorbed power $P_{abs}$ is measured on site for each sample as the difference between incident and transmitted plus reflected light intensities probed by a calibrated system based on a cube non-polarising beam splitter with an error of $\Delta P_{abs} = 5\%$.

The probe laser beam with wavelength 532 nm is focused on the sample from the top, as explained in the previous section, and works as a temperature probe. To minimise the influence of the probe laser beam on the measurement, its power is set below
The value (typically <10% of the heating laser power) which results in a measurable temperature rise.

The 2LRT experiment consists of two consecutive scans:

(a) no heating applied (‘baseline’). This measurement also helps to assess the sample quality (strain, contamination, etc).
(b) Heating applied using 405 nm wavelength laser coupled from below the sample.

The spectra are collected every 0.5 µm using Märzhäuser stage with Tango controller, which provides repeatability <1 µm (bidirectional) and resolution of 0.01 µm (smallest step size). The difference between the baseline and the scan with applied heating is then converted to temperature using χ.

During long-time measurements (>12 h) drift in sample position can be observed. This is taken into account in the data analysis by: (a) introducing relative spatial shift between the centre of the heating laser and the probe laser (y0) (see section 6.3); (b) adjusting the error in k.

6.3. FEM simulations of 2LRT

The spatial distribution of the temperature rise induced by a laser beam absorbed in a solid is reduced to a 1D integral which is evaluated numerically. The solution for a general laser intensity distribution is specialized to the case of a Gaussian beam [25].

In order to extract the thermal conductivity k we need to solve Fourier’s heat equation in the steady state:

\[ \frac{P_{\text{abs}}}{A} = -k \nabla T \]

where A is the cross-sectional area of the heat flux, k is the thermal conductivity, and T is the temperature. Assuming Gaussian laser beam distribution:

\[ P(r) = P_0 \exp \left( -\frac{2r^2}{w_0^2} \right) \]

where r is the distance from the membrane centre and \( P_0 \) and \( w_0 \) are the Gaussian beam amplitude and waist size, respectively. The relationship between the total absorbed power \( P_{\text{abs}} \) and \( P_0 \) is:

\[ P_0 = 2P_{\text{abs}} / \left( \pi w_0^2 \right). \]

Because of the symmetry of the membrane and its isotropic in-plane thermal conductivity, the model was simplified to a 2D stationary heat flow study.

In case of 1LRT temperature \( T_p \) probed at the sample can be approximated by the formula:

\[ T_p \approx \frac{\int_0^R T(r) P(r) r \, dr}{\int_0^R P(r) r \, dr} \]

where \( T(r) \) is the temperature distribution obtained from the FEM simulation and R is the membrane radius.

The simulations of 2LRT have been made using a FEM commercial software (COMSOL). We have assumed an effective medium model which simulates the temperature spatial profile over the circular membranes volume aiming to mimic the 2LRT experiment. As input parameters we use the absorbed power \( P_{\text{abs}} \) (distributed in a Gaussian profile, which can be shifted from the centre of the membrane by an amount parametrized as \( x_0 \)), the effective thickness and radius of the membrane (the temperature of the edges of the membrane, i.e. where the MoS2 contacts the substrate, is kept to be 300 K), a temperature-independent thermal conductivity (\( k_0 \)) and the relative spatial shift between the centre of the heating laser and the probe laser (\( y_0 \)). The latter means that, when doing the line profile, the probe laser does not exactly pass over the heating laser, the minimum distance between them being \( y_0 \).

We have simulated spatial temperature distributions \( T(r) \) for a wide range of values for \( x_0 \), \( k_0 \) and \( y_0 \) (having the other parameters fixed to the values measured experimentally) with the objective of minimizing the difference between the experimental and simulated temperature curves. The figures reported reflect the results of this study, putting a special focus on the results obtained for the set of parameters that generate a simulated temperature profile that fits best to the experimental results.

6.4. FEM simulations of G

The simulations of G were performed using FEM commercial software (COMSOL). We have developed a model which simulates the temperature in the MoS2 layer in the centre of the circular membrane, aiming to mimic the 2LRT experiment. The membrane is composed of two layers, corresponding to MoS2 and hBN with thermal conductance \( G \) at the interface. As input parameters we use the absorbed power \( P_{\text{abs}} \) (distributed in a Gaussian profile), the effective thickness of MoS2 and hBN, the \( k_{\text{MoS2}} \) and radius of the membrane.

In the model we have assumed isotropic, temperature-independent thermal conductivity for both materials. We assume that all the laser light was absorbed in the MoS2 layer, due to large hBN bandgap. The measured the absorption of MoS2 and MoS2/hBN and differs by less than 10% The temperature of the edges of the membrane, i.e. where the MoS2 contacts the substrate, was kept to 300 K, as in the experiment. We have simulated the temperature for \( k_{\text{hBN}} \) varied between 450 Wm\(^{-1}\)K\(^{-1}\) and 600 Wm\(^{-1}\)K\(^{-1}\) as reported in literature and \( G \) between 15 MW m\(^{-2}\) K\(^{-1}\) and 100 MW m\(^{-2}\) K\(^{-1}\) in order to cover wide range of parameters.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.
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ORCID iDs

Marius V Costache https://orcid.org/0000-0001-7432-6175
Juan F Sierra https://orcid.org/0000-0002-5438-0534
Kenji Watanabe https://orcid.org/0000-0003-3701-8119
Sergio O Valenzuela https://orcid.org/0000-0002-4632-8891
Clivia M Sotomayor Torres https://orcid.org/0000-0001-9986-2716
Marianna Sedzinska https://orcid.org/0000-0001-8592-1121

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