Confined transverse electric phonon polaritons in hexagonal boron nitrides

Musa, Muhyiddeen Yahya; Renuka, Maturi; Lin, Xiao; Li, Rujiang; Wang, Huaping; Li, Erping; Zhang, Baile; Chen, Hongsheng

2018

Musa, M. Y., Renuka, M., Lin, X., Li, R., Wang, H., Li, E., . . . Chen, H. (2018). Confined transverse electric phonon polaritons in hexagonal boron nitrides. 2D Materials, 5(1), 015018-. doi:10.1088/2053-1583/aa9643

<https://hdl.handle.net/10356/106098>

<https://doi.org/10.1088/2053-1583/aa9643>

© 2018 IOP Publishing Ltd. All rights reserved. This is an author-created, un-copyedited version of an article accepted for publication in 2D Materials. IOP Publishing Ltd is not responsible for any errors or omissions in this version of the manuscript or any version derived from it. The definitive publisher authenticated version is available online at <https://doi.org/10.1088/2053-1583/aa9643>

Downloaded on 26 Apr 2023 23:21:16 SGT

Confined transverse electric phonon polaritons in hexagonal boron nitrides

Muhyiddeen Yahya Musa¹, Maturi Renuka¹, Xiao Lin^{2,*}, Rujiang Li¹, Huaping Wang^{1,3}, Erping Li⁴, Baile Zhang^{2,5}, and Hongsheng Chen^{1,4*}

¹*State Key Laboratory of Modern Optical Instrumentation, The Electromagnetics Academy at Zhejiang University, Zhejiang University, Hangzhou 310027, China.*

²*Division of Physics and Applied Physics, School of Physical & Mathematical Sciences, Nanyang Technological University, Singapore 637371, Singapore.*

³*Institute of Marine Electronics Engineering, Zhejiang University, Hangzhou 310058, China*

⁴*College of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027, China.*

⁵*Centre for Disruptive Photonic Technologies, NTU, Singapore 637371, Singapore.*

**Corresponding authors: xiaolinbnwj@ntu.edu.sg (X. Lin); hansomchen@zju.edu.cn (H. Chen)*

Abstract: We predict the existence of confined transverse electric (TE) phonon polaritons in an ultrathin hexagonal boron nitride (*h*BN) slab below *h*BN's second transverse optical frequency. The skin depth of TE phonon polaritons can be decreased to subwavelength scale by increasing the thickness of *h*BN to several nanometers. Due to the strong spatial confinement, these TE phonon polaritons, different from TE graphene plasmons, can stably exist even when the permittivities of the superstrate and substrate are largely different. These revealed advantages of TE phonon polaritons might lead to potential applications of *h*BN in the manipulation of TE waves, such as the design of novel waveguides, polarizers, and the exploration of negative refraction between TE polaritons.

1. Introduction

Highly squeezed polaritons, such as plasmon polaritons in graphene and phonon polaritons in hexagonal boron nitride (*hBN*) [1-4], have attracted intensive attention and can enable many potential applications, including hyperlens [5], negative refraction [6], subwavelength guidance [7,8], and optoelectronics devices [9]. This is mainly due to their unique ability to control the flow of light at the nanoscale. However, most of previous studies are focused on the transverse magnetic (TM, or *p*-polarized) polaritons, and the transverse electric (TE, or *s*-polarized) polaritons are comparatively less discussed. This is because the spatial confinement of TE graphene plasmons is extremely weak, as being pointed out by the pioneering work in 2007 [10] which firstly proposed the concept of TE plasmon polaritons in graphene. Moreover, the existence of TE plasmons in monolayer and even multilayer graphene [11] are very sensitive to the temperature, the chemical potential [12], and especially the surrounding dielectric environments [13]. For example, the TE graphene plasmons are known to exist only when the permittivities of the substrate and superstrate are almost the same [14], otherwise they will turn into the leaky TE modes. These facts unavoidably limit their practical applications. Actually, although the work in 2007 ignited many researches of TE plasmon polaritons in graphene [15-18] and other 2D materials [19-21], only a few of their potential nanophotonic applications have been reported, such as polarizers [22], waveguide phase and amplitude modulators [23], optical sensors [24] and Brewster effects [25]. Therefore, it is highly desirable yet challenging to enhance the spatial confinement of TE polaritons, which can further enable their potential applications. Due to the abundant types of polaritons existing in 2D materials [1,2], it shall be judicious to explore other TE polaritons in 2D materials, such as TE phonon polaritons supported by *hBN*. It is worthy to note that while TM phonon polaritons [1,2,4] in *hBN* slabs have been extensively discussed, the existence of TE phonon polaritons in *hBN* slabs along with their basic properties still remain elusive.

Here we reveal that the well-confined TE phonon polaritons can stably exist in an ultrathin *hBN* slab mainly in the range of 39-41 THz, which is close to *hBN*'s second transverse optical frequency (i.e. 41 THz). In this work, the thickness of the *hBN* slab considered is at least 100 times smaller than the

wavelength in free space, and henceforth the term “ultrathin” is used. For the monolayer structure, the spatial confinement of h BN’s TE phonon polaritons is found to be much better than that of TE graphene plasmons. Moreover, the spatial confinement of these TE phonon polaritons is largely enhanced by increasing the thickness of the h BN slab, with their skin depth being able to be decreased to subwavelength scale. This makes the existence of TE phonon polaritons in an ultrathin h BN insensitive to the surrounding dielectric environment, where the permittivities of the substrate and superstrate can be largely different. These revealed advantages indicate that h BN can provide a versatile platform for the future demonstration of TE phonon polaritons and for the manipulation of TE waves. We note that while in h BN, the wavelength of TM phonon polaritons can be two orders of magnitude smaller than the wavelength in free space [1,2,4], the wavelength of TE phonon polaritons is still comparable to the wavelength in free space.

2. Results and discussion

In order to find out the general existence condition of TE polaritons, we begin with the analytical derivation of the dispersion for TE polaritons. We consider that there is a surface conductivity σ_s at the dielectric interface (parallel to the x - y plane) between region 1 ($z > 0$) and region 2 ($z < 0$); see figure 1. The relative permittivities of lossless regions are denoted as ϵ_{r1} and ϵ_{r2} , respectively. For TE waves, the electric field only has the component in the y direction, i.e. E_y . From the electromagnetic theory [26], one can set the electric fields in each region as;

$$\bar{E}_1 = \hat{y}E_1 e^{iqx} e^{-ik_{1z}z} \quad (1)$$

$$\bar{E}_2 = \hat{y}E_2 e^{iqx} e^{+ik_{2z}z} \quad (2)$$

In the above equations, q and $k_{z1,2} = \sqrt{\frac{\omega^2}{c^2} \epsilon_{r1,2} - q^2}$ are the components of the wavevector parallel and perpendicular to the interface, respectively. The magnetic fields in each region can be obtained by using $\nabla \times \bar{E} = i\omega\mu_0 \bar{H}$. By enforcing the boundary conditions [26] and after some algebra, one can obtain the dispersion of TE polaritons as:

$$k_{z1} + k_{z2} + \sigma_s \omega \mu_0 = 0 \quad (3)$$

where μ_0 is the permeability in free space. Since $\text{Im}(k_{z1,2}) > 0$ for TE polaritons, equation (3) requires $\text{Im}(\sigma_s)$ to be negative for the existence of TE polaritons [10]. From equation (3), the solution of k_{z1} and k_{z2} can be expressed as follows:

$$k_{z1} = \frac{\omega}{c} \left[\frac{(\sigma_s \mu_0 c)^2 + (\varepsilon_{r1} - \varepsilon_{r2})}{-2\sigma_s \mu_0 c} \right] \quad (4)$$

$$k_{z2} = \frac{\omega}{c} \left[\frac{(\sigma_s \mu_0 c)^2 - (\varepsilon_{r1} - \varepsilon_{r2})}{-2\sigma_s \mu_0 c} \right] \quad (5)$$

where c is the speed of light in free space. From equations (4-5), one can see that the value of $k_{z1,2}$ is a function of both the surface conductivity and the relative permittivities of the surrounding environment. In particular, when the structure is symmetric, i.e. $\varepsilon_{r1} = \varepsilon_{r2} = \varepsilon_r$, one has $k_{z1} = k_{z2} = \frac{-\sigma_s \omega \mu_0}{2}$.

The surface conductivity in equation (3) can be attributed to the existence of an ultrathin dielectric slab at the interface. For example, for an ultrathin *hBN* slab, the effective surface conductivity can be obtained from its relative in-plane permittivity $\varepsilon_{r\perp, hBN}(\omega)$ (the component of permittivity perpendicular to the z direction or the optic axis [27,28] of *hBN*) as follows:

$$\sigma_{s, hBN, d} = [\varepsilon_{r\perp, hBN}(\omega) - \varepsilon_{r\perp}(\infty)] \varepsilon_0 \omega d \quad (6)$$

where $\varepsilon_{r\perp}(\infty) = \lim_{\omega \rightarrow \infty} \varepsilon_{r, hBN}(\omega) = 4.87$ [29], ε_0 is the permittivity of free space, and d is the thickness of *hBN*. We note that the surface conductivity and the relative in-plane permittivity of *hBN* have a similar dependence on the frequency; see Fig.3(a) and Fig.S1. The relative in-plane permittivity of *hBN* is given as [29]: $\varepsilon_{r\perp, hBN}(\omega) = \varepsilon_{r\perp}(\infty) + s_v \frac{\omega_v^2}{\omega_v^2 - i\gamma_v \omega - \omega^2}$, where the normal frequency of vibration $\hbar\omega_v = 170.1$ meV, the amplitude decay rate $\hbar\gamma_v = 0.87$ meV, the dimensionless coupling factor $s_v = 1.83$, and $\hbar$ is the reduced Planck's constant. We note that the electromagnetic properties of *hBN* can be quite different when its thickness decreases down to monolayer, which may have large influence on the properties

of TE phonon polaritons (see more discussion in Fig.S2). For graphene, since the TE plasmons have the wavevector q very close to the wavevector in the surrounding materials, the nonlocal response can be neglected. This way, the Kubo formula can be used to model graphene's surface conductivity [22], i.e.

$$\sigma_{s,gr} = \sigma_{intra} + \sigma_{inter} \quad ; \quad \sigma_{intra} = \frac{ie^2 k_B T}{\pi \hbar^2 (\omega + i/\tau)} [(\mu_c/k_B T) + 2 \ln(e^{-\mu_c/k_B T} + 1)] \quad \text{and} \quad \sigma_{inter} = \frac{ie^2 (\omega + i/\tau)}{\pi \hbar^2} \int_0^\infty \frac{F(-x) - F(x)}{(\omega + i/\tau)^2 - 4(x/\hbar)^2} dx$$

represent the contribution from the intraband and interband transitions, respectively; $F(x) = [e^{(x-\mu_c)/k_B T} + 1]^{-1}$ is the Fermi distribution function; T is the temperature, and e is the electron charge. In this work, we consider the chemical potential to be $\mu_c = 0.42 \text{ eV}$ and the relaxation time to be $\tau = 0.2 \text{ ps}$. The corresponding electron mobility is $\mu = 4800 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$, which is achievable in experiments [30, 31].

We first discuss the basic properties of TE plasmon polaritons in a monolayer graphene surrounded by air in figure 2. Figure 2(a) shows the surface conductivity of monolayer graphene. When $\hbar\omega/\mu_c > 1.67$ (1.63) at 0 (300) K, one has $\text{Im}(\sigma_{s,gr}) < 0$, which fulfills the existence condition of TE graphene plasmons as stated in equation (3). Figure 2(b-c) shows the dispersion and the skin depth [i.e. $\delta = 1/\text{Im}(k_z)$] of TE graphene plasmons at different temperatures, respectively. Since $\text{Re}[q / (\omega/c)]$ is very close to one, the spatial confinement for TE graphene plasmons is extremely poor, where the skin depth is much larger than the wavelength in free space. See more discussion of the temperature effect on the TE graphene plasmons in the supporting information.

As comparison, figure 3 shows the properties of TE phonon polaritons supported by a monolayer $h\text{BN}$ surrounded by air. Figure 3(a) shows the surface conductivity $\sigma_{s,h\text{BN},mono}$ of a monolayer $h\text{BN}$. One has $\text{Im}(\sigma_{s,h\text{BN},mono}) < 0$ when $\frac{\omega}{2\pi} < 41 \text{ THz}$, and the large negative value of $\text{Im}(\sigma_{s,h\text{BN},mono})$ mainly exists between 39 – 41 THz. This indicates that the TE phonon polaritons can exist below 41 THz, and the well-confined TE phonon polaritons mainly exist within the range of 39-41 THz. Figures 3(b-c) show the dispersion and the skin depth of TE phonon polaritons supported by a monolayer $h\text{BN}$, respectively. It can

be seen that h BN's TE phonon polaritons in figures 3(b-c) is better confined than TE graphene plasmons in figures 2(b-c). It is worthy to note that our work here is different from Ref. [20], which studied the TE plasmons supported by h BN in the visible regime.

Since a large propagation length of polaritons is favorable for practical applications, we compare the propagation characteristics of TE polaritons supported by a monolayer h BN and graphene in figure 4. Here we use the inverse damping factor $\frac{Re(q)}{Im(q)} = 4\pi \frac{L_p}{\lambda_{spp}}$ [19], which is a dimensionless figure of merit, to characterize the propagation length L_p of TE polaritons, where λ_{spp} is the polariton wavelength. From figure 4, the value of $Re(q)/Im(q)$ for both TE polaritons are very large, which is in the order of 10^6 . In addition, the maximum value of $Re(q)/Im(q)$ for h BN's TE phonon polaritons can be much larger (~ 4 times) than that of graphene's TE plasmon. Consequently, the corresponding maximum propagation length for h BN's TE phonon polaritons is $\sim 0.6 \mu m$ at 39 THz, while that of TE graphene plasmons is $0.14 \mu m$ at $\hbar\omega/\mu_c = 1.7$ (the corresponding frequency is ~ 170 THz).

The spatial confinement of TE phonon polaritons can be enhanced by increasing the thickness of the h BN slab, as shown in figure 5. Figure 5(a-b) shows the dispersion and skin depth of TE phonon polaritons in an ultrathin h BN slab (i.e. the multilayer h BN). When the h BN thickness increases from 10 nm, 20 nm to 30 nm, the maximum value of $Re[q/(\omega/c)]$ at 40.8 THz increases respectively from 1.2, 1.7 to 2.3 in figure 5(a), far larger than the value of ~ 1.00018 at 40.8 THz for a monolayer h BN (~ 0.345 nm) [32] in figure 3(b). Consequently, the skin depth of TE phonon polaritons is largely decreases for a thicker h BN slab in figure 5(b). For example, when the h BN thickness increases from 10 nm, 20 nm to 30 nm, the minimum value of the normalized skin depth of TE phonon polaritons δ_{hBN}/λ at 40.8 THz decreases from 0.24, 0.12 to 0.08, respectively. This indicates that the minimum skin depths of TE phonon polaritons in an ultrathin h BN slab (with a thickness of several nanometers) in figure 5(b) can be subwavelength scale, while that for monolayer h BN is much larger than the wavelength in figure 3(c). These enhanced spatial confinements of TE phonon polaritons in an ultrathin h BN slab might facilitate their direct observation in

experiments. More discussion of TE phonon polaritons in an ultrathin *h*BN slab can be found in the supporting information. In addition, all-angle negative refraction of highly confined TM plasmon and phonon polaritons in graphene-*h*BN heterostructure has been proposed [6]. By following the thought in Ref. [6], the enhanced spatial confinement might facilitate the further exploration of negative refraction between highly confined TE plasmon and phonon polaritons in graphene-*h*BN heterostructure.

The existence condition of TE phonon polaritons supported by an ultrathin *h*BN slab in an asymmetric structure, i.e. $\varepsilon_{r1} \neq \varepsilon_{r2}$, is discussed, since the realistic experimental structures are generally asymmetric. Due to $Im(k_{z1,2}) > 0$ in equations (4-5), the general existence condition for TE phonon polaritons requires $|\varepsilon_{r1} - \varepsilon_{r2}| < (\mu_0 c)^2 \left[\left(Re(\sigma_{s,hBN,d}) \right)^2 + \left(Im(\sigma_{s,hBN,d}) \right)^2 \right]$; see detailed derivation in the supporting information. For the ideal lossless case (i.e. $Re(\sigma_{s,hBN,d}) = 0$), the existence condition above reduces to $|\varepsilon_{r1} - \varepsilon_{r2}| < (\mu_0 c)^2 \left(Im(\sigma_{s,hBN,d}) \right)^2$. Here we can see that the existence of loss allows a larger value of $|\varepsilon_{r1} - \varepsilon_{r2}|$, indicating a wider range of choice for the superstrate and substrate. Therefore, the loss plays a positive role for the existence condition of TE phonon polaritons (which is quite counterintuitive), while the loss is generally detrimental to the propagation of TE phonon polaritons. In order to investigate the influence of *h*BN's thickness, figure 4 show the critical existence condition of TE phonon polaritons, i.e. $|\varepsilon_{r1} - \varepsilon_{r2}| = (\mu_0 c)^2 \left[\left(Re(\sigma_{s,hBN,d}) \right)^2 + \left(Im(\sigma_{s,hBN,d}) \right)^2 \right]$ for the lossless case ($Re(\sigma_{s,hBN,d}) = 0$) and the lossy case ($Re(\sigma_{s,hBN,d}) \neq 0$), as a function of *h*BN's thickness at 40.9 THz. As expected, the value of $|\varepsilon_{r1} - \varepsilon_{r2}|$ increases when a thicker *h*BN slab is applied. For example, when the thickness of *h*BN is 30 nm the value of $|\varepsilon_{r1} - \varepsilon_{r2}|$ reaches ~ 19 and ~ 28 for the lossless and lossy cases, respectively. This indicates that the usage of a thin *h*BN slab (in the order of several nanometers), instead of a monolayer *h*BN slab, can provided more choices of the superstrate and substrate to support TE phonon polaritons. This is due to the enhanced spatial confinement of TE phonon polaritons in a thin *h*BN slab, as discussed in figure 5.

3. Conclusion

In conclusion, we for the first time reveal the existence of infrared TE phonon polaritons in an ultrathin *h*BN slab, and systematically study their fundamental properties. These revealed TE phonon polaritons supported by a monolayer *h*BN are found to have better spatial confinement than TE plasmon polaritons supported by a monolayer graphene. Moreover, the spatial confinement of TE phonon polaritons can be largely enhanced by using a thin *h*BN slab, which can enable the robust existence of TE phonon polaritons in various asymmetric structures. Therefore, these well-confined TE phonon polaritons in an ultrathin *h*BN slab can help to pave a way for the future experimental detection and practical applications of TE polaritons.

Acknowledgement

This work was sponsored by the National Natural Science Foundation of China under Grants No. 61625502, No. 61574127, and No. 61601408, the ZJNSF under Grant No. LY17F010008, the Top-Notch Young Talents Program of China, the Fundamental Research Funds for the Central Universities under Grant No. 2017XZZX008-06, the Innovation Joint Research Center for Cyber-Physical-Society System, the Nanyang Technological University for Nanyang Assistant Professorship Start-Up Grant, the Singapore Ministry of Education under Grants No. MOE2015-T2-1-070 and No. MOE2011-T3-1-005, and Tier 1 RG174/16(S).

References

- [1] Basov D N, Fogler M M, García de Abajo F J 2016 “Polaritons in van der Waals materials.” *Science* **354** aag1992
- [2] Low T, Chaves A, Caldwell J D, Kumar A, Fang N X, Avouris A, Heinz T F, Guinea F, Martin-Moreno L and Koppens F 2017 “Polaritons in layered two-dimensional materials” *Nat. Materials* **16** 182-194
- [3] Lin X *et al* 2017 “Splashing transients of 2D plasmons launched by swift electrons” *Sci. Adv.* **3** 1-6
- [4] Zhao Z, Wu H and Zhou Y 2016 “Surface-confined edge phonon polaritons in hexagonal boron nitride thin films and nanoribbons” *Opt. Express* **24** 22930-42
- [5] Li P, Lewin M, Kretinin M A V, Caldwell J D, Novoselov K S, Taniguchi T, Watanabe K, Gaussmann F and Taubner T 2015 “Hyperbolic phonon-polaritons in boron nitride for near-field optical imaging and focusing.” *Nat. Commun.* **6** 7507
- [6] Lin X, Yang Y, Rivera N, Lopez J, Shen Y, Kaminer I, Chen H, Zhang B, Joannopoulos J and Soljačić M 2017 “All-angle negative refraction of highly squeezed polaritons in graphene boron nitride heterostructures.” *Proceedings of the National Academy of Sciences of the United States of America* **114** 6717-21
- [7] Xu Y, Premkumar N, Yang Y and Lail B A 2016 “Hybrid surface phononic waveguide using hyperbolic boron nitride.” *Opt. Express* **24** 17183-92
- [8] Caldwell J D *et al* 2014 “Sub-diffraction, volume-confined polaritons in the natural hyperbolic material: hexagonal boron nitride.” *Nat. Commun.* **5** 5221
- [9] Bao Q and Loh K P 2012 “Graphene photonics, plasmonics, and broadband optoelectronic devices.” *ACS Nano* **6** 3677-94
- [10] Mikhailov S A and Ziegler K 2007 “New electromagnetic mode in graphene.” *Phys. Rev. Lett.* **99** 016803
- [11] Jablan M, Buljan H and Soljačić M 2011 “Transverse electric plasmons in bilayer graphene.” *Opt. Express* **19** 11236-41
- [12] Bordag M and Pirozhenko I G 2015 “Surface plasmons for doped graphene.” *Phys. Rev. D* **91** 085038
- [13] He X Y, Tao J and Meng B 2013 “Analysis of graphene TE surface plasmons in the terahertz regime.” *Nanotechnology* **24** 345203
- [14] Kotov O V, Kol'chenko M A and Lozovik L E 2013 “Ultrahigh refractive index sensitivity of TE-polarized electromagnetic waves in graphene at the interface between two dielectric media.” *Opt. Express* **21** 13533-46
- [15] Ye Q, Wang J, Liu Z, Deng Z, Kong X, Xing F, Chen X, Zhou W, Zhang C and Tian J 2013 “Polarization-dependent optical absorption of graphene under total internal reflection.” *Appl. Phys. Lett.* **102** 021912
- [16] Bludov Y V, Smirnova D A, Kivshar Y S, Peres N M R and Vasilevskiy M I 2014 “Nonlinear TE-polarized surface polaritons on graphene.” *Phys. Rev. B* **89** 035406
- [17] Bordag M and Pirozhenko I G 2014 “Transverse-electric surface plasmon for graphene in the Dirac equation model.” *Phys. Rev. B* **89** 035421
- [18] Chamanara N and Caloz C 2016 “Graphene transverse electric surface plasmon detection using nonreciprocity modal discrimination.” *Phys. Rev. B* **94** 75413
- [19] Lin X, Rivera N, Lopez J J, Kaminer I, Chen H and Soljačić M 2016 “Tailoring the energy distribution and loss of 2D plasmon.” *New J. Phys.* **18** 105007
- [20] Merano M 2016 “Transverse electric surface mode in atomically thin Boron-Nitride.” *Opt. Lett.* **41** 2668-71

- [21] Ukhtary M S, Nugraha A R T E, Hasdeo H and Saito R 2016 “Broadband transverse electric surface wave in silicene.” *Appl. Phys. Lett.* **109** 063103
- [22] Bao Q, Zhang H, Wang B, Ni Z, Lim C H Y X, Wang Y, Tang D Y and Loh K P 2011 “Broadband graphene polarizer.” *Nat. Photonics* **5** 411-5
- [23] Shkerdin G, Alkorre H, Guoqiang H and Stiens J H 2016 “Modified TE modes of metal waveguide with integrated graphene structure in the sub-terahertz frequency range.” *IET Microw. Antennas Propag.* **10** 692-9
- [24] Sun L, Zhang Y, Wang Y, Zhang C, Min C, Yang Y, Zhu S and Yuan X 2017 “Refractive index mapping of single cells with a graphene-based optical sensor.” *Sensors and Actuators B* **242** 41-6
- [25] Lin X, Shen Y, Kaminer I, Chen H and Soljacic M 2016 “Transverse-electric Brewster effect enabled by nonmagnetic two-dimensional materials.” *Phys. Rev. A* **94** 023836
- [26] Kong J A 2008 *Electromagnetic Wave Theory* (EMW Publishing)
- [27] Lee S L, Ng S S, Abu Hassan H, Hassan Z and Dumelow T 2014 “Crystal orientation dependence of polarized infrared response of sapphire crystal” *Optical Materials* **37** 773-9
- [28] Lee S C, Ng S S, Abu Hassan H, Hassan Z and Dumelow T 2014 “Surface phonon polariton responses of hexagonal sapphire crystals with non-polar and semi-polar crystallographic planes” *Optic Lett.* **39** 5467-70
- [29] Woessner A *et al* 2015 “Highly confined low-loss plasmons in graphene–boron nitride heterostructures.” *Nat. Mater.* **14** 4
- [30] Bolotin K I, Sikes K J, Jiang Z, Klima M, Fudenberg G, Hone J, Kim P and Stormer H L 2008 “Ultrahigh electron mobility in suspended graphene.” *Solid State Commun.* **146**, 351-5
- [31] Dean C R *et al* 2010 “Boron nitride substrates for high-quality graphene electronics.” *Nat. Nanotech.* **5**, 722-6
- [32] Golla D, Chattrakun K, Watanabe K, Taniguchi T, LeRoy B J and Sandhu A 2013 "Optical thickness determination of hexagonal boron nitride flakes." *Appl. Phys. Lett.* **102**, 161906

Figure 1. Structural schematic. A surface conductivity σ_s , which can either be an ultrathin *h*BN slab or graphene, exists at the interface between two dielectric regions. The optical axis of graphene and *h*BN is along the *z* direction.

Figure 2. Properties of TE plasmons supported by a monolayer graphene at different temperatures. Graphene, with a chemical potential of 0.42 eV and a relaxation time of 0.2 ps, is surrounded by air. (a) Surface conductivity of monolayer graphene $\sigma_{s,gr}$. $G_0 = e^2/4\hbar$ is the universal optical conductivity, (b) dispersion and (c) skin depth δ_{gr} of TE graphene plasmons. The wavelength in free space is $\lambda = 2\pi c / \omega$.

Figure 3. Properties of TE phonon polaritons in a monolayer $h\text{BN}$. The monolayer $h\text{BN}$, surrounded by air, is characterized by a surface conductivity $\sigma_{s,hBN,mono}$. (a) Surface conductivity of monolayer $h\text{BN}$, (b) dispersion, and (c) skin depth δ_{hBN} of $h\text{BN}$'s TE phonon polaritons.

Figure 4. Inverse damping ratio $Re(q)/Im(q)$ of TE polaritons supported by (a) a monolayer hBN , and (b) a monolayer graphene at room temperature. Both graphene and hBN are surrounded by air. The setup of graphene is the same as that in Fig.2, and the setup of hBN is the same as that in Fig.3.

Figure 5. (a) Dispersion, and (b) skin depth δ_{hBN} of TE phonon polaritons supported by an ultrathin h BN slab with different thicknesses. The h BN slab is surrounded by air.

Figure 6. The critical existence condition of TE phonon polaritons i.e. $|\epsilon_{r1} - \epsilon_{r2}| = (\mu_0 c)^2 \left[\left(\text{Re}(\sigma_{s,d}) \right)^2 + \left(\text{Im}(\sigma_{s,d}) \right)^2 \right]$, as a function of *hBN*'s thickness at 40.9 THz. $\text{Re}(\sigma_{s,hBN,d})$ is nonzero (zero) for the lossy (lossless) case. The red dot represents the critical existence condition (with the value of $|\epsilon_{r1} - \epsilon_{r2}|$ very close to zero) for TE plasmons in a monolayer graphene.