I. Overview of my Future Research

I plan to build a laboratory on **nano-optics** of **quantum, bio** and other **emerging materials** in Texas Tech University. My laboratory aims to reveal physical properties with unprecedented spatial (**nanometer**) and temporal (**femtosecond**) resolution, and to develop the related **optical**, **quantum** and **bio** applications assisted by conventional electromagnetic and **machine learning** design.

Nanoscale light-matter interaction is a subject of increasing importance as it discloses nontrivial physical phenomena inaccessible with conventional methods due to the diffraction law[1]. In the reversed fashion, proper design of nano-optical devices with emerging materials can render tailored functionalities with superior figures of merits[2]. My future research will cover both the fundamental science and technological application and can be overviewed below.

My Expertise 1
Super-resolution & ultrafast imaging, spectroscopy and manipulation ~ 10 nm

My Expertise 2
(Meta)material design (conventional methods + machine learning)

- **Super-resolution and ultrafast dynamic imaging, spectroscopy and manipulation of quantum, bio and other emerging materials**
  (Measure optical, optoelectronic, thermal, magnetic, photoluminescence with ~ 5nm spatial resolution. Provide information for material property, fingerprint, composition distribution, structure, inhomogeneous, defect etc.)
- **Quantum nanophotonics, plasmonics and polaritonics**
  (Additive manufacturing + conventional/machine learning design)
- **Nanophotonic biochemical sensing, emission, energy transfer, electromagnetic manipulation**
  (Additive manufacturing + conventional/machine learning design)

Targeted Funding

NSF: CAREER, DMR, ECCS, CBET
NIH: NIBIB
ONR: YIP, Electronics, Sensors and Networks; Naval Materials
DOE (BES): Condensed Matter & Material Physics (MSE Division)
AFOSR: YIP, Physical Science
DARPA: YFA, Microsystems Technology Office (MTO)
Army (ARO): YIP, Physics, Electronics, Material Science Division
DTRA: Basic & Applied Science
Northrop Grumman
...

My research group will be equipped with cutting-edge **nano** and **ultrafast** characterization capabilities based on the scanning probe optical techniques, including: 1) Nanoscale physical properties characterization with a spatial resolution down to ~ 10 nm. 2) Nano spectroscopy with frequency coverage from terahertz to visible. 3) Ultrafast optical and electronic characterization capability with ~ 40 fs temporal resolution.

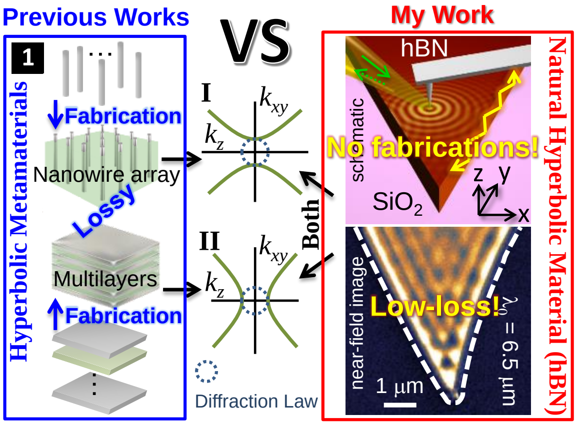
II. Research Accomplishments

UC San Diego (2011 – 2017, PhD Student in Condensed Matter Physics):
21 peer-reviewed papers (19 published + 2 under review): **6 first-author** publications: 1 in ***Science***, 1 in ***Nature Nano.***, 1 in ***Nature Comm.***, 1 in ***Nano Letters*** and 2 under review. 3 second-author publications (responsible for the experimental part): 1 in ***Nature Mater.***, 1 in ***Nano Letters*** and 1 in Imaging and Applied Optics.
1 awarded **Postdoc Fellowship**. 1 invited talk at **APS March Meeting**, 5 invited seminar talks.

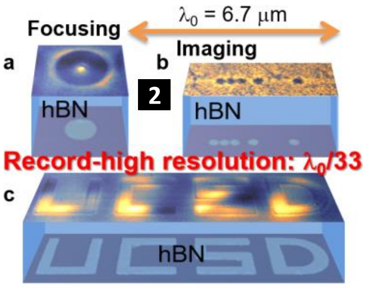
UT Austin (2017 – Present, Postdoc Fellow):
4 first-author publications: 1 in ***Adv Mater.***, 1 in ***Nano Letters***, 1 under review, 1 in preparation. 4 invited seminar talks.

I have been pioneering in nanoscale light-matter interaction with contributions in nanophotonics of van der Waals (vdW) materials[3, 4]. At UC San Diego, I worked on **fundamentals** of hybrid light-matter modes – the polaritons. My representative discoveries include natural hyperbolicity, phonon polaritons in hexagonal boron nitride (hBN)[5, 6], hybrid polaritons in graphene/hBN heterostructures[7] and 2D phonon polaritons in single atomic layer. At UT Austin, I worked on polaritonic **applications**. I have accomplished steering of propagating polaritons[8], tomographic material internal structure diagnosis with polaritons[9] and nano-optical lithography.

➢ **Natural Hyperbolicity** [Dai et al., ***Science***, 343, 1125 (2014)] **and Record-high-resolution Focusing and Imaging** [Dai et al., ***Nature Comm.***, 6, 6963 (2015)]

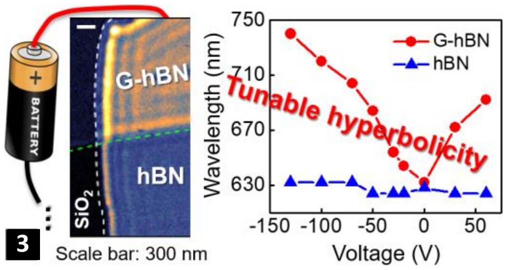


Electromagnetic hyperbolicity[10, 11] (Type I: $\varepsilon_z < 0$, $\varepsilon_{xy} > 0$, Type II: $\varepsilon_z > 0$, $\varepsilon_{xy} < 0$) is important[12-15] but is **previously** achieved **only** with **metamaterials** which request **sophisticated artificial fabrication** and are **lossy** due to the fabrication imperfection (Fig. 1 blue box). I discovered[5] that hBN crystal **naturally** (without any fabrication) possesses both I and II hyperbolicity thanks to the anisotropic phonons (lattice vibrations along *z* and in-plane directions). The hyperbolicity in hBN is low-lossy as demonstrated in the near-field image of hyperbolic phonon polaritons. Unlike plasmonic materials, phonon polaritonic media are **immune to electronic losses** and thus facilitate **longer propagation length** without the cost of losing optical confinement. By exciting high-momentum hyperbolic polaritons, I accomplished subdiffractional focusing[6] via hBN slab with a **record-high resolution** $\lambda_0/33$ (Fig. 2a). My result is deeply **below the diffraction limit** (~ $\lambda_0/2$) and is much smaller than **previous records** (~ $\lambda_0/10$) using metamaterial lens[14]. This originates from the high upper momentum cutoff of light set by the **interatomic spacing in natural lattices**. At another frequency, I achieved 1 to 1 image projection from the subsurface (Figs. 2b-c). These works embody a paradigm shift in the field of plasmonics, metamaterials and nanophotonics by searching new materials with low-cost and/or better functionalities.

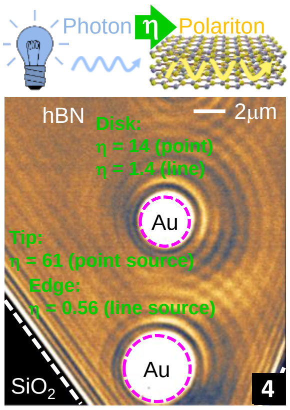


➢ **Tunable hyperbolicity and hybrid polaritons** [Dai et al., ***Nature Nanotech.***, 10, 682 (2015)]

While plasmons in graphene[16-22] and hyperbolic phonon polaritons in hBN[5, 23-26] exhibit exciting merits, they have certain **limitations** such as **loss** in graphene and **lack of tunability** in hBN. I built the concept of **polaritonic vdW metamaterials** in a hybrid structure of graphene on hBN (G-hBN)[7]. I discovered that plasmons and phonon polaritons got **strongly hybridized** in G-hBN. Remarkably, **monolayer** graphene can modify hyperbolic phonon polaritons in hBN as thick as **300 layers**. Hybrid polaritons in vdW metamaterial possess **combined virtues** from the components: they are **low-lossy** (hBN) and can be **tuned** by both electrostatic gating (graphene) and varying the structure thickness (hyperbolicity in hBN). This work uncovers a practical approach for vdW metamaterials for desired and intertwined electronic, plasmonic, phononic and/or excitonic properties[27, 28] by stacking various vdW materials.

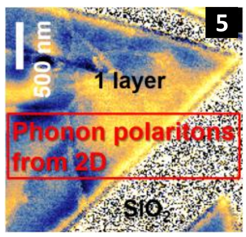


➢ **Polariton wave launching and launching efficiency** [Dai et al., ***Nano. Letters***, 17, 5285 (2017)]



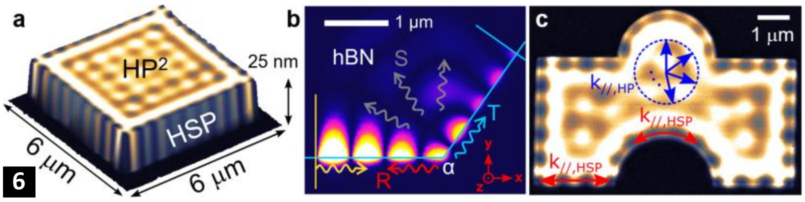
Both fundamental and application studies of plasmonics and nanophotonics requests **effective launching** and excitation of polaritonic waves. I led the experimental and theoretical investigation[29] of polariton launchers and **defined** the **concept** of **launching efficiency** – the ability to transfer photons into polaritonic electromagnetic waves. I found that polaritons can be practically launched from various types of sources (AFM tip, fabricated structure, crystal edge, defect and impurities). The launching efficiency was extracted from these sources to evaluate their performance. This work prompted a thorough understanding of nanoscale electromagnetic wave launching and extraction for convenient conversion between free space photons and strongly confined polaritons. Practical applications including nanoscale information/energy transfer[30], polaritonic/plasmonic circuits are rendered accessible through properly designed high-efficiency polariton launchers and extractors.

➢ **Single atomic layer surface phonon polaritons** [Dai et al., under review (2018)]



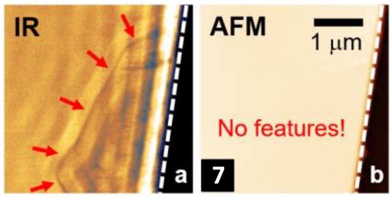
Dimension is primarily important for most scientific problems, the transition from 3D to 2D often delivers new physics and properties. While the studies of surface phonon polaritons all rely on bulk polar crystals, I observed **for the first time** phonon polariton modes from a **single atomic layer** of hBN[31]. Surface phonon polaritons supported in a **2D system** exhibit mode hardening effects and are fundamentally different than those in 3D hosts thus can allow a series of innovations in polaritonic science and application.

- **Manipulation and Steering of Nanoscale Electromagnetic waves** [[Dai et al., ***Adv Mater.*** 1706358 (2018)]]



Wave manipulation and steering is one of the most compelling emerging areas in metamaterials and applied photonics. Here I demonstrated[8] the **manipulation** of **reflection** (R), **transmission** (T) and **scattering** (S) of hyperbolic surface polaritons (HSPs) along sidewalls of the hBN slab by varying the corner angles (Figs. 6a-b). I also achieved a [9]**high-degree propagation steering** of HSPs via engineering the hBN slab geometry (Fig. 6c). The manipulation and steering of nano-polaritons in this work can facilitate advanced functionalities in photonics and metamaterials for nanoscale optical engineering, polaritonic circuits and communications.

- **Polariton Internal structure diagnosis/tomography** [[Dai et al., ***Nano. Letters***, 18, 5205 (2018)]]



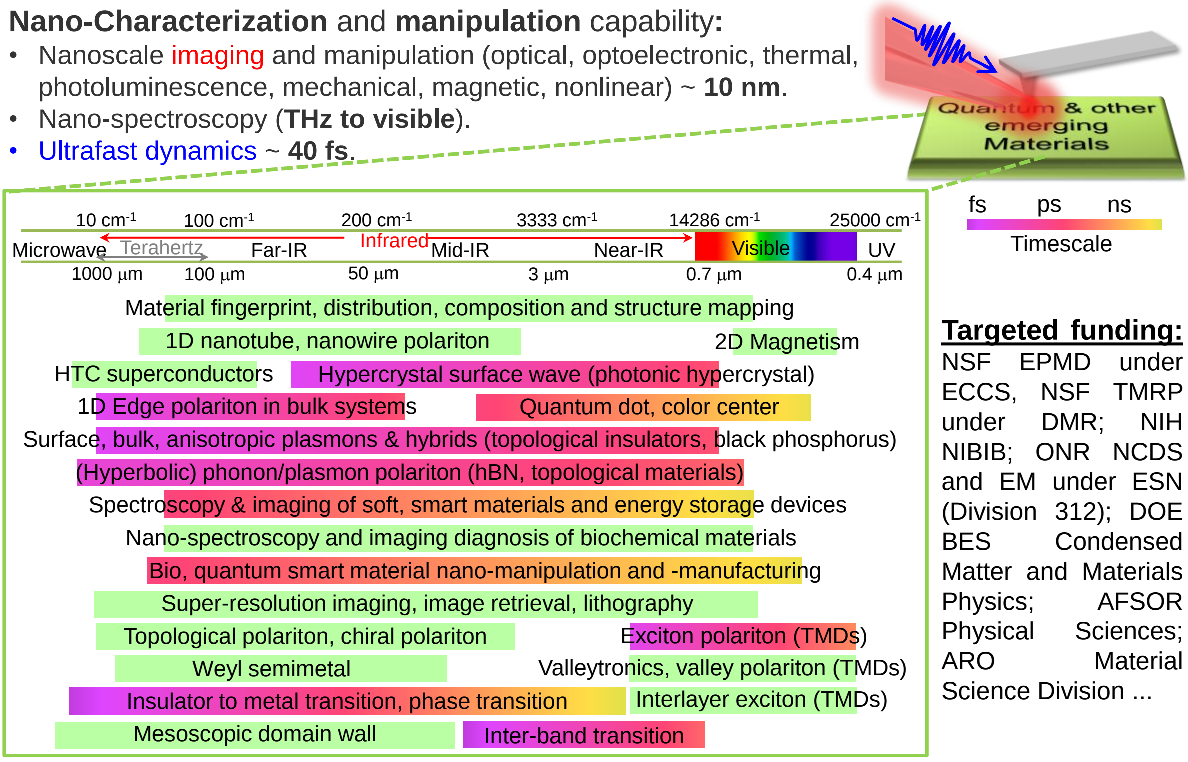
The superior properties of nano-polaritons hold great potential for practical applications. Utilizing the waveguided nature of hyperbolic polaritons, I accomplished the **internal structure diagnosis** (red arrows in Fig. 7a, no features in topography Fig. 7b) – a primary realization of polariton tomography[9]. Detailed analysis of the polariton features indicates the **position**, **size** and **geometry** of the buried object/defect. The polariton tomography is a **nondestructive** technique of diagnose inner structure with a sensitivity down to **few nanometers** and is envisioned to for next-generation bio-medical imaging, sensing and fine structure analysis.

III. Representative future research directions

- **Super-resolution and ultrafast dynamic imaging, spectroscopy and manipulation of quantum, bio and other emerging materials**

Background: Conventional material characterizations probe physical phenomena with a limited resolution, especially from the aspect of imaging and spectroscopy. Yet for emerging systems, such as quantum and biomedical materials, almost none of them are uniform at the lengthscale of micro and nanometers.

Based on the super resolution advantage of scanning probe optical technique in my lab, I plan to characterize quantum materials, biomedical samples and other emerging systems and perform nanoscale manipulation of them. I also propose to investigate dynamic response of emerging materials with combined super-resolution and ultrafast spectroscopy technique. Below are representative topics may be covered in this project.



Targeted funding agency: NSF Electronics, Photonics and Magnetic Devices (EPMD) program under the division of electrical, communications and cyber systems (ECCS), Topical Materials Research Program (TMRP) under the division of materials research (DMR); NIH National Institute of Biomedical Imaging and Bioengineering (NIBIB); ONR Nanoscale Computing Devices and Systems program (NCDS) and Electromagnetic Materials Program (EM) under electronics, sensors and networks research division (ESN, Division 312); DOE BES Condensed Matter and Materials Physics (MSE Division); AFSOR Physical Sciences Department; Army Research Office (ARO) Material Science Division.

- **Quantum nanophotonics, plasmonics and polaritonics**

Background: Quantum technologies and devices provide as the next generation information processing frontier. Nanophotonics and polaritonics investigating optics and light-matter interaction at ultimate small scales may miniaturize and improve current quantum devices in a hybrid fashion. On the other hand, nanophotonic phenomena, plasmons and polaritons can exhibit intriguing quantum effects at a reduced dimension or lengthscale.

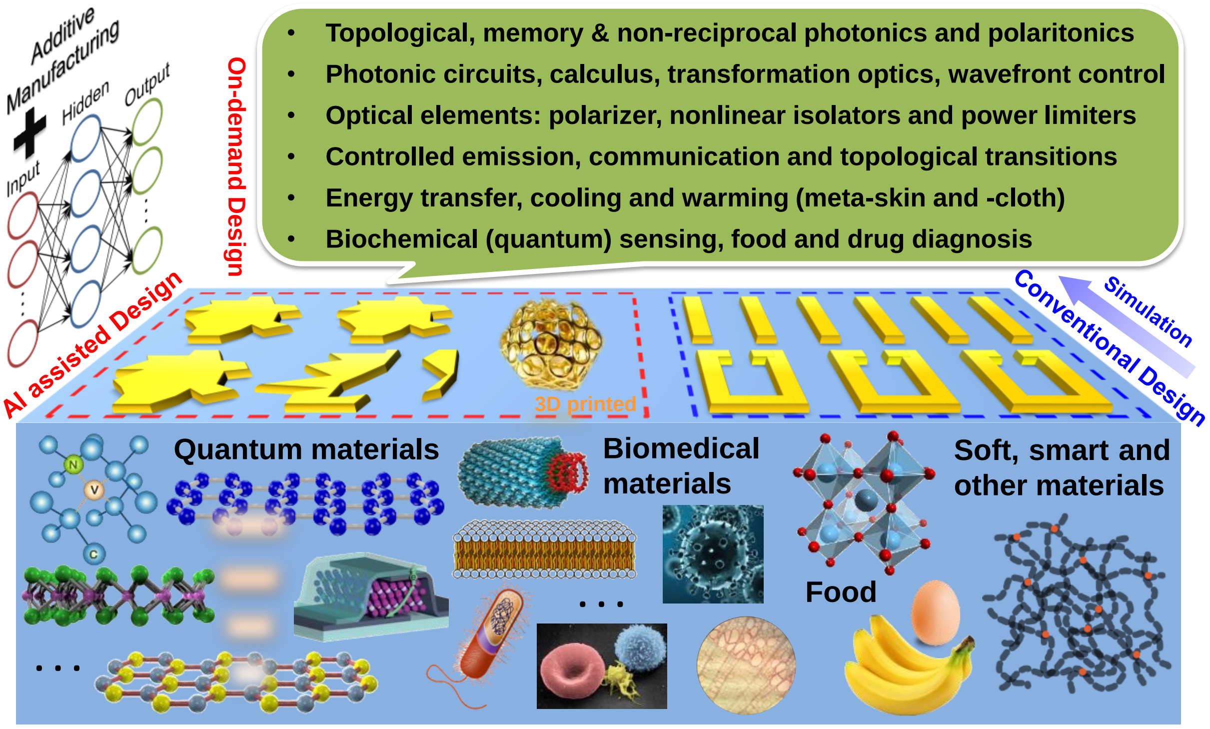
Prime examples of topics in this research project are: 1) Plasmon, polariton and electromagnetic hyperbolicity enhanced quantum emission and sensing; 2) Quantum and tunneling plasmonics and polaritonics in low-dimensional materials and engineered nanostructures; 3) Quantum polaritonic on-chip devices: entanglement, circuits, networks and communications; 4) Quantum polaritonic metasurfaces; 5) Polaritonic dissipation driven quantum dynamics.

Targeted funding agency: NSF DMR and CMMI; ONR NCDS and EM under ESN (Division 312); AFSOR Physical Sicenes; DARPA MTO.

- **Nanophotonic biochemical sensing, energy transfer and electromagnetic wave manipulation**

Background: Emerging materials with their unique physical properties provide as excellent choices for integrated nanodevices of tailored functionalities. On the other hand, current metamaterial and nanostructure design[2] is mainly based on scientists' intuition and is cost unfriendly especially for on-demand device design.

I propose to apply machine learning techniques to reduce the computation cost and design functional nanophotonic devices thanks to its advantage in straightforward back propagation. The designed nanostructures may also be fabricated with state-of-the-art additive manufacturing techniques. The proposed nanophotonic devices will combine emerging systems with conventional metallic elements for a variety of goals:



Targeted funding agency: NSF EPMD under ECCS, Thermal Transport Process program under the division of Chemical, Bioengineering, Environmental and Transport Systems (CBET); ONR Nanomaterials Program under Naval Materials (Division 332), Atomic, Molecular & Quantum Physics Program under ESN (Division 312); AFSOR Physical Sciences Department; ARO Electronics Division, Physics Division. DARPA Microsystems Technology Office (MTO); DTRA Basic and Applied Science Department; Northrop Grumman Foundation.

IV. Collaboration

The Physics Department at Texas Tech University provides a world-class environment for my career goals and proposed research. The physicists there conduct high-profile research on emerging material synthesis, electronic, magnetic, thermal as well as optical and photoelectron spectroscopy characterizations where my expertise in near-field optics and quantum materials can serve as a perfect complementation. I am eager to collaborate with faculties in emerging material synthesis, optics and plasmonics, biomaterials and biophysics, phase transformations, topological and quantum materials and theory and computation to attract external funding for our future research.

Reference:

1. Novotny, L. & Hecht., B. Principles of Nano-Optics. (Cambridge University Press, Cambridge; 2006).
2. Cai, W. & Shalaev, V. Optical Metamaterials: Fundamentals and Applications. (Springer, New York; 2010).
3. Basov, D.N., Fogler, M.M. & García de Abajo, F.J. Polaritons in van der Waals materials. *Science* **354** (2016).
4. Low, T. et al. Polaritons in layered two-dimensional materials. *Nat Mater* **16**, 182 (2016).
5. Dai, S. et al. Tunable Phonon Polaritons in Atomically Thin van der Waals Crystals of Boron Nitride. *Science* **343**, 1125-1129 (2014).
6. Dai, S. et al. Subdiffractional focusing and guiding of polaritonic rays in a natural hyperbolic material. *Nat Commun* **6** (2015).
7. Dai, S. et al. Graphene on hexagonal boron nitride as a tunable hyperbolic metamaterial. *Nat Nano* **10**, 682-686 (2015).
8. Dai, S. et al. Manipulation and Steering of Hyperbolic Surface Polaritons in Hexagonal Boron Nitride. *Advanced Materials* **30**, 1706358 (2018).
9. Dai, S. et al. Internal Nanostructure Diagnosis with Hyperbolic Phonon Polaritons in Hexagonal Boron Nitride. *Nano Letters* **18**, 5205-5210 (2018).
10. Poddubny, A., Iorsh, I., Belov, P. & Kivshar, Y. Hyperbolic metamaterials. *Nat Photon* **7**, 948-957 (2013).
11. Smith, D.R. & Schurig, D. Electromagnetic Wave Propagation in Media with Indefinite Permittivity and Permeability Tensors. *Physical Review Letters* **90**, 077405 (2003).
12. Hoffman, A.J. et al. Negative refraction in semiconductor metamaterials. *Nat Mater* **6**, 946-950 (2007).
13. Smith, D.R., Schurig, D., Mock, J.J., Kolinko, P. & Rye, P. Partial focusing of radiation by a slab of indefinite media. *Applied Physics Letters* **84**, 2244-2246 (2004).
14. Liu, Z., Lee, H., Xiong, Y., Sun, C. & Zhang, X. Far-Field Optical Hyperlens Magnifying Sub-Diffraction-Limited Objects. *Science* **315**, 1686 (2007).
15. Lu, D., Kan, J.J., Fullerton, E.E. & Liu, Z. Enhancing spontaneous emission rates of molecules using nanopatterned multilayer hyperbolic metamaterials. *Nat Nano* **9**, 48-53 (2014).
16. Chen, J. et al. Optical nano-imaging of gate-tunable graphene plasmons. *Nature* **487**, 77-81 (2012).
17. Fei, Z. et al. Gate-tuning of graphene plasmons revealed by infrared nano-imaging. *Nature* **487**, 82-85 (2012).
18. Ju, L. et al. Graphene plasmonics for tunable terahertz metamaterials. *Nat Nano* **6**, 630-634 (2011).
19. Brar, V.W., Jang, M.S., Sherrott, M., Lopez, J.J. & Atwater, H.A. Highly Confined Tunable Mid-Infrared Plasmonics in Graphene Nanoresonators. *Nano Letters* **13**, 2541-2547 (2013).
20. Fang, Z. et al. Gated Tunability and Hybridization of Localized Plasmons in Nanostructured Graphene. *ACS Nano* **7**, 2388-2395 (2013).
21. Yan, H. et al. Damping pathways of mid-infrared plasmons in graphene nanostructures. *Nat Photon* **7**, 394-399 (2013).
22. Gerber, J.A., Berweger, S., O'Callahan, B.T. & Raschke, M.B. Phase-Resolved Surface Plasmon Interferometry of Graphene. *Physical Review Letters* **113**, 055502 (2014).
23. Caldwell, J.D. et al. Sub-diffractional volume-confined polaritons in the natural hyperbolic material hexagonal boron nitride. *Nat Commun* **5** (2014).
24. Xu, X.G. et al. One-dimensional surface phonon polaritons in boron nitride nanotubes. *Nat Commun* **5** (2014).
25. Li, P. et al. Hyperbolic phonon-polaritons in boron nitride for near-field optical imaging and focusing. *Nat Commun* **6** (2015).
26. Yoxall, E. et al. Direct observation of ultraslow hyperbolic polariton propagation with negative phase velocity. *Nat Photon* **9**, 674-678 (2015).
27. Xia, F., Wang, H., Xiao, D., Dubey, M. & Ramasubramaniam, A. Two-dimensional material nanophotonics. *Nat Photon* **8**, 899-907 (2014).
28. Caldwell, J.D. et al. Atomic-scale photonic hybrids for mid-infrared and terahertz nanophotonics. **11**, 9 (2016).
29. Dai, S. et al. Efficiency of Launching Highly Confined Polaritons by Infrared Light Incident on a Hyperbolic Material. *Nano Letters* **17**, 5285-5290 (2017).
30. Boriskina, S.V., Ghasemi, H. & Chen, G. Plasmonic materials for energy: From physics to applications. *Materials Today* **16**, 375-386 (2013).
31. Dai, S. et al. Phonon Polaritons in Monolayer and Bilayer hexagonal boron nitride. *under review* (2018).