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**Nonequilibrium Electron and Phonon Thermal Transport Driven by External Fields: Towards In Situ Thermal Property Characterization of Active Devices**

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<b>14. ABSTRACT</b> The overarching objective of the proposed program is to demonstrate the effects of externally applied stimuli on thermal transport in materials and active devices, simulating the external loads and energetic excitations and particles that would be impinging on materials and devices in energetic plasma environments. This proposed work has two main goals: 1) experimental quantification of the role of externally applied stimuli and the resulting changes in metal/nonmetal interfacial energy barriers on thermal transport processes in metal thin films and at metal/non-metal interfaces; and 2) experimental quantification and computational simulation of the role of electrical and/or optical excitations on changes in the electron-phonon spectral energy landscape and thermal conductivity of materials. The overarching hypothesis driving this work is that externally applied stimuli and species that are present in plasma fields (e.g., electric fields, optical pulses, accelerated ions) can manipulate both carrier scattering rates and distributions, resulting in changes to thermal transport properties of materials. We culminated this program with the development for a method to measure the carrier scattering rates and temperature changes of surfaces when subjected to directed plasmas, which enabled the measurement of plasma cooling, in which an impinging plasma jet can be used to locally cool			
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The overarching objective of the proposed program is to demonstrate the effects of externally applied stimuli on thermal transport in materials and active devices, simulating the external loads and energetic excitations and particles that would be impinging on materials and devices in energetic plasma environments. This proposed work has two main goals: 1) experimental quantification of the role of externally applied stimuli and the resulting changes in metal/non-metal interfacial energy barriers on thermal transport processes in metal thin films and at metal/non-metal interfaces; and 2) experimental quantification and computational simulation of the role of electrical and/or optical excitations on changes in the electron-phonon spectral energy landscape and thermal conductivity of materials. The overarching hypothesis driving this work is that externally applied stimuli and species that are present in plasma fields (e.g., electric fields, optical pulses, accelerated ions) can manipulate both carrier scattering rates and distributions, resulting in changes to thermal transport properties of materials. We culminated this program with the development for a method to measure the carrier scattering rates and temperature changes of surfaces when subjected to directed plasmas, which enabled the measurement of plasma cooling, in which an impinging plasma jet can be used to locally cool a surface. We published 19 refereed journal publications and presented work from this project as part of 31 presentations during this reporting period (9 invited talks by Hopkins and 21 contributed talks/posters at conferences by Hopkins or students).

## Accomplishments

### **Research Objectives:**

The overarching objective of the proposed program is to demonstrate the effects of externally applied stimuli on thermal transport in materials and active devices, simulating the external loads and energetic excitations and particles that would be impinging on materials and devices in energetic plasma environments. This proposed work has two main goals:

- 1) experimental quantification of the role of externally applied stimuli and the resulting changes in metal/non-metal interfacial energy barriers on thermal transport processes in metal thin films and at metal/non-metal interfaces.
- 2) experimental quantification and computational simulation of the role of electrical and/or optical excitations on changes in the electron-phonon spectral energy landscape and thermal conductivity of materials.

The technical approach to achieve these goals are based on laser-based pump-probe techniques to selectively excite various carries in materials, and probe as a function of time the lifetime and temperature changes of these excited species. The approach in this work involved applying these pump-probe techniques to materials and devices in which additional external fields are applied to measure the temperature changes and roles of carrier excitations and interface scattering on the resulting properties to assess the role of electron-phonon and interfacial nonequilibrium. We applied these laser-based probes to materials and device architectures, including the development of a novel configuration in which we used a directed plasma excitation to excite the surface of a material and used laser probes to measure the resulting carrier dynamics and temperature changes. This is shown below in Figure 1.

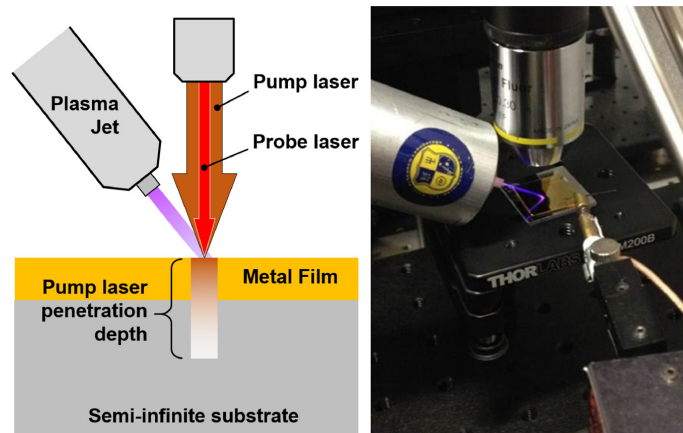


Figure 1. Schematic of typical material system that is interrogated with pump-probe laser technique. As part of this program, we developed the capability to integrate directed plasma jets into the pump-probe laser experiment to measure the role of plasma excitations on the nonequilibrium electron and phonon dynamics in materials. A picture of this experimental detection is shown on the right. Figure from *J. Appl. Phys.* 124, 043301 (2018).

## Accomplishments:

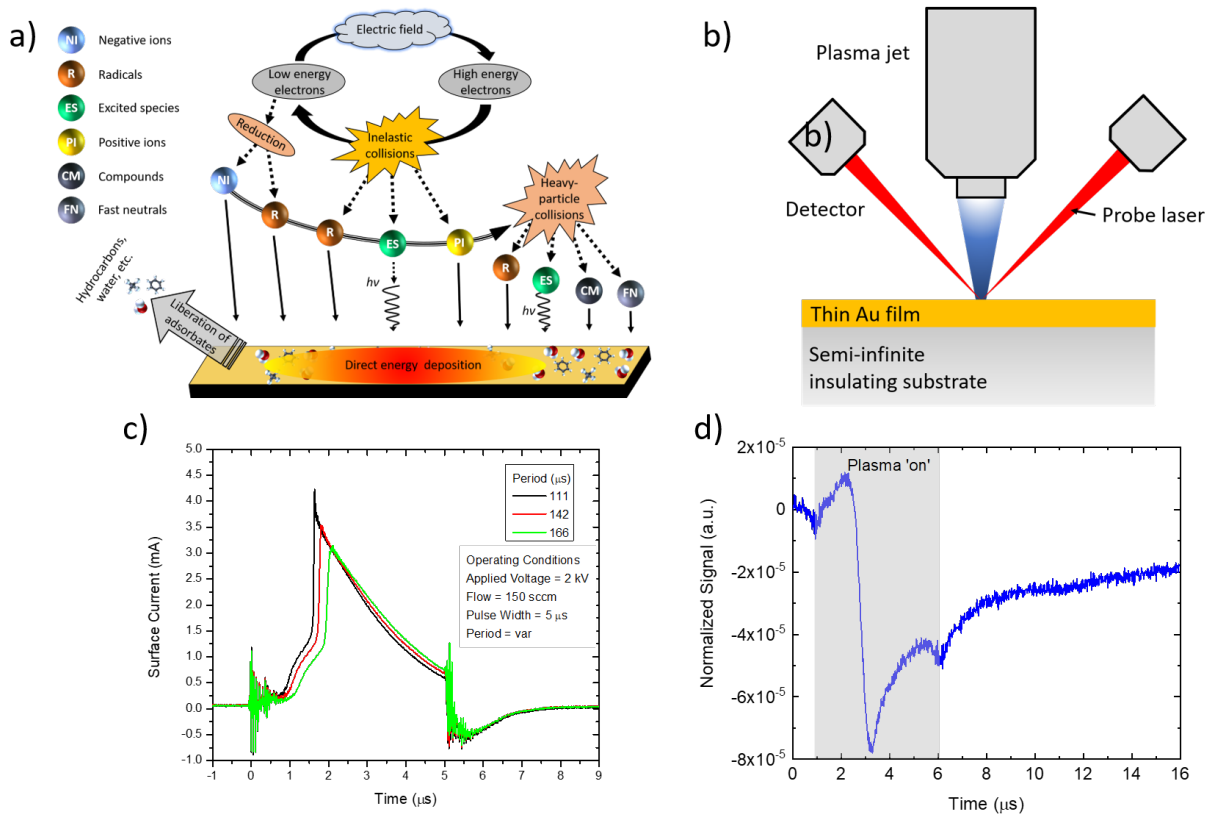
**1) Plasma Cooling:** Tomko, J.A., Johnson, M.J., Boris, D.R., Petrova, T.B., Walton, S.G., Hopkins, P.E., “Plasma-induced surface cooling,” *Nature Communications* **13**, 2623 (2022).

Our current understanding of energy delivery from a plasma to a material surface is guided using a variety of ancillary plasma diagnostics, steady-state temperature measurements, models, and post-treatment, *ex-situ* surface characterization to ‘re-construct’ energy deposition and absorption. More recently, *in-situ* materials characterization techniques have been developed that allow for real time or quasi-real time analysis. While certainly of value, none of these approaches provide a direct measure of the localized, transient response associated with the energy flux at the surface. To realize plasma cooling, the transient thermal response of a material to each energetic species in the plasma must be monitored to separate the localized and transient energy transport mechanisms from the spatially and temporally averaged net power transfer and temperature rise.

In this work, we experimentally demonstrate the ability of an incident plasma to cool the surface of a material. While seemingly counterintuitive that an incident beam of energy would lead to a decrease in surface temperature, this plasma cooling is enabled by the spectrum of different energetic processes that are intrinsic to directed plasma energy (Fig. 2a), which we show through time resolving the relative temperature changes occurring in a material exposed to a directed plasma *in situ* with nanosecond resolution. Our experiment relies on a pulsed atmospheric plasma jet incident upon an 80 nm Au film supported by a sapphire substrate. We simultaneously measure the reflectance of a continuous wave laser from the Au surface following the plasma-surface interaction (e.g., plasma pump - laser probe measurements); a simplified schematic of our experimental configuration is shown in Fig. 2b. For the operating conditions in this work, there are negligible laser-plasma interactions, and the reflected beam is not affected by any direct interactions. Rather, we rely on the strong thermorefectance coefficient of Au at visible wavelengths to directly measure the plasma-induced temperature rise on the Au surface by means of lock-in detection at the plasma jet repetition frequency, with the use of a periodic waveform analyzer to obtain nanosecond time resolution during the plasma-surface energy transfer process.

In considering plasma interactions, there is an incident flux containing various species including, but not particularly limited to, photons, ions, and neutrals, (Fig. 2a) which leads to a net electrical current from the jet to the plasma-exposed material. This phenomena can be measured as a net surface current, as shown for example in Fig. 2c for our experimental system. Likewise, as the reflectance of Au is linearly proportional to temperature, we can directly measure the temperature rise induced by the flux of these various species; an example of our measured thermorefectance data is shown in Fig. 2d. As is the case for these example data of surface current above, this thermorefectance data is measured for a voltage across the electrodes in the plasma

jet that has a 5  $\mu\text{s}$  duration; this voltage width will henceforth be considered the plasma 'pulse-width.' Note, the thermorefectance coefficient for this laser wavelength (637 nm) is negative, and thus surface heating corresponds to a decrease in measured reflectance .

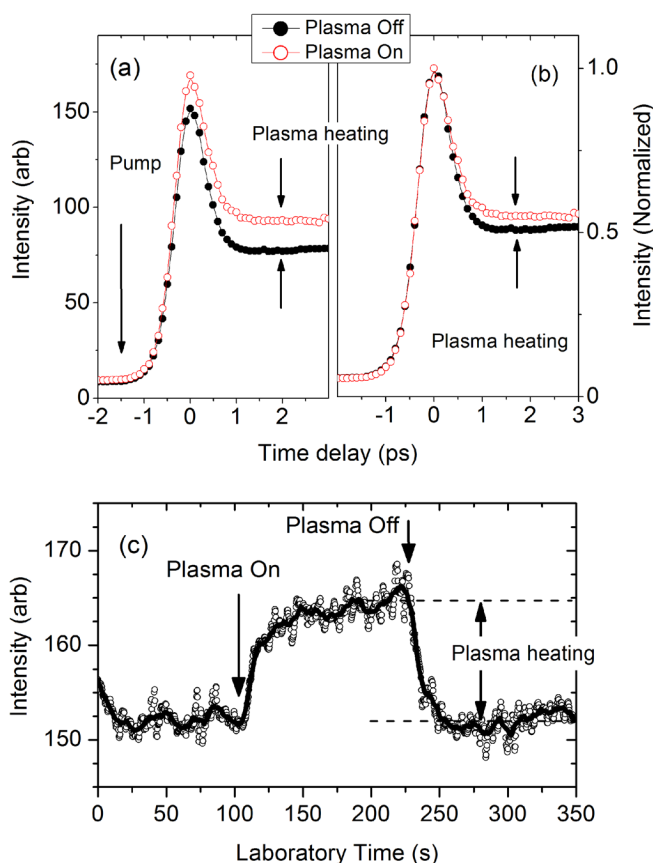


**Figure 2. a) Experimental schematic. A pulsed atmospheric plasma jet bombards an Au surface, while a continuous wave laser monitors the thermorefectance of the Au surface to gain insight to the plasma-surface energy transfer mechanisms. c) Measured thermorefectance as a function of time for a 5  $\mu\text{s}$  plasma pulse and d) the measured surface current at the Au film.**

**2) Development of capability to probe ultrafast electron-phonon response and spatial distribution of energy transfer during plasma excitation:** Walton, S.G., Foley, B.M., Tomko, J., Boris, D.R., Gillman, E.D., Hernandez, S.C., Giri, A., Petrova, Tz.B., Hopkins, P.E., "Plasma-surface interactions in atmospheric pressure plasmas: In situ measurements of electron heating in materials," *Journal of Applied Physics* **124**, 043301 (2018). \*Editor's Pick

The energy flux to a surface during plasma exposure and the associated surface heating are of long standing interest as they contribute to the physico-chemical changes that occur during plasma-based materials synthesis and processing. Indeed, the energy delivered to the surface, via a flux of particles and photons, in concert with a flux of reactive species serves to chemically modify, etch, and/or deposit materials, with an efficacy that depends on the plasma processing environment. A unique feature of

plasma synthesis and processing is that most of the delivered energy is absorbed at or very near the surface over short (picosecond) time scales. The dissipation of thermal energy proceeds through electron-electron and/or electron-phonon interactions as they propagate through the material, with relaxation time scales that can be orders of magnitude slower. Typically then, the surface is not in thermal equilibrium with the bulk material. Fast, surface-sensitive techniques are thus required to fully appreciate the dynamics of the plasma-surface interaction. In this work, we employ pump-probe Time-Domain Thermorefectance, a surface sensitive technique typically used to measure thermal properties of thin films, to determine electron heating of thin metal films during exposure to an atmospheric pressure plasma jet. The results, in conjunction with current measurements, are used to develop a first order understanding of plasma jet-surface interactions. The results show that the energy delivered by the plasma jet causes a localized increase in electron energy within the thin film over an area commensurate with the plasma jet radius.



**Figure 3. TDTR measurements showing the effect of the plasma jet. (a) TDTR signal intensity as a function of pump-probe delay time with and without the plasma jet operating and (b) those signals after normalizing to the peak intensity. The latter illustrates the differences in signals after accounting for any experimental variations. (c) The peak TDTR signal with and without plasma running as a function of lab time (real time). The solid line is the raw data (open symbols) after smoothing. The measurements employ an AC-driven jet and the material is 200 nm thick Au films on Si substrates. The laser and jet spots at the surface are co-aligned.**

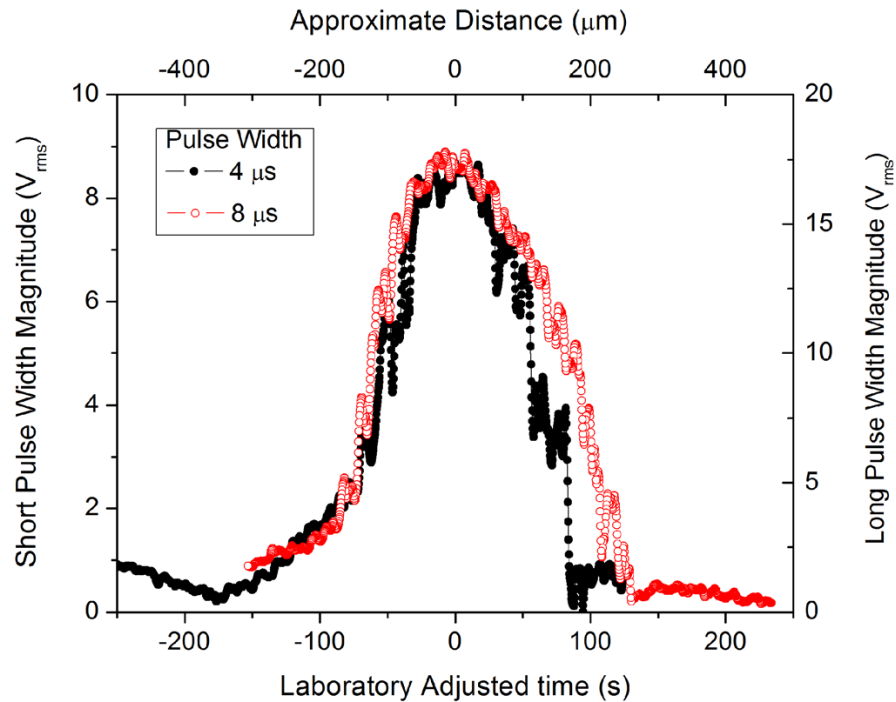


Figure 4. The change in plasma-driven thermorefectance as a function of position for pulsed (10kHz) jets with pulsed widths of 4 $\mu$ s and 8 $\mu$ s. The left ordinate corresponds to the signal intensity of the probe laser response when the pulse width is 4 $\mu$ s, while the right corresponds to the signal intensity when the pulse width is 8 $\mu$ s. Note the factor of 2 difference in intensity along with a slightly broader profile when the pulse width is 8 $\mu$ s.

### **3) Extremes in electron-phonon coupling in metals and metal alloys during conditions of strong nonequilibrium**

Giri, A., Tokina, M.V., Prezhdov, O.V., Hopkins, P.E., "Electron-phonon coupling and related transport properties of metals and intermetallic alloys from first principles," *Materials Today Physics* **12**, 100175 (2020).

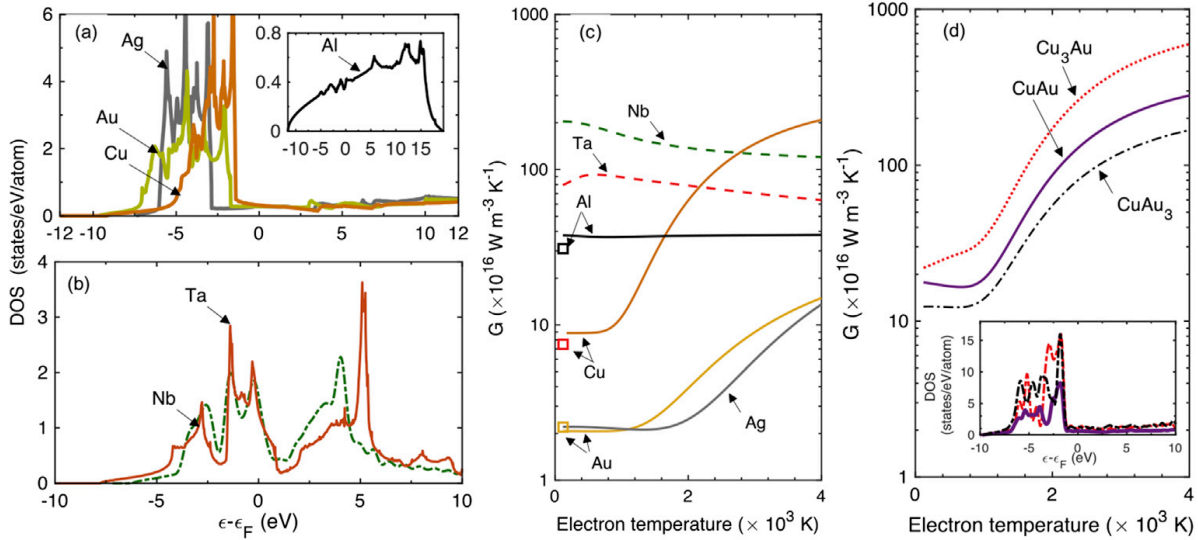
The fundamental scattering mechanisms between electrons and phonons in metals and metallic alloys dictate a wide range of phenomena in their materials' physics. Using first-principles calculations carried out on dense electron and phonon wavevector grids, we determine the mode-level descriptions of electron-phonon interactions for nine characteristic metals, shedding light on their electrical and thermal transport properties at a range of electron and phonon temperatures. Our results reveal that even though there are similarities between the phonon densities of states of various simple metals, the electronic structure can significantly affect the modal contributions to electron-phonon coupling in metals.

We find that even though the phonon density of states for Al resembles closely the density of states of the noble metals (Au, Ag, and Cu), the spectral functions and the contributions from the longitudinal and transverse phonon modes vary drastically be-

tween these metals; the longitudinal contribution to electron-phonon coupling in Al is almost twice that of the noble metals. We attribute this to the drastically different electronic density of states for the free-electron-like Al in comparison to the noble metals with high density of d-bands close to the Fermi level. For the intermetallic copper-gold alloys and the superconducting metals (Nb and Ta), the peaks in the Eliashberg spectral functions are mostly dictated by their corresponding phonon density of states. The electron temperature-dependent volumetric electron-phonon coupling factors are also calculated for the metals and the results demonstrate that  $G$  can either increase (as in the case of Au, Ag, Cu, copper-gold alloys) or decrease (as in the case of Nb and Ta), or it can also demonstrate a non-monotonic change (as in the case of Al) as a function of electron temperature, depending on the electronic structures of the metals. For the alloys, the electron-phonon coupling strength,  $\lambda$ , and the volumetric electron-phonon coupling parameter,  $G$ , cannot be taken as the geometric mean of the two metals and are relatively much larger than that of their elemental constituents. We also find that the electron thermal conductivity of the 50/50 CuAu alloy is relatively higher than that of  $\text{Cu}_3\text{Au}$  and  $\text{CuAu}_3$ , and the electron thermal conductivities of the 25/75 and 75/25 alloys are similar to experimental measurements of disordered copper-gold alloys with the same compositions.

As a snapshot of our results, Fig. 5 shows electron temperature on the volumetric electron-phonon coupling factor. Figure 5 a – d show our calculations of the electronic density of states and  $G$  for the elemental metals and the copper-gold alloys as a function of electron temperature up to 4,000 K. In Fig. 5c, we also include the room-temperature measurements of  $G$  for Al, Au, and Cu from pump-probe thermoreflectance measurements for comparison with our calculations. Overall, the calculations agree very well with the pump-probe experimental results at room temperature for three metals. Note, experimental results at relatively high electron temperatures are non-existent in literature, which is mostly due to the lack of analytical formulations (that can be applied beyond the Drude approximations) to correctly interpret the results from pump-probe thermoreflectance experiments, a problem we are currently working on as part of this program. For Al,  $G$  is independent of electron temperature, which is characteristic of the free-electron-like density of states of Al (see inset of Fig. 5a). For the rest of the metals with d-band electrons, at relatively weak thermal excitations, where the density of states is similar to the free-electron gas model with negligible d-band excitation,  $G$  is independent of temperature. However, at relatively large thermal excitations, significant d-band electrons can be excited resulting in a sharp increase in  $G$ . The d-band electrons in Au, Cu, and their alloys (as shown in Fig. 5a and inset of Fig. 5d, respectively) lie  $\sim 2$  eV below the Fermi energy, therefore  $G$  starts to increase at electron temperatures of  $\sim 3000$  K. However, for Ag,  $G$  remains relatively constant below and electron temperature of  $\sim 5000$  K since the d-bands are located  $\sim 3$  eV below the Fermi energy as shown in Fig. 5a. In contrast to the aforementioned metals,  $G$  decreases monotonically with electron temperature for the transition metals. This can be attributed to the fact that both Nb and Ta have a wider electron energy spectrum (with  $\sim 10$  eV window around Fermi level) and a local dip in the density of states around the Fermi level as shown in Fig. 5b.

These results have major implications in the thermal conductivity of metals subjected to high energy, pulsed interactions, such as those experienced in space, during an intense blast or high-Mach number re-entry, or in any plasma environment, where the electrons experience a strong degree of nonequilibrium from short and intense energy fluxes.



**Figure 5.** The electronic density of states for (a) Au, Cu, Ag, Al (inset), (b) Ta, and Nb as calculated from electronic structure performed with Quantum Espresso package. Volumetric electron-phonon coupling factor,  $G$ , for (c) the elemental metals along with experimental data for Al, Cu, and Au, and (d) copper-gold alloys as a function of electron temperature. The electronic density of states for the alloys are also shown in the inset.

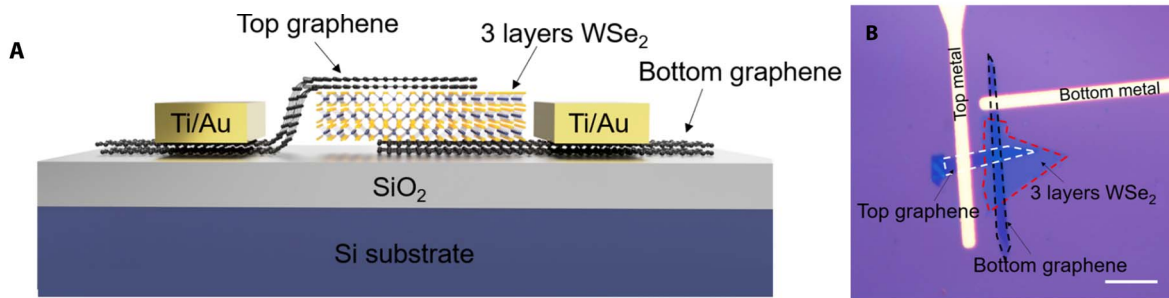
#### **4) Nonequilibrium heat transfer across interfaces during thermionic transport:**

Rosul, Md. G., Lee, D., Olson, D.H., Liu, N., Wang, X., Hopkins, P.E., Lee, K., Zebarjadi, M., "Thermionic transport across gold-graphene-WSe<sub>2</sub> van der Waals heterostructures," *Science Advances* **5**, eaax7827 (2019).

Solid-state thermionic (SSTI) power generators can be viewed as intermediate between vacuum-state thermionic converters and thermo-electric power generators. Like many other heat engines, these devices can work either as power generators where they convert input heat to electricity or as coolers where applied electricity is used to pump heat. These devices are made by inserting a semiconducting layer between metallic electrodes. The semiconducting layer forms an energy barrier for charge carriers, allowing only hot ones to pass. This current flow is referred to as thermionic current. The SSTI devices are similar to vacuum-state thermionic ones wherein the vacuum is replaced by the semiconducting layer. Because of the lower energy barrier, the SSTI devices operate at temperatures much smaller than the vacuum-state thermionic devices. The SSTI devices are also very similar to thermoelectric devices. The most important difference is that the thermionic transport in SSTI devices is ballistic, whereas the thermoelectric transport is diffusive. In SSTI converters, to maintain ballistic transport of the hot electrons, the semiconducting layer thickness,  $L$ , should be equal or less than the electron mean free path. On the other hand, a minimum length is needed

to suppress the tunneling of electrons, which is undesirable because low-energy electrons (with energies smaller than the chemical potential) act as holes and lower the efficiency of the electron transmitting device. Additionally, the efficiency of SSTI devices is inversely related to the thermal conductance across the device, and thus the thermal resistance of this ballistic device and the thermal resistances at the contacts, which experience varying degrees of electron-phonon nonequilibrium, are of utmost importance to minimize to increase conversion efficiency.

In this work, We study thermionic cooling across gold-graphene- WSe<sub>2</sub>-graphene-gold structures shown in Fig. 6. The measured Seebeck coefficient, thermal and electrical conductance, and ZT values at room temperatures are in agreement with the theoretical predictions using first-principles calculations combined with real-space Green's function formalism. This work lays the foundation for development of efficient thermionic devices.



**Fig. 6. Au-Gr-3WSe<sub>2</sub>-Gr-Au device.** (A) Illustration of the cross-section of the Au-Gr-3WSe<sub>2</sub>-Gr-Au structure. The three layers of WSe<sub>2</sub> flake are sandwiched by top and bottom graphene layers on a Si/SiO<sub>2</sub> substrate, and contact metals (Ti/Au) are deposited on top and bottom graphene layers. (B) Optical microscope image of an Au-Gr-3WSe<sub>2</sub>-Gr-Au device. The three layers WSe<sub>2</sub>, top graphene, and bottom graphene are highlighted by red, white, and black dashed lines, respectively. Scale bar, 20  $\mu\text{m}$ .

For the device shown in Fig. 6, We used TDTR to characterize the conductance of the Gr-3WSe<sub>2</sub>-Gr structure. We first coated a nominal 80-nm Al transducer onto our Gr-3WSe<sub>2</sub>-Gr structure, which had been mechanically exfoliated previously onto silicon with a thermal oxide of 300 nm. The thickness of the Al was confirmed via pico-second acoustics, while its thermal conductivity was determined from reference specimens placed near the Gr-3WSe<sub>2</sub>-Gr sample during deposition. The effective  $1/e^2$  pump/probe radius is  $\sim 1.5 \mu\text{m}$ . The measured conductance at the Al-Gr-SiO<sub>2</sub> interface was found to be  $20 \text{ MW m}^{-2} \text{ K}^{-1}$ , while that of the Al-Gr-3WSe<sub>2</sub>-Gr-SiO<sub>2</sub> interfaces was  $9 \text{ MW m}^{-2} \text{ K}^{-1}$ . Because these two measurements reflect the series resistances of the structures, we can use these values to determine the thermal conductance of the Gr-3WSe<sub>2</sub>-Gr structure alone. Doing so allowed us to extract a conductance of  $17 \text{ MW m}^{-2} \text{ K}^{-1}$  for the structure.

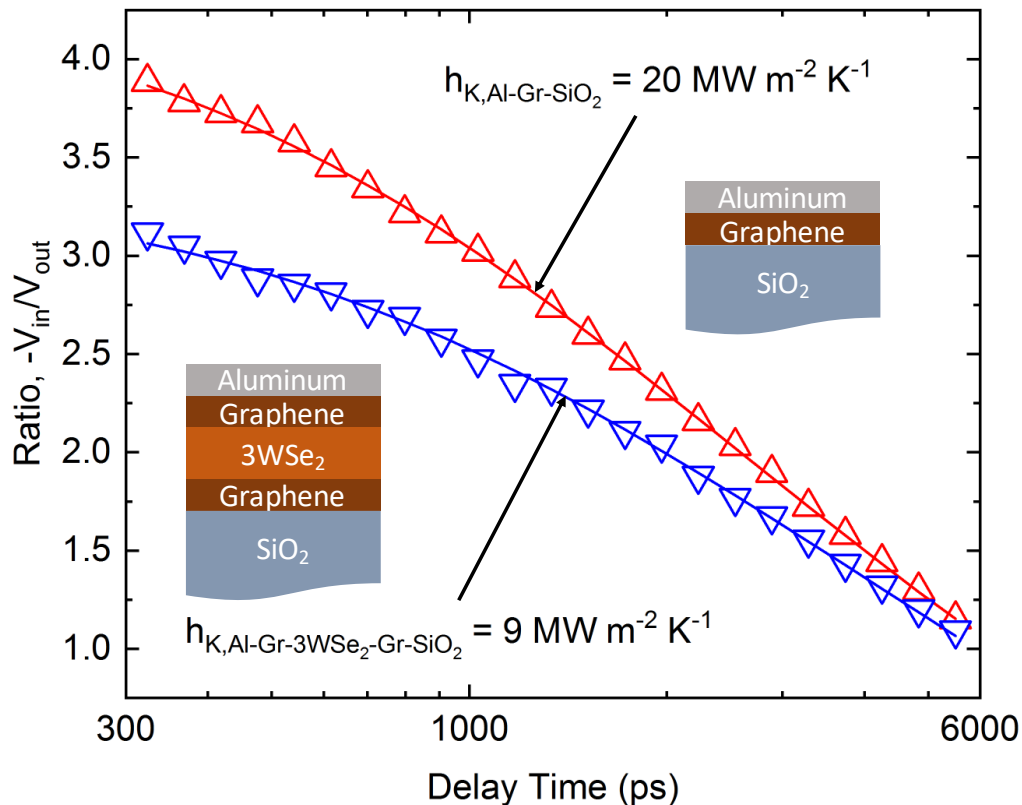


Fig. S1. TDTR measurement. Best fits for the Al-Gr-SiO<sub>2</sub> and Al-Gr-3WSe<sub>2</sub>-Gr-SiO<sub>2</sub> interfacial regions.

**Dissemination:**

**Refereed Journal Papers: 19 published over lifetime of grant**  
**Notes: 1 Editors Pick, 2 in *Science Advances*, 2 in *Nature Communications*,  
 1 *Nano Letters***

Walton, S.G., Foley, B.M., Tomko, J., Boris, D.R., Gillman, E.D., Hernandez, S.C., Giri, A., Petrova, Tz.B., Hopkins, P.E., "Plasma-surface interactions in atmospheric pressure plasmas: In situ measurements of electron heating in materials," *Journal of Applied Physics* **124**, 043301 (2018). \*Editor's Pick

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Aryana, K., Gaskins, J.T., Nag, J., Stewart, D.A., Bai, Z., Mukhopadhyay, S., Read, J.C., Olson, D.H., Høglund, E.R., Howe, J.M., Giri, A., Grobis, M.K., Hopkins, P.E., "Interface controlled thermal properties of ultra-thin chalcogenide-based phase change memory devices," *Nature Communications* **12**, 774 (2021).

Tomko, J.A., Johnson, M.J., Boris, D.R., Petrova, T.B., Walton, S.G., Hopkins, P.E., "Plasma-induced surface cooling," *Nature Communications* **13**, 2623 (2022).

### **Presentations: 34 over lifetime of grant**

#### *Invited Talks by Hopkins (13 total)*

"Role of ballistic electron transport and electron-injection on thermal conductance across metal/non-metal interfaces," Panel on Fundamentals of Non-Equilibrium Transport, 2018 ASME International Mechanical Engineering Congress and Exposition, Pittsburgh, PA, November 9 – 15, 2018.

"Emergent phonon thermal transport properties in dielectric and ferroelectric materials," 2018 ISAF-FMA-AMF-AMEC-PFM Joint Conference (IFAAP 2018), Hiroshima, Japan, May 27 – June 1, 2018.

"Ultrafast electron-phonon and plasmon scattering effects in metals, non-metals and interfaces probed with tunable wavelength sub-picosecond pulses," 2019 Materials Research Society Spring Meeting, Phoenix, April 22 – 26, 2019.

“Actively and passively controlling the thermal conductivity of materials,” Institute for Applied Materials – Applied Materials Physics, Karlsruhe Institute of Technology, Karlsruhe, Germany, August 20, 2019.

“Phonon heat transport processes and thermal conductivity of II-Oxide and III-V superlattices: Wave-like coherent transport in  $\text{CaTiO}_3/\text{SrTiO}_3$  superlattices and ballistic diffusive transport in GaAs/AlAs superlattices,” 235<sup>th</sup> ECS Meeting, Dallas, TX, May 26 – 30, 2019.

“Controlling heat and light in chemically modified materials,” Department of Chemistry Seminar, University of Illinois Urbana-Champaign (UIUC), Champaign, Illinois, March 4, 2020.

“Thermal boundary resistances at WBG material interfaces: defect, structure and processing effects,” UWBG RF Virtual Workshop, Virtual, May 14, 2020.

“Thermal conductivity and heat transport processes in ion irradiated and laser heated solids,” TMS 2021, Virtual, March 15-18, 2021.

“Interfacial coupling across solid/liquid, solid/gas and solid/plasma interfaces,” XXIX International Materials Research Conference (IMRC 2021), Virtual, August 16, 2021.

“Ultrafast Infrared Pump-probe Measurements for Time Domain Measurements of Electron, Phonon and Polariton (Plasmon and Phonon) Relaxation,” 2021 Materials Research Society (MRS) Fall Meeting, November 29 – December 2, 2021.

“Ultrafast electron, phonon and infrared polaritonic thermal transport across thin films and interfaces,” Department of Physics Seminar Series, Missouri University of Science and Technology – Missouri S&T, Virtual, October 28, 2021.

“Ultrafast pump-probe measurements of electron, phonon and infrared polaritonic coupled thermal transport across interfaces,” Swiss Federal Laboratories for Materials Science and Technology (EMPA) Seminar Series, October 5, 2021.

“Steady-state thermorelectance on electronic components,” Thermtest webinar, Virtual, May 4, 2021.

*Contributed Conference Talks by Hopkins and/or Students (12 total)*

DeCoster, M., Gaskins, J.T., Hopkins, P.E., Chen, X., Baumgart, H., “The effects of nano-structuring on the thermal conductivity of PbTe/PbSe superlattice thin films,” ASME 2018 International Technical conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems (InterPACK), San Francisco, CA, August 27 – 30, 2018.

Hopkins, P.E., Ghosh, A.W., Poon, S.J., Cheaito, R., Polanco, C., Balakrishnan, G., Donovan, B.F., "Ballistic transport of long wavelength phonons in superlattices and nanograined alloys," ASME 2018 International Technical conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems (InterPACK), San Francisco, CA, August 27 – 30, 2018.

Scott, E.A., Gaskins, J.T., Hopkins, P.E., Hattar, K., Goorsky, M., "Phonon scattering effects in the thermal conductivity reduction of ion irradiated diamond," ASME 2018 International Technical conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems (InterPACK), San Francisco, CA, August 27 – 30, 2018. (Best Poster Presentation).

DeCoster, M.E., Chen, X., Zhang, K., Baumgart, H., Hopkins, P.E., "Thermal conductivity of ALD grown PbTe/PbSe superlattice thin films," 2018 ASME International Mechanical Engineering Congress and Exposition (IMECE), Pittsburgh, PA, November 9 – 15, 2018.

Aryana, K., Rastgar, R., Olson, D., Gaskins, J., Giri, A., Norris, P.M., Hopkins, P.E., "The effect of adhesion layer on the thermal boundary conductance," 2018 ASME International Mechanical Engineering Congress and Exposition (IMECE), Pittsburgh, PA, November 9 – 15, 2018. (Poster)

Hopkins, P.E., Walton, S., Foley, B.M., Tomko, J.A., Boris, D.R., Gillman, E.D., Hernandez, S.C., Giri, A., Petrova, T.B., "Plasma-surface interactions in atmospheric pressure plasmas: In situ measurements of electron heating in materials," Pacific Rim Symposium on Surfaces, Coatings & Interfaces (PACSURF), Waikoloa Beach, Hawaii, December 2 – 6, 2018. (Poster)

DeCoster, M.E., Chen, X., Zhang, K., Baumgart, H., Hopkins, P.E., "Thermal conductivity of PbTe/PbSe superlattice thin films," Electronic Materials and Applications 2019 (EMA 2019), Orlando, FL, January 23 – 25, 2019.

Scott, E.A., Hattar, K., Goorsky, M., Hopkins, P.E., "Phonon scattering from mass impurities and strain fields in ion irradiated silicon and diamond," Electronic Materials and Applications 2019 (EMA 2019), Orlando, FL, January 23 – 25, 2019

Koh, Y.R., Gaskins, J.T., Braun, J.L., Hopkins, P.E., "Characterization of 2D surface acoustic waves in silicon gratings via time-domain thermoreflectance (TDTR)," 2019 Materials Research Society Spring Meeting, Phoenix, April 22 – 26, 2019 (Poster).

DeCoster, M.E., Chen, X., Zhang, K., Baumgart, H., Hopkins, P.E., "Thermal conductivity of ALD grown PbTe/PbSe superlattices thin film," 2019 Materials Research Society Spring Meeting, Phoenix, April 22 – 26, 2019 (Poster).

Kelliher, A.P., DeCoster, M., Hopkins, P.E., “Understanding thermal transport of gold nanorods in vitro for photothermal cancer therapy,” 2019 Materials Research Society Spring Meeting, Phoenix, April 22 – 26, 2019 (Poster).

Scott, E., Hattar, K., Taylor, C., Gaskins, J.T., Bai, T., Wang, Y., Ganski, C., Goorsky, M., Hopkins, P.E., “Phonon scattering effects in the thermal conductivity reduction of ion irradiated diamond,” 2019 Materials Research Society Spring Meeting, Phoenix, April 22 – 26, 2019 (Poster).

Aryana, K., Gaskins, J.T., Nag, J., Grobis, M., Hopkins, P.E., “Thermal properties of non-volatile phase change memories at device length scales,” 235<sup>th</sup> ECS Meeting, Dallas, TX, May 26 – 30, 2019.

Olson, D., Zhu, H., Granzier-Nakajima, T., Terrones, M., Hopkins, P.E., “Substitutional Nitrogen Defects Enhance Thermal Transport across Graphene Interfaces,” 235<sup>th</sup> ECS Meeting, Dallas, TX, May 26 – 30, 2019.

Scott, E.A., Smith, S.W., Henry, M.D., Rost, C.M., Giri, A., Gaskins, J.T., Fields, S.S., Jaszewski, S.T., Ihlefeld, J.F., Hopkins, P.E., , “Thermal conductivity and heat capacity of dielectric and ferroelectric hafnium zirconium oxide thin films,” Joint ISAF-ICE-EMF-IWPM-PFM Joint Conference, Lausanne, Switzerland, July 14 – 19, 2019.

Scott, E.A., Hattar, K., Braun, J., Rost, C.M., Gaskins, J.T., Bai, T., Wang, Y., Ganski, C., Fazli, M., Esfarjani, K., Goorsky, M., Hopkins, P.E., “Thermal property manipulation through ion implantation of crystalline materials,” The 2<sup>nd</sup> Pacific Rim Thermal Engineering Conference (PRTEC2019), Maui, Hawaii, December 13-17, 2019.

Aryana, K., Nag, J., Grobis, M., Read, J., Gaskins, J.T., Olson, D.H., Hoglund, E., Howe, J., Hopkins, P.E., “Electron and phonon thermal conductance in ultra-thin (<40 nm) Ge<sub>2</sub>Sb<sub>2</sub>Te<sub>5</sub> layers in phase change memory devices,” Electronic Materials and Applications 2020 (EMA 2020), Orlando, FL, January 22 – 24, 2020.

Giri, A., Hopkins, P.E., “Experimental and computational advances in thermal boundary conductance and nanoscale thermal transport across solid interfaces,” Electronic Materials and Applications 2020 (EMA 2020), Orlando, FL, January 22 – 24, 2020.

Galib, R., Olson, D.H., Tomko, J.A., Giri, A., Gaskins, J.T., Hopkins, P.E., “Excited carrier relaxation in GaAs by mid-IR pump-probe spectroscopy,” APS March Meeting 2020, Virtual, March 2 – 6, 2020.

Aryana, K., Gaskins, J.T., Nag, J., Stewart, D.A., Bai, Z., Mukhopadhyay, S., Read, J.C., Olson, D.H., Hoglund, E.R., Howe, J.M. and Giri, A., Grobis, M., Hopkins, P.E., “Thermal Properties of Carbon Nitride Toward Use as an Electrode in Phase Change Memory Devices,” 2020 Materials Research Society (MRS) Fall Meeting, Virtual, November 2020.

Aryana, K., Gaskins, J.T., Nag, J., Stewart, D.A., Bai, Z., Mukhopadhyay, S., Read, J.C., Høglund, E.R., Olson, D.H., Howe, J.M., Giri, A., Grobis, M.K., Hopkins, P.E., "Thermal Properties of Carbon Nitride Toward Use as an Electrode in Phase Change Memory Devices," 2020 Virtual Materials Research Society Spring/Fall Meeting, Virtual, November 27 – December 4, 2020.

**Presentations: 34 over lifetime of grant**

## Impacts

This work resulted in the emergence of a new diagnostic that will enable deeper understanding of plasma-surface interactions. Specifically, the ability to combine laser heating and probing with plasma sources unlocks the possibility of probing the plasma-surface dynamics with temporal resolution on the order of picoseconds. This will result in the ability to unlock a deeper understanding into how different energetic species in a plasma exchange energy with electron and phonons in a solid. This advanced diagnostic is detailed in the following two papers from this program that are also outlined above

Tomko, J.A., Johnson, M.J., Boris, D.R., Petrova, T.B., Walton, S.G., Hopkins, P.E., "Plasma-induced surface cooling," *Nature Communications* **13**, 2623 (2022).

Foley, B.M., Tomko, J., Boris, D.R., Gillman, E.D., Hernandez, S.C., Giri, A., Petrova, Tz.B., Hopkins, P.E., "Plasma-surface interactions in atmospheric pressure plasmas: In situ measurements of electron heating in materials," *Journal of Applied Physics* 124, 043301 (2018). \*Editor's Pick

This advance not only has major impacts in the fields of thermal transport and materials science, but also has major impacts in plasma physics disciplines.