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6. AUTHORS
David Cahill

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7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
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14. ABSTRACT
We applied frequency-dependent measurements of thermal transport properties using time-domain thermoreflectance (TDTR) to advance understanding of thermal transport in low dimensional copper-oxides that display extraordinary thermal transport by thermal excitations of spin degrees of freedom. We measured for the first time the magnon-phonon coupling parameter of a spin-ladder compound over a wide temperature range. We developed advances in the analysis of TDTR that enable measurements of materials such as low dimensional

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Report Title

Final Report: Extraoridinary Spin-Wave Thermal Conductivity in Low-Dimensional Copper Oxides

ABSTRACT

We applied frequency-dependent measurements of thermal transport properties using time-domain thermoreflectance (TDTR) to advance understanding of thermal transport in low dimensional copper-oxides that display extraordinary thermal transport by thermal excitations of spin degrees of freedom. We measured for the first time the magnon-phonon coupling parameter of a spin-ladder compound over a wide temperature range. We developed advances in the analysis of TDTR that enable measurements of materials such as low dimensional copper oxides with more than one significant type of heat carrier; and measurements of the anisotropic thermal conductivity of materials that lack in-plane symmetry.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
01/18/2015	2.00	Joseph P. Feser, Jun Liu, David G. Cahill. Pump-probe measurements of the thermal conductivity tensor for materials lacking in-plane symmetry, Review of Scientific Instruments, (10 2014): 104903. doi: 10.1063/1.4897622
01/18/2015	3.00	Gregory T. Hohensee, R. B. Wilson, Joseph P. Feser, David G. Cahill. Magnon-phonon coupling in the spin-ladder compound <math><msub><mrow><mtext>Ca</mtext></mrow><mn>9</mn></msub></math><math><msub><mrow><mtext>La</mtext></mrow><mn>5</mn></msub></math><math><msub><mrow><mtext>Cu</mtext></mrow><mn>24</mn></msub></math><math><msub><mrow><mtext>O</mtext></mrow><mn>41</mn></msub></math> measured by time-domain thermoreflectance, Physical Review B, (01 2014): 24422. doi: 10.1103/PhysRevB.89.024422
01/18/2015	4.00	Gyung-Min Choi, Byoung-Chul Min, Kyung-Jin Lee, David G. Cahill. Spin current generated by thermally driven ultrafast demagnetization, Nature Communications, (07 2014): 4334. doi: 10.1038/ncomms5334
01/18/2015	5.00	R. B. Wilson, Joseph P. Feser, Gregory T. Hohensee, David G. Cahill. Two-channel model for nonequilibrium thermal transport in pump-probe experiments, Physical Review B, (10 2013): 144305. doi: 10.1103/PhysRevB.88.144305

TOTAL: **4**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

David G. Cahill, G. Hohensee, G. Choi, R. Wilson, J. Feser, "Magnon-phonon coupling in copper-oxides and the coupling of spin and heat currents in metallic multilayers," invited talk at Spin Caloritronics V, Columbus, OH, May 12-15, 2013.

D. G. Cahill, G. Hohensee, and Gyung-Min Choi, "Coupling of heat and spin currents in cuprates and metallic multilayers," invited talk at US-Japan Joint Seminar on Nanoscale Transport Phenomena, Santa Cruz, CA, July 13--16, 2014.

D. G. Cahill, "Time-domain thermoreflectance: fundamentals and advanced techniques," tutorial lectures, International Conference on Phononics and Thermal Energy Sciences, Tongji University, Shanghai, China, May 26--28, 2014.

D. G. Cahill, Greg Hohensee, and Gyung-Min Choi, "Coupling of heat and spin currents in cuprates and metallic multilayers," keynote talk, Eurotherm Seminar 103: NMHT IV, Lyon, France, October 15--17, 2014.

Number of Presentations: 4.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

08/31/2013 1.00 Gregory T. Hohensee, R. B. Wilson, Joseph P. Feser, David G. Cahill. Magnon-phonon Coupling in $Ca_9La_5Cu_{24}O_{41}$ Spin Ladders Measured by Time-Domain Thermoreflectance, Physical Review B (submitted) (08 2013)

TOTAL: **1**

Number of Manuscripts:

Books

Received Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Yeram S. Touloukian Award, ASME 2015; citation: For sustained, pioneering contributions to heat conduction metrology including the 3-omega and optical pump-probe methods, which are pervasive in laboratories worldwide; and for landmark contributions on the minimum and ultralow thermal conductivity of solids.

Fellow of the Materials Research Society, 2012; citation: For the pioneering development of measurement techniques and scientific understanding of thermal transport in materials at nanometer length scales.

Elected to the cycle of vice-chair, program-chair, chair of the Division of Materials Physics, American Physical Society, 2011-2014.

Editorial Board of Applied Physics Letters and Journal of Applied Physics, 2010--2013.

Graduate Students

NAME	PERCENT SUPPORTED	Discipline
Gyung-Min Choi	0.15	
Trong Tong	0.15	
Greg Hohensee	0.20	
FTE Equivalent:	**0.50**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT SUPPORTED
Joseph Feser	0.33
FTE Equivalent:	**0.33**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
David Cahill	0.05	
FTE Equivalent:	**0.05**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

We have quantitatively analyzed the thermal conductivity of (Ca,La)14Cu24O41 over a wide range of temperature and measurement frequency. We developed a rigorous analytical model to incorporate two-channels of heat conduction (in this case, magnons and phonons) into the analysis of data measured by time-domain thermoreflectance. This new capability enables us to accurately extract the strength of the phonon-magnon coupling that thermalizes magnons with the phonon heat bath. Near the peak of the thermal conductivity, the volumetric thermal conductance that connects phonons and magnons is 10^{15} W m^{-3} K^{-1}, more than an order of magnitude smaller than the conductance of the weakest electron-phonon coupling observed in Au. A comparison of the thermalization rate for magnons and the scattering rate for magnons derived from the magnitude of the magnon thermal conductivity shows that approximately magnon-phonon scattering is quasi-elastic. The similar temperature dependence, however, suggests that magnon-phonon coupling is the dominate scattering mechanism that limits the thermal conductivity. A full description of the experiments and analysis of a spin-ladder thermal conductivity has been published as a full-length article in Physical Review B. A completely description of the two-channel solution of the heat diffusion equation in layered materials has also been published in Physical Review B.

We extended our 2004 model of thermal transport in layered systems to the case of an arbitrary tensor thermal conductivity. This extension allows w us to
quantitatively analyze data acquired by time-domain thermoreflectance on an arbitrarily oriented anisotropic material. This capability is particularly important for the study of 2D magnon systems where the high thermal conductivity directions are normal to the plane of the surface and one in-plane direction. We validated the model on samples with known anisotropic thermal conductivity such as crystalline quartz. A full length paper has been published in Review of Scientific Instruments.

Technology Transfer