REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
14-10-2021	Final Report	19-Jul-2018 - 14-Jul-2021

4. TITLE AND SUBTITLE
Final Report: Enabling Gigantic Antiferromagnetic Spin Caloritronic Effects through Spin Heat Accumulation

5a. CONTRACT NUMBER
W911NF-18-1-0364

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of California - Riverside
200 University Office Building

Riverside, CA 92521 -0001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
71928-MS-YIP.13

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Richard Wilson
					19b. TELEPHONE NUMBER
					951-827-3374

RPPR Final Report
as of 18-Oct-2021

Agency Code: 21XD

Proposal Number: 71928MSYIP

Agreement Number: W911NF-18-1-0364

INVESTIGATOR(S):

Name: Richard Wilson
Email: richard.wilson@ucr.edu
Phone Number: 9518273374
Principal: Y

Organization: **University of California - Riverside**
Address: 200 University Office Building, Riverside, CA 925210001
Country: USA

DUNS Number: 627797426 EIN: 956006142
Report Date: 14-Oct-2021 Date Received: 14-Oct-2021
Final Report for Period Beginning 19-Jul-2018 and Ending 14-Jul-2021
Title: Enabling Gigantic Antiferromagnetic Spin Caloritronic Effects through Spin Heat Accumulation
Begin Performance Period: 19-Jul-2018 **End Performance Period:** 14-Jul-2021
Report Term: 0-Other

Submitted By: Richard Wilson Email: richard.wilson@ucr.edu
Phone: (951) 827-3374

Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 2 **STEM Participants:** 4

Major Goals: Our project had four major goals. (1) Develop pump/probe methodologies capable of quantifying spin-polarized heat transfer in magnetic heterostructures on picosecond time scales. (2) Understand how electron-phonon interactions govern transport in magnetic metals. (3) Discover how magnetic properties, especially antiferromagnetic exchange interactions, affect spin caloritronic transport properties. (4) Quantify the interfacial spin Seebeck effect in a metal/antiferromagnetic insulator system.

Accomplishments: (1) We developed a pump/probe method capable of independently measuring a metal's electron temperatures, phonon temperatures, and magnetic moment. Our method works by monitoring temperature and magnetism-induced changes in optical properties at wavelengths between 400 and 1000 nm. (2) We used our new pump/probe methodology to explore how composition-induced changes in electronic band structure enable novel magnetic and thermal transport properties in FeCo alloys. We discovered that CoFe alloys have remarkable composition-dependent thermal transport properties. We did not observe evidence that heat-currents are spin-polarized (spin heat accumulation). However, we were able to identify how composition, band structure, and electron-phonon interactions give rise to unique thermal and magnetic properties. (3) We measured the interfacial spin-Seebeck effect in Au/rare-earth iron garnet bilayers. We discovered that the magnitude of the spin Seebeck effect in an Au/iron-garnet system is enhanced by a factor of three by replacing Yttrium with Thulium or Terbium. Replacing Yttrium with Thulium or Terbium modifies the antiferromagnetic exchange interaction between the two antiferromagnetically coupled Fe sublattices in the iron-garnet. By performing wavelength-dependent pump/probe measurements, we discovered that the spin Seebeck effect causes ultrafast demagnetization of the iron garnet layer. In addition to spin Seebeck effect measurements, we also characterized the thermal interface conductance of a large number of spin-caloritronic material systems. The conductance is an important property for interpreting spin caloritronic experiments, but prior to our study, there were few reports of its value for spin caloritronic material systems. (4) We performed spin Seebeck effect measurements of the following metal/antiferromagnetic trilayers: Au/Cu/Cr2O3 (1120) and Au/Cu/Cr2O3 (1000). To understand the effect of surface morphology, we prepared a series of samples with different thermal histories and different interfacial roughness. Despite a magnetic moment that is orders of magnitude lower than that of the iron-garnets, we observe an interfacial spin Seebeck effect in Au/Cu/Cr2O3 that is comparable magnitude as the Au/iron-garnet systems. In the presence of a ~1.25 T field, Au/Cr2O3 has an electron-magnon interface conductance of ~0.5 MW/(m^2-K). For comparison, we observe an electron-magnon conductance in Au/YIG of ~1 MW/(m^2-K).

Training Opportunities: Nothing to Report

Results Dissemination: Our results have been reported in scientific journals such as Physical Review Materials, Communications Physics, Review of Scientific Instruments, and Nature Electronics. We presented our findings in contributed and invited talks at MRS and APS.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Richard Brian Wilson
Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Frank Angeles
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Victor Ortiz
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Michael Gomez
Person Months Worked: 10.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Ramya Mohan
Person Months Worked: 7.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Bhartendu Satywali
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Xinping Shi
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Review of Scientific Instruments
Publication Identifier Type: DOI Publication Identifier: https://doi.org/10.1063/1.5126121
Volume: 91 Issue: First Page #: 023905
Date Submitted: 8/31/20 12:00AM Date Published:
Publication Location:
Article Title: High Sensitivity Pump-Probe Measurements of Magnetic, Thermal, and Acoustic Phenomena with a Spectrally Tunable Oscillator
Authors: Michael Gomez, Kexin Liu, Jonathan Lee, Richard B. Wilson
Keywords: thermal transport, ultrafast magnetism, pump/probe
Abstract: Understanding how photoexcited electron dynamics depend on electron-electron (e-e) and electron-phonon (e-p) interaction strengths is important for many fields, e.g. ultrafast magnetism, photocatalysis, plasmonics, and others. Here, we report simple expressions that capture the interplay of e-e and e-p interactions on electron distribution relaxation times. We observe a dependence of the dynamics on e-e and e-p interaction strengths that is universal to most metals and is also counterintuitive. While only e-p interactions reduce the total energy stored by excited electrons, the time for energy to leave the electronic subsystem also depends on e-e interaction strengths because e-e interactions increase the number of electrons emitting phonons. The effect of e-e interactions on energy-relaxation is largest in metals with strong e-p interactions. Finally, the time high energy electron states remain occupied depends only on the strength of e-e interactions, even if e-p scattering rates are
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Journal of Magnetism and Magnetic Materials
Publication Identifier Type: DOI Publication Identifier: https://doi.org/10.1016/j.jmmm.2020.166478
Volume: 502 Issue: First Page #: 166478
Date Submitted: 8/31/20 12:00AM Date Published: 1/22/20 8:00AM
Publication Location:
Article Title: Progress towards ultrafast spintronics applications
Authors: Amal El-Ghazaly, Jon Gorchon, Richard B. Wilson, Akshay Pattabi, Jeffrey Bokor
Keywords: Ultrafast, All-optical switching
Abstract: This review discusses our most recent advances in addressing these challenges and bridging together the two fields of spintronics and ultrafast magnetism to enable the integration of ultrafast spintronic devices. Our research shows that, not only sub-picosecond optical pulses, but also picosecond excitations in the form of optical and electrical (heat current) pulses can result in the switching of the magnetization direction between two opposite states in ferrimagnetic GdFeCo. We also demonstrate ultrafast single shot switching of ferromagnetic Co/Pt exchange coupled to a GdFeCo layer. Furthermore, we observe ultrafast switching in nanoscale patterned GdCo dots. These achievements pave the way towards the construction of nanoscale ferromagnetic tunnel junctions capable of picosecond magnetization write times and electrical readout.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: University of California - Riverside
Date Received: 29-Aug-2019 Completion Date: 3/31/19 7:52PM
Title: Heat Transport and Spin Accumulation in Nanoscale Magnetic Multilayers
Authors: Michael Gomez
Acknowledged Federal Support: **N**

Publication Type: Thesis or Dissertation
Institution: University of California Riverside
Date Received: 14-Oct-2021 Completion Date: 9/1/21 11:05PM
Title: Influence of Structural and Compositional Heterogeneities on Nanoscal Thermal Transport and Magnetization Dynamics
Authors: Ramya Mohan
Acknowledged Federal Support: **Y**

Partners

,

Jon Gorchon, University of Lorraine, Nancy France. Jing Shi, University of California Riverside, CA, United States.(

I certify that the information in the report is complete and accurate:
Signature: Richard Brian Wilson
Signature Date: 10/14/21 10:54PM

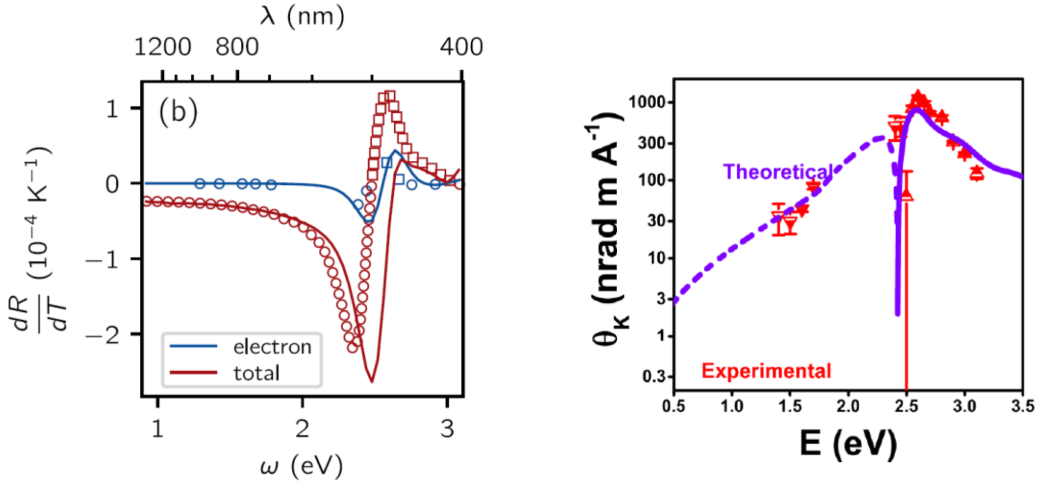

Fig. 1. Experimental measurements of how Au's optical properties vs. wavelength depend on electron temperature (blue circles in left panel), phonon temperature (red circles in left panel), and magnetism (red triangles right panel).

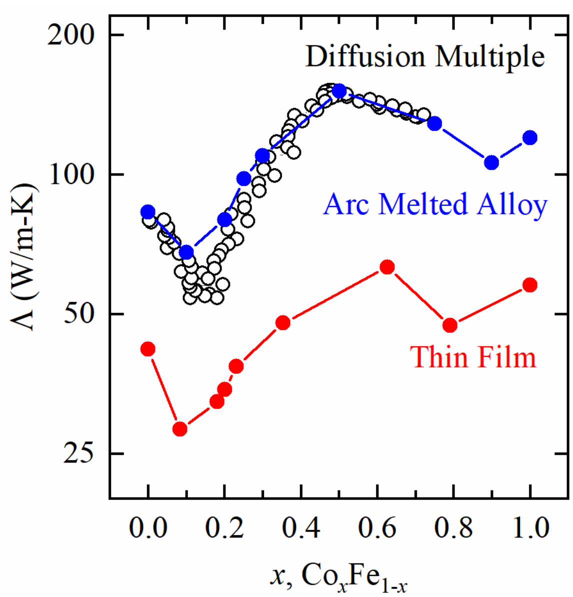

Fig. 2. Thermal conductivity of CoFe alloys. To explore how spin-polarized heat currents depend on electron-phonon interactions, we studied thermal transport as a function of composition. The band-structure at the Fermi-level in CoFe alloys, and therefore electron-phonon interaction strengths, depends strongly on composition. We did not find evidence of spin-heat accumulation. However, surprisingly, we did observe that transport is unimpeded by compositional disorder provided the alloys is more then 50% Fe.

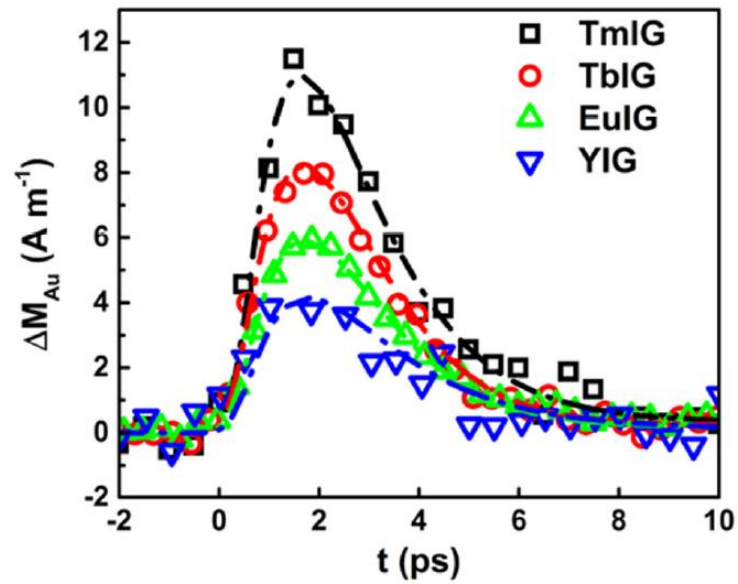

Fig. 3. Transient magnetic moment of Au following ultrafast heating of Au/iron-garnet bilayers. The spin Seebeck effect is 2 and 3x larger in TbIG and TmIG than YIG due to changes in the antiferromagnetic exchange interaction.

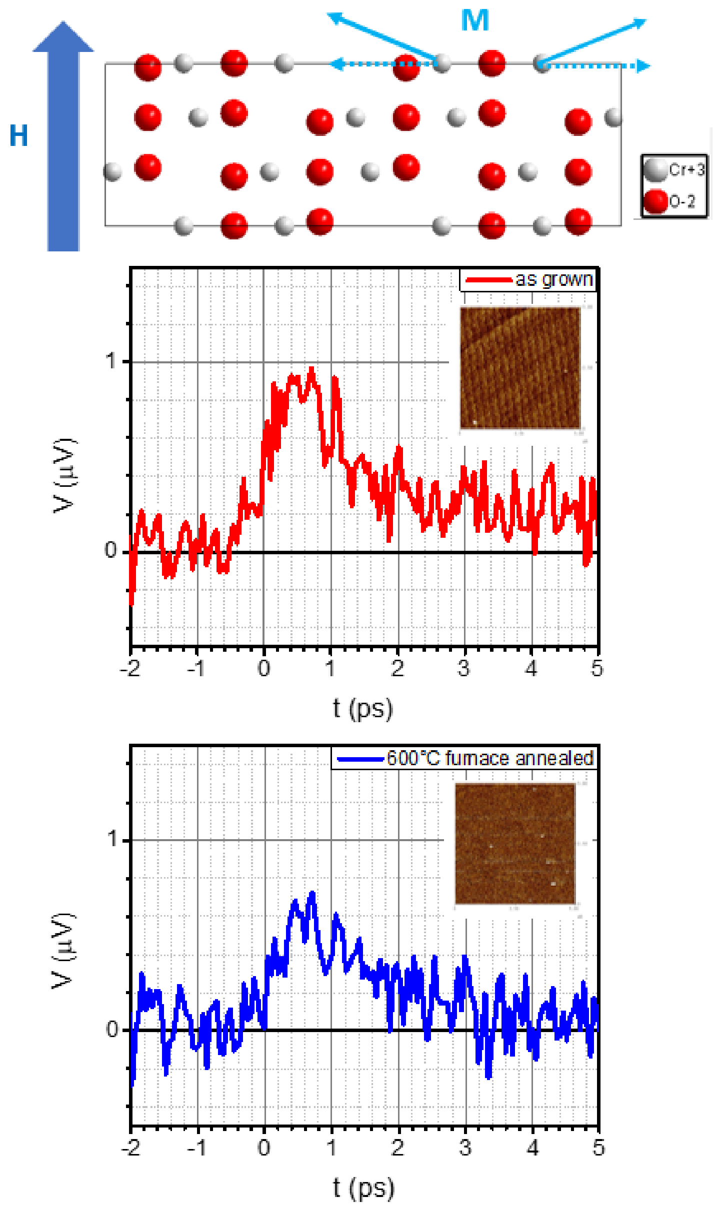

Fig. 4. Antiferromagnetic Spin Seebeck effect measurements of Au/Cu/Cr_2O_3. In these experiments, we applied an external field of 1.25 Tesla to cant the magnetic moment of the antiferromagnetic sublattices in the out-of-plane direction. We use a picosecond laser to heat the Au/Cu layers. We then monitor an optical signal vs. time-delay. The optical signal is proportional to the magnetic moment of the Au layer. The amplitude of the signal depends on the magnitude of the spin Seebeck effect. The spin Seebeck effect induced signal in Au/Cu/Cr_2O_3 is comparable to what we observe in the Au/iron-garnet systems (Fig. 3), despite Cr_2O_3 being antiferromagnetic. We observe that an increase in interfacial roughness leads to a decrease in the spin Seebeck effect.