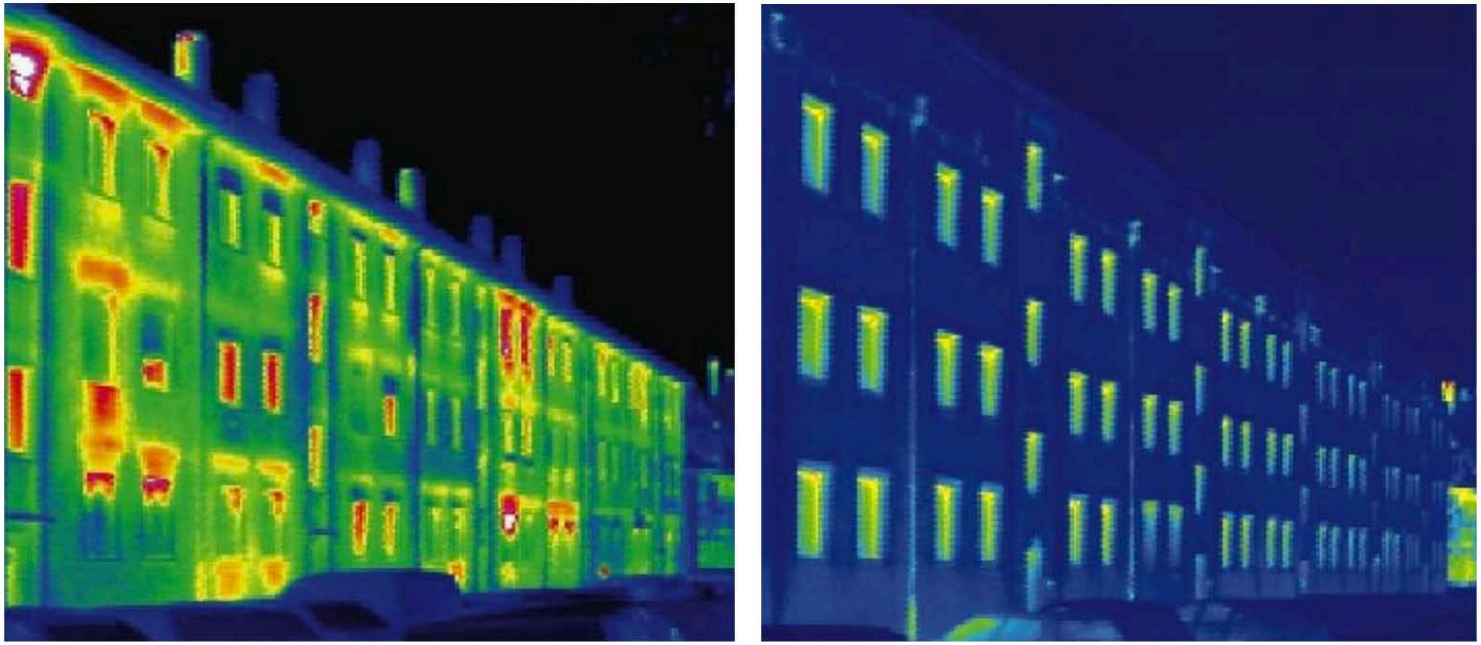
U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Robust Insulation at a Competitive Price



Performing Organization(s) : Lawrence Berkeley National Lab and Oak Ridge National Lab
PI Name and Title: Ravi Prasher, Divison Director, Energy Storage and Distributed Resources, LBNL
PI Tel and/or Email: 510-486-7291, rsprasher@lbl.gov

Project Summary

Timeline:

Start date: Oct 1st, 2016

Planned end date: Dec 31st, 2019

Key Milestones

1. Milestone 1; Identified key surface functionalization chemistries to reduce surface energy less than < 100 mJ/m^2 and get contact angle > 90°
2. Milestone 2; Demonstrated R/inch of 6.4 for sample with diameter one inch by end of Q4

Budget:

Total Project $ to Date:

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- DOE: $774,638
- Cost Share: $0

Total Project $: 1,600,000

- DOE : $1,350,000 (LBNL) and $150,000 (ORNL)
- Cost Share: $100,000 (CEC)

Key Partners:

Oak Ridge National Lab
California Energy Commission (CEC)

Project Outcome:

The focus of the project is to manipulate heat transport at the interfaces at the nanoscale and achieve high R/inch value. By tweaking size, surface energy and acoustic mismatch, our **current R/inch value is 7.84** By end of this project we aim to achieve R/inch ≥ 12 with mechanical strength 10 times that of aerogel.

Team

LBNL

Ravi Prasher,
Principal Investigator
LBNL

Area of expertise:
Phonon Transport

Sean Lubner,
Postdoc, LBNL

Area of expertise:
Advanced thermal metrology

Howdy Goudey, LBNL

Area of expertise:
Macro scale thermal measurement

Suman Kaur,
Project Scientist
LBNL

Area of expertise:
Nanomaterial synthesis and surface chemistry

D. Charlie Curcijia, LBNL

Area of expertise:
Window and Energy Analysis

ORNL

Andre Omer Desjarlais,
ORNL

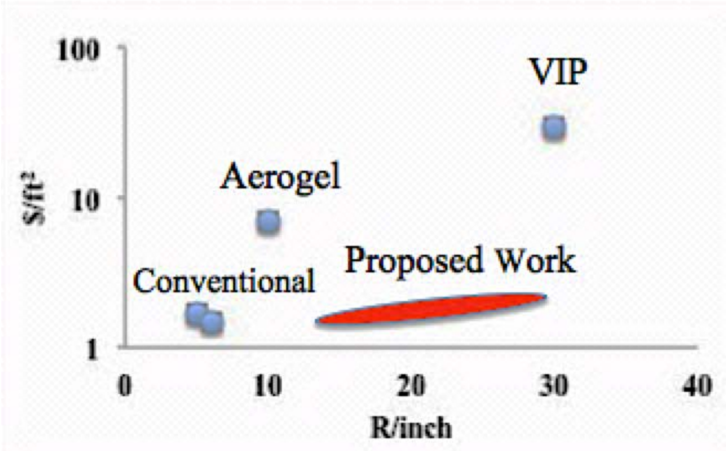
Area of expertise:
Energy Saving Analysis

CEC

Karen Perrin, California Energy Commission (CEC)

Energy Commission Specialist (Efficiency)

Challenge



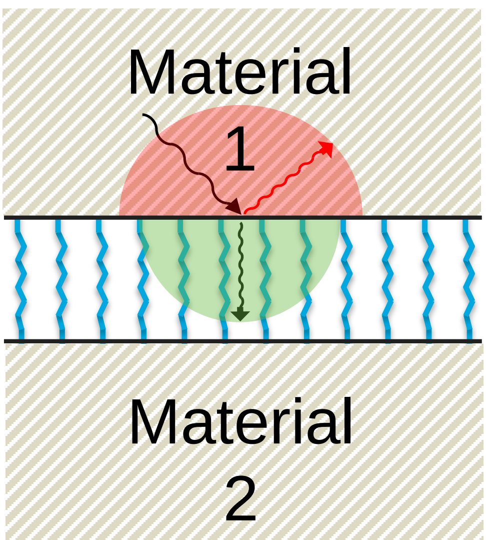
- Space heating and cooling accounts for 37% of overall building energy consumption amounting to **15.1 quads**.
- US building sector is dominated by under-insulated existing buildings. Even by 2035, more than 50 percent of both residential and commercial stock will be pre-2010 buildings. Therefore a significant market for building insulation is the retrofit market.

Current and emerging insulation solutions

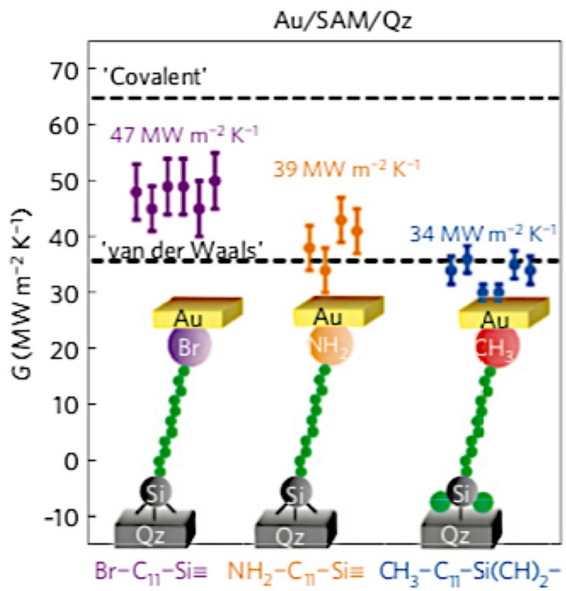
- **Conventional insulation materials such as fiberglass and XPS, although cheap have** relatively low R/inch value. Hence they reduce living space when placed on interior walls or require significant alteration of window/door openings and face zoning regulations. Very labor intensive and invasive for customers.
- Emerging insulations such as aerogel or VIPs have high R/inch value but are @10 times more expensive than conventional insulations. **Not cost-effective for customers.**
- **The Challenge is to make affordable insulation especially for retrofit market.**

Approach

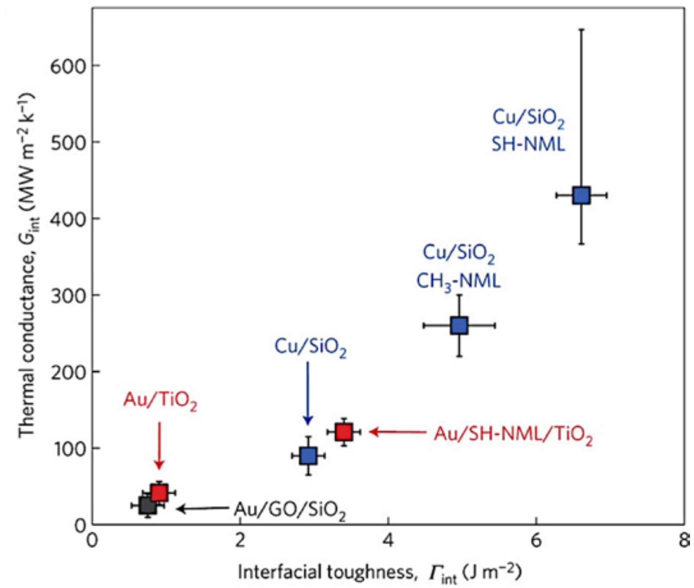
The R&D efforts in insulation field so far have centered on achieving high R-values by either reducing the solid volume fraction (as in aerogel) or making VIPs. The scientific and technological question for a game-changing high-R insulation is: ***Does achieving a high R-value require using either a low volume fraction of solids (as in aerogel) or vacuum-enclosed panels?*** **Our approach is to achieve very low thermal conductivity in nanoparticle bed cost-effectively by understanding and manipulating the heat transfer at nano-scale.**



Prasher, APL, 2009



Losego et al. 2012 (Nature Materials)



Peter J. O'Brien et al., 2012 (Nature Materials)

$$\tau_{\text{v-AMM}} = \frac{4z_1 z_2 \cos\theta_1 \cos\theta_2}{(z_1\cos\theta_1 + z_2\cos\theta_2)^2 + \frac{\omega^2}{K_A^2}(z_1 z_2 \cos\theta_1 \cos\theta_2)^2}.$$

$$K = {}^{16\Delta\gamma}\!/_{z_0^2}$$

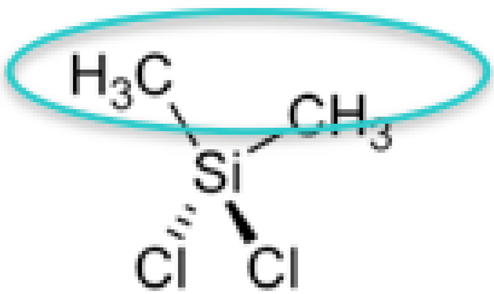
Approach

Surface Energy

- Reduce surface energy significantly
- Use gas phase technique to avoid nanoparticle agglomeration

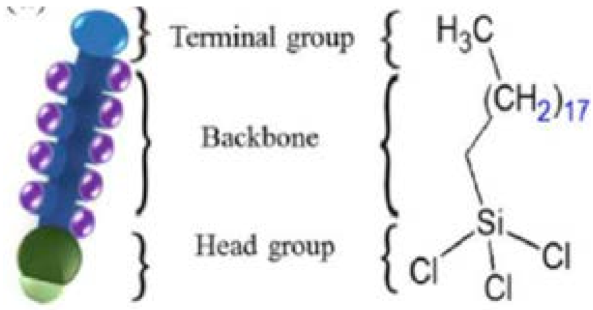
The chemistries selected

1) Dichlorodimethylsilane (DDMS)



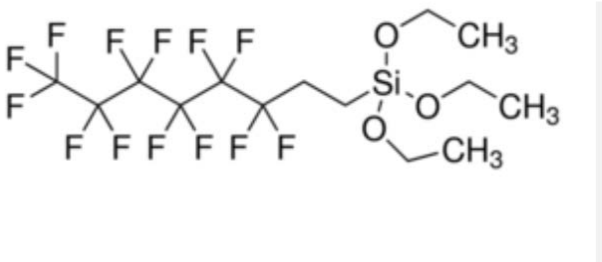
Shorter chain
(1 carbon),
Terminal group CH_3

2) Octadecyltrichlorosilane (OTS)



Longer chain
(17 carbon),
Terminal group CH_3

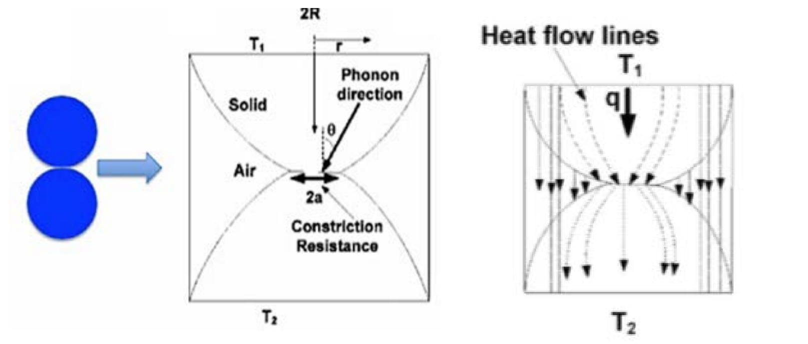
3) 1H, 1H, 2H,2H-Perfluorooctyltrichlorosilane (FDTS)

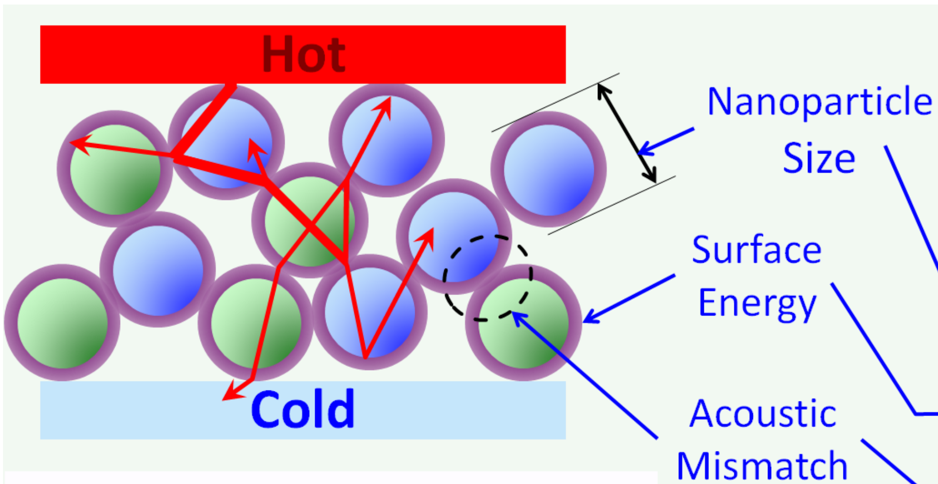


Long chain
(8 carbon),
Terminal group F

Approach

In case of interfaces between nanoparticles, constrictions play significant role in reducing thermal transport: **a^2/R where a is constriction and R is nanoparticle radius respectively**





$k_{eff} = (1/3)cvl_{eff}$

k_{eff} = effective thermal conductivity
c = specific heat per unit volume
v = speed of phonons (sound)

Reducing the effective mean free path (l_{eff}) of phonons reduces a material's thermal conductivity. For two contacting nanoparticles of radius *R*, l_{eff} is given by:

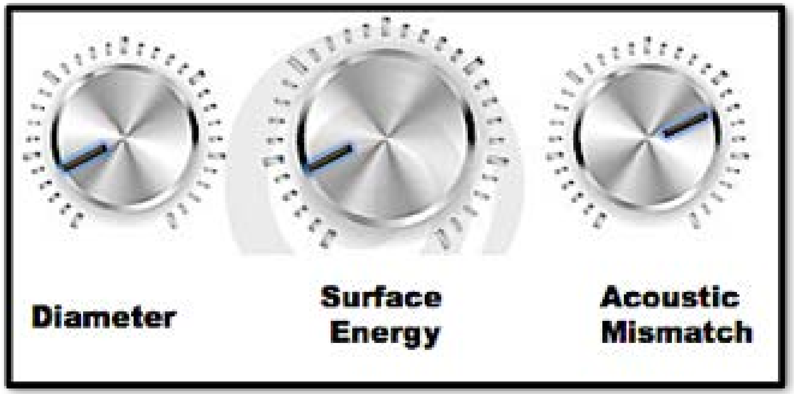
$$l_{eff} = 3\left(1.125\frac{\pi\gamma}{E}\right)^{\frac{2}{3}} R^{\frac{1}{3}} \int \tau \sin\theta \cos\theta \, d\theta$$

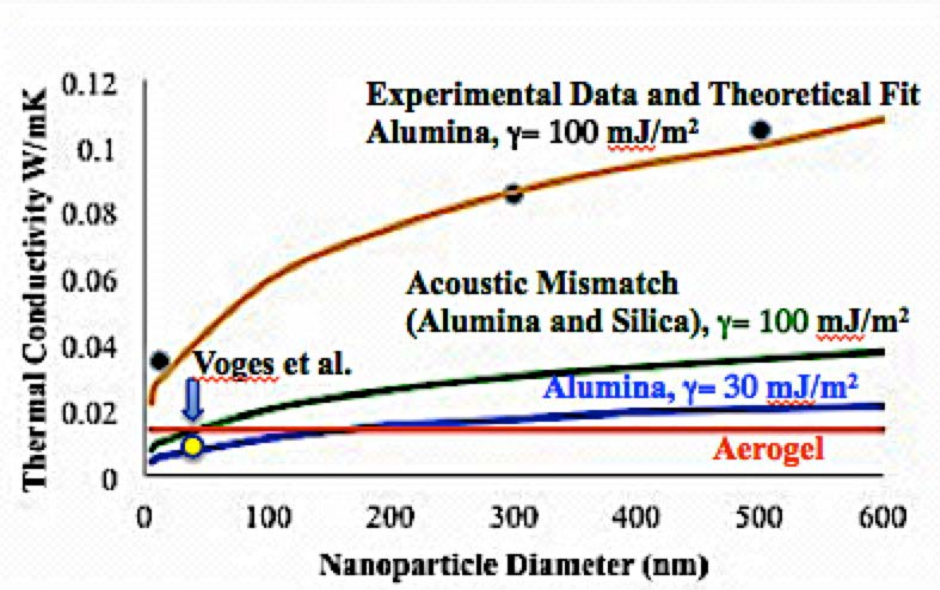
$$\tau = \frac{4 z_1 z_2 \cos\theta_1 \cos\theta_2}{\left(z_1\cos\theta_1 + z_2\cos\theta_2\right)^2 + \frac{\omega^2}{K_A^2}\left(z_1 z_2 \cos\theta_1 \cos\theta_2\right)^2}$$

Prasher, Phys. Rev. B, 2006

Approach

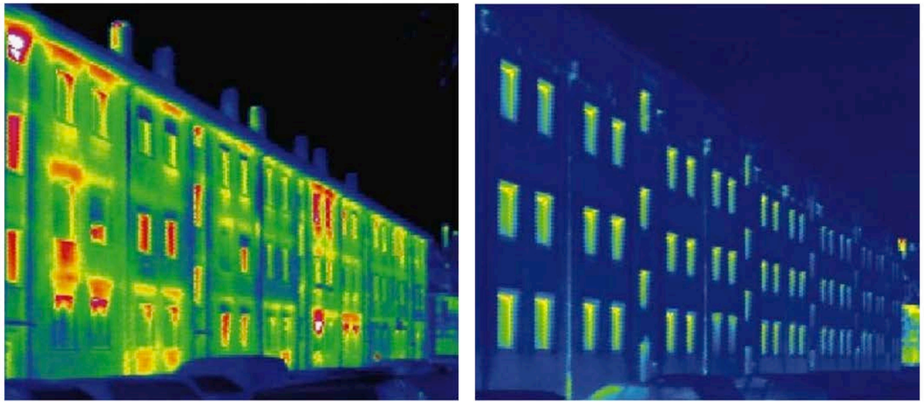
The KEY Knobs





- Experimental data showing effect of size of alumina nanoparticles on thermal conductivity (*Hu et al. Applied Physics Letters 91, 203113, 2007*) with volume fraction ~ 0.6. Our preliminary data from other nanoparticles such as silica and titania show similar size effects.
- The impact of surface energy (100 mJ/m^2 and 30 mJ/m^2) and acoustic mismatch by mixing two types of nanoparticles (alumina and silica) as estimated by theoretical model is also shown.
- Vogue et. al.(*Physica Status Solidi (a) 212, 2014*) showed less than air k in bed of nanoparticles with volume fraction~0.5 by just using acoustic mismatch and size.

Impact



Energy demand dropped by 90% after refurbishment
(Nature 452, 3 April 2008)

We anticipate that the new insulation technology being developed in this project would be a potential replacement for insulations used in walls of residential buildings and walls and roofs of commercial buildings

Building Sector	Market Size 2030, (TBtu)	Technical Potential 2030, (TBtu)	Unstaged Max Adoption potential 2030, (TBtu)
Residential Sector	1592	836	267
Commercial Sector	1434	836	267
	3026	1672	534

R&D Roadmap For Emerging Window And Building Envelope Technologies

Due to the use of high volume compatible and low energy consumption manufacturing process we expect the cost to be significantly reduced.

Progress

Quick Overview

- Q1: **Procurement, characterization and selection of nanoparticles**
  Select and source at least 3 different diameters for thermal evaluation for both silica alumina and titania nanoparticles which meets the selection criteria. **Milestone achieved**

- Q2: **Impact on particle size and acoustic mismatch on thermal and mechanical properties. IDENTIFY Thermal and Mechanical metrology.**
  Achieve thermal conductivity < 0.14 W/m·K, R/inch >1 and compressive strength > 1 MPa (>10x better than aerogel) **Milestone achieved**

- **Q3: Surface modification of nanoparticle for lower surface energy**
  Identify surface functionalization chemistries with surface energy less than < 100 mJ/m^2 and contact angle > 90^o using substrates made of same material as the nanoparticles **Milestone achieved**

- **Q4 GO/No Decision: Optimize all parameters to achieve R/inch of 6 in sample area of 1cm^2: Milestone achieved**

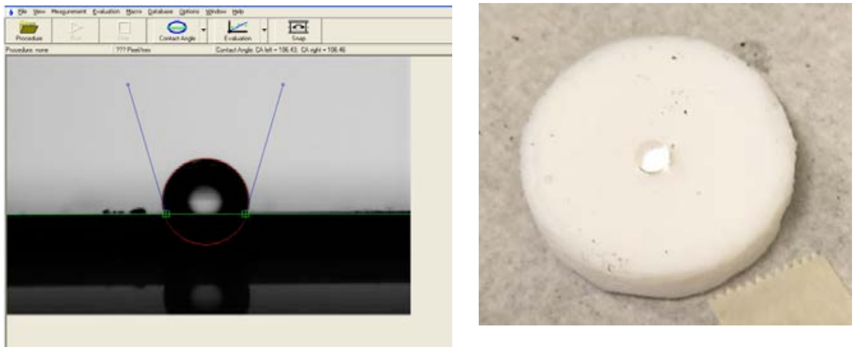
- **Provisional patent filed. Journal paper showing effect of pressure on Van Der Waals contacts published.** *Acoustic Mismatch Model for Thermal Contact Conductance of Van Der Waals Contacts Under Static Force* *(Nano and Microscale Thermophysical Engineering)*

- **Project is in mid stage**

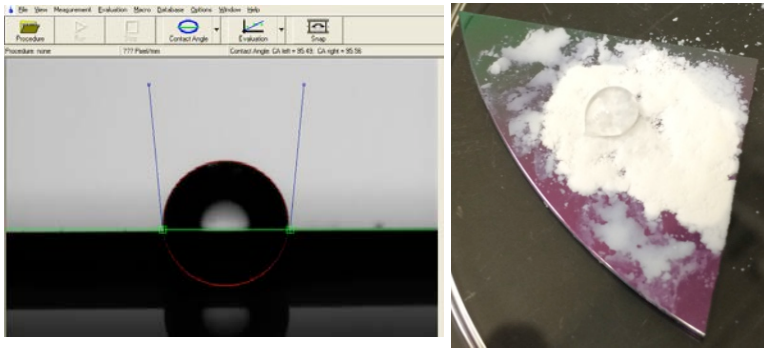
Progress

Main Highlight: Knob 2, Surface Energy

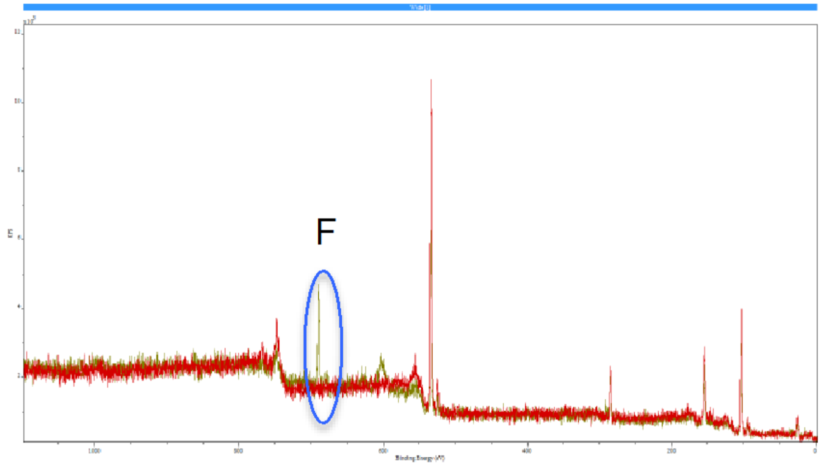
Pristine nanoparticles



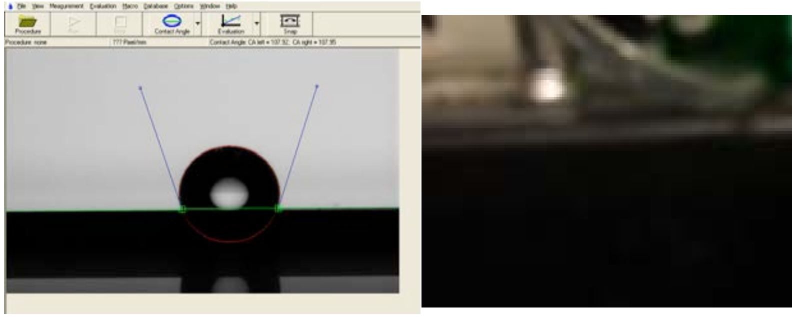
FDTS (F-terminal group) treated (left) Si wafer with contact angle 106.4^0 (right) Nanoparticle pellet



DDMS (Short Chain) treated (left) Si wafer with contact angle 95.5^0 (right) pressed nanoparticle



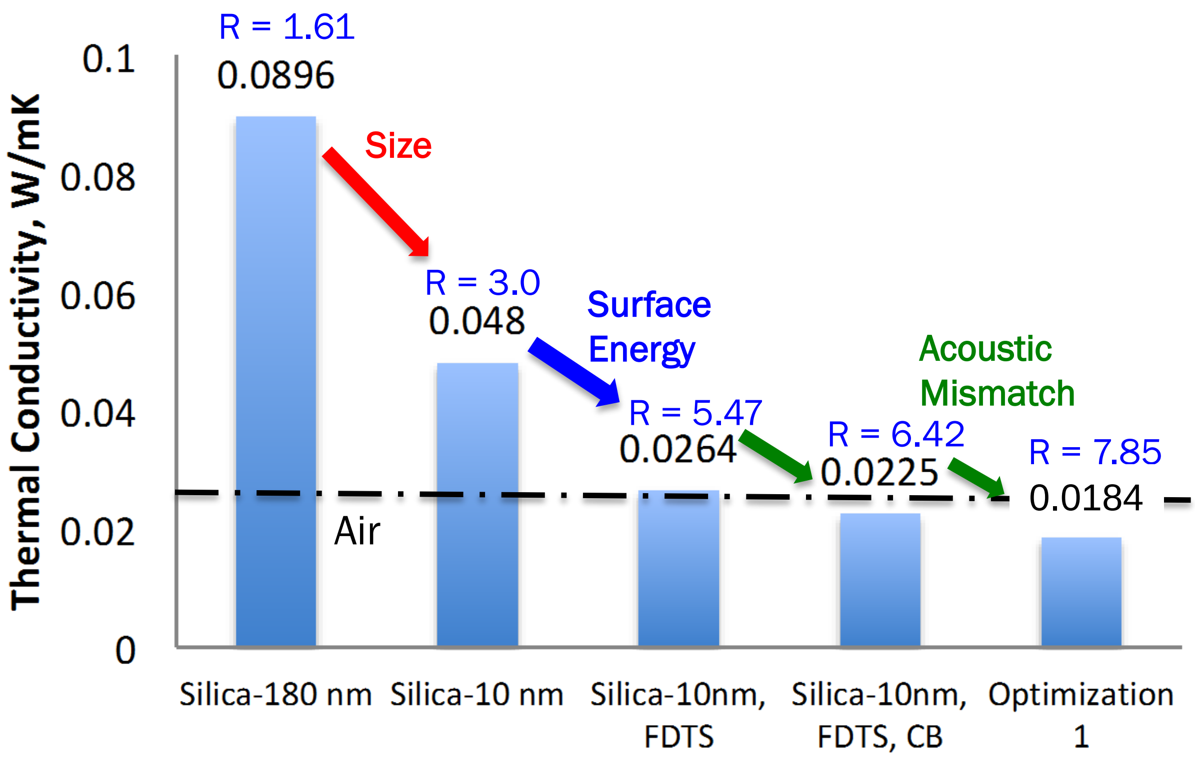
XPS spectrum of nanoparticles before and after FDTS treatment showing presence of F after functionalization



OTS (long chain) treated (left) Si wafer with contact angle 107.9^{0,} (right) Nanoparticle

Progress

All knobs together: Effect of Size, Surface energy, and Acoustic Mismatch



The road map to R/inch ≥ 12

- More materials for acoustic mismatch: alumina, titania or metal
- More variables : morphology of nanoparticles, packing density, functionalization optimization (so far mostly efforts focused on FDTS)

Risk mitigation: Relaxing nanoparticle uniformity and mono dispersity condition, using simple manufacturing and functionalization techniques for scale up.

Progress

Key Challenge for Progress: Selection of Thermal Metrology

Q1

Initial Evaluation – Preference to available thermal metrology at LBNL: Guarded Hot Plate and TDTR

Q1-Q2

Selected and Built in house thermal capabilities of 3-omega

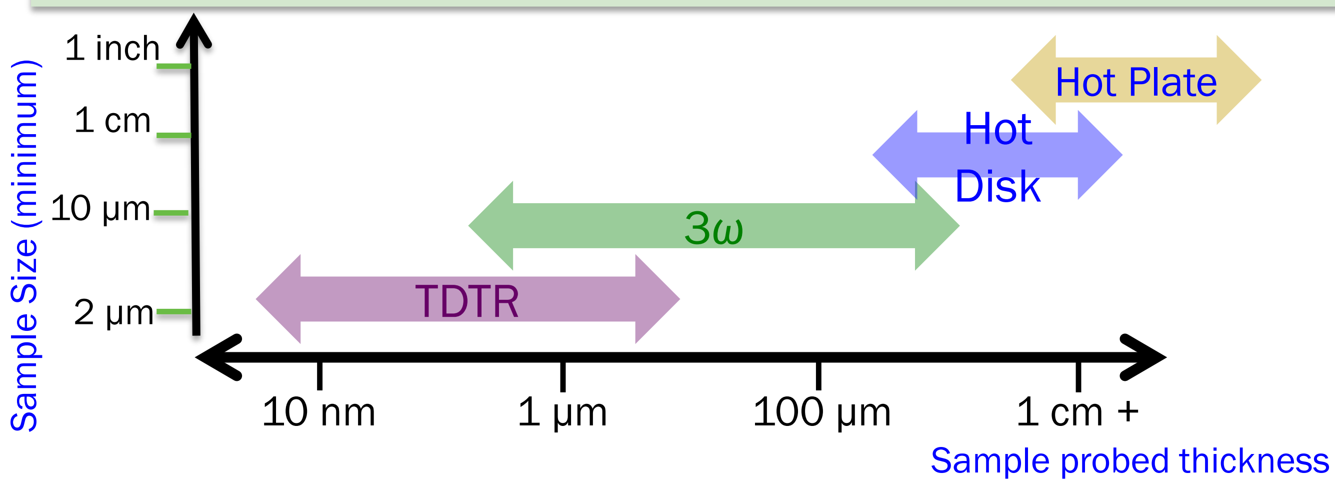
Q3

Bought commercially available Hot Disk for high throughput

Q4-Present

Realized accuracy issues with transient techniques.

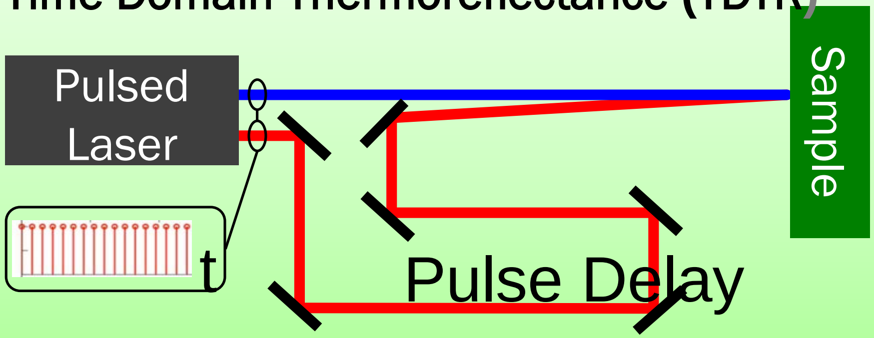
Using Guarded Hot Plate and Hot Disk in parallel



Progress

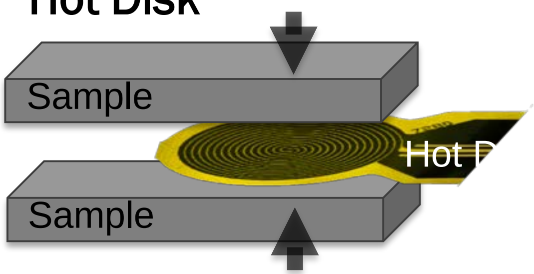
Thermal Metrologies in our lab and Molecular Foundry

Time Domain Thermoreflectance (TDTR)



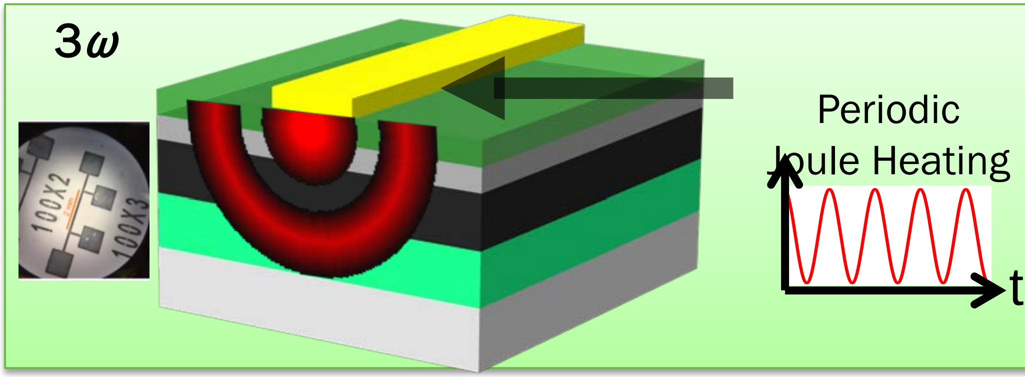
Time domain measurement (ultrafast)
Delayed pump + probe pulsed laser
Multilayered geometry

Hot Disk



Time domain measurement
Transient plane heating

3ω



Frequency domain measurement
Multilayered geometry

Stakeholder Engagement

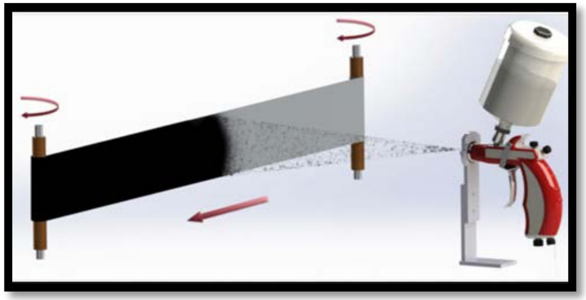
- We constituted an industry advisory board of people from insulation and energy efficiency industries and academia. The board will advise us on potential funding opportunities, guiding us on early stage applications and market.
- Industry advisory board consists of
  - 3M: Raghu Padiyath, Division Scientist
  - **Stone Energy Associates:** Nehemiah Stone, Principal

    Energy efficiency and renewable energy expert with extensive experience in the design, implementation, management and evaluation of utility programs,
  - **Arizona State University**: Patrick Phelan, Professor
  - **Inficold Inc**: Himanshu Pokharna, CEO

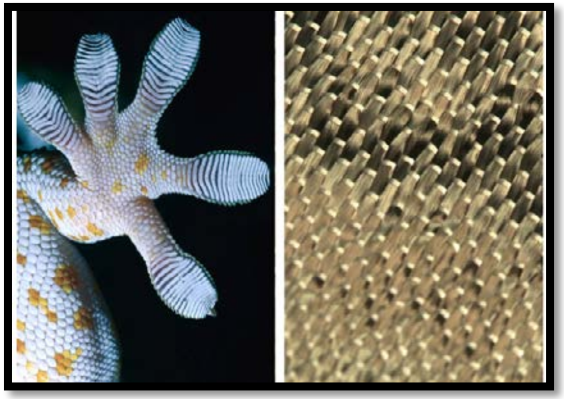
    Thermal storage integrated refrigeration technology
  - **McHugh Energy Consultants Inc :** Jon McHugh, **PE**

    Energy efficiency company serving public agencies, utilities and other entities. They do market assessments and life cycle costing to provide decision-makers with strategic energy information for policy or investment decisions
- Presented our work to Jeffrey Marqusse, who has over 20 years of government leadership in research, technology development, and policy in Department of Defense (DoD). He expressed significant interest and advised us to explore DoD for future funding.

Remaining Project Work



Karakaya et. al. Applied Physics Letters 105, (2014)



Near Future

- Process optimization for the right combination of nanoparticle size, surface chemistry and acoustic mismatch to achieve final goal of R/inch = 12
- Using the optimized recipe, we plan to develop a roll-to-roll (R2R) spray process for making flexible insulation

Distant Future: Attach-on Insulation

- To make an easy-to-use final insulation product which can be easily and quickly adhere to existing inner (may be exterior) surfaces of the walls, we propose make re-workable attach on insulation using dry adhesive.
- Less Labor-intensive, DIY
- Retrofit market, DoD, recreational applications

Thank You

Performing Organization(s): LBNL, ORNL
PI Name and Title: **Ravi Prasher, ESDR Division Director, LBNL**
PI Tel and/or Email: 510-486-7291 & rsprasher@lbl.gov

REFERENCE SLIDES

Project Budget

Project Budget: DOE budget was $1,500,000 over 3 years (last year –no cost extension) and then CEC was part of a cost share agreement for $100,000
Variances: There was a delay in funding the CEC award due to significant administrative hurdles which have since been cleared, and cost share will soon be spent.
Cost to Date: $774,638
Additional Funding: The cost share is being provided by California Energy Commission for $100,000.

Budget History					
Oct1st, 2016– FY 2017 (past)		FY 2018 (current+planned)		FY 2019 – 12/20/2019	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
489,786	0	571,703	50,000	289,510	50,000

Project Plan and Schedule

Project Schedule		
Project Start: Oct 1st, 2016		Completed Work
Projected End: Dec 31st, 2019		Active Task (in progress work)
		Milestone/Deliverable (Originally Planned) use for missed milestones
		Milestone/Deliverable (Actual) use when met on time

	FY2017				FY2018				FY2019			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Q1 Milestone: Procurement of nanoparticles and characterization of procured nanoparticles												
Q2 Milestone: Achieve thermal conductivity < 0.14 W/m·K, R/inch >1 and compressive strength > 1 MPa (>10x better than aerogel)												
Q3 Milestone:: Identify surface functionalization chemistries with surface energy less than < 100 mJ/m2 and contact angle > 90 deg using substrates made of same material as the nanoparticles												
Q4 Go/No Go Decision: Achieve thermal conductivity < 0.024 W/m·K, R/inch of 6, using the right surface chemistry, particle size and acoustic mismatch												
Q5: Milestone: Identify target market applications and develop a product requirements, Energy saving Report*												
Q5: Constitute Industrial advisory Board												
Current/Future Work												
Q6: Milestone: Introduce technology to DOE deployment												