Superatom Thermoelectric Materials

2cd Multifunctional Materials for Defense Workshop

30 July 2012

Materials & Manufacturing Directorate

AFRL/RXBT

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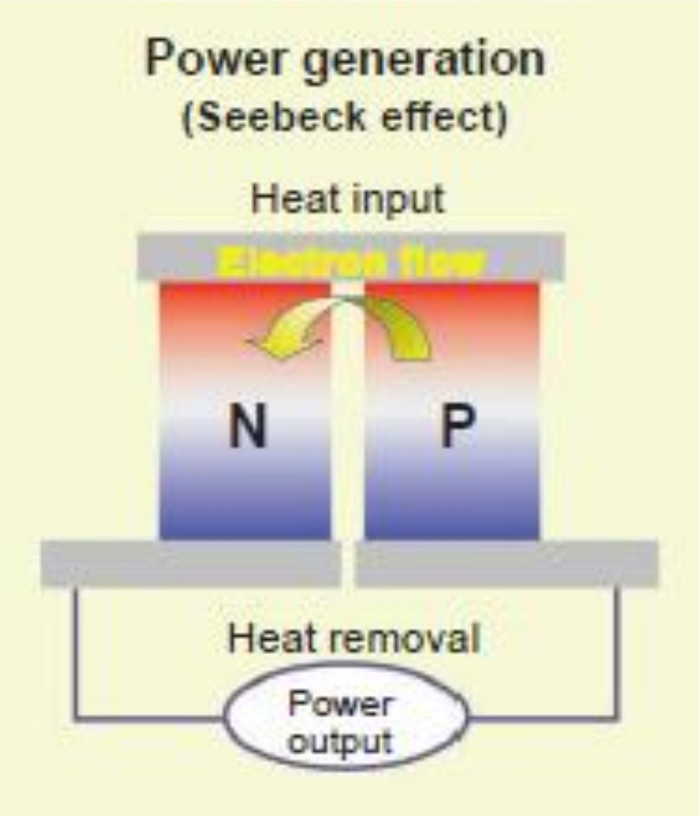
Outline

- **Thermeoelectrics**
- **Materials Challeneges**
- **Advantages of Superatoms**
- **Fullerenes/Fullerides**
- **Progress**
- **Conlcusions**

Thermoelectric Architecture

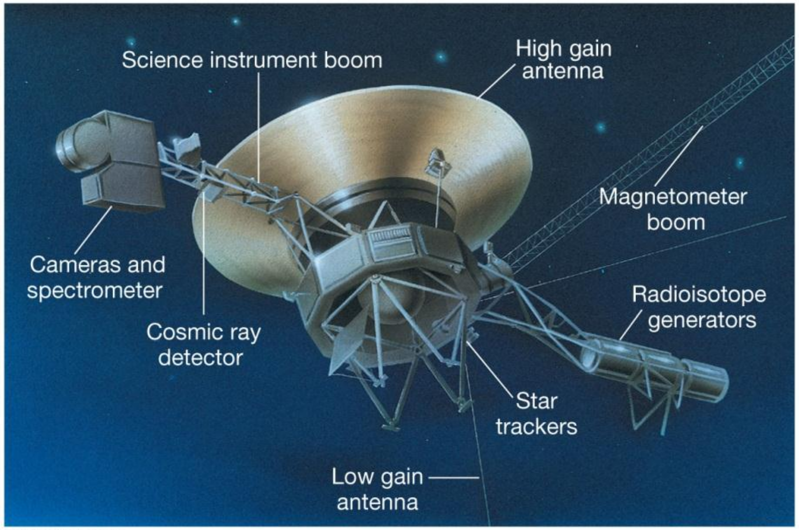
- Two materials in contact
  - N and P refer to desired direction that the electron wants to travel through the material
    - Examine electrons for P-type and holes for N-type
- Temperature differential allows for electron to be excited and released



ANAOLGIES:

Mechanical: ***Solid State Heat Pump electrons are working fluid***
Photovoltaic: ***Energy Harvester with thermal excitation instead of light***

Where TE's are used today…



http://www.aerospaceweb.org
voyager spacecraft

Amerigon.com

Newsroom.orange.co.uk/

Thermoelectric Interest & Relevance

AF Impacts	***Advantages***
DEW Lasers	***Precision Temp Control***
Satellites	***Reconfigurable, Long Life, No Vibrations***
Pilot Suits	***Independent of Orientation & g-forces***
UAVs, Sensors	***Efficient for small applications***
Electronics	***Solid State, switchable***

Air Force Research Laboratory TE Interest

- Propulsion Directorate (AFRL/RZ)
- Human Effectiveness (AFRL/RZH
- Directed Energy Directorate (AFRL/RD)
- Air Vehicle Directorate (AFRL/RB)
- Space Vehicles Directorate (AFRL/RV)
- Information Directorate (AFRL/RI)
- Materials & Manufacturing Directorate (AFRL/RX)

Thermoelectric Efficiencies

If you want to cool a meat locker, use vapor compression cycle.
If you want to cool a hot dog, use a thermoelectric.

Specific Power:

High Eff. Stirling 25 kW est.:	220 W/kg
NASA Stirling 5 kW System:	140 W/kg
Bi-Te Thermeoelctric 14.7 W:	300 W/kg

Similarly, thermoelectric energy harvesting on small scale can be better than other options.

UAV ~ 100W generator based on waste heat reutilization.
Replace mechanically based generator.
(ongoing program)

Notion that thermoelectrics are inefficient is misguided – question of scale.

Ming Xie and Dieter Gruen, J. Phys. Chem. B, 2010,..

Scramjet Characteristics
Power and Thermal Challenges

- **X-51 Waverider: Longest duration scramjet flight 2+ minutes at Mach 5**
- **High Speed Strike Weapon**

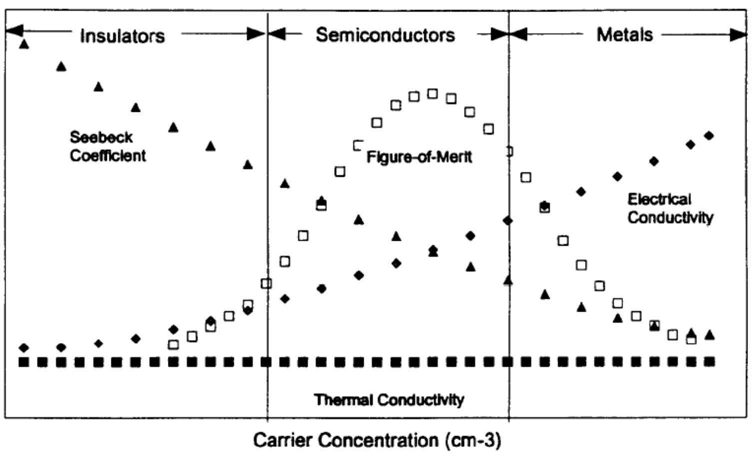
Thermal
- High temperature heat loads
  - Large surface area
  - ΔT - array of fuel cooling paths
- Heat capacity of fuel as heat sink
- Air inlet drag limitations
- Altitude - convection

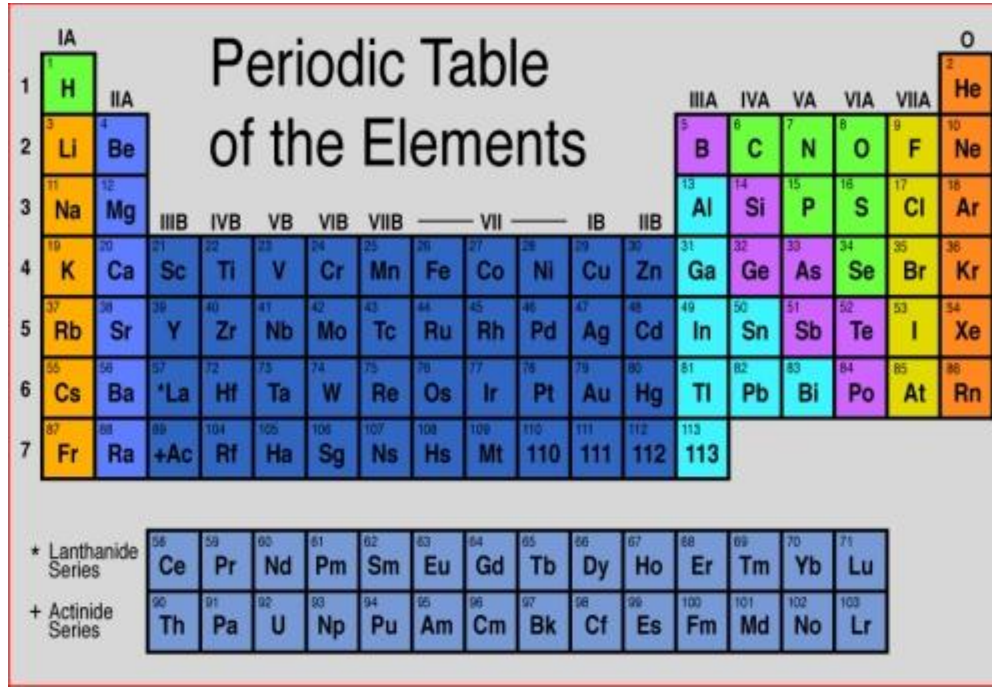
Power
- No rotating shaft
- High electrical power requirements
- Inlet air drag
- Altitude – air breathing technologies

Relation to Thermoelectric Materials

$$ZT = \frac{\left(S(T)\right)^2 \cdot \sigma(T)}{\kappa_e(T) + \kappa_l(T)} \cdot T$$

We want a phonon glass, electron crystal material.

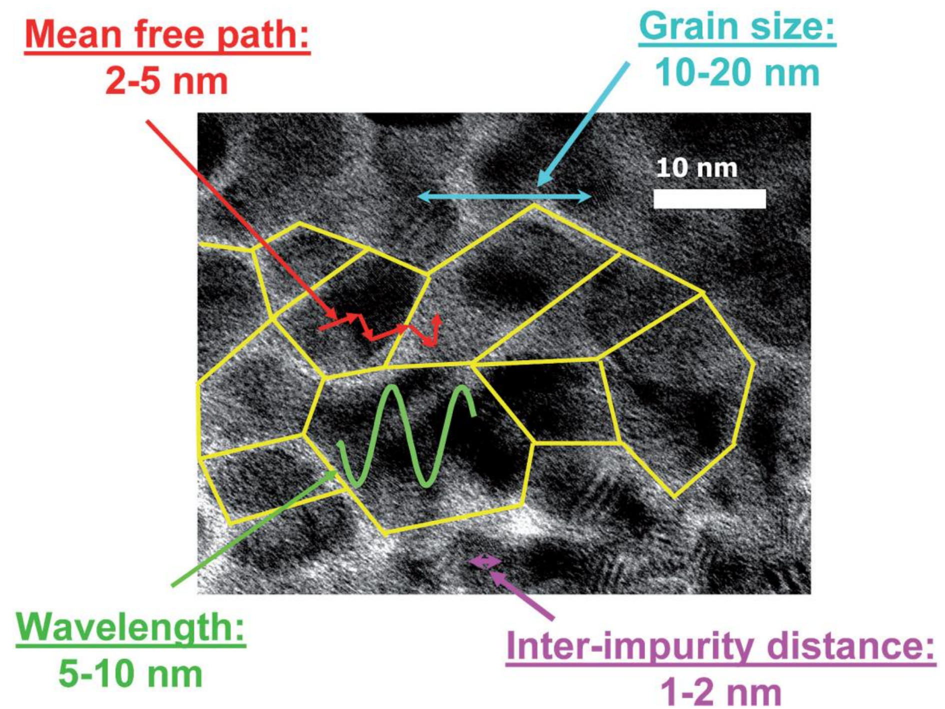


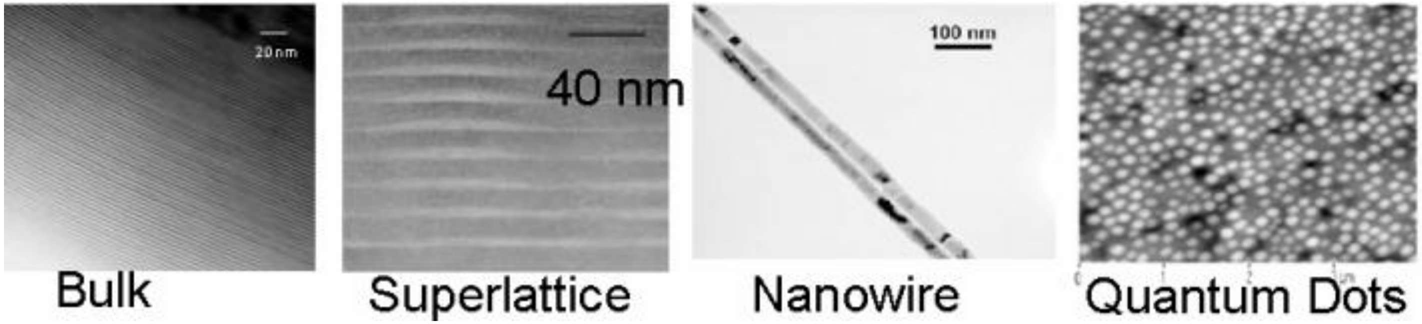


σ(T) is electrical conductivity [S/cm]
κ(T) is thermal conductivity [W/(m*K)]
S(T) is the Seebeck coefficient/thermopower [μV/K]

Current Approaches

- **Decreasing thermal conductivity contribution**
  - **Nanostructing**
    - **Superlattices (2D), nanowires (1D), and quantum dots (0D)**
  - **Doping with heavier element**
    - **Allows for lower sound velocities**
    - **i.e. $Bi_xSb_{2-x}Te_3$, $Si_{80}Ge_{20}$**
- **Electron Filtering**



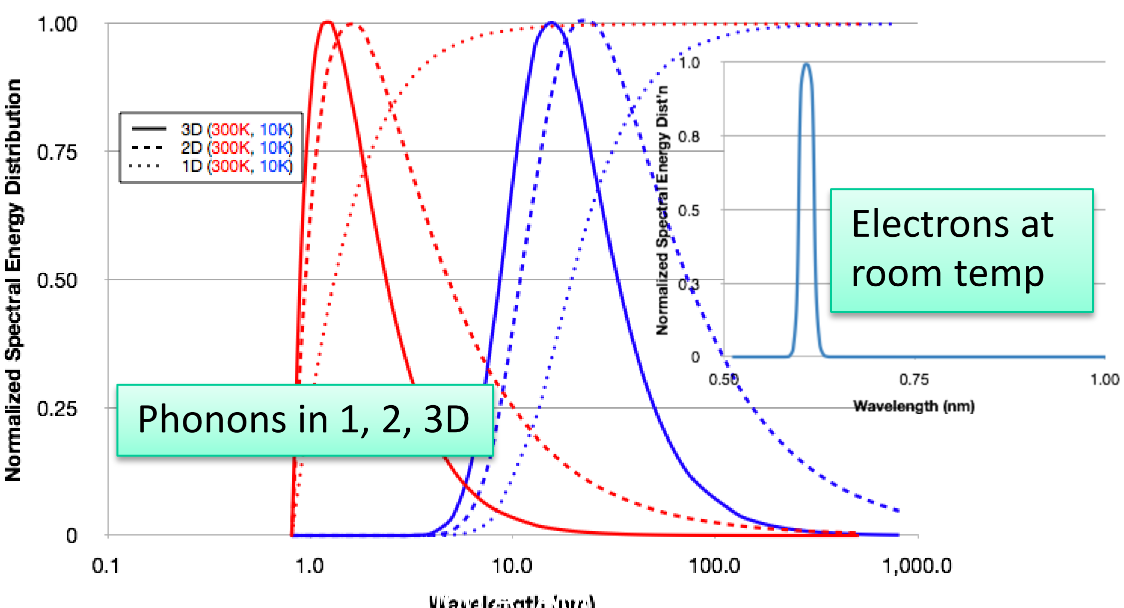


Phonon Glass Electron Crystals

PGEC: ***G. A. Slack, in "CRC Handbook of Thermoelectrics," edited by D. M Rowe (CRC Press, London), 1995, p. 407.***

An ideal thermoelectric material will behave like a crystal in terms of electrical conductivity, but will behave like a glass in terms of thermal conductivity.

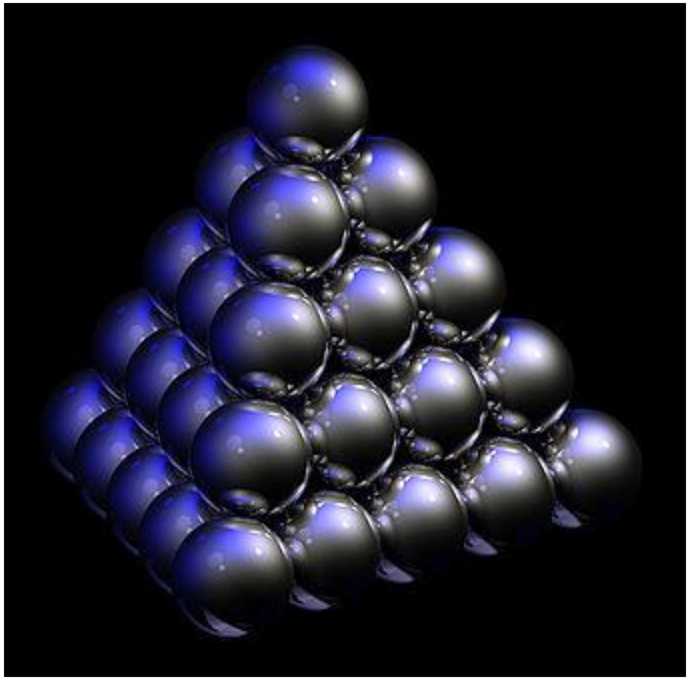
Electron wavelengths and phonon wavelengths are very different : *can be decoupled*.

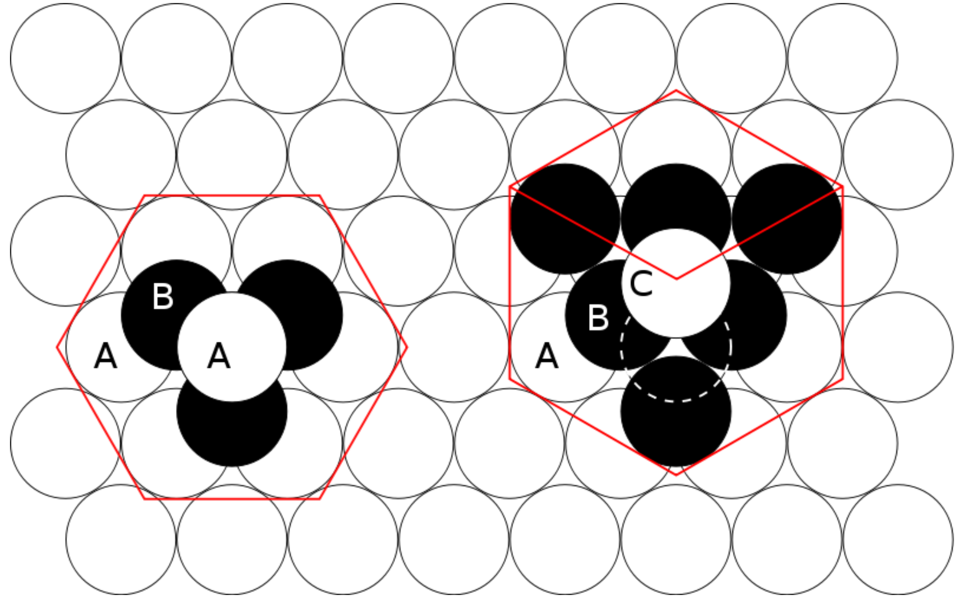


High σ / High κ Graphite Silver	High σ / Low κ ???
Low σ / High κ Diamond	Low σ / Low κ Polymers Molecular Matls

Fullerides as PGECs

Closest Packing Considerations: AgI Fast Ion Conduction





http://en.wikipedia.org/wiki/Close-packing

Silver Iodide: Great Example of Size Mismatch in CP Structures

Room Temperature: Wurtzite Structure

Ag^+ 1.15 A (115 pm)

Above 147 C, NaCl Structure

I^- 2.20 A (220 pm)

Becomes Fast Ion Conductor (the silver sub-lattice melts)

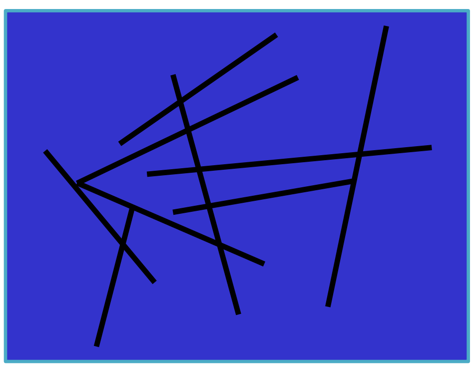
Diminished Thermal Conductivity in Nanowires
Importance of Interfaces

Silicon Nanowires as Efficient Thermoelectric Materials

A. I. Bouka, Y. Bunimovich, J. Tahir-Kheli, J.-K. Yu, W. A. Goddard, J. R. Heath, ***Nature Letters***, ***451***, 2008, 168-171.

Enhanced Thermoelectric Performance of Rough Silicon Nanowires

A. I. Hochbaum, R. Chen, R. D. Delgado, W. Liang, E. C. Garnett, M. Najarian, A. Majumdar, and P. Yang, ***Nature Letters***, ***451***, 2008, 163-168.



- Diameter of nanowire < phonon mean free path
- Charge can hop (real particle); phonon can't

"While nanostructured thermoelectric materials can increase ZT>1, the materials (Bi, Te, Pb, Sb and Ag) and processes used are not often easy to scale to practically useful dimensions."

Build Thermoelectric Materials Incorporating Superatoms

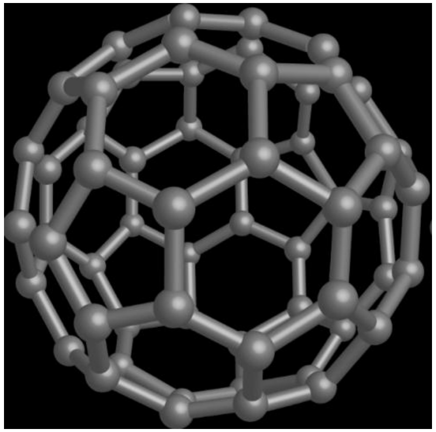
Superatoms ~ cluster than can behave as a unit / have characteristics similar to an atom.

Diamond
CNTs (Parallel)

~ 2000+ W/mK

CNTs (vdW)

~ 10 W/mK



Buckyball

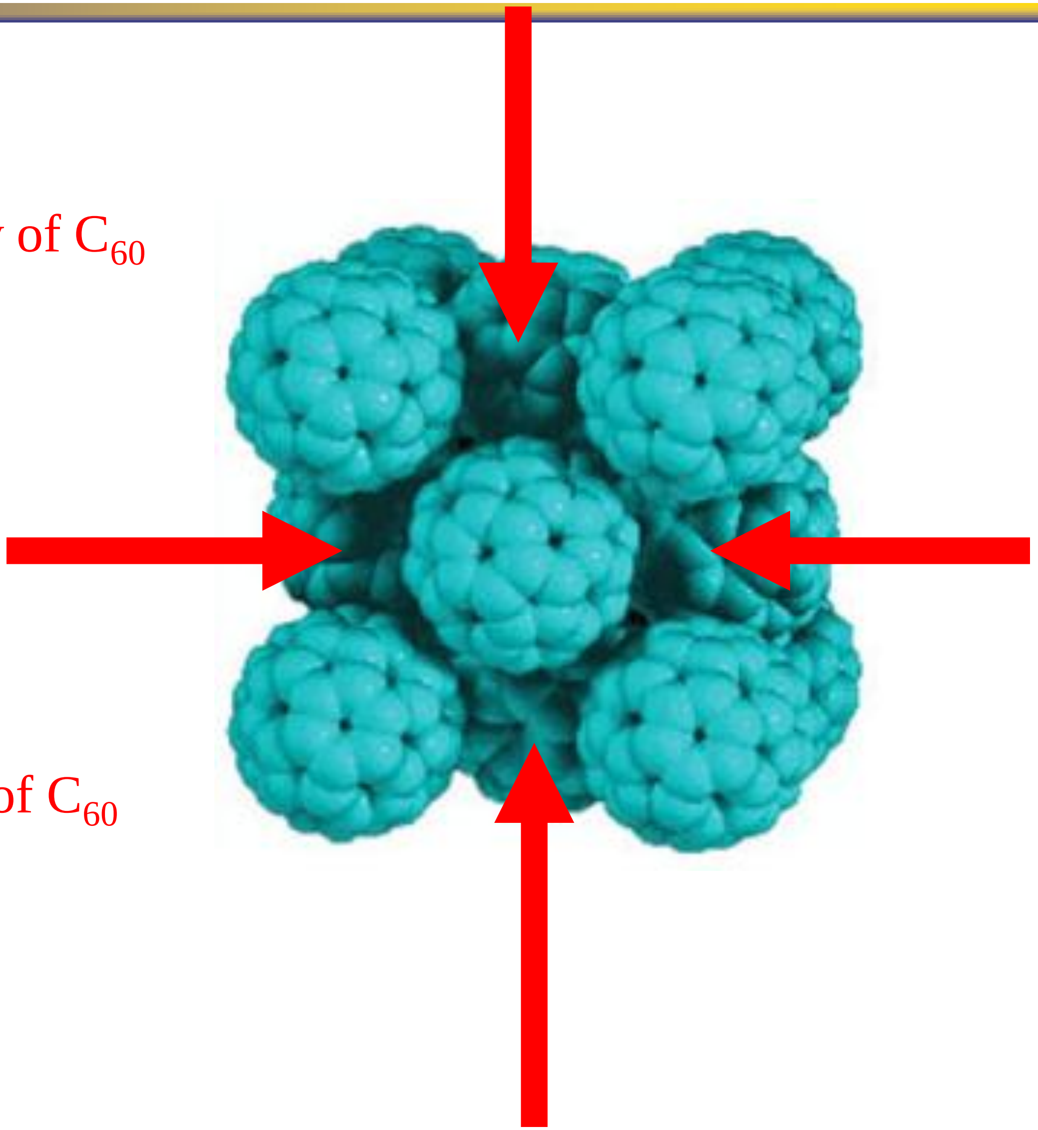
~ 0.5 W/mK

While fullerenes can be thought of as closest packing like atomic closest packing, there is a size mismatch relative to thermal energy transport. Within a buckyball, coupling length ~ 0.14 nm, but from inter-buckyball length ~ 1.5 nm.

C_{60} Characteristics

Goal: Increase electrical conductivity of C_{60}

How? **Fulleride formation**



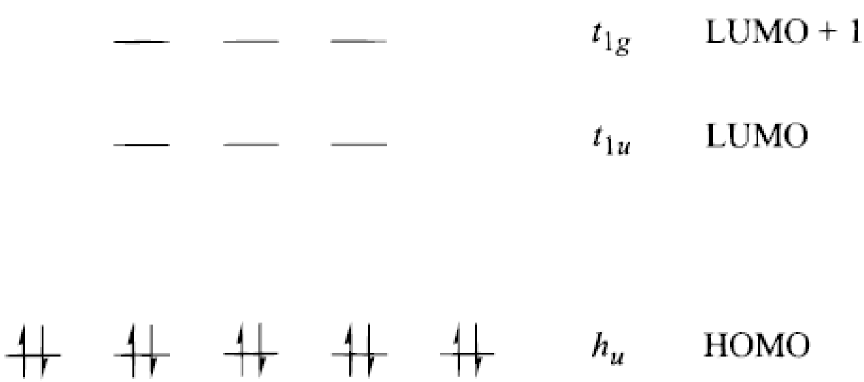
Goal: Decrease thermal conductivity of C_{60}

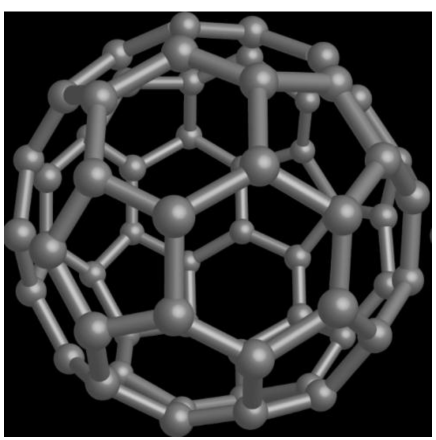
How? **Fulleride formation**

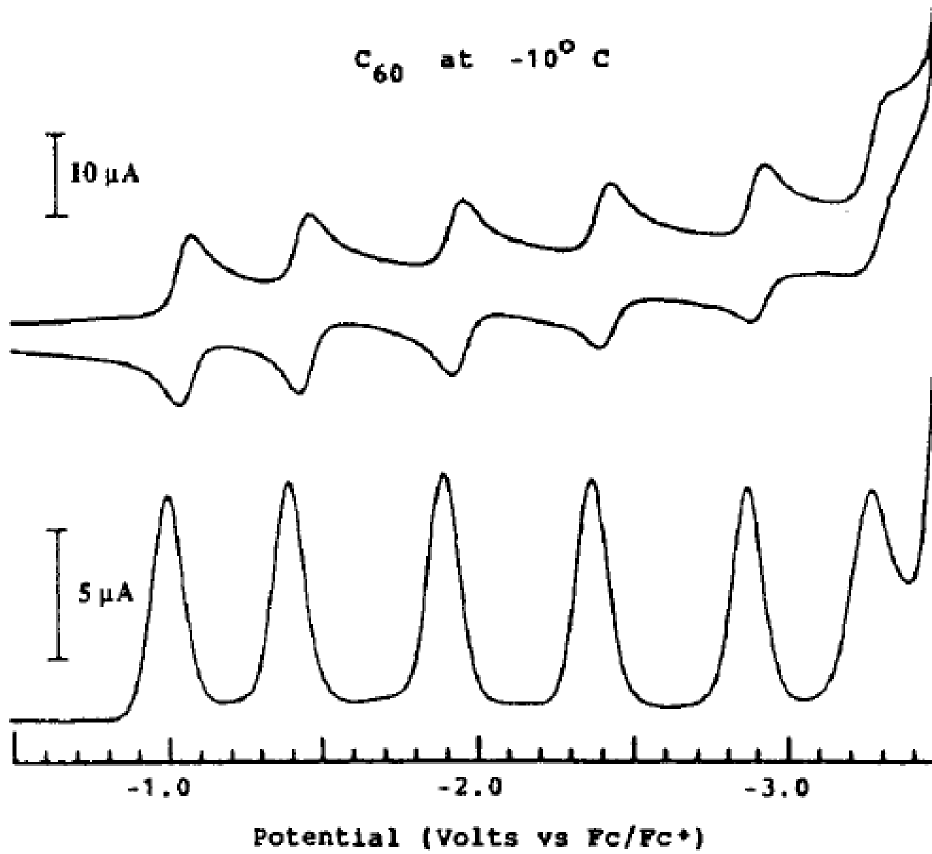
Fullerides as PGECs

Why C_{60}?

- Inherently low thermal conductivity
- Similar to skutterudites
- Multiple charge/spin states

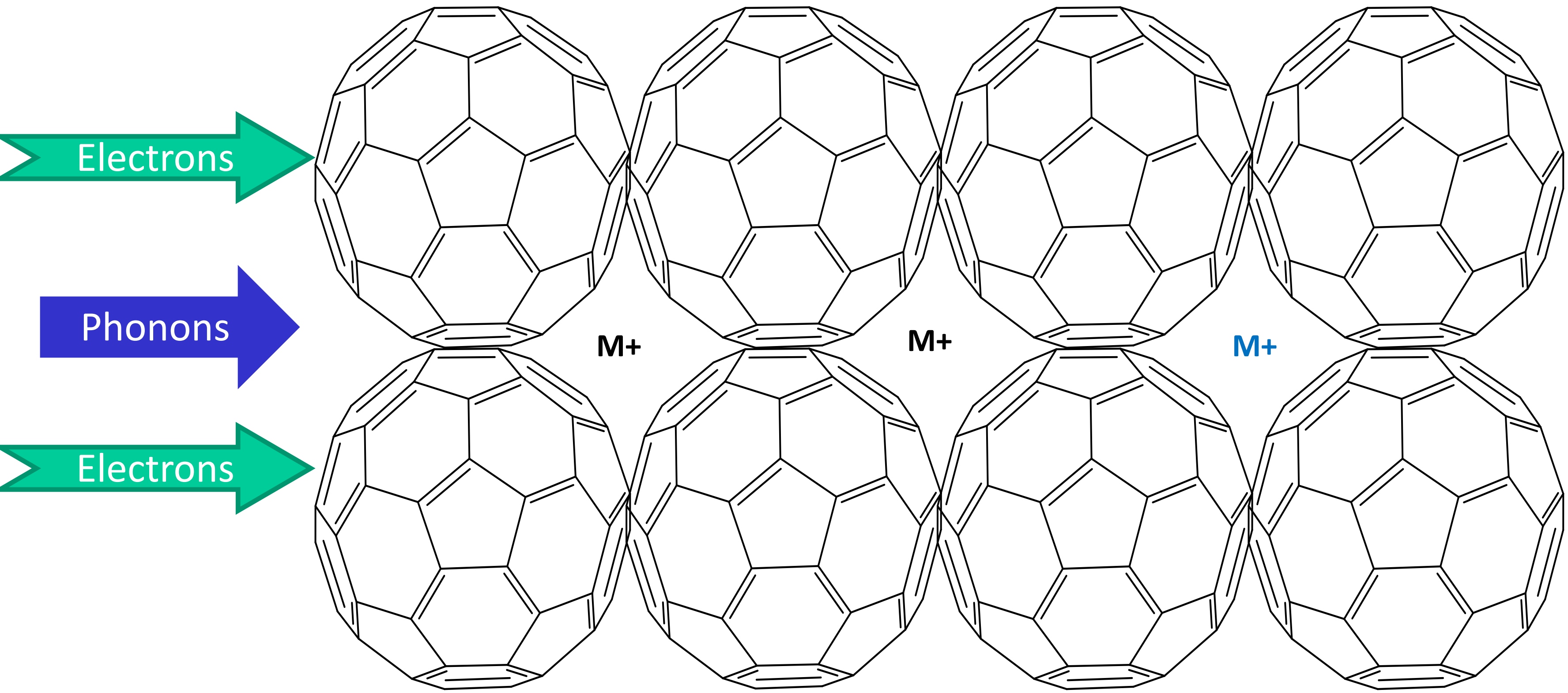






Potential for Jahn-Teller Distortion:
"Selective e-phonon coupling" ?

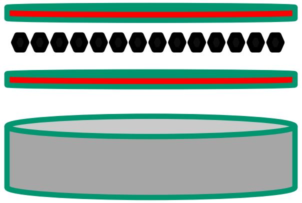
Rattler Effect in Fullerides



- Gigantic Rattler Effect?
- Alloying Enhancements (Lowering) of κ
- Uncouples electron and & phonon transport

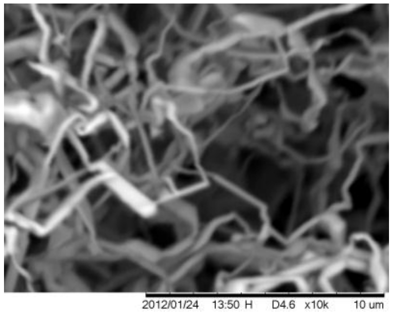
Synthesis of Materials

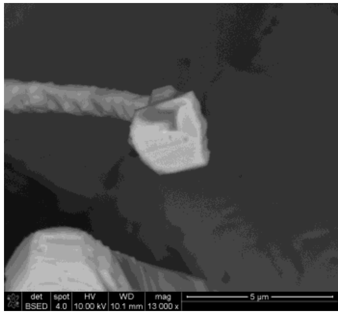
- Thin Film
  - Performed in a deep vacuum deposition chamber
  - Used magnetron sputtering to deposit zinc and thermal evaporator to deposit C_{60}



- Wet Synthesis
  - Based on redox potentials of transition metals

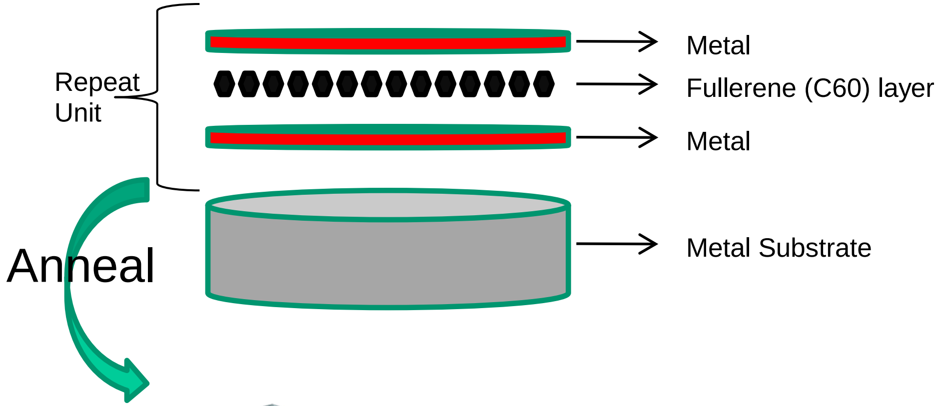
- Chemical Vapor Deposition
  - Grown in a process using a zoned furnace system and vacuum system





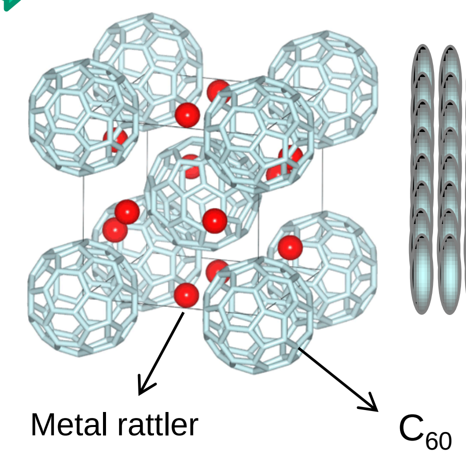
High Electrical Conductivity Phonon Blocking Layers

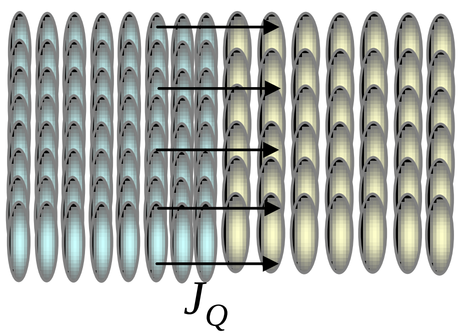
Objective: Demonstration of high electrical conductivity, low thermal conductivity phonon-blocking layer (PBL) formation through novel deposition and annealing techniques

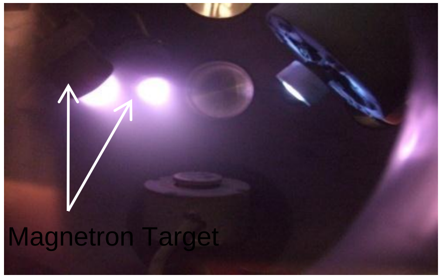


Novel concepts addressed :

- Incorporation of nanoparticle scattering sites inside a thin film structure
- Demonstration of a air stable metal fulleride (Zn C_{60})
- Demonstration of low thermal conductivity and high electrical conductivity of fulleride (rattlers)
- Demonstrate the use of thin film deposition technique for use in combinatorial analysis.

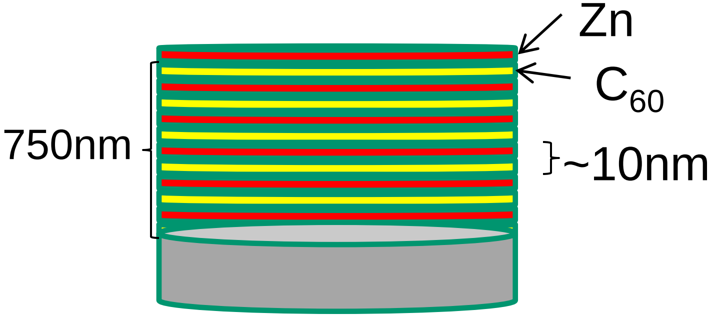




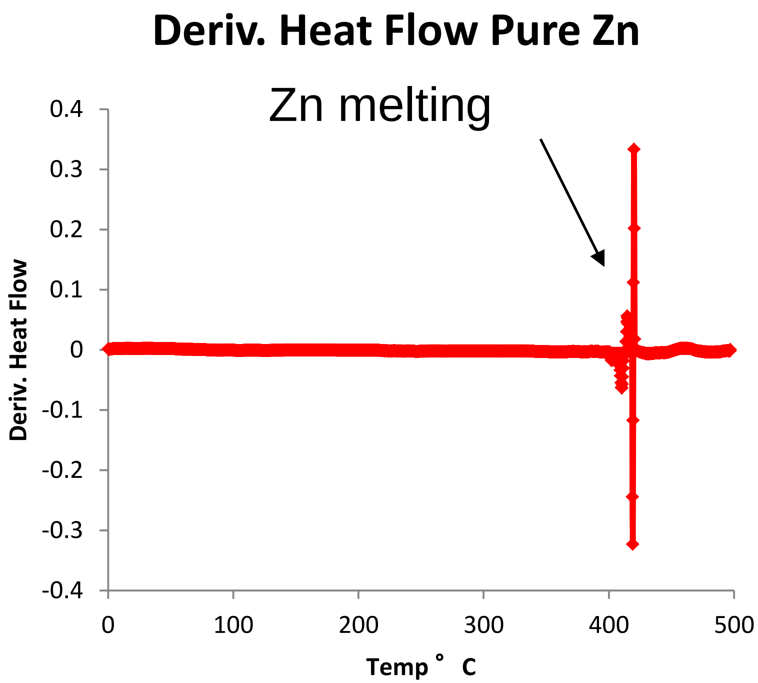


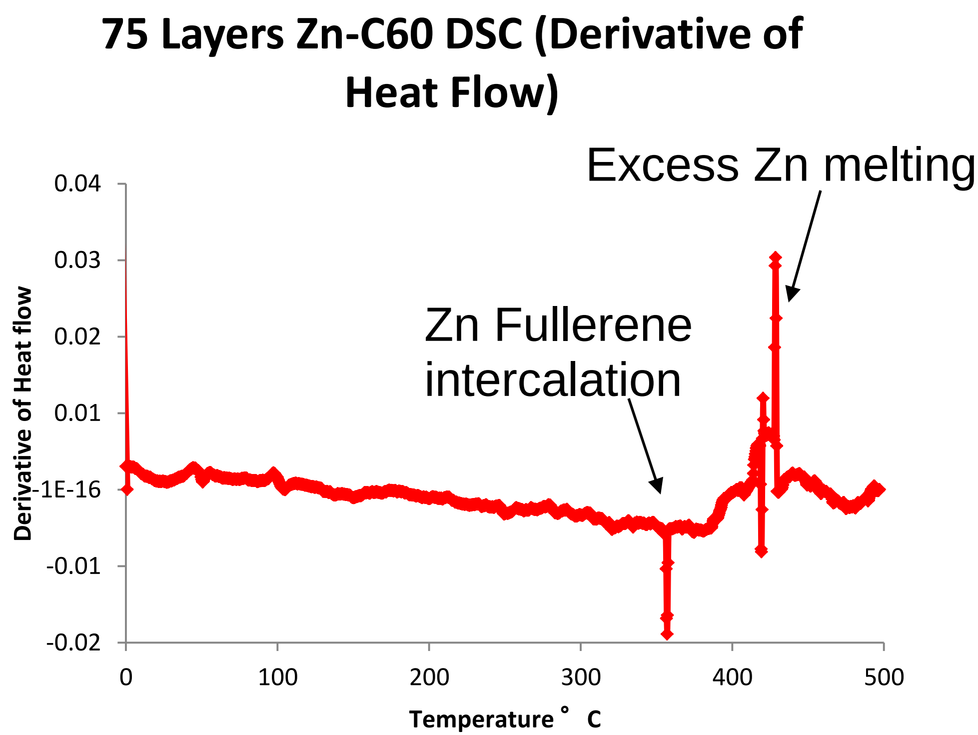
$$Z = \frac{S(T)^2 \sigma(T)}{\kappa(T)}$$

DSC of Zn C_{60} layers

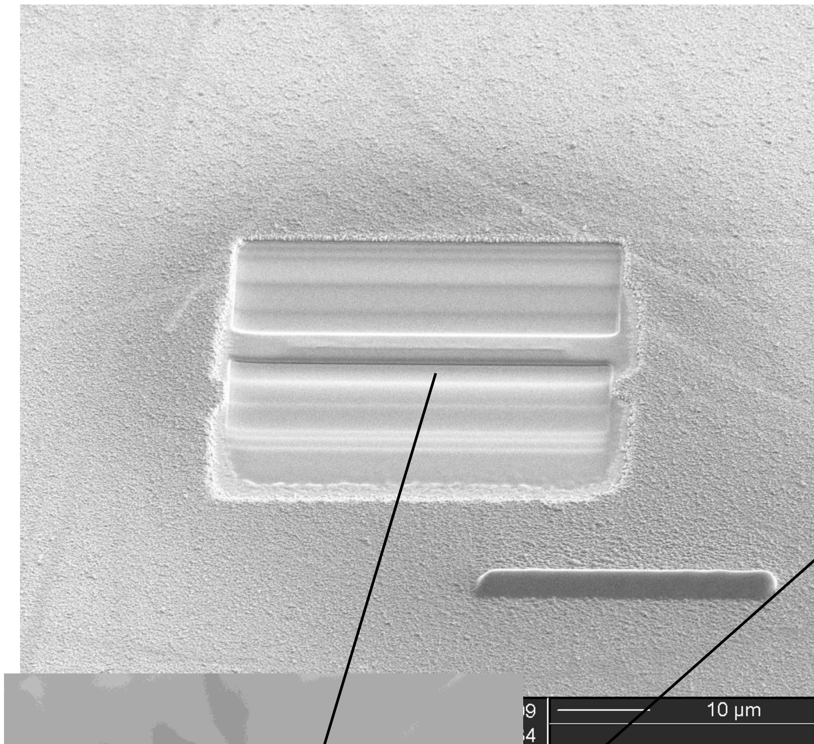


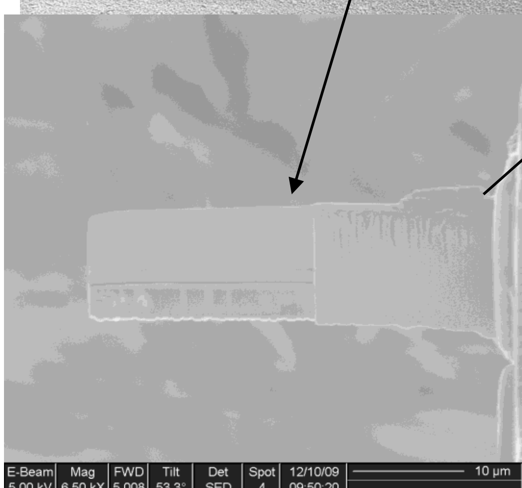
- Sample made with 75 layers. Each layer was ~10nm thick with alternating Zn/C_{60}
- Looking for exotherms and endotherms on DSC to confirm Zn intercalation into the C_{60}

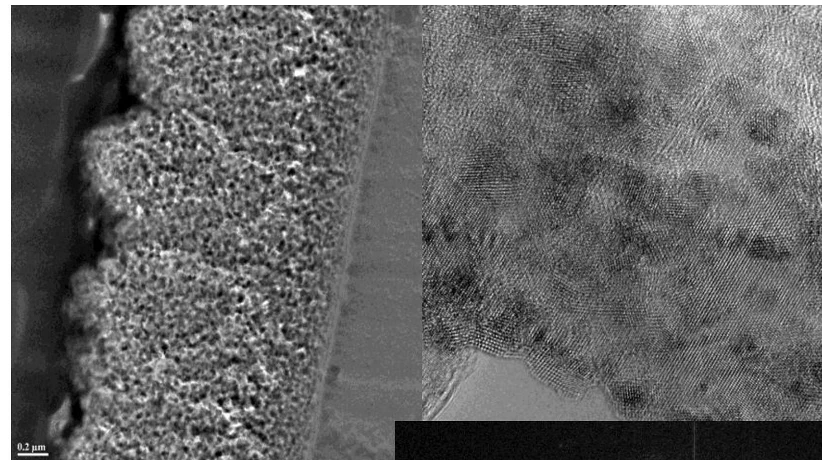


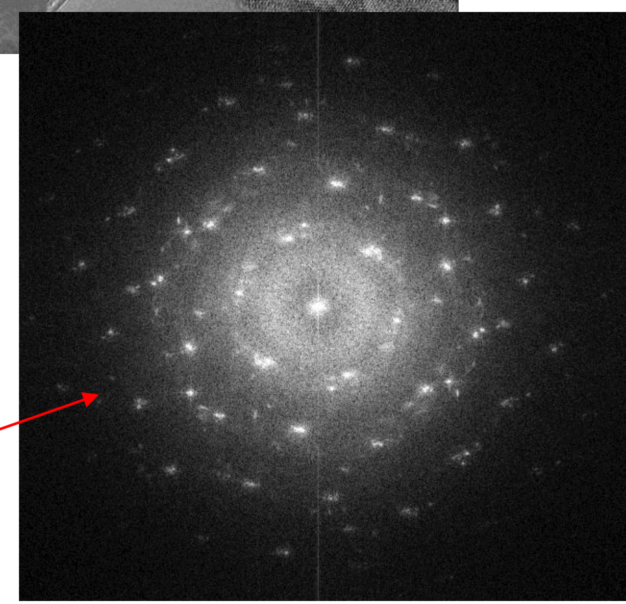


TEM and e$^-$ Diffraction





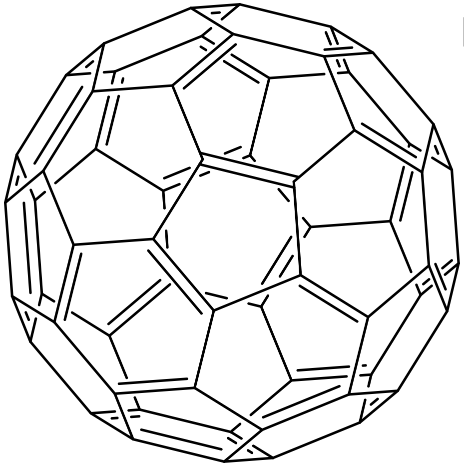




Does not show a separate phase for Zn

Wet Chemical Approaches

Reactants and solvent was mixed together in glove box to remove all oxygen



C_{60}
34 mg (0.047 mmol)

+ $Zn_{(s)}$
130 mg (2 mmol, excess)

+ NaOH
400 mg (10 mmol)

$\xrightarrow{\text{20 mL of THF}}$

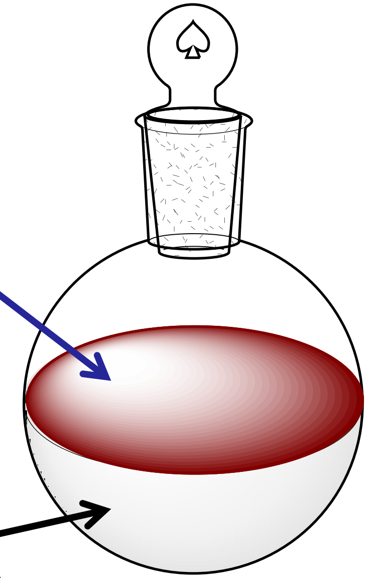
Reactants do not dissolve in THF, vial is sealed with a septum and removed from glove box

5 mL of de-oxygenated water is added via syringe

- Water was boiled for 20 minutes to removed non-condensed gases, then cooled and mineral oil was added to the surface, then nitrogen was bubbled through water for 30 minutes

$Zn \rightarrow Zn^{2+} + 2e^{-} = +0.76$ V

Rapid reaction occurred, H_2 gas evolved, two layers produced

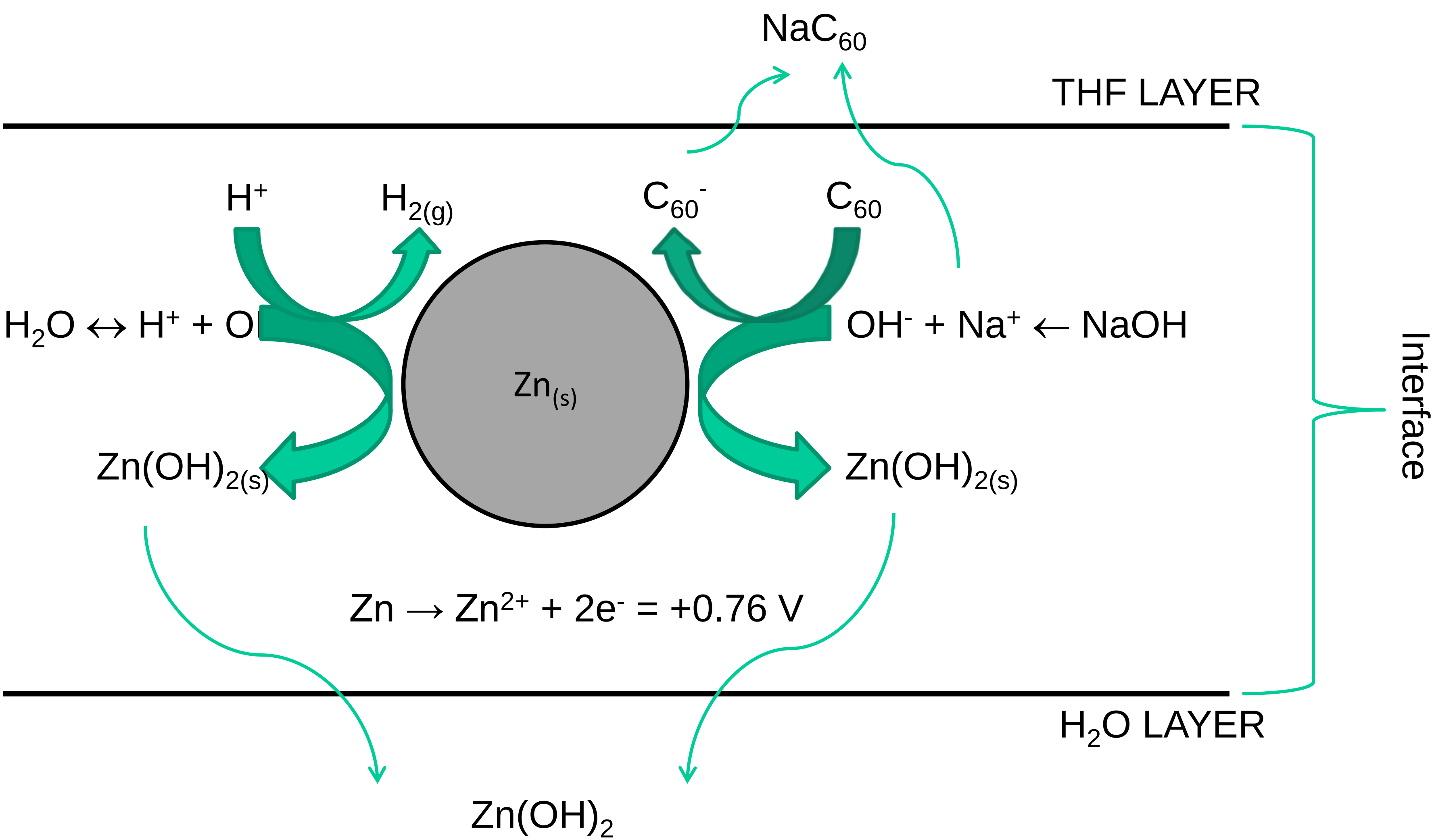


Top Layer:
THF + NaC_{60}

Bottom Layer:
$H_2O + Zn(OH)_2$ + unreacted starting material

Mingfei Wu, Xianwen Wei, Ling Qi, and Zheng Xu, *Tetrahedron Letters*, Volume 37, Number 41, pages 7409 – 7412.

Proposed Mechanism of Reaction



Synthetic Protocol for Metal Fullerides

Procedure: Based on Redox Potentials of Starting Materials and Solvents and Activity Series of Metals Involved

Reactants and solvent was mixed together in glove box to remove all oxygen

$Zn(NO_3)_2$ + NaOH

C_{60} + $Zn_{(s)}$ + $Zn(OH)_2$

34 mg (0.047 mmol) 130 mg (2 mmol, excess) 1 g (10 mmol)

20 mL of THF

Reactants do not dissolve in THF, vial is sealed with a septum and removed from glove box

5 mL of de-oxygenated water is added via syringe

- Water was boiled for 20 minutes to removed non-condensed gases, then cooled and mineral oil was added to the surface, then nitrogen was bubbled through water for 30 minutes

Reaction occurred much slower, H_2 gas evolved, two layers produced to an extent

Sodium Nitrate Contaminents!

Top Layer = THF + $Zn_x(C_{60})_y$

Bottom Layer = H_20 + $Zn(OH)_2$ + unreacted starting materials

Standard Reduction Potentials for Fullerene

$E_{1/2}$ of various C_{60} anions in solvents in 0.1 M $(TBA)ClO_4$				
Solvent	C_{60}^{0}/C_{60}^{-}	C_{60}^{-}/C_{60}^{2-}	C_{60}^{2-}/C_{60}^{3-}	C_{60}^{3-}/C_{60}^{4-}
THF	-0.33	-0.92	-1.49	-1.99
THF	-0.35	-0.93	-1.43	-2.01
DMF	-0.26	-0.72	-1.31	-1.85
DMSO	-0.16	-0.66	---	---

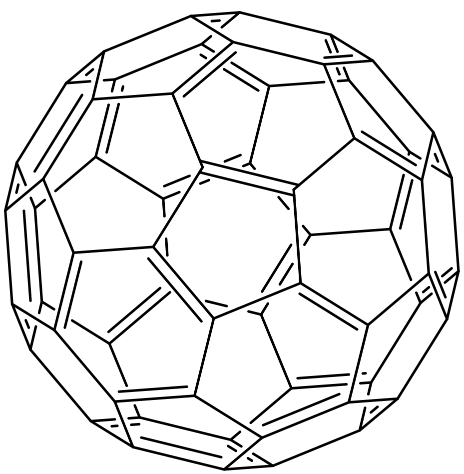
Reduction Potentials of C_{60}				
Solvent	C_{60}^{0}/C_{60}^{-}	C_{60}^{-}/C_{60}^{2-}	C_{60}^{2-}/C_{60}^{3-}	C_{60}^{3-}/C_{60}^{4-}
ACN	---	-0.735	-1.225	-1.685
DMF	-0.312	-0.772	-1.362	-1.902
Aniline	-0.396	-0.693	-1.158	-1.626
Benzonitr.	-0.397	-0.817	-1.297	-1.807
DCM	-0.468	-0.858	-1.308	-1.758
THF	-0.473	-1.063	-1.633	-2.133
Chlorofor.	-0.554	-0.908	---	---

Aprotic Polar Solvents
Dichloromethane
Tetrahydrofuran
Ethyl Acetate
Acetone
DMF
Acetonitrile
DMSO

Reaction seems to prefer certain aprotic polar solvents

Standard Reduction Potentials for Viable Metals

Reduction Potential for Metals in Water	
Half-Reaction	**E° (V)**
$Fe^{2+}_{(aq)} + 2e^{-} \rightarrow Fe_{(s)}$	-0.44
$Cr^{3+}_{(aq)} + 3e^{-} \rightarrow Cr_{(s)}$	-0.74
$Zn^{2+}_{(aq)} + 2e^{-} \rightarrow Zn_{(s)}$	-0.76
$Mn^{2+}_{(aq)} + 2e^{-} \rightarrow Mn_{(s)}$	-1.18
$Al^{3+}_{(aq)} + 3e^{-} \rightarrow Al_{(s)}$	-1.66



C_{60}
0.047 mmol

+ $M_{(s)}$
2 mmol, excess

+ $M(OH)_x$
10 mmol

Synthetic Protocol for Metal Fullerides

5.00 g C_{60}
19.1 g $Zn_{(s)}$ granular
1 L THF

Placed into a 2 L round bottom flask, sealed with a septum, and removed from the glove box

150 g of freshly made $Zn(OH)_2$ needs to be synthesized

270.75 g of $Zn(SO_4) \cdot H_2O$ dissolved into 2 L of water

Add 203.75 mL of NH_4O

$Zn(OH)_2$

Re-dissolved in 1 L ammonium hydroxide

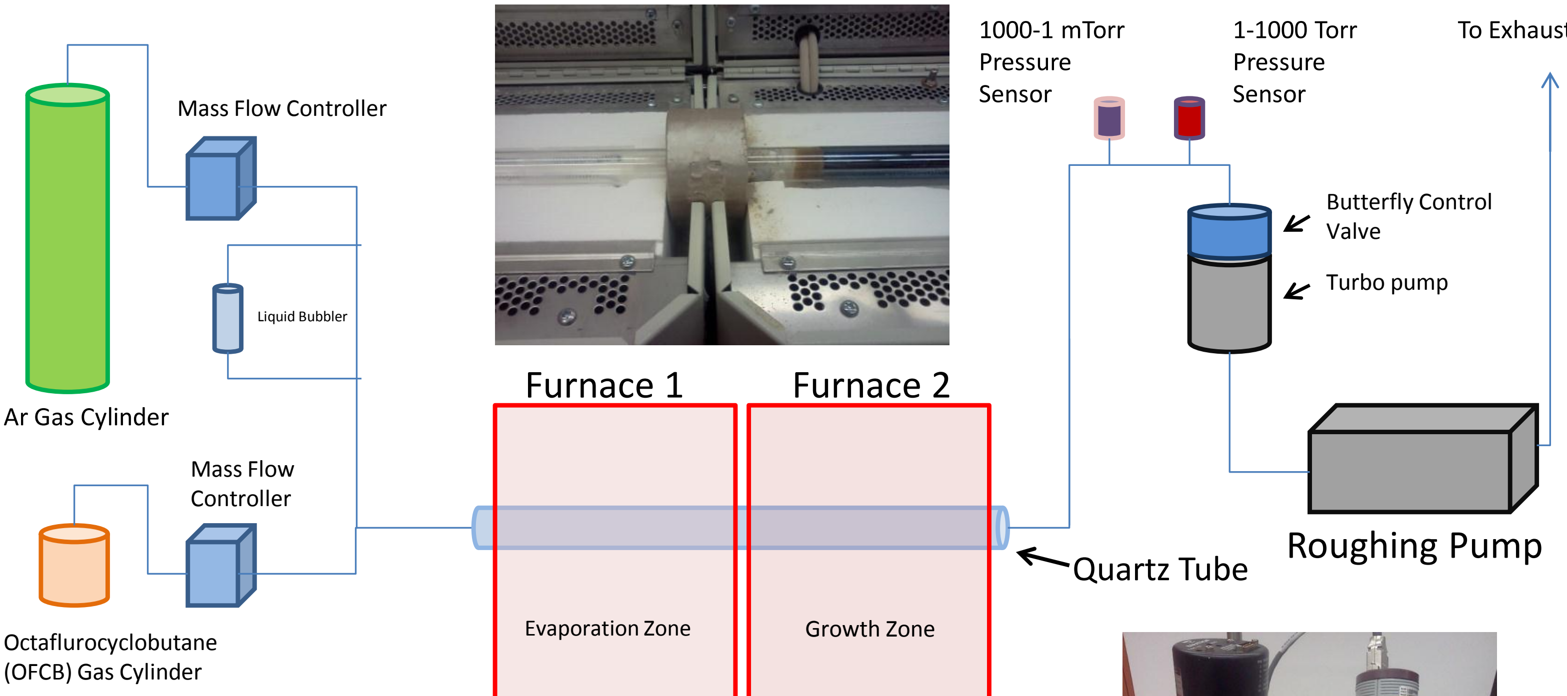
$[Zn(NH_3)_4](OH)_2$

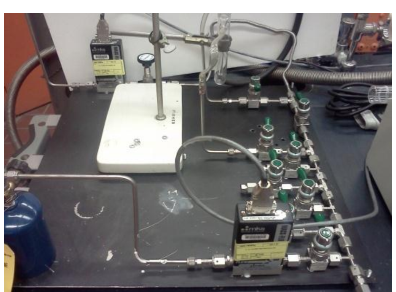
Syringed into 2 L round bottom
React at 45 ^oC for 5 days

Zinc Fulleride (+ 7 grams of product, brown powder)

Zn Nanowires +

Schematic Layout of CVD system

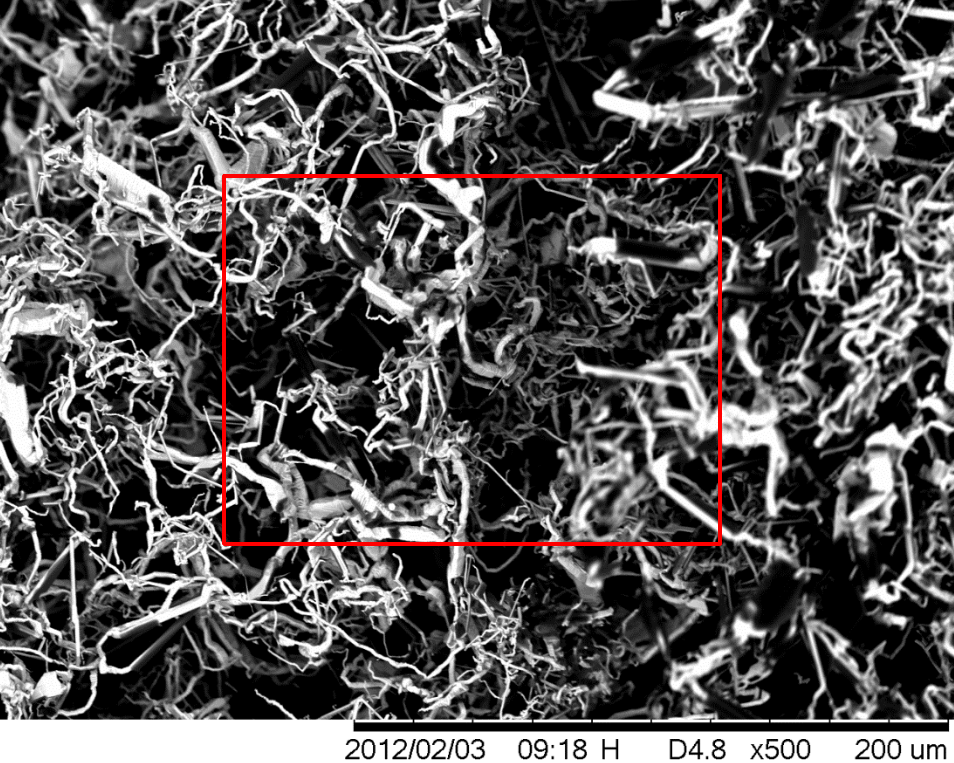




Zn wires with C60 coating

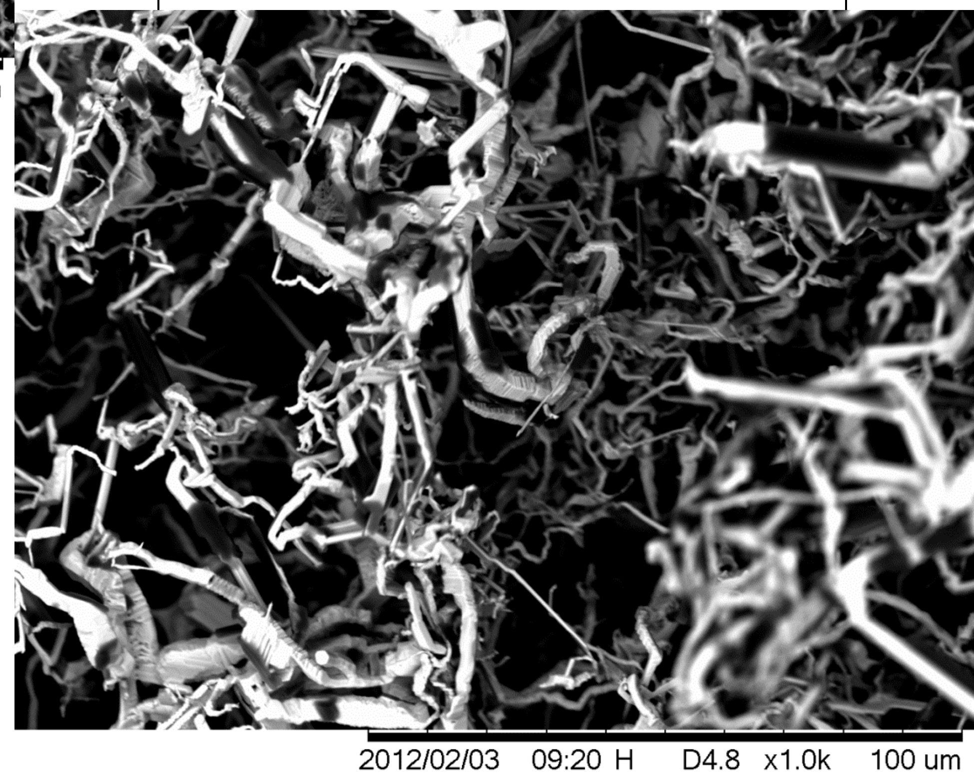
Hold Zn boat at 950° C/325° C for 15 hr
Maintain constant 3 Torr and 50 SCCM Ar
Cool to RT and swap out empty boat for C60 boat
Hold at 1000° C/350° C for 15 hr
Maintain constant 3 Torr and 100 SCCM Ar

Note:	All pictures can be enlarged while keeping good picture quality.

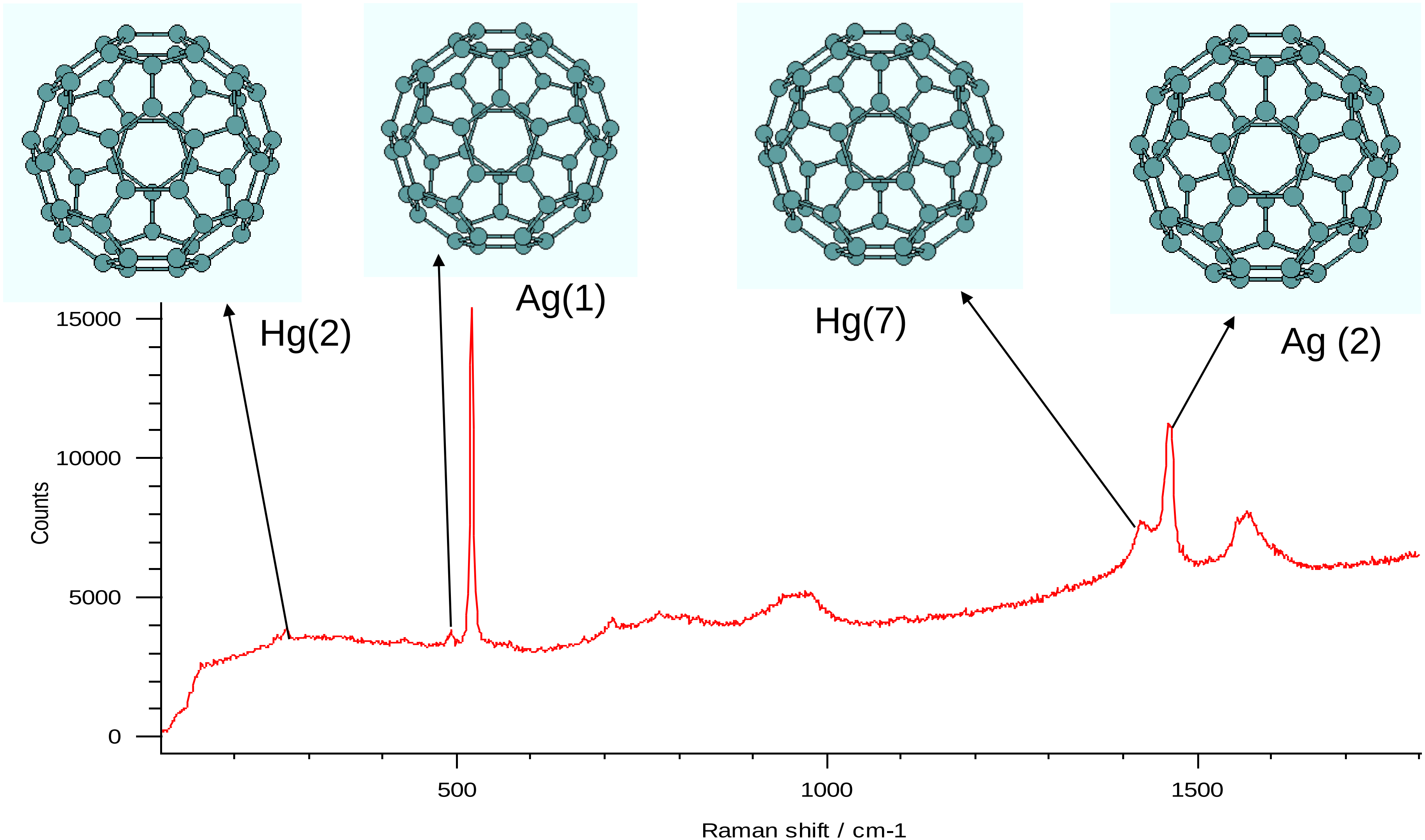


Region 1 (x500)

Region 1 (x1000)



Raman Modes in Neutral C_{60}



Raman Spectroscopy of Zn_xC_{60}

Landau damping and lifting of vibrational degeneracy in metallic potassium fulleride

J. Winter and H. Kuzmany
Universität Wien, Institut für Festkörperphysik, Strudlhofgasse 4, A-1090 Wien, Austria
(Received 21 July 1995)

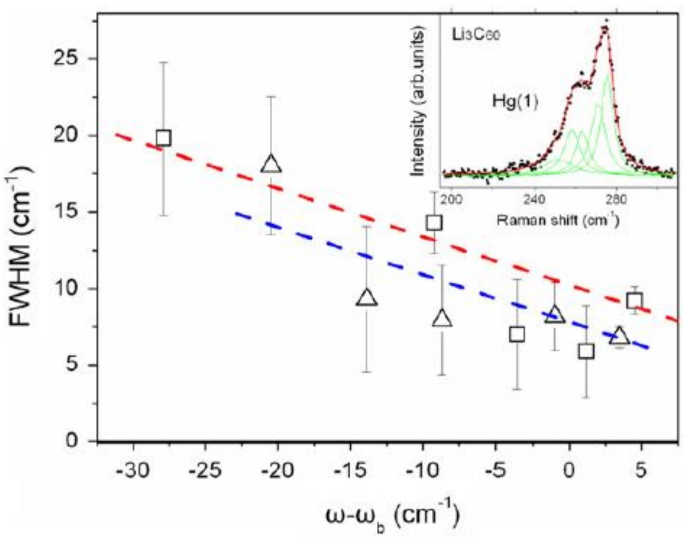
• A rather strong shift of vibrational modes as a consequence of charge transfer
• The electron-phonon interaction may well be considered in c case as the reason for the broadening and for the shift of the lines and electron-phonon coupling constants may be deduce
• For the description of the relation between phonon linewidth and electron-phonon coupling constants for a single particle excitation Allen's formula may be used

$$\gamma_i = \frac{1}{g_i}\,\frac{\pi}{2}\,N(0)\,\lambda_i\,\omega_{bi}^2$$

γ_i	Is the full width at half max of the line
$N(0)$	Density of States at the Fermi level per spin and molecule
λ_i and g_i	Dimensionless electron phonon coupling constants
ω_{bi}	Bare phonon frequency before coupling to the electrons

Raman study of the electron–phonon interaction in light alkali metal intercalated metallic fullerides

Mingguang Yao[1,2], Vittoria Pischedda[1] and Alfonso San Miguel[1]



Electron-phonon coupling uses the phonon widths measured in Raman scattering. In metallic systems a phonon can decay in an electron-hole pair excitation. The extra width due to this decay is a measure of the coupling.

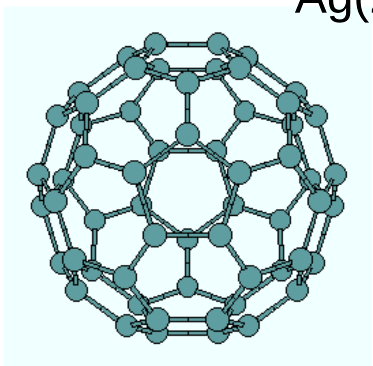
Raman Spectroscopy of Zn_xC_{60} thin film

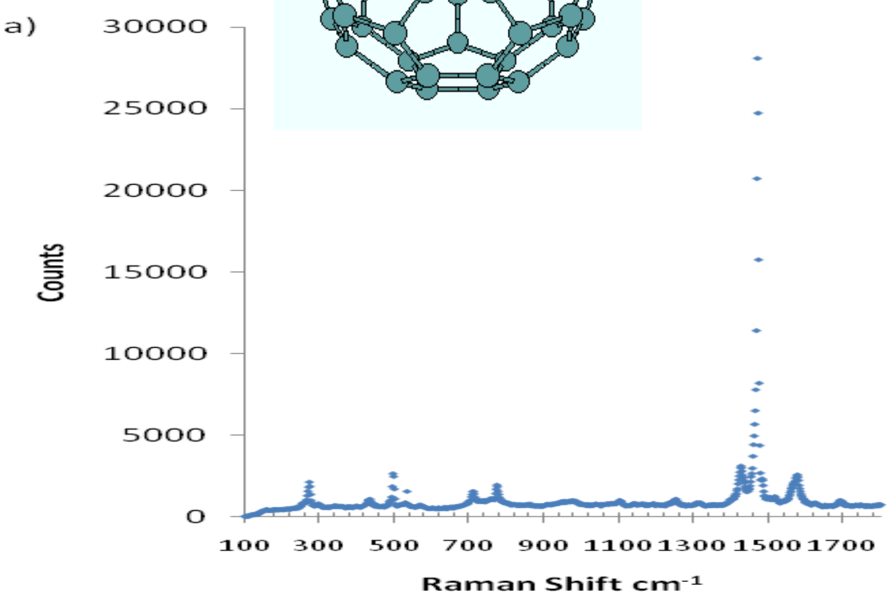
Sample is 75 Layers of C_{60} and Zn (C_{60} and Zn Layers are 10nm thick) After Annealing in furnace at 400° C

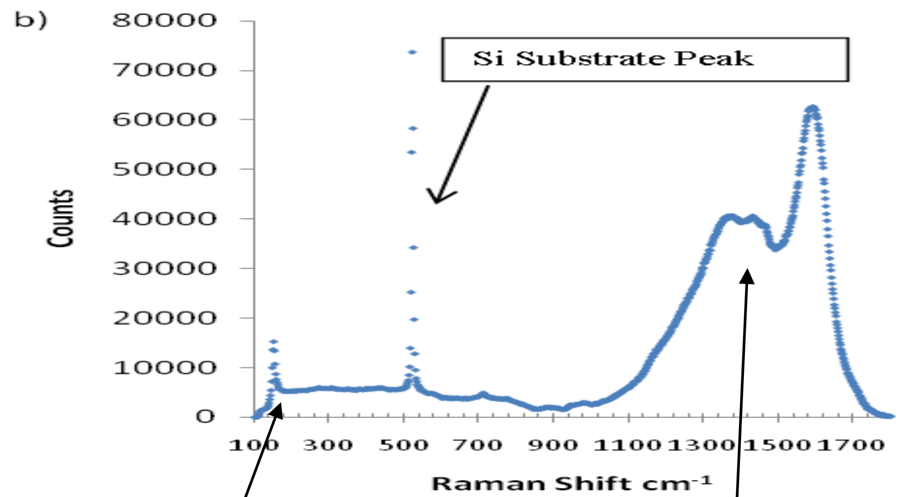
Ag(2)

Zn_XC_{60}

Neutral





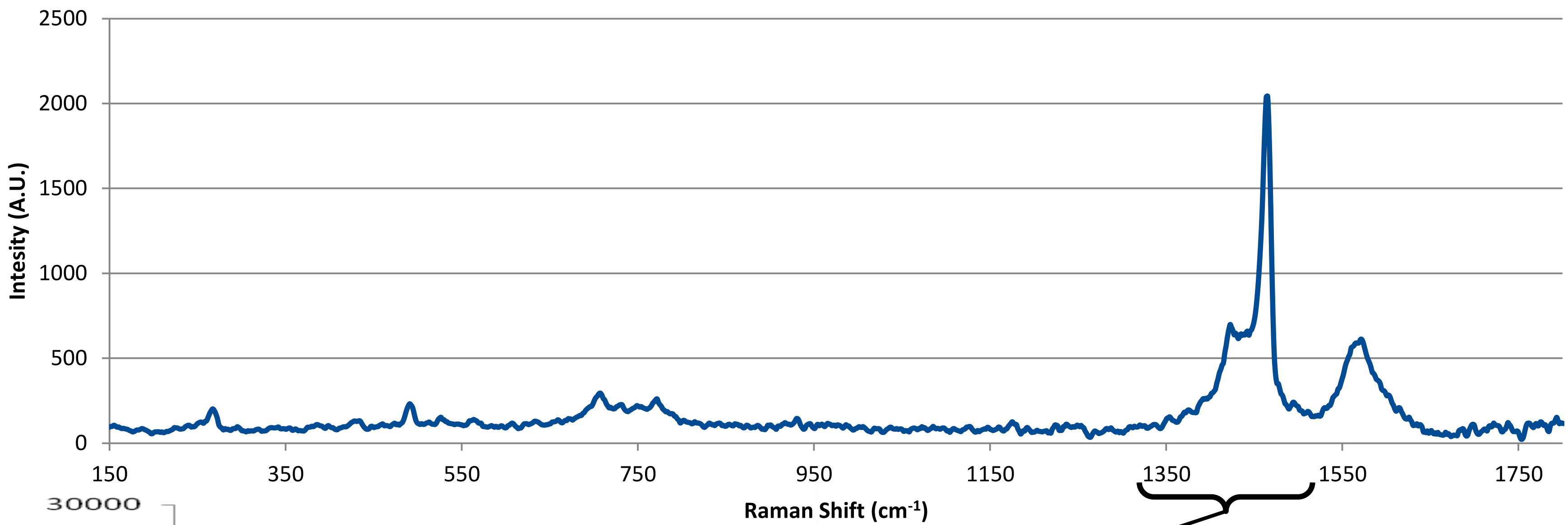


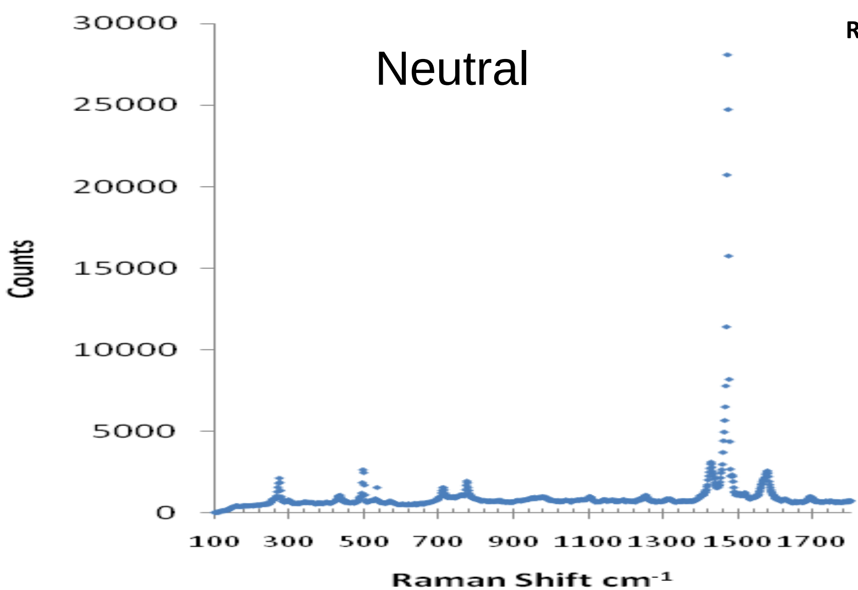
Suggested Metal – C_{60}
"Intercage" Vibration

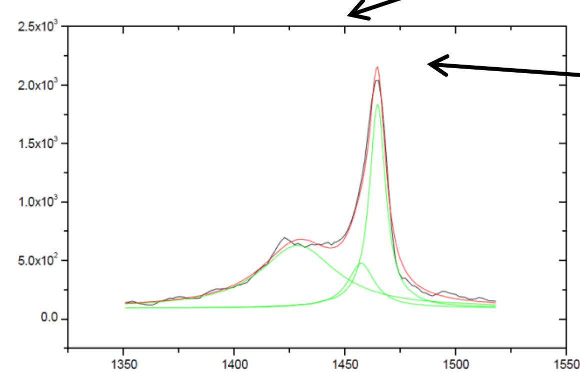
This compound shows a shift of approximately 30 cm^{-1} which would suggest that the C_{60} molecule is holding between 4 and 5 electrons advocating x = 2 – 3 for Zn_xC_{60}.

A.V. Talyzin, U. Jansson / Thin Solid Films 429 (2003) 96–101

Raman Spectroscopy of Zn_xC_{60} produced by bulk synthesis route

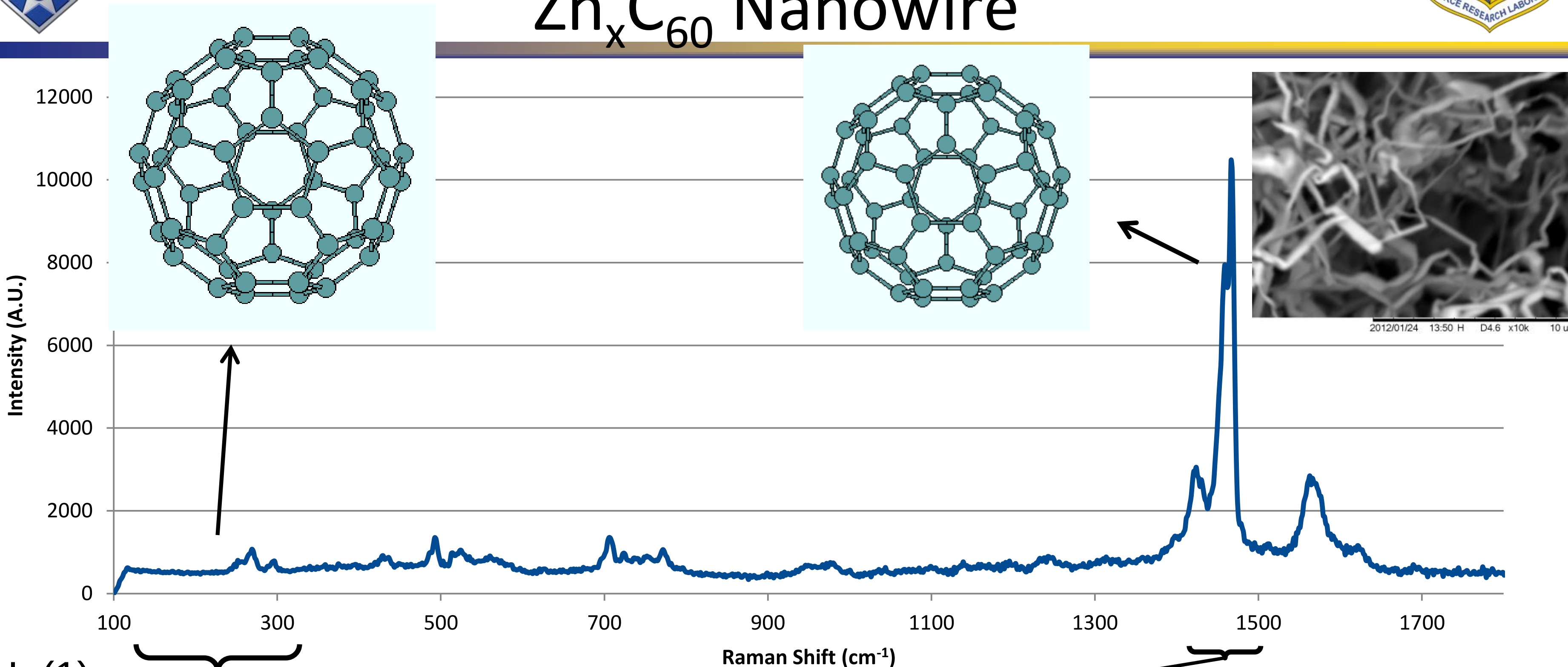




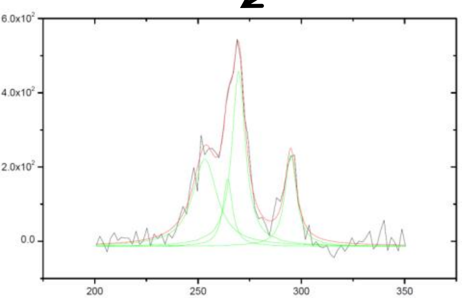


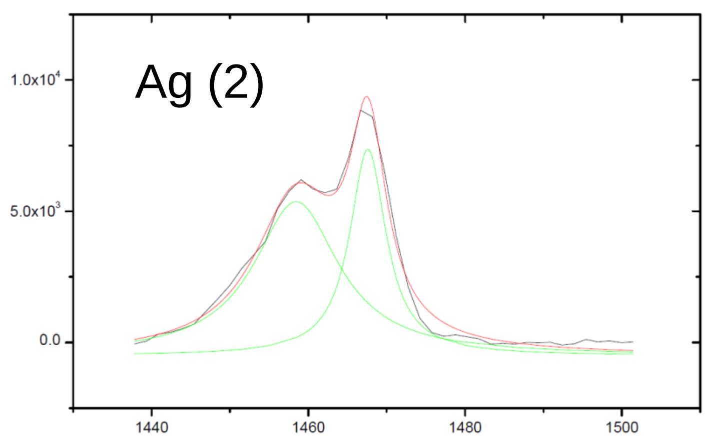
Ag(2) peak occurs at 1463 cm^{-1} suggesting there is an electron on the C_{60} molecule. This would lead to x = 0 – 1 for Zn_XC_{60}.

Raman Spectroscopy of Zn_xC_{60} Nanowire



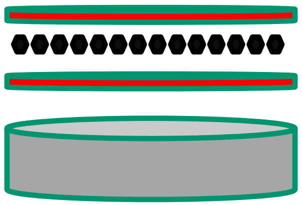
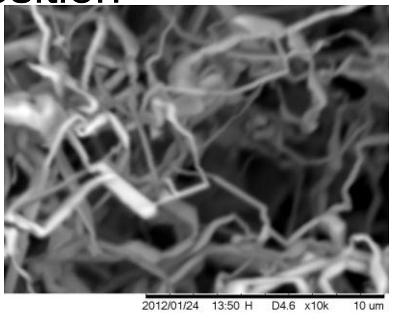
Hg(1)





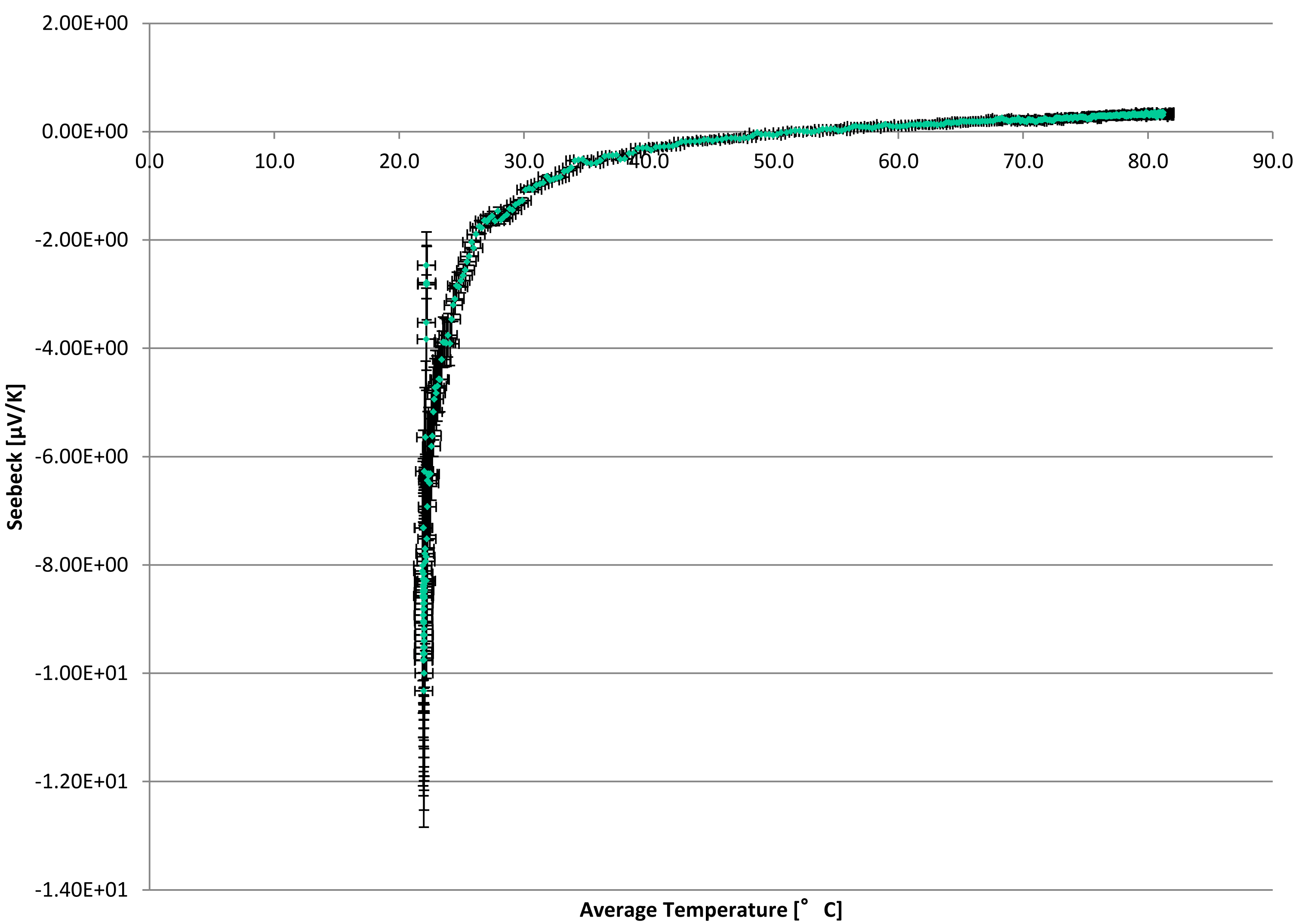
Ag(2) peak occurs at 1468 cm^{-1} and 1458 cm^{-1} which is suggestive of two C60 phases. Approximately 60% of the C60 is incorporated to the nanowire and charged. However, the remainder is most likely in a second phase and not closely associated with the majority zinc wire structure.

Thermal Properties of Fulleride Compound

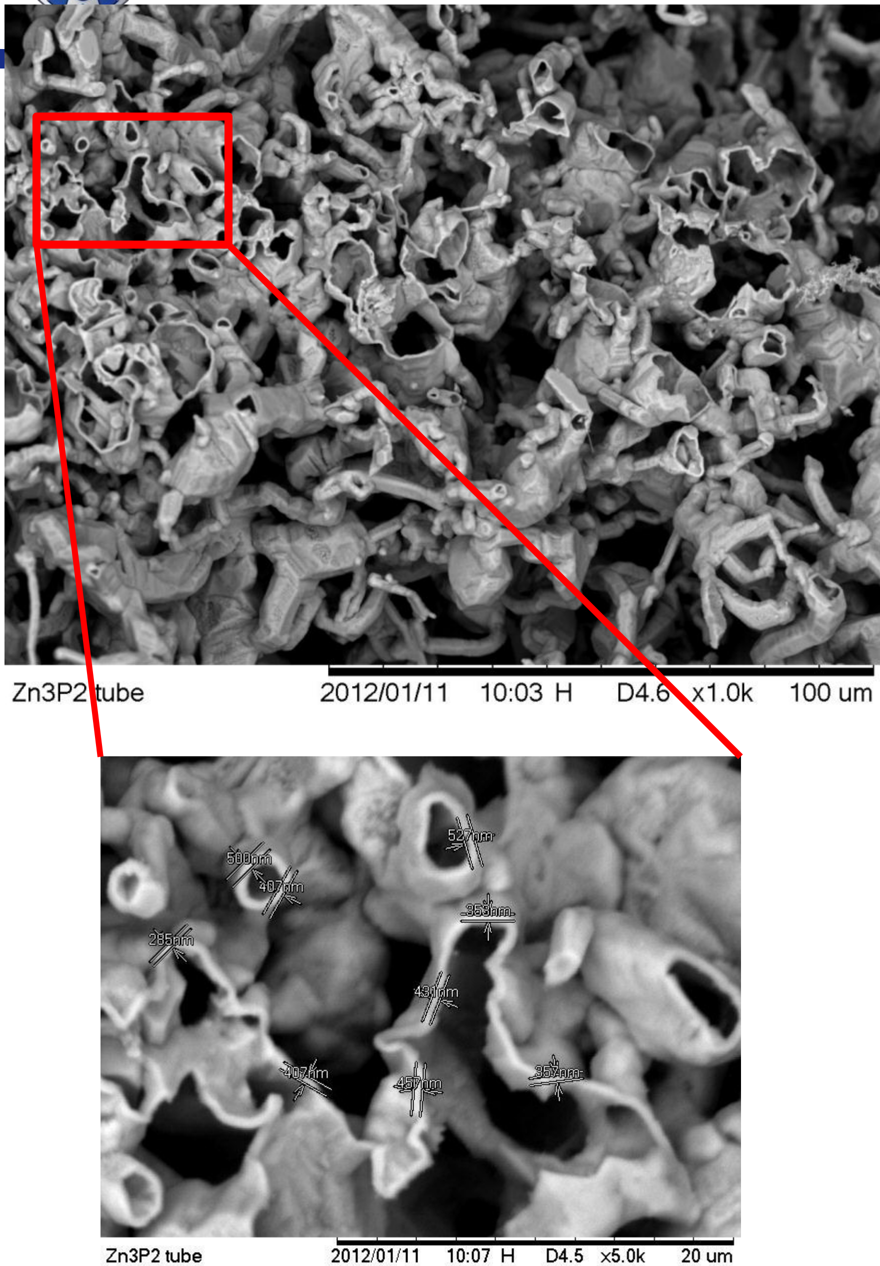
•Thin Film	•Wet Synthesis	•Chemical Vapor Deposition
		
κ = 0.13 W/(m*K)	κ = 0.24 W/(m*K)	κ = 3 – 5 W/(m*K)
TDTR	HotDisk	HotDisk

Thermal Conductivity of Glass = 1 W/(m*K)

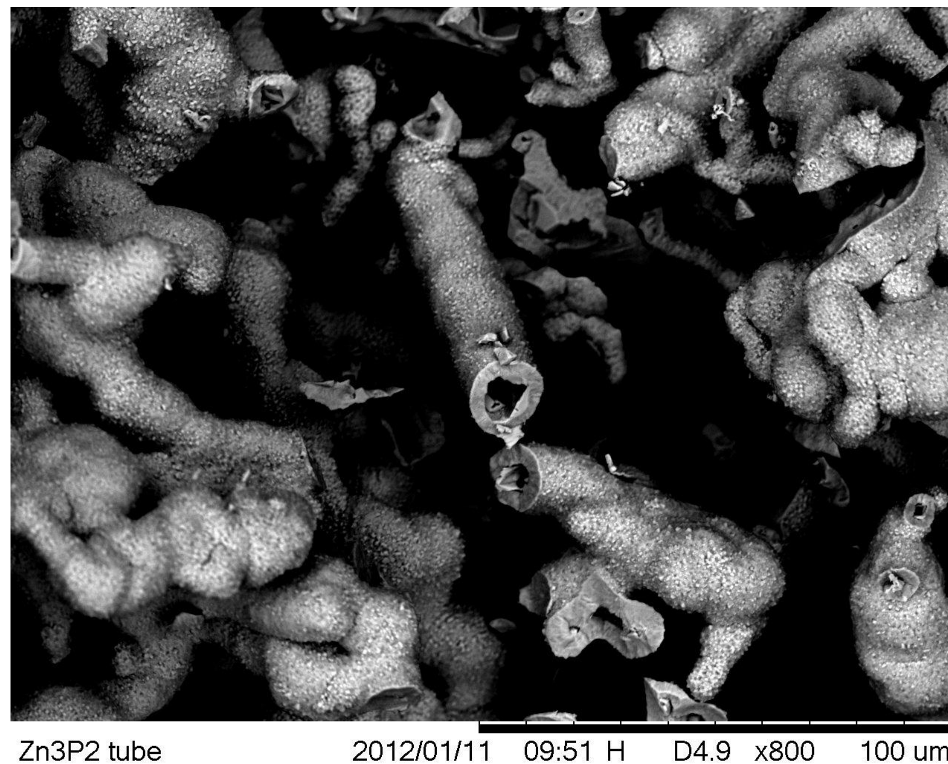
Zn-Fulleride + Zn Nanowire Composites



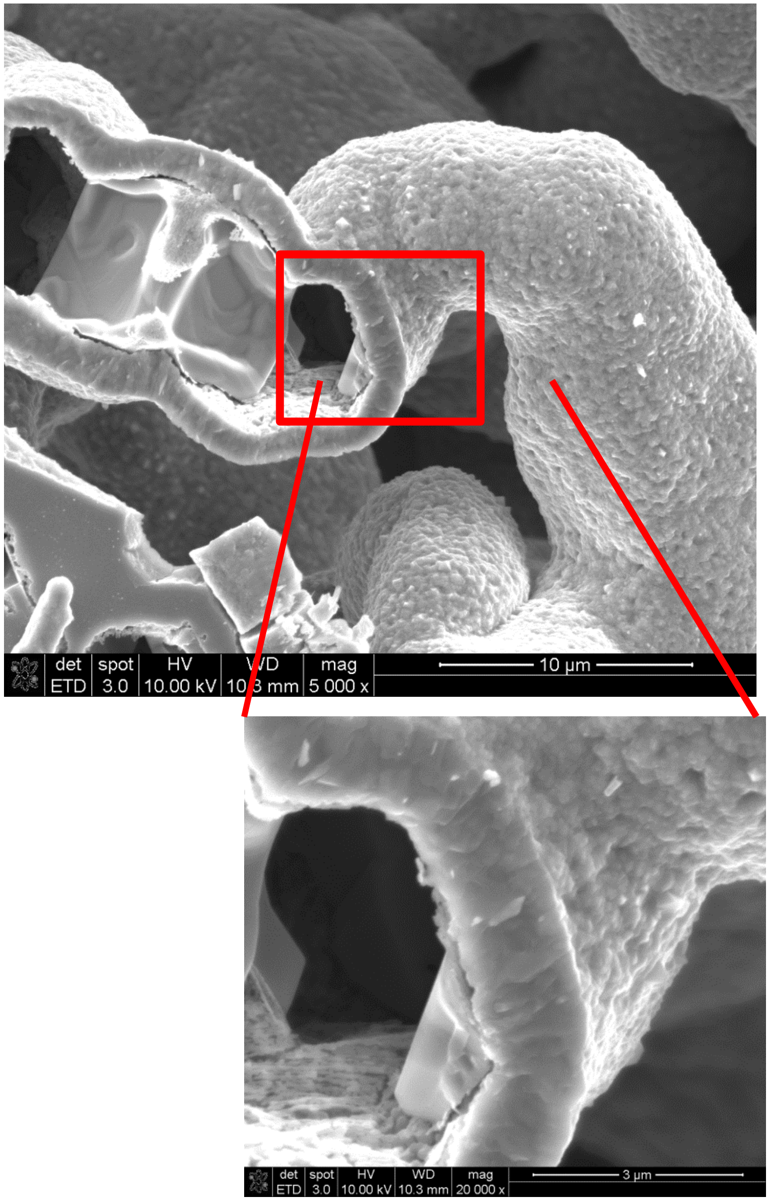
Zinc Phosphide Nanotube Growth

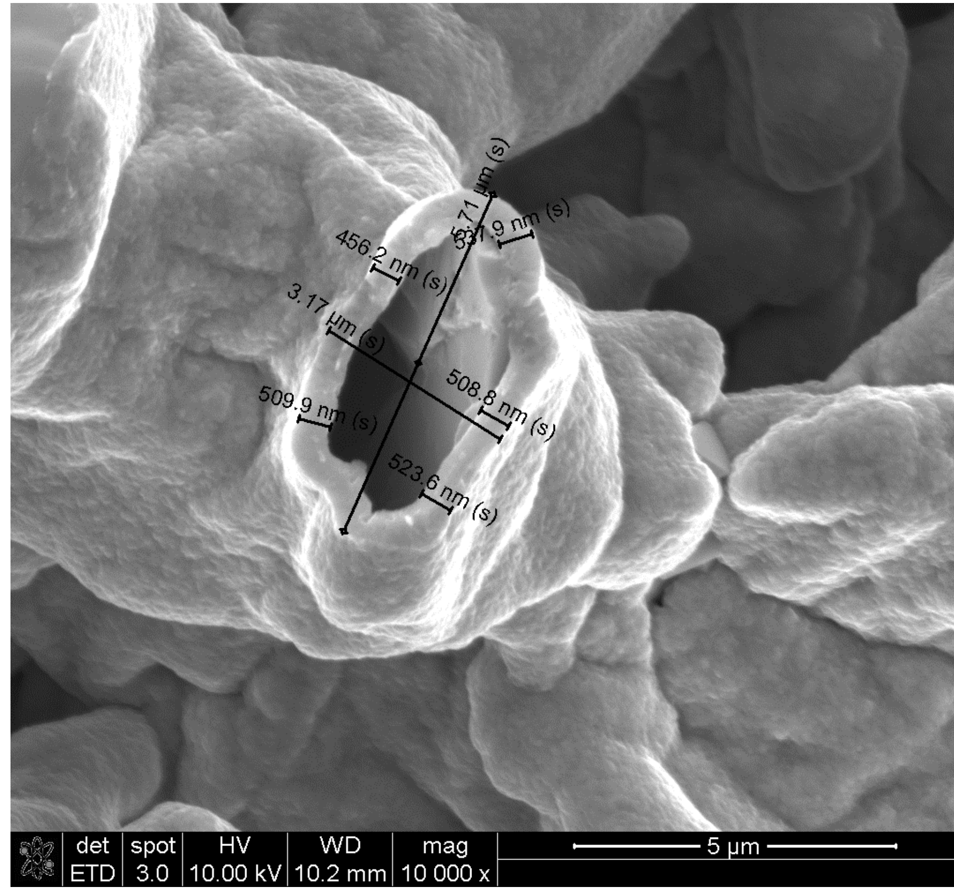


- Zinc nanowire were first grown under std conditions and then Red Phosphorus was evaporated and reacted on the tubes
- Zn_3P_2 Micro/Nanotubes were grown
- Two distinct types of tubes were identified
- Possible reaction mechanism is presented



Zinc Phosphide Tubes High Res SEM

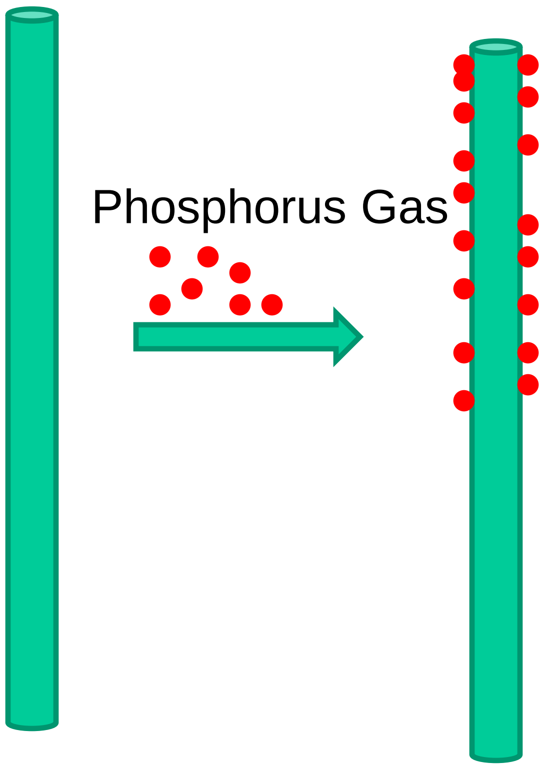




Self Templated growth of Zinc Phosphide Nanotube Growth

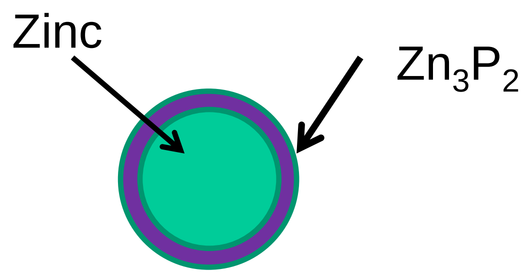
Phosphorus reaction with ZNW

Zinc Nanowire



Wire Cross Section

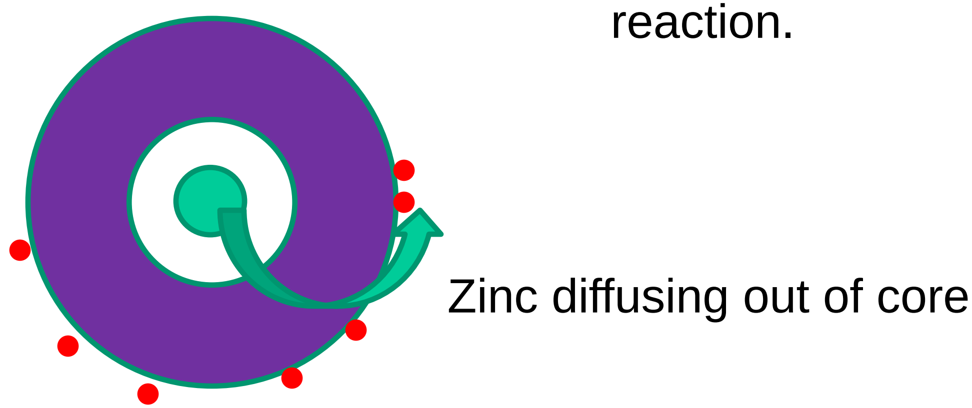
Initial creation of Zn_3P_2 monolayer



Initiation and reaction held at 400° C

Zinc Phosphide growth is mediated by template of the Zinc wires that initiate the reaction.

Zn_3P_2 Nanotube Growth



Confirmation Tests to Identify Fulleride Product

1. UV/Vis-NIR: Examine Near Infrared region of spectrum to determine oxidation state of fulleride ion. Each oxidation state has very specific $\lambda_{max(es)}$ in this region.

2. RF-ICP: Determine counter-ion/cation to fulleride
   - The ICP analysis of the THF solution containing $Zn_x(C_{60})_y$ had emission peaks at 213.86 nm from the contents of zinc and 193.09 nm from the carbon contents.
   - Leads us to believe that C_{60} is present with Zn^{2+} as its counter-ion.

3. XPS: Determine surface molecular contents of crystallized complexes of products collected

4. Raman: Determine vibrational modes present in crystallized samples.

5. EPR: Determine if fullerene is holding a charge.

6. ^{13}C-NMR: Amount of downfield shift can also determine oxidation state of fulleride, as well as determine if fulleride is present and intact

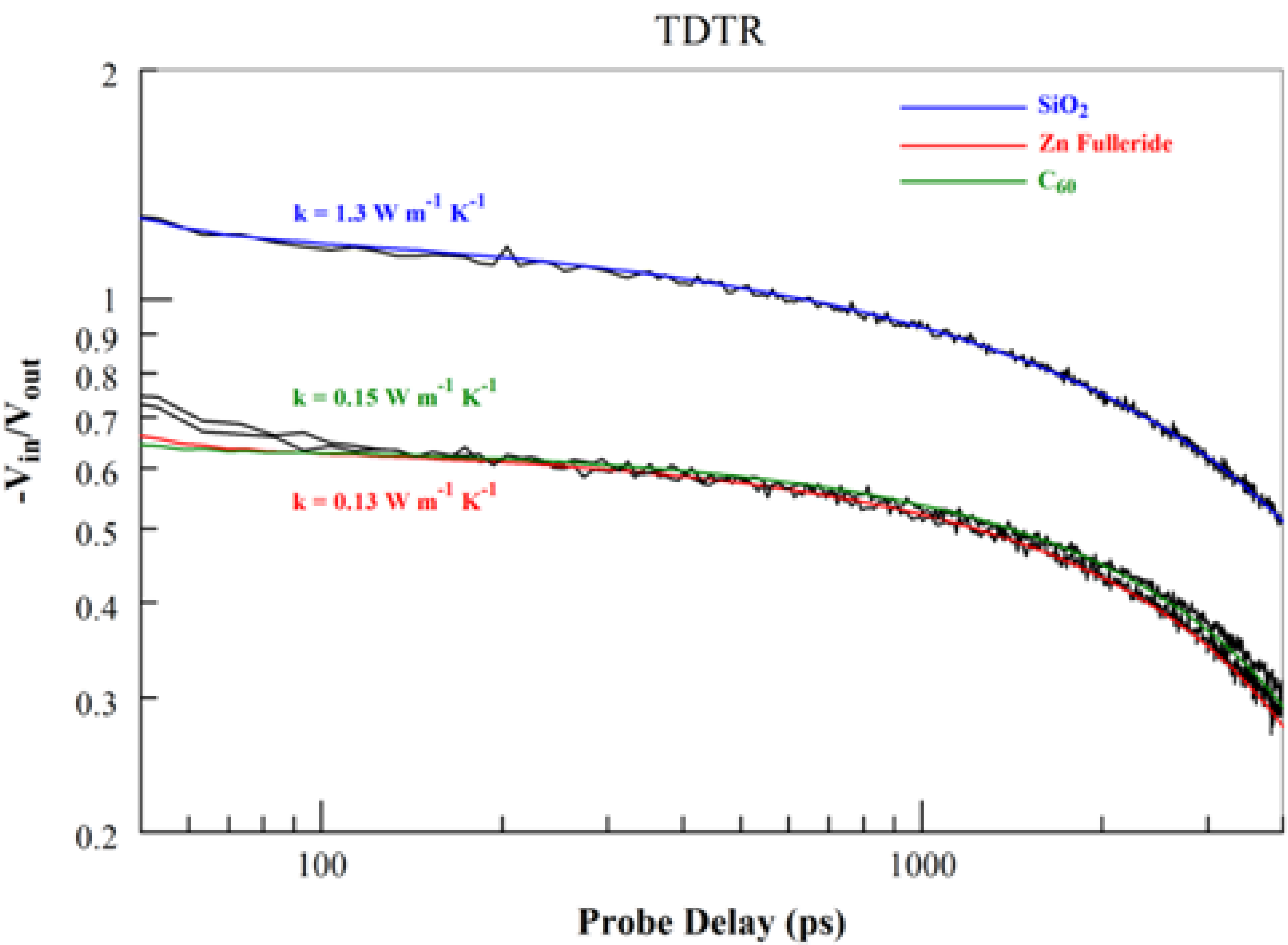
7. SEM of powder appeared to be homogenous

Conclusions

- 3 different preparation routes for fulleride synthesis
- Demonstration of ultra-low thermal conductivities
- Gradient sample were able to produce thousands of different stoichiometries on one sample

Questions?

AIR FORCE RESEARCH LABORATORY


TDTR
SiO_2
Zn Fulleride
C_{60}
k = 1.3 W m^{-1} K^{-1}
k = 0.15 W m^{-1} K^{-1}
k = 0.13 W m^{-1} K^{-1}
$-V_{in}/V_{out}$
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
100
1000
Probe Delay (ps)

•

•

Third Remarkable Fullene Characteristic: Fulleride Formation

"High" Tc Molecular Superconductors

Table 6.3. Lattice constants (a_0) and position of the alkali elements for A_3C_{60} fullerides at ambient temperature

A_3C_{60}	a_0 (Å)	$A_1(T)A_2(T)A_3(O)$	Type	T_c (K)
Cs_3C_{60}	–		A15	40[a]
$RbCs_2C_{60}$	14.555	Rb(T)Cs(T)Cs(O)	fcc	33
KCs_2C_{60}	unstable		fcc	–
Rb_2CsC_{60}	14.431	Rb(T)Rb(T)Cs(O)	fcc	31
Rb_3C_{60}	14.384	Rb(T)Rb(T)Rb(O)	fcc	29
KRb_2C_{60}	14.337	K(T)Rb(T)Rb(O)	fcc	27
K_2CsC_{60}	14.292	K(T)K(T)Cs(O)	fcc	24
K_2RbC_{60}	14.267	K(T)K(T)Rb(O)	fcc	23
K_3C_{60}	14.240	K(T)K(T)K(O)	fcc	19
Na_2CsC_{60}	14.126	Na(T)Na(T)Cs(O)	fcc → sc	12
Na_2RbC_{60}	14.092	Na(T)Na(T)Rb(O)	fcc → sc	3.5
$Na2KC_{60}$	14.122	Na(T)Na(T)K(O)	fcc → sc	2.5
Na_3C_{60}	14.191	Na(T)Na(T)Na(O)	fcc[b]	< 2 K
Li_2CsC_{60}	14.075	Li(T)Li(T)Cs(O)	fcc	< 50 mK
Li_2CsC_{60}[#]	14.008	Li(T)Li(T)Cs(O)	fcc	< 50 mK
Li_2KC_{60}	13.896	Li(T)Li(T)Rb(O)	–	< 50 mK
Li_2KC_{60}	multiphase	–	–	–
$Na_2Cs(NH_3)_4C_{60}$	14.473	$Na(T)Cs(T)Na(NH_3)_4(O)$	fcc	30
Ba_6C_{60}	11.182		bcc	6
Sr_6C_{60}	10.975		bcc	4
Ca_5C_{60}	14.01		sc	8.5
$Yb_{2.75}C_{60}$	superlattice		orthorhombic	6
$Sm_{2.75}C_{60}$	superlattice		orthorhombic	8

[a] Under hydrostatic pressure.
[b] Stable at T > 180 K.
Different batch of samples.

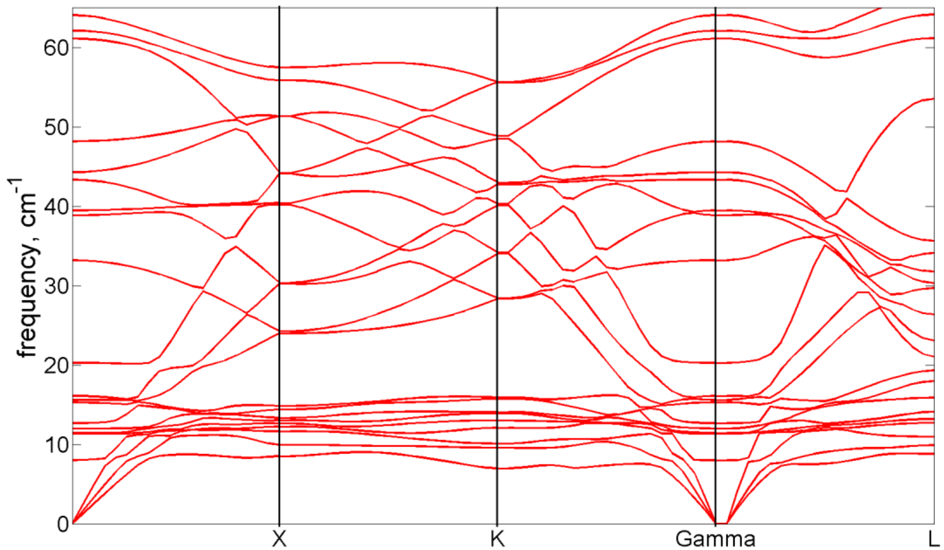
"Handbook of Conductive Molecules and Polymers," H. S. Nalwa, ed., Wiley & Sons, 1997, Vol. 1, p. 317

M_xC_{60}

X =
Alkali
Alkaline Earth
Transition Metal
Rare Earth Metal
Main Group

Many fullerides known; semiconductive fullerides relatively unexplored!

C_{60} FCC Dispersion – Validation



REBO Force Field

PHYSICAL REVIEW B VOLUME 46, NUMBER 7 15 AUGUST 1992-I

Ground-state structural and dynamical properties of solid C_{60} from an empirical intermolecular potential

X.-P. Li
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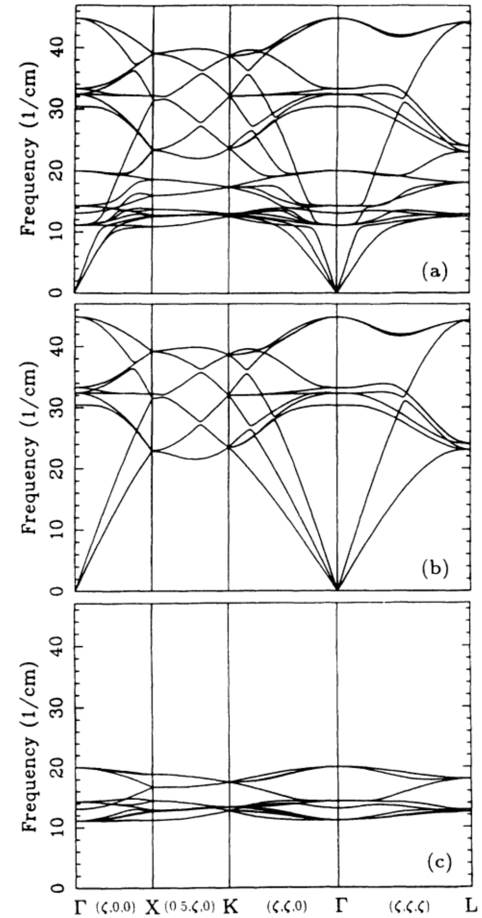
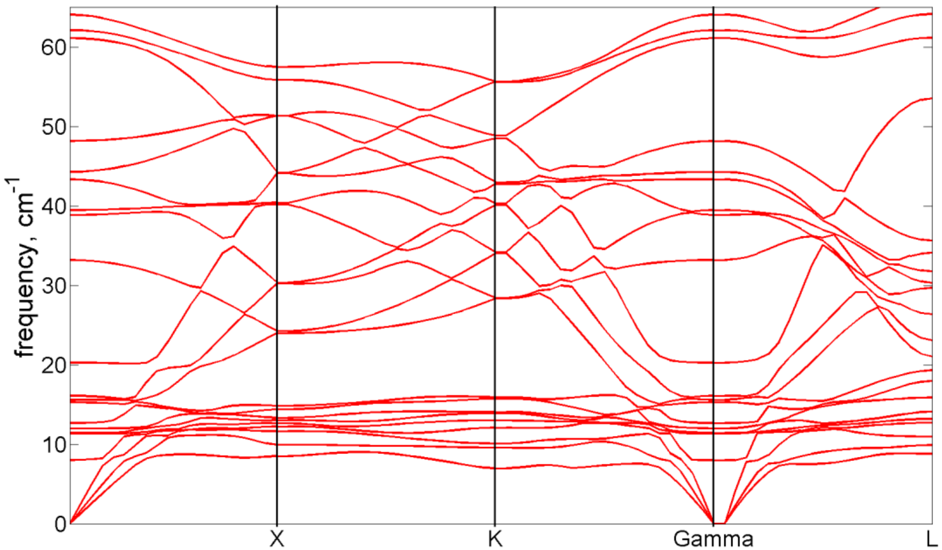
Jian Ping Lu and Richard M. Martin
Department of Physics, University of Illinois at Urbana-Champaign, 1110 West Green Street, Urbana, Illinois 61801 and Materials Research Laboratory, University of Illinois at Urbana-Champaign, 1110 West Green Street, Urbana, Illinois 61801



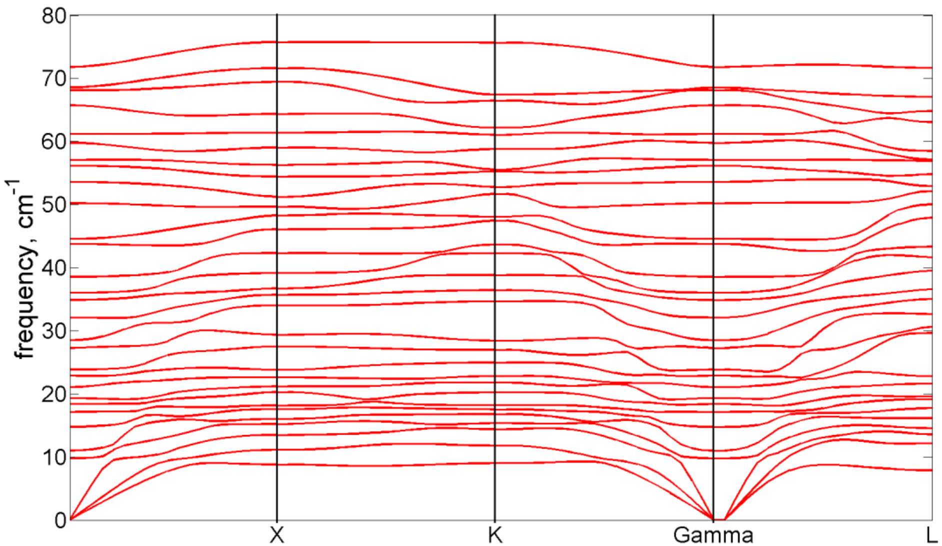
Ba_3C_{60} BCC Dispersion and C_v



C_{60}

$C_v = 0.026824$ eV/K

Molecule breaks symmetry – lattice constants 9.98, 12.80, 12.83



Ba_3C_{60}

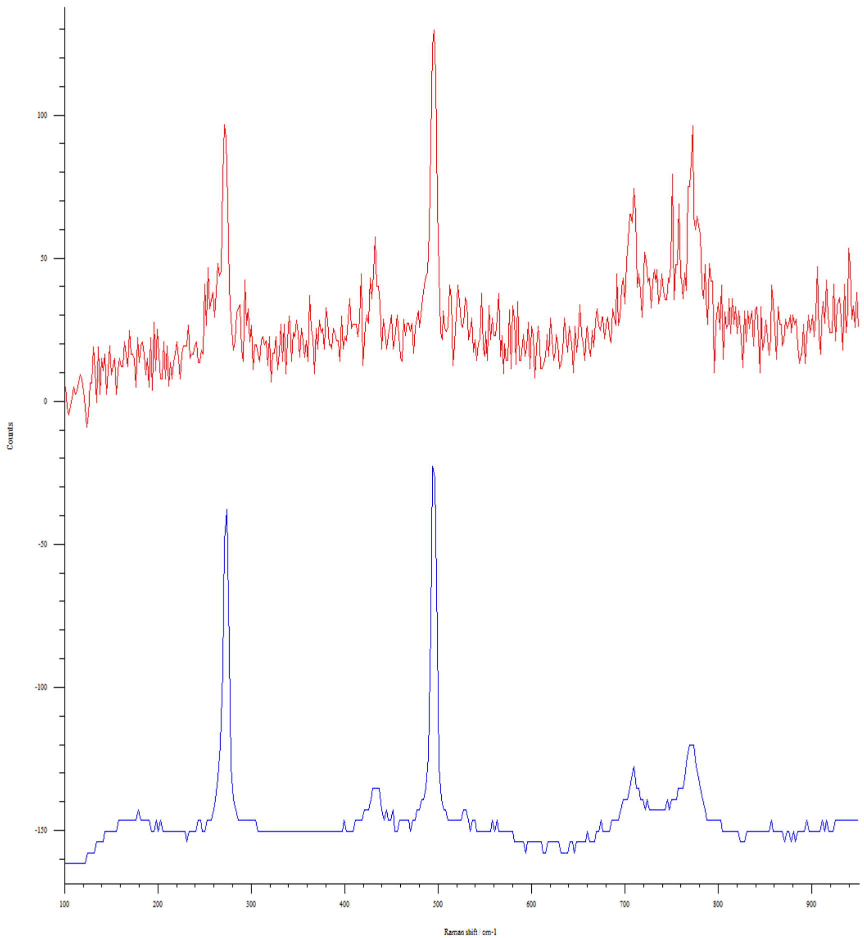
$C_v = 0.015051$ eV/K

Still plotting the high symmetry points of FCC. Group velocities appear lower

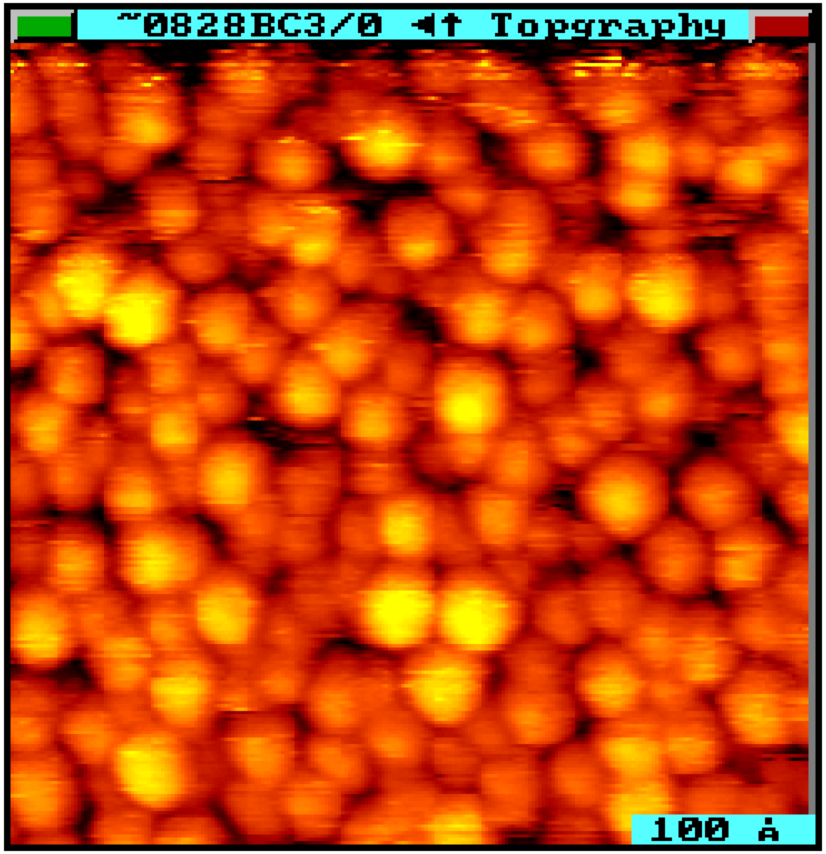
$$k = \frac{1}{3} C_v v_g l$$

Thermal Evaporation of C_{60}

Raman Spectra of Thermal Evap C_{60}



Visible	Hit	Quality	Library	Spectrum Info	Library Index
	1	0.342296	Inorgan.lib	Buckminster Fullerene (Organic)	561
	2	0.169309	Inorgan.lib	Buckminster Fullerene (Organic)	789

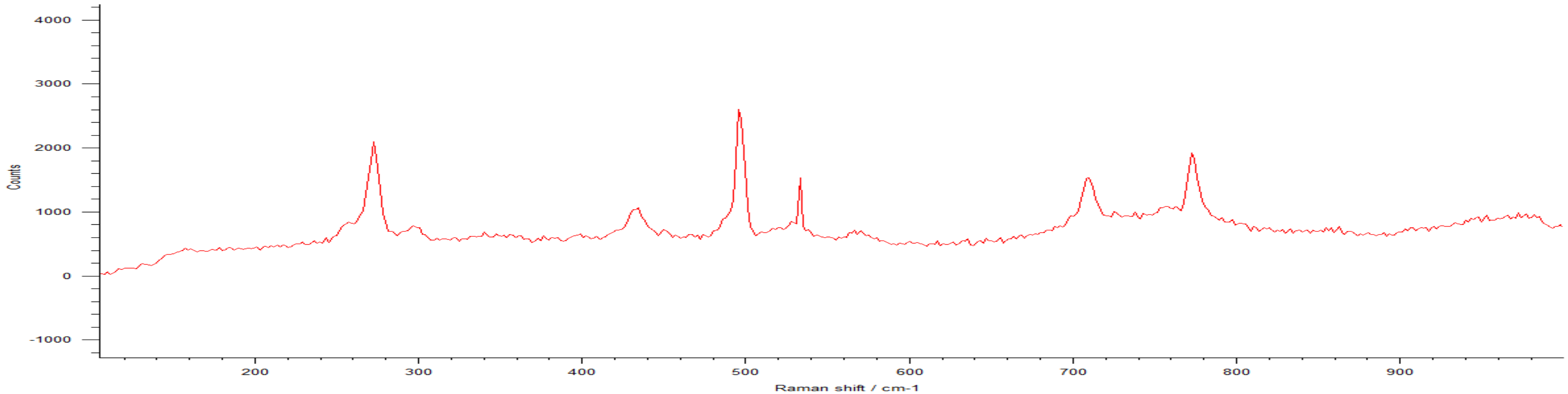


STM Image Courtesy of Dr. Altfeder

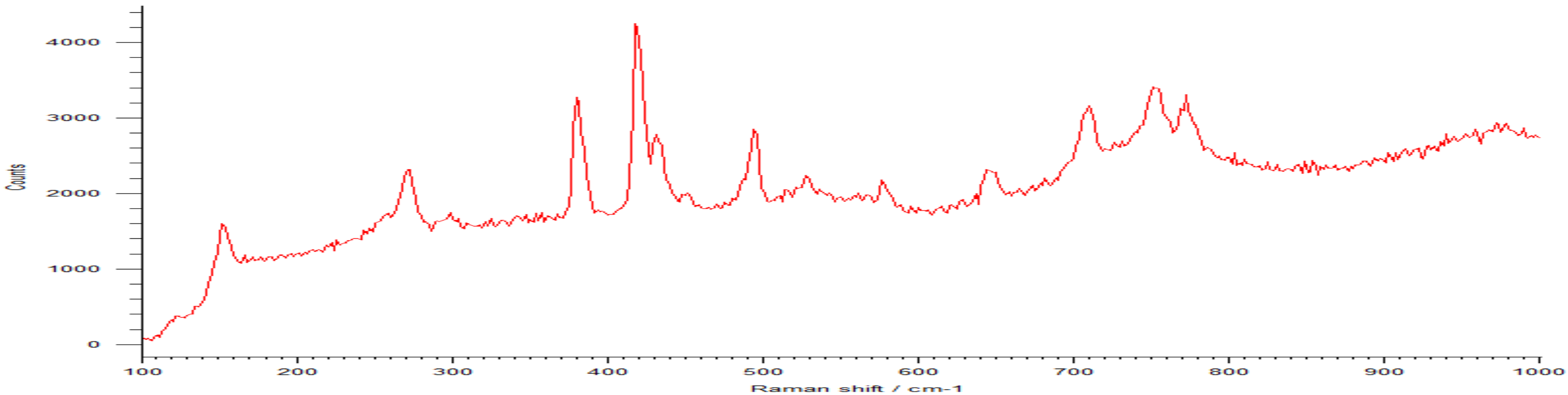
Raman Spectroscopy of C_{60}

Sample is 75 Layers of C_{60} and Zn (C_{60} and Zn Layers are 10nm thick) After Annealing in furnace at 400° C

Pure C60 – Deposited by Thermal Evap

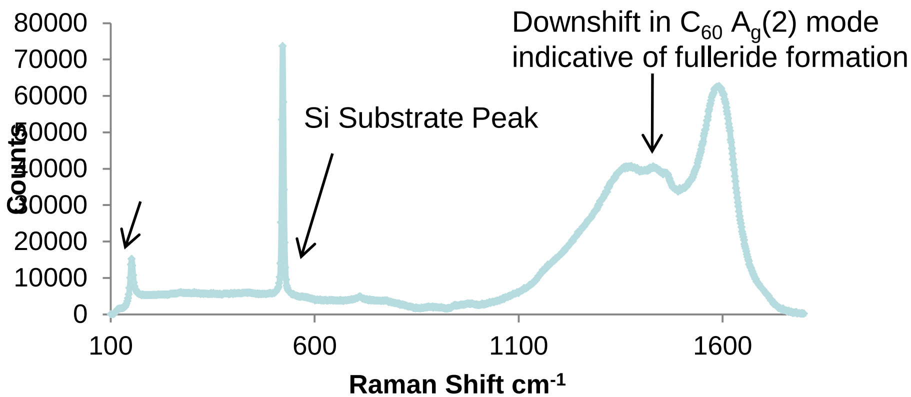


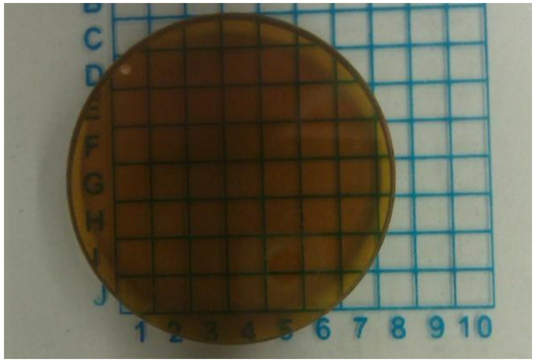
Zn-C_{60} after the anneal



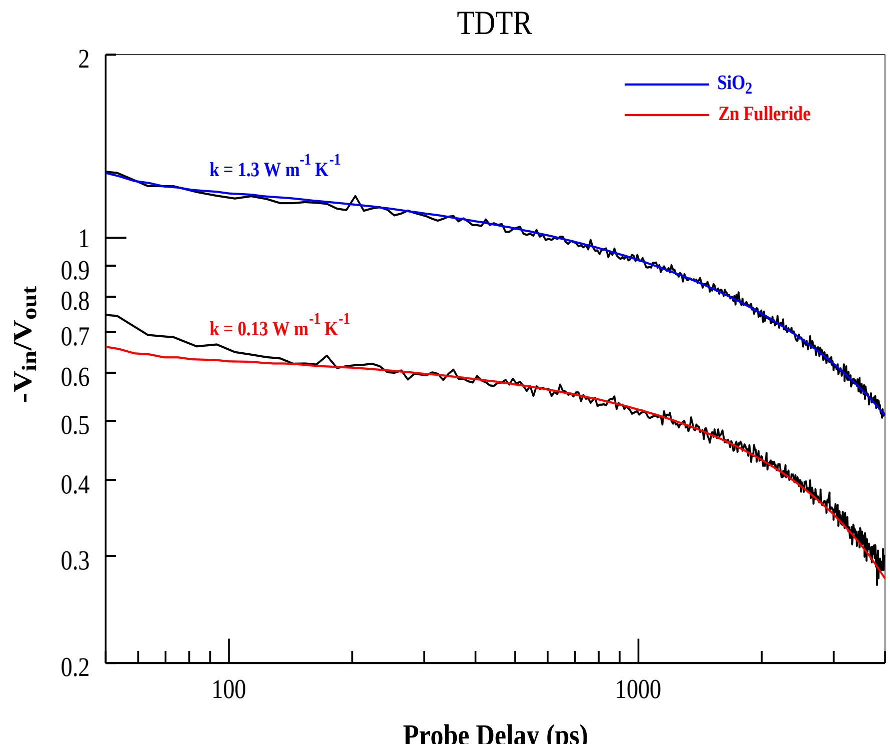
Project Results: Increased σ, Decreased κ And …

Zn_xC_{60} after Anneal Step





Time domain thermal reflectance data of Fulleride materials shows a 10x reduction in Thermal conductivity compared to glass



SUCCESSES:

•Exceptionally good phonon blocking achieved with a ~10^8 (S/cm) increase in electrical conductivity

• Contruction of automated thermal evaporator for layered materials synthesis

•Unanticipated optically transparent electrically conductive films created