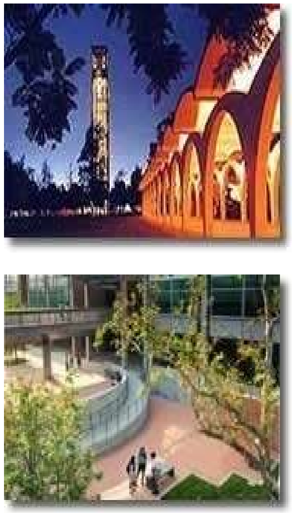
Unique Thermal Properties of Graphene:

Implications for Graphene Devices and Electronics



Alexander A. Balandin

Nano-Device Laboratory
Department of Electrical Engineering and
Materials Science and Engineering Program
University of California – Riverside

IEEE Nano, Portland, Oregon 2011

DARPA SRC FCRP FENA ONR Office of Naval Research

| Nano-Device Laboratory >

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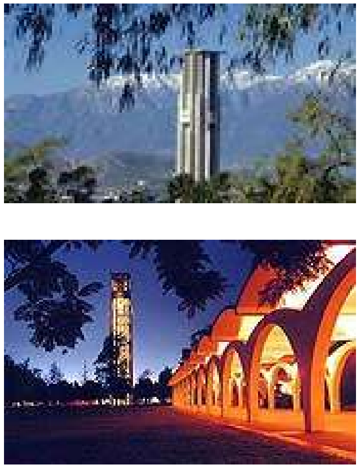
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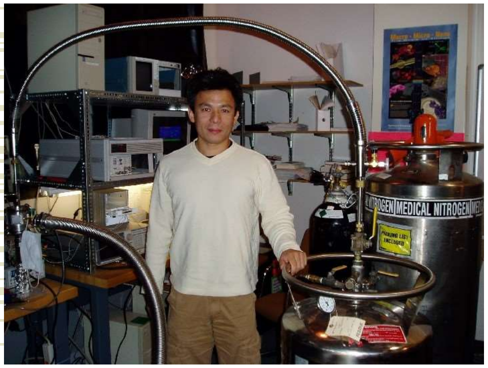
Joshua Tree Park, California

Nano-Device Laboratory (NDL)
Department of Electrical Engineering
University of California – Riverside

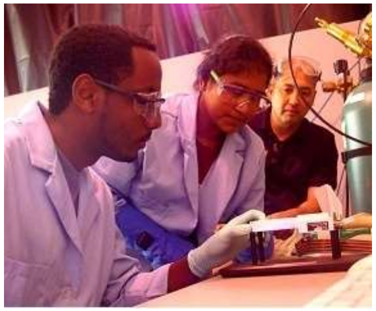
Profile: experimental and theoretical research in phonon engineering and nanodevices

PI: Alexander A. Balandin

Thermal and Electrical Characterization



Device Design and Characterization



Research & Applications

Electronic Devices and Circuits

Direct Energy Conversion

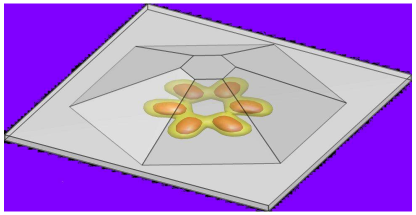
Optoelectronics

Bio-Nanotech

Raman, Fluorescence and PL Spectroscopy

Theory and Modeling

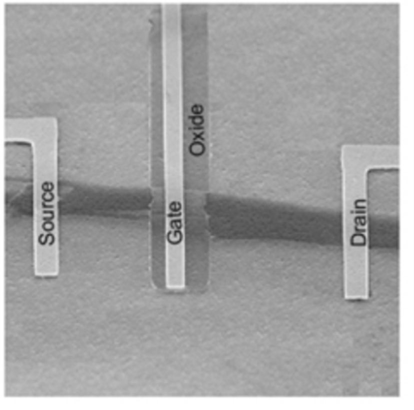
Nanoscale Characterization



Research at NDL was funded by NSF, ONR, SRC, DARPA, NASA, ARO, AFOSR, CRDF, as well as industry, including IBM, Raytheon, TRW, etc.

Outline

- *Motivations*
- *Thermal Properties of Graphene*
    - *Experiments and theoretical interpretation*
    - *Comparisons with other materials*
- *Graphene Applications in Thermal Management*
    - *Lateral heat spreaders and thermal interface materials - TIMs*
- *Graphene Device Applications*
    - *Transparent electrodes and interconnects*
    - *Transistors for high-frequency communications*
- *From Graphene to Topological Insulators*
    - *Exfoliated topological insulators*
    - *Device applications of topological insulators*
- *Conclusions*



The Nobel Prize in Physics 2010

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2010 to

Andre Geim and **Konstantin Novoselov**

University of Manchester, UK

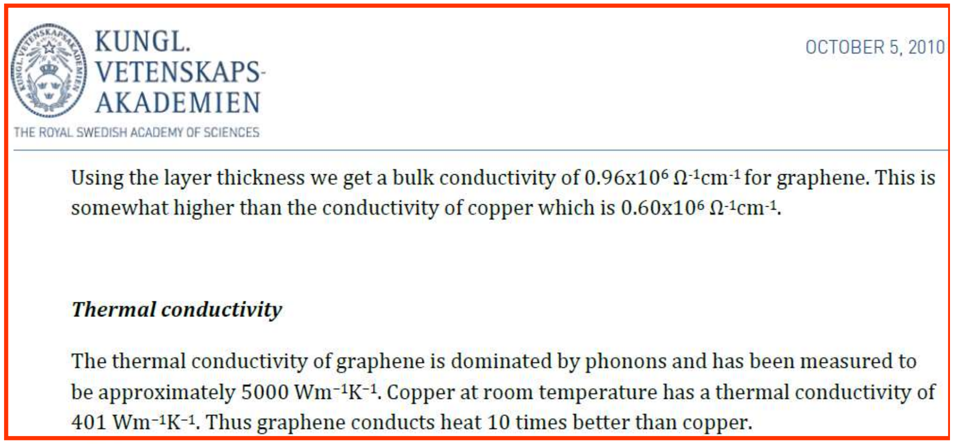
University of Manchester, UK

"for groundbreaking experiments regarding the two-dimensional material graphene"

Graphene – the perfect atomic lattice

A thin flake of ordinary carbon, just one atom thick, lies behind this year's Nobel Prize in Physics. Andre Geim and Konstantin Novoselov have shown that carbon in such a flat form has exceptional properties that originate from the remarkable world of quantum physics.

Graphene is a form of carbon. As a material it is completely new – not only the thinnest ever but also the strongest. As a conductor of electricity it performs as well as copper. As a conductor of heat it outperforms all other known materials. It is almost completely transparent, yet so dense that not even helium, the smallest gas atom, can pass through it. Carbon, the basis of all known life on earth, has surprised us once again.



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THE ROYAL SWEDISH ACADEMY OF SCIENCES

OCTOBER 5, 2010

Using the layer thickness we get a bulk conductivity of $0.96\times10^6\ \Omega^{-1}\text{cm}^{-1}$ for graphene. This is somewhat higher than the conductivity of copper which is $0.60\times10^6\ \Omega^{-1}\text{cm}^{-1}$.

Thermal conductivity

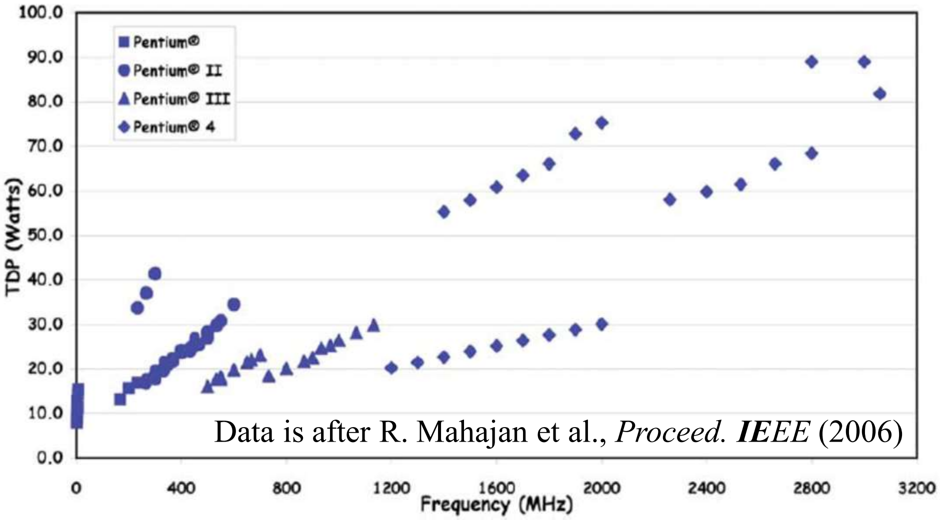
The thermal conductivity of graphene is dominated by phonons and has been measured to be approximately 5000 $\text{Wm}^{-1}\text{K}^{-1}$. Copper at room temperature has a thermal conductivity of 401 $\text{Wm}^{-1}\text{K}^{-1}$. Thus graphene conducts heat 10 times better than copper.

This year's Laureates have been working together for a long time now. Konstantin Novoselov, 36, first worked with Andre Geim, 51, as a PhD-student in the Netherlands. He subsequently followed Geim to the United Kingdom. Both of them originally studied and began their careers as physicists in Russia. Now they are both professors at the University of Manchester.

http://nobelprize.org/nobel_prizes/physics/laureates/2010/press.html

Practical Motivation: Thermal Bottleneck for CMOS Downscaling

IEEE Spectrum illustration of the thermal issues in the feature article *Chill Out: New Materials and Designs Can Keep Chips Cool* by A.A. Balandin.



Data is after R. Mahajan et al., *Proceed. **IEEE*** (2006)

No BIG fan solutions!

→The switch to multi-core designs alleviates the growth in the thermal design power (TDP) increase but does not solve the hot-spot problem

→ Non-uniform power densities leading to hot-spots (>500 W/cm^2)

Basics of Heat Conduction

Definitions and Basic Theory

Fourier's law:

$$\frac{\dot{Q}}{S} = -K\nabla T$$

Phonon vs. electron conduction:

$$\frac{K_e}{\sigma} = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2 T$$

Heat current carried by phonons :

$$Q = \sum_{q,j} N_{\mathbf{q},i}(\mathbf{q})\hbar\omega_i(\mathbf{q})\frac{\partial\omega}{\partial\mathbf{q}},$$

RT thermal conductivity of important materials:

Silicon (Si): 145 W/mK

SiO_2: 0.5-1.4 W/mK

Copper: 400 W/mK

RT thermal conductivity for carbon materials:

Diamond: 1000 – 2200 W/mK

Graphite: 200 – 2000 W/mK (orientation)

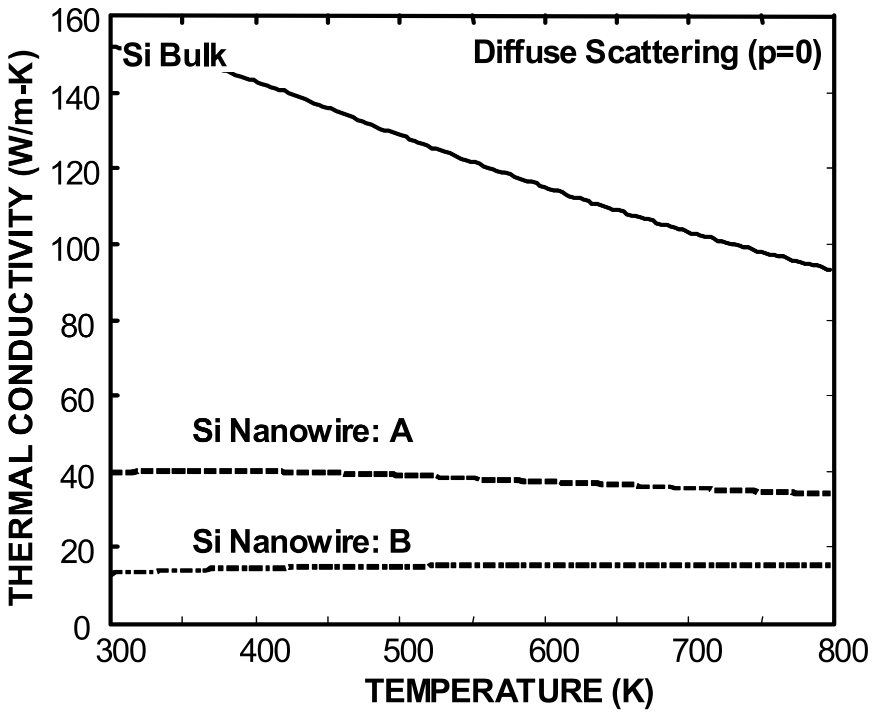
DLC: 0.1 – 10 W/mK

CNTs: 3000 – 3500 W/mK

→ Very wide range of K for carbon materials depending on their lattice and dimensionality

Degradation of Thermal Conduction in Nanostructures

Thermal conductivity usually decreases as one goes from bulk material to nanostructure or thin film



J. Zou and A.A. Balandin, *J. Appl. Phys.*, **89**, 2932 (2001).

←Thermal conductivity of bulk Si at room temperature: **K= 148 W/m-K**

← Thermal conductivity of Si nanowire with cross section of 20 nm x 20 nm: **K=13 W/mK**

→ Phonon thermal conductivity:

$$K_p = (1/3)C_p \upsilon \Lambda$$

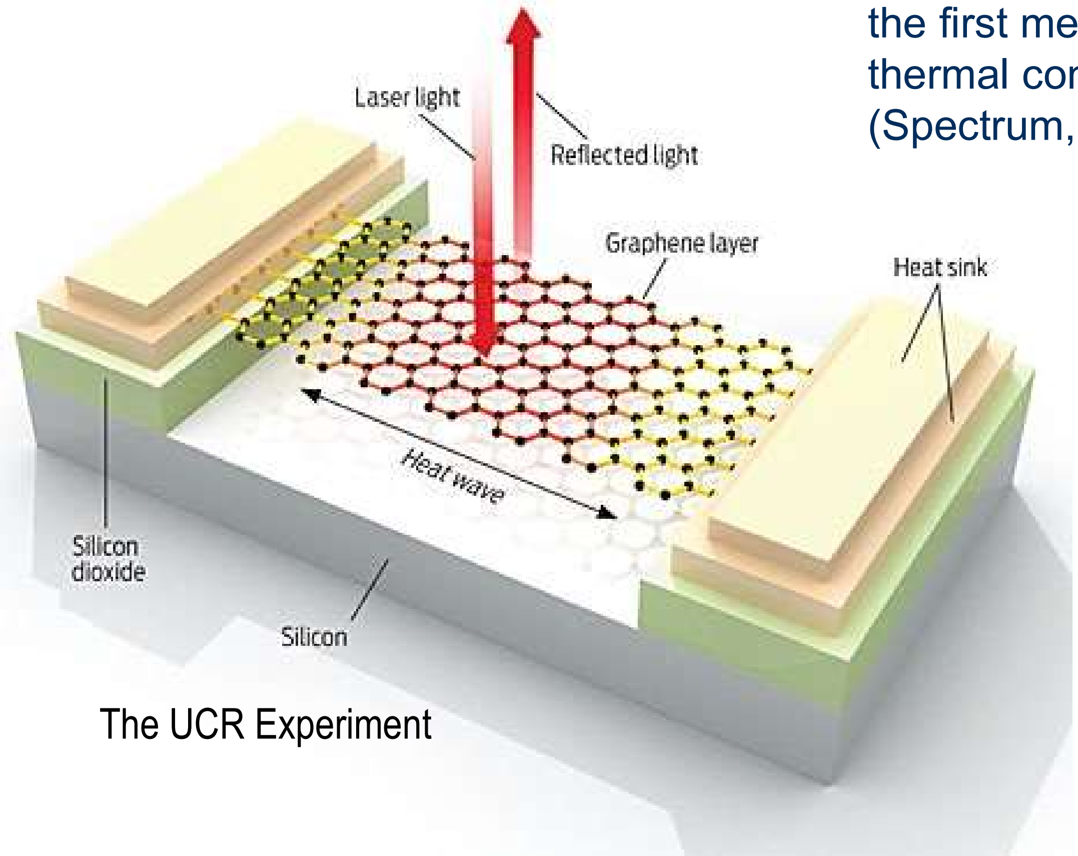
→ Boundary-limited MFP ($\Lambda = v\tau$):

$$1/\tau_B = (\upsilon / D)[(1-p)/(1+p)]$$

$$K_p \sim C_p \upsilon \Lambda \sim C_p \upsilon^2 \tau_B \sim C_p \upsilon D$$

What happens in CNTs and graphene?

Part I: Thermal Conductivity of Graphene

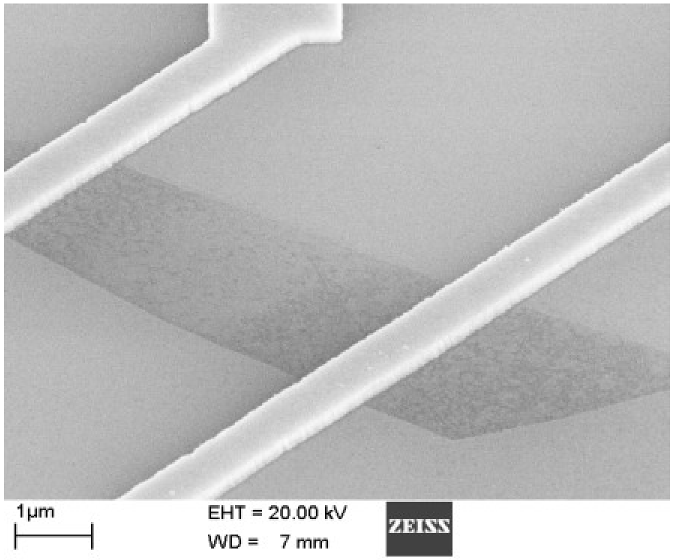


The UCR Experiment

←*IEEE Spectrum* illustration of the first measurements of thermal conductivity of graphene (Spectrum, October, 2009)

Raman Spectroscopy of Graphene

Visualization on Si/SiO$_2$ substrates



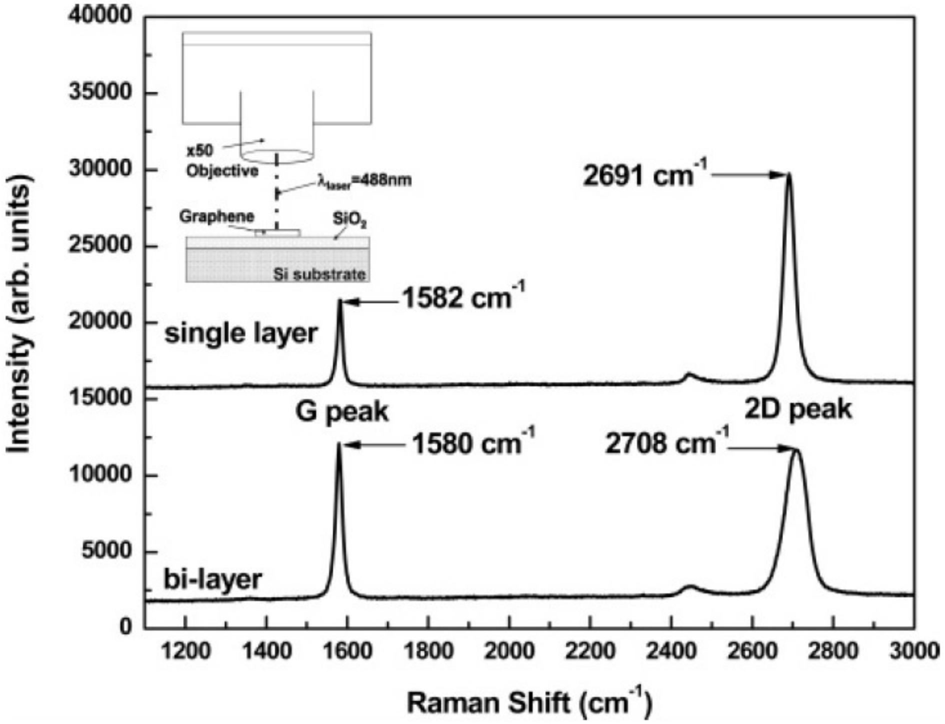
Other techniques:

→ low-temperature transport study

→cross-sectional TEM

→ few other costly methods

D band: **A$_{1g}$ (~1350 cm^{-1}); *G peak:* E$_{2g}$; *2D* band**

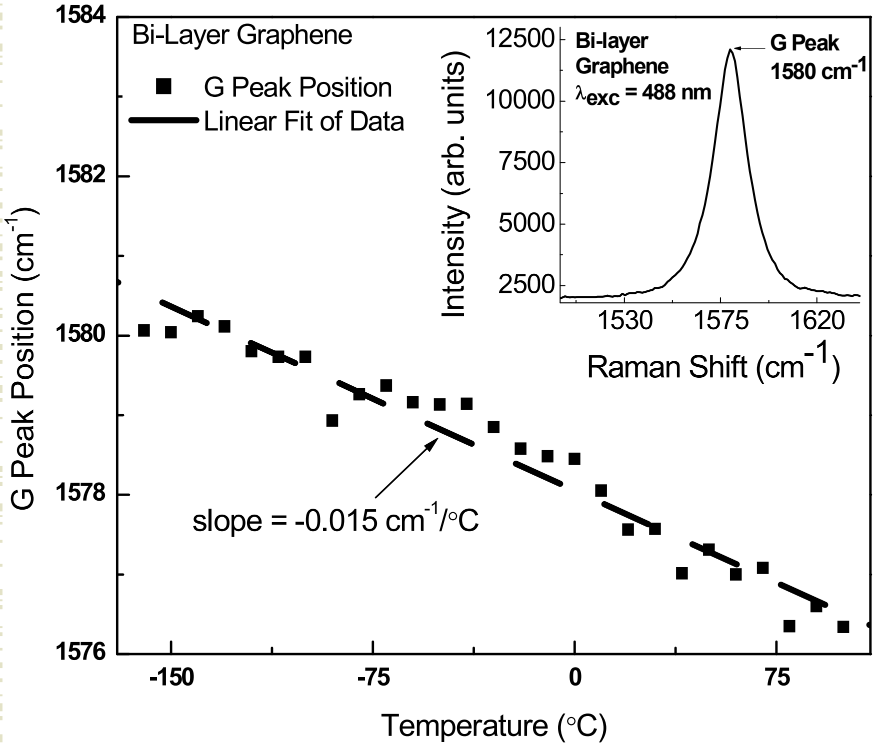


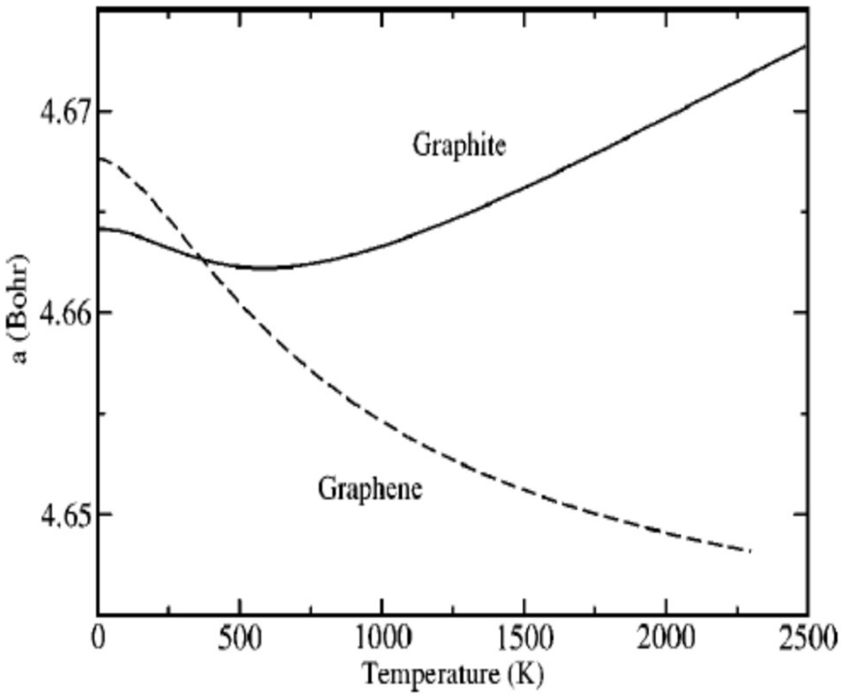
A.C. Ferrari et al., *Phys. Rev. Lett*. **97**, 187401 (2006).

I. Calizo, et al., *Nano Lett.*, **7**, 2645 (2007).

Temperature Effects on Raman Spectrum – Converting Spectrometer into "Thermometer"

Note: the sign is negative





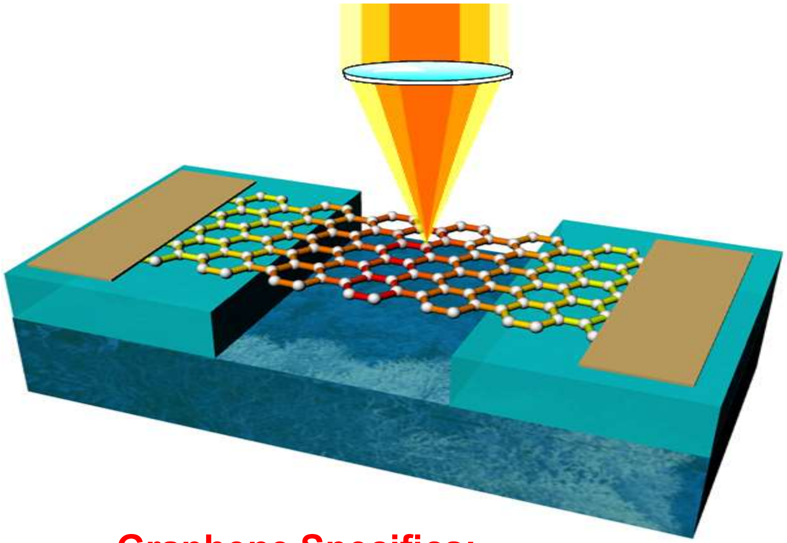
Temperature is controlled externally; very low excitation power on the sample surface is used (< 0.5 – 1 mW).

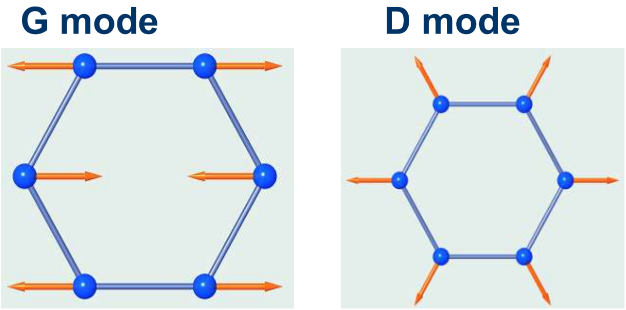
Phonon frequency downshift with T is unusual when the bond-bond distances shorten with T since normally lattice contraction leads to the upward shift of the frequencies.

Thermal Conductivity Measurements with Micro-Raman Spectrometer

Idea of the Experiment:

→ Induce locale hot spot in the middle of the suspended graphene flake and monitor temperature rise in the middle with increasing excitation laser intensity.





Importance of the Suspended Portion of Graphene

→ Formation of the specific in-plane heat front propagating toward the heat sinks

→ Reduction in the graphene – substrate coupling

→ Determining the fraction of the power dissipated in graphene through callibration procedure

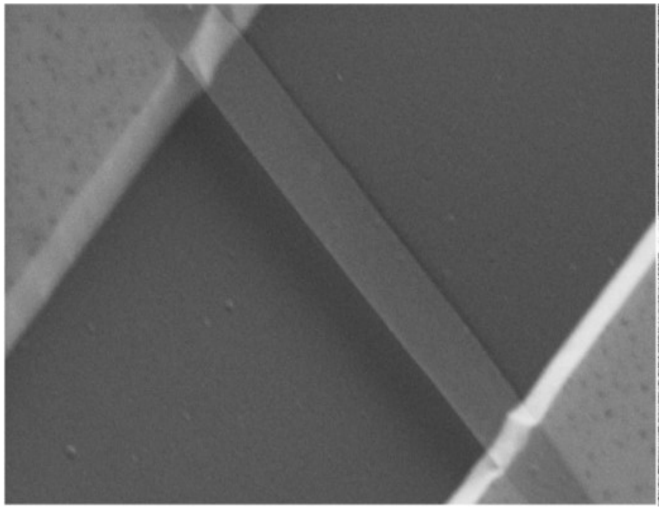
Graphene Specifics:

→ Atomic thickness: good for this method

→ Heat transport: diffusive or partially diffusive thermal transport

→ In-plane phonon modes: less effect from the substrate and possibility of graphite calibration

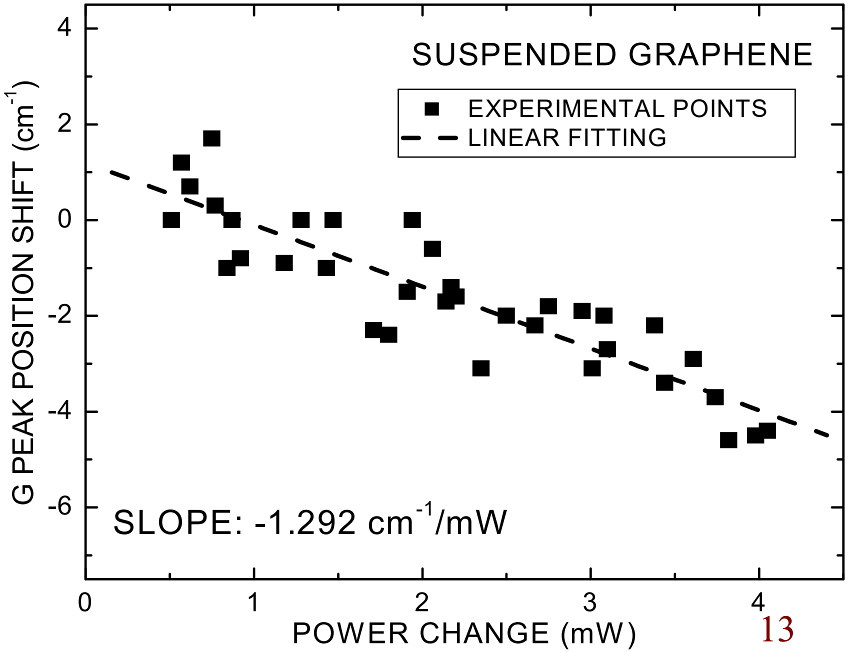
Optothermal Method for Measuring Thermal Conductivity of Graphene



→ Laser acts as a heater (confirmed by Stoke – Anti-Stoke intensity ratio): ΔP_G

→ Raman “thermometer”: $\Delta T_G=\Delta\omega/\chi_G$

→ Thermal conductivity: $K=(L/2a_G W)(\Delta P_G/\Delta T_G)$



Thermal conductivity of rectangular flake (*L* is the half-length):

$$K = (L/2a_G W)\chi_G(\Delta\omega/\Delta P_G)^{-1}.$$

Connect ΔP_D ← → ΔP_G *through calibration*

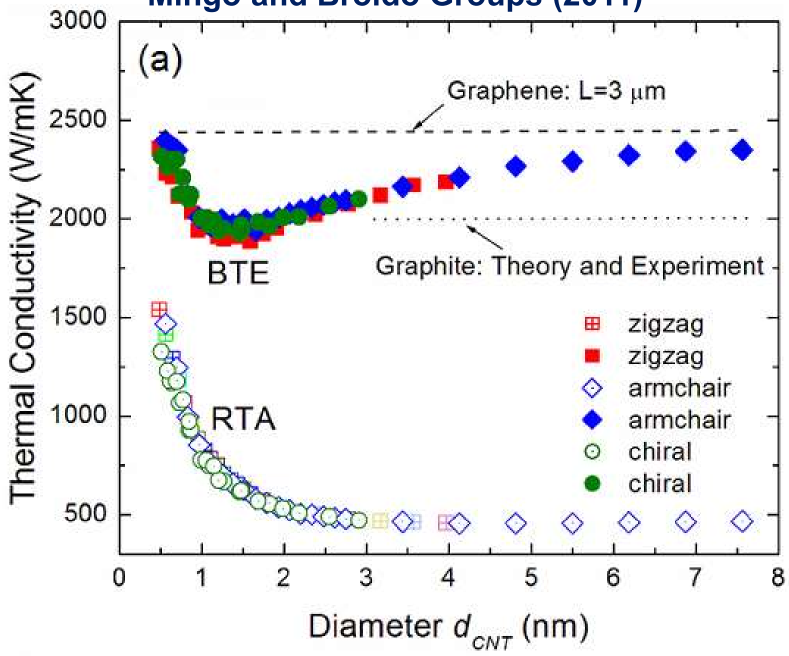
A.A. Balandin, S. Ghosh, W. Bao, I. Calizo, D. Teweldebrhan, F. Miao and C.N. Lau, *Nano Letters*, **8**: 902 (2008).

Thermal Conductivity of Graphene: Comparison with CNTs and Theory

Sample	*K (W/mK) near RT*	*Method*	*Comments*	*Refs*
MW-CNT	>3000	electrical self-heating	individual; diffusive	10
SW-CNT	~3500	electrical self-heating	individual; boundary	11
SW-CNTs	1750 - 5800	thermocouples	bundles; diffusive	63
SW-CNT	3000 - 7000	thermocouples	individual; ballistic	64
CNT	1500 - 2900	electrical	individual	65
CNT	~6600	Theory: MD	$K_{CNT} < K_{graphene}$	66
CNT	~3000	Theory: MD	strong defect dependence	67
SW-CNT	~2500	Theory: BTE	$K_{CNT} < K_{graphene}$	69
graphene	~2000 - 5000	Raman optothermal	suspended; exfoliated	UCR
FLG	~1300 - 2800	Raman optothermal	suspended; exfoliated; *n*=4-2	UCR
graphene	~2500	Raman optothermal	suspended; CVD	UTA
graphene	1500 - 5000	Raman optothermal	suspended; CVD	Purdue
graphene	600	Raman optothermal	suspended; exfoliated; T~660 K	CNRS
FLG ribbon	1100	electrical self-heating	supported; exfoliated; *n*<5	GIT
graphene	600	electrical	supported; exfoliated	UTA
graphene	2000 - 5000	Theory: VFF, BTE, $\gamma(q)$	strong width dependence	79
graphene	1 - 5000	Theory: RTA, γ_{TA}, γ_{LA}	strong size dependence	62
graphene	8000 - 10000	Theory: MD, Tersoff	square graphene sheet	80
graphene	1400 - 3400	Theory: BTE	length dependence	69
graphene	~4000	Theory: ballistic	strong width dependence	82

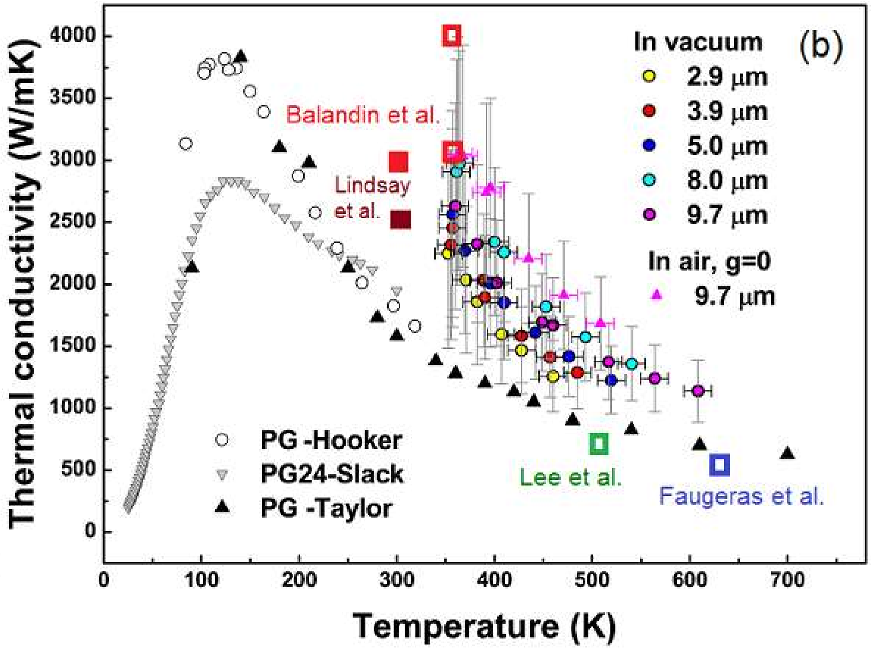
Comparison with Recent Independent Experimental and Theoretical Studies

Mingo and Broido Groups (2011)



L. Lindsay, et al., *Phys. Rev. B*, **82**, 161402R (2010);

Li Shi and Ruoff Groups (2011)

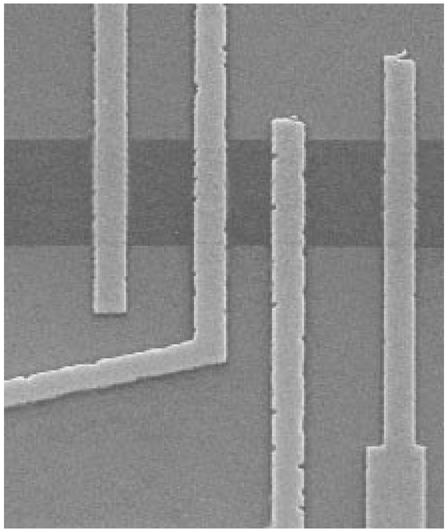


S. Chen, et al., *ACS Nano*, **5**, 321 (2011).

- → **Experimental thermal conductivity is above bulk graphite**
- → **Theoretical thermal conductivity of graphene is above that of CNTs: ~2500 W/mK at RT for L=3 μm**
- → **Theoretical value is size dependent: Balandin group and Mingo – Broido group**
- → **Ballistic limit for graphene: ~12800 W/mK**

Part II: Practical Applications of Graphene

technology review



Communications

Graphene Transistors Do Triple Duty in Wireless Communications
A single graphene transistor that does the job of many conventional ones could lead to compact chips for cell phones.

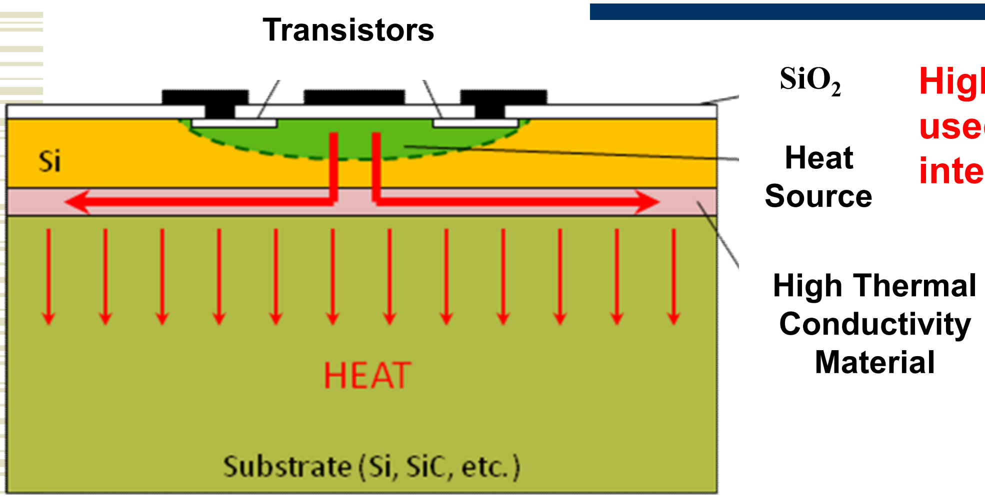
Friday, October 22, 2010

By Katherine Bourzac

Triple transistor: Single graphene transistors like this one can be made to operate in three modes and perform functions that usually require multiple transistors in a circuit.

Credit: Alexander Balandin

Passive High-Heat Flux Thermal Management



High thermal conductivity materials can be used as lateral hot-spot spreaders or thermal interface materials (TIM)

Issues:

→ Compatibility with Si CMOS technology
→ Electrical insulator vs conductor
→ Bulk vs nanostructure
→ Anisotropy
→ Coefficient of thermal expansion
→ Temperature stability

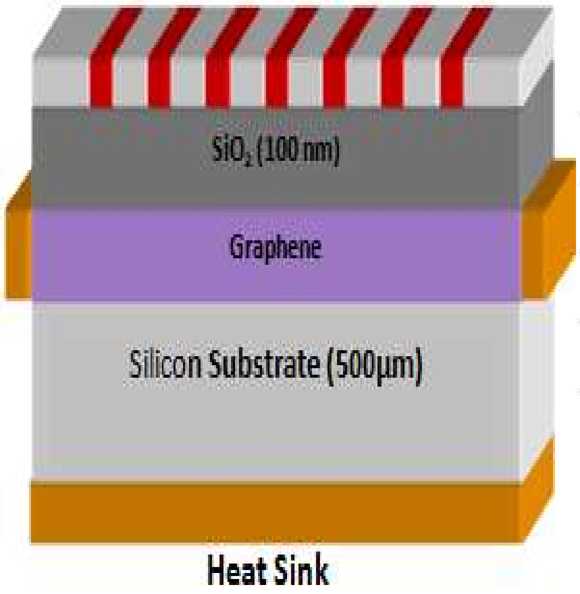
Table : Room-temperature thermal conductivity of best heat conductors

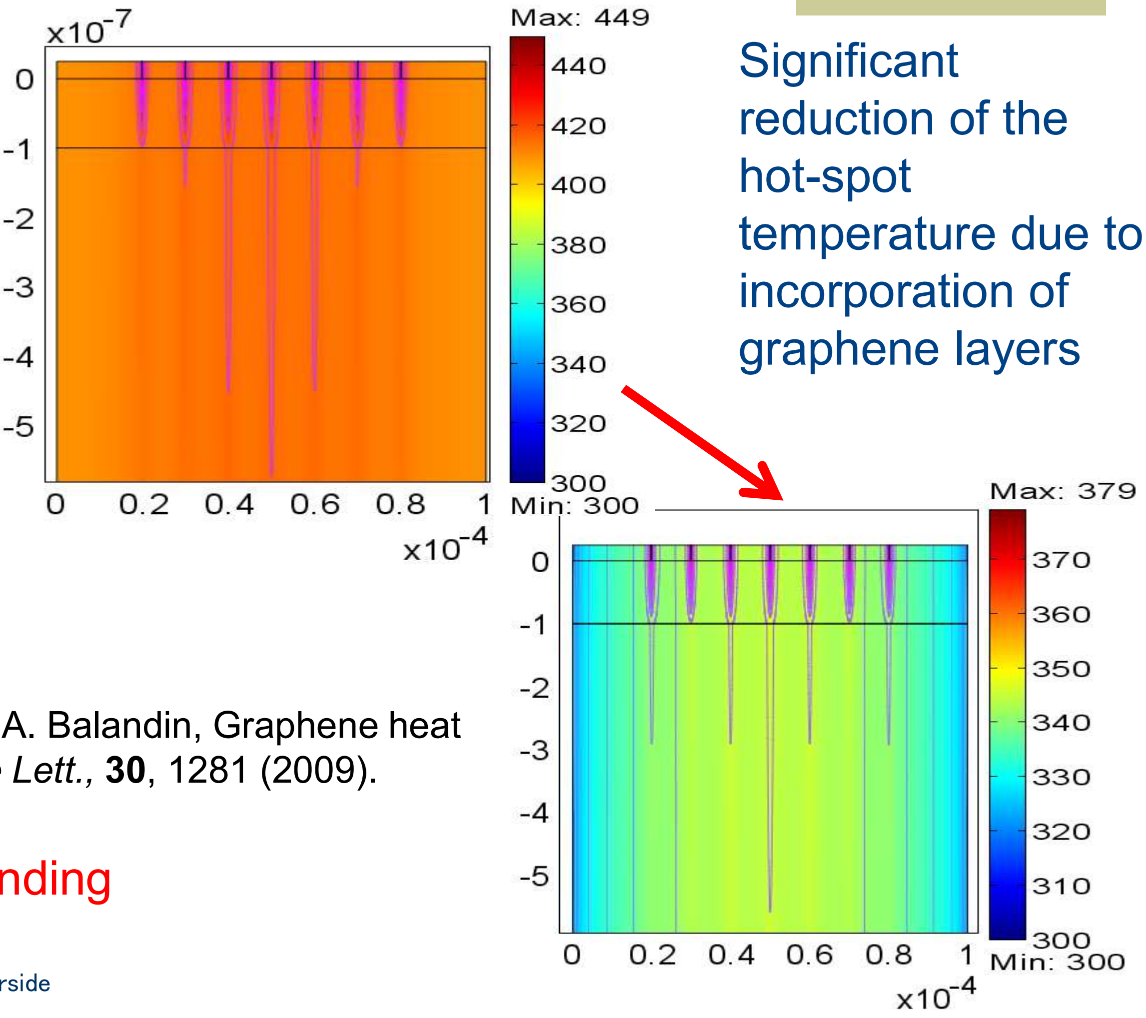
Sample	K (W/mK)	Method	Comments	Reference
diamond	~ 1000 – 2200	3-omega; other	bulk	Berman *et al.*
MW-CNT	> 3000	electrical	individual	Kim *et al.*
SW-CNT	~ 3500	electrical	individual	Pop *et al.*
SW-CNT	1750 – 5800	thermocouples	bundles	Hone *et al.*

Theoretical Suggestions:
→ Graphene should have very high thermal conductivity; flat geometry is a major benefit

Extra Benefits:
→ Graphene and CNTs can become foundations of the carbon or hybrid Si-carbon electronics

Graphene as Interconnects and Laterals Heat Spreaders



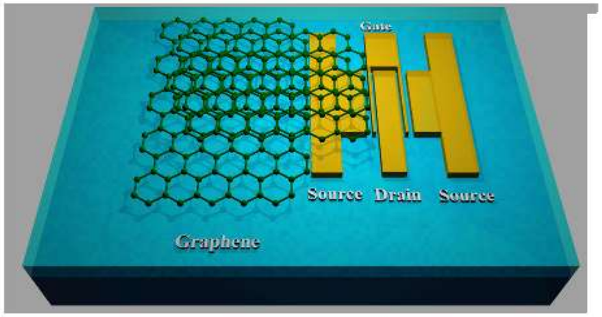


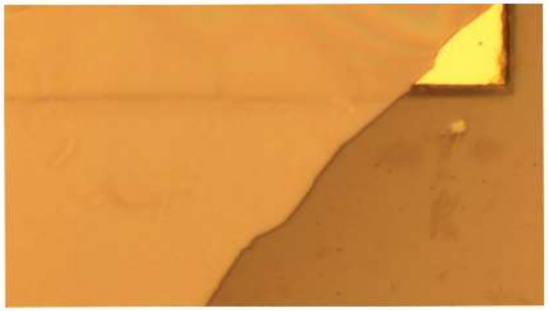
Significant reduction of the hot-spot temperature due to incorporation of graphene layers

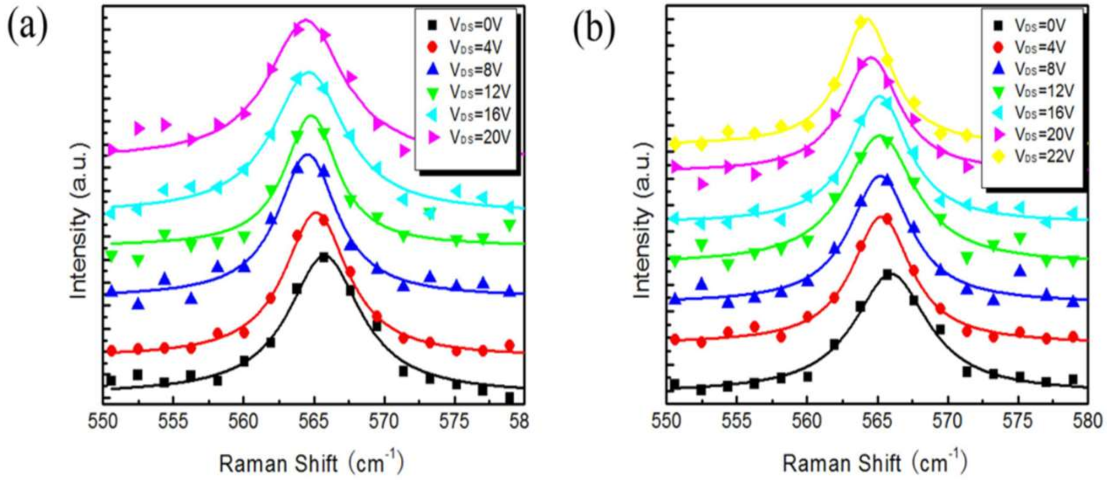
S. Subrina, D. Kotchetkov and A.A. Balandin, Graphene heat spreaders, *IEEE Electron Device Lett.,* **30**, 1281 (2009).

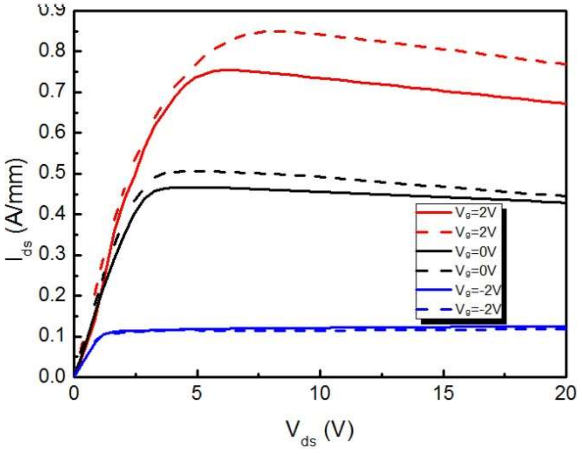
US Patent Pending

Experimental Demonstration of Graphene Lateral Heat Spreaders for GaN FETs









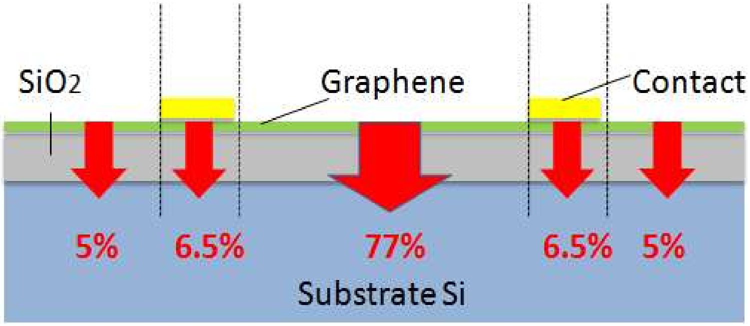
Raman measurement of GaN HFET device with (a) and without (b) graphene heat spreaders. Gate bias was fixed at 0V.

I-V characteristics before (solid line) and after (dashed) introducing graphene heat spreader.

→ Red lines were measured at 2V gate bias;
Black lines were measured at 0V gate bias;
Blue lines were measured at -2V gate bias.

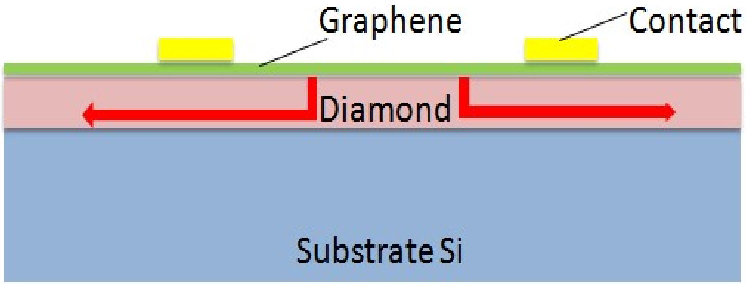
Graphene-on-Diamond Top-Gate Transistors with Enhanced Performance

STUDENT TALK

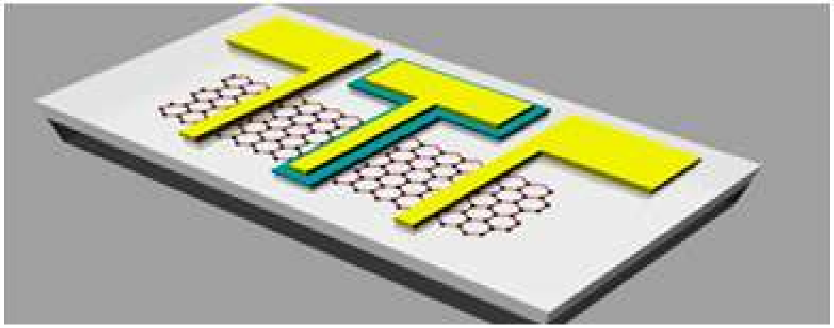


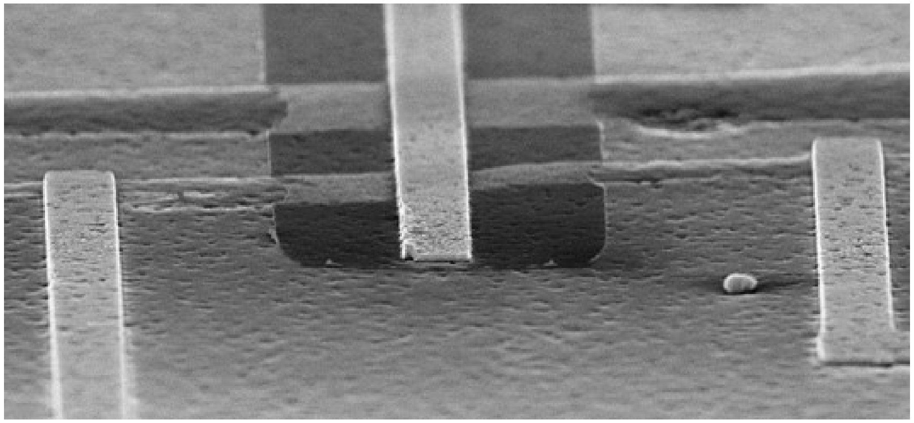
M. Freitag, et al., *Nano Letters*, 9, 1883 (2008)

Our approach:



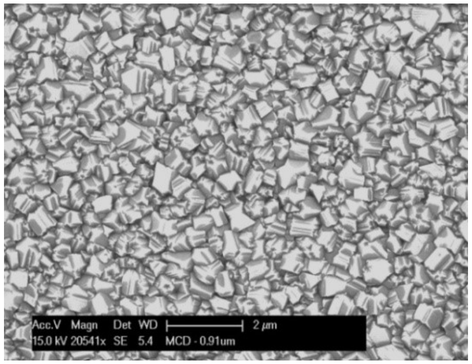
Schematic of graphene on diamond top gated devices the green part is the HfO_2 dioxide and the yellow are the metal pads (Ti 10 nm / Au 60 nm).



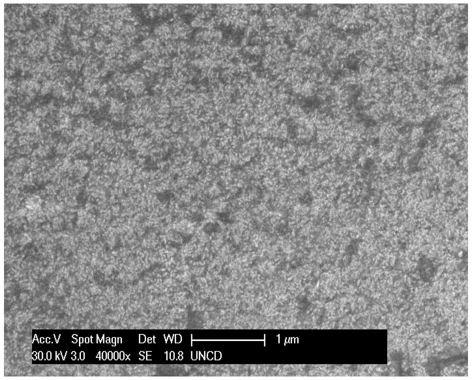


SEM of the top-gate graphene-on-diamond FET.

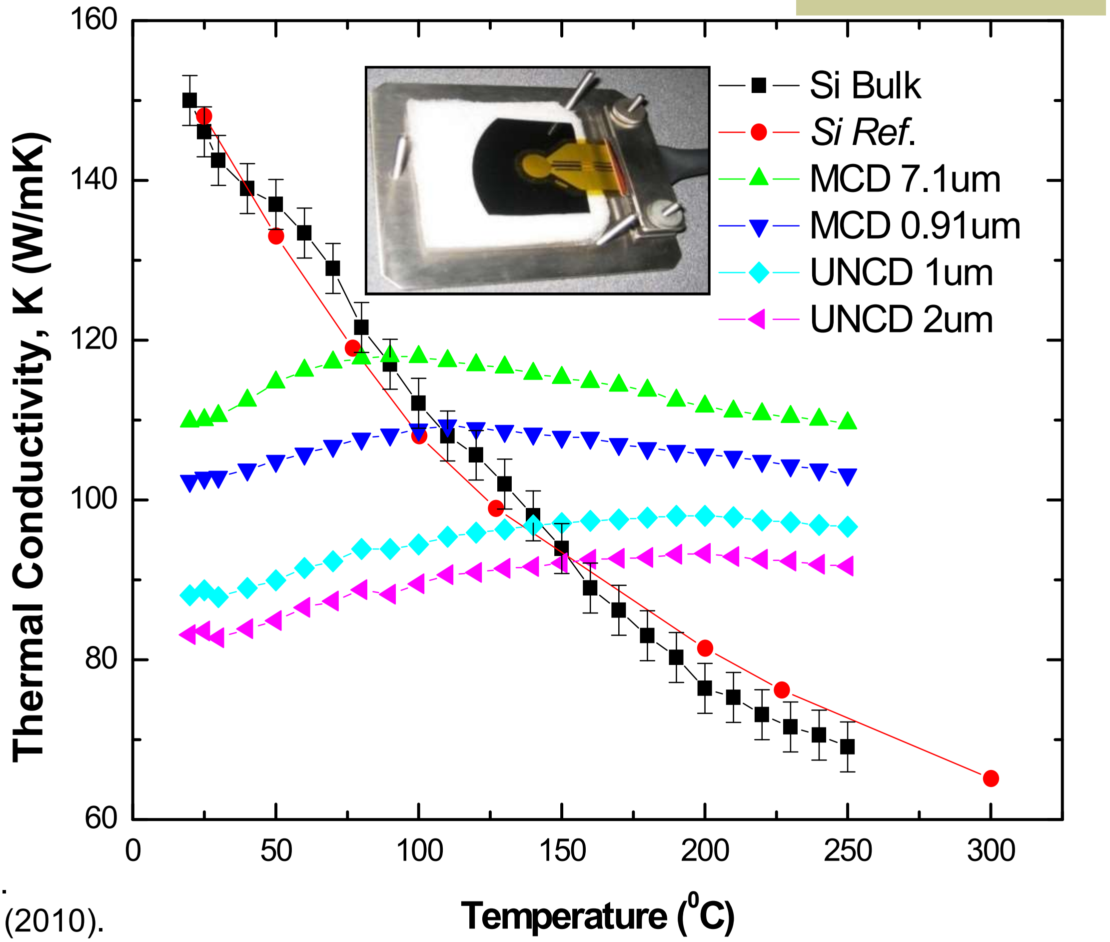
Thermal Conduction in Composite Synthetic Diamond – Silicon Substrates



Grain size: ~0.5 – 0.8 µm



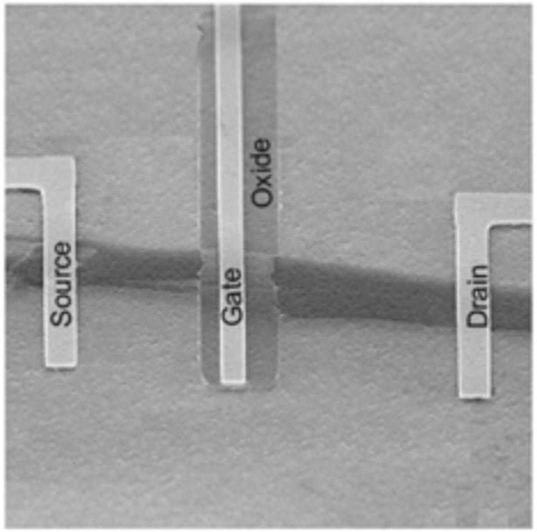
Grain size: ~5 – 10 nm



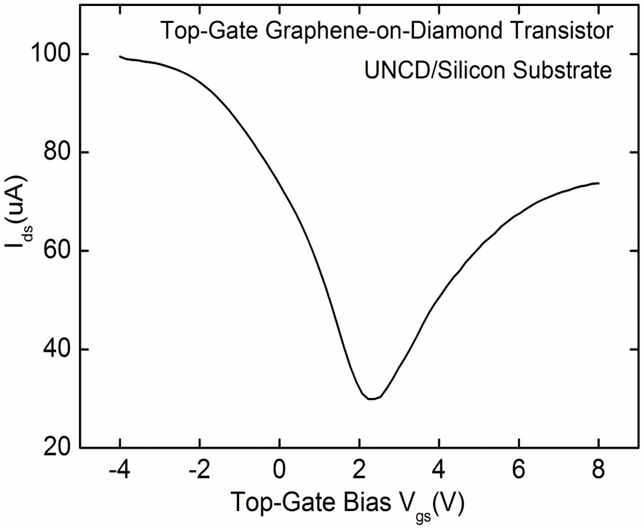
V. Goyal, S. Subrina, D.L. Nika and A.A. Balandin, *Appl. Phys. Lett.*, **97**, 031904 (2010).

Characteristics of Graphene-on-Diamond Field-Effect Transistors

STUDENT TALK



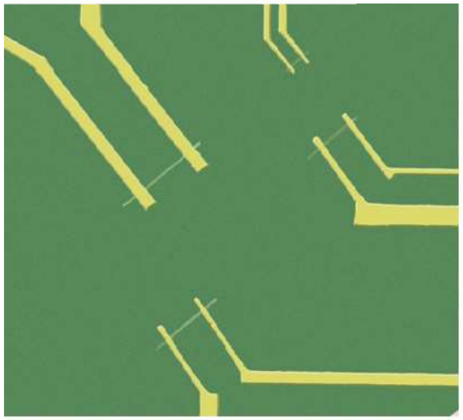
UNCD: D=5-10 nm
Roughness: ~ 1nm
Leakage: ~1 nA



J. Yu, G. Liu and A.A. Balandin, *Proceedings of IEEE Nano*, Portland, Oregon (2011)

→ Dielectric constants: 5.68 for Diamond; 11.7 for Si; 3.9 for SiO_2

→ Typical mobility in graphene-on-diamond FETs is ~ 2500 cm^2/Vs for holes and ~ 1500 cm^2/Vs for electrons



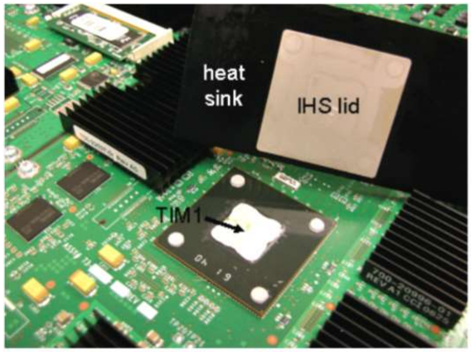
→Graphene-on-Si revealed the breakdown current density ~ 10^8 A/cm^2.

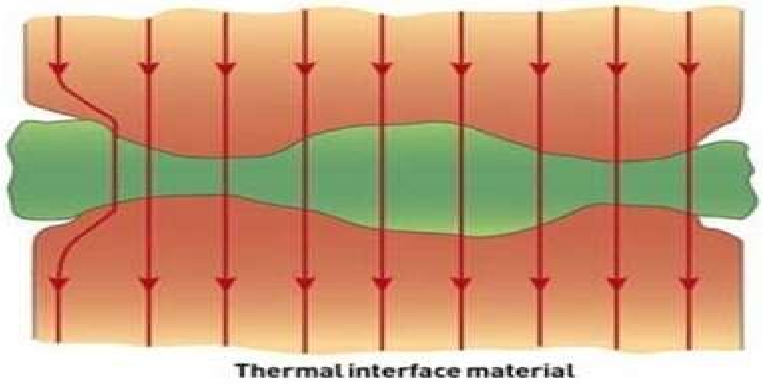
→ Average J_{BR}~2 x 10^8 A/cm^2 for UNCD/Si substrates

→ Order of magnitude improvement in J_{BR} of graphene FETs on the high-quality synthetic diamond with larger grains and on single-crystal diamond.

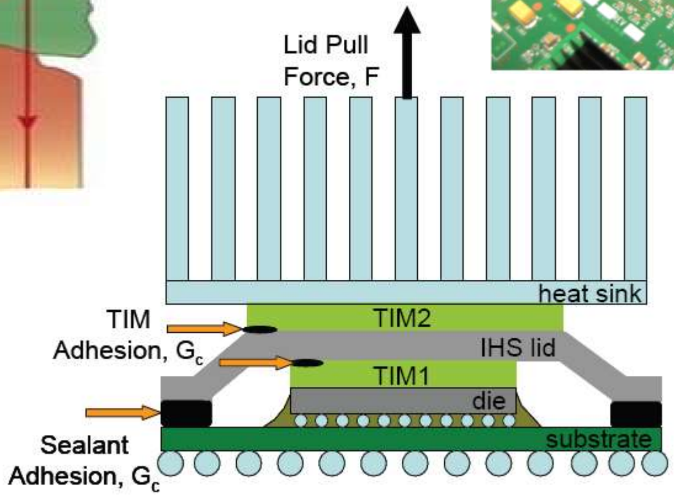
Increasing Importance of the Thermal Interface Materials - TIMs

TIMs are materials with the relatively high thermal conductivity introduced to the joint to fill the air gaps.





$$R_{effective} = \frac{BLT}{k_{TIM}A} + R_{c_1} + R_{c_2}$$



Current TIM based on polymer, grease filled with silver, alumina require 50-70% loading to achieve 1-5 W/mk.

F. Sarvar et al. Elect. Sys. Technology Conference (2006)

http://www.ecnmag.com/tags/products/Materials/

Hybrid Graphene – Nanoparticles Composites as Efficient TIMs

STUDENT TALK

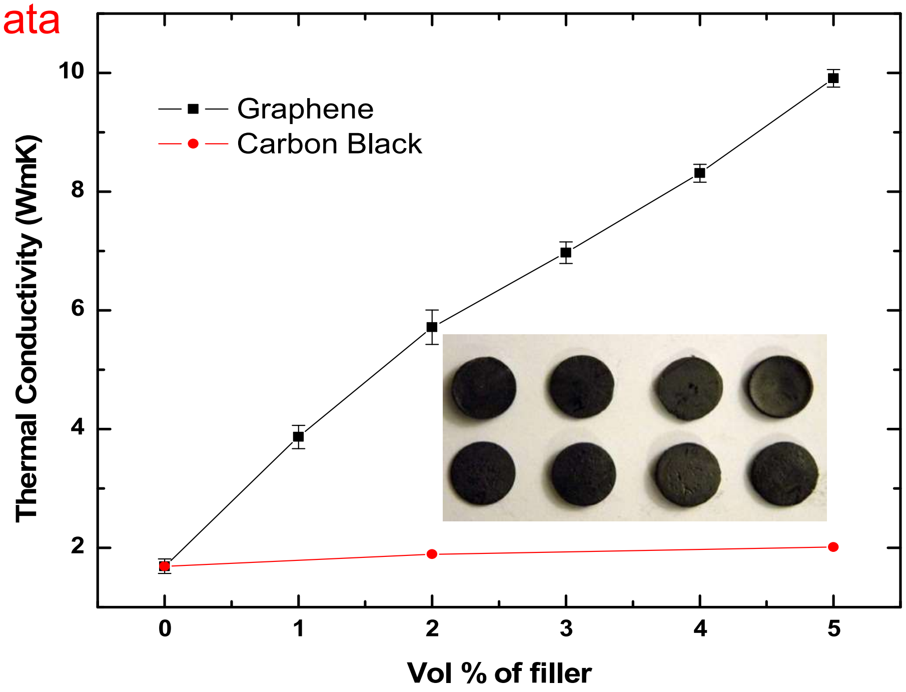
Preliminary Experimental Data

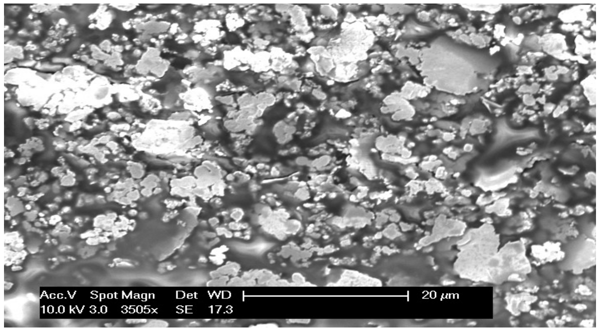
pristine silver epoxy:
K~1.67 W/mK

K increases with T

→ Pristine epoxy: K ~0.21 W/mK → Epoxy with graphene: K~ 2.35 W/mK at 4.3 % vol.

→ Conventional TIMs: require 50-70 vol % to achieve comparable K



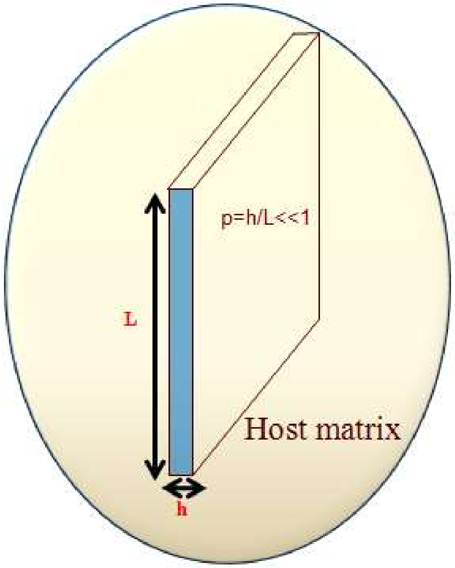


→ The RT thermal conductivity of silver epoxy increases by ~500% with a graphene loading of ~5 vol %.

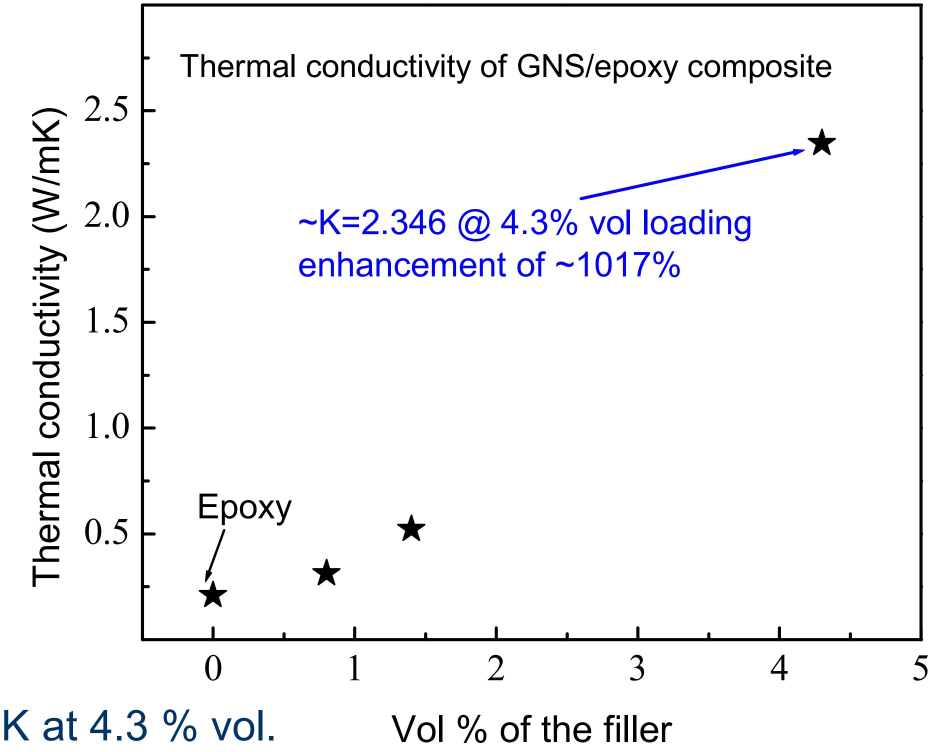
→ The RT thermal conductivity of pristine epoxy increases by ~1000% with a graphene loading of ~5 vol %.

Graphene – Epoxy Composite as TIMs

Effective Medium Approximation Predictions: Graphene is better than CNTs



Preliminary Experimental Data after K.M.F. Shahil and A.A. Balandin, UCR, 2010



Pristine epoxy: K ~0.21 W/mK
Epoxy with graphene: K~ 2.35 W/mK at 4.3 % vol.
Conventional TIMs: require 50-70 vol % to achieve comparable K

Graphene-Polymer TIM Composites: Comparison with CNT Composites

STUDENT TALK

Filler	*Enhancement*	*Volume Fraction*	*Base Material*	*Refs*
MW-CNT	**160%**	**1.0 vol%**	**oil**	Choi et al
SW-CNT	**125%**	**1.0 wt%**	**epoxy**	Biercuk et al.
SW-CNT	**200%**	**5.0 wt%**	**epoxy**	A. Yu et al.
Graphene	**500%**	**5.0 vol%**	**silver epoxy**	Goyal, Shahil, Balandin
Graphene	**1000%**	**5.0 vol%**	**epoxy**	Shahil, Balandin

← Simulation findings: Kapitza resistance reduction is the key to better composite TIM performance

← Graphene provides strongest enhancement at given volume fraction

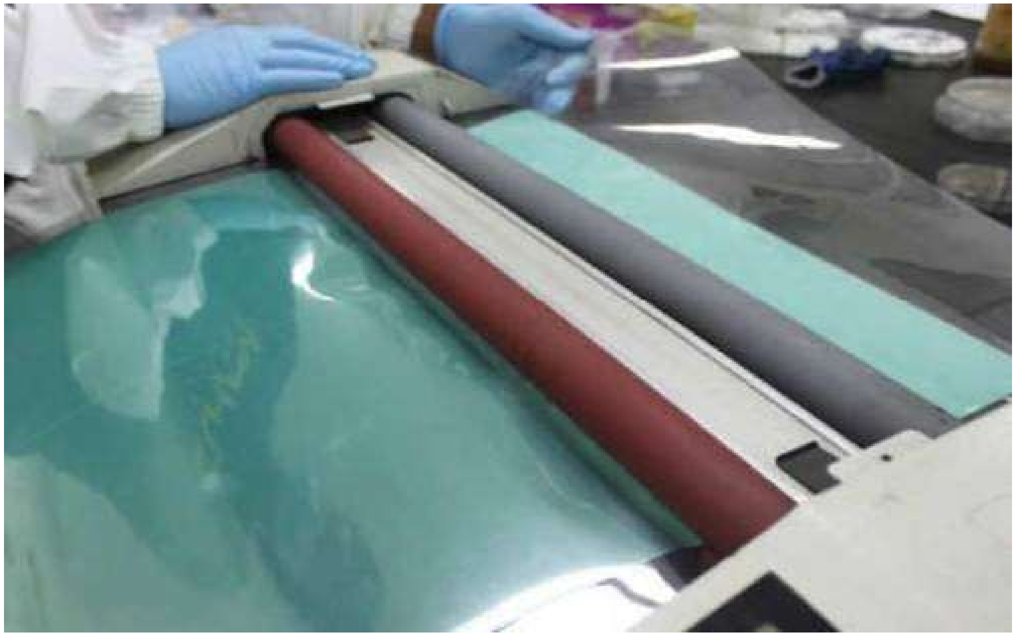
TBR does not strongly depend on the matrix material →

Interface	*Thermal Resistance*	*Method*	*Reference*
Graphene/SiO$_2$	**~4 × 10^{-8} (Km^2/W)**	**Raman/Electrical**	**Freitag et al. (2008)**
Graphene/SiO$_2$	**~(0.6-12) × 10^{-8} (Km^2/W)**	**Electrical**	**Chen et al. (2009)**
Graphene/SiO$_2$	**~2 × 10^{-8} (Km^2/W)**	**Pump-Probe**	**Mak et al. (2010)**
Au/Ti/graphene/SiO$_2$	**~4 × 10^{-8} (Km^2/W)**	**Raman/Electrical**	**Koh et al. (2010)**
Bulk Graphite/Metal	**~(1 - 3) × 10^{-8} (Km^2/W)**	**Reflectance**	**Schmidt et al.(2010)**
Graphene/a-SiO$_2$	**~4 × 10^{-8} (Km^2/W)**	**Theory**	**Persson et al. (2010)**
Graphene/Oil	**~(0.4-4) × 10^{-8} (Km^2/W)**	**Theory**	**Konatham (2009)**

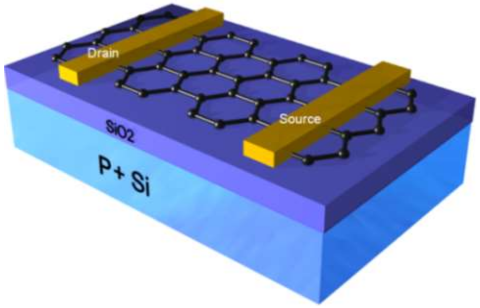
Graphene as Transparent Electrode for Touch Screens and Flexible Electronics

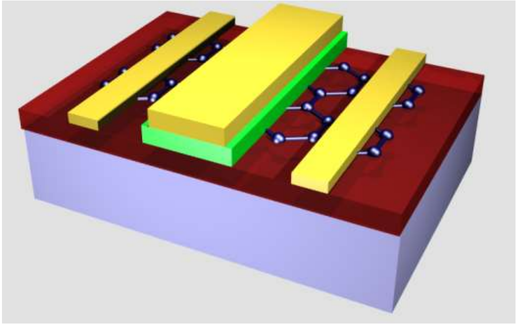
Flexible graphene sheet with silver electrodes printed on it can be used as a touch screen when connected to control software. Credit: Byung Hee Hong, SKKU.

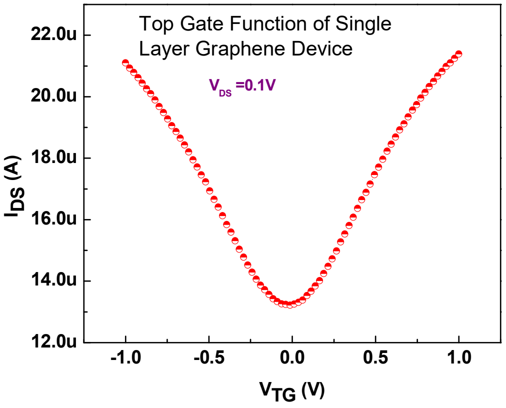
http://www.technologyreview.com/computing/25633/page1/

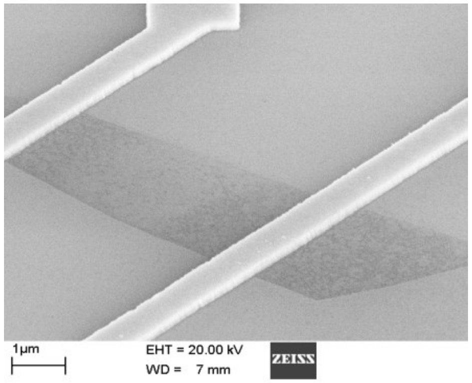


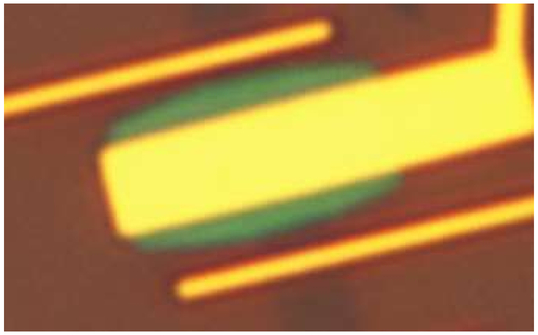
Bottom-Gate and Top-Gate Graphene Field-Effect Transistors

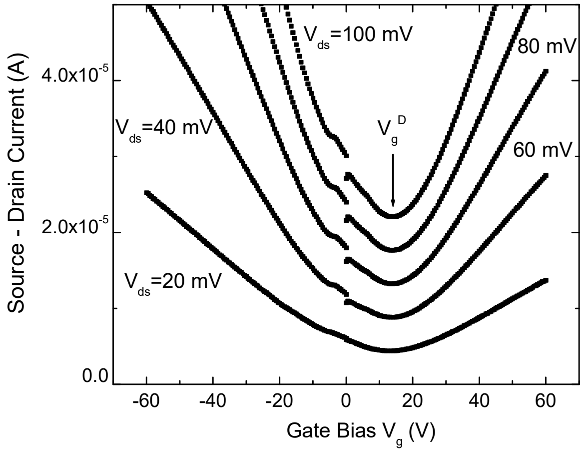










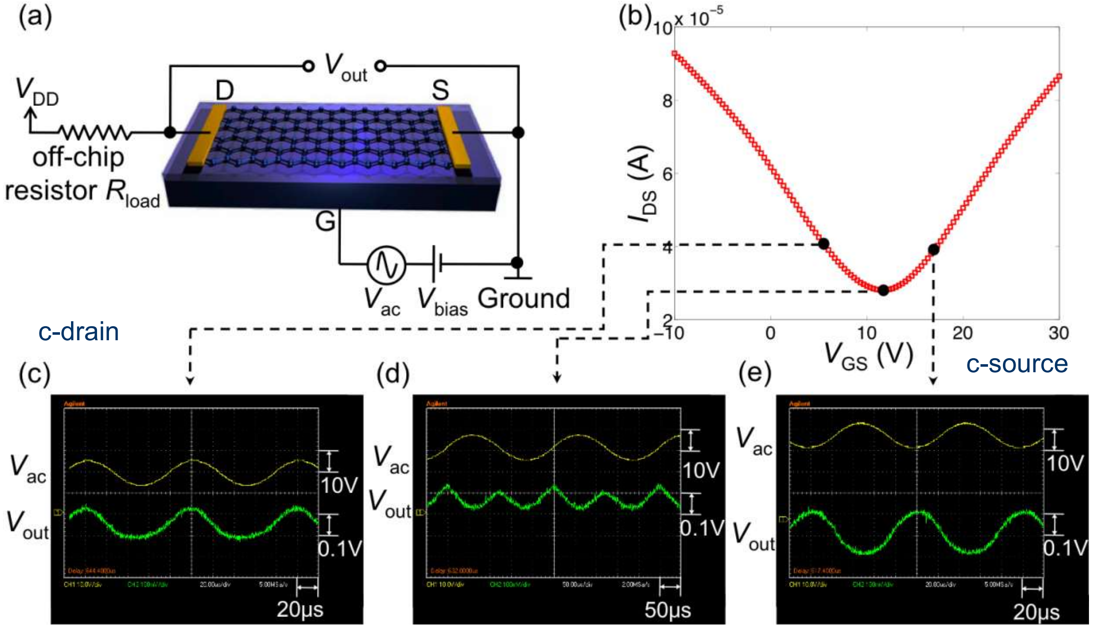


The fabrication of pads and contact bars was performed using electron beam lithography Cr/Au metal deposition by electron beam evaporator.

Top gate dielectric of ~20 nm HfO2 is grown by the atomic layer deposition (ALD).

The low-temperature ALD allows for fabrication of the dielectric with low leakage.

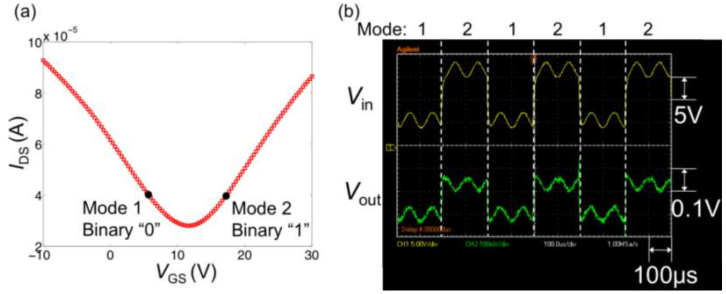
Demonstration of the Triple-Mode Graphene Amplifier and Phase Detector

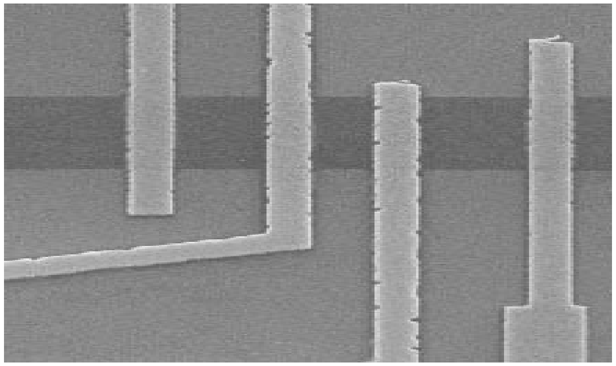


← c) common-drain mode: output has the same frequency and phase as the input; d) frequency multiplication mode: *f* of the output is doubled as compared to *f* of input; e) common-source mode: the same frequency but 180^{o} shifted as compared to the input.

The graphene circuit can realize the modulation necessary for phase shift keying and frequency shift keying

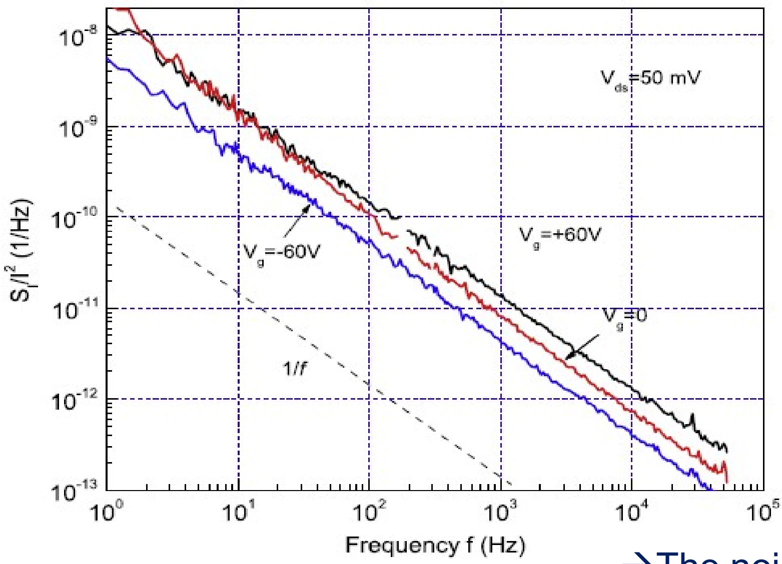
Binary phase shift keying (BPSK) modulation with graphene amplifiers: (a) biasing points and (b) experimental results. →



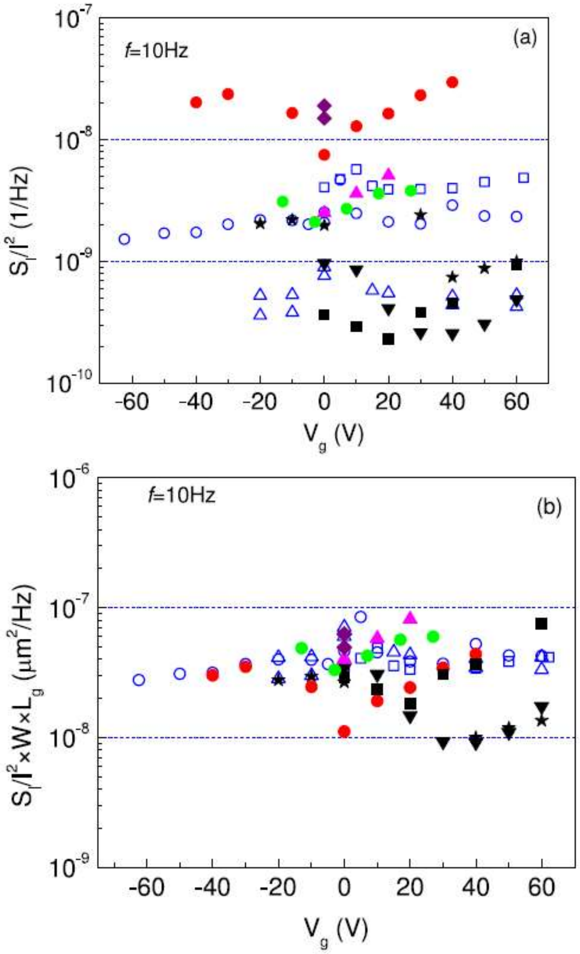


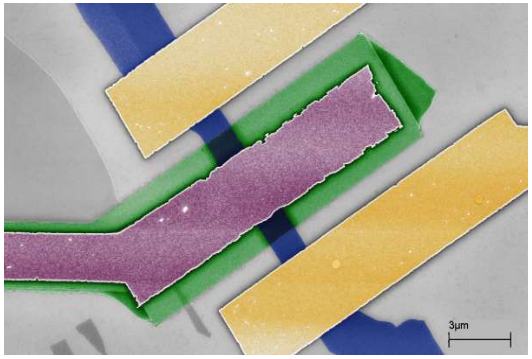
X. Yang, et al., *ACS Nano*, **4**, 5532 (2010).

Electronic Noise Reduction in Graphene Transistors



S. Rumyantsev, G. Liu, W. Stillman, M. Shur and A.A. Balandin, *J. Physics: Condensed Matter*, 22, 395302 (2010).

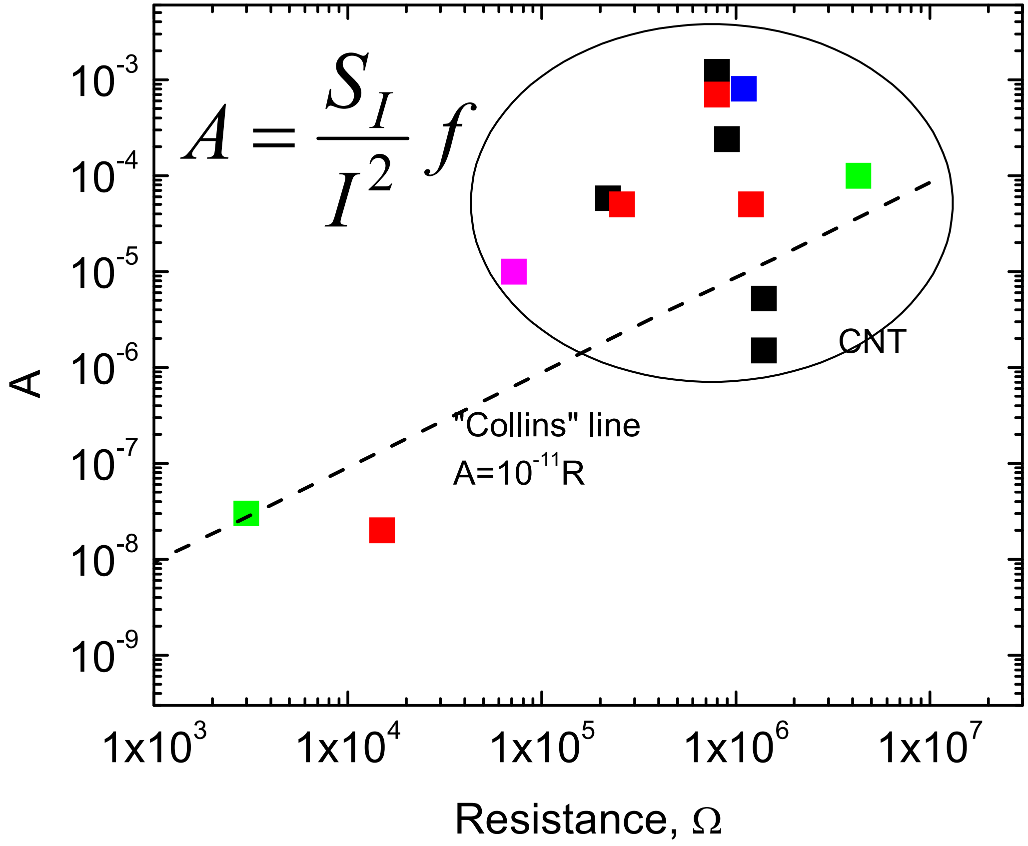




→The noise level in graphene transistors scales with the graphene channel area, which suggests that the dominant noise source is graphene channel itself.

→ No clear G-R peaks observed in graphene devices.

Graphene vs. CNT Transistors: Flicker Noise Levels



G. Liu, W. Stillman, S.L. Rumyantsev, M. Shur and A.A. Balandin, "Low-frequency electronic noise in graphene transistors: Comparison with carbon nanotubes," *Int. J. High Speed Electronics and Systems*, 20, 161 (2011).

→Upper bound: number of carriers equal to the number of atoms in CNTs.

→ Different role of contacts

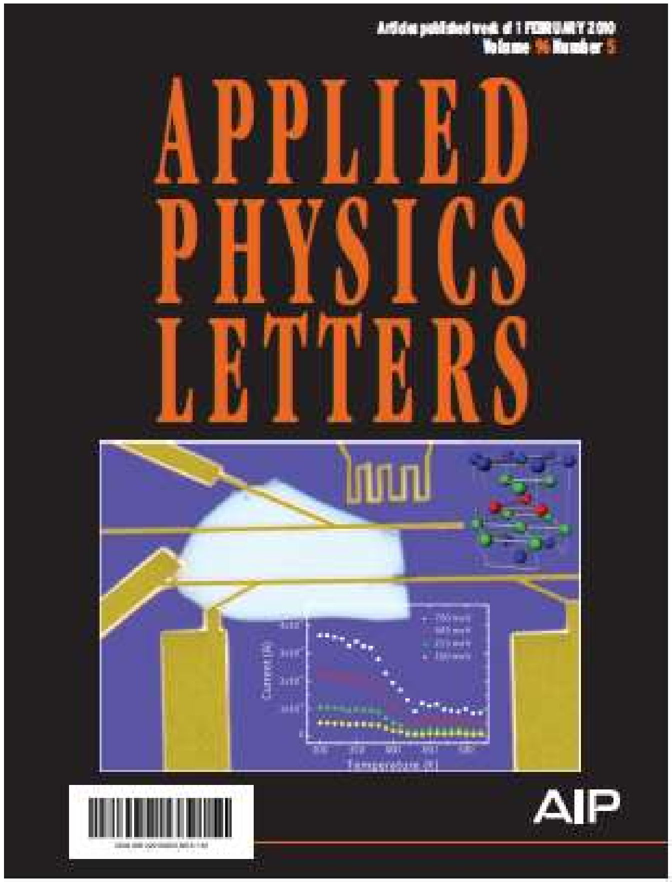
→ Different exposure to environment

$$\alpha_H = \frac{S_I}{I^2} fN$$

$$\alpha_H \sim 1-10$$

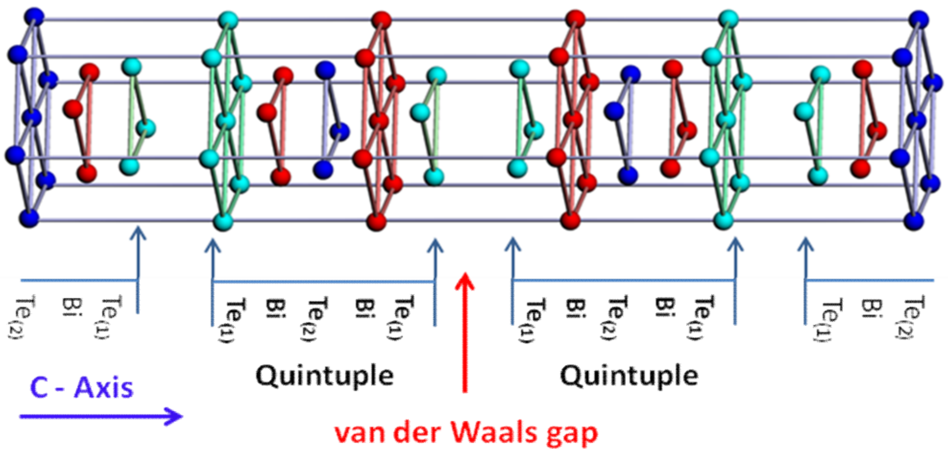
Graphene $\alpha_H \approx 10^{-3}$

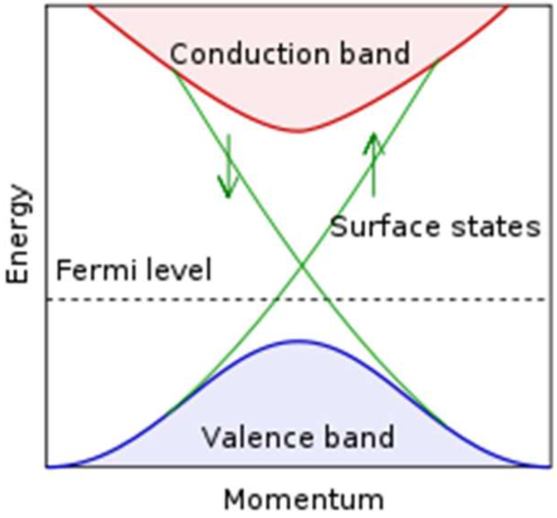
Part II: Dirac Materials: From Graphene to Topological Insulators

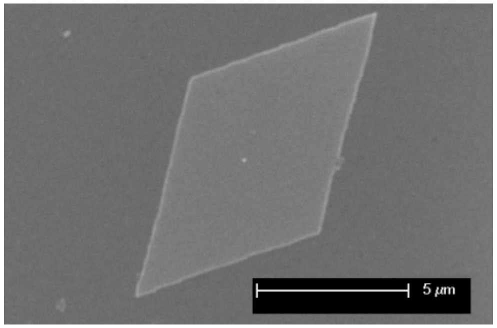


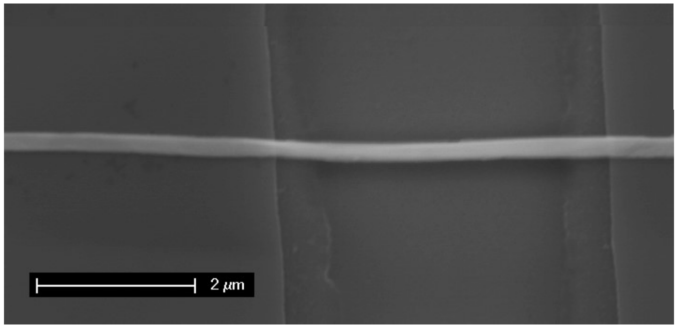
← D. Teweldebrhan, V. Goyal, M. Rahman and A.A. Balandin, "Atomically-thin crystalline films and ribbons of bismuth telluride," Applied Physics Letters, 96, 053107 (2010). *- Issue's Cover*

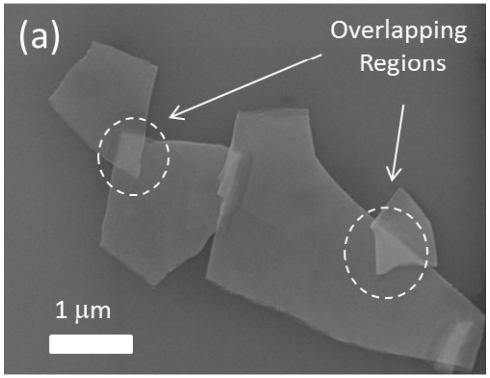
"Graphene-Like" Exfoliation of Different Type of Materials





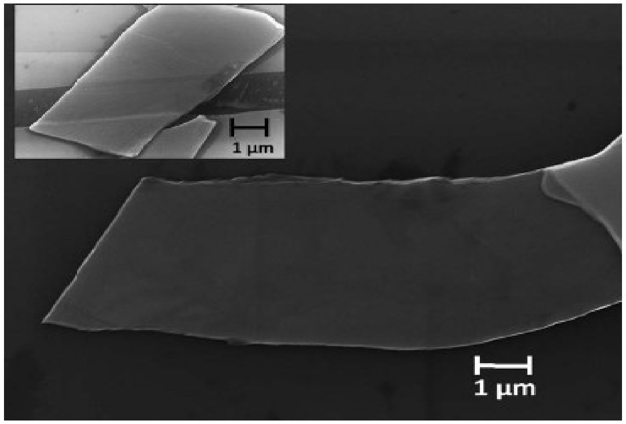


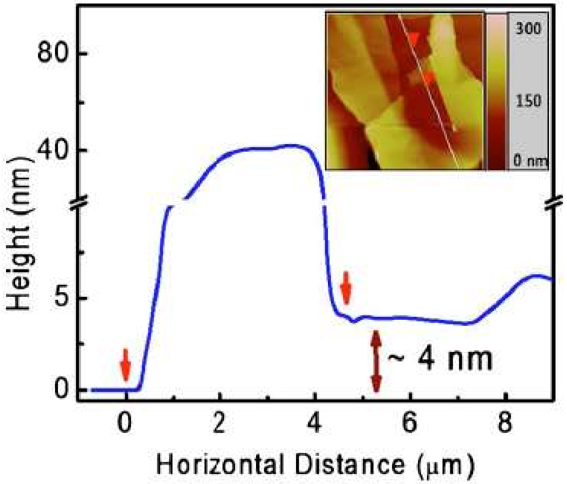


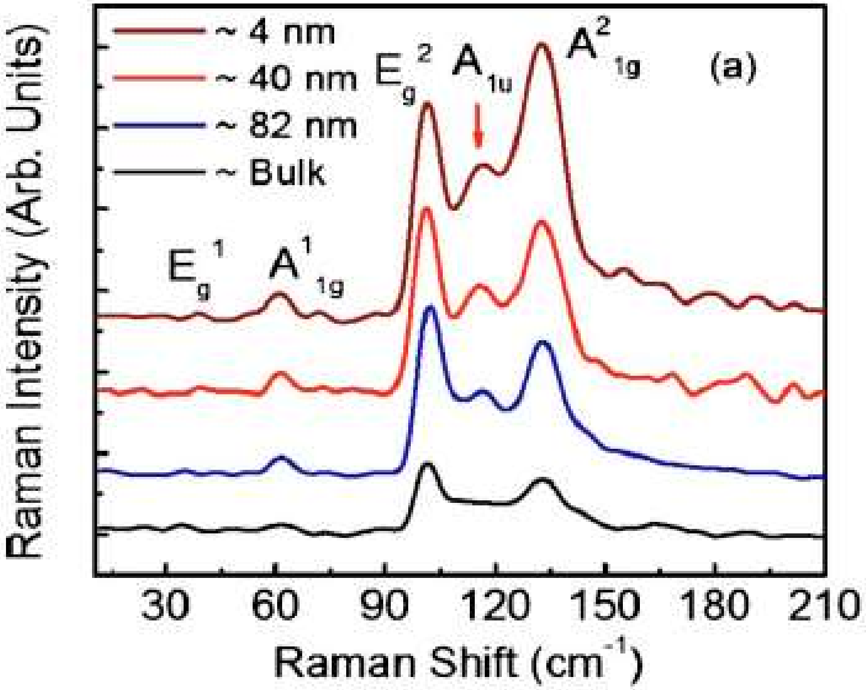


D. Teweldebrhan, V. Goyal and A.A. Balandin, "Exfoliation and characterization of bismuth telluride atomic *quintuples* and quasi-2D crystals," *Nano Letters*, 10, 1209 (2010).

Raman Spectroscopy of the Atomically Thin Films of Bi-Te Topological Insulators

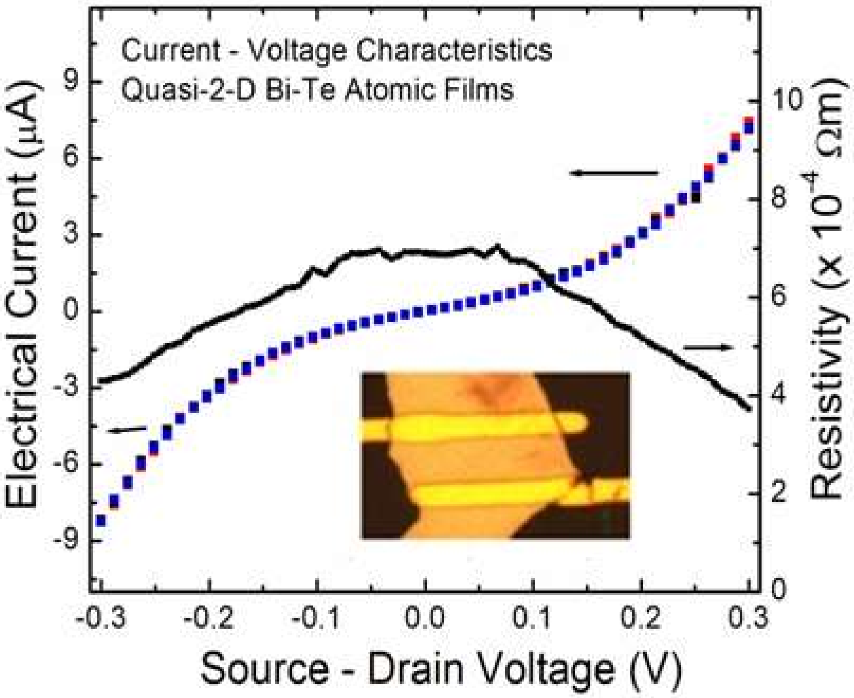


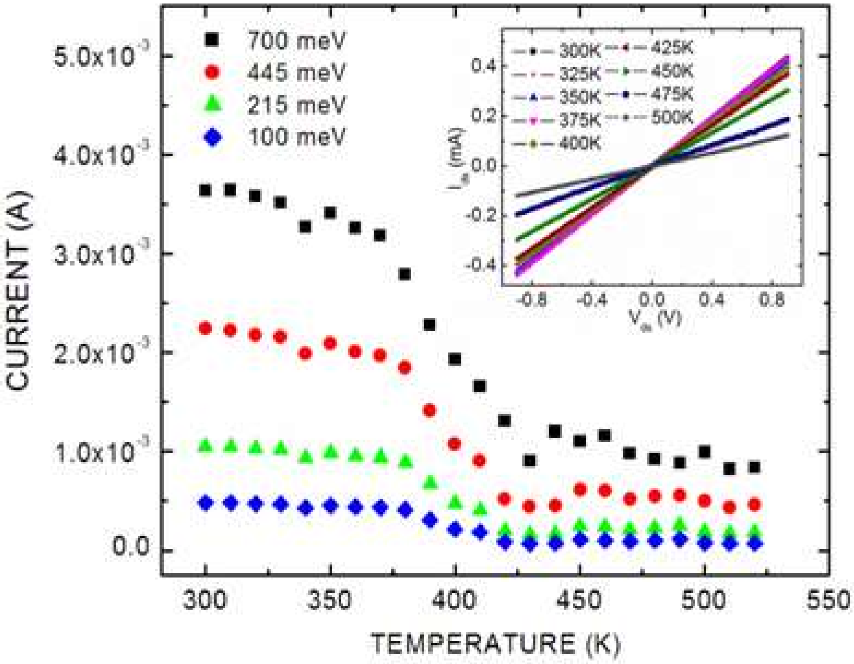




K.M.F. Shahil, M.Z. Hossain, D. Teweldebrhan and A.A. Balandin, "Crystal symmetry breaking in few-quintuple Bi_2Te_3 films: Applications in nanometrology of topological insulators," *Appl. Phys. Lett.*, **96**, 153103 (2010).

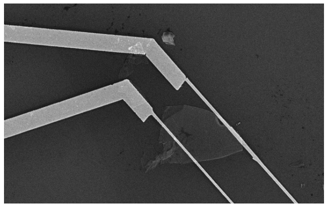
Room-Temperature Electrical Characterization Bi-Te Atomic Films





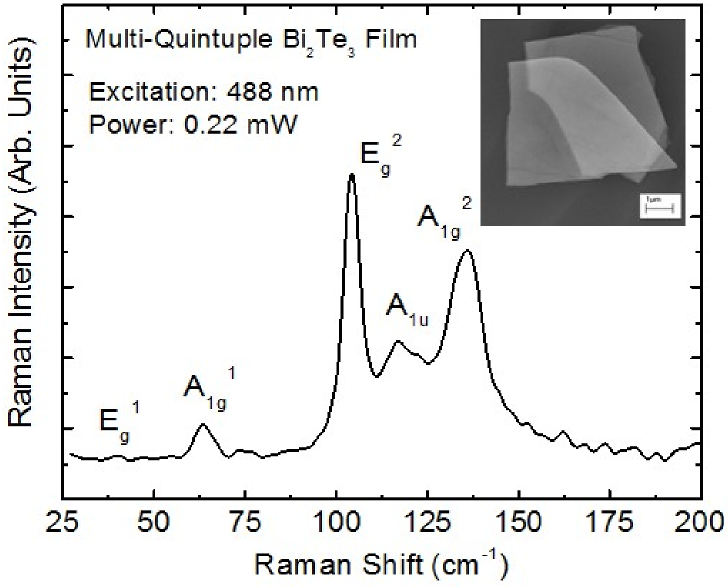
→Weak gating at RT

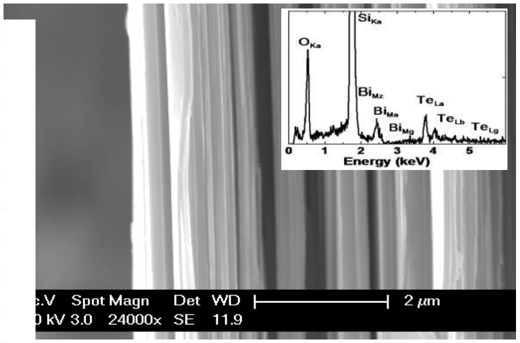
→ Resistivity is ~10^{-4} Ωm



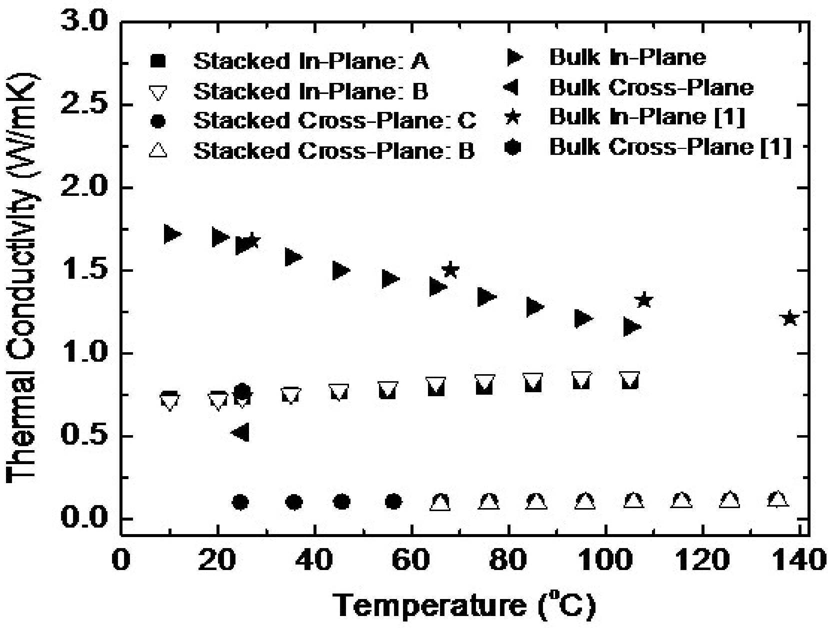
D. Teweldebrhan, V. Goyal, M. Rahman and A.A. Balandin, "Atomically-thin crystalline films and ribbons of bismuth telluride," *Appl. Phys. Lett.*, **96**, 053107 (2010). - ***Issue's Cover***

Thermoelectric Topological Insulators





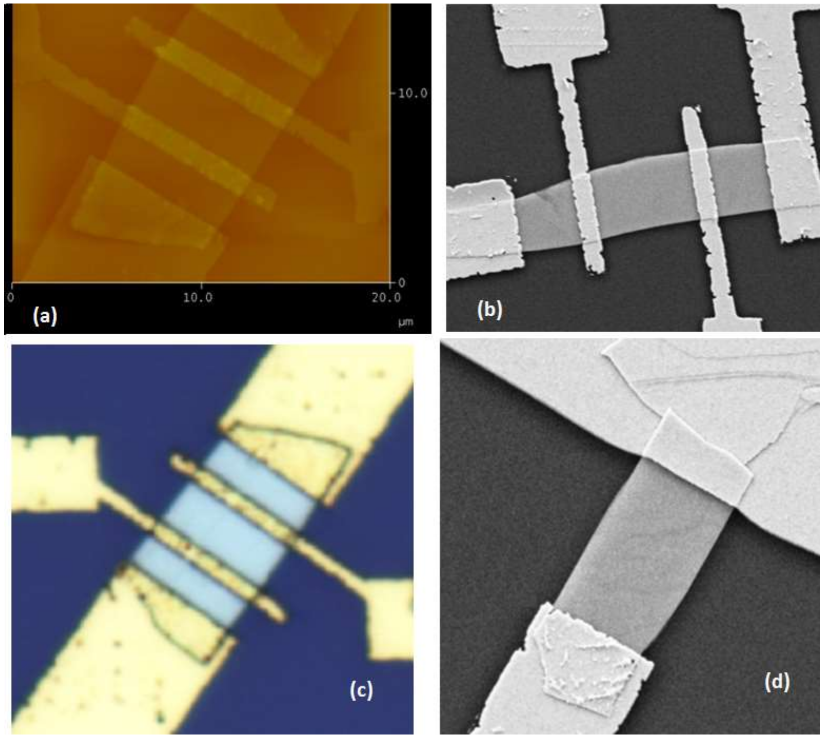
V. Goyal, D. Teweldebrhan and A.A. Balandin, “Mechanically exfoliated stacks of thin films of Bi$_2$Te$_3$ topological insulator films”, Appl. Phys. Lett. (2010).



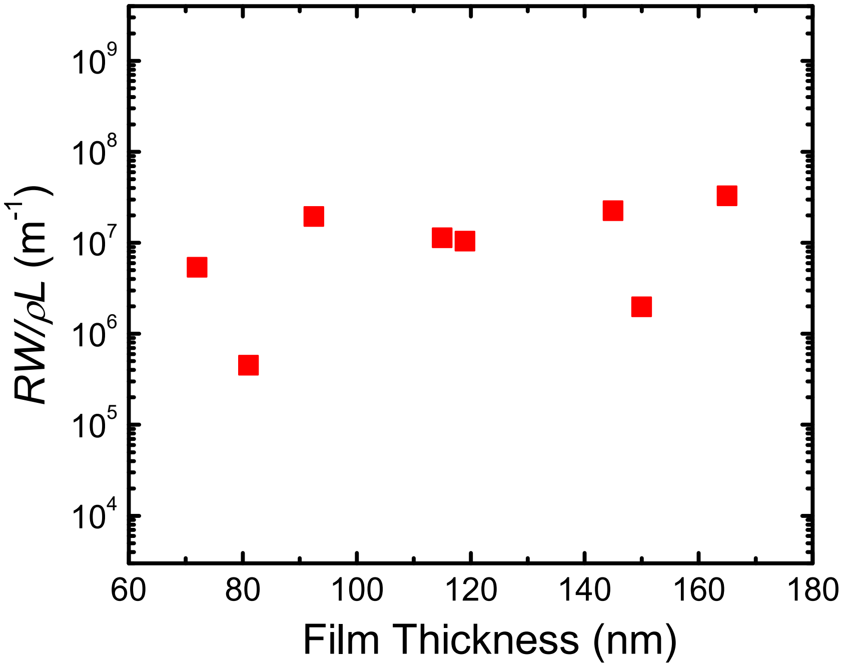
ZT increase by ~140 – 250% at room temperature

The enhancement is expected to be larger at low T

Distinguishing between Surface and Volume Transport in Topological Insulator Films



M.Z. Hossain, S.L. Rumyantsev, D. Teweldebrhan, K.M.F. Shahil, M. Shur and A.A. Balandin, “Low-frequency current fluctuations in “graphene-like” exfoliated thin-films of bismuth selenide topological insulators," *ACS Nano*, ASAP (2011).

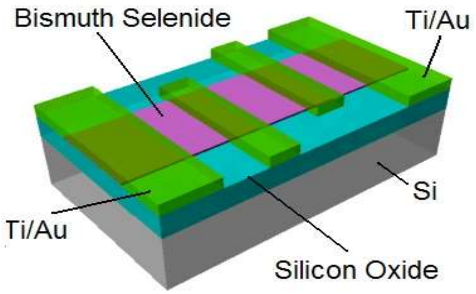


The absence of scaling of the normalized resistance with the film thickness indicates that surface transport is dominant in the exfoliated films.

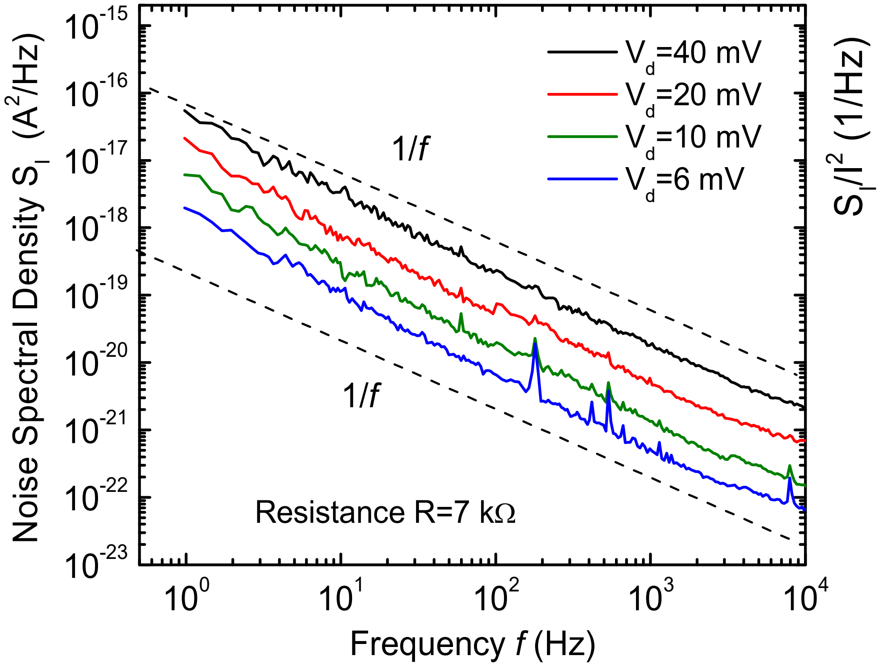
Contacts: 20 nm Ti / 180 nm Au

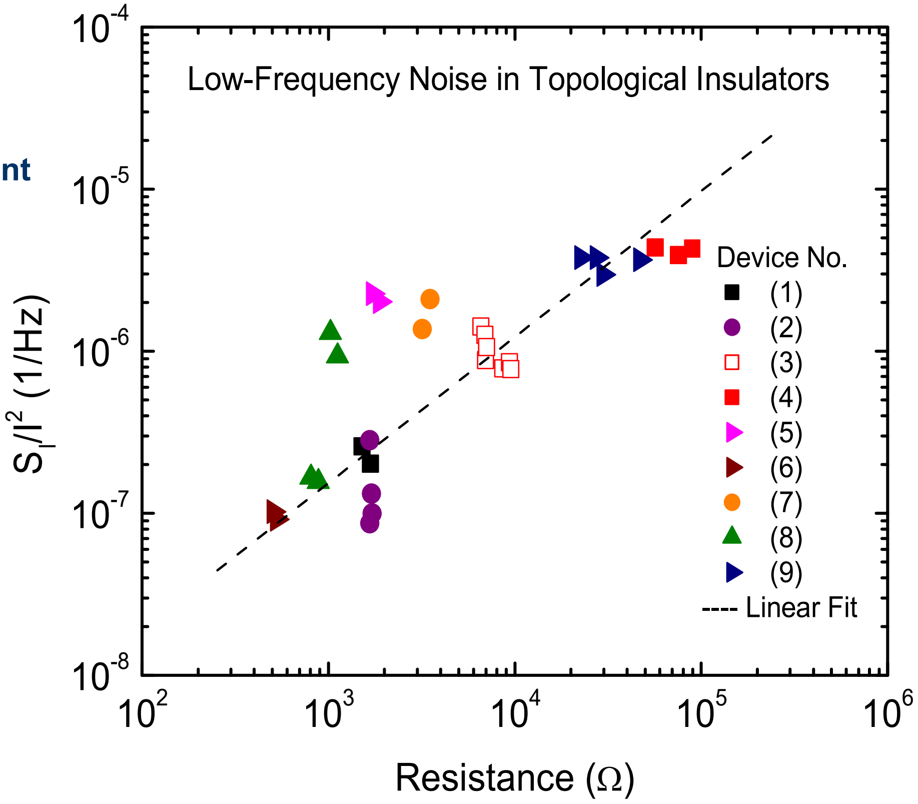
Resistance: 1 kΩ to 100 kΩ

Topological Insulators as Low-Noise Interconnects



Absence of the generation – recombination (GR) peaks indicates that there are no dominant defect/trap states

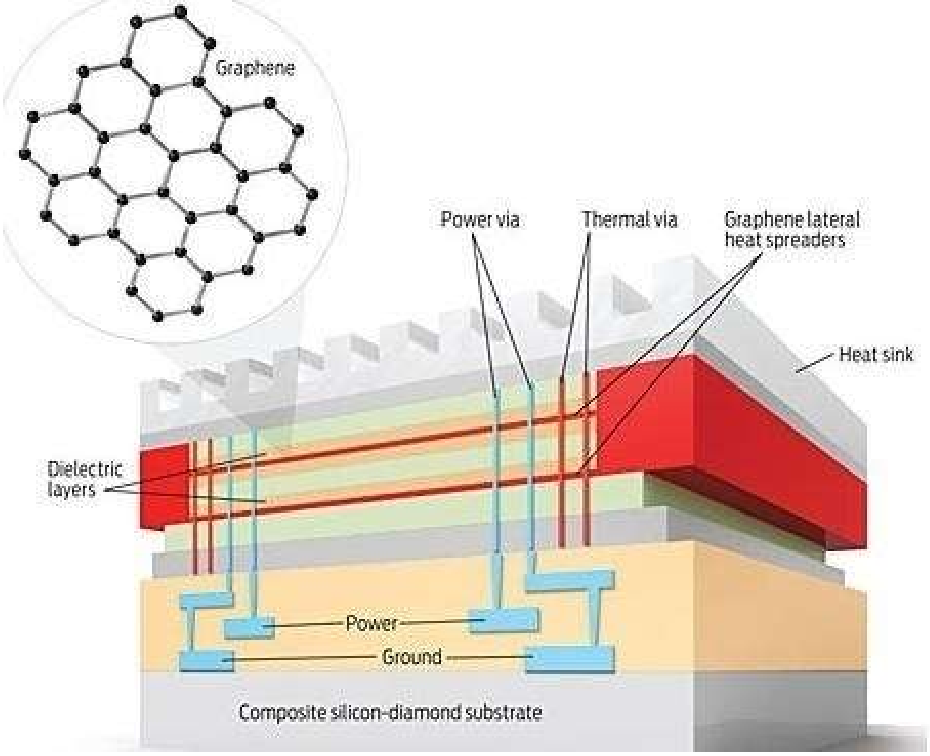




M.Z. Hossain, S.L. Rumyantsev, D. Teweldebrhan, K.M.F. Shahil, M. Shur and A.A. Balandin, *ACS Nano*, ASAP (2011).

| Nano-Device Laboratory >

“Carbon World” vs. “Hybrid Carbon-Silicon World” vs. “Dirac World” vs.?



IEEE Spectrum artistic rendering of the hybrid silicon – carbon 3D chip with graphene heat spreaders, interconnects and gtransistors. IEEE Spectrum illustration of the thermal issues in the feature article *Chill Out: New Materials and Designs Can Keep Chips Cool* by A.A. Balandin.

Graphene Applications

- → *Transparent electrodes*
- → *Touch screens*
- → *Heat spreaders*
- → *TIMs*
- → *Sensors*
- → *Super-capacitor electrodes*
- → *Battery electrodes*
- → *High-frequency*
- → *Interconnects*
- → *Analog, RF, mixed signal*

nature materials

REVIEW ARTICLE

PUBLISHED ONLINE: 22 JULY 2011 | DOI: 10.1038/NMAT3064

Thermal properties of graphene and nanostructured carbon materials

Alexander A. Balandin

RT Thermal Conductivity of Carbon Materials:

Diamond: 1000 – 2200 W/mK

Graphite: 20 – 2000 W/mK

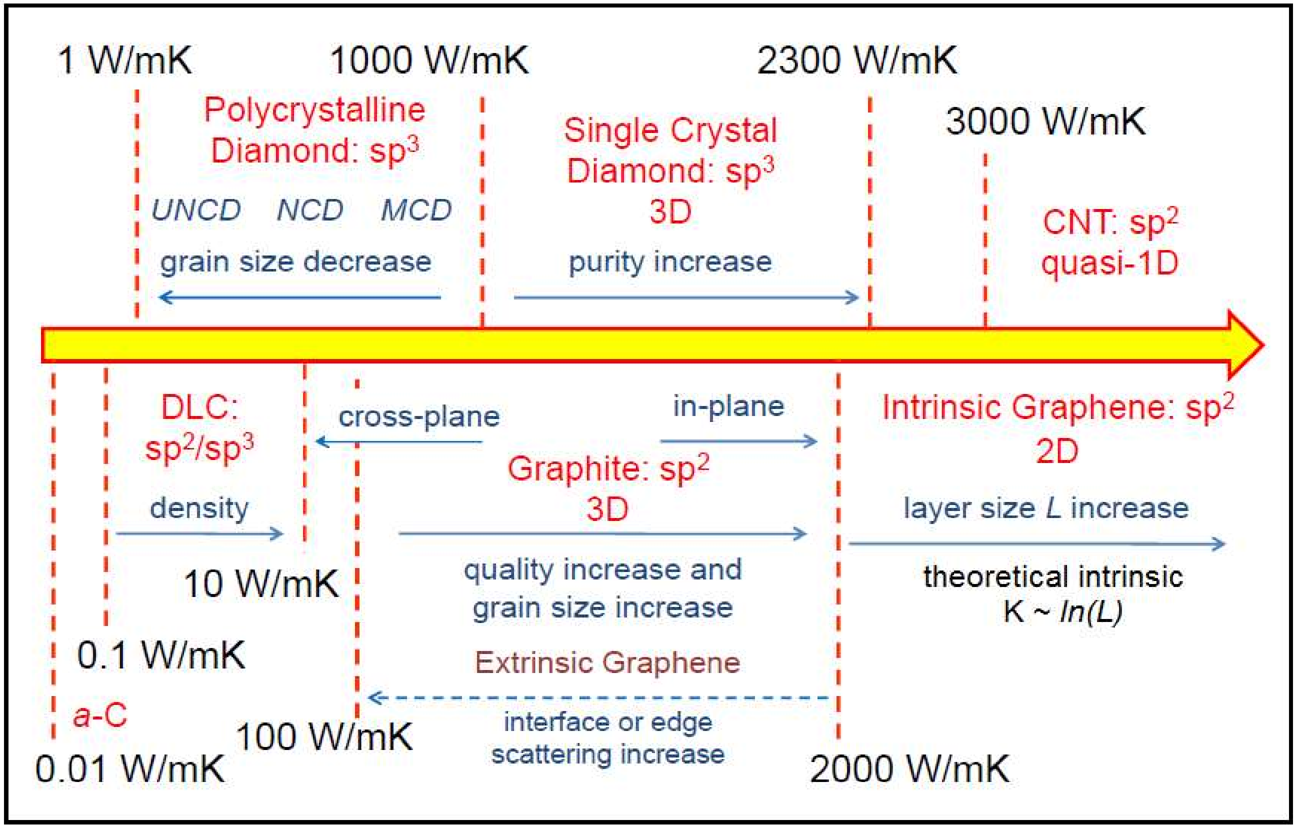
DLC: 0.1 – 10 W/mK

***a*-C: 0.01 – 1 W/mK**

NCD-MCD: 1 – 1000 W/mK

CNTs: 1000 – 3500 W/mK

Graphene: 2000 – 5000 W/mK



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Dr. K. M. F. Shahil (GF)*

Ms. Jie Yu (Siemens)*

Mr. Guanxiong Liu

Mr. Hossain Zahid

Mr. Zhong Yan