Title: Superconductivity and Charge Density Waves in the Clean 2D Limit

Date: May 12, 2016 11:00 AM

URL: http://pirsa.org/16050035

Abstract: We have recently demonstrated an experimental platform to isolate 2D materials that are unstable in the ambient environment. I will discuss our recent studies of the charge density wave compound 1T-TaS2 and superconducting 2H-NbSeÂ¬ in the atomically thin limit, made possible using this technique. In TaS2, we uncover a new surface charge density wave transition that is distinct from that in the bulk layers, as well as demonstrate continuous electrical control over this phase transition. In NbSe2, a small perpendicular magnetic field induces a transition to a quantum metallic phase, the resistivity of which obeys a unique field-scaling consistent with that predicted for a Bose metal. These methods and experiments open new doors for the study of other correlated 2D systems in the immediate future.

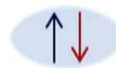
Superconductivity and Charge Density Waves in the Clean 2D Limit

A. W. Tsen
University of Waterloo

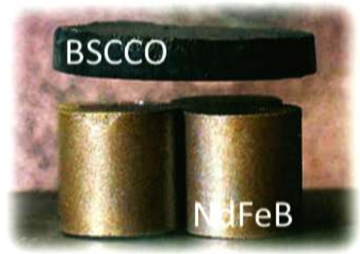
Understanding and Controlling Electronic Phases of Matter

Metal

Insulator

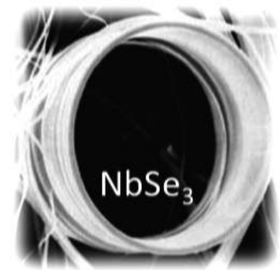


Superconductor



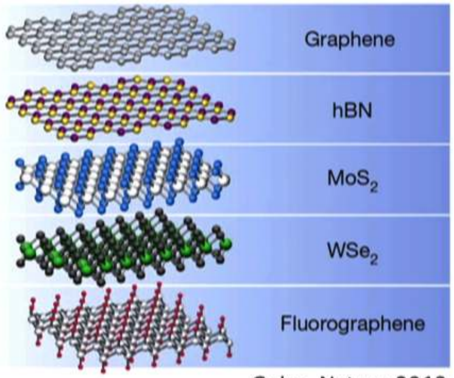
Ferromagnet

Charge Density Wave

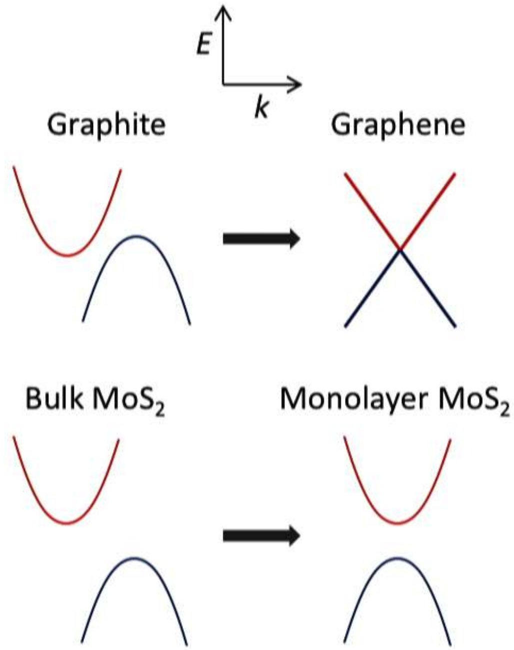


Spin Density Wave

Dimensional Control of Electronic Structure

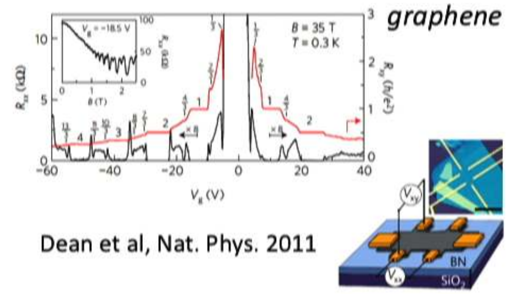


Geim, Nature 2013



Quantum Hall Effect

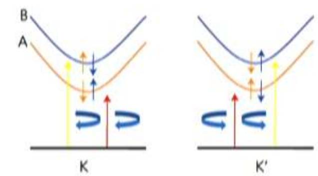
graphene

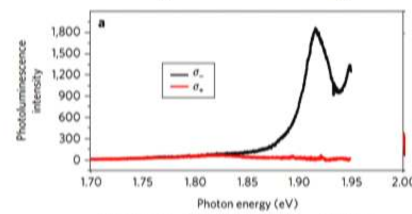


Dean et al, Nat. Phys. 2011

Spin-Valley

MoS_2





Mak et al, Nat. Nano. 2012

<table>
<tr><td>Graphene family</td><td>Graphene</td><td colspan="3">hBN
'white graphene'</td><td>BCN</td><td colspan="2">Fluorographene</td><td>Graphene oxide</td></tr>
<tr><td rowspan="2">2D chalcogenides</td><td colspan="2" rowspan="2">MoS_2, WS_2, $MoSe_2$, WSe_2</td><td colspan="3" rowspan="2">Semiconducting dichalcogenides:
$MoTe_2$, WTe_2,
ZrS_2, $ZrSe_2$ and so on</td><td colspan="3">Metallic dichalcogenides:
$NbSe_2$, NbS_2, TaS_2, TiS_2, $NiSe_2$ and so on</td></tr>
<tr><td colspan="3">Layered semiconductors:
GaSe, GaTe, InSe, Bi_2Se_3 and so on</td></tr>
<tr><td rowspan="2">2D oxides</td><td>Micas, BSCCO</td><td colspan="2">MoO_3, WO_3</td><td colspan="3" rowspan="2">Perovskite-type:
$LaNb_2O_7$, $(Ca,Sr)_2Nb_3O_{10}$,
$Bi_4Ti_3O_{12}$, $Ca_2Ta_2TiO_{10}$ and so on</td><td colspan="2">Hydroxides:
$Ni(OH)_2$, $Eu(OH)_2$ and so on</td></tr>
<tr><td>Layered Cu oxides</td><td colspan="2">TiO_2, MnO_2, V_2O_5,
TaO_3, RuO_2 and so on</td><td colspan="2">Others</td></tr>
</table>

Geim, Nature 2013

PNAS

Structure and control of charge density waves in two-dimensional 1T-TaS_2

Adam W. Tsen[a], Robert Hovden[b], Dennis Wang[c], Young Duck Kim[d], Junichi Okamoto[e], Katherine A. Spoth[b], Yu Liu[f], Wenjian Lu[f], Yuping Sun[f,g,h], James C. Hone[d], Lena F. Kourkoutis[b,i], Philip Kim[a,j,1], and Abhay N. Pasupathy[a,1]

[a]Department of Physics, Columbia University, New York, NY 10027; [b]School of Applied and Engineering Physics, Cornell University, Ithaca, NY 14853; [c]Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY 10027; [d]Department of Mechanical Engineering, Columbia University, New York, NY 10027; [e]Department of Physics, University of Hamburg, D-20355 Hamburg, Germany; [f]Key Laboratory of Materials Physics, Institute of Solid State Physics, Chinese Academy of Sciences, Hefei 230031, People's Republic of China; [g]High Magnetic Field Laboratory, Chinese Academy of Sciences, Hefei 230031, People's Republic of China; [h]Collaborative Innovation Centre of Advanced Microstructures, Nanjing University, Nanjing 210093, People's Republic of China; [i]Kavli Institute at Cornell for Nanoscale Science, Ithaca, NY 14853; and [j]Department of Physics, Harvard University, Cambridge, MA 02138

Abhay Pasupathy

Philip Kim

Robert Hovden

Lena Kourkoutis

Distinct surface and bulk charge density waves in ultrathin 1T-TaS_2

Rui He[1*], Junichi Okamoto[2], Zhipeng Ye[1], Gaihua Ye[1], Heidi Anderson[1], Xia Dai[3], Xianxin Wu[3], Jiangping Hu[4], Yu Liu[5], Wenjian Lu[5], Yuping Sun[5,6,7], Abhay N. Pasupathy[8], and Adam W. Tsen[9*]

http://arxiv.org/abs/1603.02110

LETTERS

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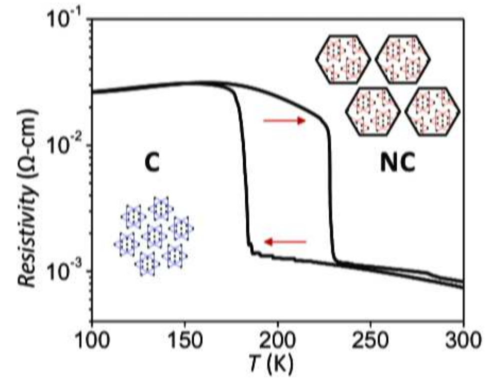
nature physics

Nature of the quantum metal in a two-dimensional crystalline superconductor

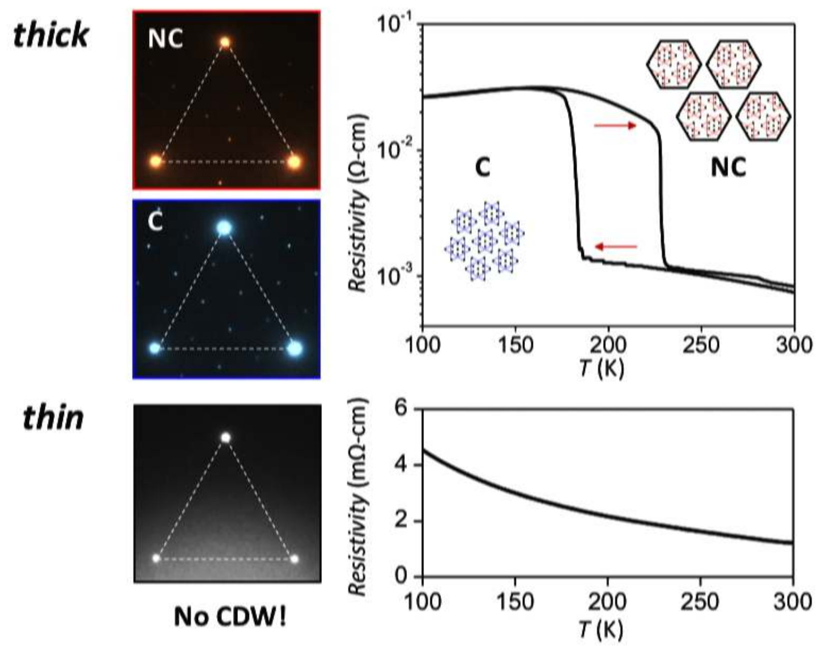
A. W. Tsen[1], B. Hunt[1†], Y. D. Kim[2], Z. J. Yuan[3], S. Jia[3,4], R. J. Cava[5], J. Hone[2], P. Kim[6], C. R. Dean[1*] and A. N. Pasupathy[1*]

CDW and surface oxidation

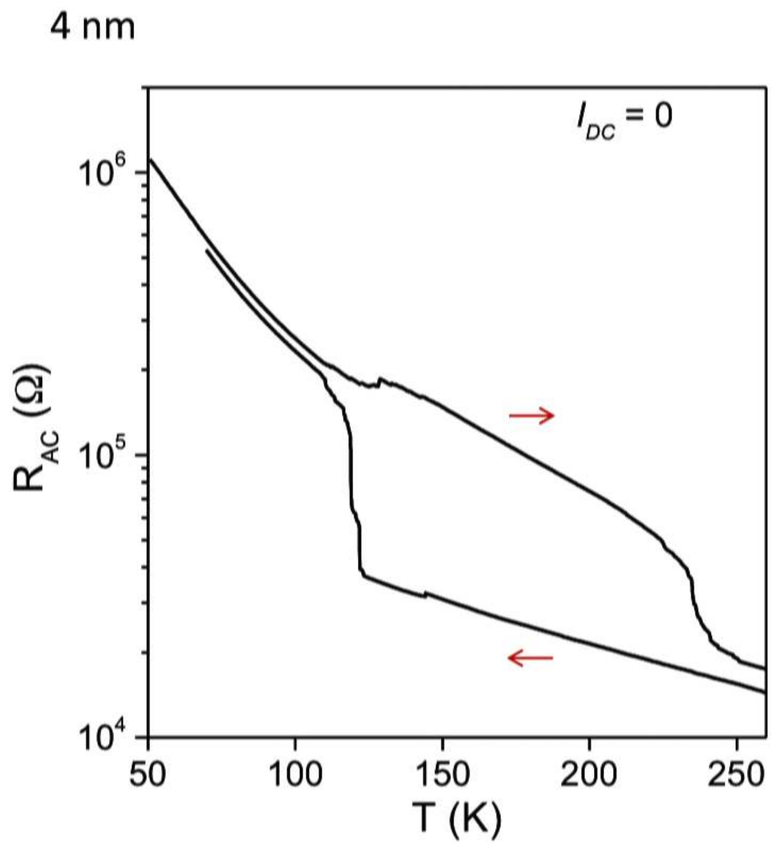
thick

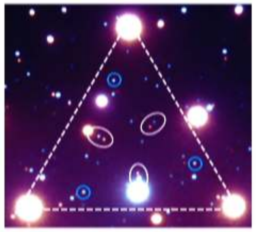


CDW and surface oxidation



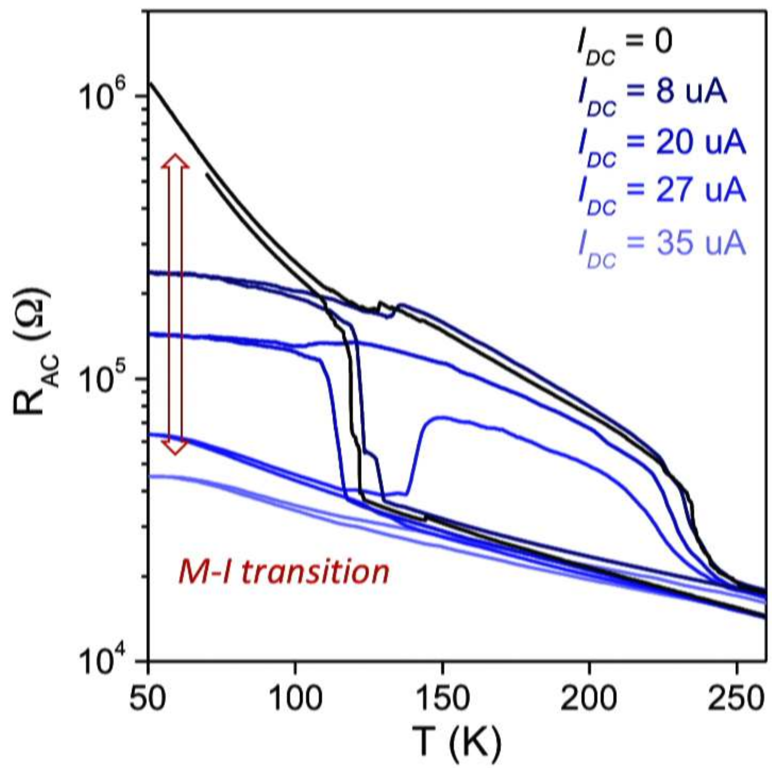
Electrical Control of CDW Phase Transition

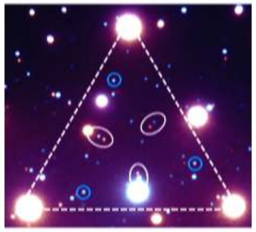




Electrical Control of CDW Phase Transition

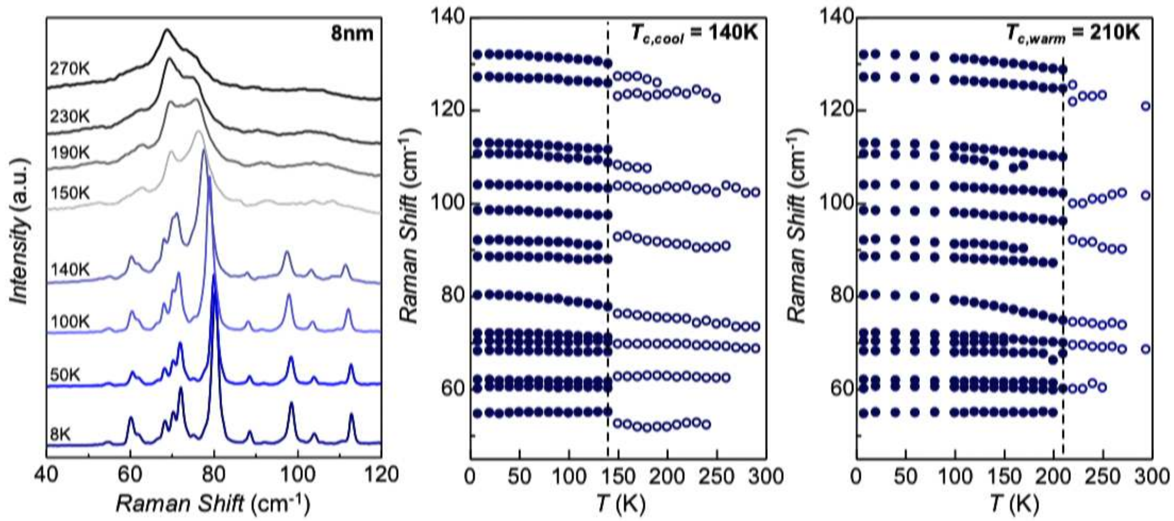
4 nm



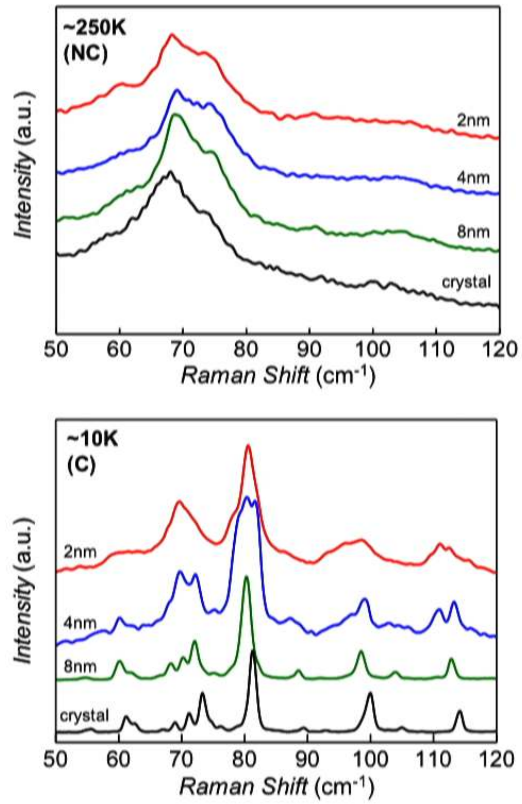


Also see Yoshisa et al. (Iwasa Group)

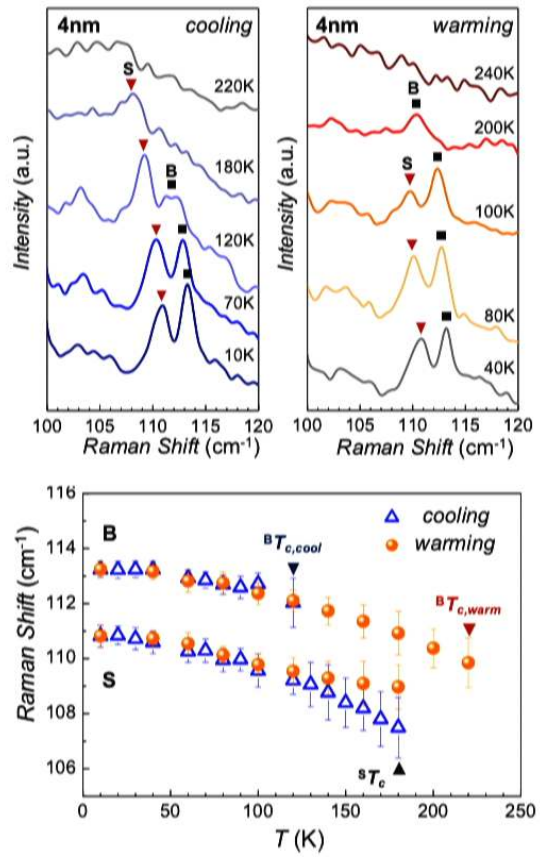
Raman Spectroscopy of 1T-TaS_2



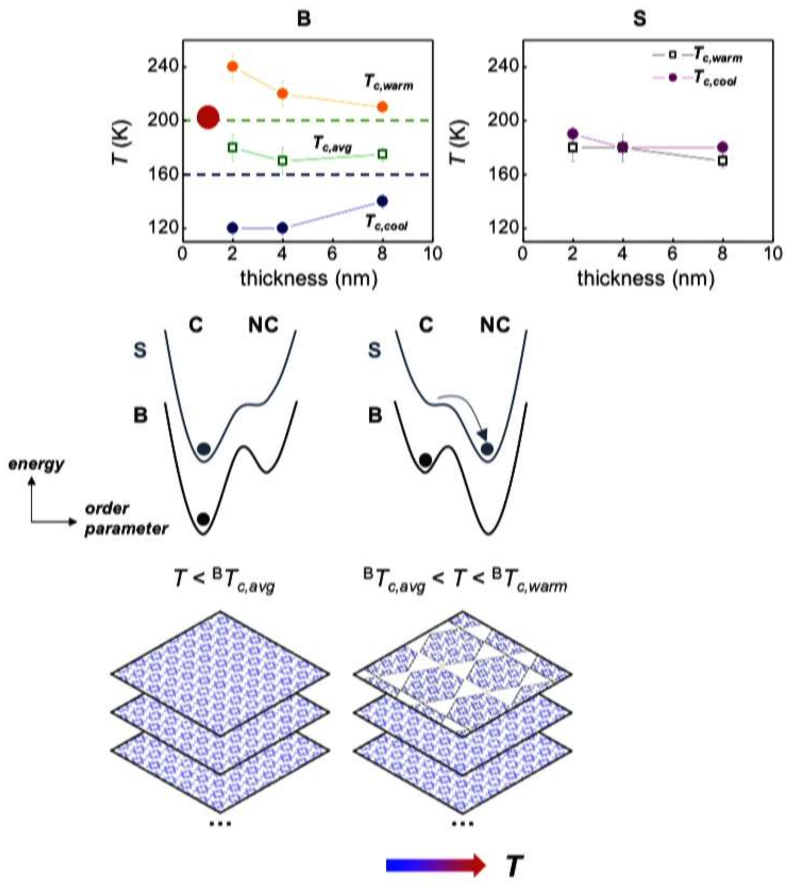
CDW Dimensional Dependence (Raman)



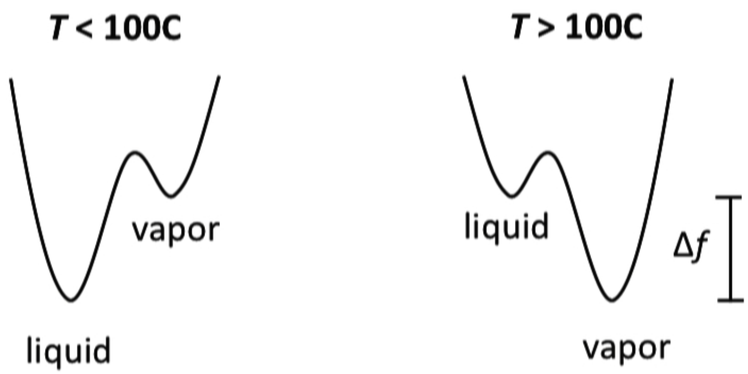
Temperature Dependence

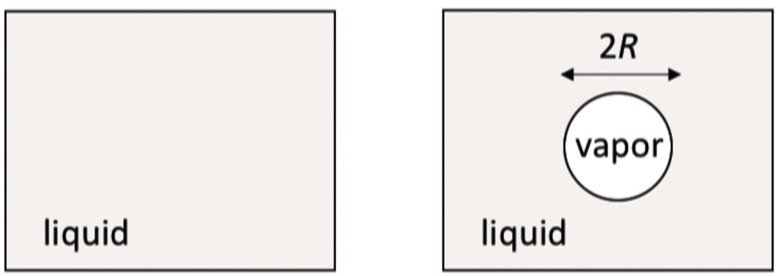


Temperature Dependence

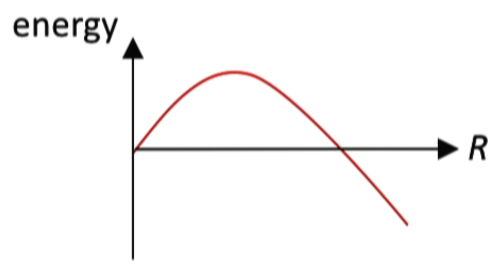


Phase Nucleation Energetics

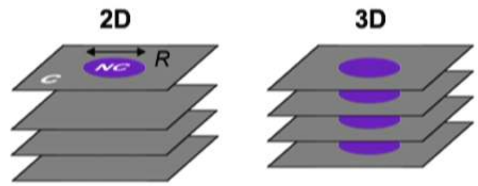




$$E(R) = -\frac{4\pi}{3}\Delta f R^3 + 4\pi\sigma R^2$$

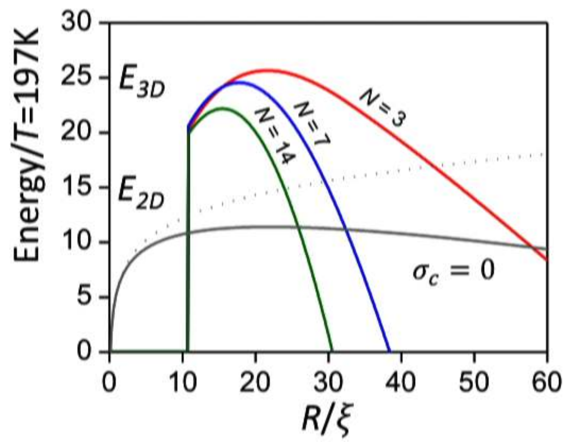


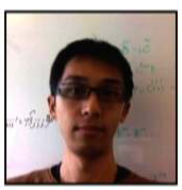
Phase Nucleation Energetics



$$E_{2D}(R) = -E_{NC}(R) + \sigma_{ab}(R) + \sigma_c(R)$$

$$E_{3D}(R) = -N[E_{NC}(R) + \sigma_{ab}(R)]$$





PNAS

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LETTERS

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nature physics

Nature of the quantum metal in a two-dimensional crystalline superconductor

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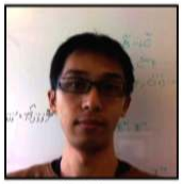
Rui He

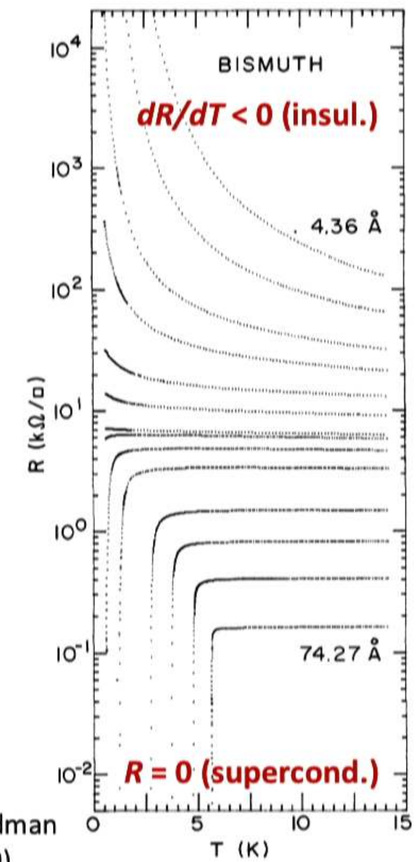

Junichi Okamoto


Ben Hunt


Cory Dean

Disorder-tuned 2D Superconductor-to-Insulator Transition

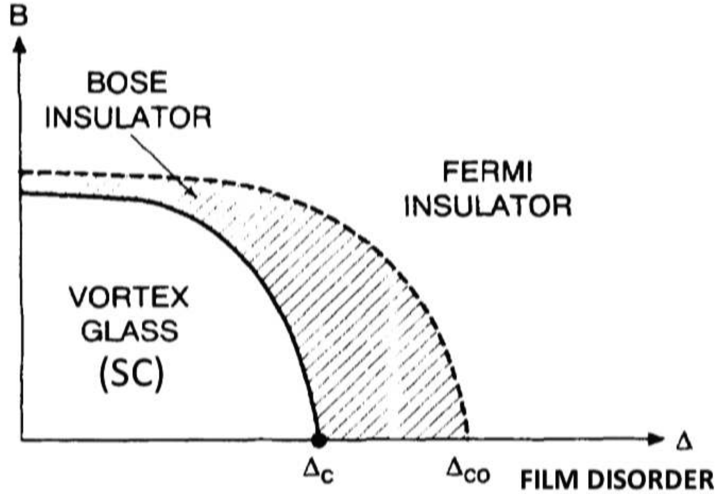
Thickness-tuned transition



Haviland, Liu, Goldman
PRL **62** 2180 (1989)

Disorder-tuned 2D Superconductor-to-Insulator Transition

Phase Diagram **(*T* = 0)**



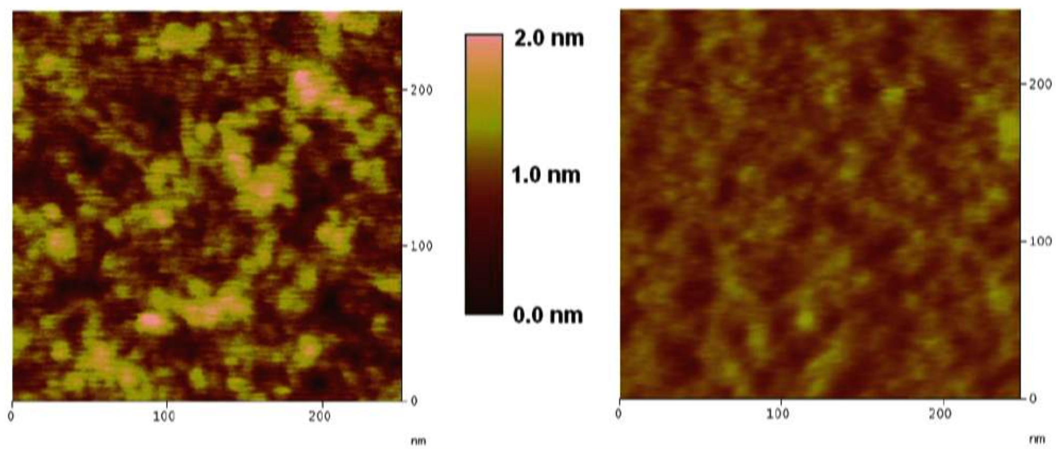
Superconductor:
condensed (de-localized) Cooper pairs

Bose Insulator:
localized Cooper pairs

Fermi Insulator:
localized single electrons

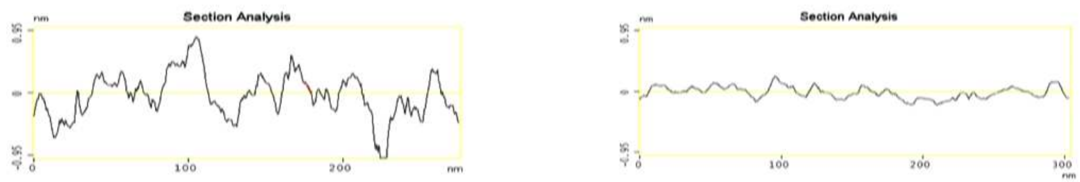
Paalanen, Hebard, Ruel
PRL **69** 1604 (1992)
Theory: Fisher, Grinstein, Girvin

Thin Film Evaporation



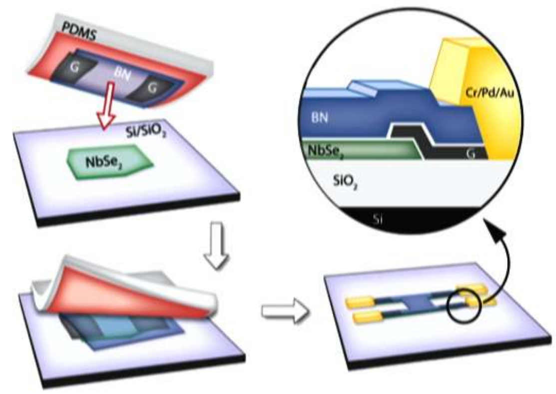
granular *a*-Bi films

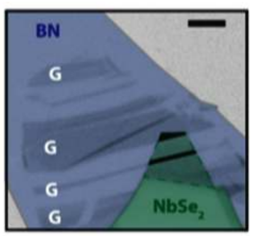
homogeneous *a*-Bi films

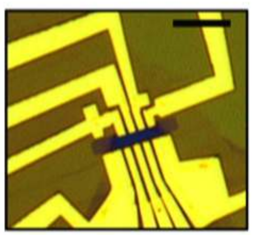


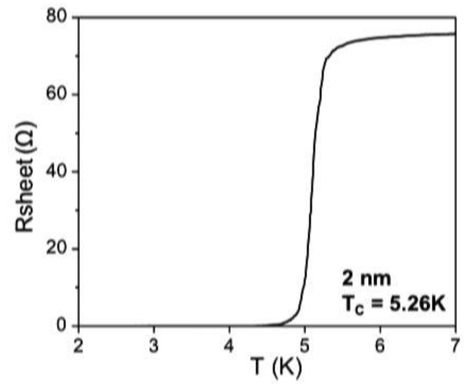
from Allen Goldman

Superconductivity in bilayer $NbSe_2$



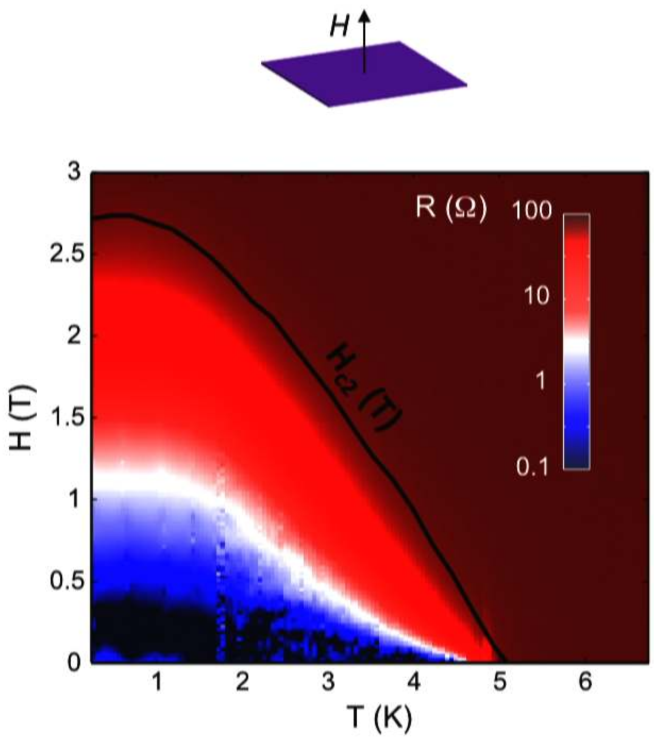




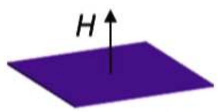


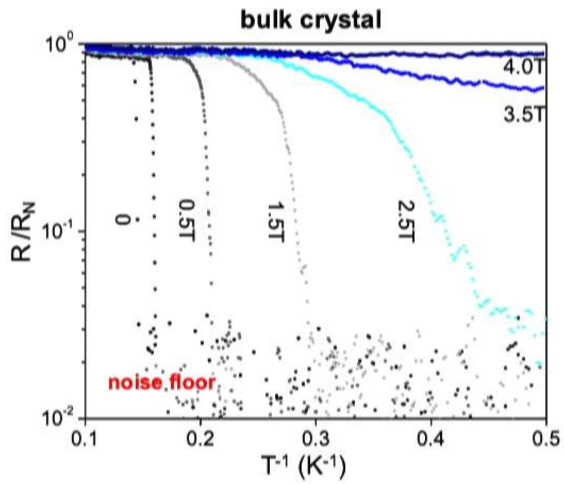
For bulk crystal:
T_c = 7.2K

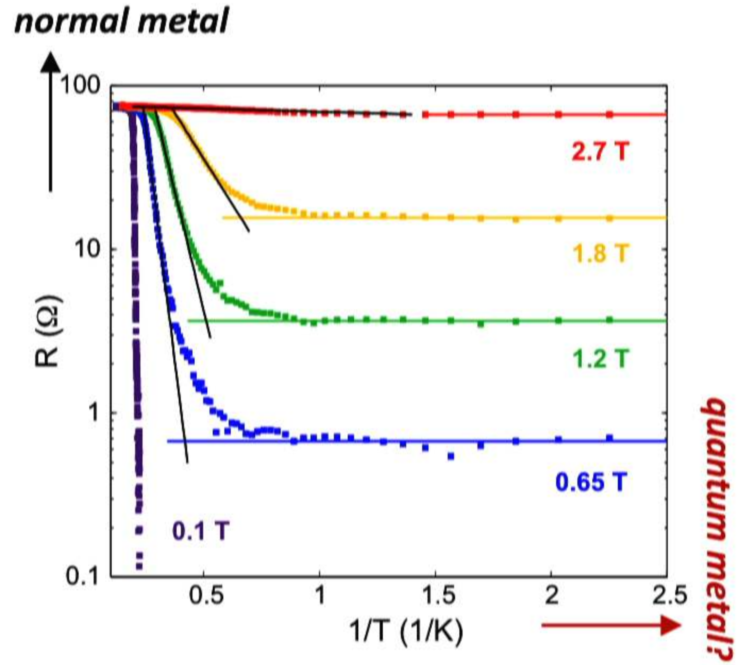
Effect of Perpendicular Magnetic Field



Effect of Perpendicular Magnetic Field

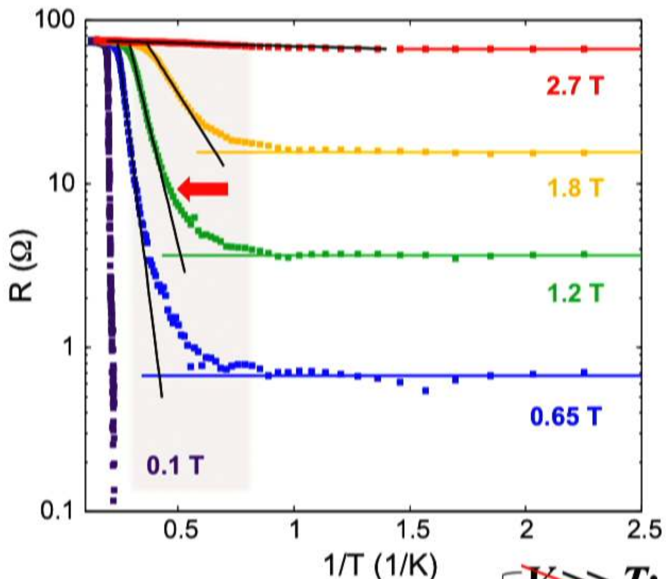


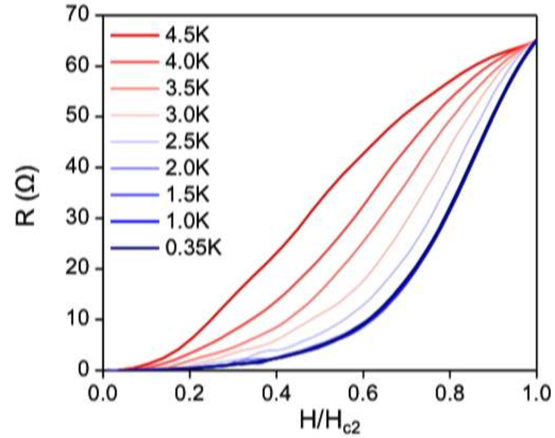




Is Quantum Metal Caused by Vortex Flow?

$R \sim e^{-U(H)/T}$

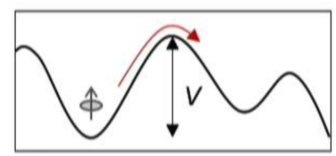




Role of "free" vortices

$V >> T$:
$R_f \sim e^{-V/T} \rightarrow 0$

$V << T$:
$R_f \sim$ # vortices $\sim H$



A Metallic State from Bosons

PHYSICAL REVIEW B VOLUME 60, NUMBER 2 1 JULY 1999-II

Existence of a Bose metal at $T=0$

D. Das
Department of Applied Physics, Stanford University, Stanford, California 94305

S. Doniach
Departments of Applied Physics and Physics, Stanford University, Stanford, California 94305
(Received 9 June 1998)

PHYSICAL REVIEW B, VOLUME 64, 134511

Bose metal: Gauge-field fluctuations and scaling for field-tuned quantum phase transitions

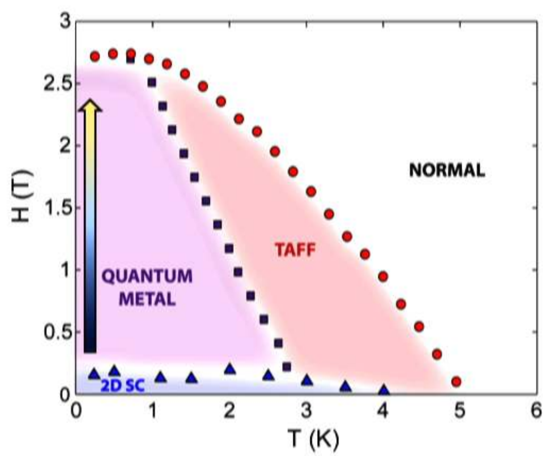
D. Das[1] and S. Doniach[1,2]
[1]*Department of Applied Physics, Stanford University, Stanford, California 94305*
[2]*Department of Physics, Stanford University, Stanford, California 94305*
(Received 21 February 2001; published 11 September 2001)

VOLUME 89, NUMBER 2 PHYSICAL REVIEW LETTERS 8 JULY 2002

Phase Glass is a Bose Metal: A New Conducting State in Two Dimensions

Denis Dalidovich[1] and Philip Phillips[2]
[1]*National High Field Magnetic Laboratory, Florida State University, Tallahassee, Florida*
[2]*Loomis Laboratory of Physics, University of Illinois at Urbana-Champaign, 1100 W. Green Street, Urbana, Illinois 61801-3080*
(Received 11 December 2001; published 19 June 2002)

A Metallic State from Bosons



superfluid correlation length

$\xi \sim (H - H_0)^{-\upsilon}$

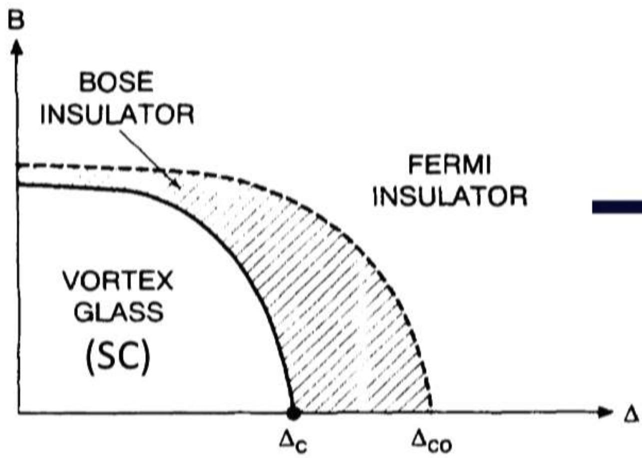
↑ critical field SC

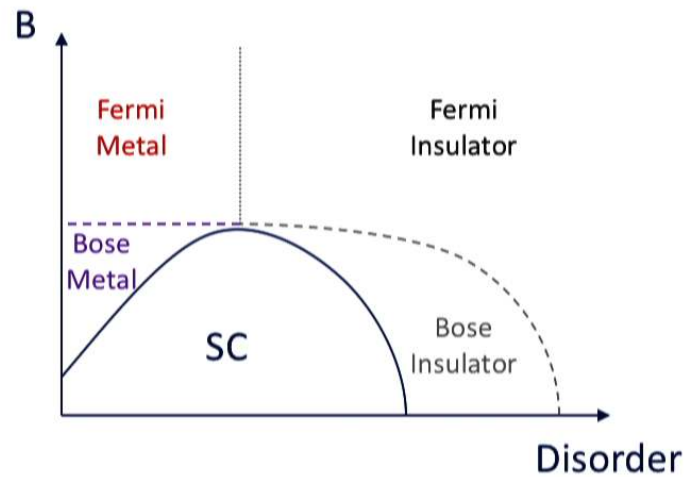
$R \sim \#\, vortices \sim 1/\xi^2$

$\sim (H - H_0)^{2\upsilon}$

Revised Phase Diagram for SC-(M)-I Transition

$T = 0$





Thank you!

Columbia:

- Abhay Pasupathy, Dennis Wang
- Cory Dean, Ben Hunt
- James Hone, Young Duck Kim

Harvard:

- Philip Kim, Jing Shi, Frank Zhao

Cornell:

- Lena Kourkoutis, Robert Hovden, Katherine Spoth

Iowa:

- Rui He, Zhipeng Ye, Gaihua Ye, Heidi Anderson

Others:

- Yuping Sun, Yu Liu, Wenjian Lu (CAS)
- Shuang Jia, Z. J. Yuan (PKU)
- Bob Cava (Princeton)
- Junichi Okamoto (Hamburg)