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Superconducting, insulating and anomalous metallic regimes in a gated two-dimensional semiconductor–superconductor array

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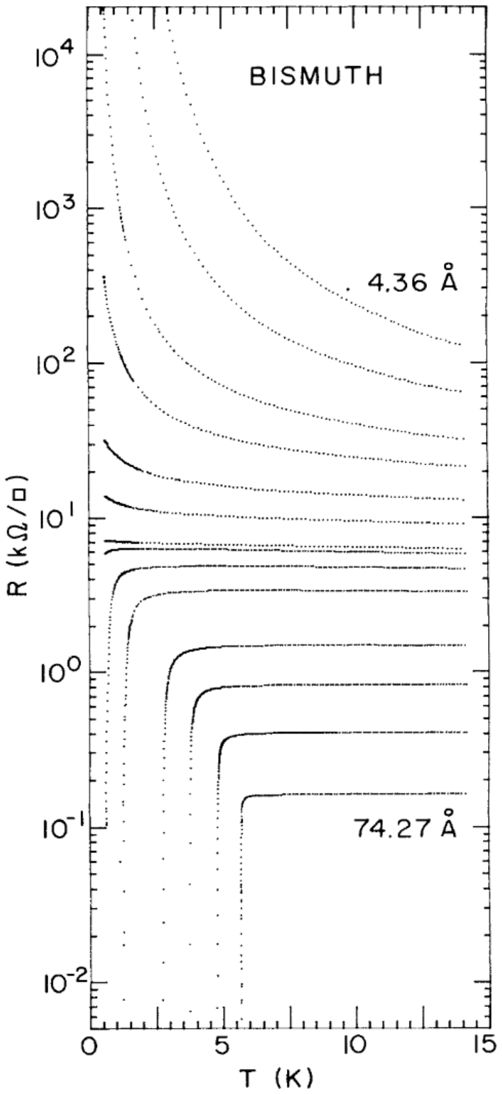
Nature Physics **14**, 1138–1144(2018) | Cite this article

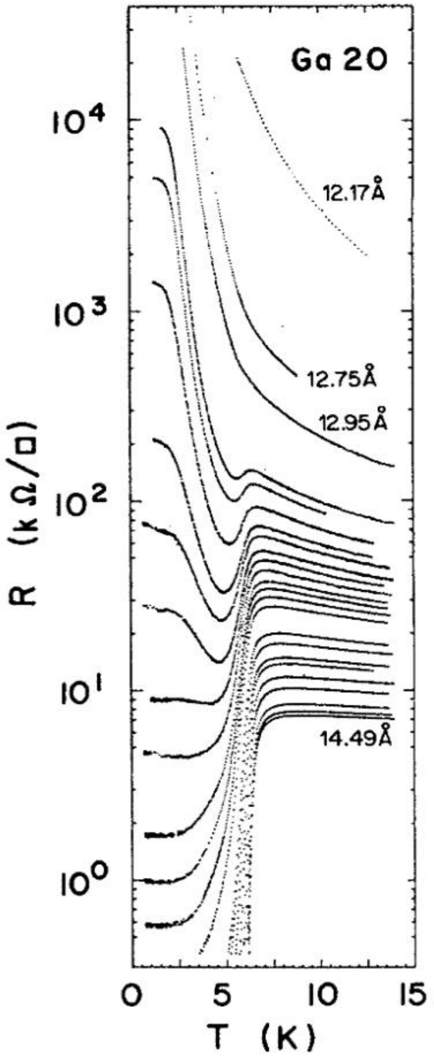
Journal Club Presentation
Mohammad Samani
October 2, 2020

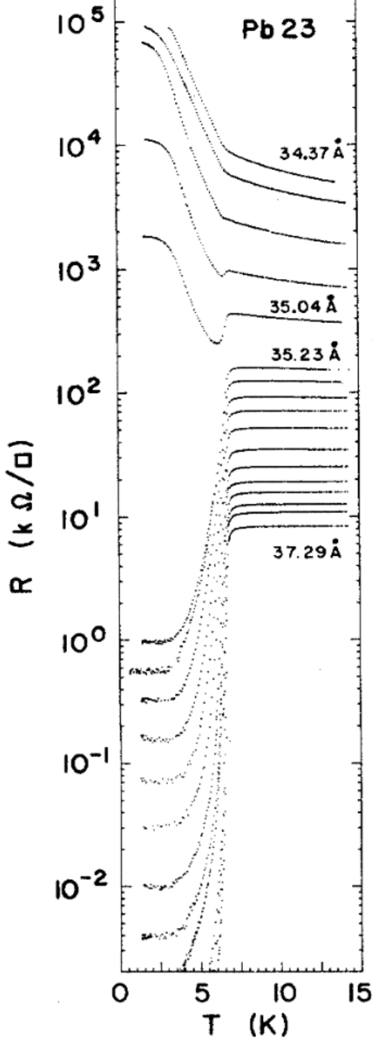
Superconductor to Insulator Transition



1. Phase fluctuations in SC order parameter localizes Cooper pairs
2. Reduced SC pairing amplitude due to unscreened repulsive interactions

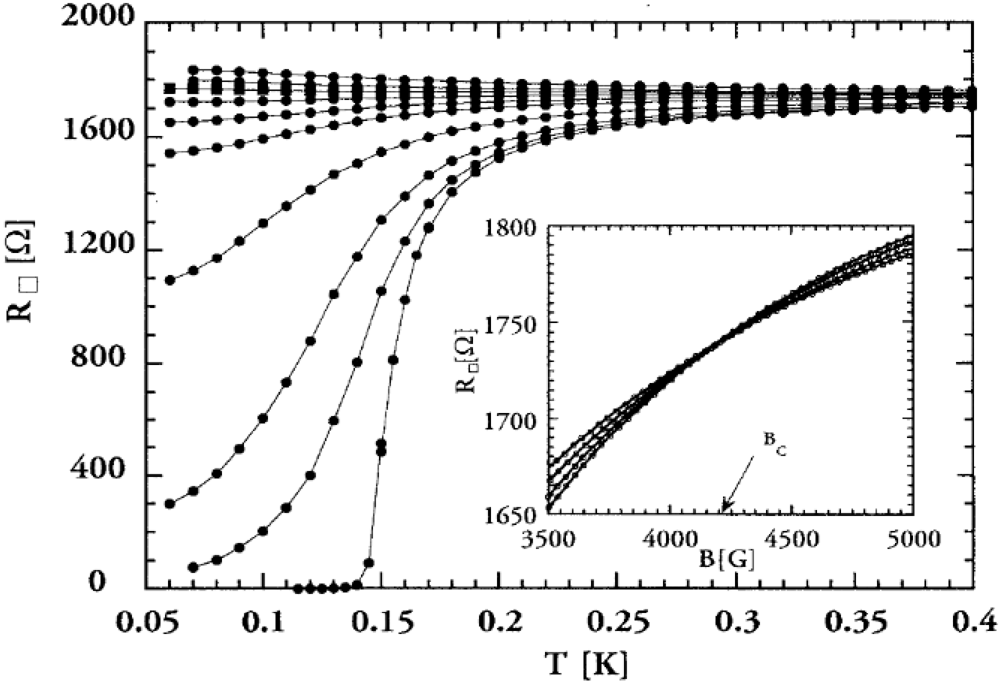
=> Direct phase transition from SC to Insulator

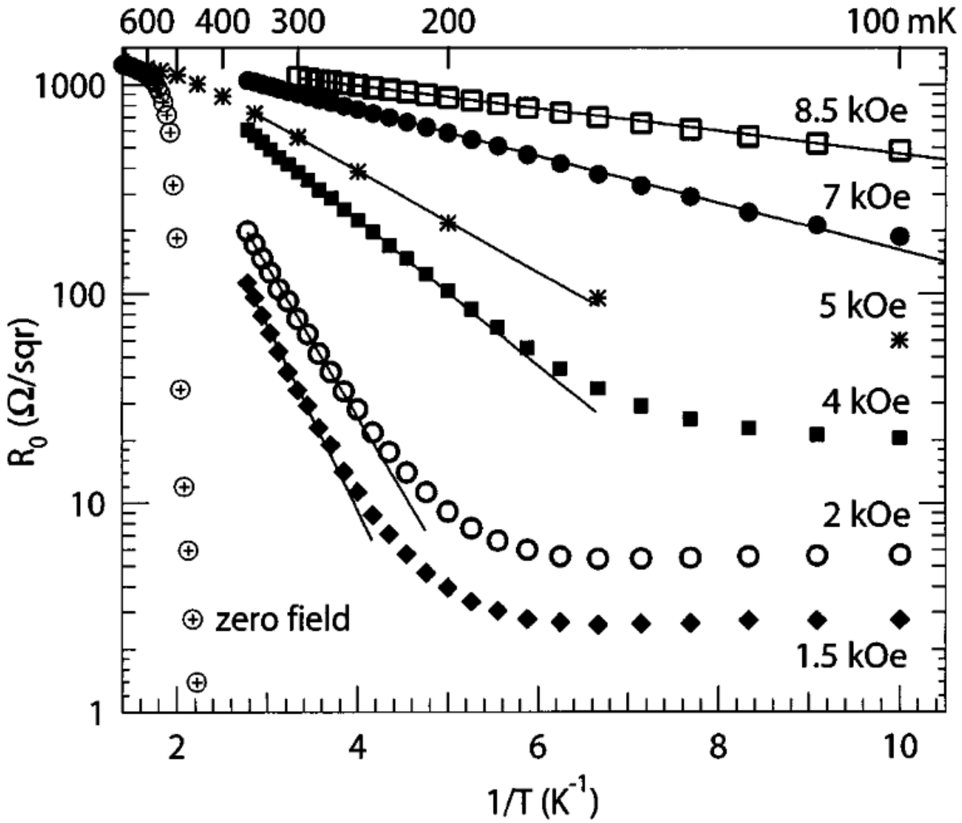




Haviland, D. B. et al. Phys. Rev. Lett. 62, 18 (1989)
Jaeger, H. M. et al. Phys. Rev. B 40, 182 (1989)

a:MoGe
B=0, 50, 100, 200, 300, 400, 440, 450, 550, 600 mT

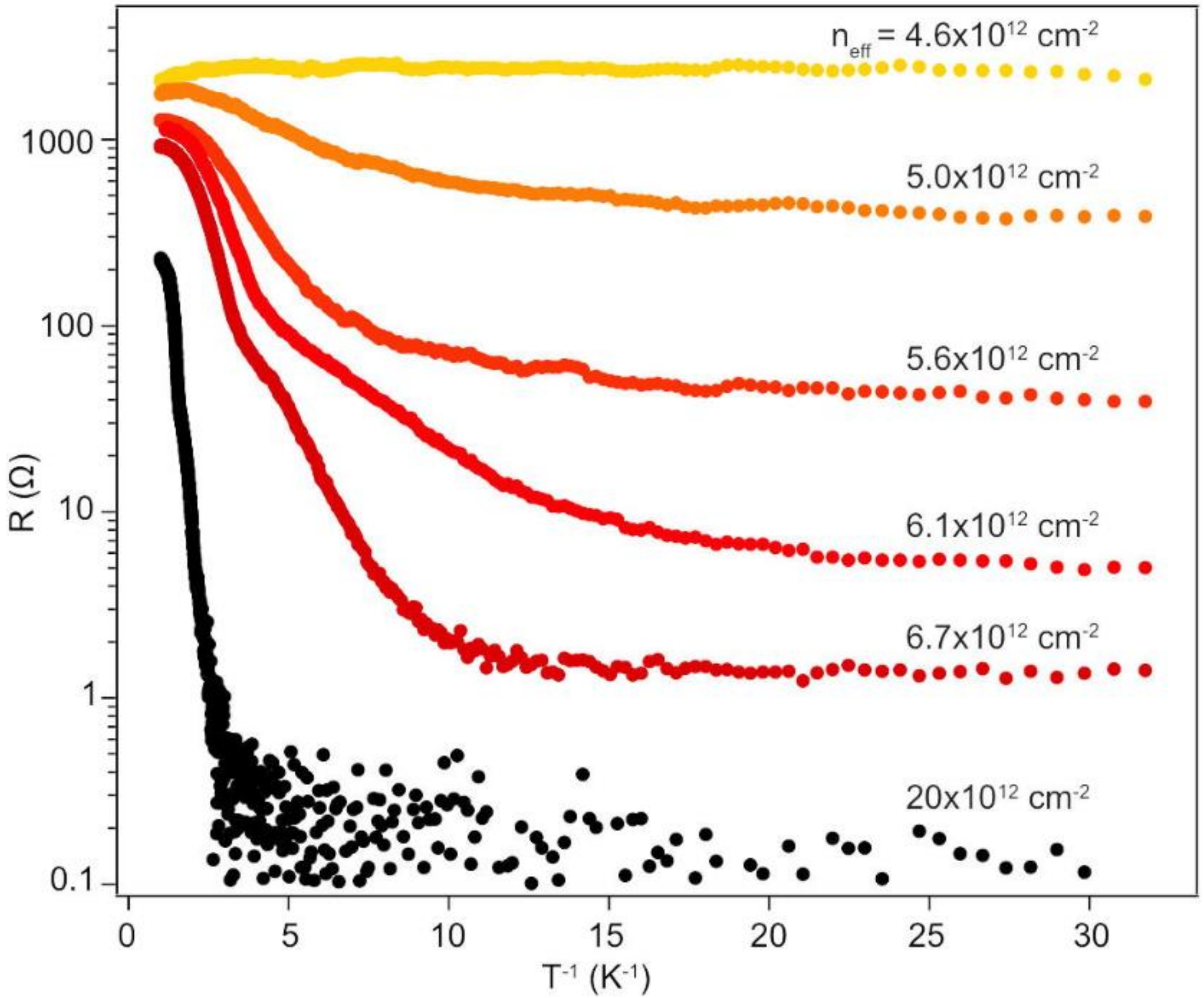




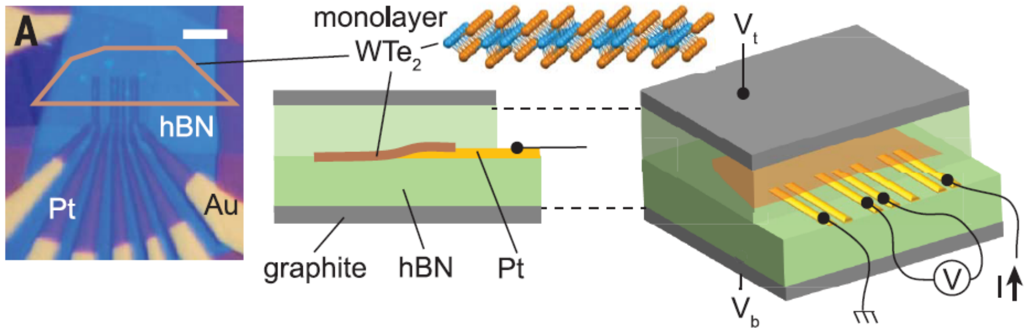
$\approx 850\ mT$

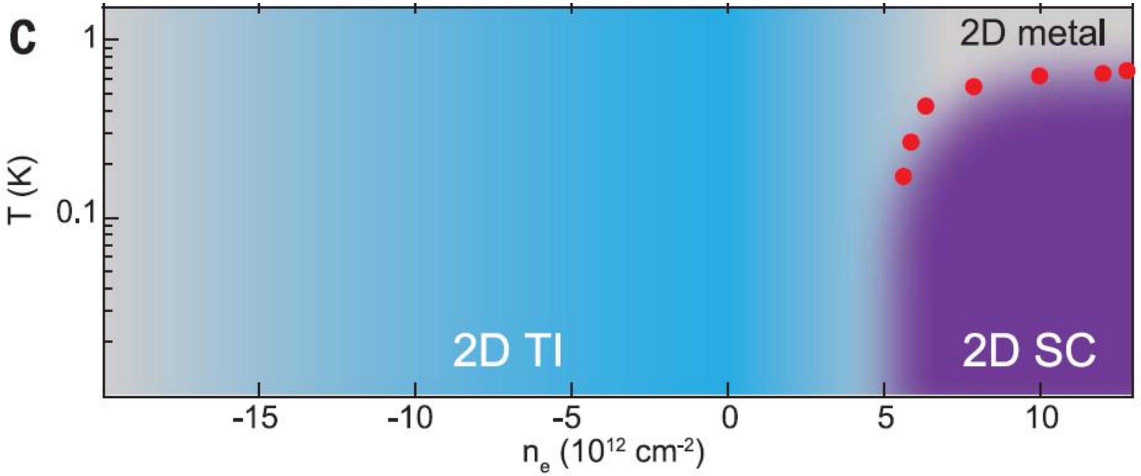
Yazdani, A. and Kapitulnik A. Phys. Rev. Lett. 74, 15 (1995)
Ephron, D. and Yazdani, A. and Kapitulnik, A. and Beasley M. R. Phys. Rev. Lett. 76, 9 (1996)

Density Driven

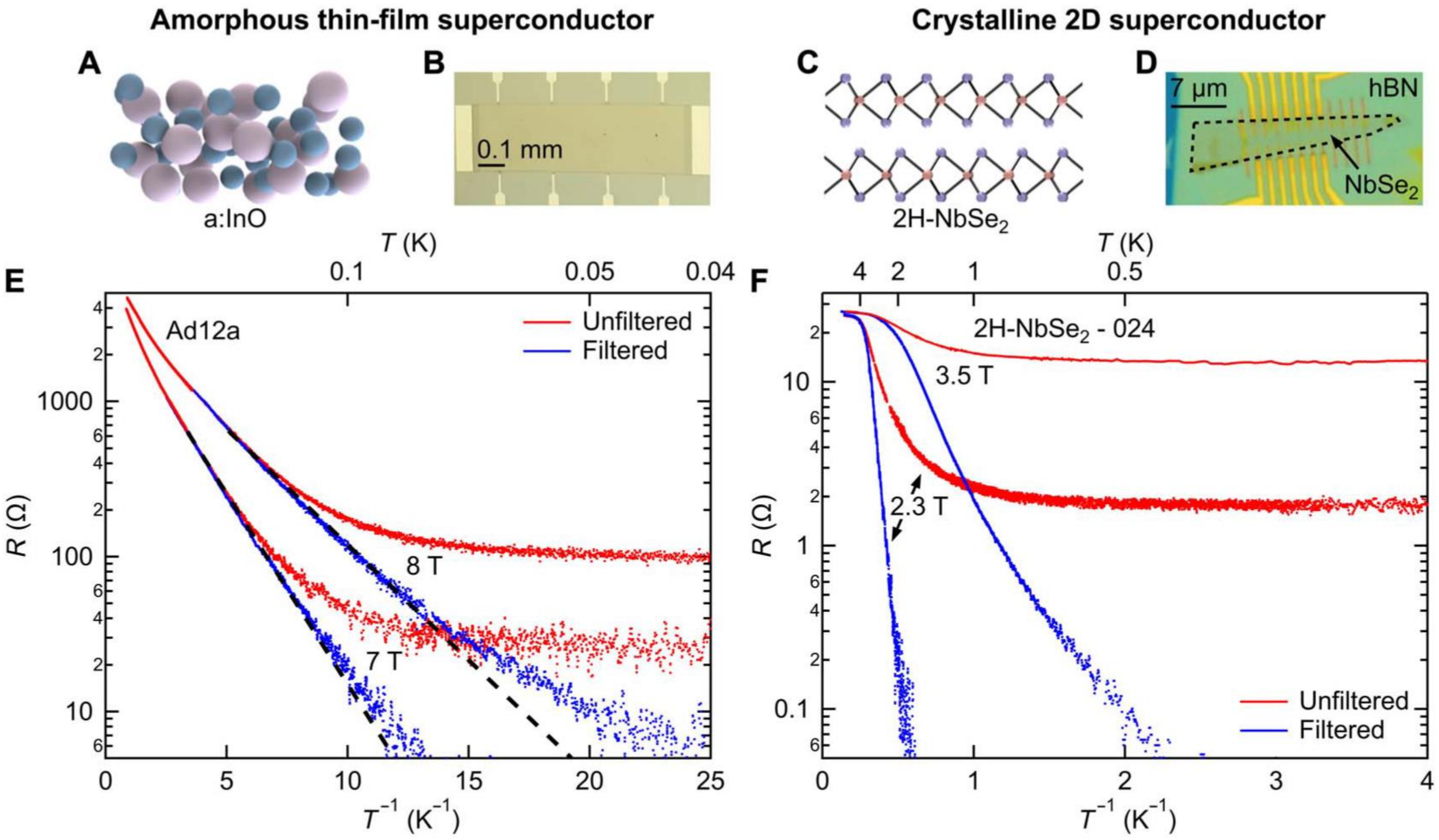


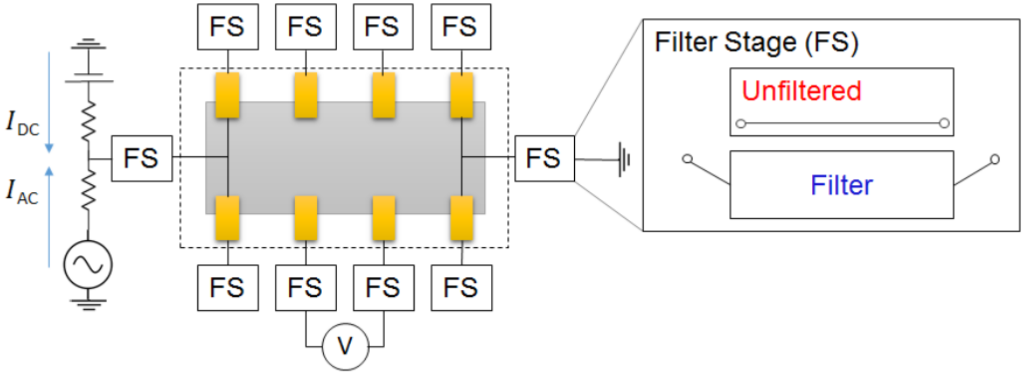
WTe$_2$ monolayer film





It’s all in your head





- Homemade RC filter
- Commercial low-pass filter
- Attenuator

Sensitivity of superconductivity in 2D

$2H-NbSe_2,\ B_c \approx 5.5$ T at low T

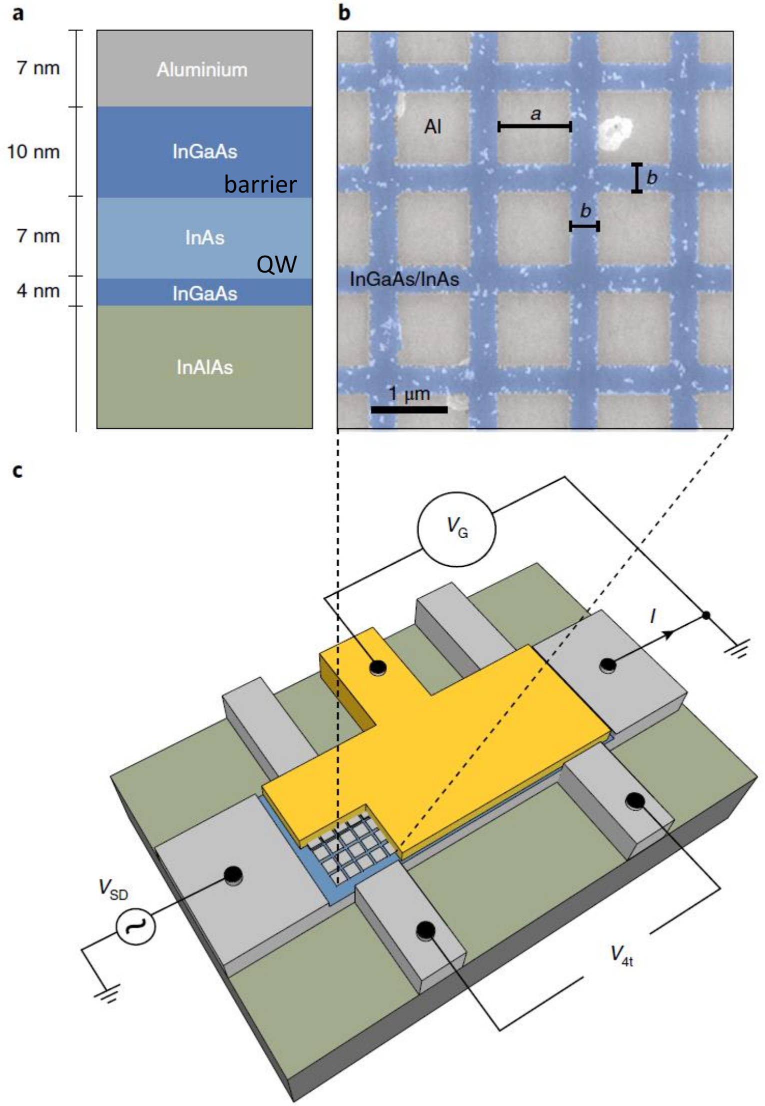
Tamir, I. et al. Sci. Adv. 5, 3 (2019)

Characteristics of Anomalous Metals

1. Most of evidence comes from 2D materials
2. Disorder, carrier density, screening properties, and magnetic field are used as tuning parameters.
3. $\sigma_D \ll e^2/h$
4. Always an intermediate regime from superconducting to metal or insulator
5. Disorder is not necessary

Kapitulnik, A. and Kivelson S. A. and Spivak, B. Rev. Mod. Phys. 91, 011002 (2019)

The Device



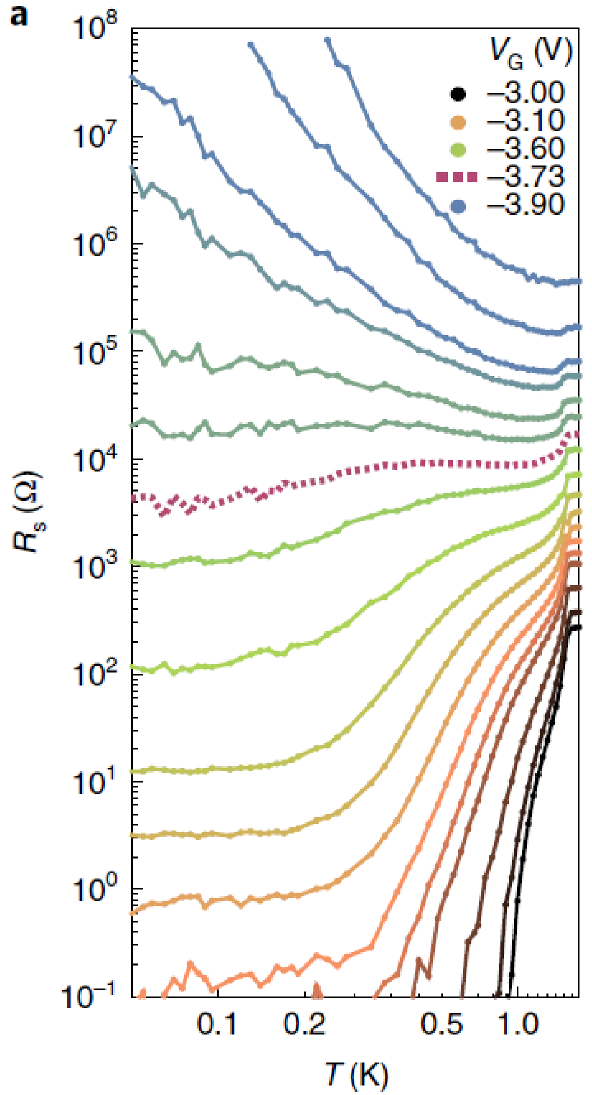
$a = 1\ \mu m$
$b = 150\ nm\ (A)\ 350\ nm\ (B)$
Mean free path = 300 nm
40×100 array of aluminium squares

40 nm of Al_2O_3 below TiAu top gate

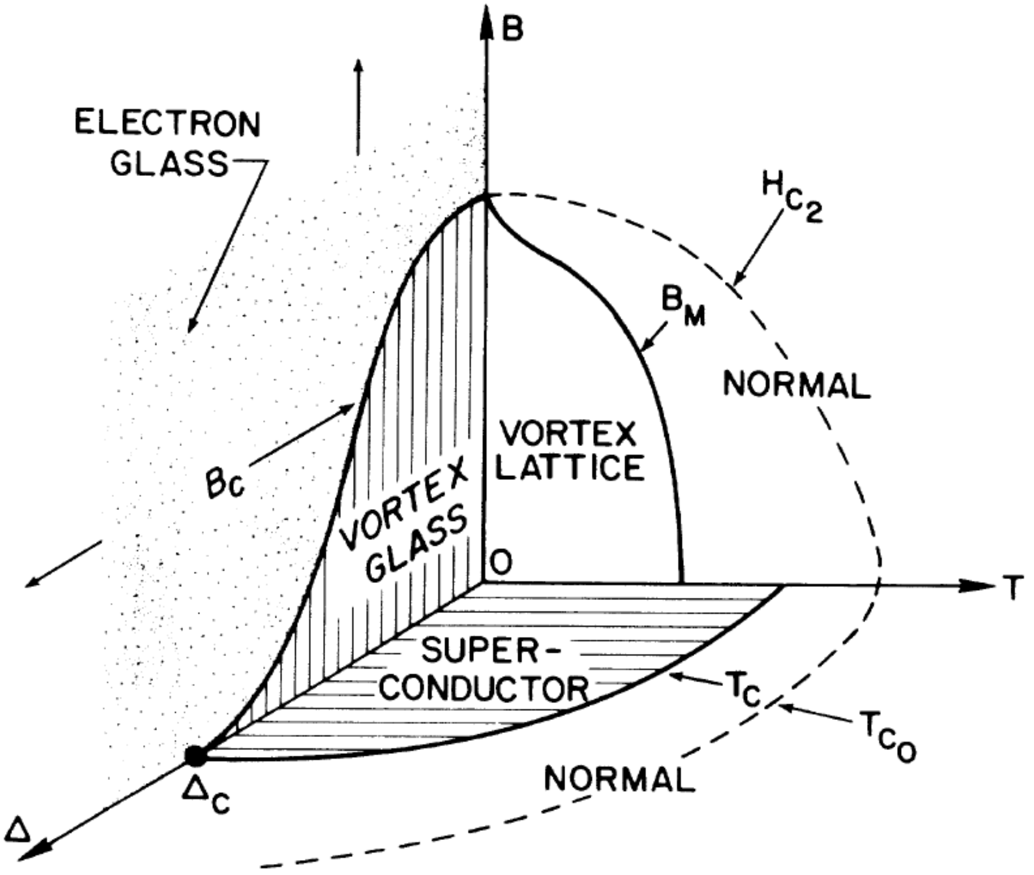
$V_{sd} \leq 5\ \mu V$

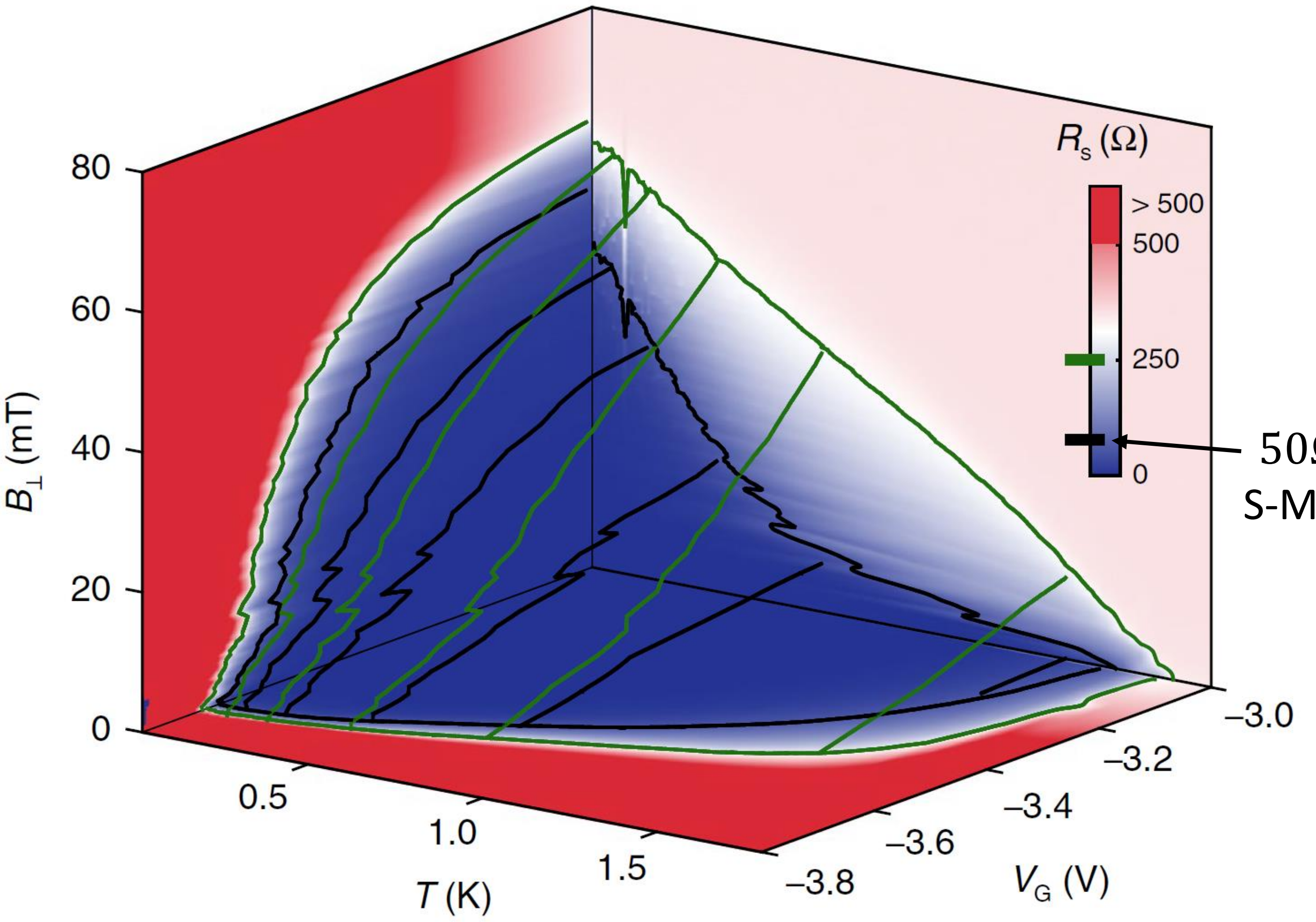
Unique combination of characteristics:

1. High mobility
2. Large g-factor
3. Strong spin-orbit coupling
4. Large $B_{\parallel}^{*} \approx 600\ mT$



Phase Diagram

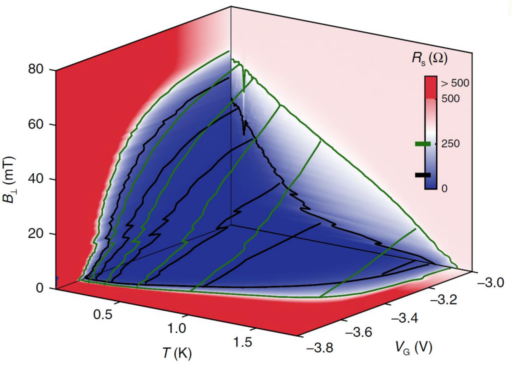


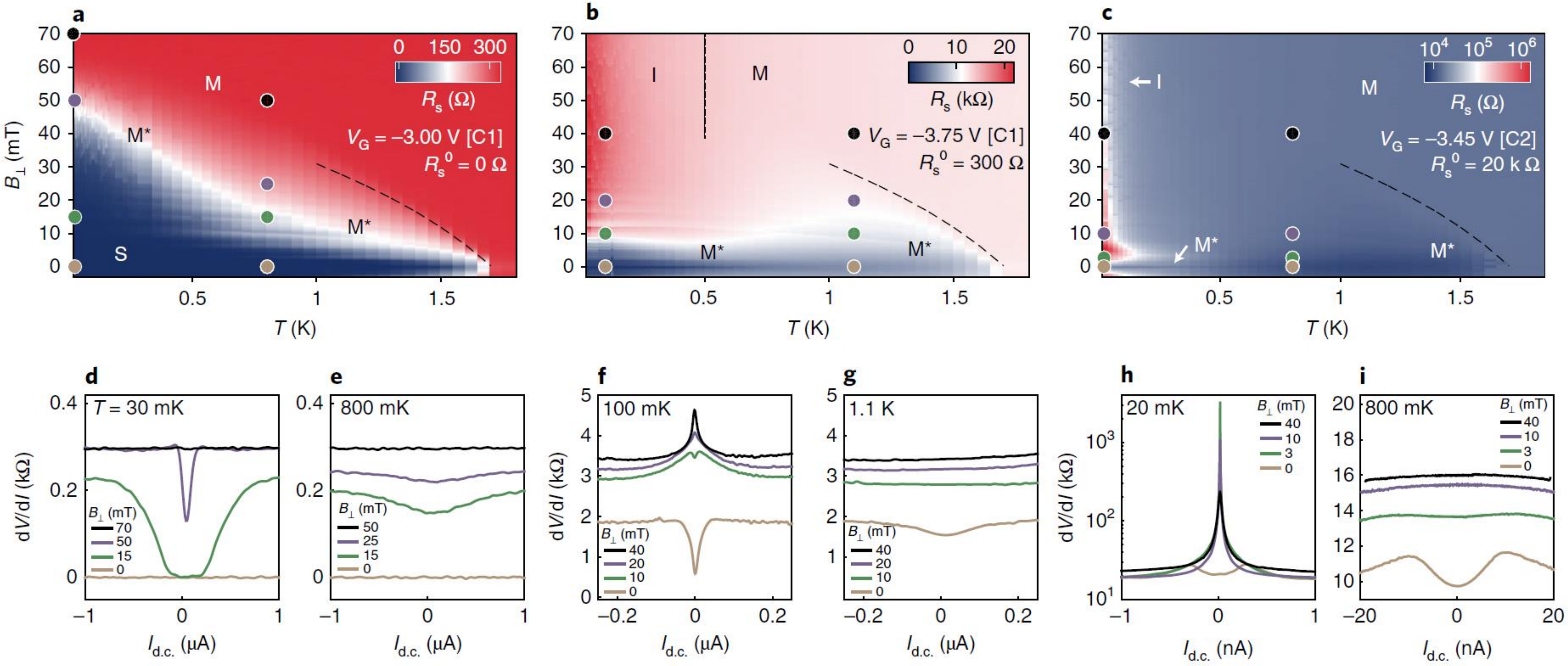


50Ω
S-M*

Fisher, M. P. A. Phys. Rev. Lett. 65, 923 (1990)

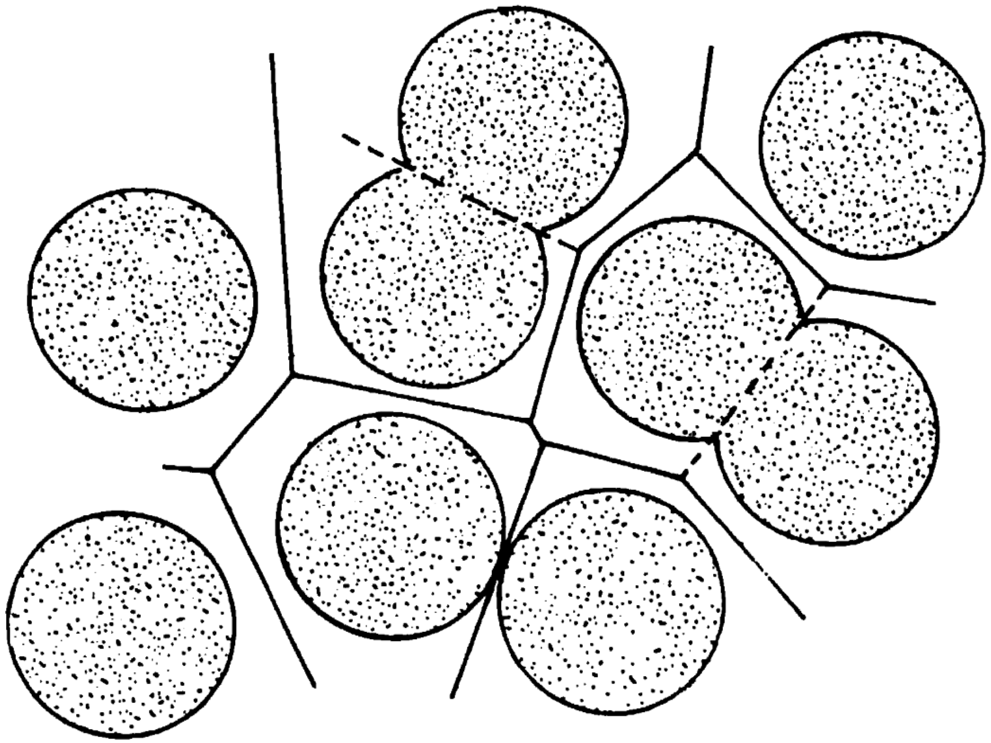
Phase Diagram





$$I_c = 20\ \mu A$$

Classical Percolation Theory



The Swiss cheese model

$$\sigma = \sigma_D F(x)$$

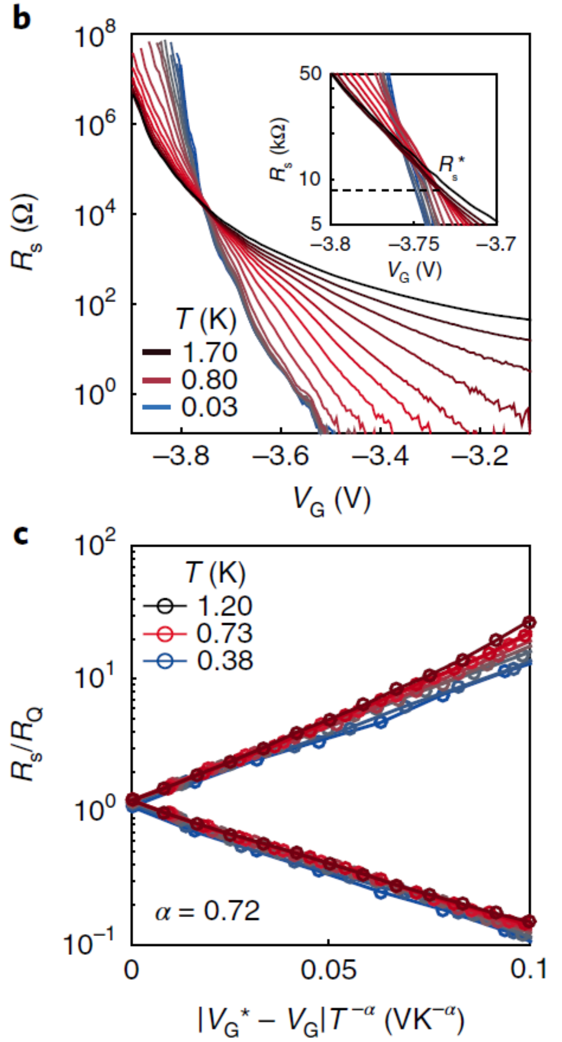
$$x \to 0 : F(x) \to 1$$

$$x \to x_c^- : F(x) \to \infty \text{ as } F(x) \sim (x_c - x)^{-s}$$

2D: $s = 4/3$

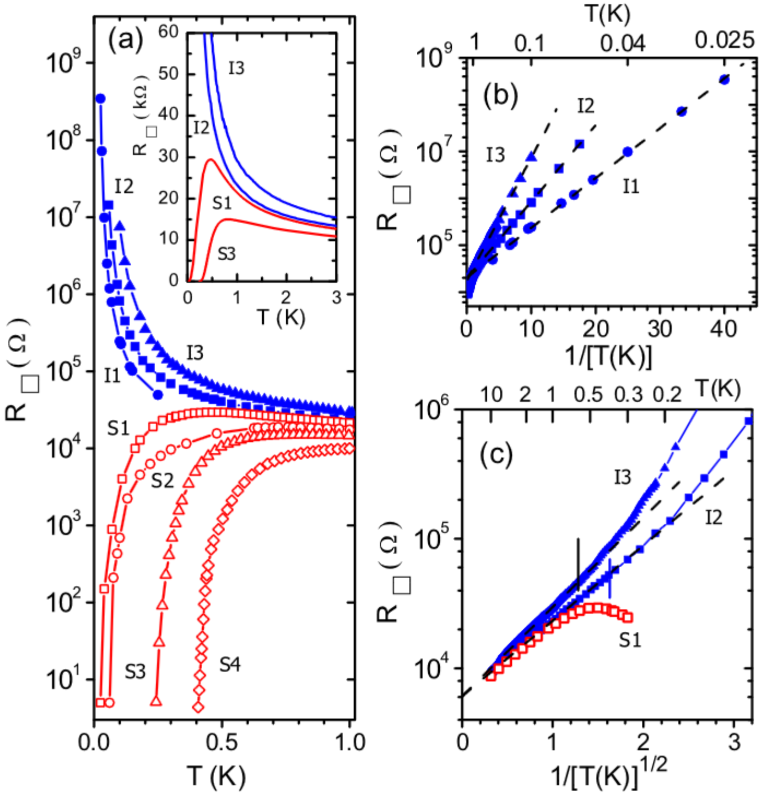
3D: $s \sim 0.73$

$$\alpha \sim 0.72 \Rightarrow s = 1.4$$

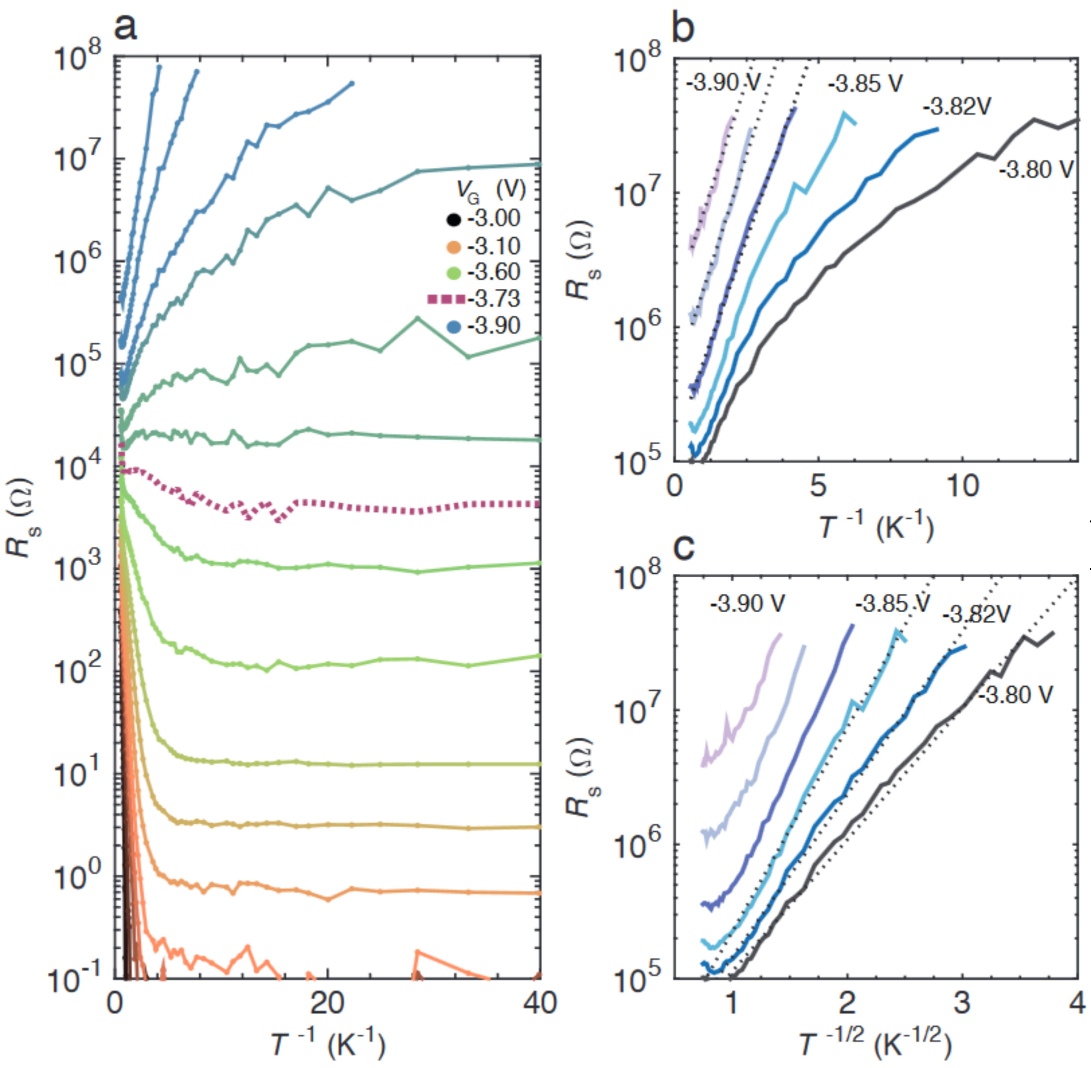


Stauffer D. and Aharony, A. Introduction to percolation theory, 2[nd]. Ed. (1994)
Fisher, M. P. A. Phys. Rev. Lett. 65, 923 (1990)

Insulating Regime



TiN superconducting films



$$R = R_0 e^{T_0/T}$$

$T_0 \approx 1.5\ K \approx T_c(B = 0)$

Arrhenius thermal activation

$$R = R_0 \exp[\sqrt{T_1/T}]$$

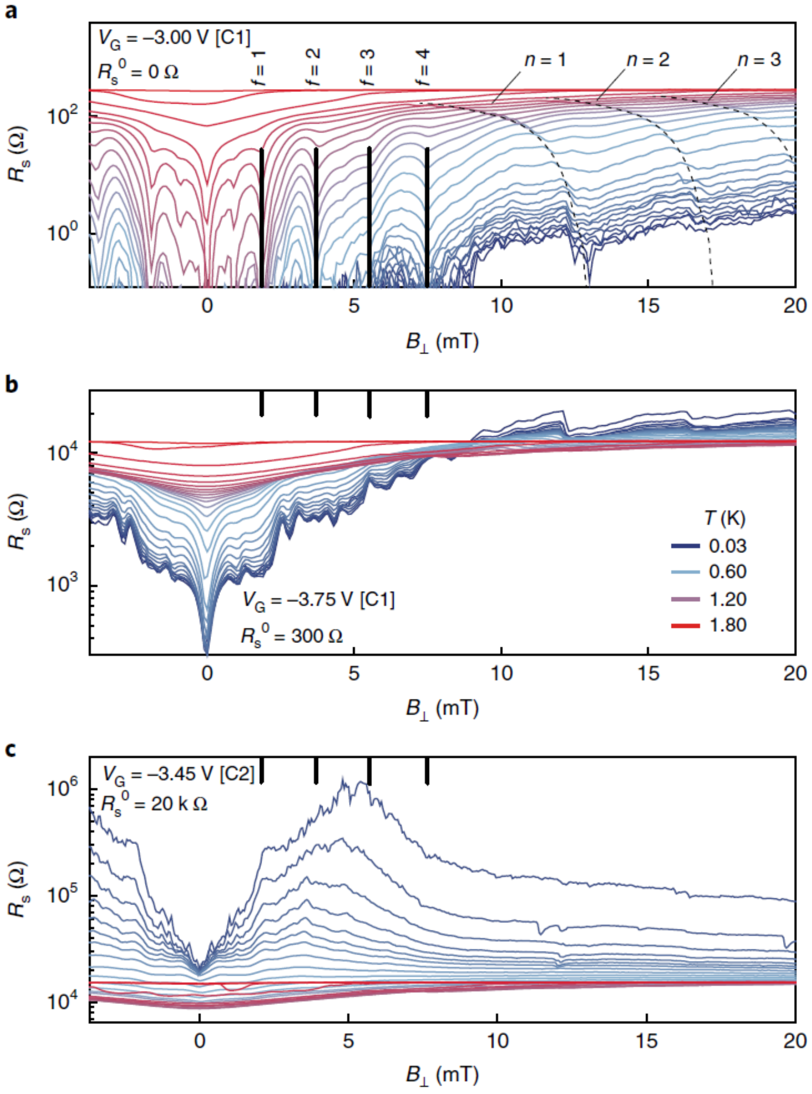
$T_1 = 2.3, 2.5, 2.8\ K$

Variable range hopping

Theory: $T_1 = 3.0\ K$

Baturina, T. I. et Al. Phys. Rev. Lett. 99, 257003 (2007)
Efros, A. L. and Shklovskii, B. I. Properties of Doped Semiconductors (Springer, Berlin, 1984)

Flux



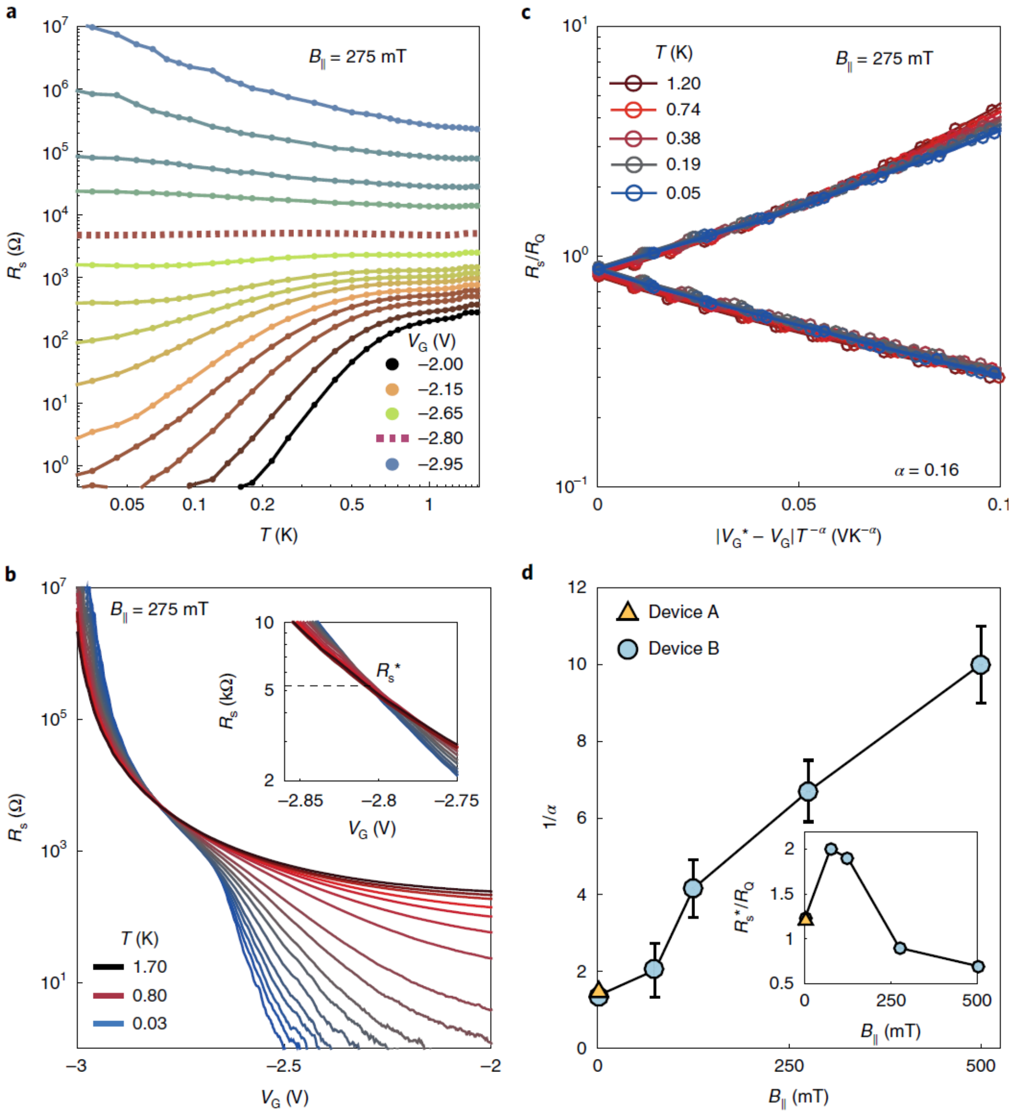
$$f = \frac{B_\perp}{B_0}, \qquad B_0 = \frac{\phi_0}{A}, \qquad A = (a+b)^2, \qquad \phi_0 = h/2e$$

B_0 is flux quantum per period of array
n=1,2,3,… vortex penetration of individual islands.

1. Saturation of R_s depends on $B_\perp$, with fluctuations smaller than B_0 => Coherence
2. Deep saturation at B=0 is a novel observation
3. Field-controlled R_s over 3 orders of magnitude => M^* is not due to poor filtering

0 to 5 mT changes R_s by 2 orders of magnitude. Phase disorder. Compatible with Variable Range Hopping theory at finite field.

Parallel Magnetic Field



Al layer is 7 nm, so critical in-plane field is large (≈ 2 T)

Large g-factor in InAs +
finite thickness of heterostructure:
Global superconductivity vanishes at $B_{||}^* \approx 600$ mT

$B_{||}$ suppresses the anomalous regime quickly

Dependence of the scaling factor on B is unexplained