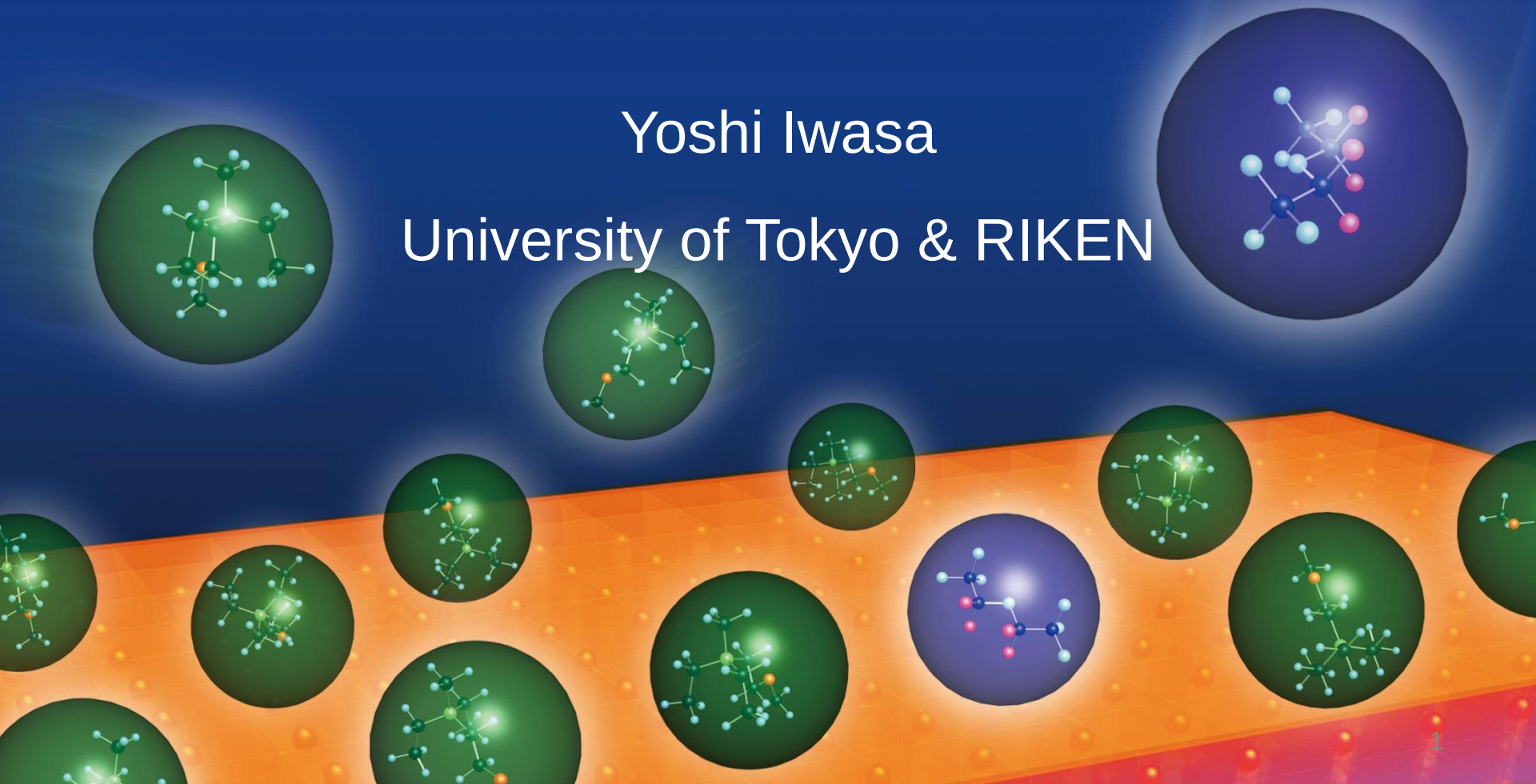
Iontronics of 2D materials

Yoshi Iwasa

University of Tokyo & RIKEN

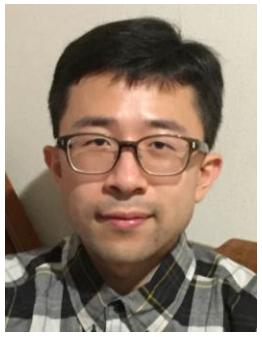


OUTLINE

1. Introduction
2. Thermoelectric properties of trilayer WSe_2
3. Giant thermopower in monolayer FeSe
4. Summary

Acknowledgements

M. Yoshida (RIKEN)



S. Shimizu,

T. Nojima,

J. Shiogai, (Tohoku Univ)

A. Tsukazaki

Iontronics

Creation of new science

Technology breakthrough

New concept of electronics controlled by ions

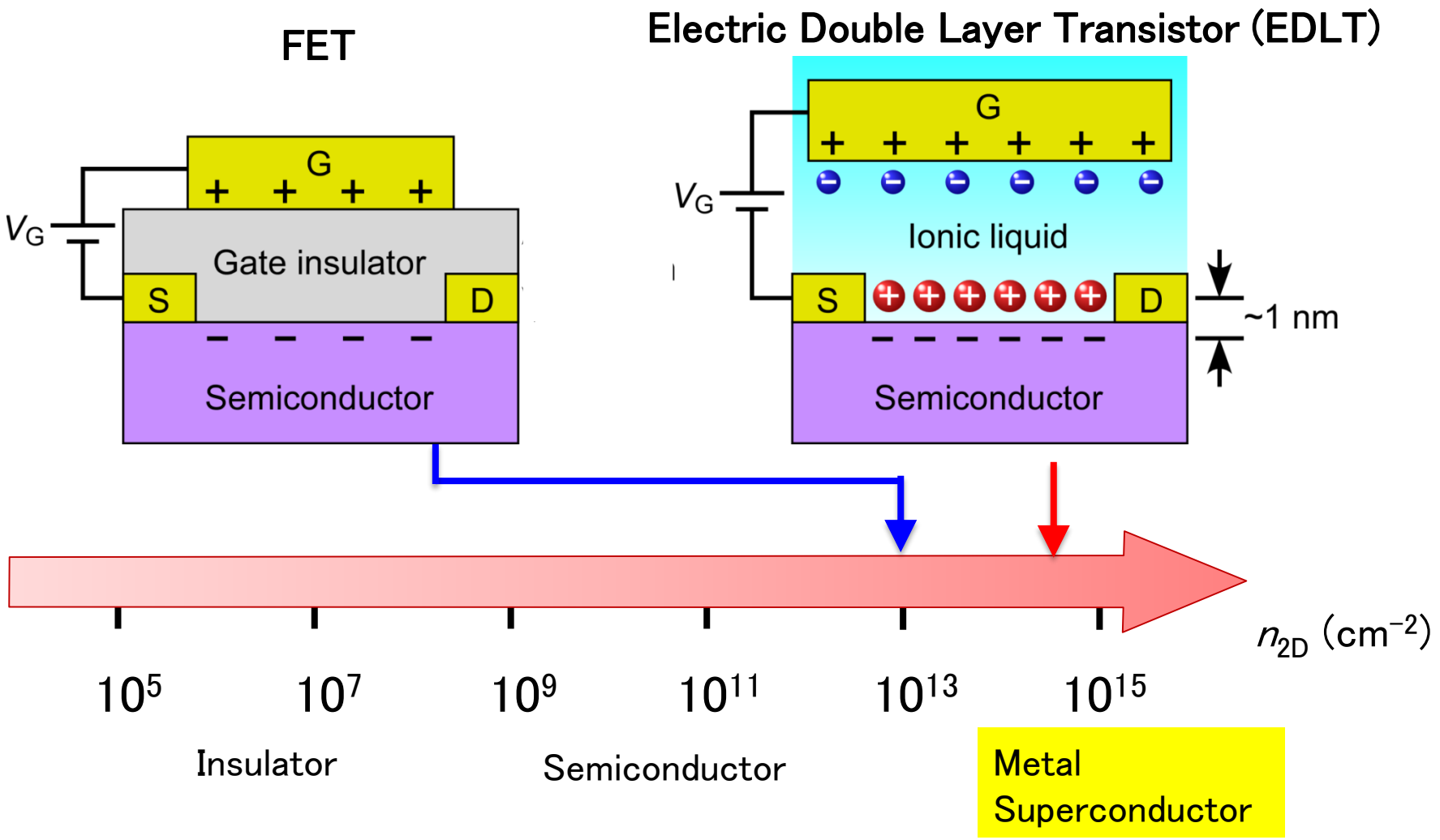
Electronics

Ionics

Transistor/light source/
solar cells

Secondary battery/capacitor

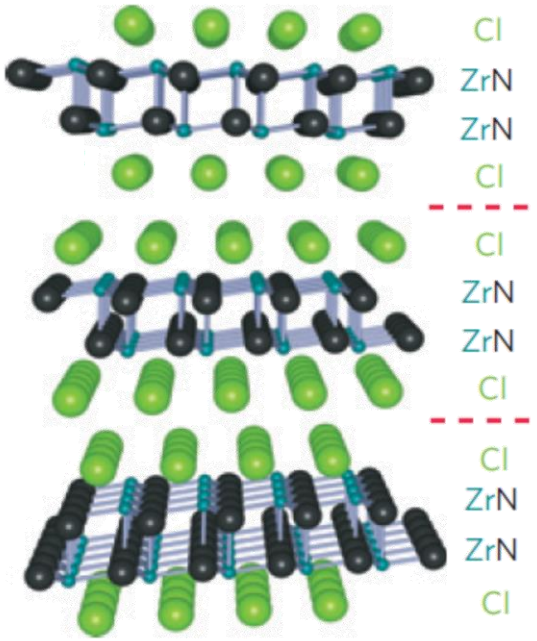
FET vs EDLT

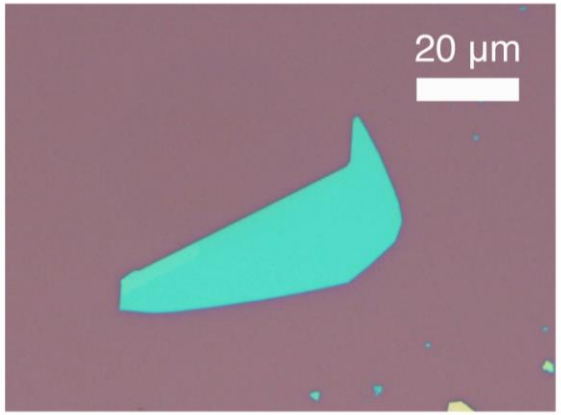

FET
Electric Double Layer Transistor (EDLT)
G
V_G
Gate insulator
S
D
Semiconductor
Ionic liquid
~1 nm
n_{2D} (cm^{-2})
10^5
10^7
10^9
10^{11}
10^{13}
10^{15}
Insulator
Semiconductor
Metal
Superconductor

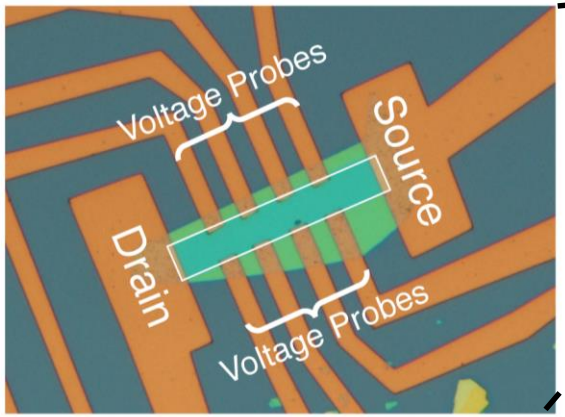
Exfoliation + EDLT devices

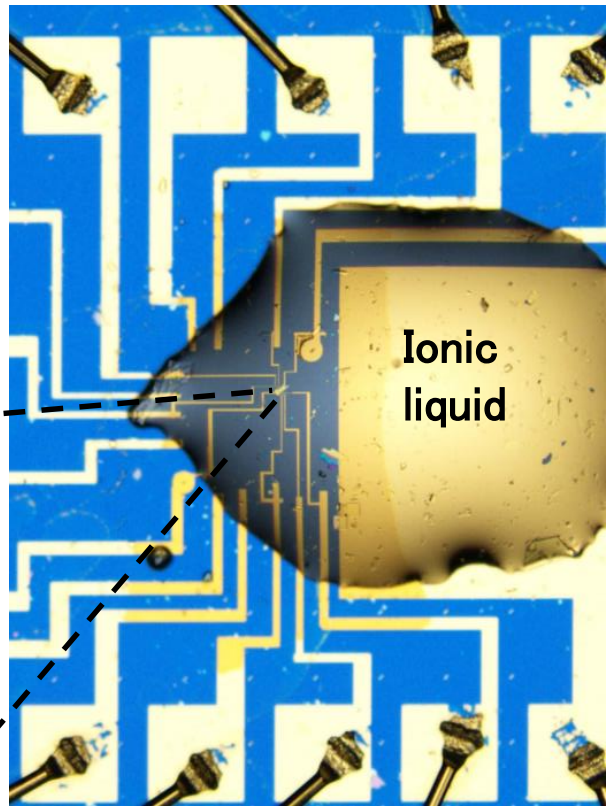
ZrNCl

J. T. Ye et al., **Nat. Mater**. 9, 125 (2010)

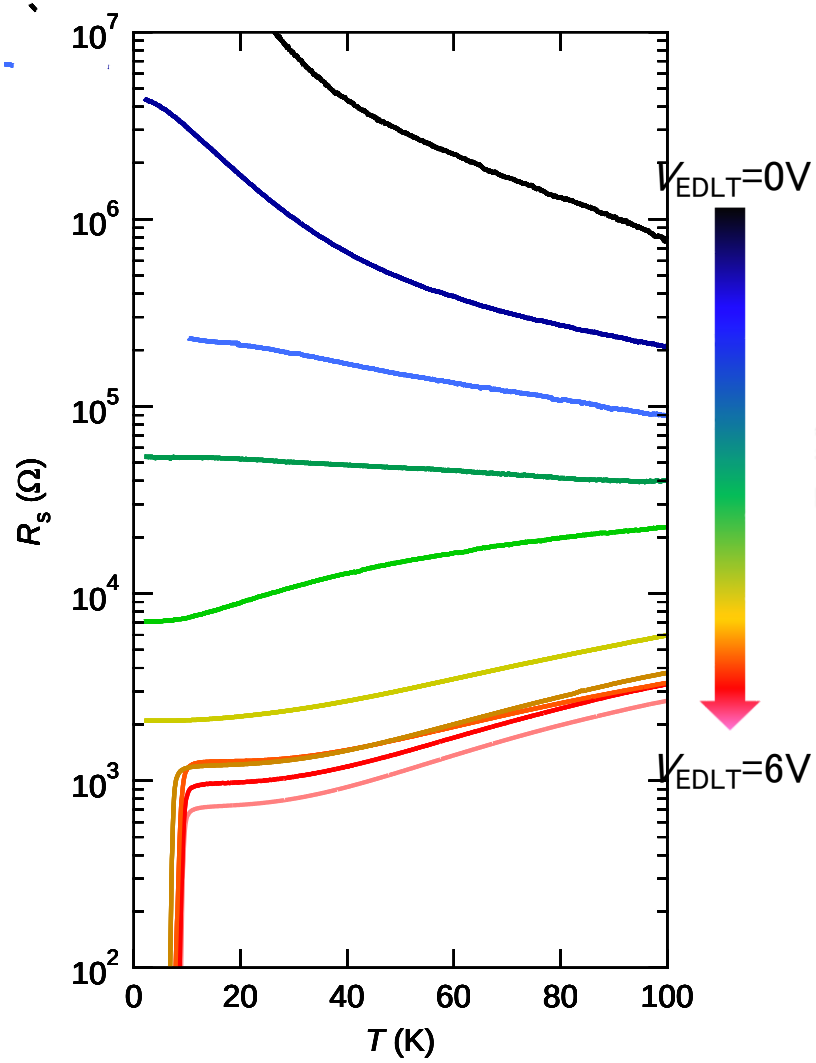


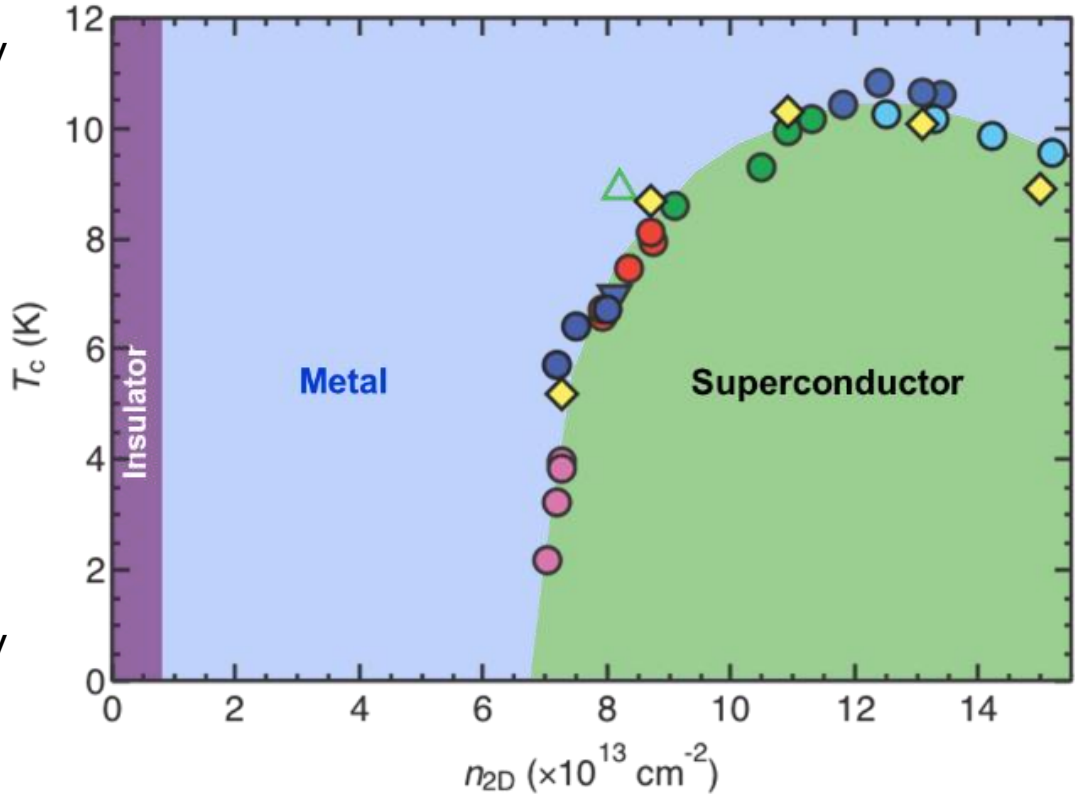






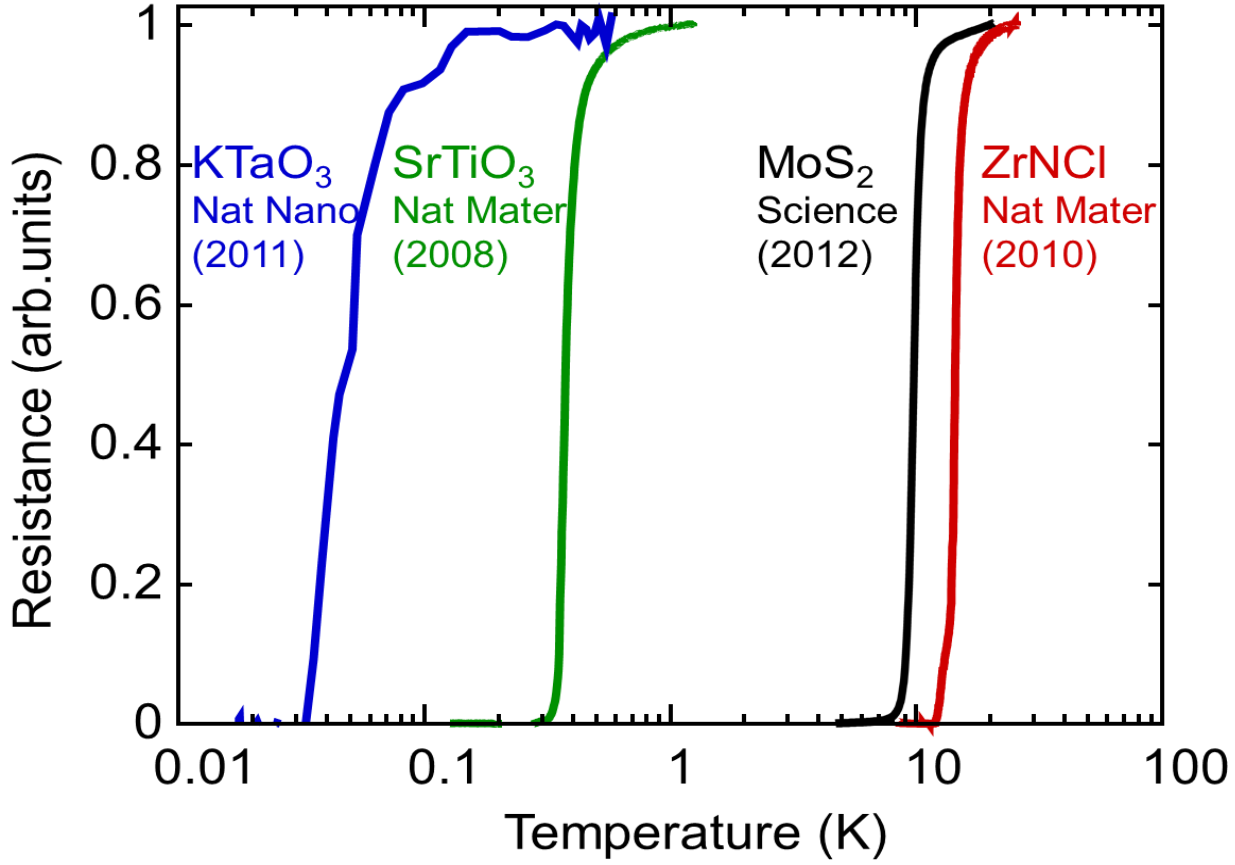
Electric field induced superconductivity in MoS_2





J. T. Ye *et al*. **Science** 338, 1193 (2012)

Gate-induced superconductivity



Electrostatic

STO, YBCO: *Goldman et al., PRL (2011)*

LSCO: *Bozovic et al., Nature (2011)*

MoS_2: *Takagi et al APL (2012)*

WS_2: *Morpurgo et al., Nano Lett (2015)*

$TiSe_2$: Castro Neto, *Nature (2016)*

Electrochemical reaction

TaS_2: Y. Zhang *et al., Nat Nano (2015)*

$MoSe_2$, $MoTe_2$: *W. Shi et al. Sci Rep (2015)*

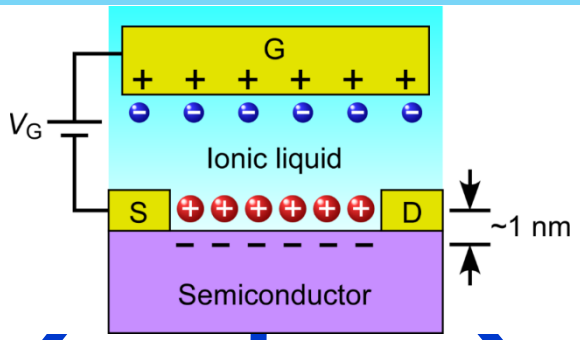
(LiFe)OHFeSe: *X. H. Chen et al., PRB (2016)*

FeSe: *J. Shiogai et al. Nat Phys (2016)*

WS_2 nanotube; *Qin et al. Nat Comm (2017)*

New platform of 2D superconductivity

Y. Saito *et al.*
Nature Reviews Materials
2, 16094 (2016)

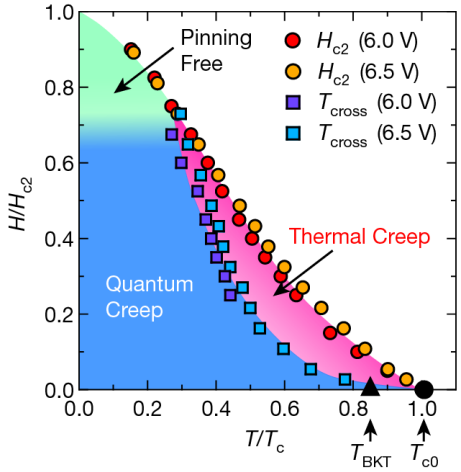


(materials)
$SrTiO_3$, $KTaO_3$, LSCO, YBCO
$ZrNCl$, MoS_2, $MoSe_2$, $TiSe_2$,
FeSe, ⋯

(weak pinning) (broken spatial inversion symmetry)

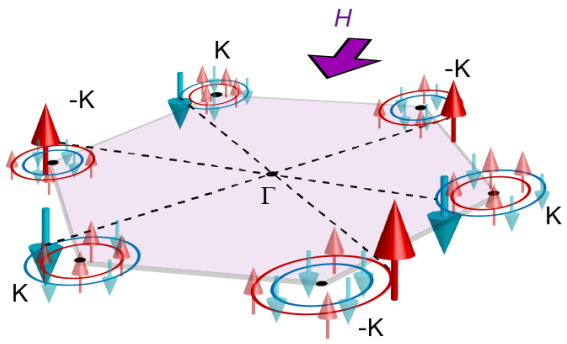
Quantum Phase Transition

Saito, Science (2015)



Enhanced Hc2 by SOI

Saito, Nat Phys (2016)

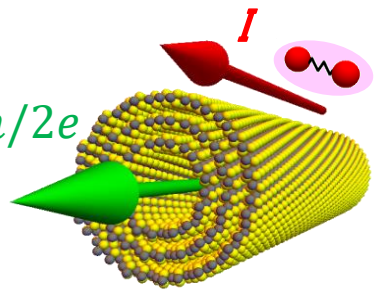


Nonreciprocal Supercurrent

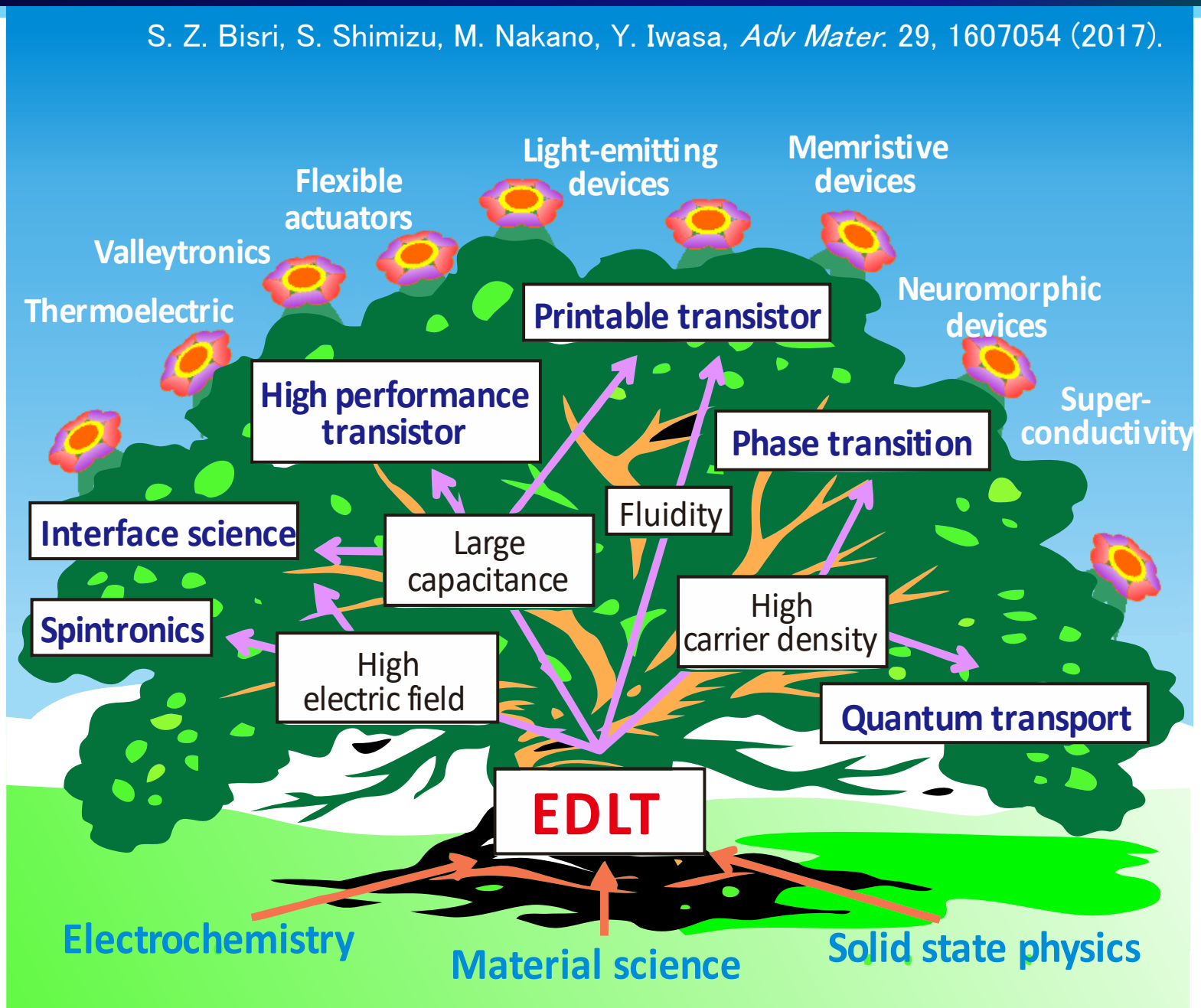
Wakatsuki/Saito, Sci Adv (2017)

Qin, Nat Comm (2017)

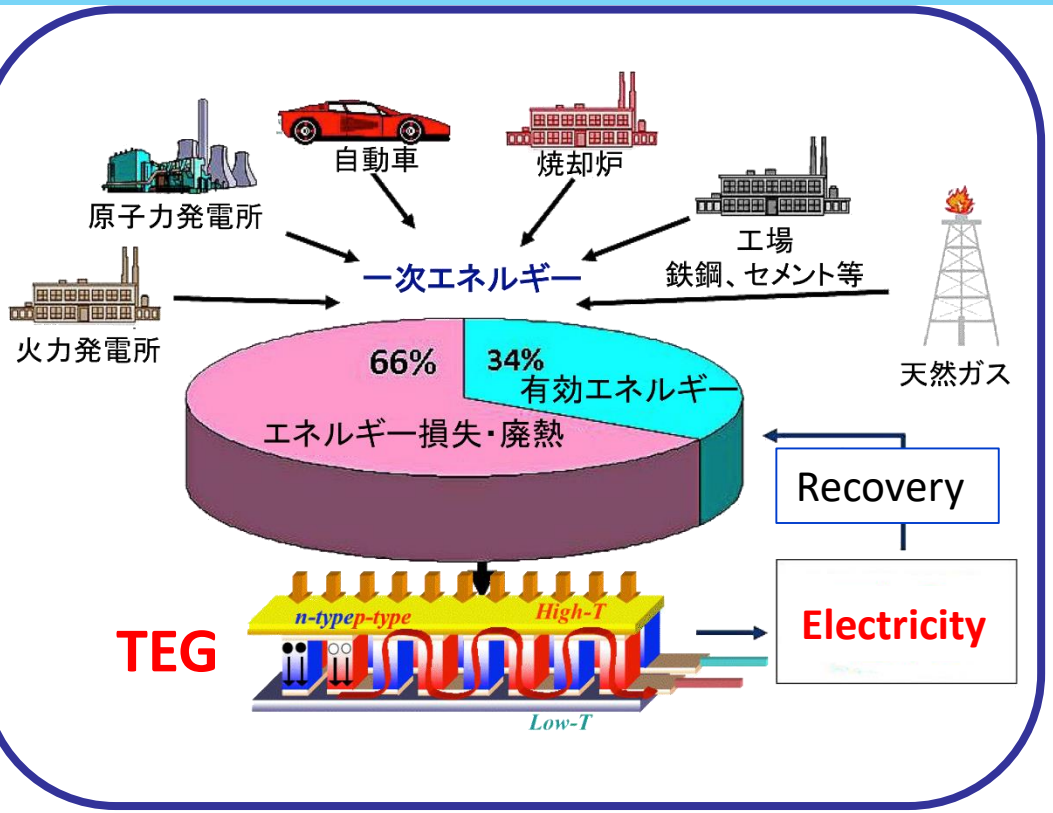
$\phi_0 = h/2e$



Iontronics: Ion controlled electronics

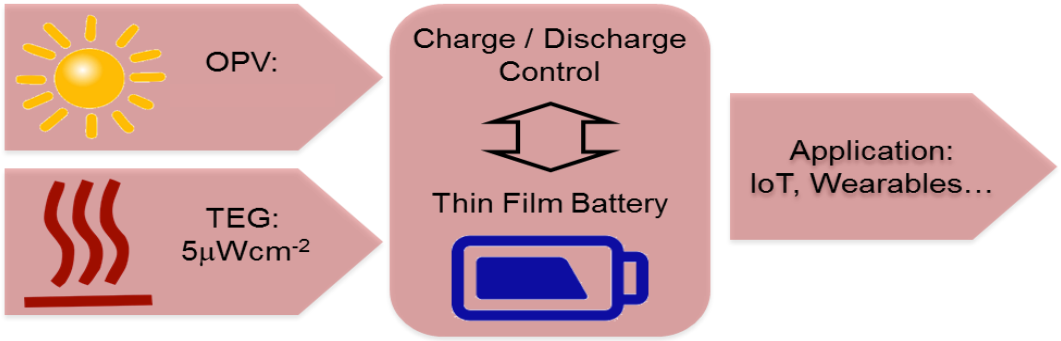


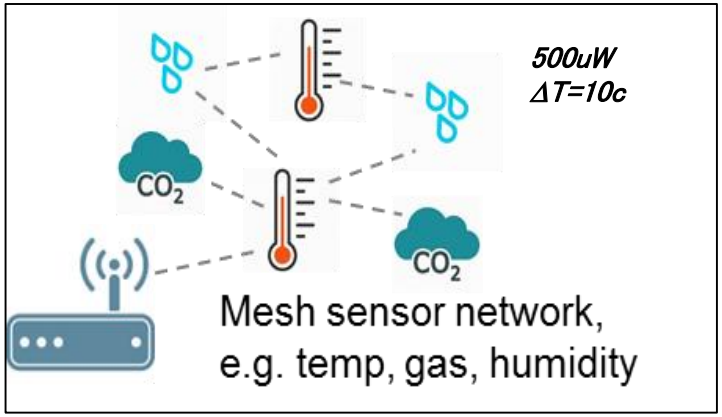
Needs of thermoelectric generation (TEG)



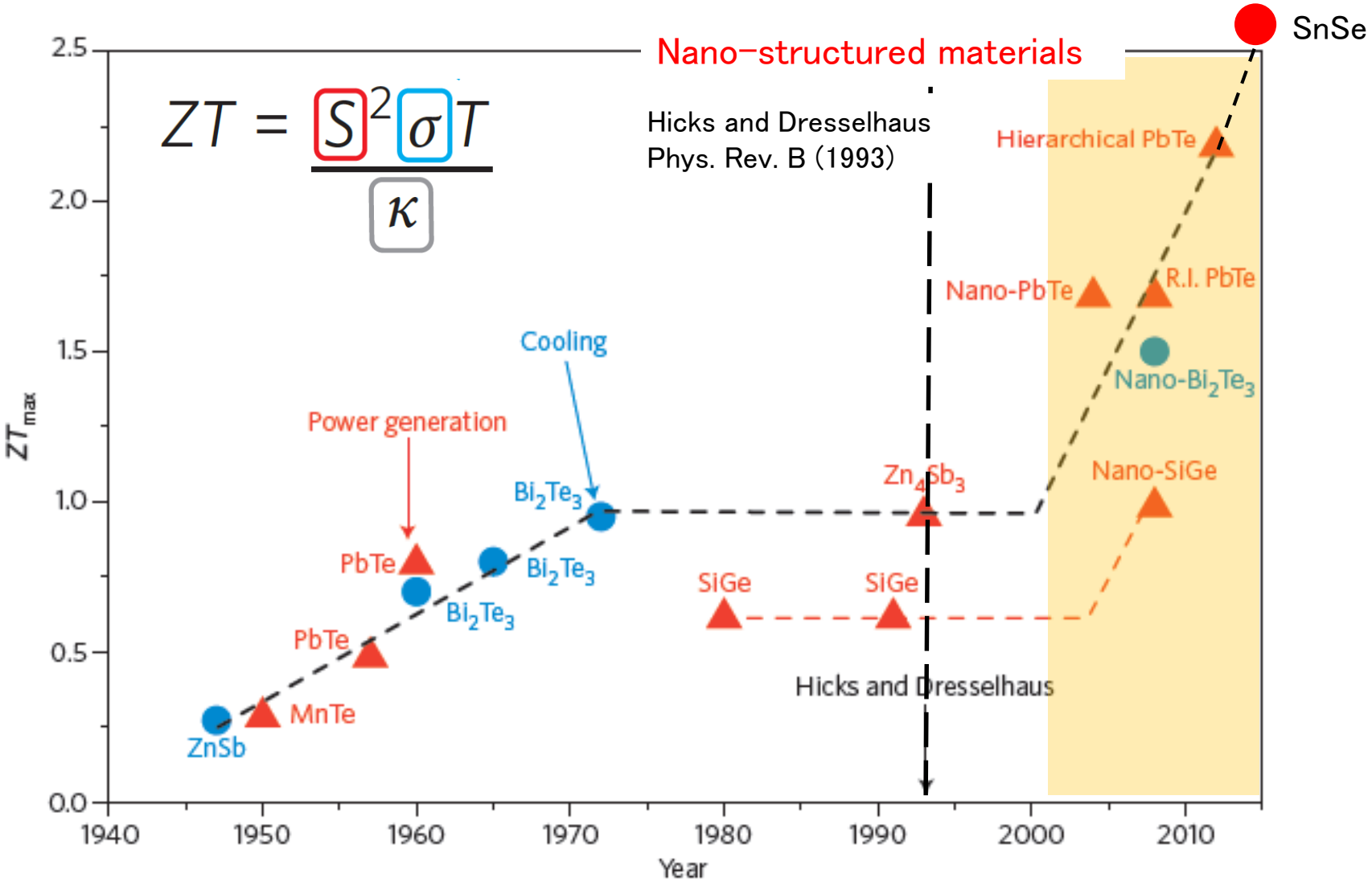
C|D|T
Cambridge Display Technology

Trillion sensors network





Thermoelectric materials, Figure of merit

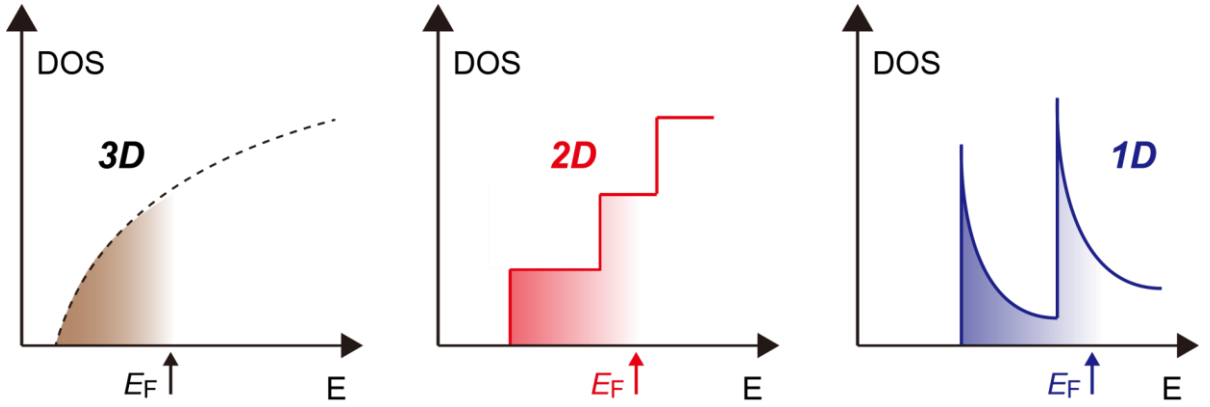


Nature Nanotechnology, 8, 471 (2013)

Guidelines

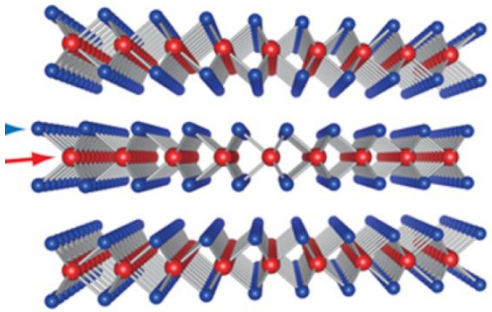
① Enhancement of *S*

L.D. Hicks and
M.S. Dresselhaus,
Phys. Rev. B (1993).

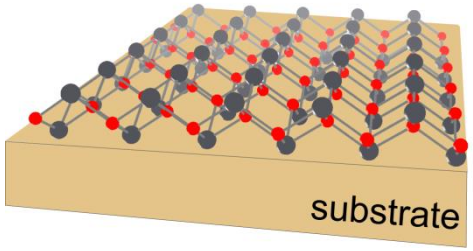


Low dimensional/Nano materials

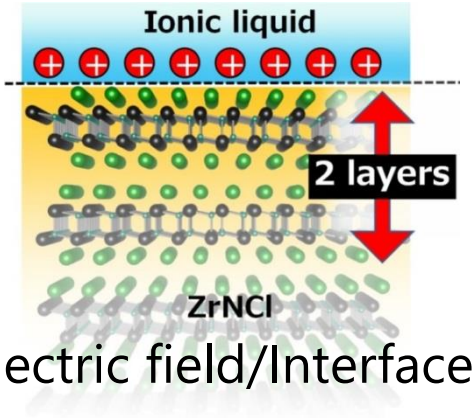
② Enhancement of σ



TMDs



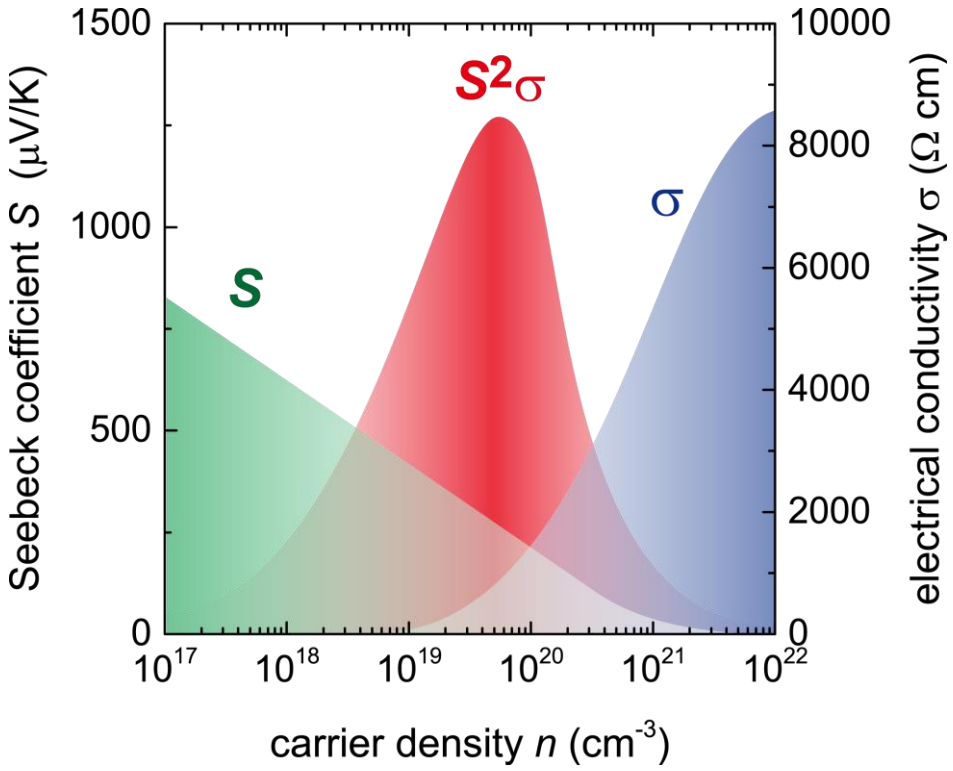
high-quality thin film



Electric field/Interface

Recent highly crystalline 2D materials

Thermoelectric power factor



$$ZT = \frac{S^2\sigma}{\kappa}T$$

Power factor

highest power factor at RT

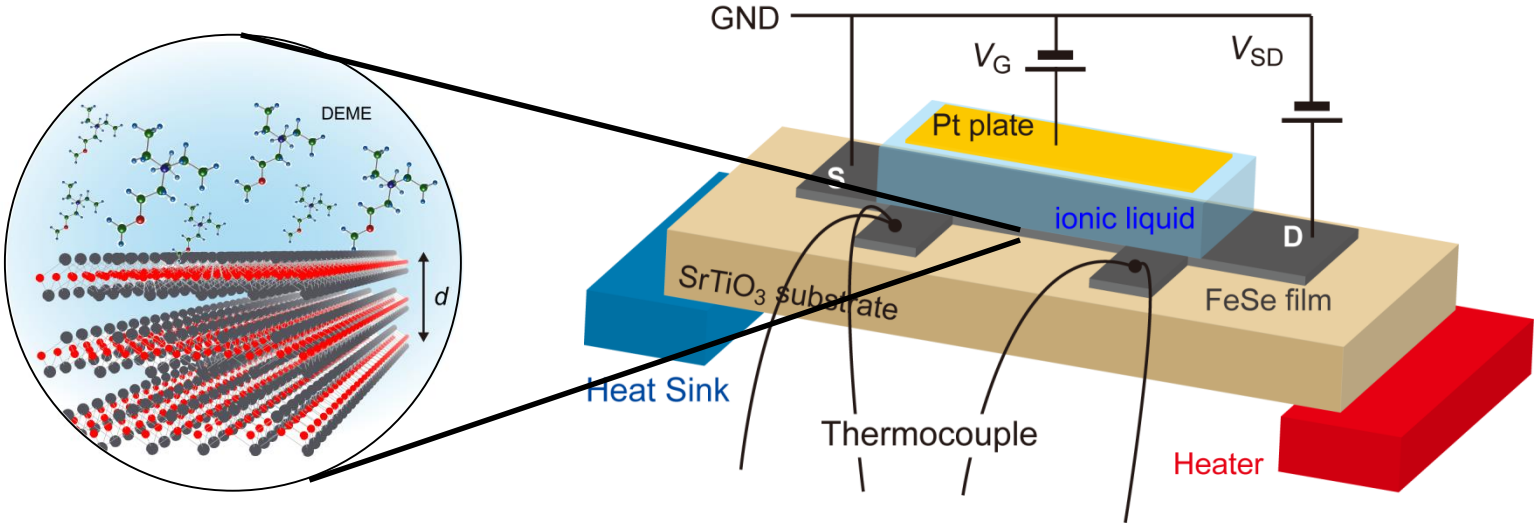
Material	$S^2\sigma$ (μW/cm/K^2)
Bi_2Te_3	~40 [1]
Na_xCoO_2	~60 [2]
SnSe	~40 [3]

1) Kulbachinskii et al., J. Solid State Chem. (2012).

2) M. Lee et al., Nature Mater. (2006).

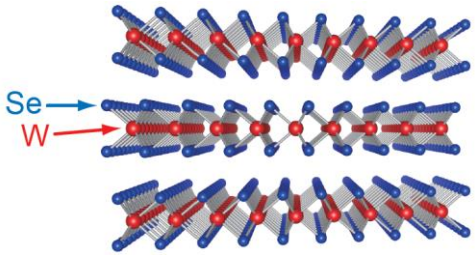
3) L. Zhao et al., Science (2016).

Seebeck measurement in EDLT devices

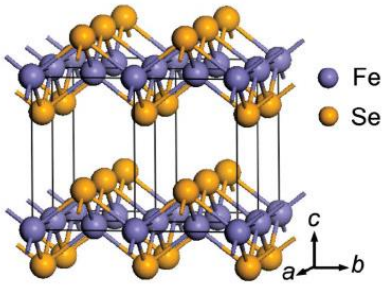


- ZnO (PNAS (2016)) · $SrTiO_3$ (PRB (2015))
- WSe_2 (Nano Lett. (2016))
- Black Phosphorus (Nano Lett. (2016))
- Carbon Nanotube (Small (2016))

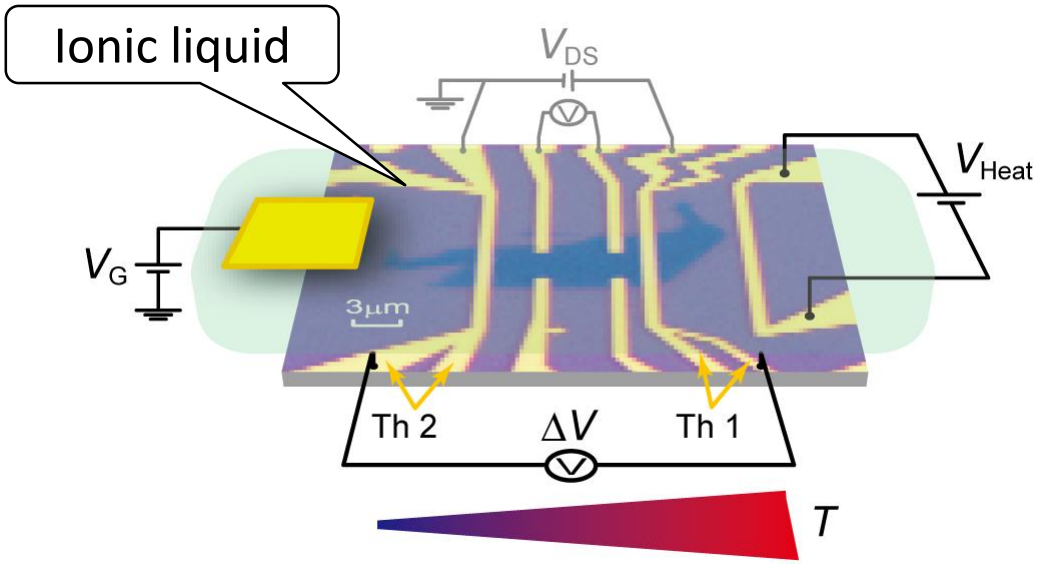
WSe_2

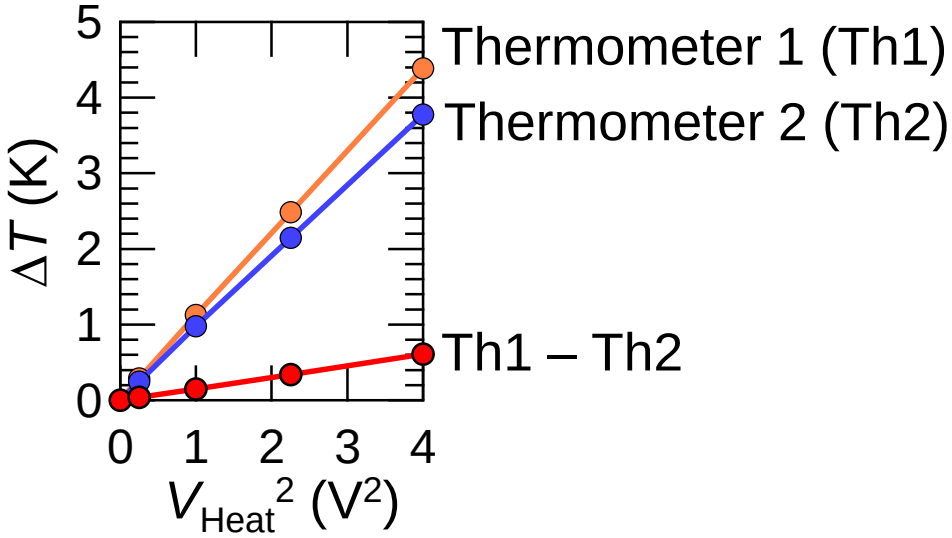


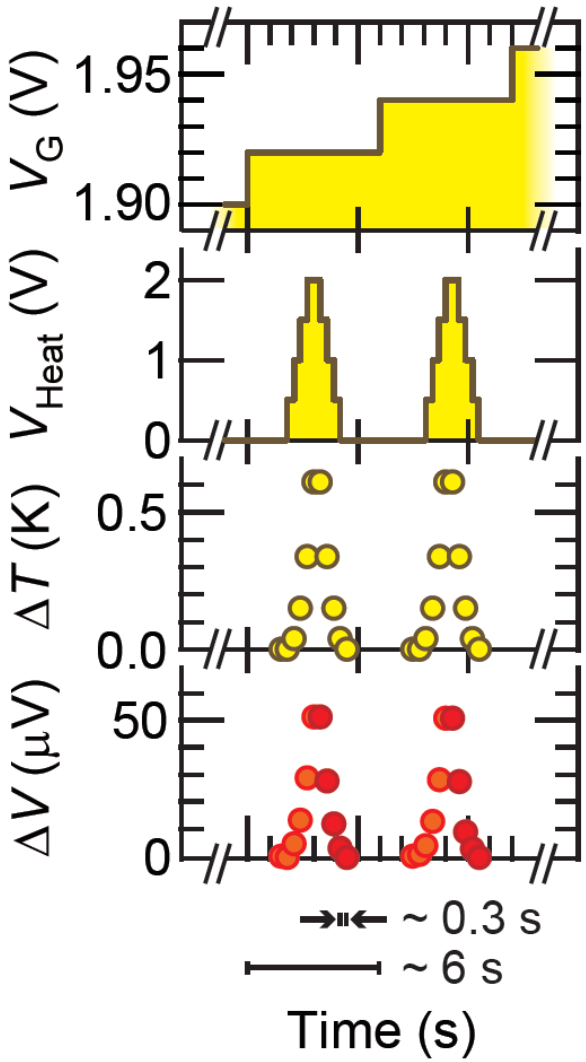
FeSe



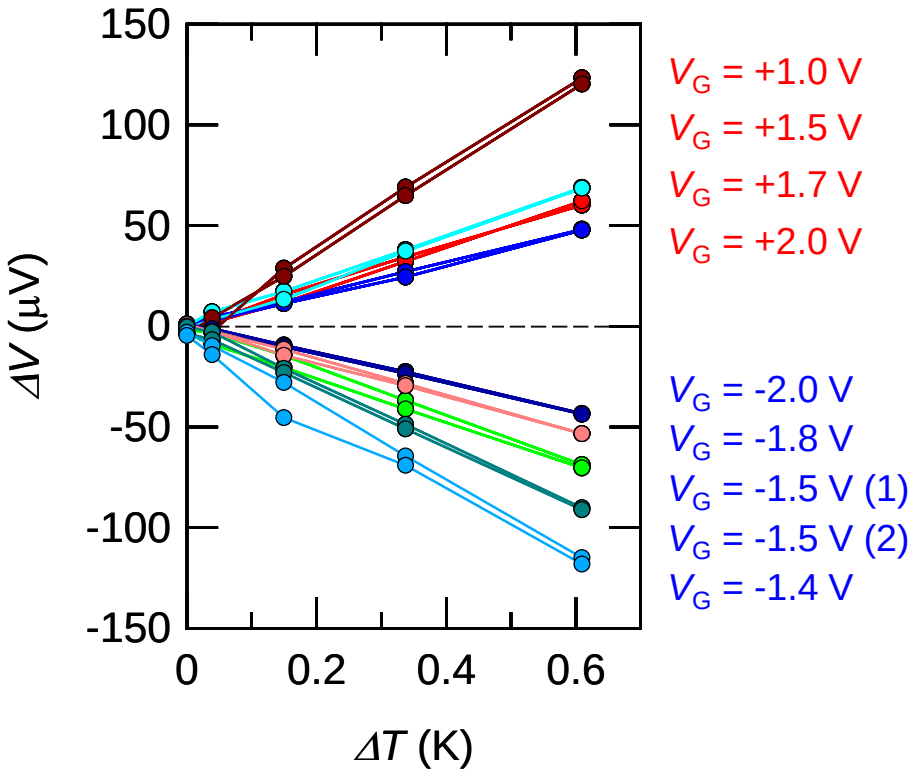
WSe_2-EDLT


Ionic liquid
V_{DS}
V_{Heat}
V_G
3μm
Th 2
ΔV
Th 1
T


ΔT (K)
V_{Heat}^2 (V²)
Thermometer 1 (Th1)
Thermometer 2 (Th2)
Th1 – Th2

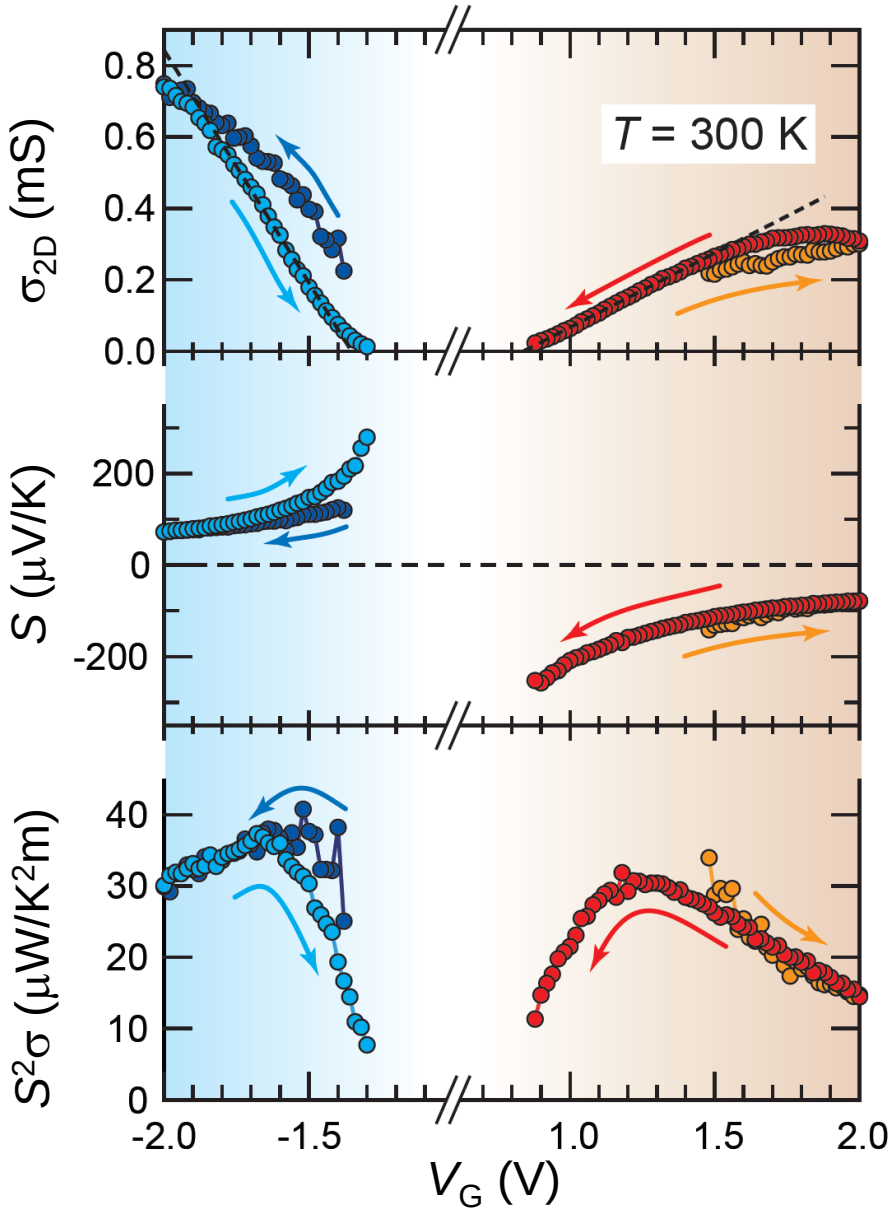

V_G (V)
V_{Heat} (V)
ΔT (K)
ΔV (μV)
~ 0.3 s
~ 6 s
Time (s)

Thermopower of a trilayer WSe_2



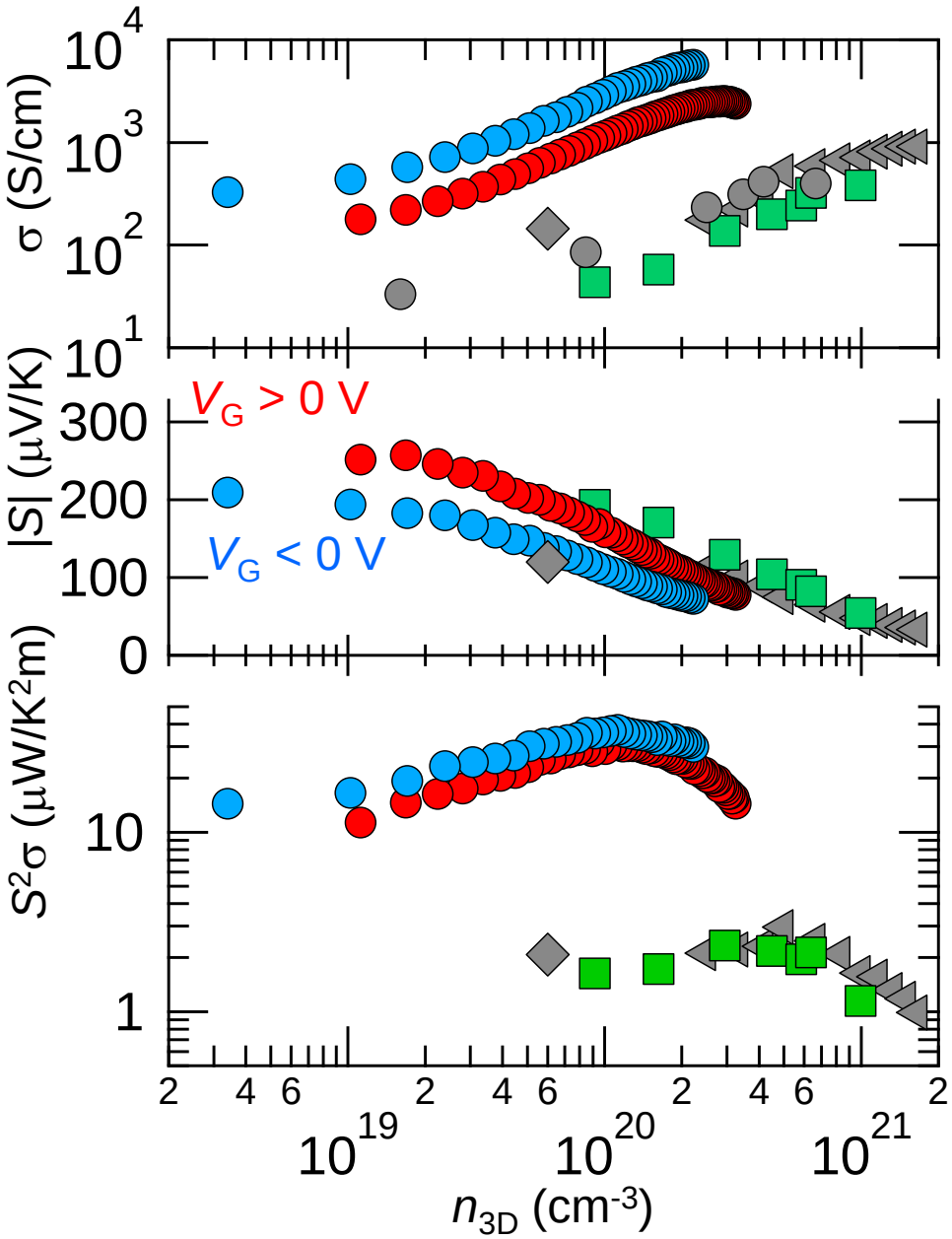
Thermopower: $S = -\Delta V / \Delta T$.

Power factor: $S^2\sigma = S^2\sigma_{2D} / t$.
(t = 1.3 nm) T. Brumme *et al.*, *PRB* **91**, 155436 (2015).



M. Yoshida et al. Nano Lett., 16, 2061 (2016,)

Comparison to chemically doped polycrystals



- C_{EDL} = 5.8 μF/cm² (electrons)
- C_{EDL} = 7.1 μF/cm² (holes)
- $n_{3D} = C_{EDL}|V_G - V_{Th}|/(e \cdot t)$ (t = 1.2 nm)

$W_xTa_{1-x}Se_2$

L. H. Brixner, *J. Electrochem. Soc.* **110**, 289 (1963).
Hicks, *J. Electrhochem. Soc.* **111**, 1058 (1964).

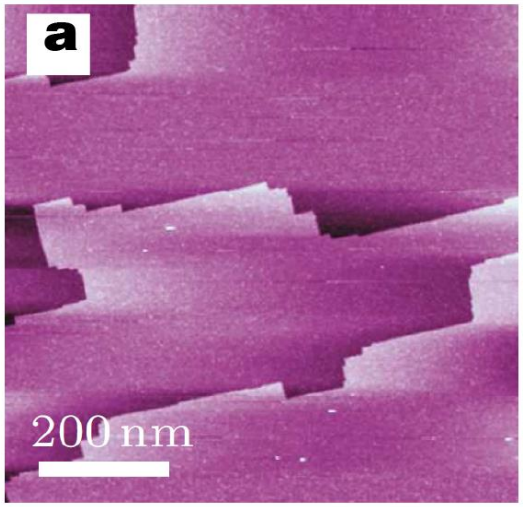
$W_xTa_{1-x}Se_{1.6}Te_{0.4}$

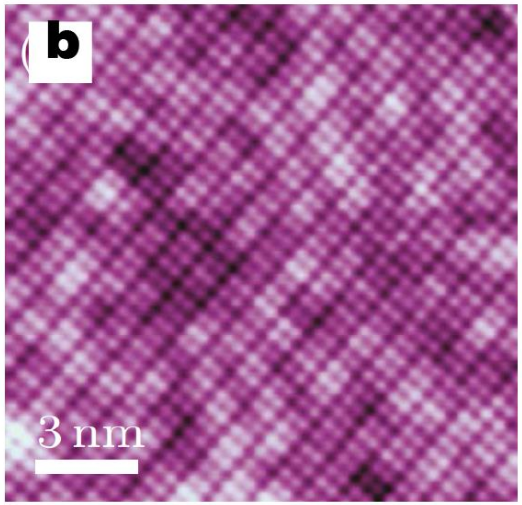
M. Kriener *et al*, *PRB* **91**, 075205 (2015).

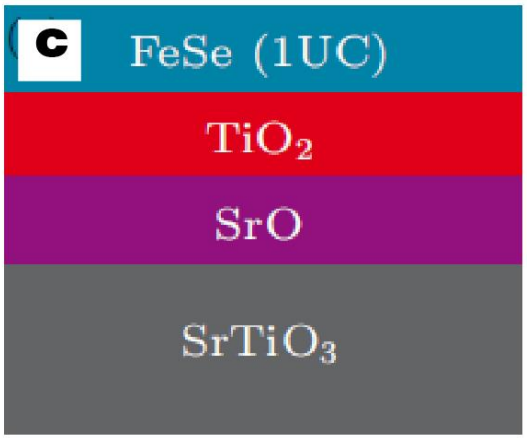
Material	$S^2\sigma$ (μW/cm/K²)
Bi_2Te_3	~40 [1)]
Na_xCoO_2	~60 [2)]
SnSe	~40 [3)]

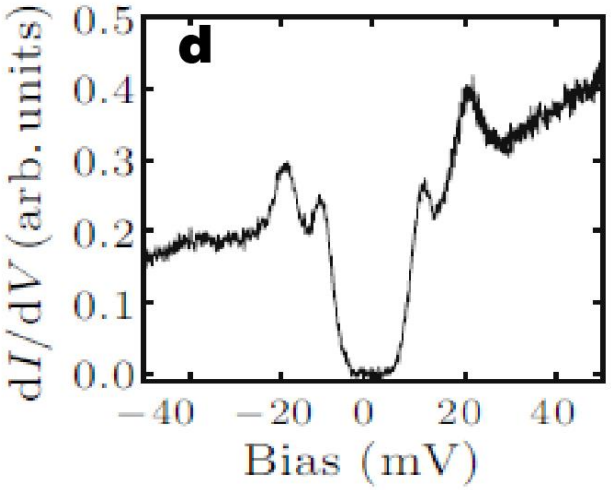
M. Yoshida et al. Nano Lett., 16, 2061 (2016,)

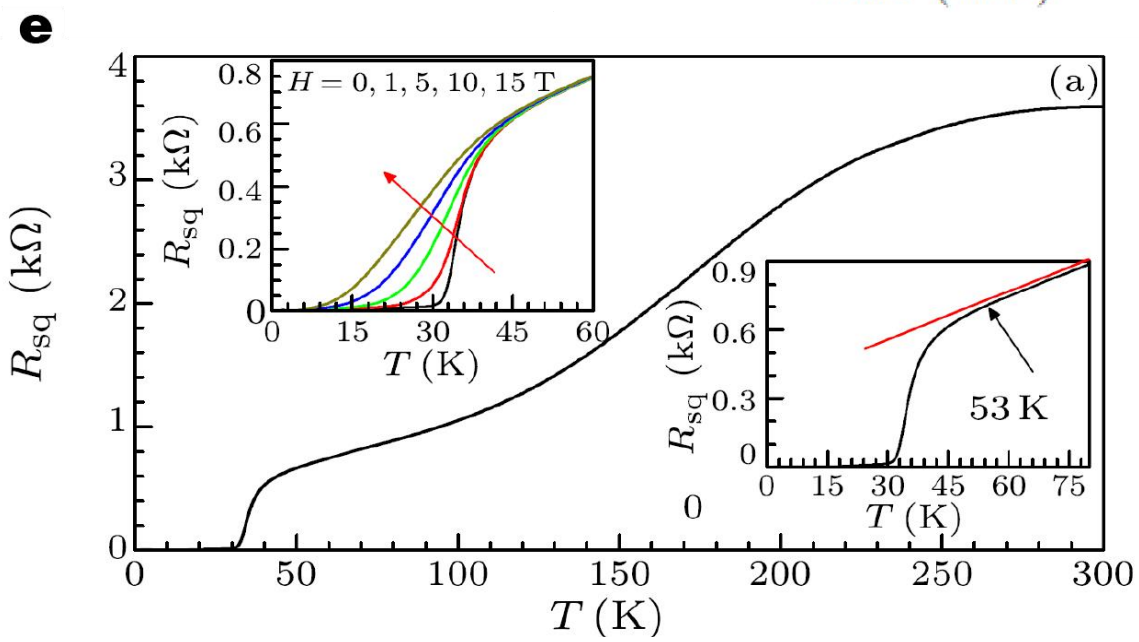
High Tc superconductivity in monolayer FeSe







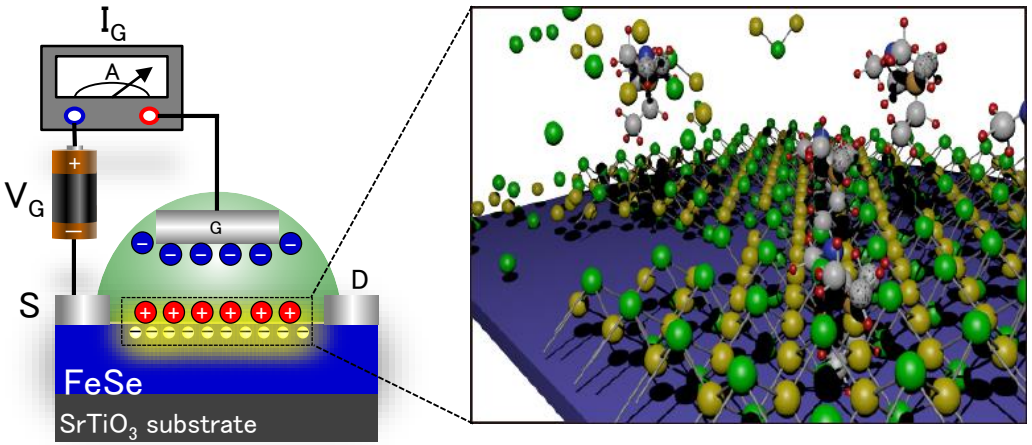




Q, −K, Xue group

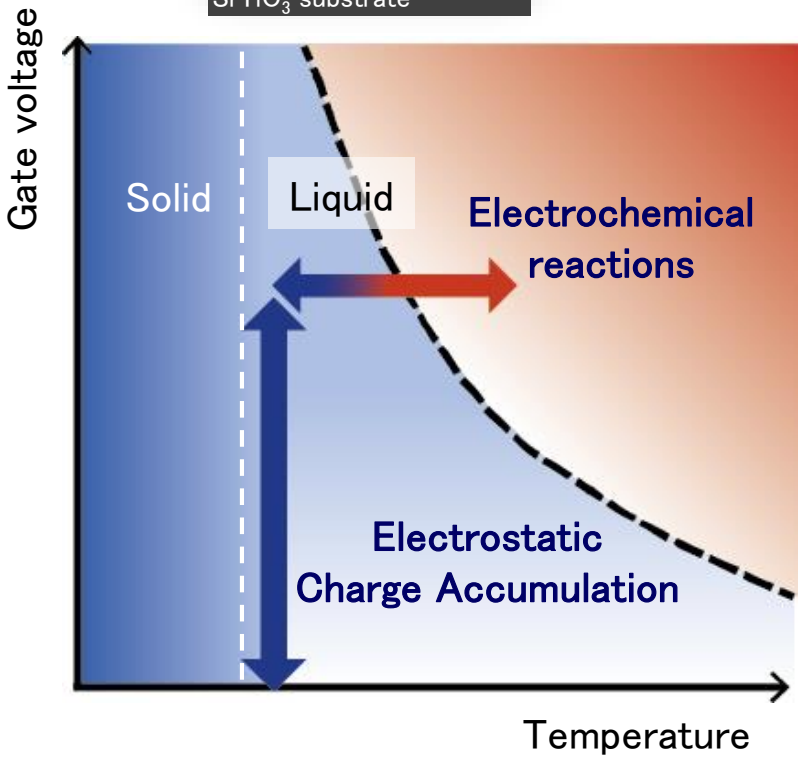
Wang *et al. Chin. Phys. Lett.* **29,** 37402 (2012).
Zhang *et al. Chin. Phys. Lett.* **31,** 017401 (2014).

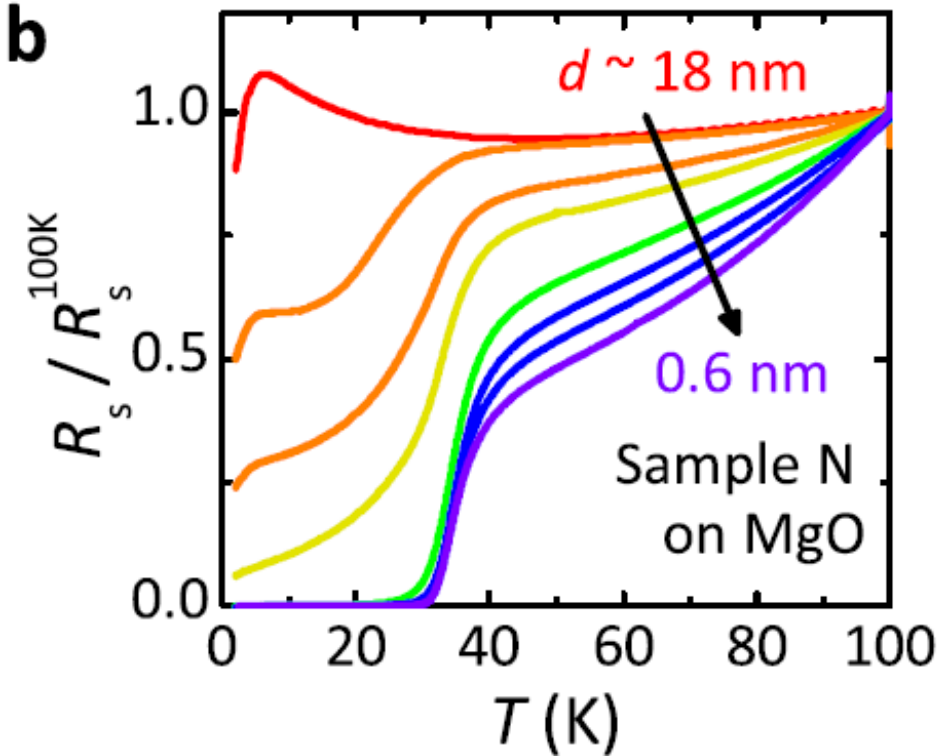
Electrochemical etching and superconductivity in FeSe



Tsukazaki

J. Shiogai *et al.*
Nature Physics **12**, 42 (2016)





Iontronics of 2D materials