ICAM 2015

Searching high T_c at interface

Lili Wang
Department of Physics, Tsinghua University

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Acknowledgements

Leader : Qi-Kun Xue (薛其坤)

Colleagues: Xucun Ma, Canli Song, Xi Chen, Ke He, Shuaihua Ji

Students: Tong Zhang, Wei Li, Qing-Yan Wang, Wen-Hao Zhang, Zhi Li
Fang-Sen Li, Chenjia Tang, …

Transport: Yayu Wang (Tsinghua) Jian Wang (Peking) C. W. Chu (Houston)

ARPES: Xingjiang Zhou (IOP) Zhixun Shen (Stanford)

TEM: Lin Gu (IOP) Mingwei Chen (Tohoku)

Theory: Shengbai Zhang (RPI) Xincheng Xie (Peking)

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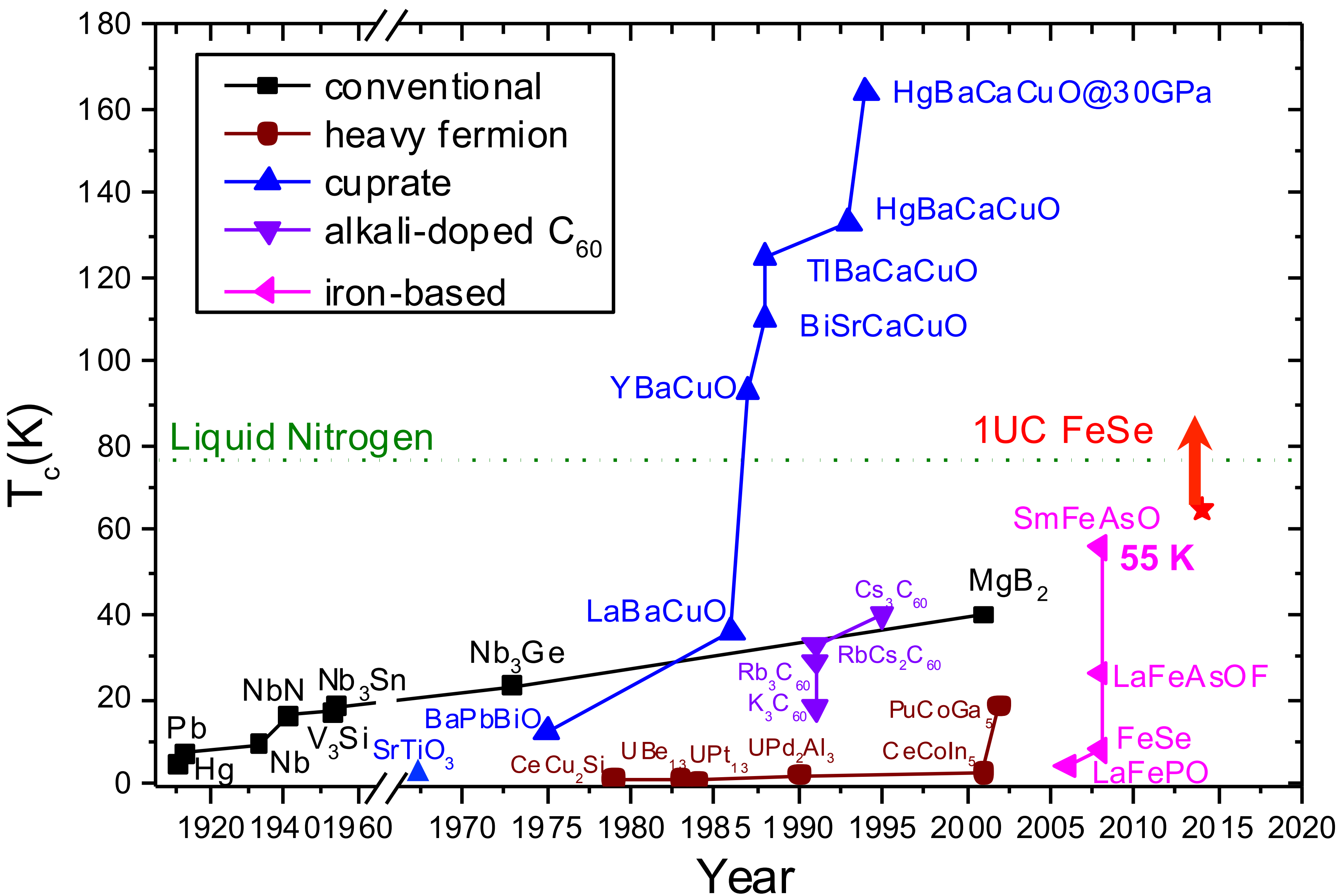
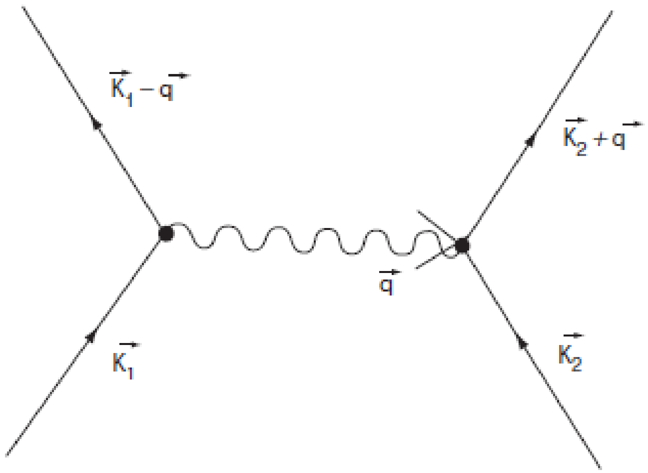


conventional
heavy fermion
cuprate
alkali-doped C60
iron-based
Tc(K)
Year
Liquid Nitrogen
1UC FeSe
HgBaCaCuO@30GPa
HgBaCaCuO
TlBaCaCuO
BiSrCaCuO
YBaCuO
LaBaCuO
BaPbBiO
SrTiO3
SmFeAsO
55 K
MgB2
Cs3C60
RbCs2C60
Rb3C60
K3C60
LaFeAsOF
FeSe
LaFePO
PuCoGa5
CeCoIn5
UPd2Al3
UPt13
UBe13
CeCu2Si2
Nb3Ge
Nb3Sn
NbN
V3Si
Nb
Pb
Hg

Conventional superconductivity：BCS theory

Electrons form cooper pairs mediated by phonon.

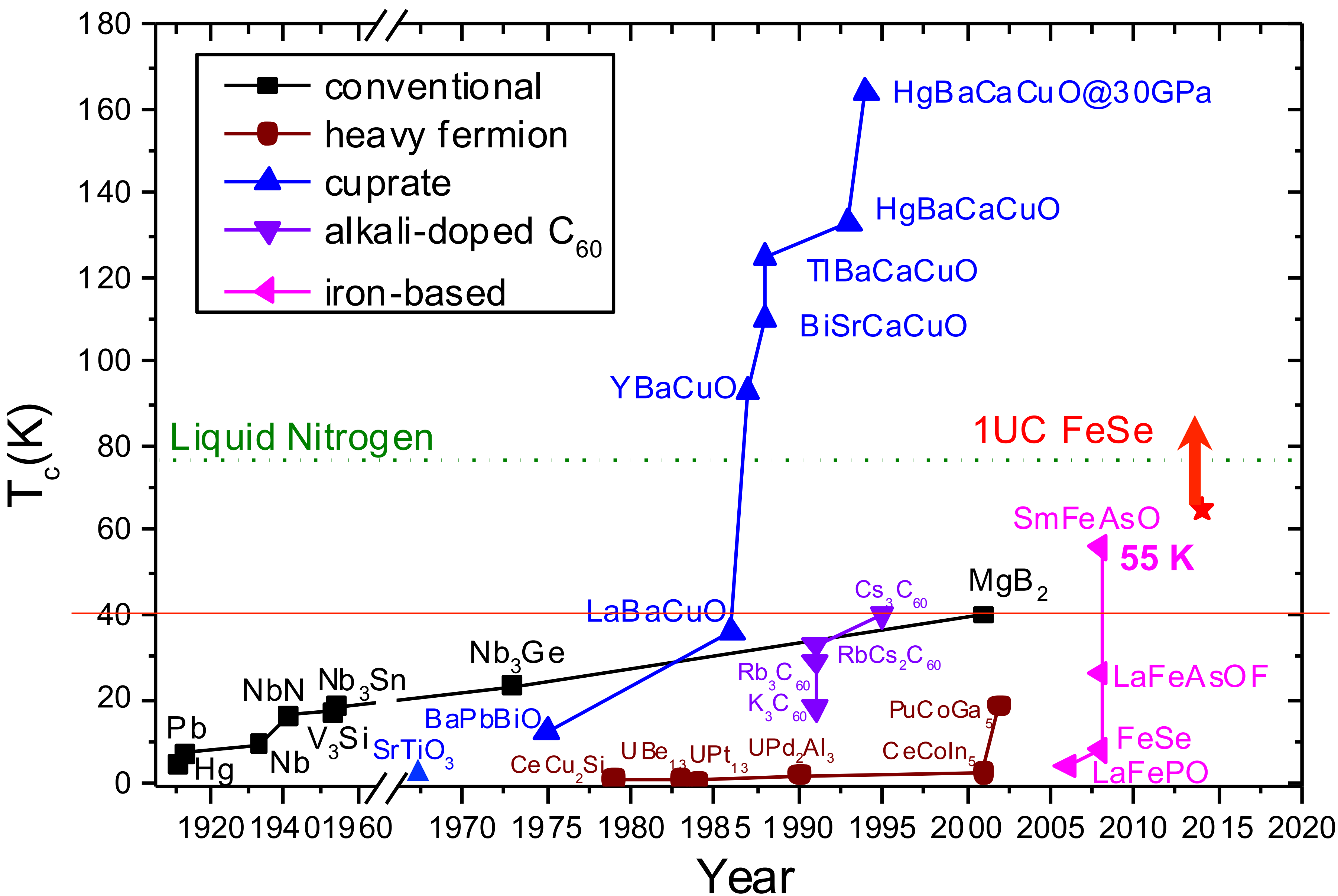


$$T_c = \frac{\Theta_D}{1.45} \exp[-\frac{1.04(1+\lambda)}{\lambda - \mu^*(1+0.62\lambda)}] \longrightarrow \sim 40\,K$$

Metal: metallic, but low Debye Θ_D

McMillan, Phys. Rev. B 16, 643 (1977)

Ceramic : high Debye Θ_D, but insulating



conventional
heavy fermion
cuprate
alkali-doped C_{60}
iron-based
HgBaCaCuO@30GPa
HgBaCaCuO
TlBaCaCuO
BiSrCaCuO
YBaCuO
Liquid Nitrogen
1UC FeSe
SmFeAsO
55 K
MgB$_2$
Cs_3C_{60}
LaBaCuO
$RbCs_2C_{60}$
Rb_3C_{60}
K_3C_{60}
LaFeAsOF
Nb$_3$Ge
NbN
Nb$_3$Sn
PuCoGa$_5$
BaPbBiO
Pb
Hg
Nb
V$_3$Si
SrTiO$_3$
CeCu$_2$Si$_2$
UBe$_{13}$
UPt$_3$
UPd$_2$Al$_3$
CeCoIn$_5$
FeSe
LaFePO
T_c(K)
Year

High temperature superconductivity - Unconventional superconductivity

(1) Resonating Valence Bond

P. W. Anderson, Science 235, 1196 (1987)

P. A. Lee, N. Nagaosa, X. G. Wen, Rev. Mod. Phys. 78, 17 (2006)

(2) Spin Fluctuation

T. A. Maier, D. Poilblanc, D. J. Scalapino, Phys. Rev. Lett. 100, 237001 (2008)

What is the mediator of Cooper pairing?

Phonon

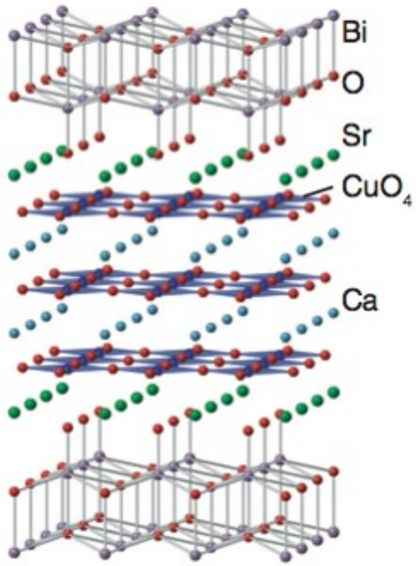
Spin fluctuation

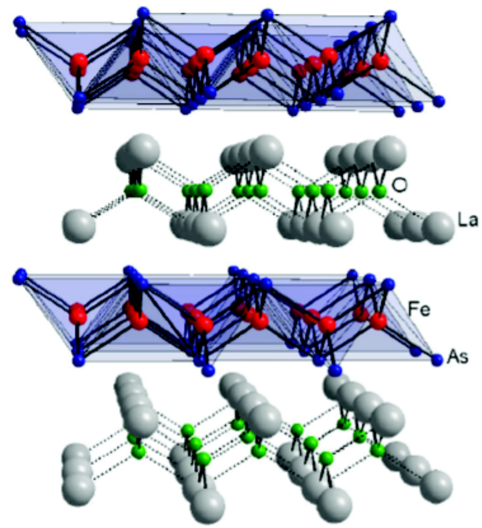
……

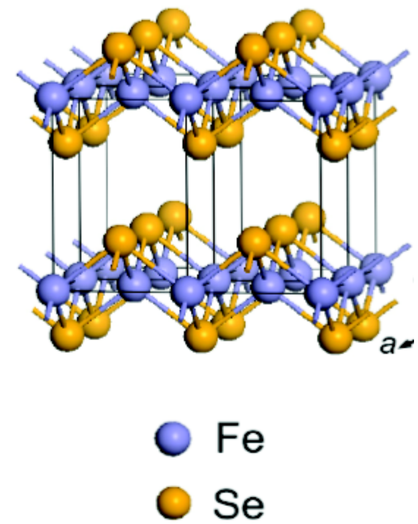
Antiferromagnetism, charge-density waves, spin-density waves, nematic correlations, orbital currents, or a combination

High temperature superconductivity

Cuprate	Fe-pnictides	Fe-chalcogenides







BSCCO
Bednorz & Müller
Z. Phys. B 64, 189 (1986)

LaOFFeAs
Hosono
JACS 130, 3296 (2008)

FeSe
M. K. Wu
PNAS *105, 14262 (2008)*

layered structure: **doping of a Mott insulator/metallic compound**

	$LaSrCuO_4$	LaOFeAs
Charge reservior	LaSrO	LaO
superconducting layer	CuO_2	FeAS

Interface superconductivity

On surface superconductivity

V.L. Ginzburg, PHYSICS LETTERS, 1964

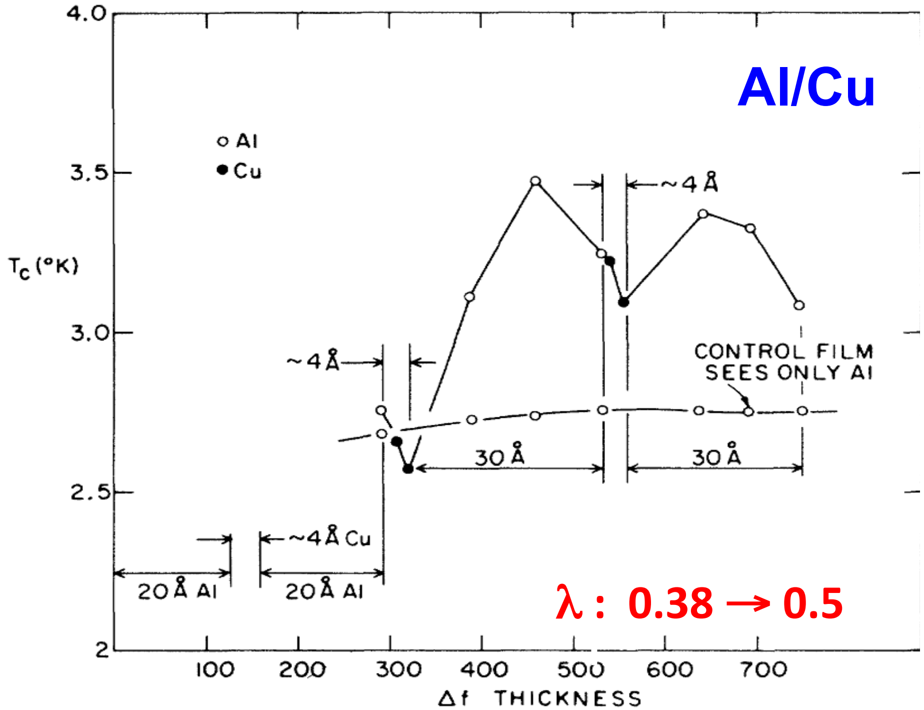
✓ **attraction takes place between electrons in the layer of metal near to the surface, while repulsion prevails in the volume.**
The interaction varies near the surface, due to the exchange by surface phonons, variation of screening, etc.

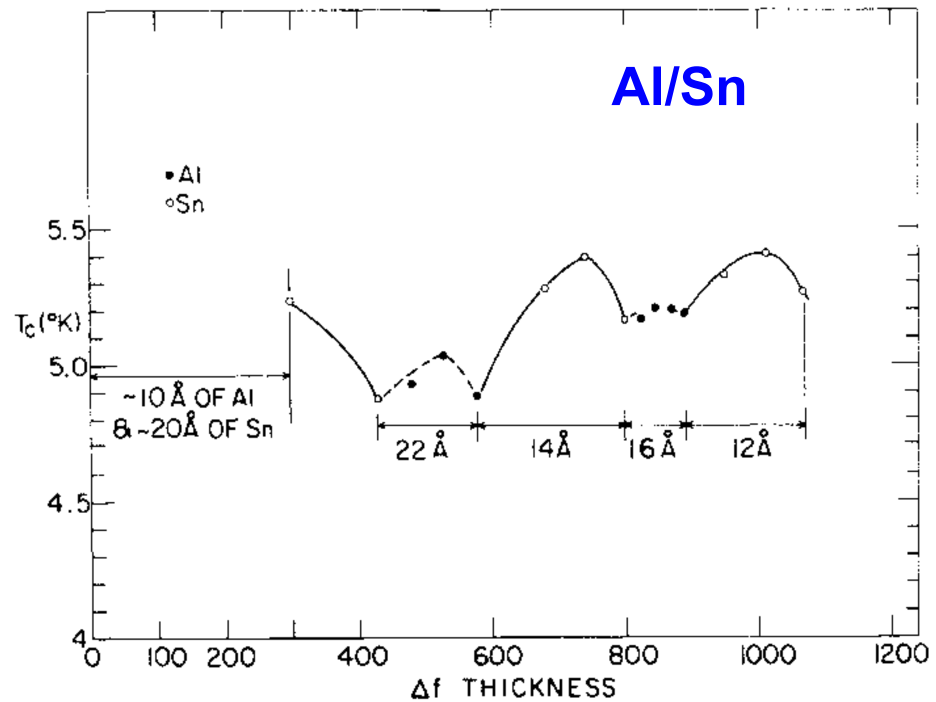
✓ **surface superconductivity is connected with the transition into the superconducting state of electrons in surface states**

non-metallic in the volume + partially filled surface band → surface metal

Interface superconductivity

Enhanced Superconductivity in Layered Metallic Films



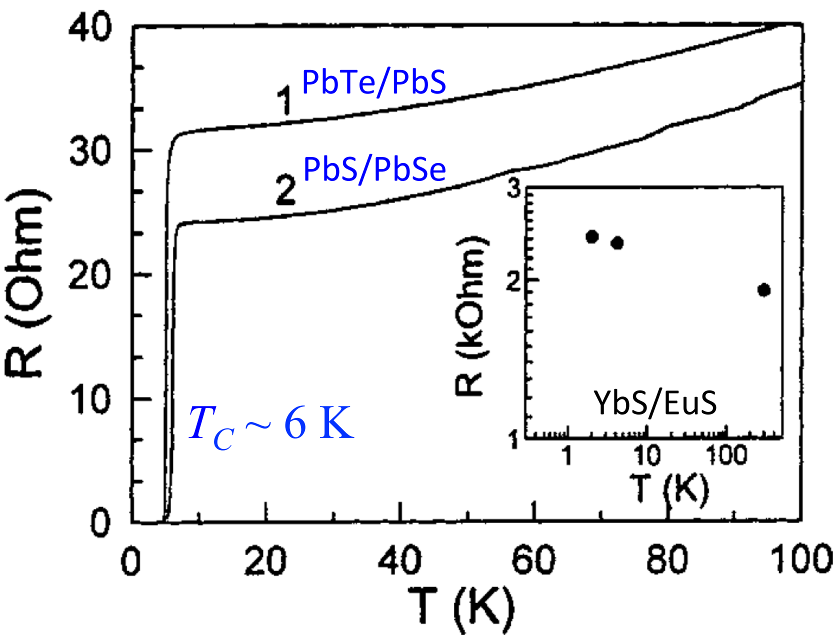


The e-p coupling at interface is enhanced due to the lowering of phonon frequencies.

Strongin et al., Phys. Rev. Lett. 21, 1320 (1968)

Interface superconductivity

semiconducting super-lattices

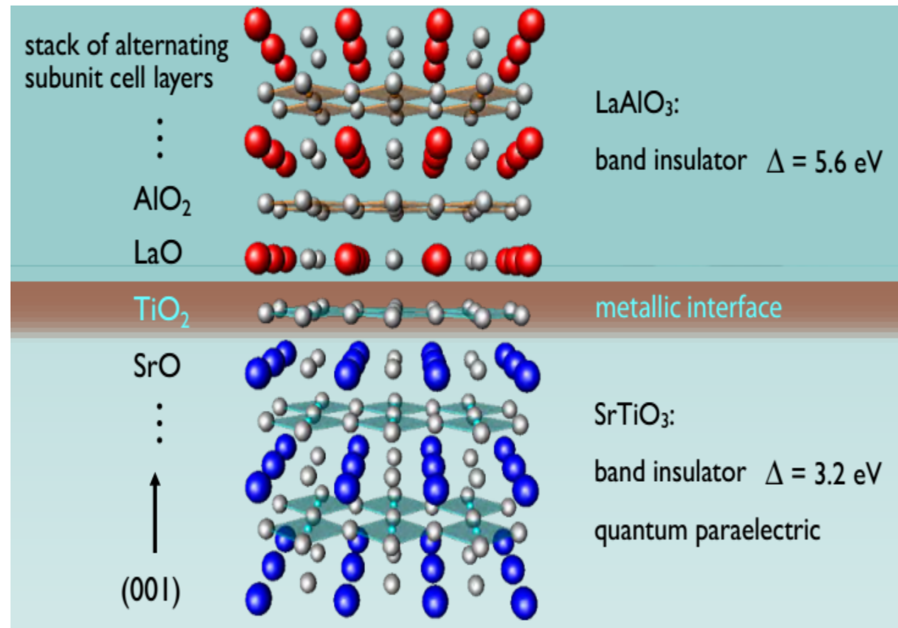


Strain effect
elastic deformation fields
band inversion effect …

Fogel et al., Phys. Rev. B 66, 174513 (2002)
Fogel et al., Phys. Rev. B 73, 161306 (2006)

$LaAlO_3/SrTiO_3$ hetero-structure

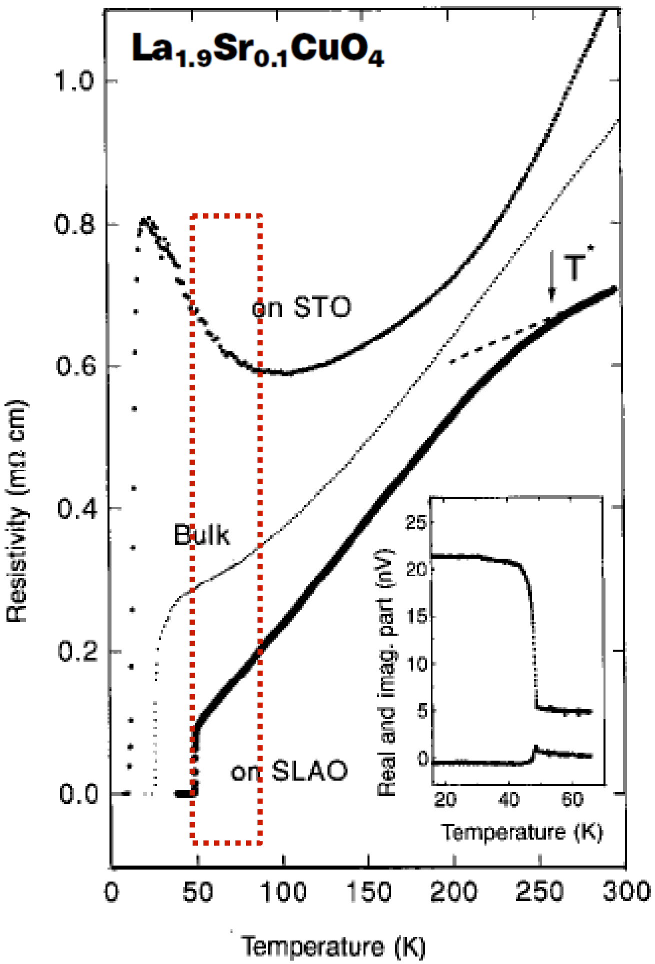
$T_C \sim 200$ mK



High mobility 2D electron gas at the interface

Ohtomo et al., Nature 427, 423 (2004)
Reyen et al., Science 317, 1196 (2007)
Hwang et al., Nat. Mater. 11, 103 (2012)

Interface superconductivity



LSCO/STO

tensile strain, T_c = 10 K

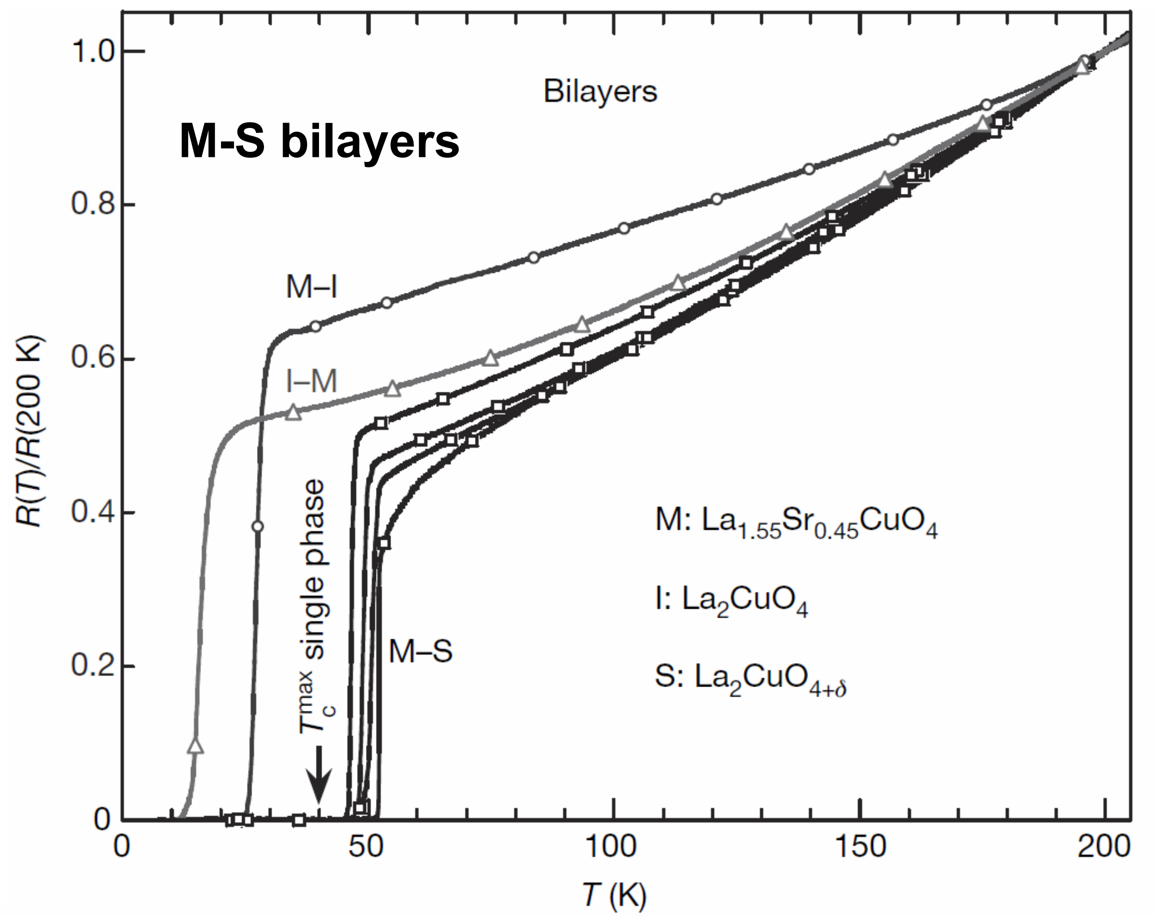
LSCO /SLAO

compressive strain, T_c = 49 K

carrier density increases

Nature 394, 453 (1998)

metallic and insulating copper oxides



La_2CuO_4
$La_{1.55}Sr_{0.45}CuO_4$

Nature 455, 782 (2008)

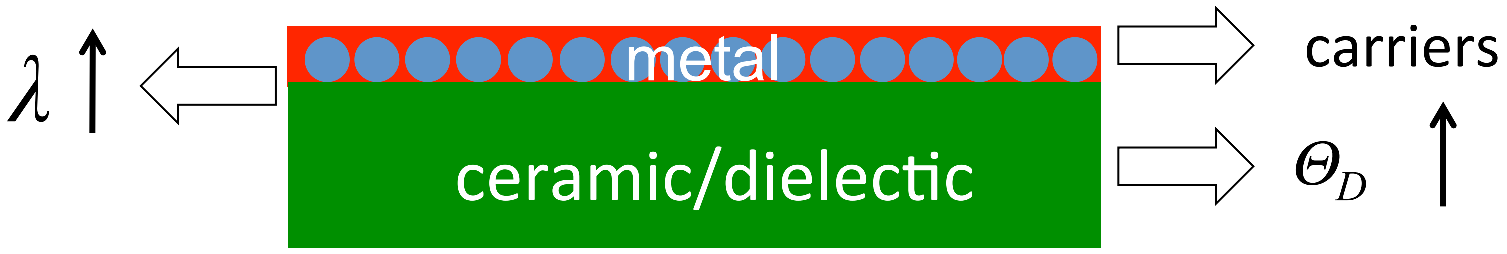
Interface superconductivity

$$T_c = \frac{\Theta_D}{1.45}\exp\left[-\frac{1.04(1+\lambda)}{\lambda-\mu^*(1+0.62\lambda)}\right] \longrightarrow \sim 40\,\mathrm{K}$$

McMillan, Phys. Rev. B 16, 643 (1977)

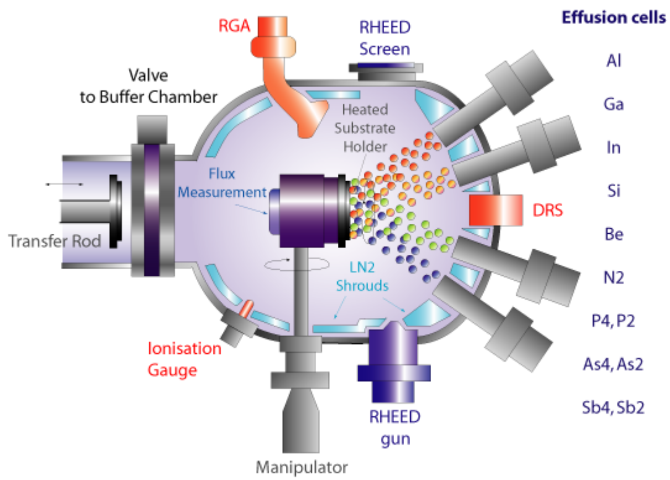
Xue group: Interface superconductivity ***Est. 2008***

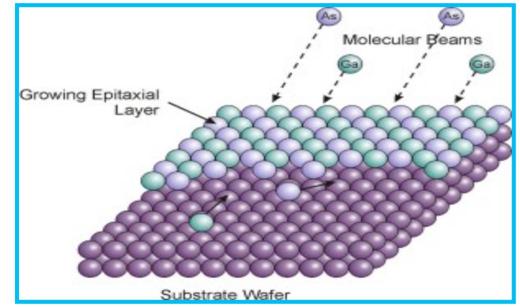
To increase T_c under BCS e-p coupling scheme



Q. -K. Xue, unpublished (2008)

Molecular Beam Epitaxy (MBE)
(Arthur & Cho, 1975)



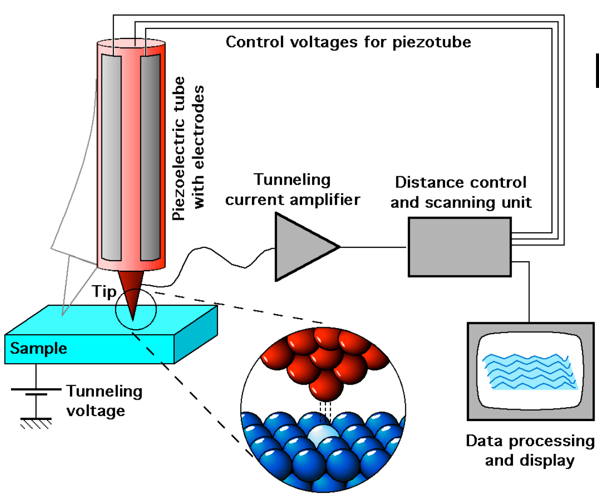


Atomic-Level

+

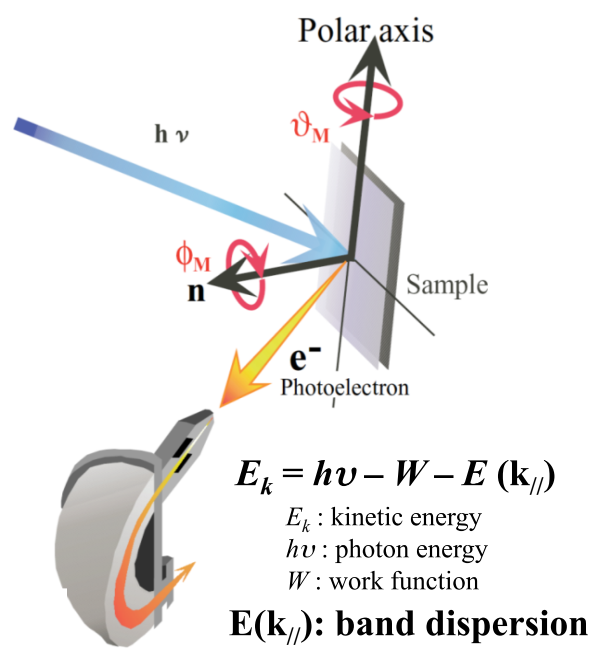
Angle-Resolved Photoemission Spectroscopy (ARPES)

Scanning Tunneling Microscope (STM)
(Binnig & Rohrer, 1981)



$$I \propto V_b \exp(-A\Phi^{1/2} d)$$

$$dI/dV \propto \rho \text{ (DOS)}$$



MBE + LT STM/STS + Transport

STM/STS: 400 mK

Magnetic field: 11 T

Vacuum: 5×10^{-11} Torr

MBE

LT-STS

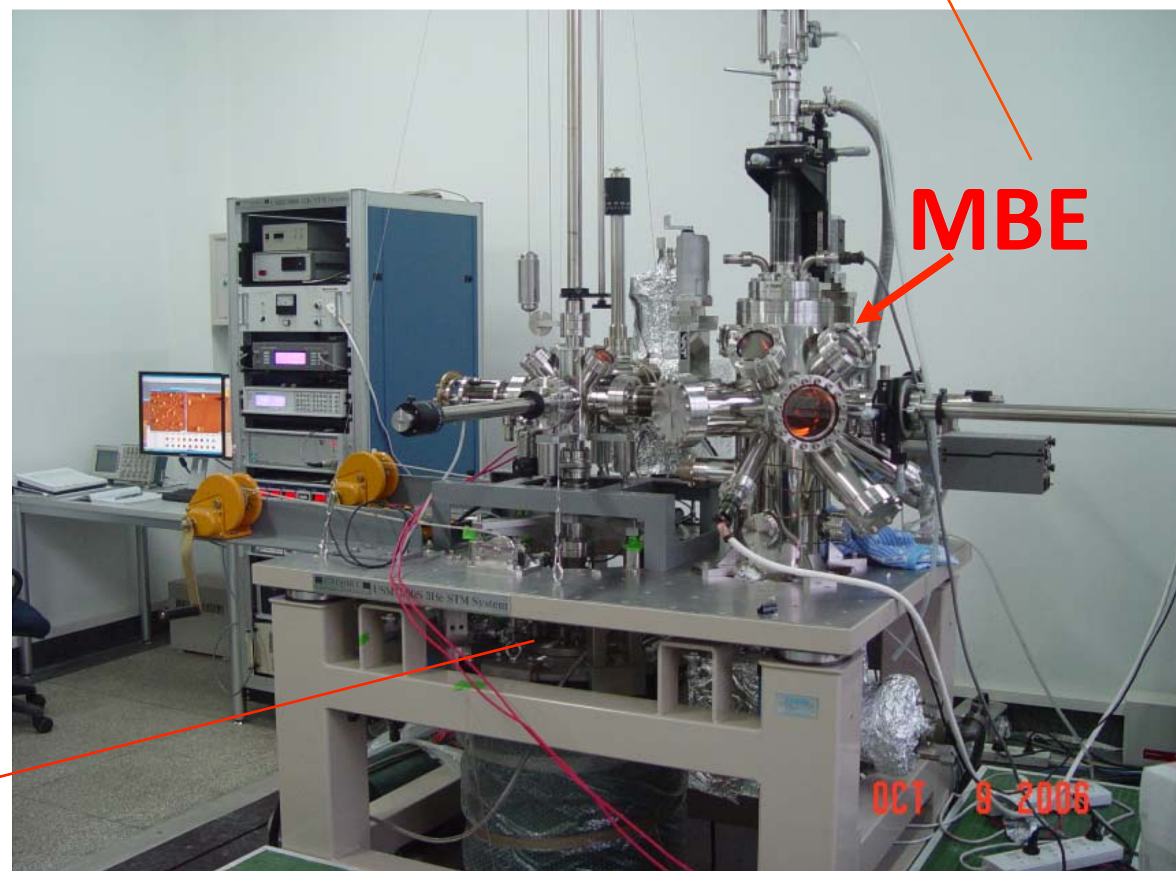
ARPES

STEM

Transport

STM

A precise control of growth flux



Interface superconductivity

Conventional superconductors: Pb/Si, In/Si

Zhang et al., Nat. Phys. 6, 104 (2010)

Unconventional superconductors: FeSe, FeSeTe, KFeSe

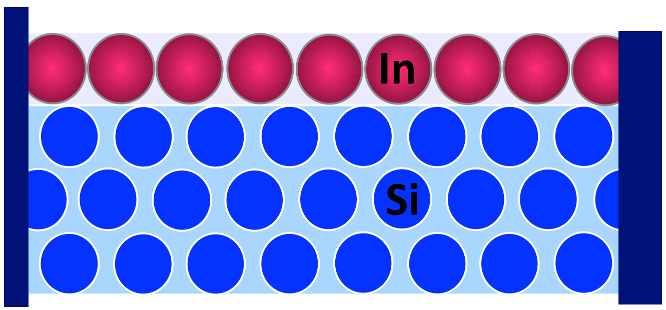
Substrate: graphene & $SrTiO_3$

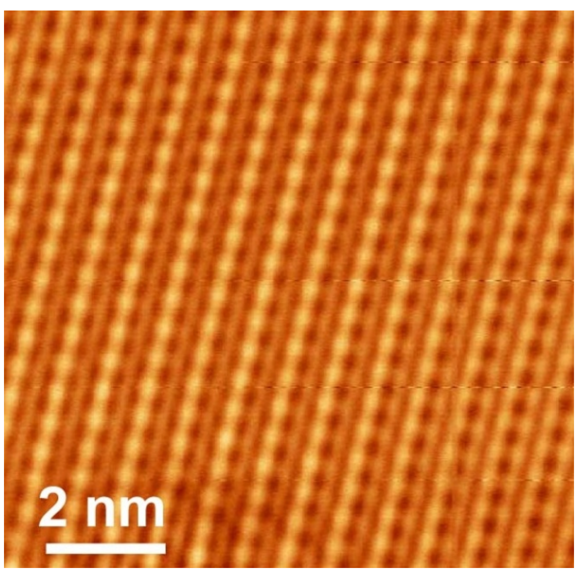
- **FeSe/graphene**
  Song et al., Science 332, 1410 (2011)
  Song et al., Phys. Rev. B 84, 020503 (2011)
  Song et al., Phys. Rev. Lett. 109, 137004 (2012)
  Song et al., Phys. Rev. Lett. 112, 057002 (2014)
- **FeSe/STO**
  Wang et al., Chin. Phys. Lett. 29, 037402 (2012)
  Zhang et al., Chin. Phys. Lett. 31, 017401 (2014)
  Zhang et al., Phys. Rev. B 31, 017401 (2014)

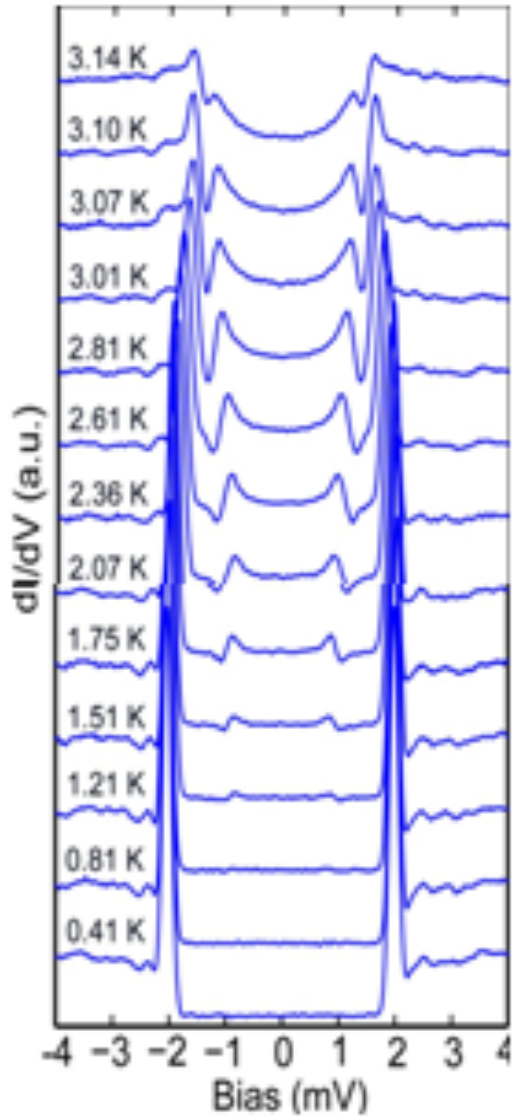
  Li et al., J. Phys.: Condens. Matter 26, 265002 (2014)
- **FeTeSe/STO**
  Li et al., Phys. Rev. B (2015)
- **KFeSe/graphene**
  Li et al., Nat. Phys.8, 126 (2011)
- **KFeSe/STO**
  Tang et al., in preparation

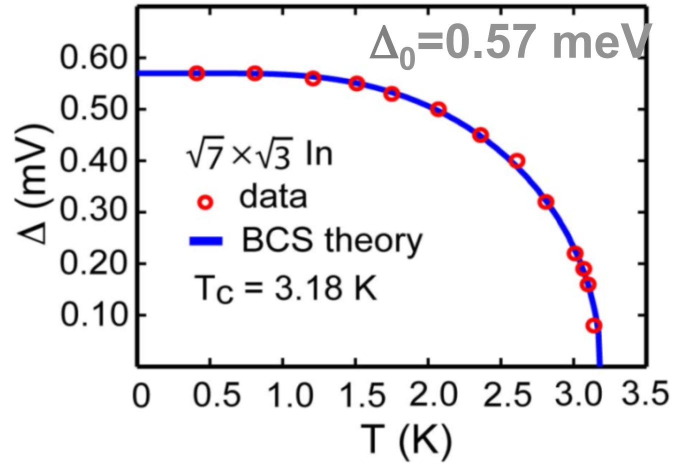
Single atomic-layer In on Si

Zhang et al., Nat. Phys. 6, 104 (2010)









T_c = 3.18 K

$(2\Delta_0/k_BT_c)$ = 4.16

Uchihashi: PRL 2011
Hasegawa: PRL 2013

Single atomic-layer In on Si

Zhang et al., Nat. Phys. 6, 104 (2010)

Bulk Indium

$T_C = 3.4$ K
$2\Delta_0/k_BTc = 3.6$

1ML In on Si

$T_C = 3.18$ K
$2\Delta_0/k_BTc = 4.16$

1ML In/graphene

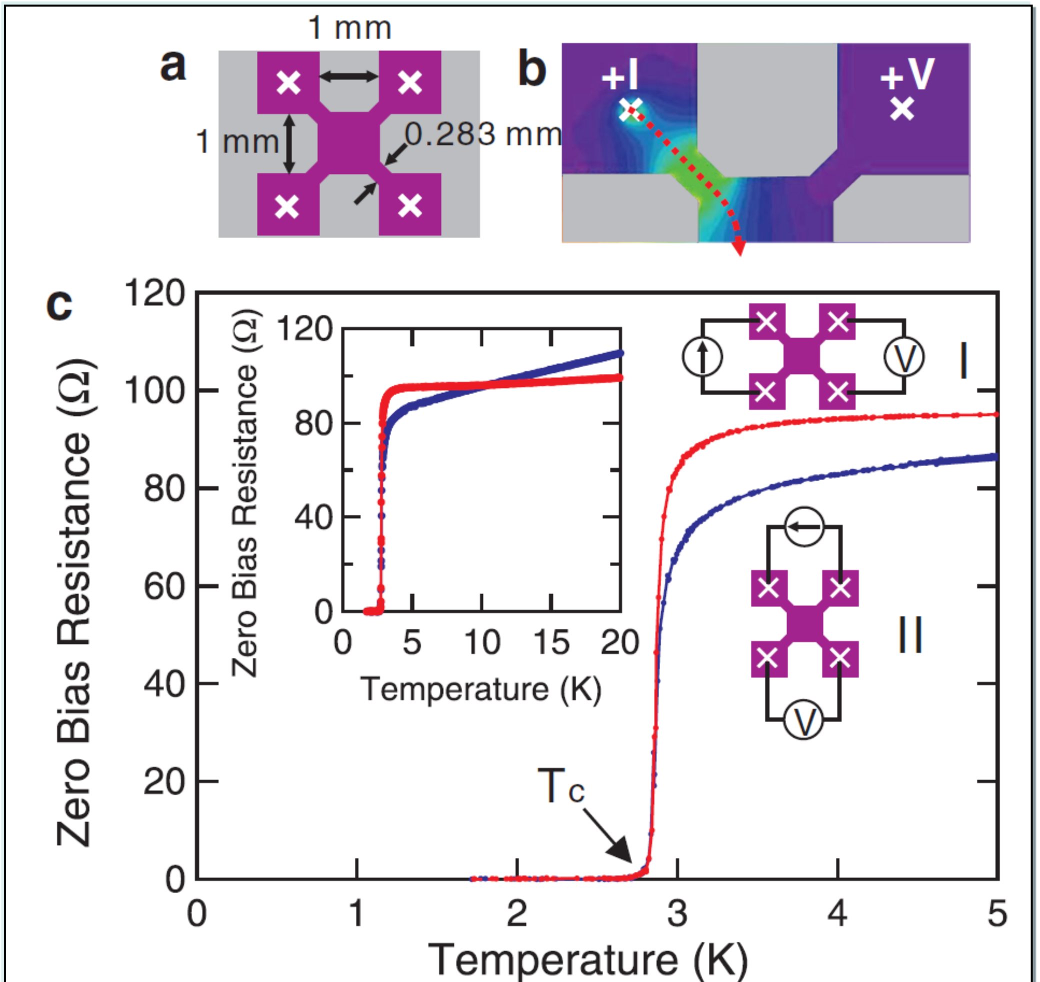
$T_C < 0.3$ K

10 times !

λ~ 1, similar to that of bulk indium.
superconducting near T_c =3.4 K of bulk In
Phys. Rev. Lett. 91, 246404 (2003).

Superconductivity in one-atomic-layer In

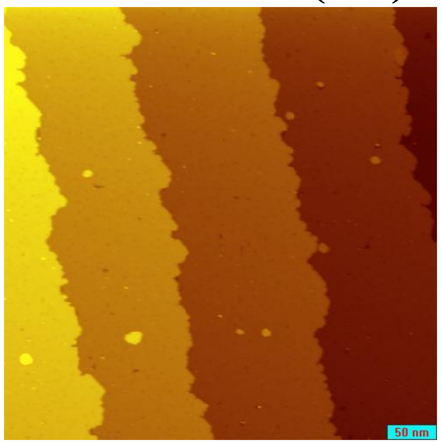
***In-situ* transport**

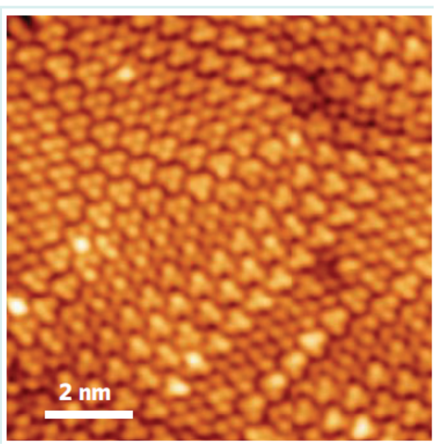


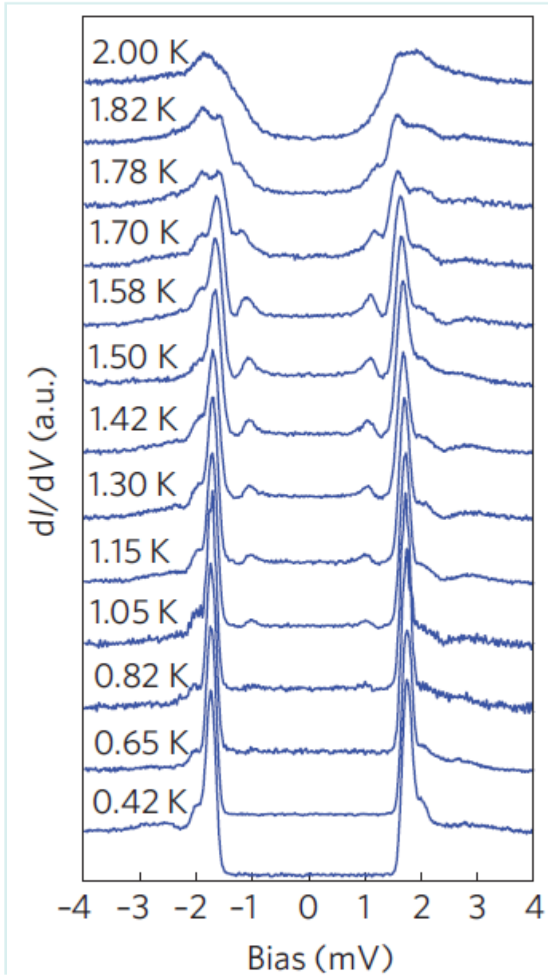
Uchihashi et al., Phys. Rev. Lett. 107, 207001 (2011)

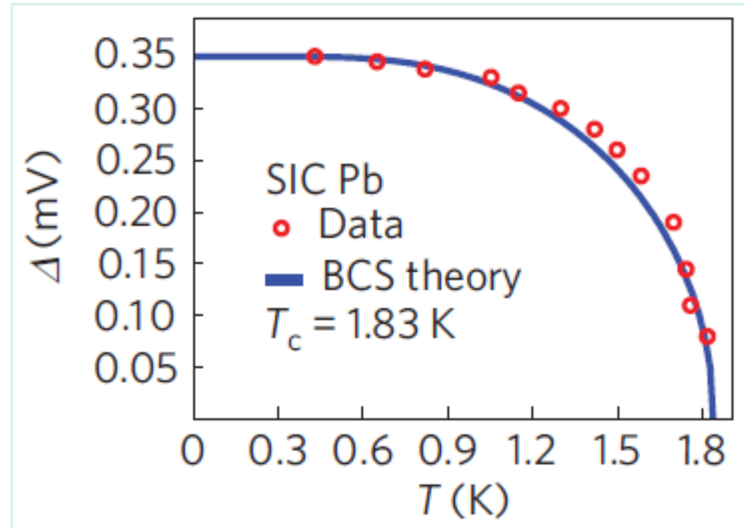
Superconductivity in one-atomic-layer Pb

Pb-SIC on Si(111)









Pb-SIC: T_c = 1.83K

$2\Delta_0/k_BT_c$ = 4.4

λ = 1.07 (ARPES)

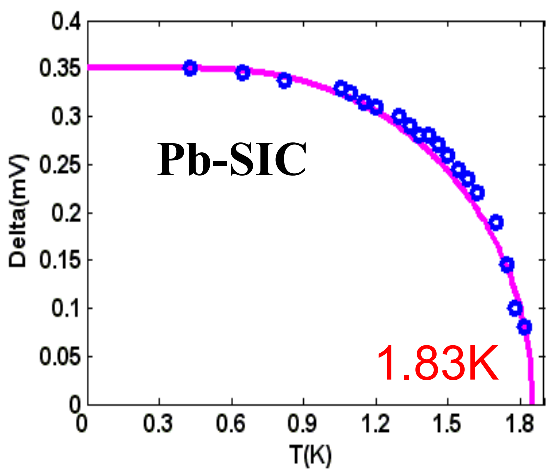
Pb-bulk: λ < 0.9

Pb-$\sqrt{7}\times\sqrt{3}$: T_c = 1.52 K

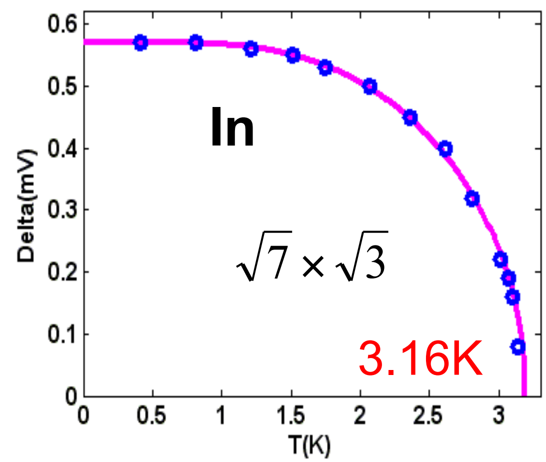
Zhang et al., Nat. Phys. 6, 104 (2010)

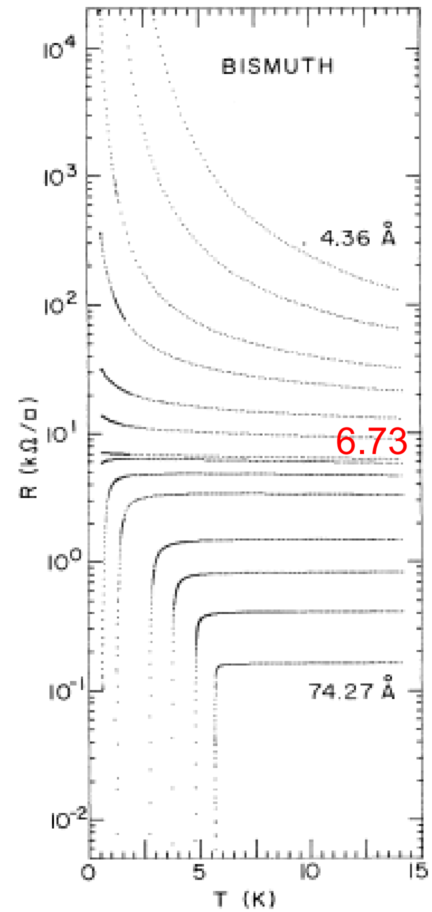
Superconductivity in one-atomic-layer Pb & In

Pb / Si(111) : SIC



In / Si(111) : $\sqrt{7} \times \sqrt{3}$





PRL 62, 2180 (1989)

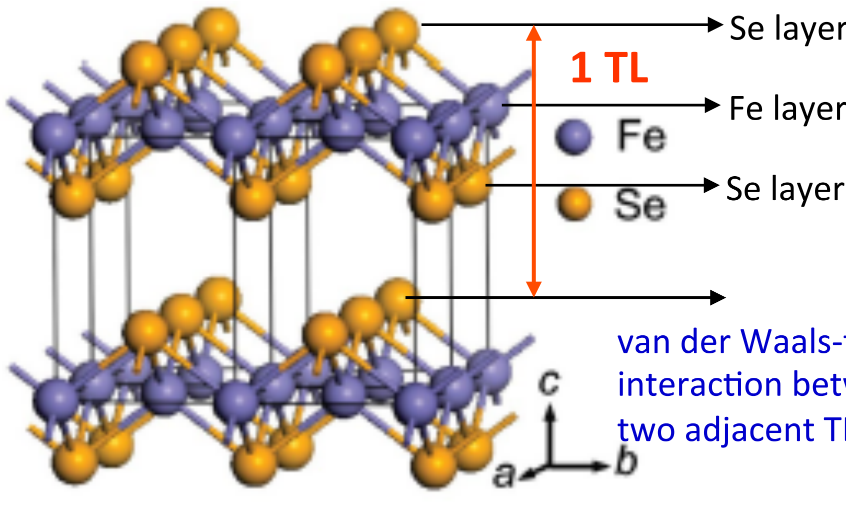
	Pb SIC	Pb bulk	In $\sqrt{7} \times \sqrt{3}$	In bulk	In/graphene
T_c	1.83 K	7.2 K	3.16 K	3.4 K	< 0.3 K
$2\Delta_0 / k_B T_C$	4.4	4.3	4.16	3.6	
λ	1.07	< 0.9	~ 1	1	

The thinnest superconductor

Interface enhanced

FeSe

FeSe$_x$ Fe(Se,Te)



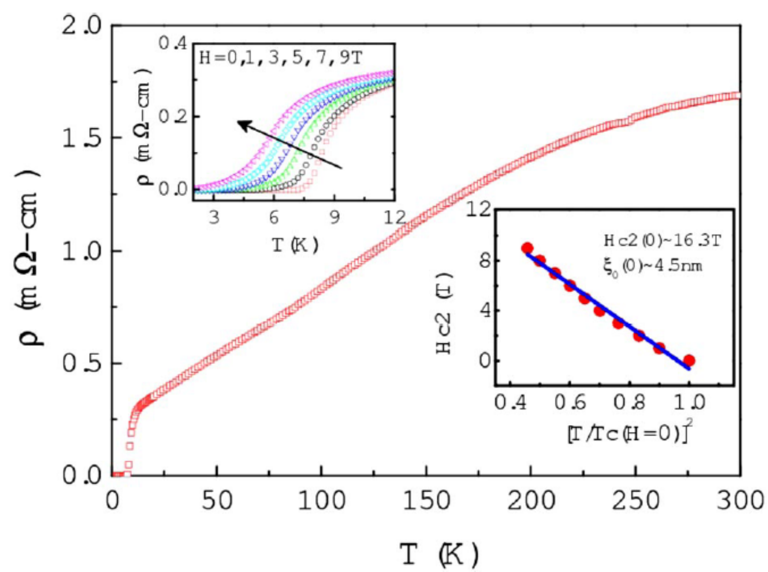
van der Waals-type interaction between two adjacent TLs

a = 0.378 nm
c = 0.55 nm

The simplest crystal structure

A clean superconducting phase

Less toxic and easier to handle



T_c ~ 8.5 K (bulk) : Se-deficient phase

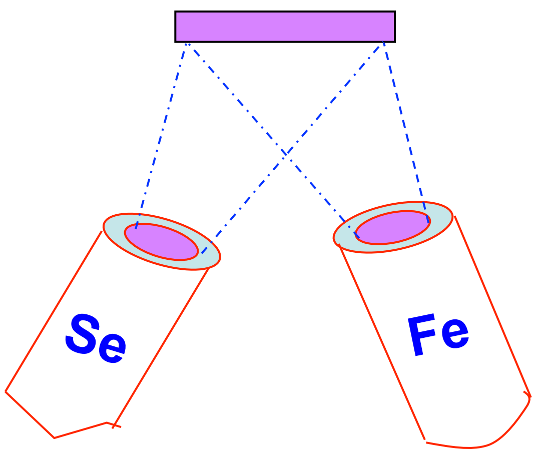
T_c ~ 37 K (8.9 GPa) : β-$Fe_{1.01}Se$

T_c ~ 15 K by Te substitution : $FeSe_{0.5}Te_{0.5}$

Hsu et al., Proc. Natl. Acad. Soc. USA 105, 14262(2008)
Khasanov et al., Phys. Rev. B 78, 220510R(2008)

Molecular beam epitaxial growth

T_s = 450℃



T_{Se} = 138 ℃ T_{Fe} = 1080 ℃

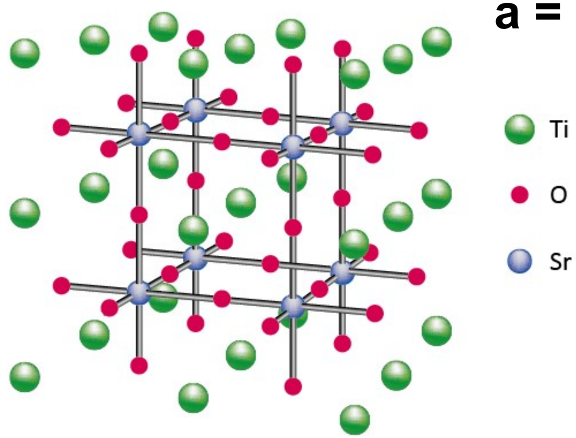
$T_{Fe} > T_{sub} > T_{se}$

Flux (Se/Fe) ~ 10 : 1

0.25 ML/min

$SrTiO_3$(100)-TiO_2 terminated

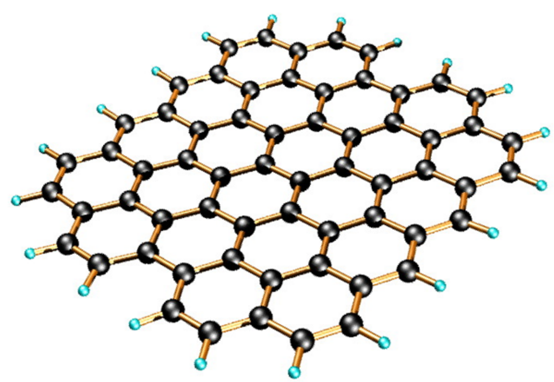
a = 3.905 nm, ε ~ 10^4 (LT)



FeSe:0.378
lattice mismatch: 1%

STM/ARPES: Nb-doped STO - conducting
Transport: Intrinsic STO - insulating

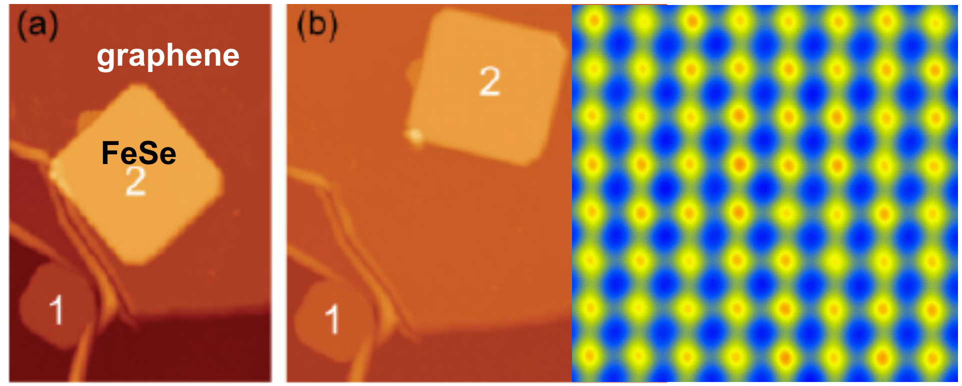
Graphene, van de Waals



Molecular beam epitaxial growth

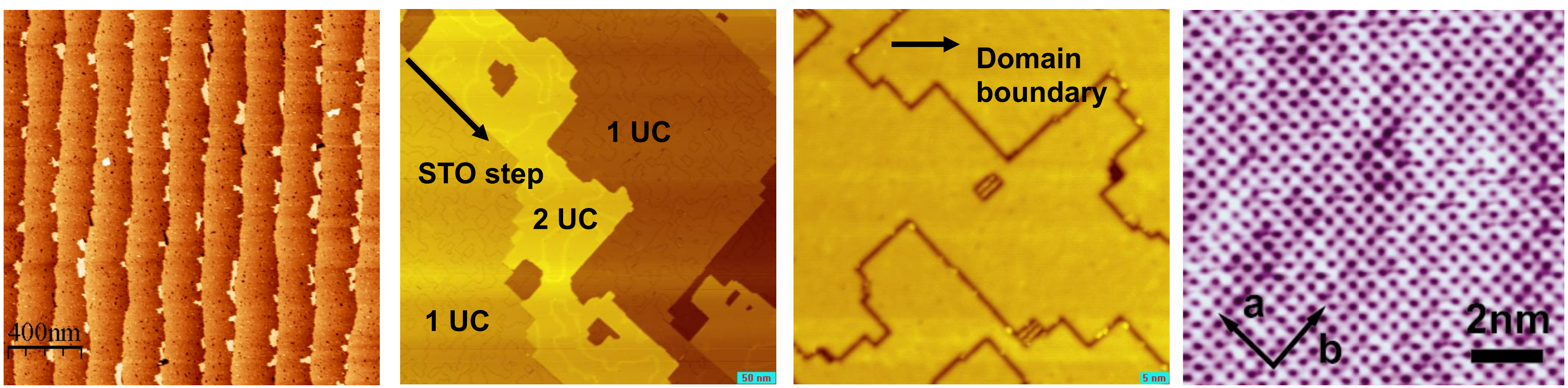
FeSe on graphene: island free standing

a = 0.38 nm



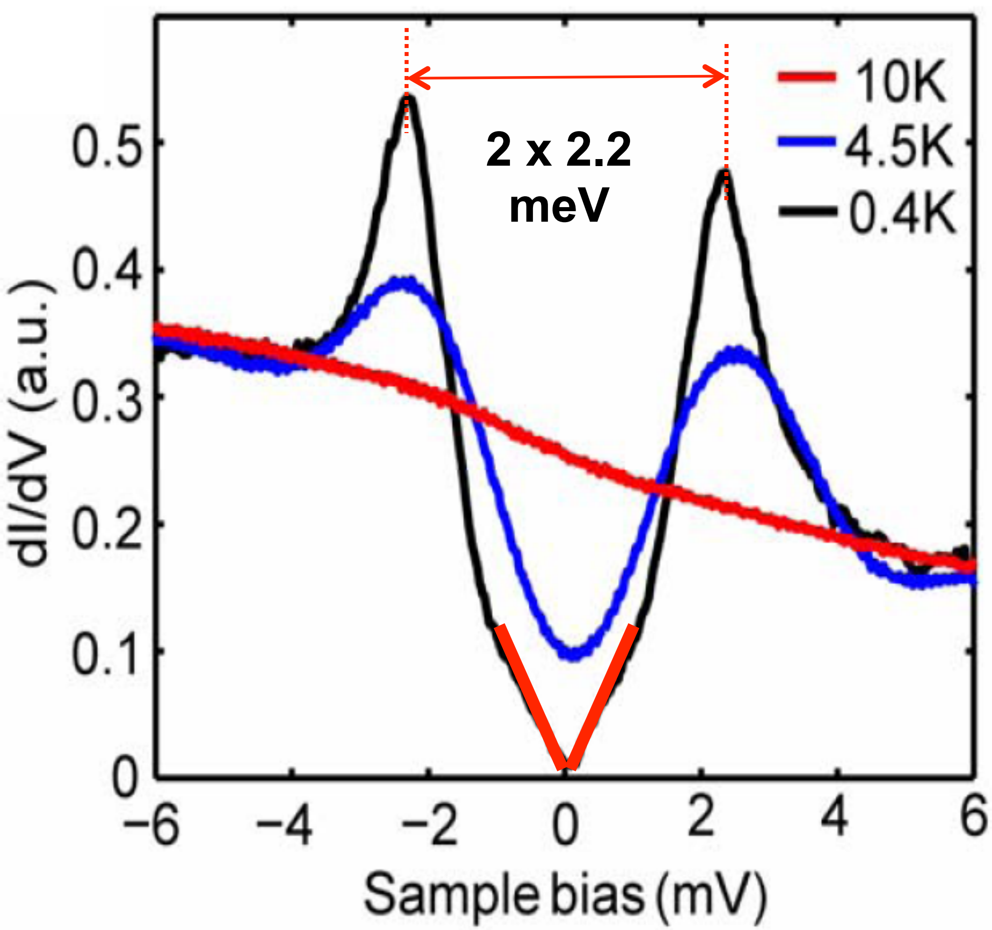
FeSe on STO: film

a = 0.39 nm



Superconductivity of FeSe on graphene

STS @ 0.4 K, 30 UC film



***Δ* = 2.2 meV**

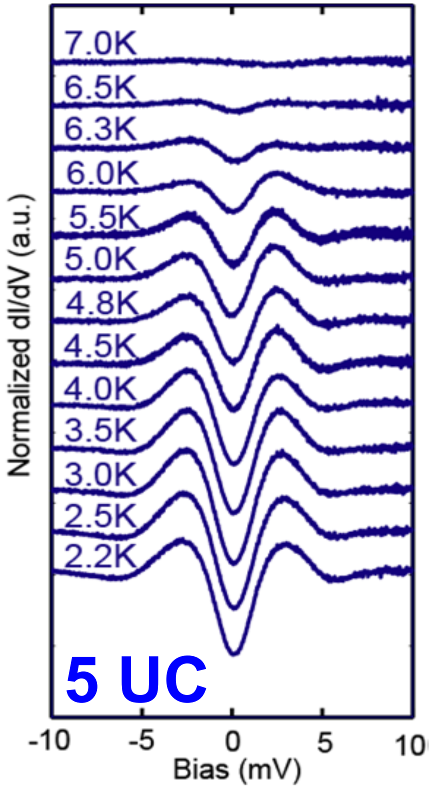
V-shaped dI/dV
linear dependence of the quasiparticle DOS on energy near E_F

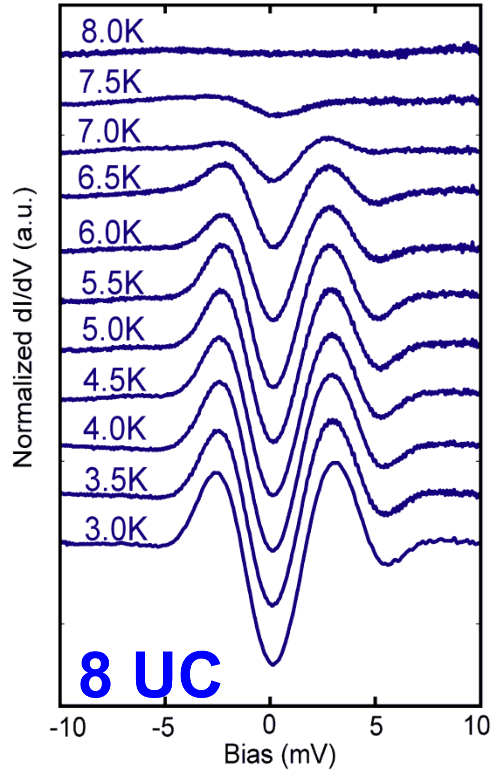
Nodes in the SC-gap function

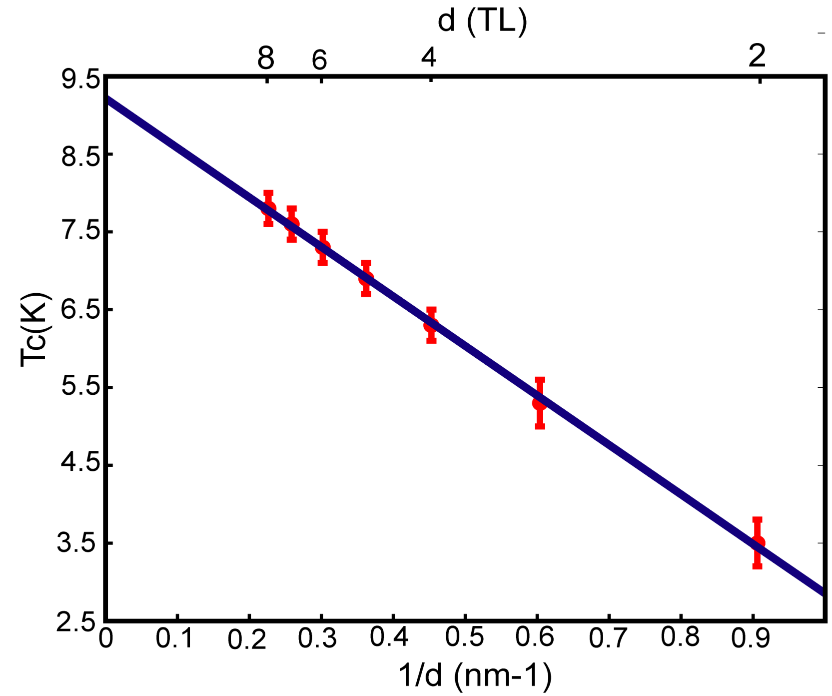
Intrinsic to the stoichiometric FeSe

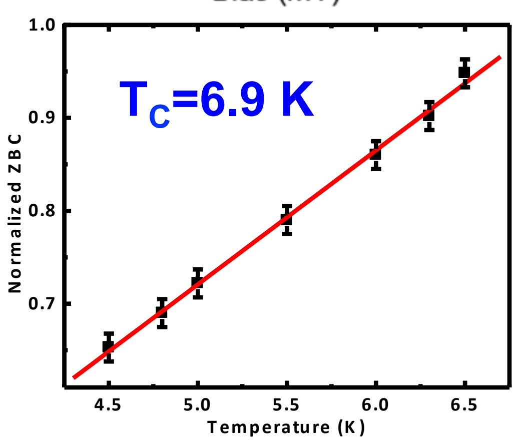
Song et al., Science 332, 1410 (2011)

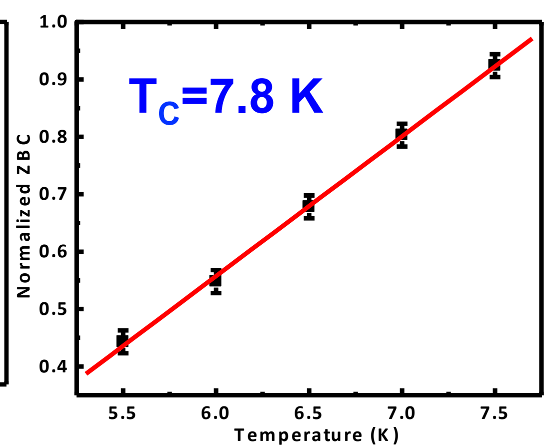
Thickness-dependent superconductivity











$$T_c(d) = T_{c0}(1\text{-}d_c/d)$$

$$d_c = 7\text{Å}\ (1.3\ \text{UC})$$

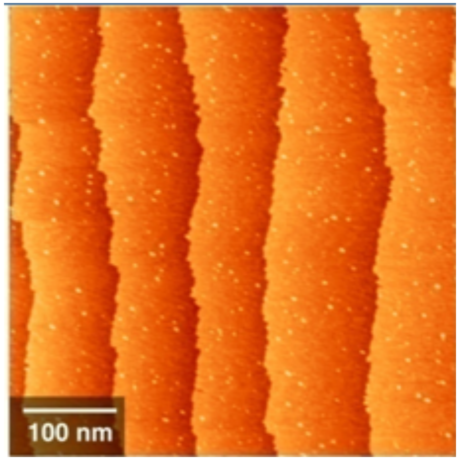
NO SC signature for 1UC FeSe /graphene (@ 400 mK)

d ↑ T_c ↑

Song et al., Phys. Rev. B 84, 020503 (2011)

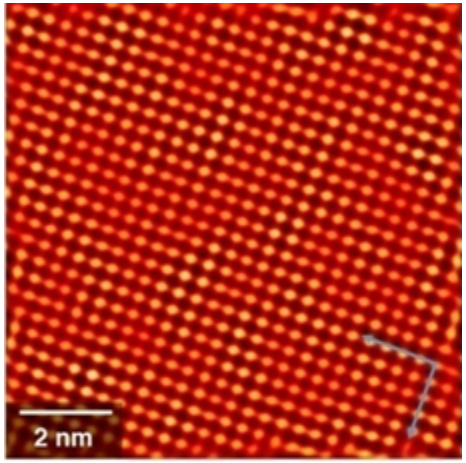
Superconductivity of 1UC FeSe on STO

as grown 1-UC FeSe



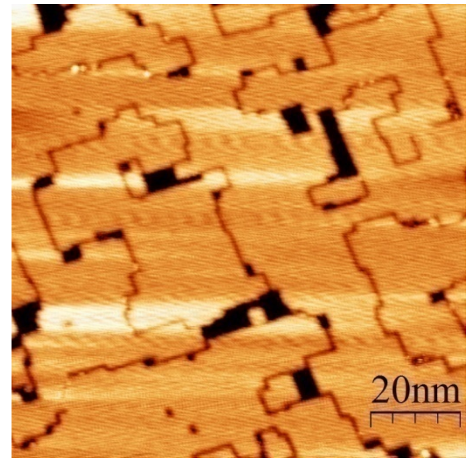
FeSe semiconducting

@450°C for 2 h

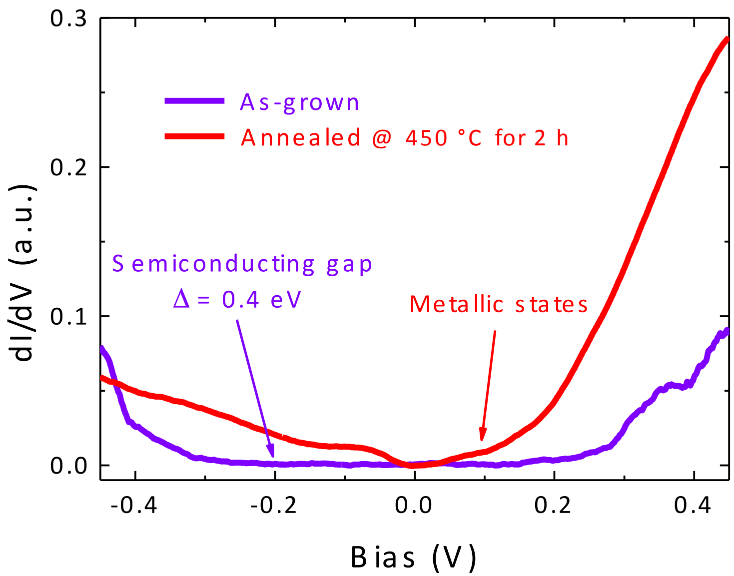


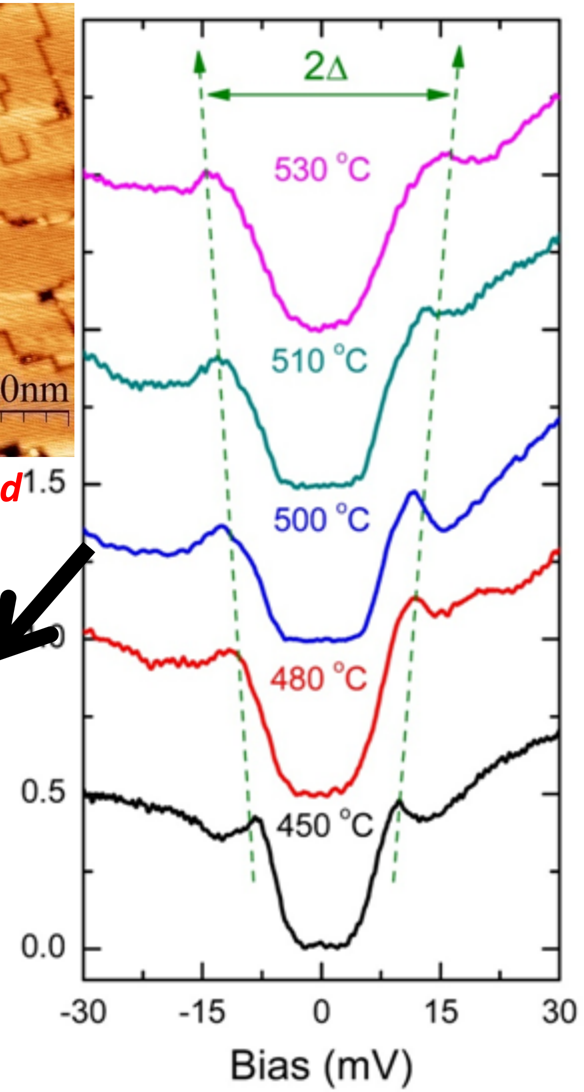
FeSe superconducting

@510°C for 2 h



FeSe decomposed





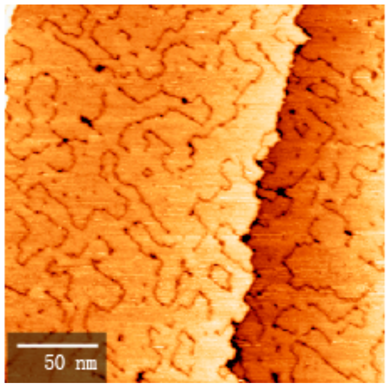
Electron doping

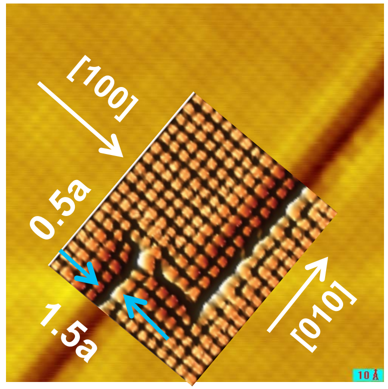
SC film: annealed@ 450-500 °C for ≥ 20 h

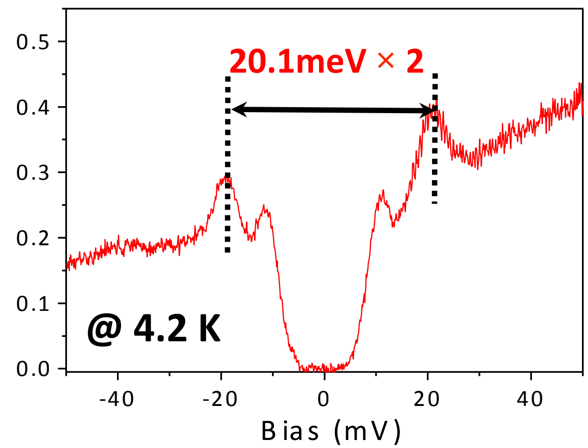
Zhang et al., Phys. Rev. B 89, 060506 (2014)

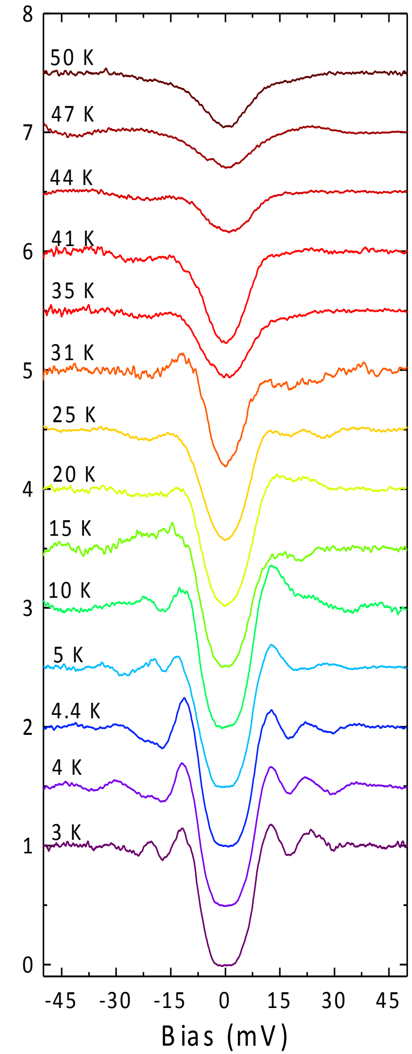
1UC FeSe: STM/STS results

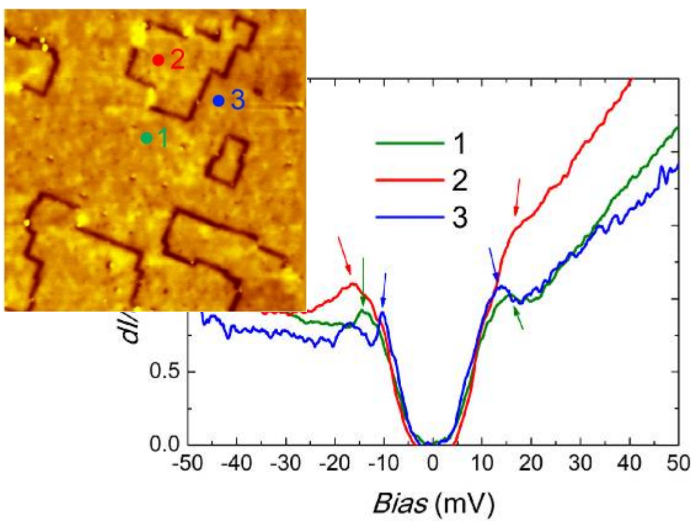
annealing @ 450°C for 20 h

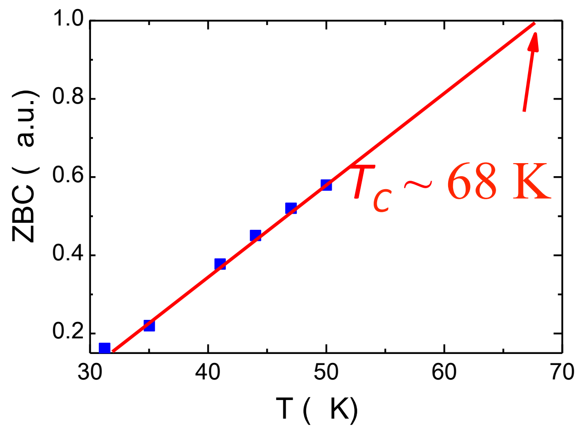










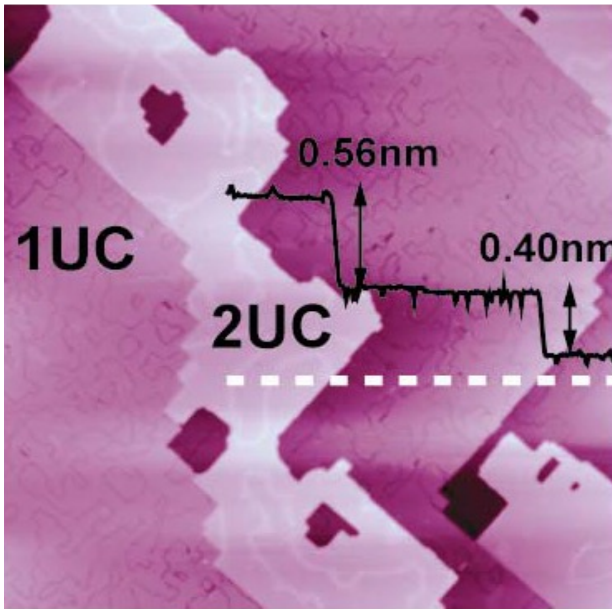


Gap: 15-20 meV

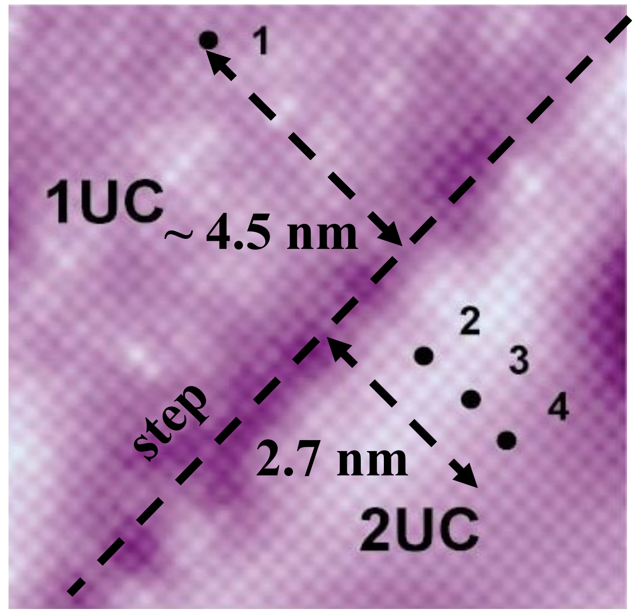
Wang et al., Chin. Phys. Lett. 29, 037402(2012)

Zhang et al., Phys. Rev. B 89, 060506 (2014)

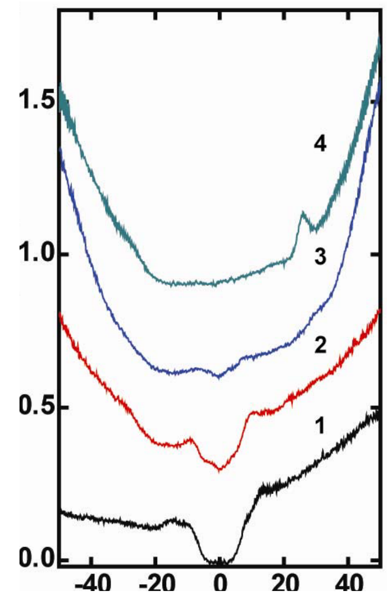
≥ 2 UC FeSe films: non-superconducting



500 nm × 500 nm



13.2 nm × 13.2 nm



Coherence length: 2.7 nm

Why?
insufficient carrier density

Wang et al., Chin. Phys. Lett. 29, 037402 (2012)
Li et al., J. Phys.: Condens. Matter 26, 265002 (2014)

Summary of STM/STS results

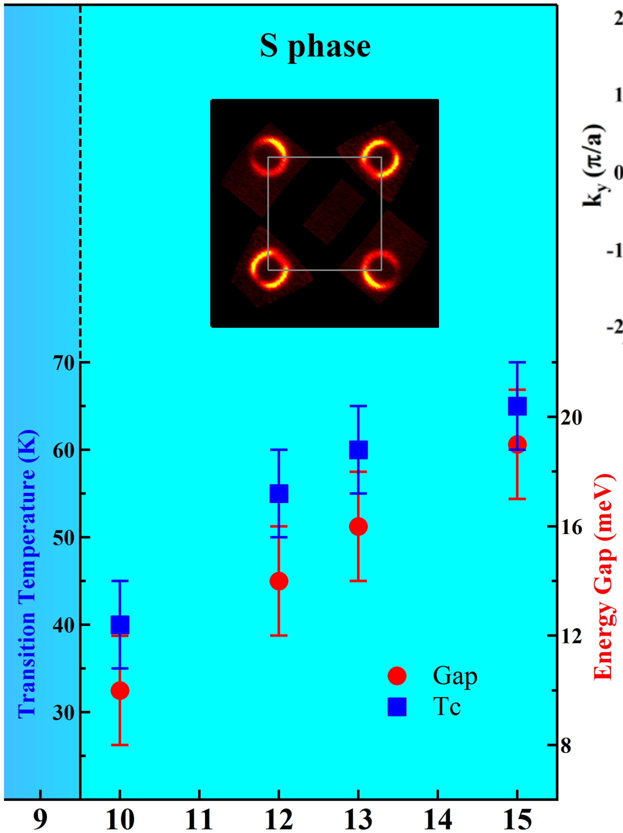
1UC FeSe/STO	Bulk	1UC FeSe/graphene
U gap	V gap	
15-20 meV	2.2 meV	
T_c ~ 80 K	T_c= 9.3 K	T_c < 2 K

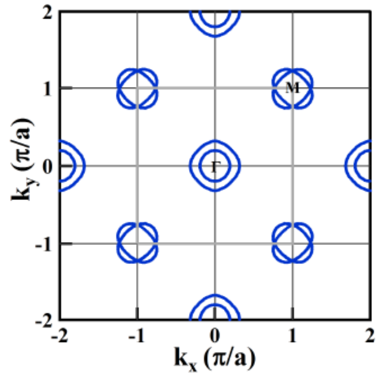
40 times !

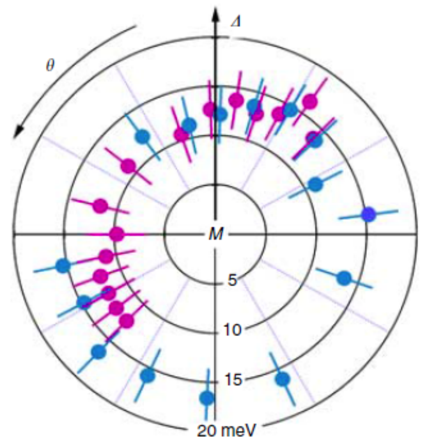
Interface effect !

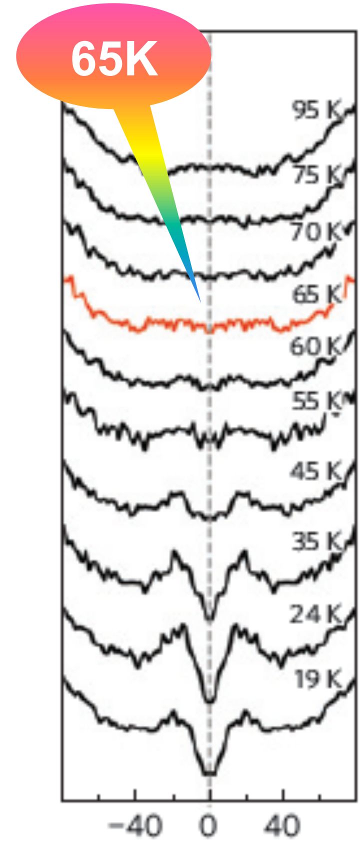
Song et al., Phys. Rev. B 84, 020503 (2011)
Wang et al., Chin. Phys. Lett. 29, 037402 (2012)

1 UC FeSe: Electronic structure (ARPES)









Electron like Fermi surface at M → heavy electron doping

No Fermi pocket at Γ → Fermi pocket at Γ is unnecessary for high Tc

isotropic gap + circular shape of Fermi surface

Electron doping

Liu et al., Nat. Commun. 3, 931 (2012)

He et al., Nat. Mater. 12, 605 (2013)

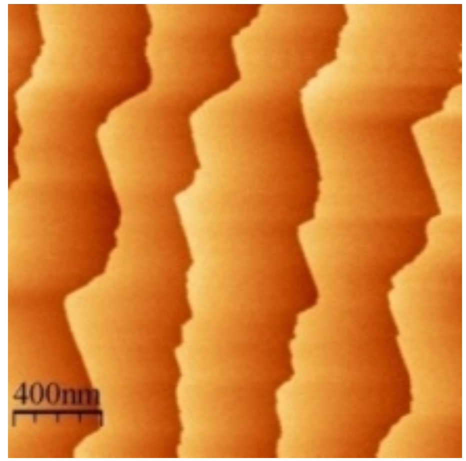
Comparison of ARPES and STS results

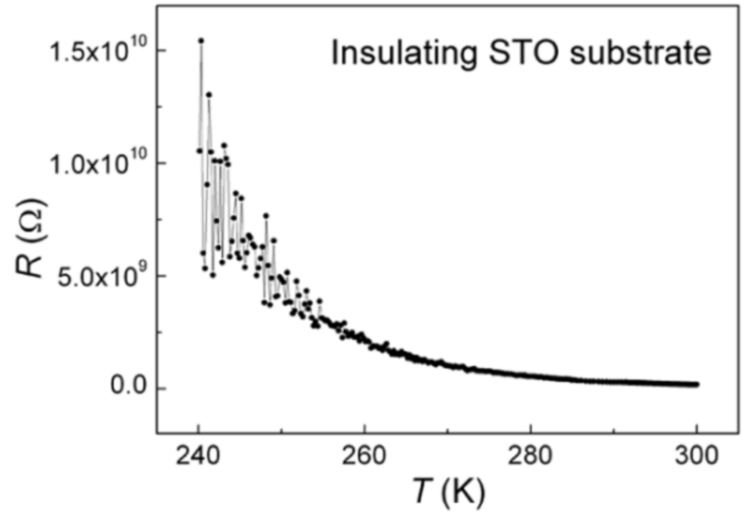
ARPES		STS
• Isotropic gap	⟷	"U"
• 15-19 meV	⟷	15-20 meV
• 65± 5 K	⟷	68 K

Signature of new record T_c in Fe-based superconductors!

1-UC FeSe for *ex-situ* transport

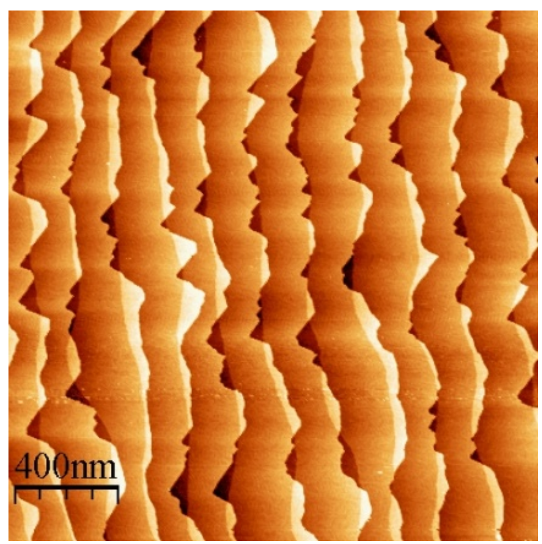
Insulating STO:
HCl/BHF etching
980°C for 10 h under O_2
600°C for 3 h in UHV



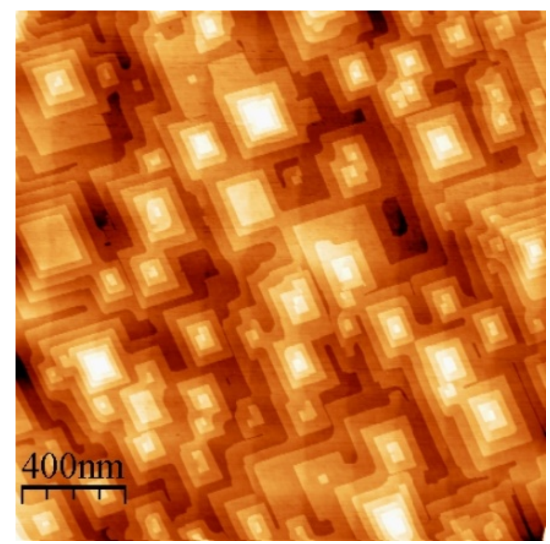


FeTe : protection layer

+ 2-uc FeTe

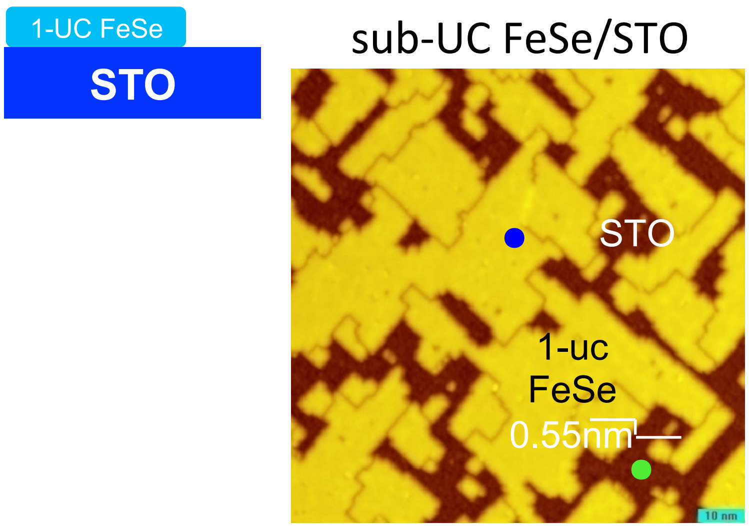


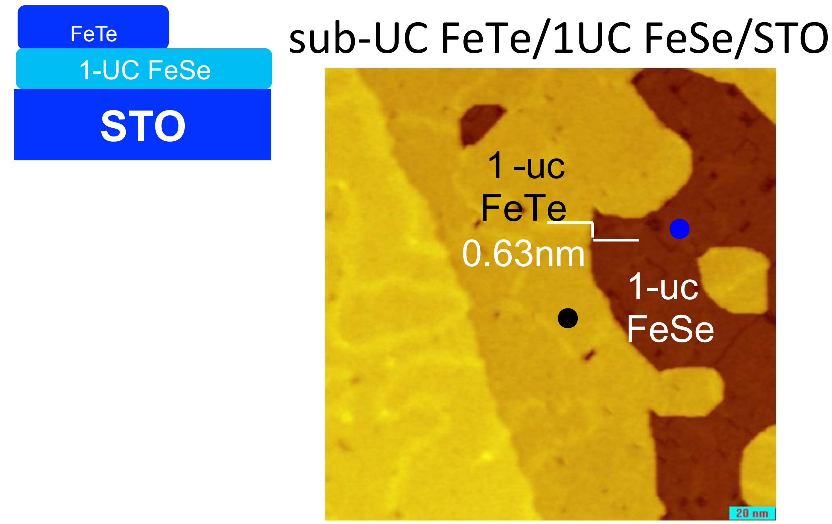
+ 10-uc FeTe

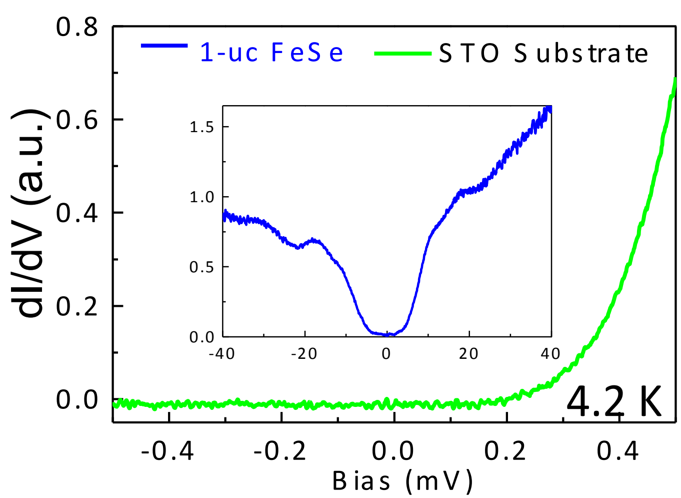


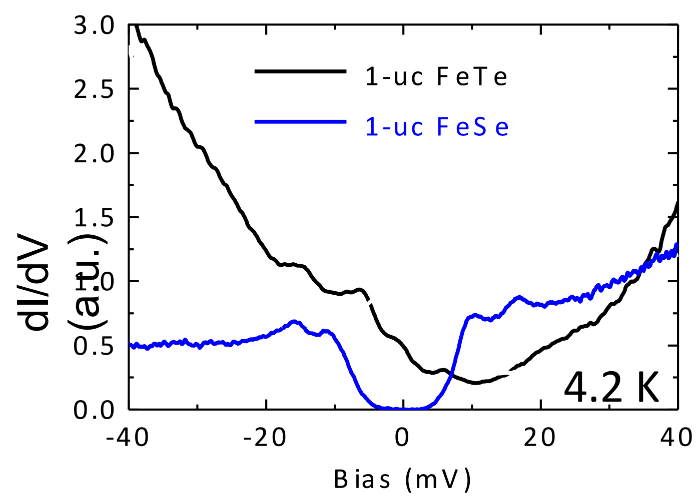
Zhang et al., Chin. Phys. Lett. 31, 017401 (2014)

1-UC FeSe for *ex-situ* transport





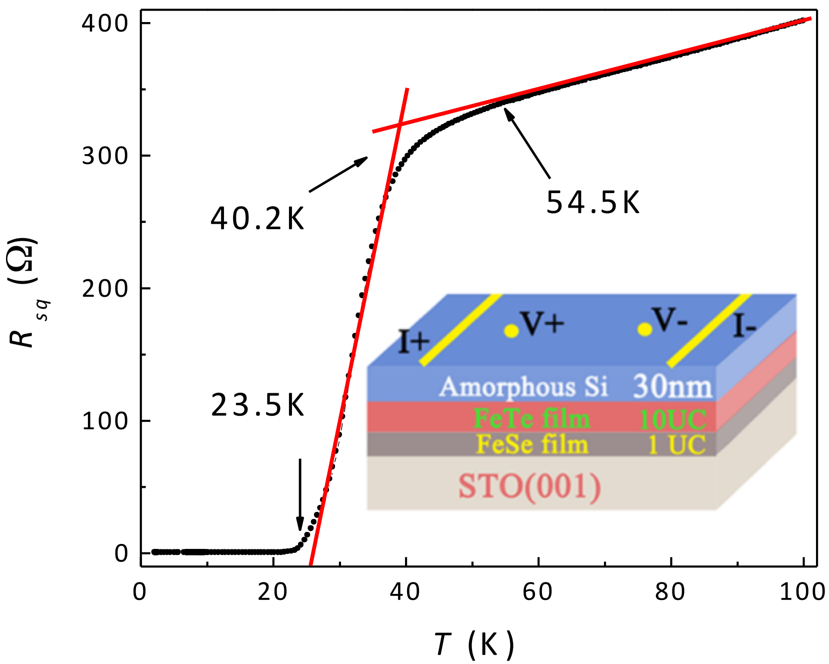


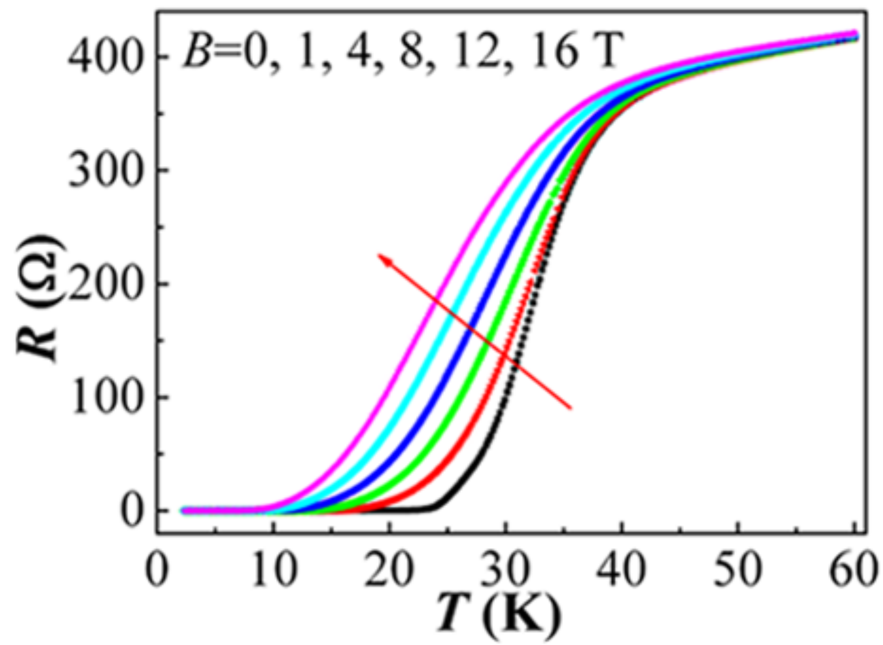


Zhang et al., Chin. Phys. Lett. 31, 017401 (2014)

1-UC FeSe: *ex-situ* transport results

Zero resistance





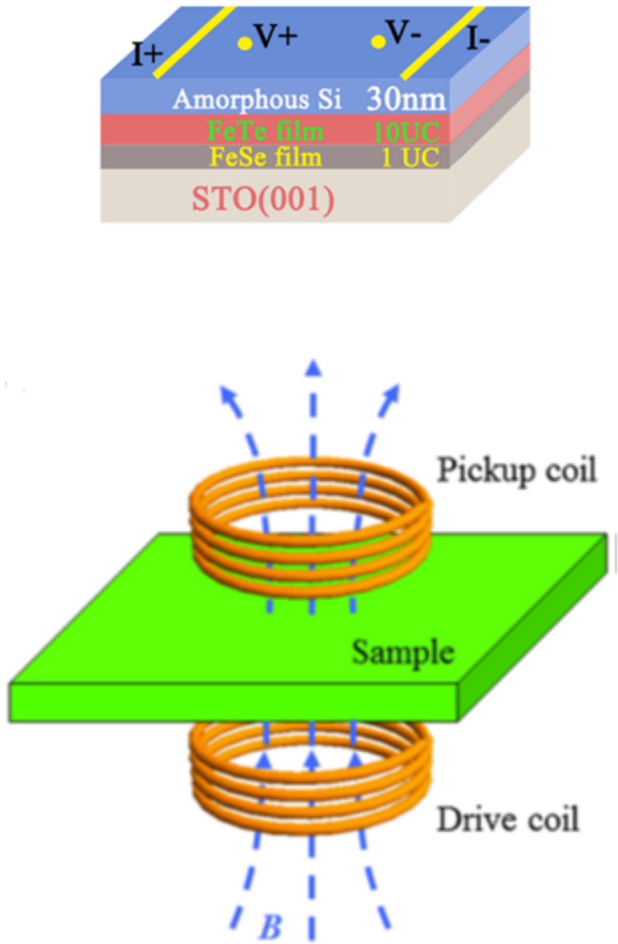
Bulk FeSe: ~8.5 K

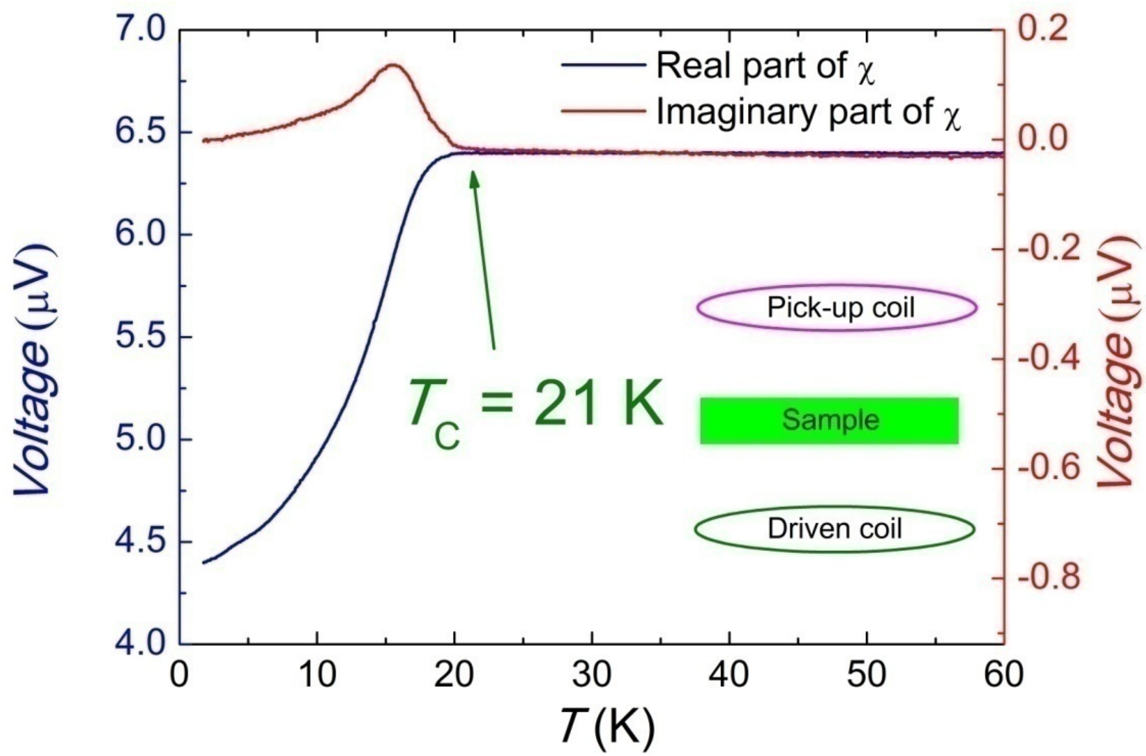
FeSe (Pressure): ~36.7 K

Zhang et al., Chin. Phys. Lett. 31, 017401 (2014)

1-UC FeSe: *ex-situ* transport results

Meissner effect



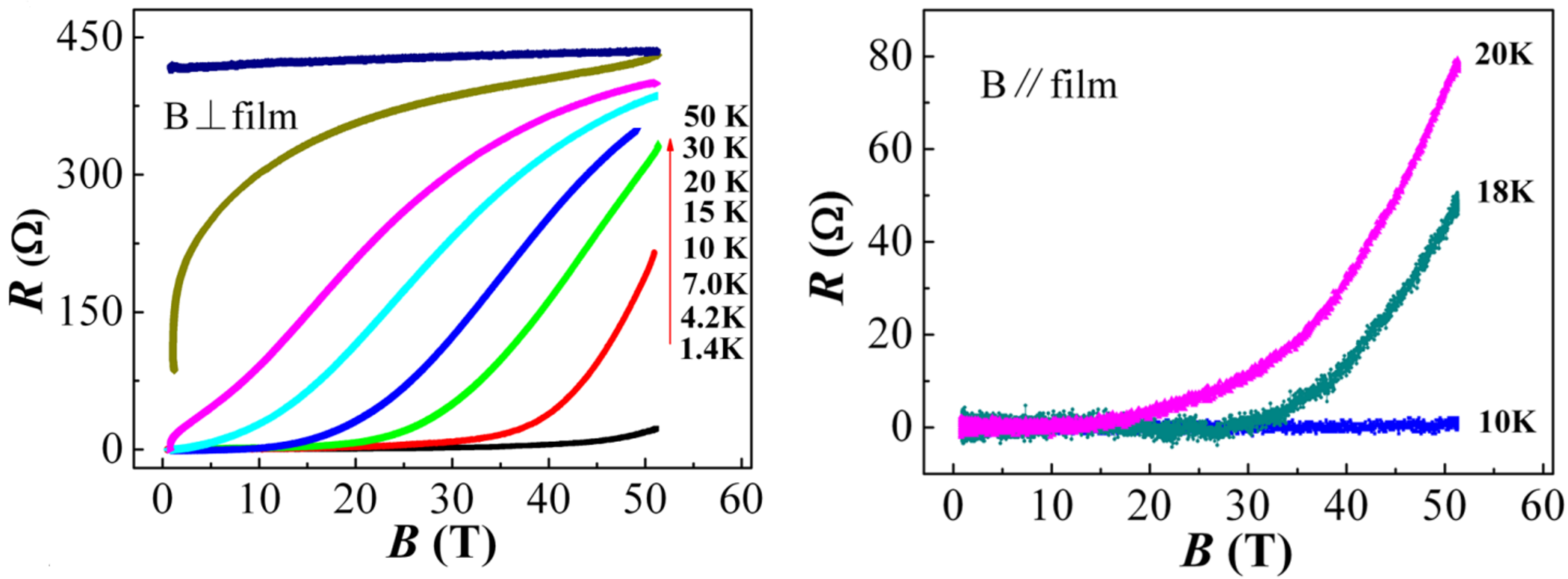


The thinnest superconductor with the highest T_c

Zhang et al., Chin. Phys. Lett. 31, 017401 (2014)

Superconductivity of 1-UC FeSe on STO

Magneto measurement up to 52 T

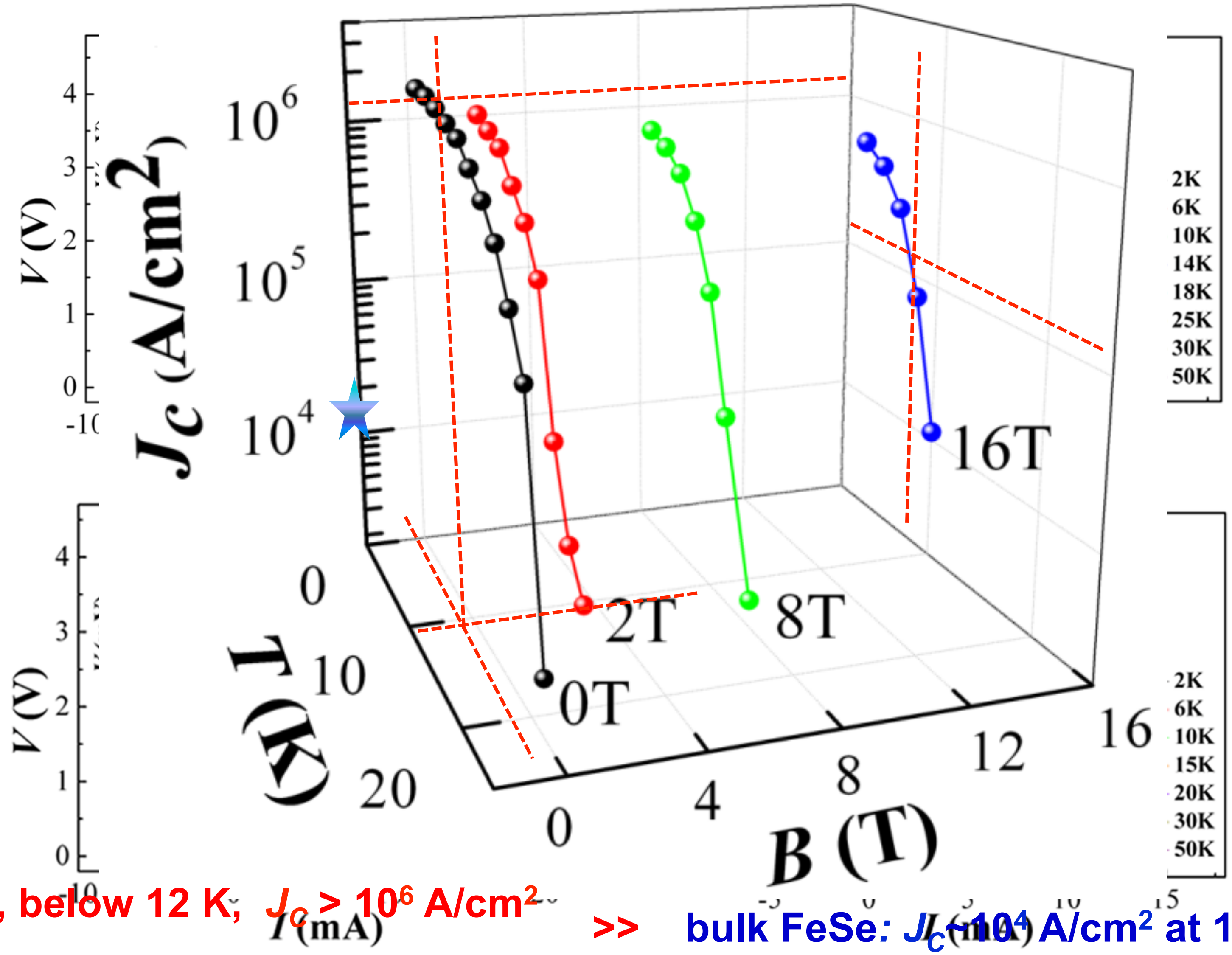


$H_{C2//}(0) >> H_{C2\perp}(0) > 52$ T

anisotropic → 2D

Superconductivity of 1-UC FeSe on STO

d = 0.55 nm



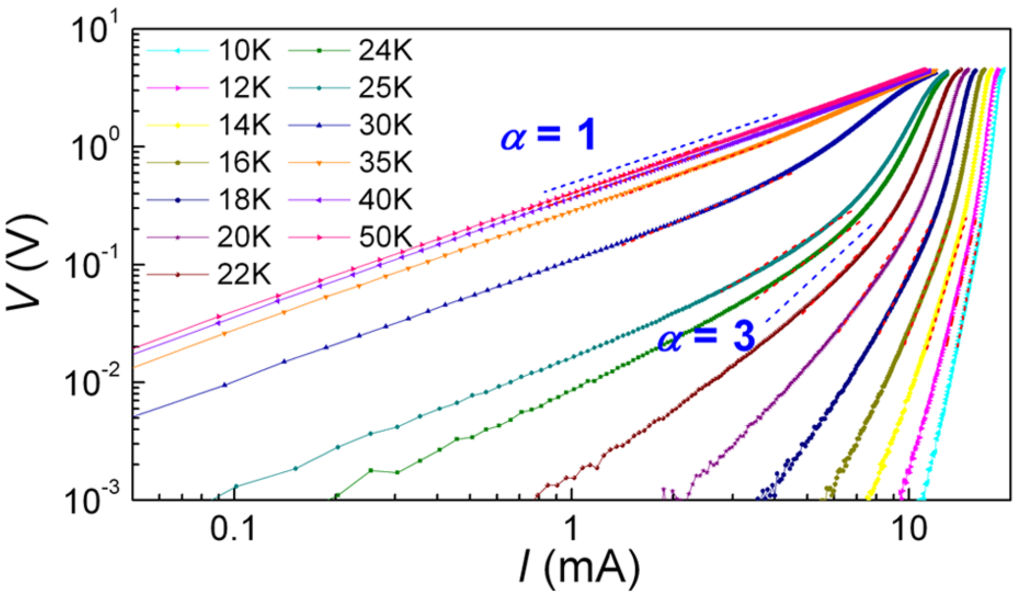
0 T, below 12 K; $J_c > 10^6$ A/cm^2

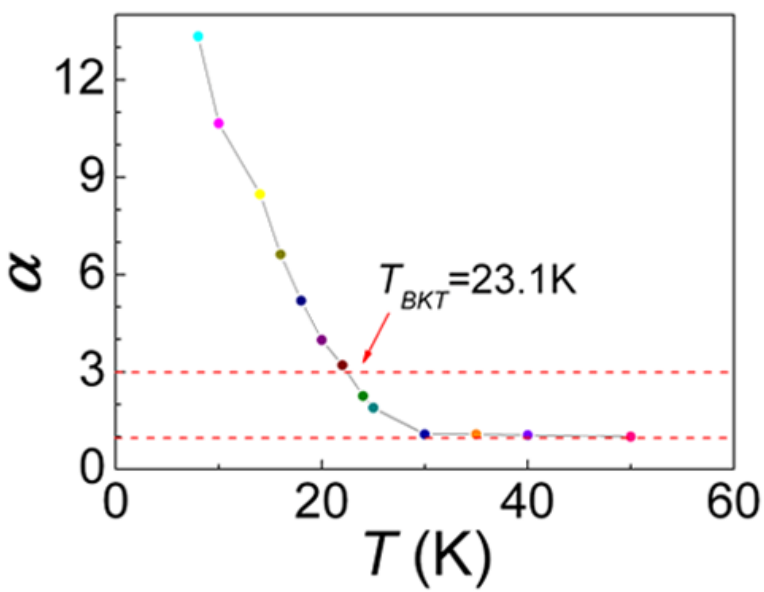
16 T, below 8 K, $J_c > 10^5$ A/cm^2

>> bulk FeSe: $J_c \sim 10^4$ A/cm^2 at 1.8 K

$T_{C,\ transport} < T_{C,ARPES}$ ($T_{C,\ STS}$) ?

$V \sim I^{\alpha}$



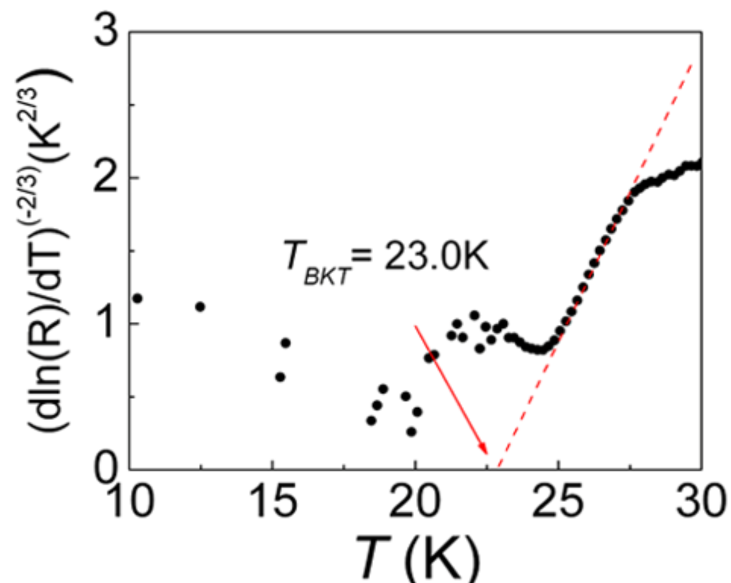


BKT transition

T_{gap}	>	T_c
Cooper pair		coherent

Halprin-Nelson formula

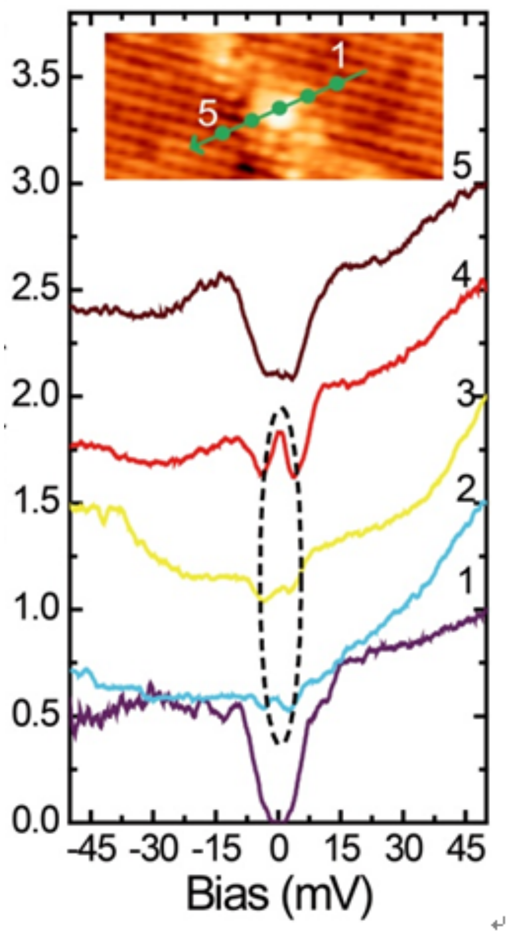
$$R(T) = R_0 exp[-b(T/T_{BKT}-1)^{-1/2}$$

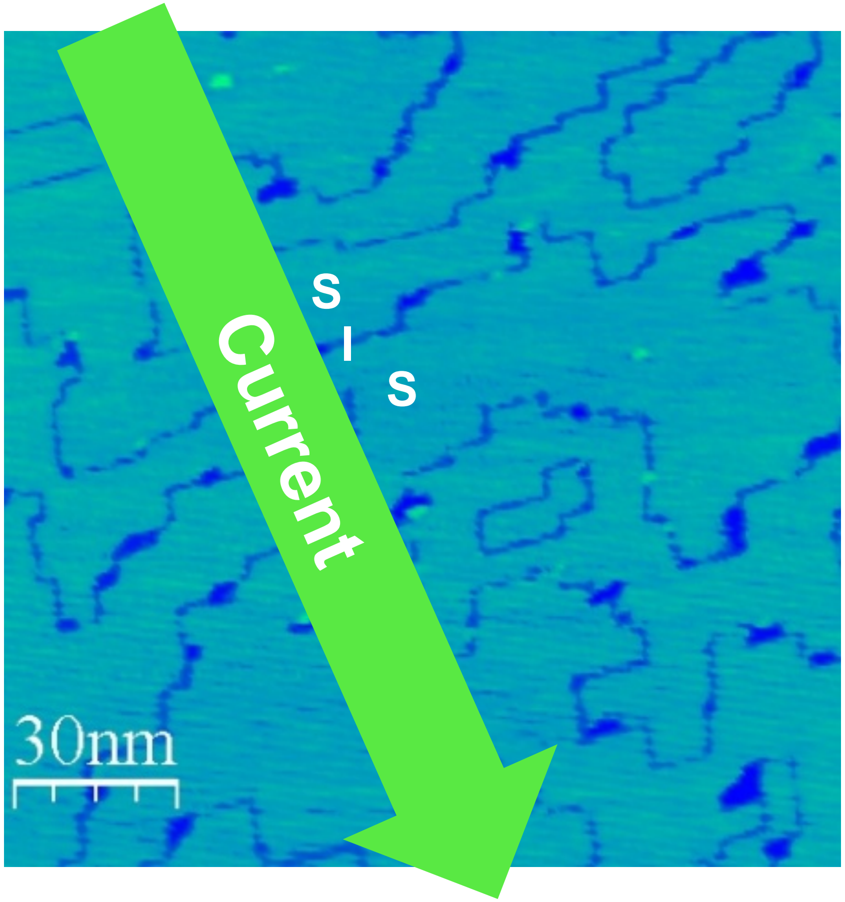


$T_{BKT} \approx T_{zero}$

$T_{C,\ transport} < T_{C,ARPES}$ ($T_{C,\ STS}$) ?

Josephson junctions and electrons scattering (domain walls and defects)

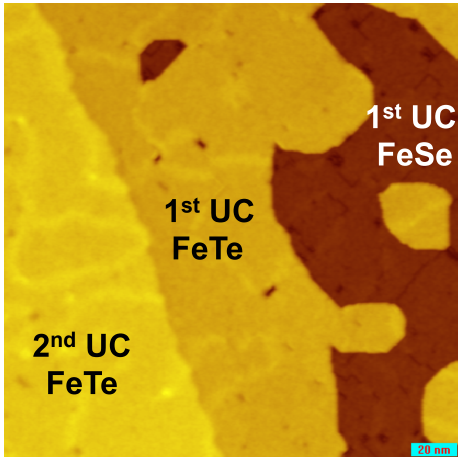


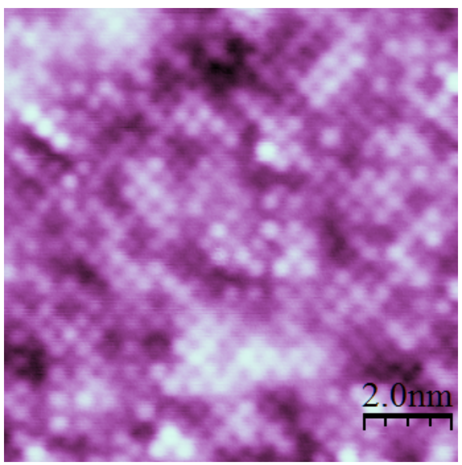


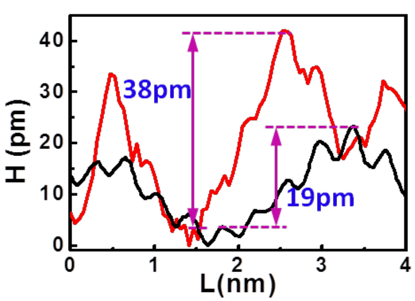
Zhang et al., Chin. Phys. Lett. 31, 017401 (2014)
Zhang et al., Phys. Rev. B 89, 060506 (2014)

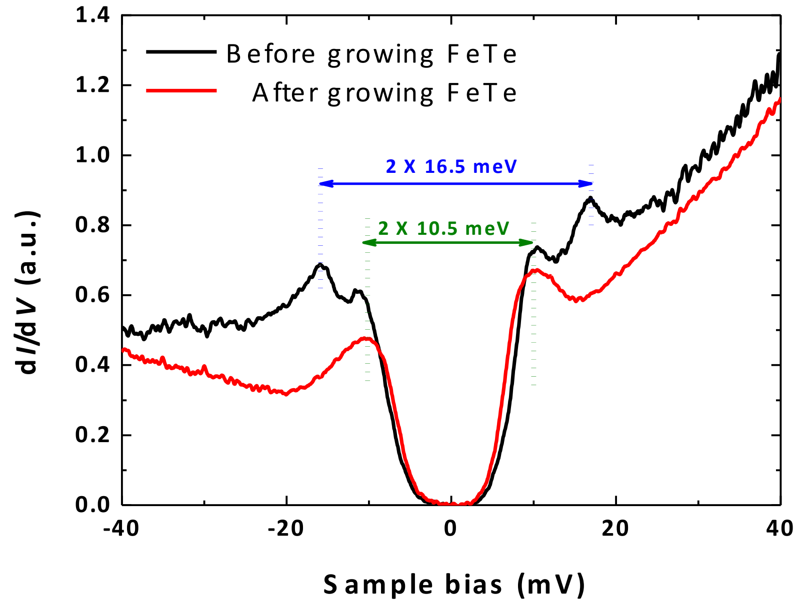
$T_{C, transport} < T_{C,ARPES}$ ($T_{C, STS}$) ?

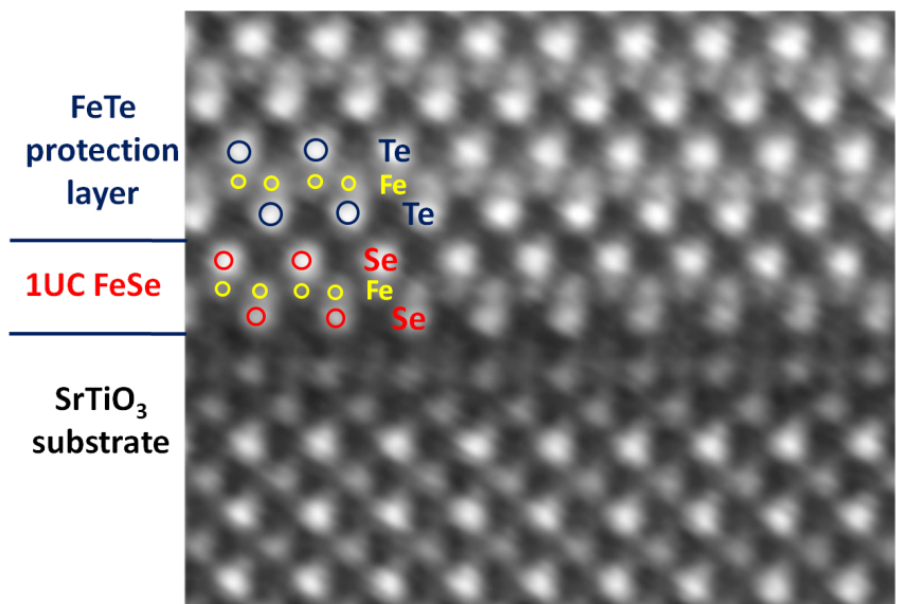
Interface Mixing: Se/Te











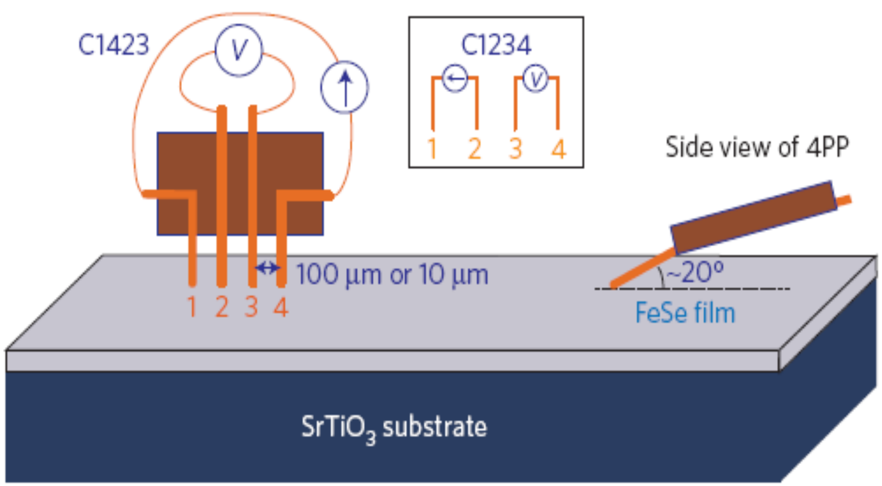
Lin Gu
(IOP)

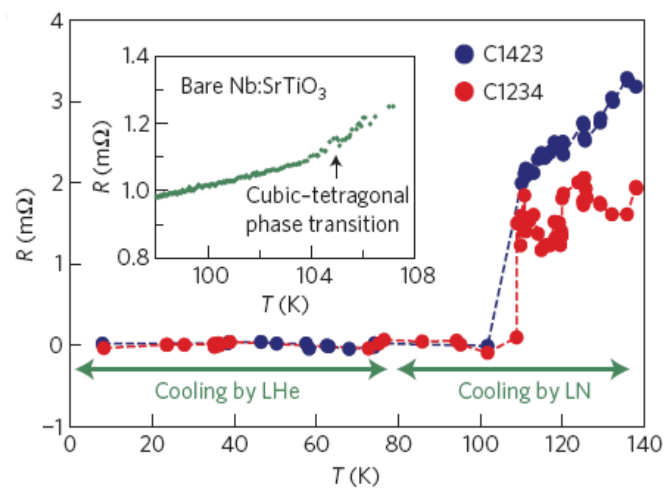
In-situ transport

nature materials
LETTERS
PUBLISHED ONLINE: 24 NOVEMBER 2014 | DOI: 10.1038/NMAT4153

Superconductivity above 100 K in single-layer FeSe films on doped $SrTiO_3$

Jian-Feng Ge[1], Zhi-Long Liu[1], Canhua Liu[1,2]*, Chun-Lei Gao[1,2], Dong Qian[1,2], Qi-Kun Xue[3]*, Ying Liu[1,2,4] and Jin-Feng Jia[1,2]*





Sci. Bull.
DOI 10.1007/s11434-015-0842-8

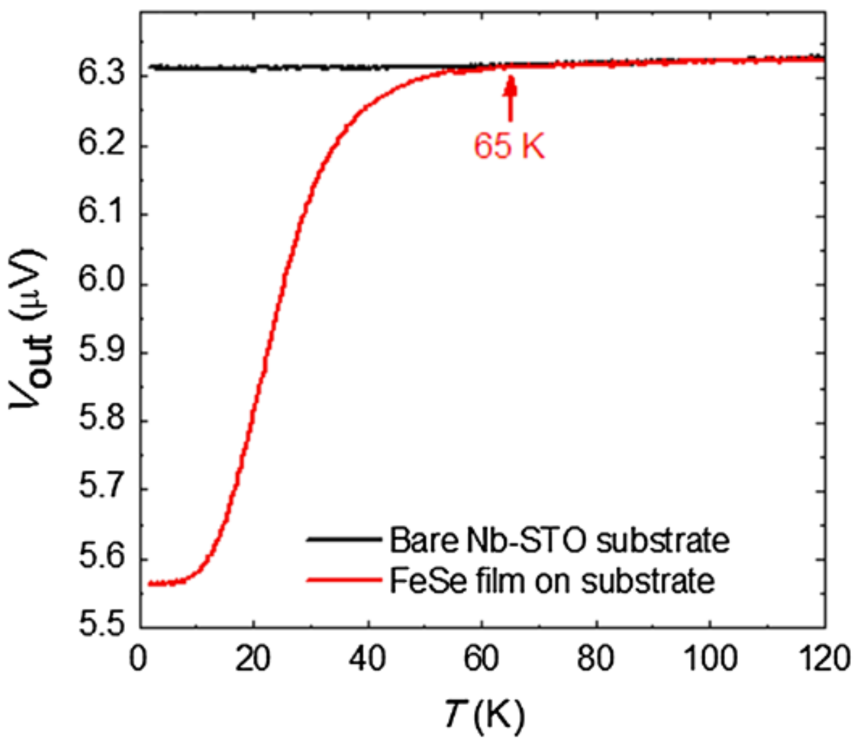
www.scibull.com
www.springer.com/scp

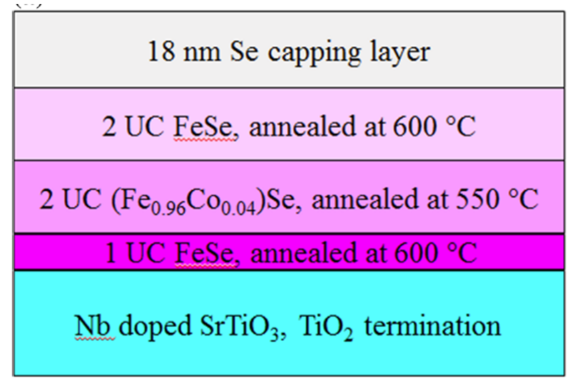
Letter

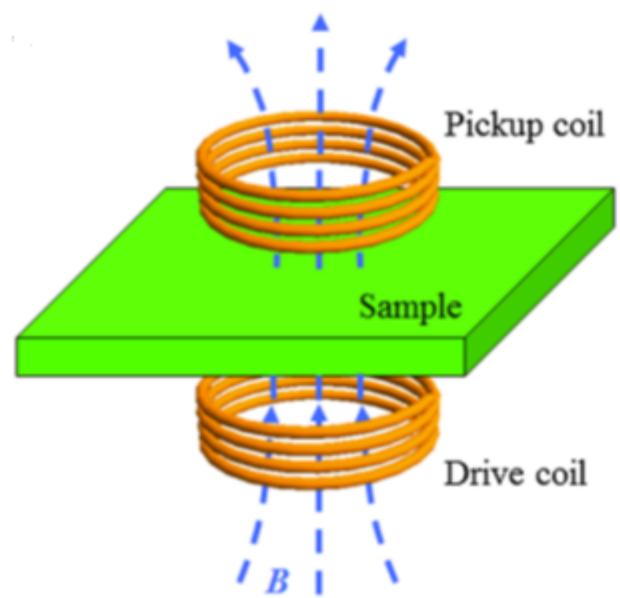
Physics & Astronomy

Onset of the Meissner effect at 65 K in FeSe thin film grown on Nb-doped $SrTiO_3$ substrate

Zuocheng Zhang · Yi-Hua Wang · Qi Song ·
Chang Liu · Rui Peng · K. A. Moler ·
Donglai Feng · Yayu Wang

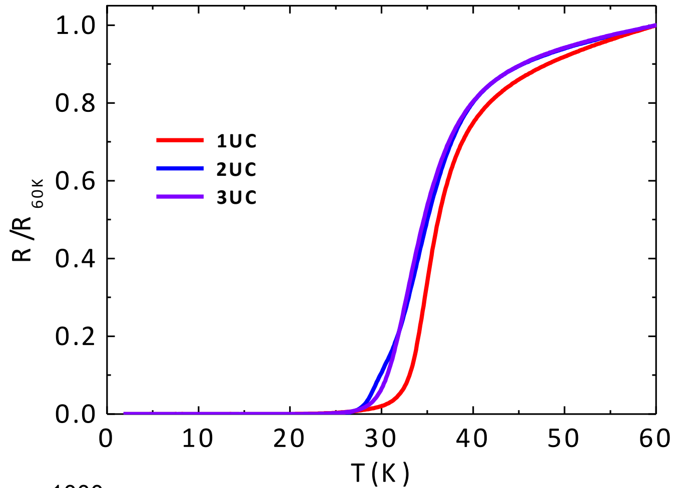


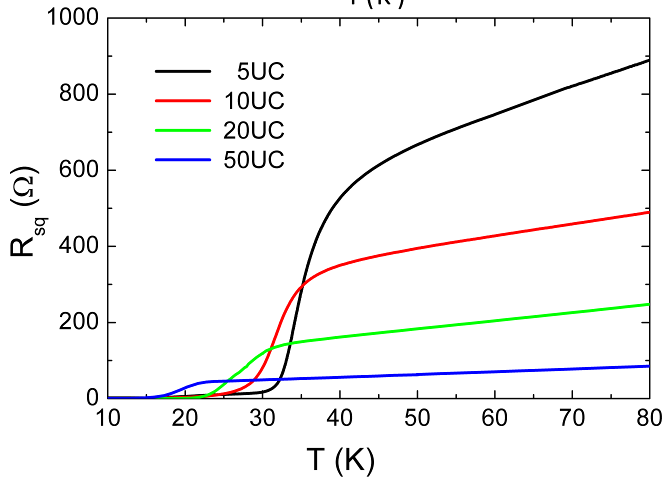




T_c-d

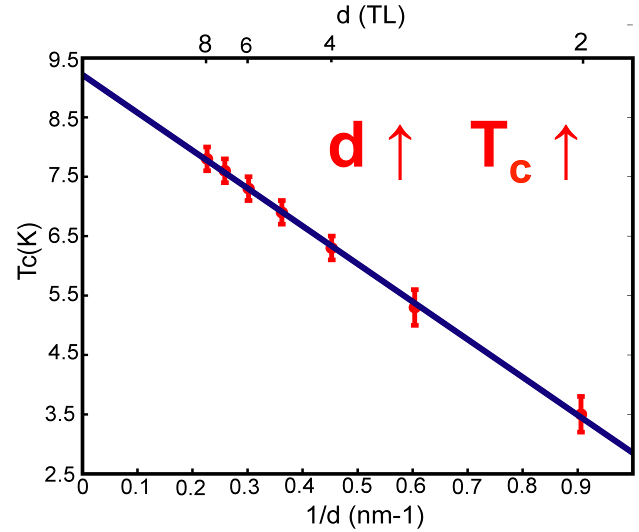
FeSe/STO



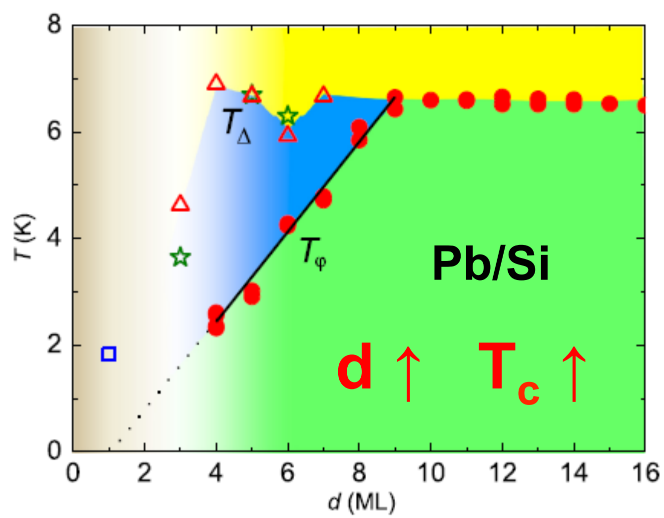


d ↑ T_c ↓

FeSe/ graphene



Phys. Rev. B 84, 020503(2011)

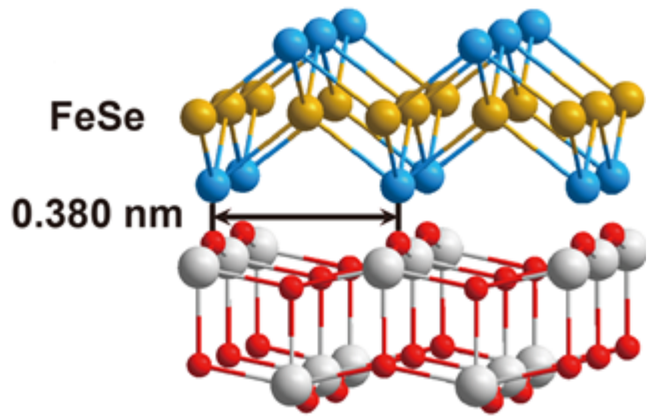


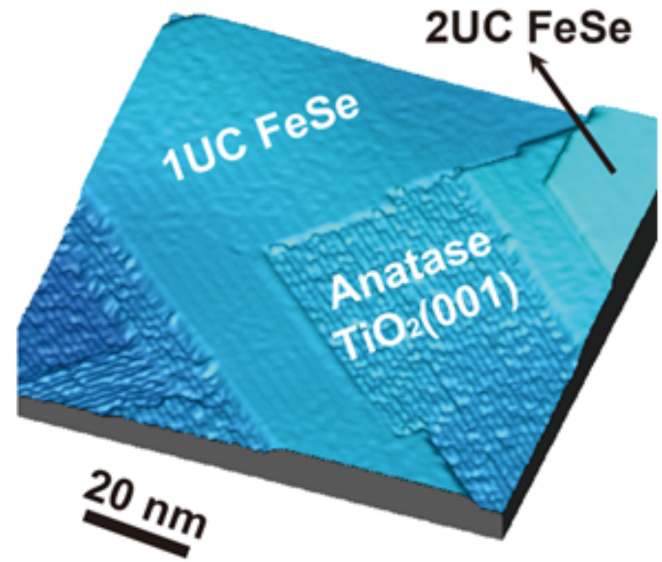
Solid State Commun.165, 59 (2013)

Single UC FeSe on TiO_2

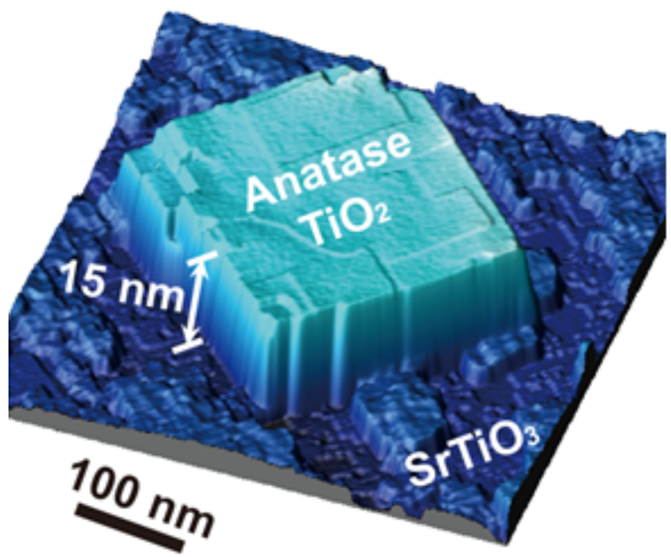
Superconductivity of 1-UC FeSe on TiO_2

Anatase TiO_2



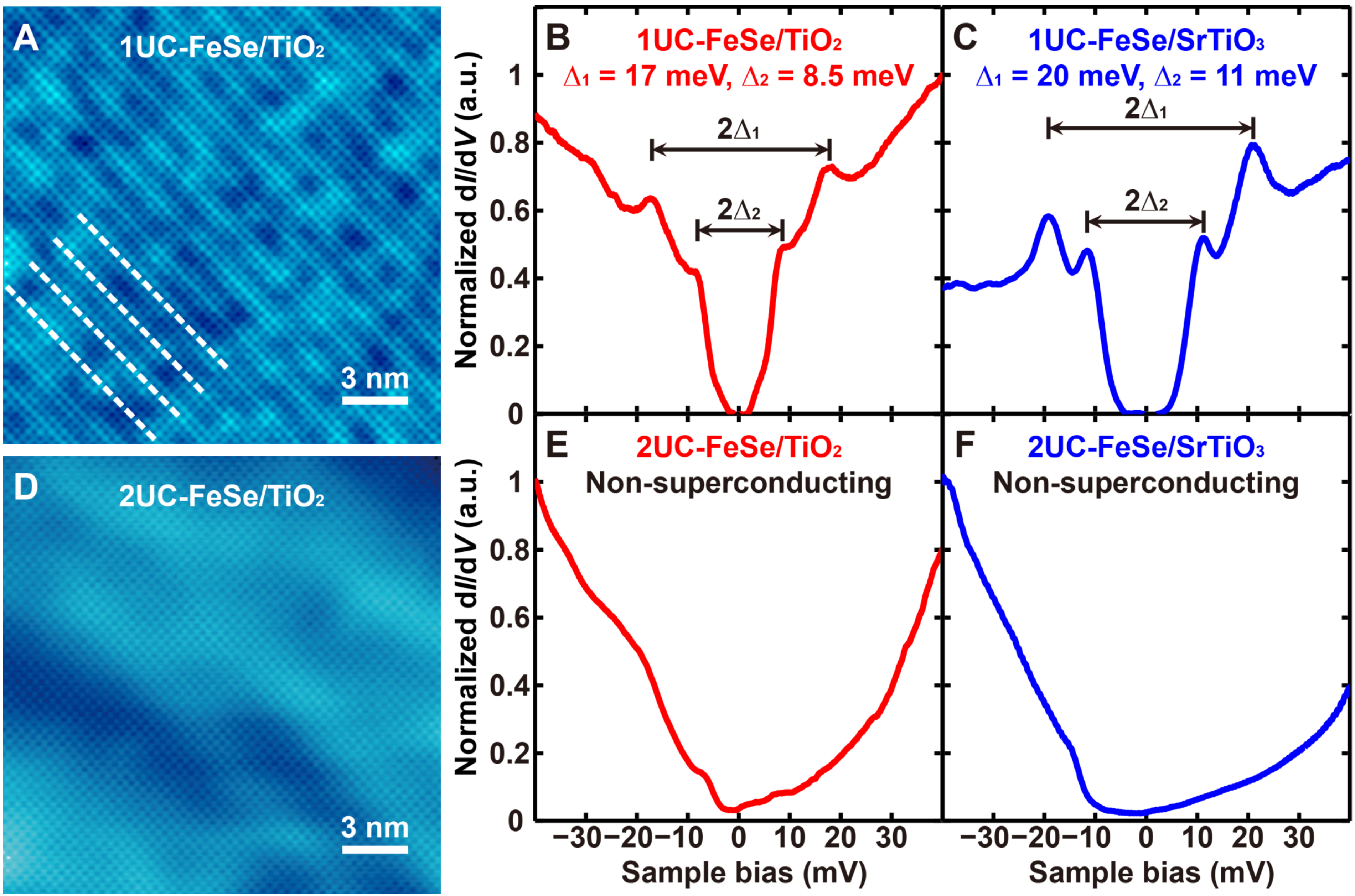


deposit Ti onto STO @ 750 °C

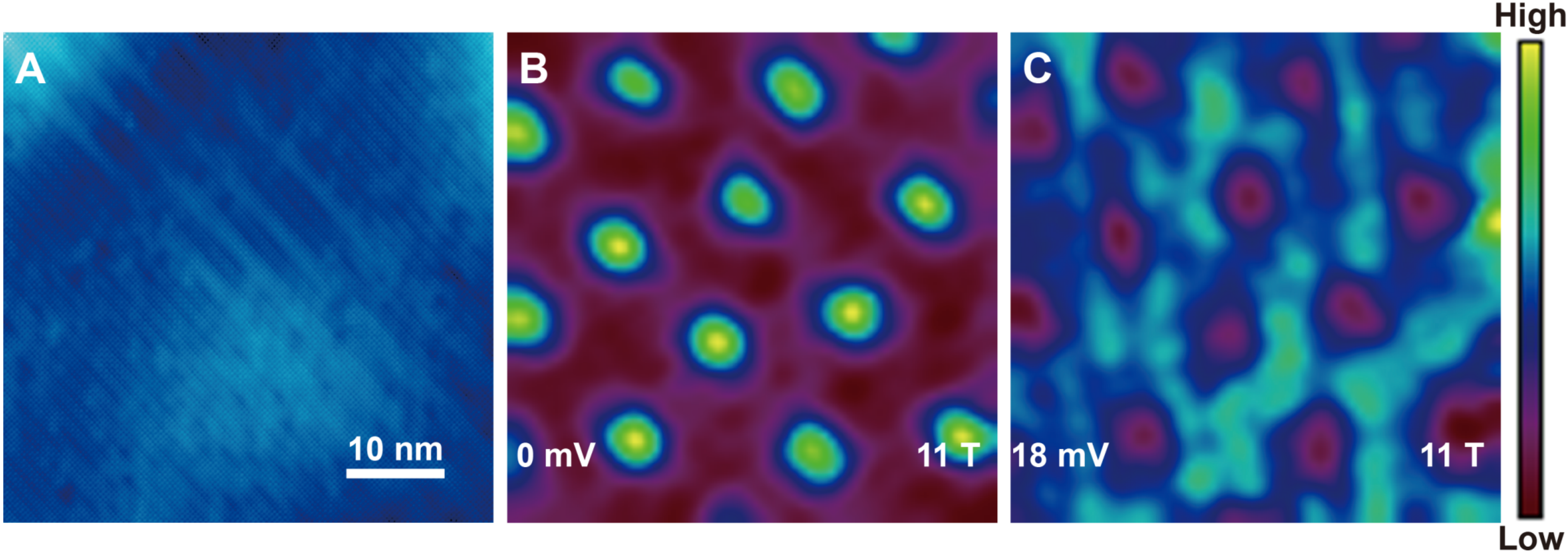


Ding et al., unpublished data

Superconductivity of 1-UC FeSe on TiO_2



Superconductivity of 1-UC FeSe on TiO_2



17meV gap

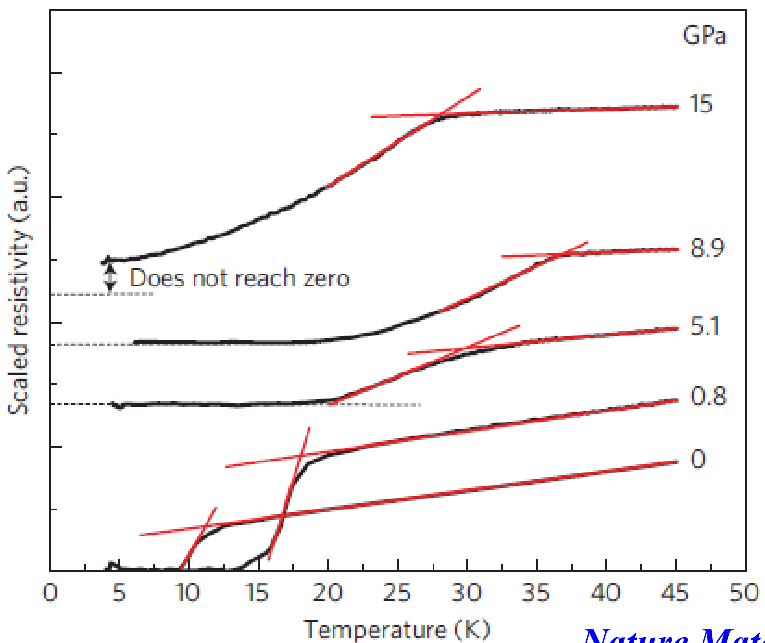
Vortex lattice

interface enhanced superconductivity

The origin of interface superconductivity

- strain
- charge transfer
- e-ph coupling

Possible mechanism: strain?



Nature Mater. 8, 630 (2009)

compressive ↓ (8.9GPa)

tensile (1 UC)

	bulk	8.9GPa	1 UC
a	0.3765	0.357	0.39
c	0.5518	0.50	*0.55*
T_c	12 K	37 K	?

tensile strain

STO: a = 0.3905 nm

FeSe: a = 0.3765 nm

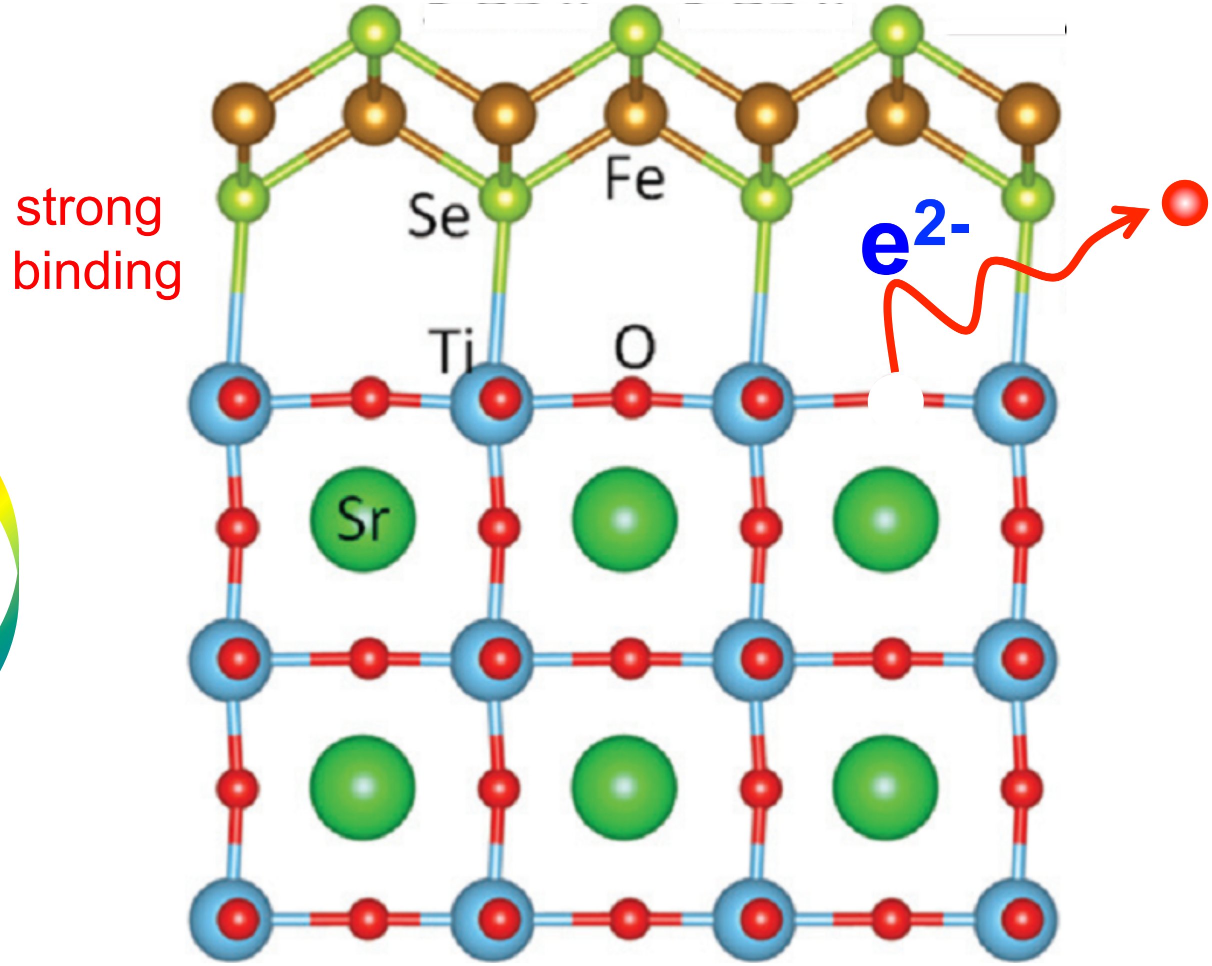
1-UC FeSe/STO: 3.91±0.02 Å, $\Delta \approx$ 20 meV — **Q. K. Xue Group**

1-UC FeSe/STO/KTO: 3.99±0.02 Å, $T_c \approx$ 70 K — **D. L. Feng Group**

1-UC FeSe/TiO_2/STO: 3.80±0.02 Å, $\Delta \approx$ 19 meV — **Q. K. Xue Group**

Chin. Phys. Lett. 29, 037402(2012)
Phys. Rev. Lett. 112, 107001 (2014)
Ding et al., unpublished data

Charge doping effect



Annealing: STS \ ARPES \ Transport

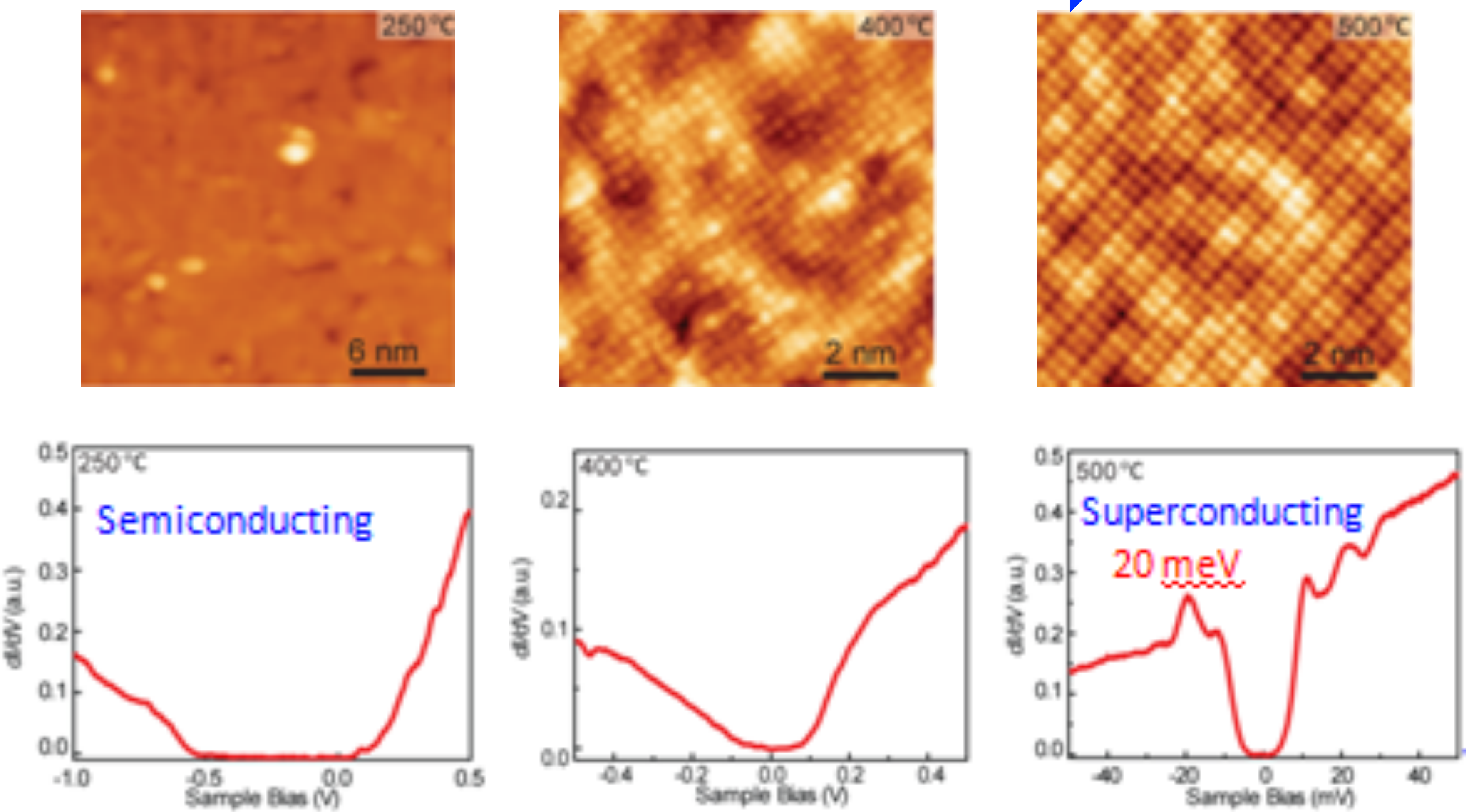
Electric field effect

J. Bang *et al. Phys. Rev. B* 87, 220503(R) (2013)

interface charge transfer

Annealing

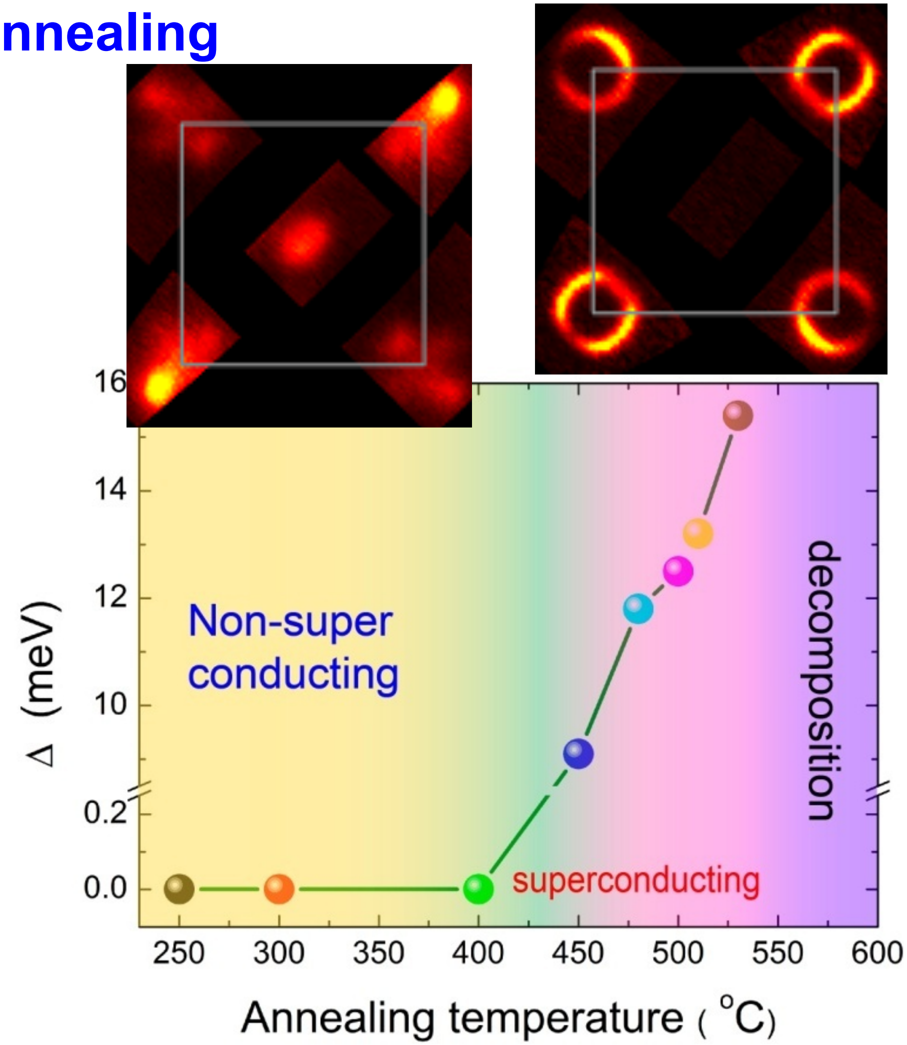
charge transfer

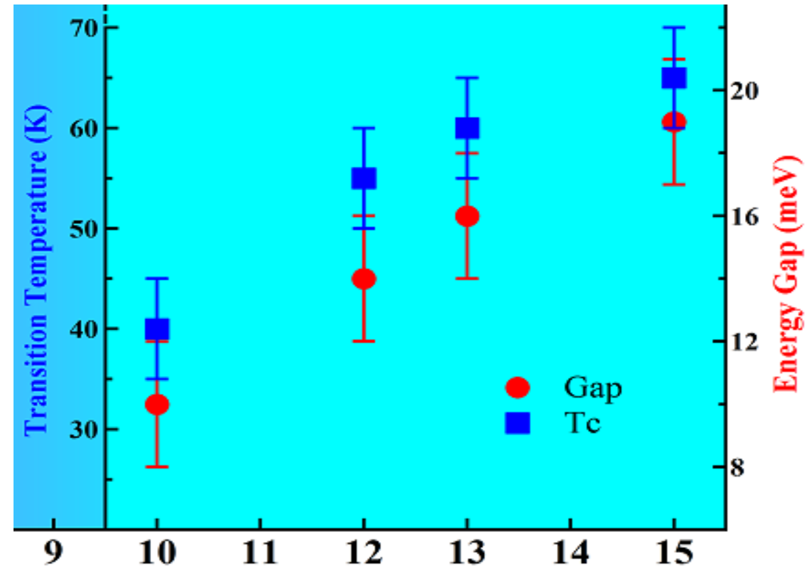


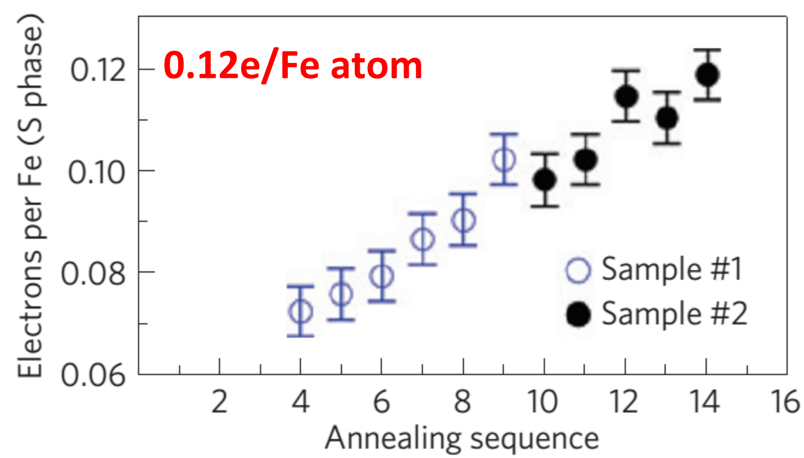
Li et al., J. Phys.: Condens. Matter 26, 265002 (2014)

interface charge transfer

Annealing

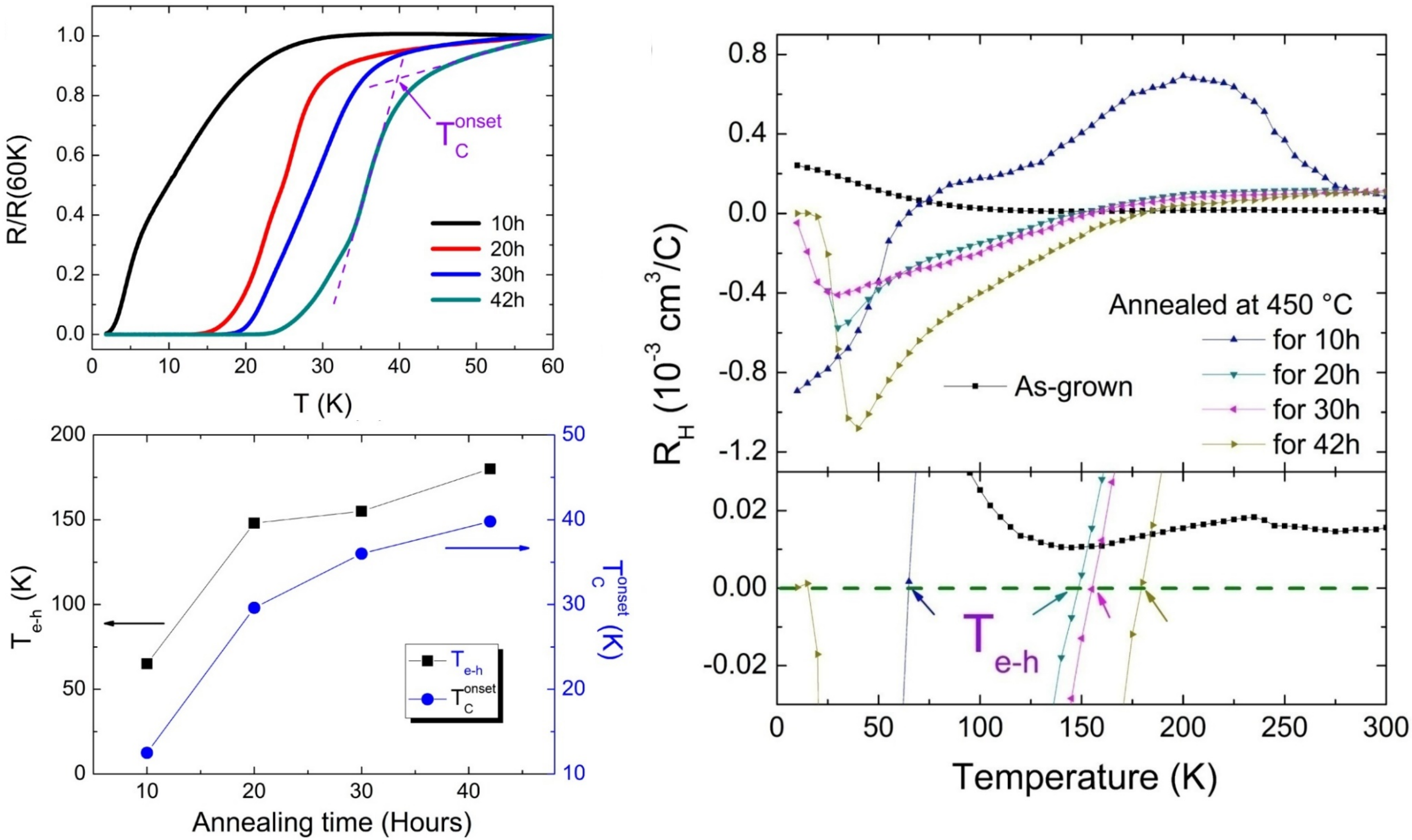






Liu et al., Nat. Commun. 3, 931 (2012); He et al., Nat. Mater. 12, 605 (2013); Zhang et al., Phys. Rev. B 89, 060506 (2014)

interface charge transfer



The longer the annealing time is, the higher the temperature of the n-p transition is.

Zhang et al., Phys. Rev. B 89, 060506 (2014)

interface charge transfer

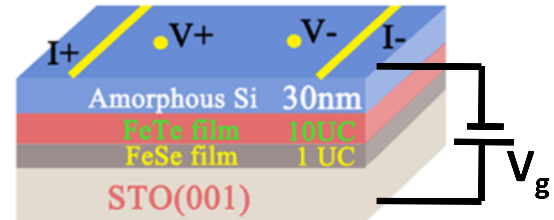
Field Effect

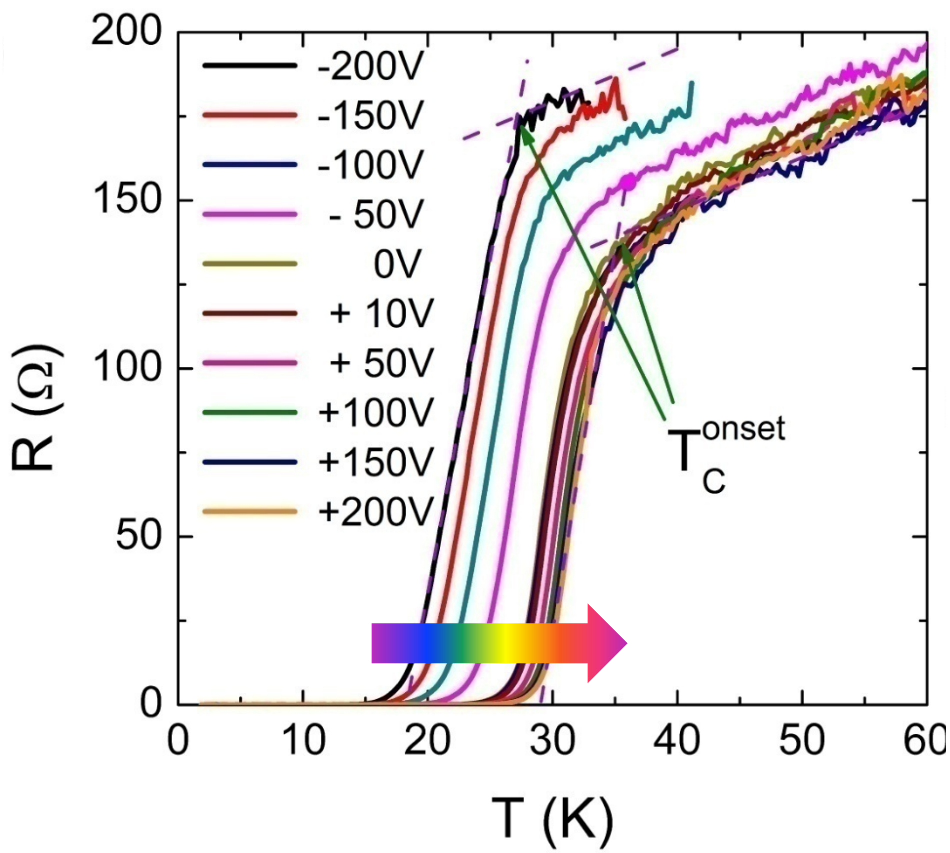
n ↑ ⇒ Gap & T_c

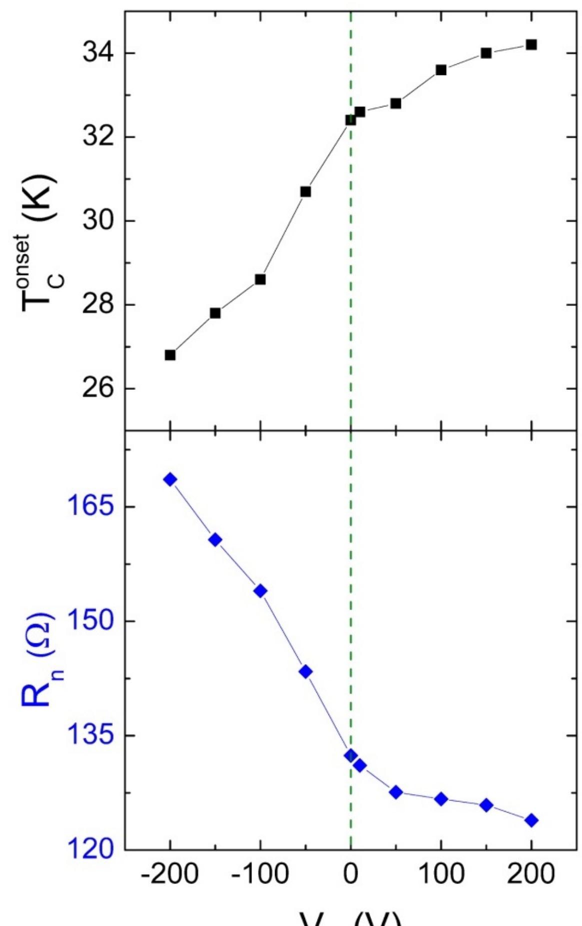
Tc: 26.5 K to 34 K

Positive bias: inject electrons, T_c ↑

Negative bias: pump out electrons, T_c ↓





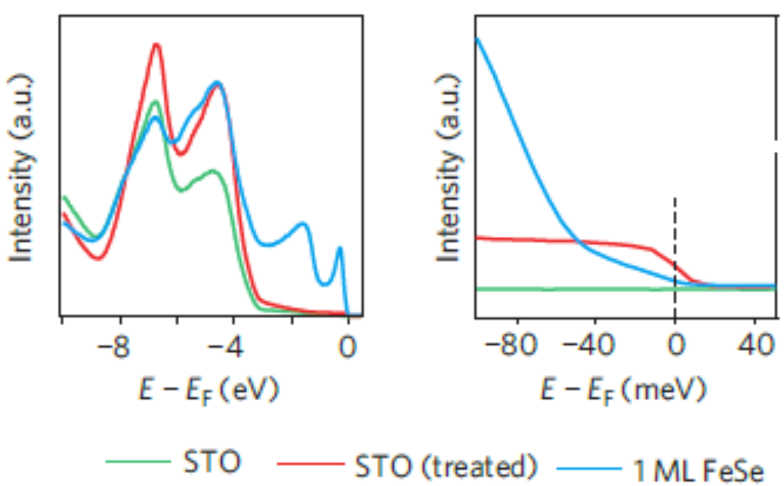


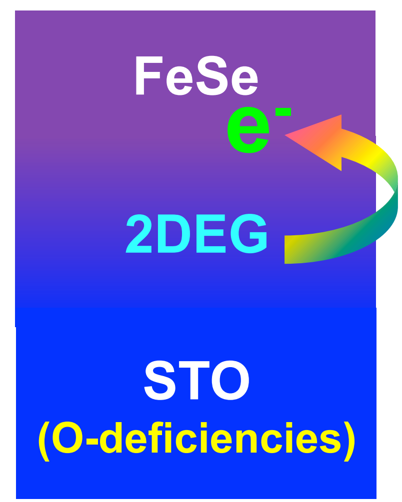
Zhang et al., Phys. Rev. B 89, 060506 (2014)

interface charge transfer

As-grown FeSe (Semiconducting) → T_C ↑ △ **Annealing** → **Annealed FeSe (Superconducting)**

STM/STS	ARPES	Hall/Gate
Strong bond Ordered chemical bond	electron doping carrier density increasing	Electron carriers dominate to enhance T_C



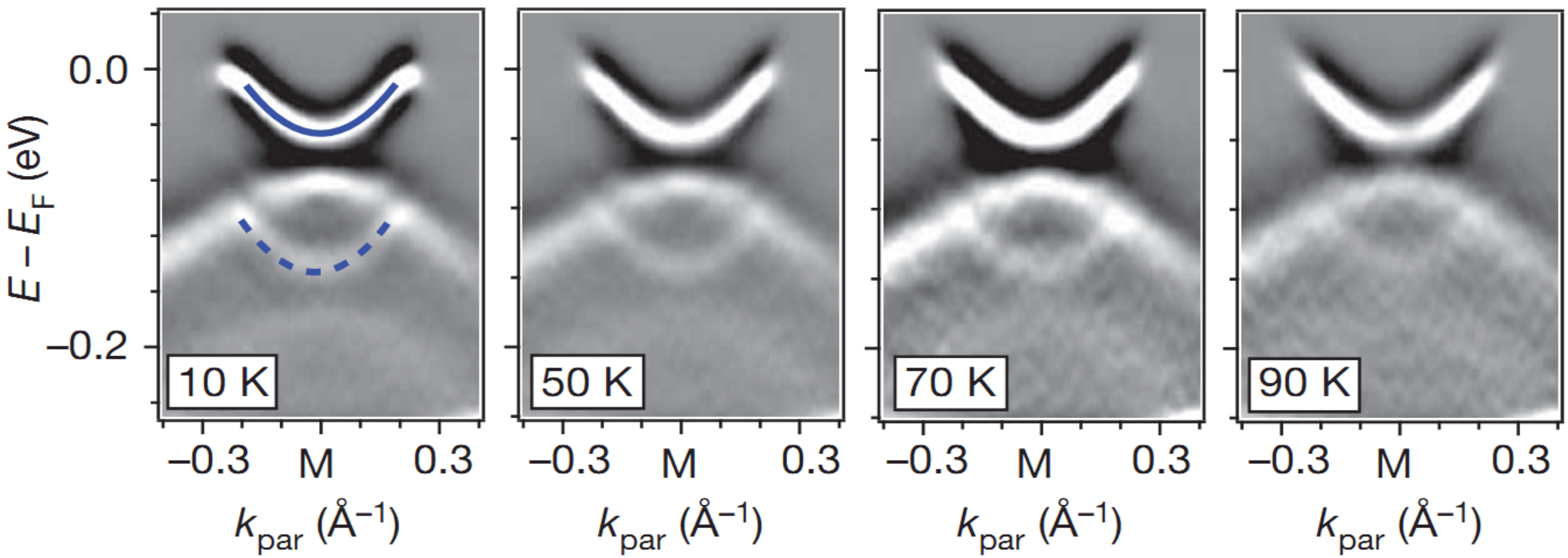


From oxygen vacancy induced states To FeSe

Donglai Feng Group: *Nat. Mater. 12, 634 (2013)*

interface enhanced e-p coupling

The Coupling between FeSe electron and STO phonon strengthens Cooper pairing.



replica bands: in 1-uc FeSe films only, persist to >T_{gap} ← **Phonon band of STO**

Effective phonon-mediated attraction strength： $\nu_{eff} \approx 10$ meV

FeSe-bulk Vs. 1 UC FeSe/STO

$\lambda \approx 0.16$

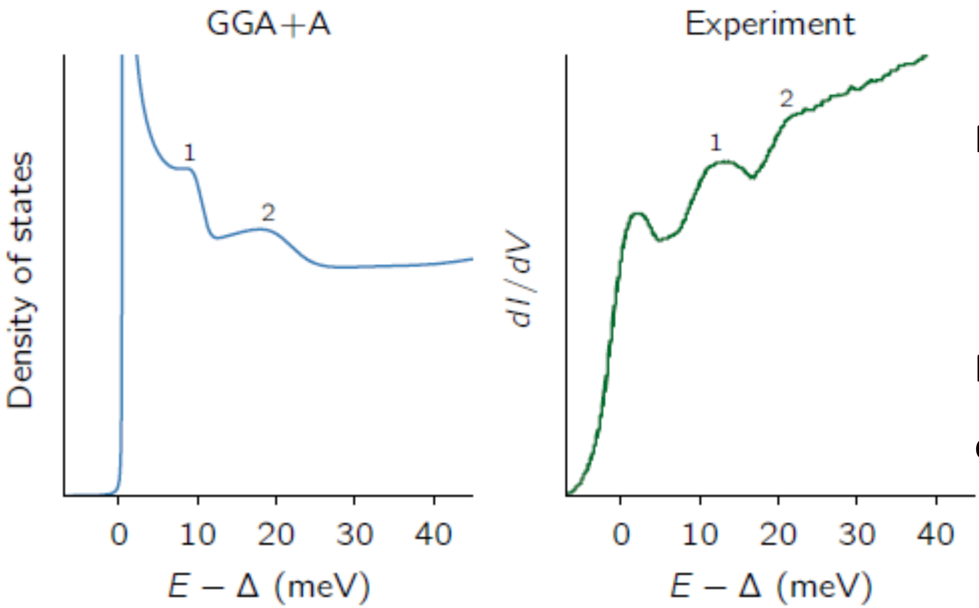
$\lambda \approx 0.5$ (ARPES) **Zhixun Shen Group:** *Nature 515, 245(2014)*

$\lambda \approx 0.48$ (Ultrafast spectroscopy) **Jimin Zhao (IOP)**: *arXiv： 1502.06339*

interface enhanced e-p coupling

Structure template increases electron-phonon

S. Coh, M. L. Cohen, S. G. Louie (arXiv. 1407.5657v1)



Phonon 1: 10 meV,

in-plane displacements of atoms

Phonon 2: 20 meV,

out-of-plane transverse displacement of Fe atoms

$$T_c \sim \overline{\omega}\lambda^{0.5}$$

- ✓**Pair FeSe electrons to high frequency phonon in STO**
- ✓**Increase the contribution of phonon 1 to the coupling**
- ✓**Keep FeSe in magnetic phase which allows coupling of phonon 2**

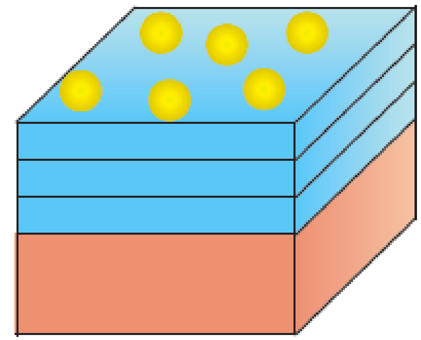
interface charge transfer

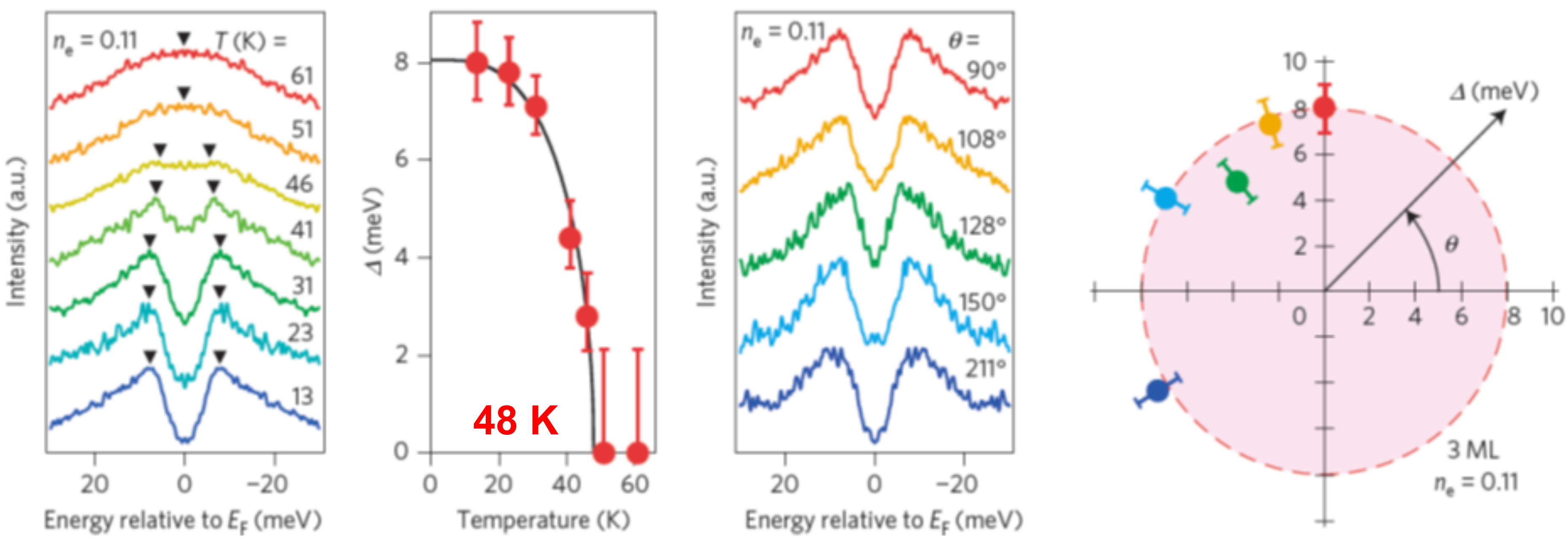
Interface enhanced charge transfer + e-ph coupling

nature materials
LETTERS
PUBLISHED ONLINE: 1 JUNE 2015 | DOI: 10.1038/NMAT4302

High-temperature superconductivity in potassium-coated multilayer FeSe thin films

Y. Miyata[1], K. Nakayama[1]*, K. Sugawara[2], T. Sato[1] and T. Takahashi[1,2]



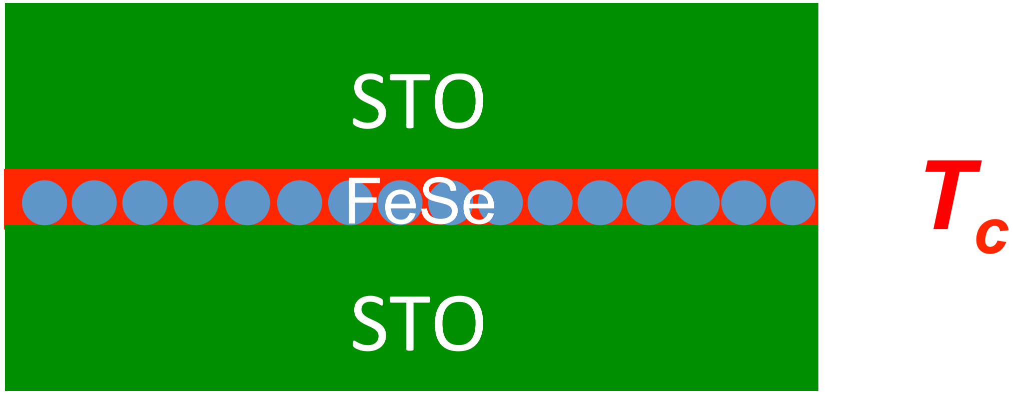


Origin of enhanced superconductivity

- Electron doping at the interface
- Interface-enhanced e-ph coupling

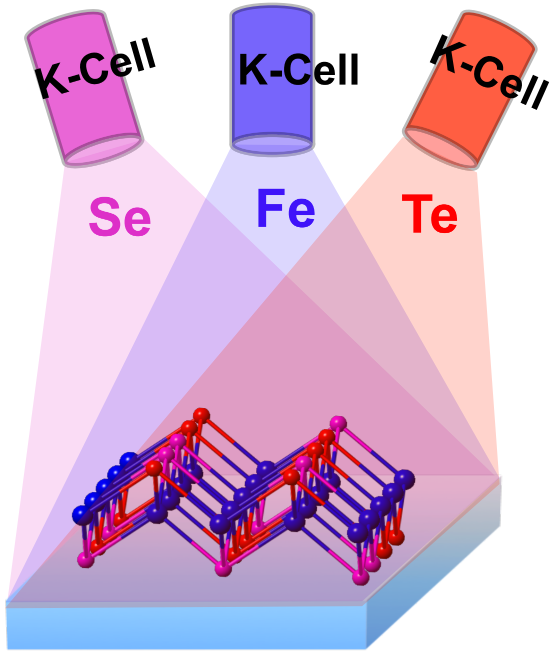
Heterostructure ⟷ Interface superconductor

An effective way for searching high Tc systems



Single UC $FeTe_{1-x}Se_x$ on STO

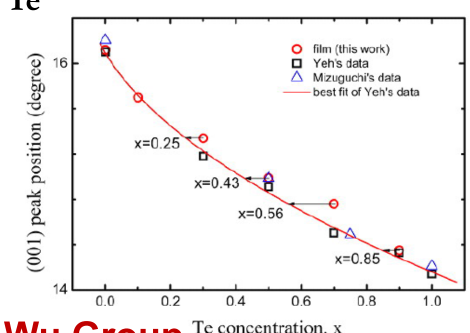
MBE Growth of $FeTe_{1-x}Se_x$ Films

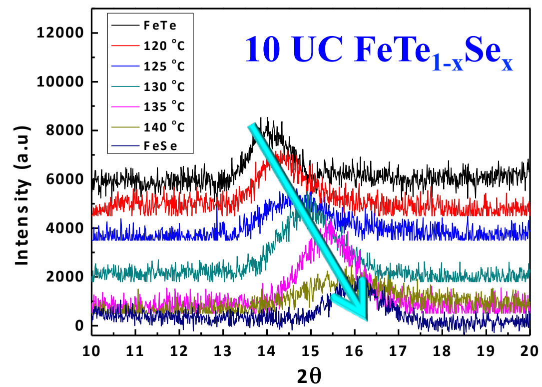


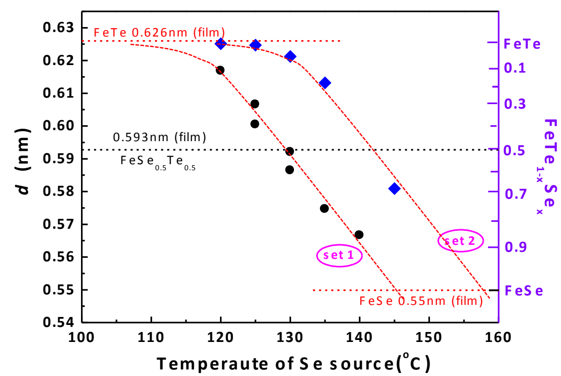
T_s : 330 ℃

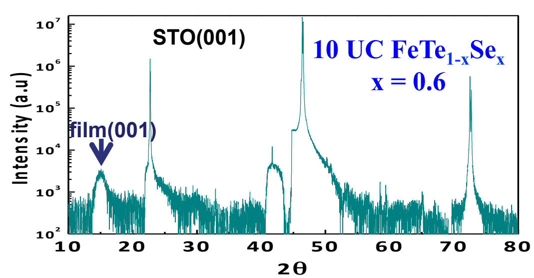
T_{se} : 120-140 ℃

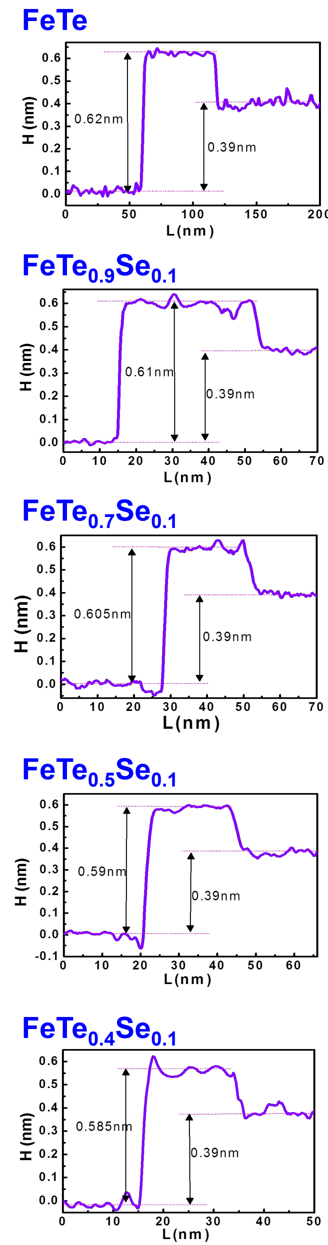
T_{Te} : 270 ℃







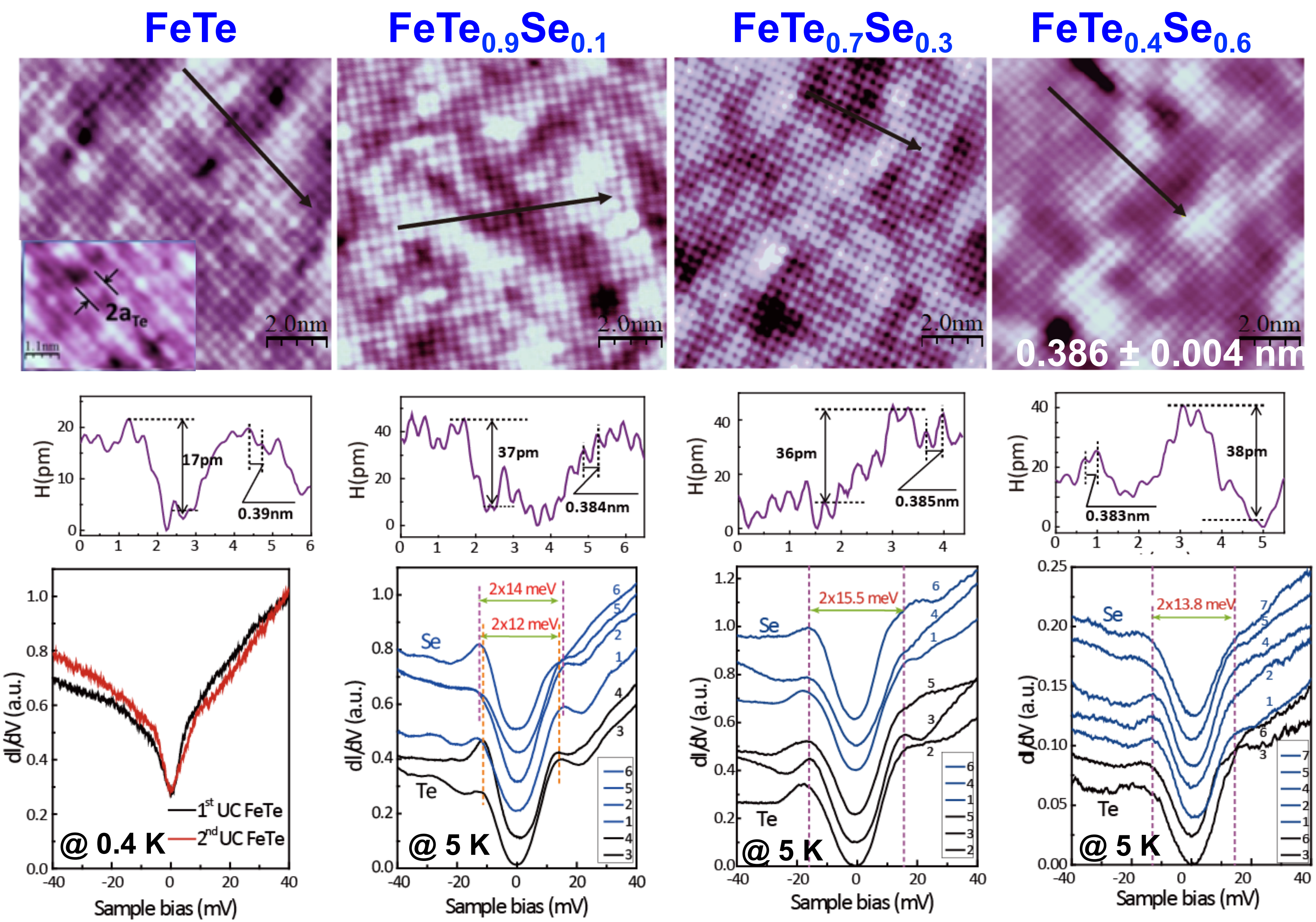




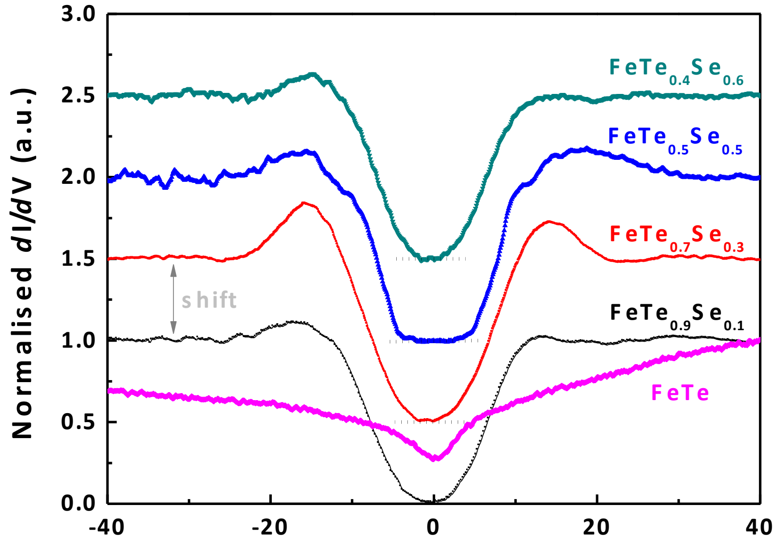
M. -K. Wu Group

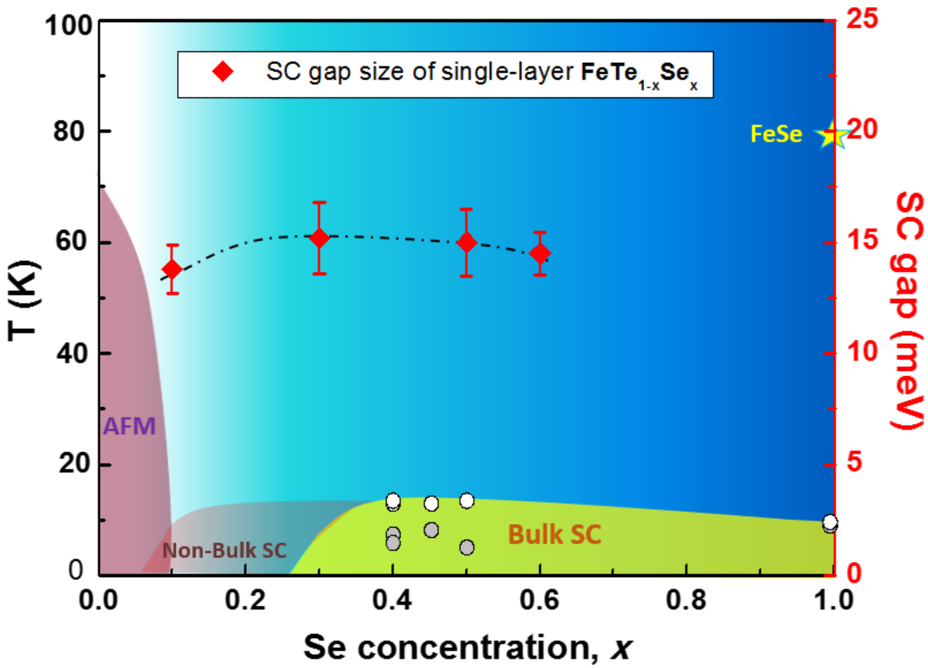
***Sci. Technol. Adv. Mater.* 14, 014402 (2013)**

Single Layer $FeTe_{1-x}Se_x$ Films on STO



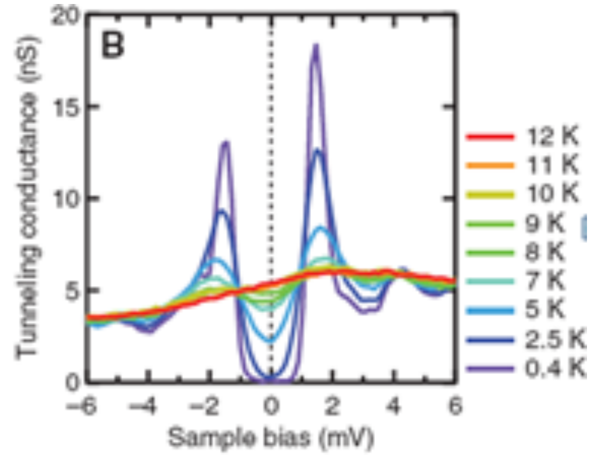
Superconductivity in Single Layer $FeTe_{1-x}Se_x$





Bulk $FeTe_{0.6}Se_{0.4}$

Hanaguri, et al., *Science*, 328, 474 (2010)



$\Delta \sim 1.7$ meV

$T_c \sim 14.5$K

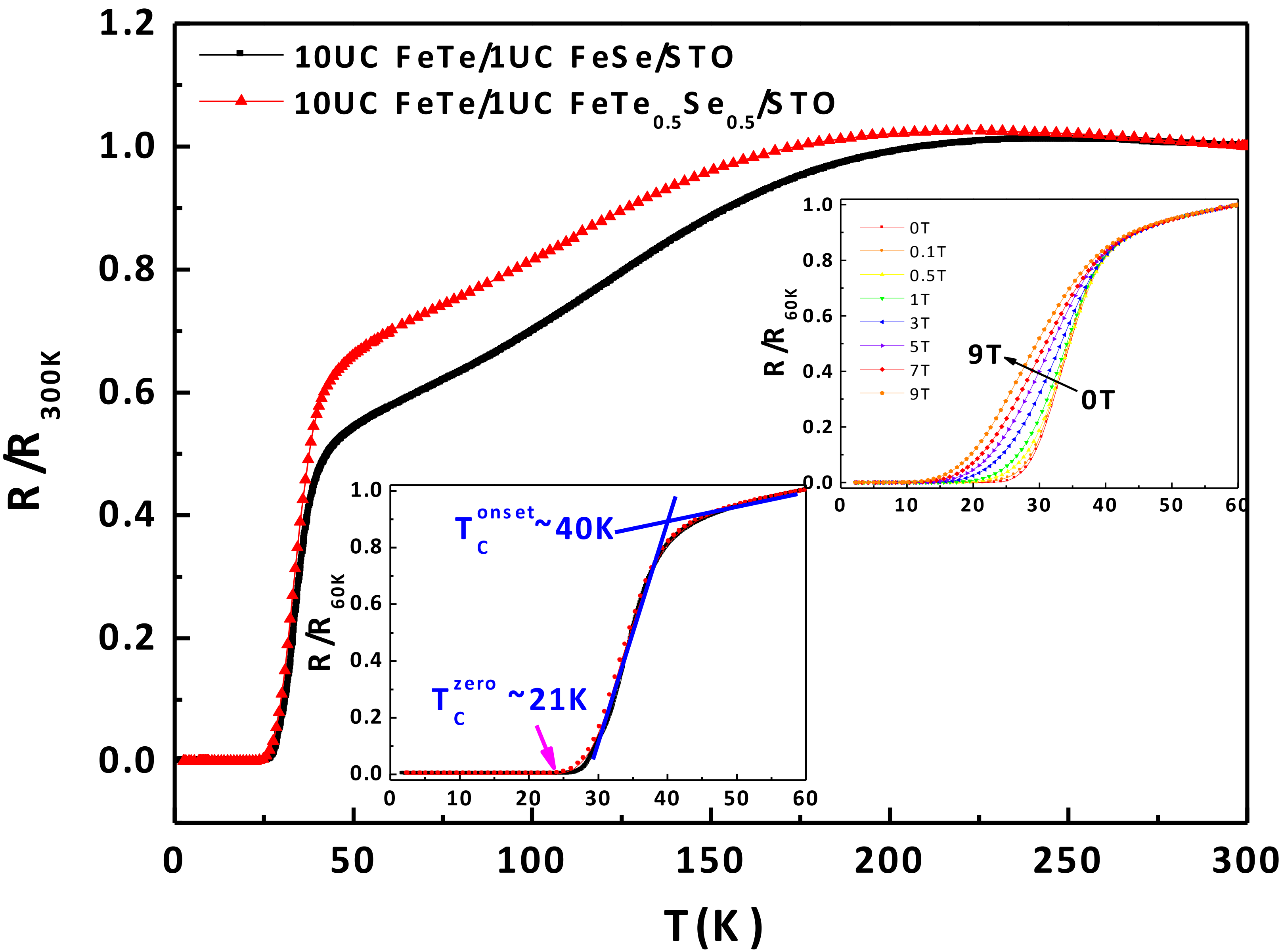
$$\frac{2\Delta}{k_B T_C} \sim 2.72$$

1UC $FeTe_{1-x}Se_x$ on STO

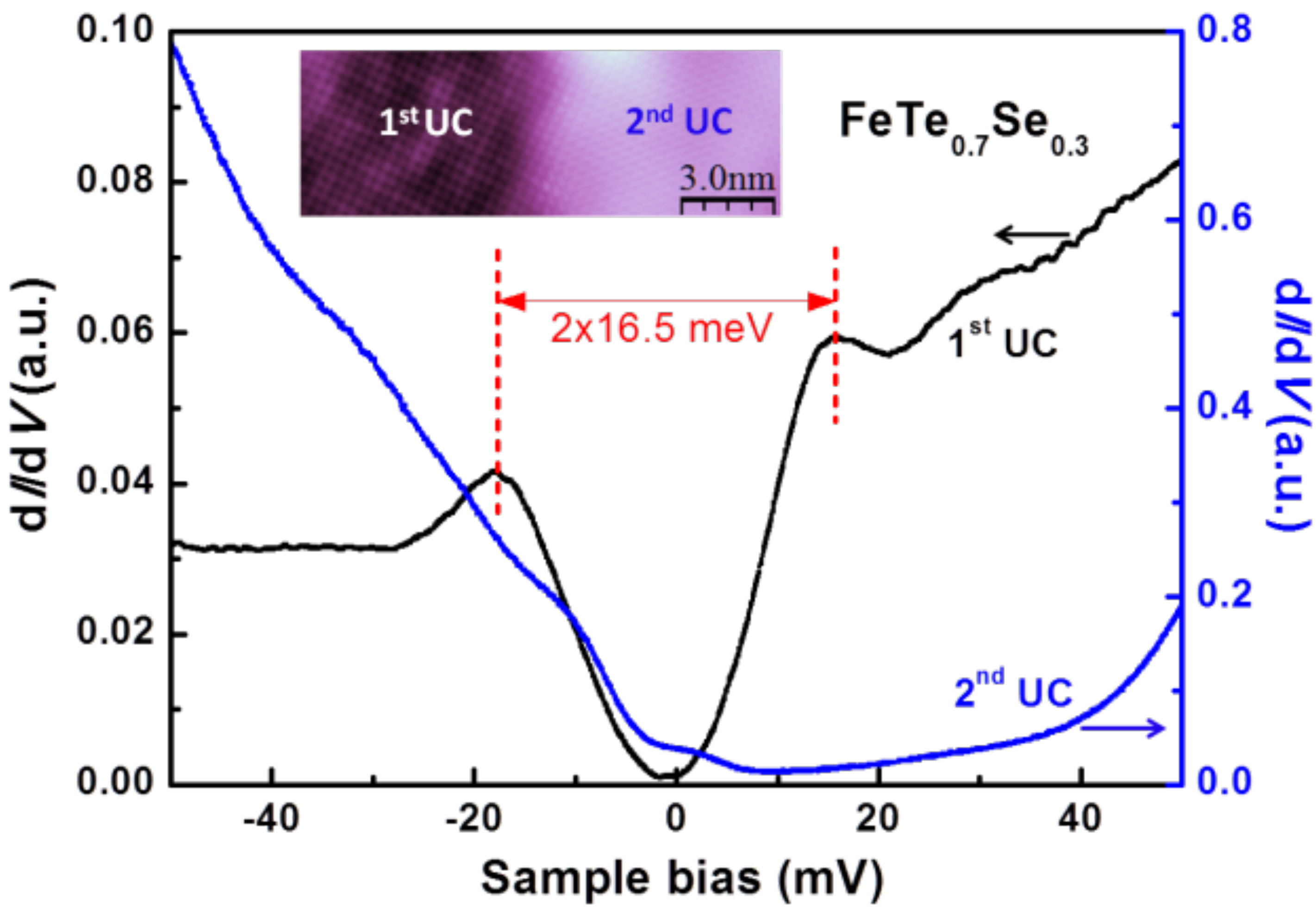
$\Delta_{max} \sim 16.5$ meV

$T_c > 77$ K ?

ex-situ transport



Interface Superconductivity

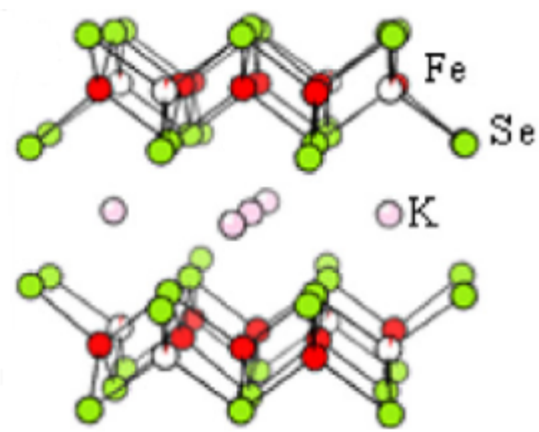


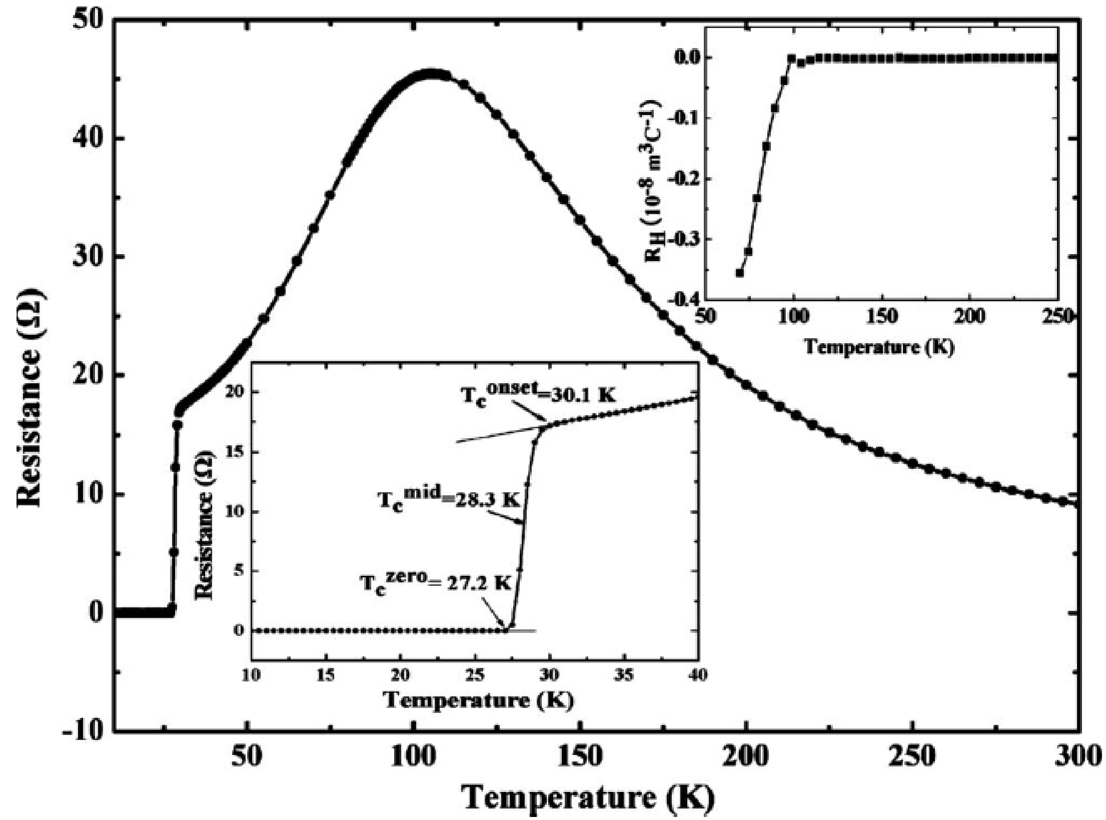
✓**1UC $FeTe_{0.9}Se_{0.1}$ shows overall superconducting behavior**

✓**the gap is nearly spatially homogeneous**

✓**gap size does not change over a wide composition range ($0.3 \leq x < 0.6$)**

$K_{1-y}Fe_{2-x}Se_2$

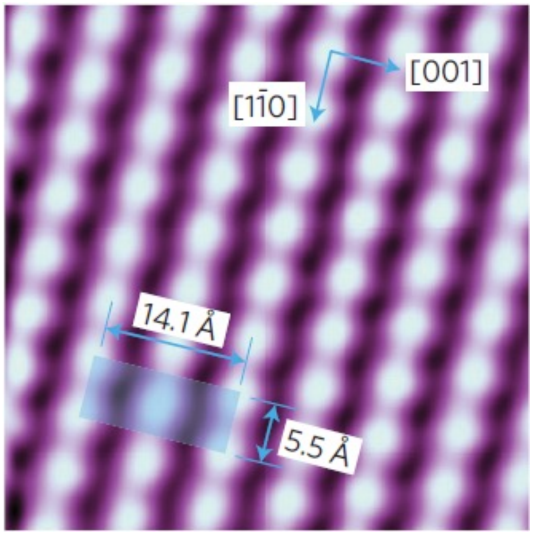


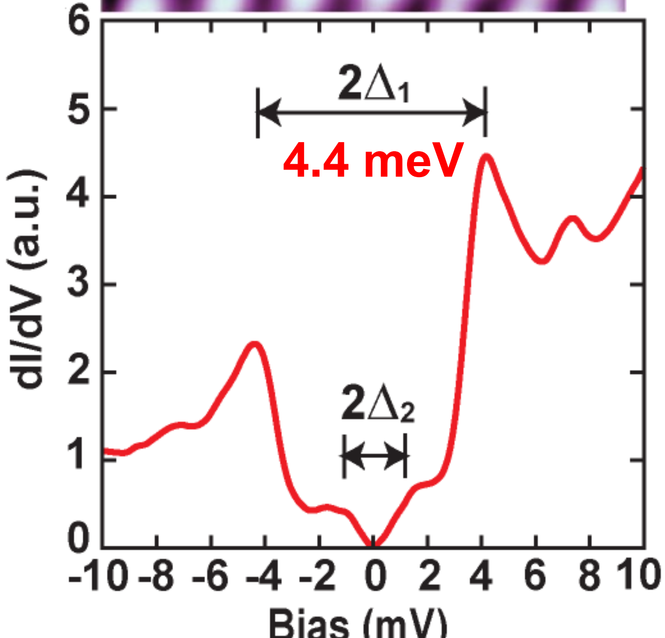


PHYSICAL REVIEW B **82**, 180520(R) (2010)

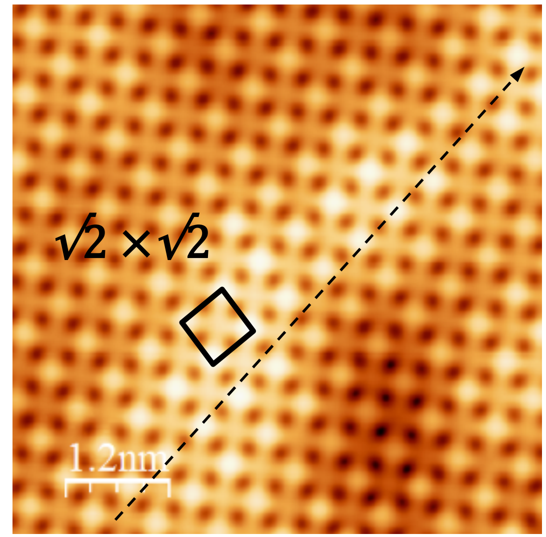
Superconductivity of $K_{1-y}Fe_{2-x}Se_2$

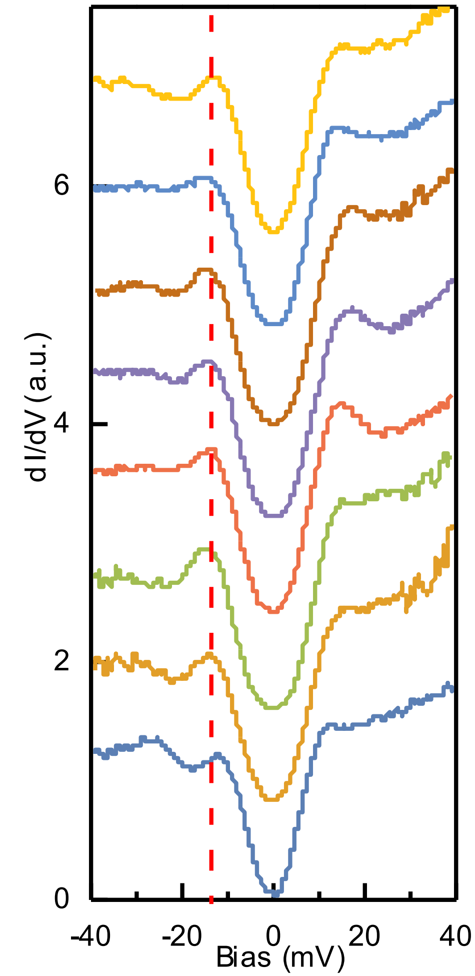
$K_{1-y}Fe_{2-x}Se_2$ on graphene





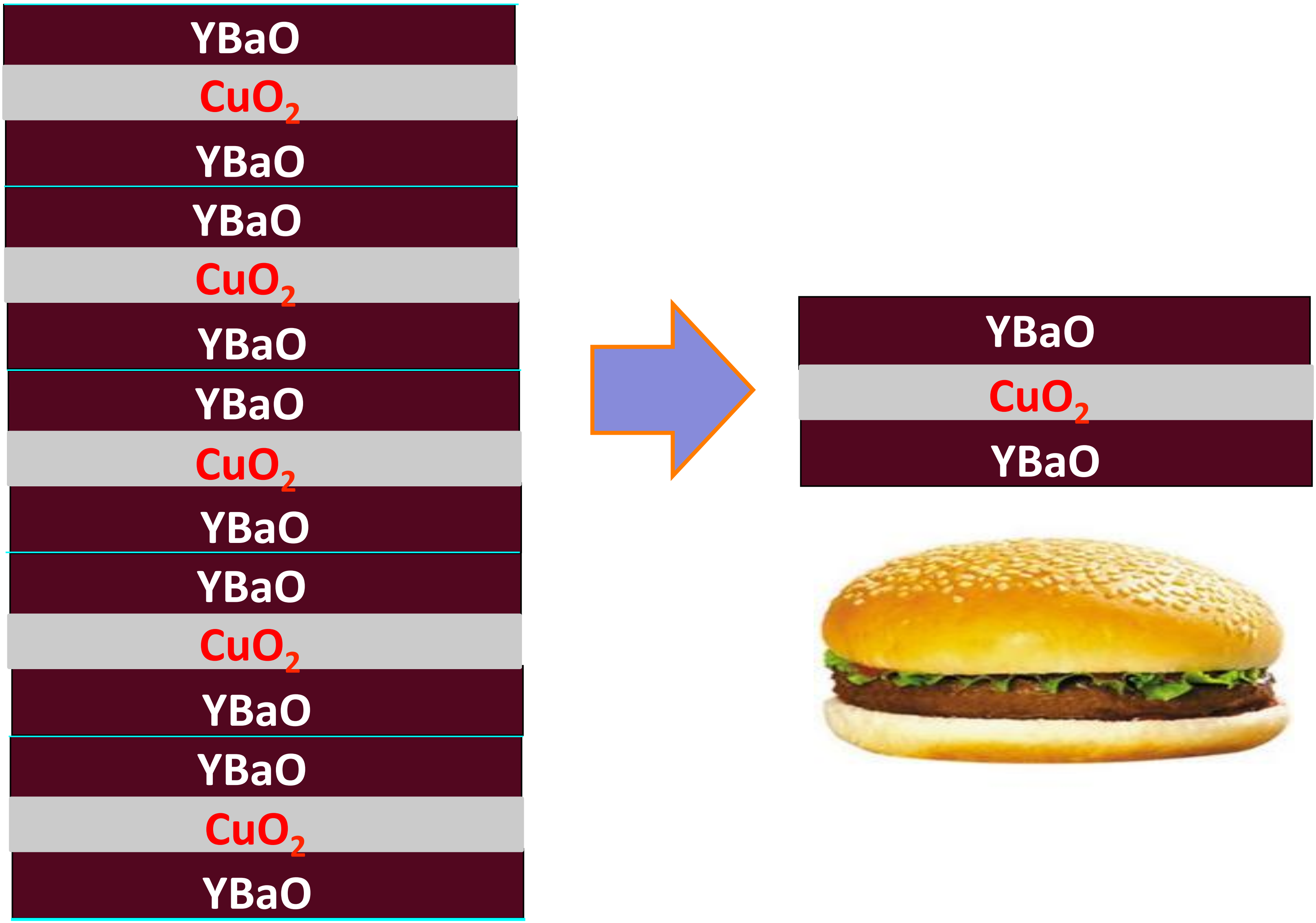
$K_{1-y}Fe_{2-x}Se_2$ on STO





14.5 meV

Layered structure of Cuprates



Previous Experiments on High Tc Superconductivity

ARPES: The electronic structure of charge reservoir layers-bread (LaSrO, LaOF), not the superconducting layers-beef (CuO_2, FeAs).

For the same material at different doping levels, ARPES data may change dramatically. This change only occurs in the bread, there is no change in the beef. Therefore, the mechanism such as the pairing symmetry shouldn't change. However, in experiment……

Only beef is superconducting

Transport (specific heat): both bread and beef contribute.

STM: nonsuperconducting surface (BiO)

Infred-optical measurement:

Very first experiments revealing the Fermi surface of the superconducting layer ?

Only beef is superconducting

non-"d-wave"?

bread

beef

bread

cuprates

FeSe

$SrTiO_3$

Summary and Perspective

Higher T_C can be expected with optimized overlayers

Improving the quality of FeSe/STO interfaces

Performing *in-situ* transport study ……

- find superconductors with high T_C

i.e., KFeSe on $BaTiO_3$ or $SrTiO_3$

Sandwich structure , superlattices

- reveal the secret of unconventional superconductivity

FeSe-TiO_2 in FeSe/STO (only half) → STO/FeSe/STO: doubling T_c?

CuO-SrO in BSCCO

FeAs-LaO in LaOFeAs