SAND2017-13101C

Quantum Transport Studies in Two Dirac Semimetals

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Sandia National Labs

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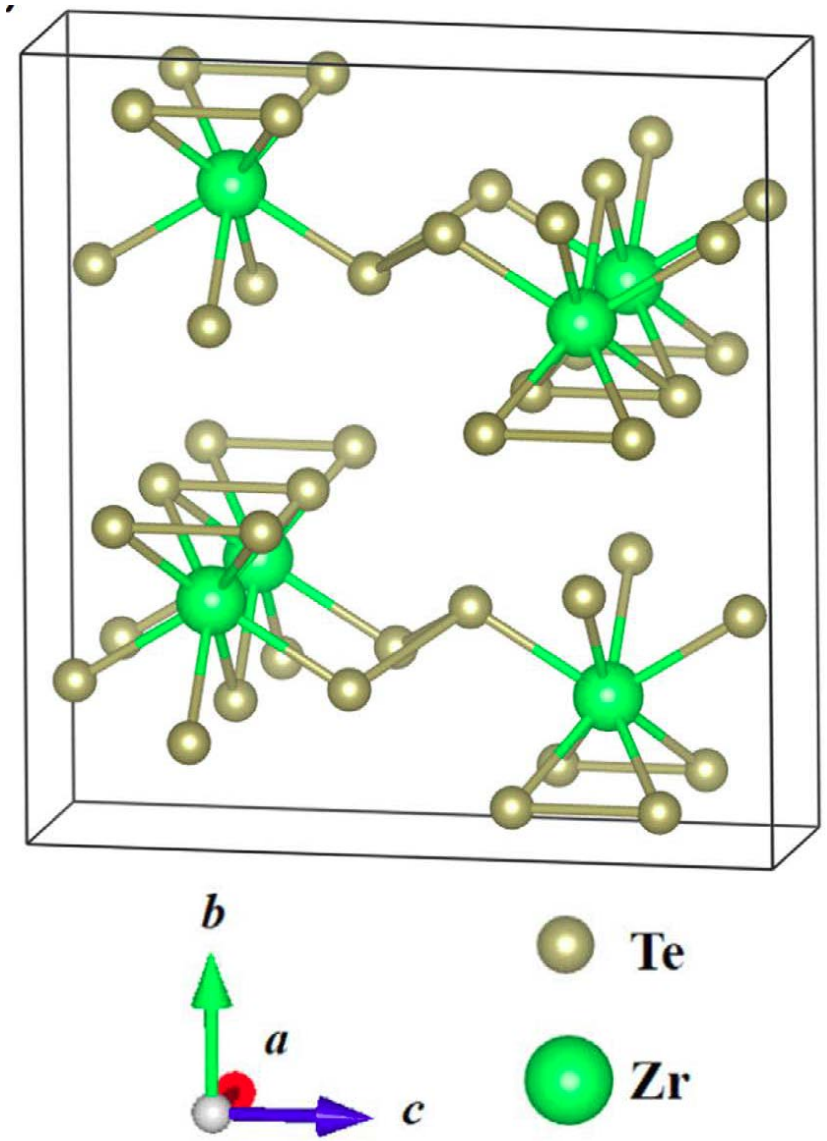
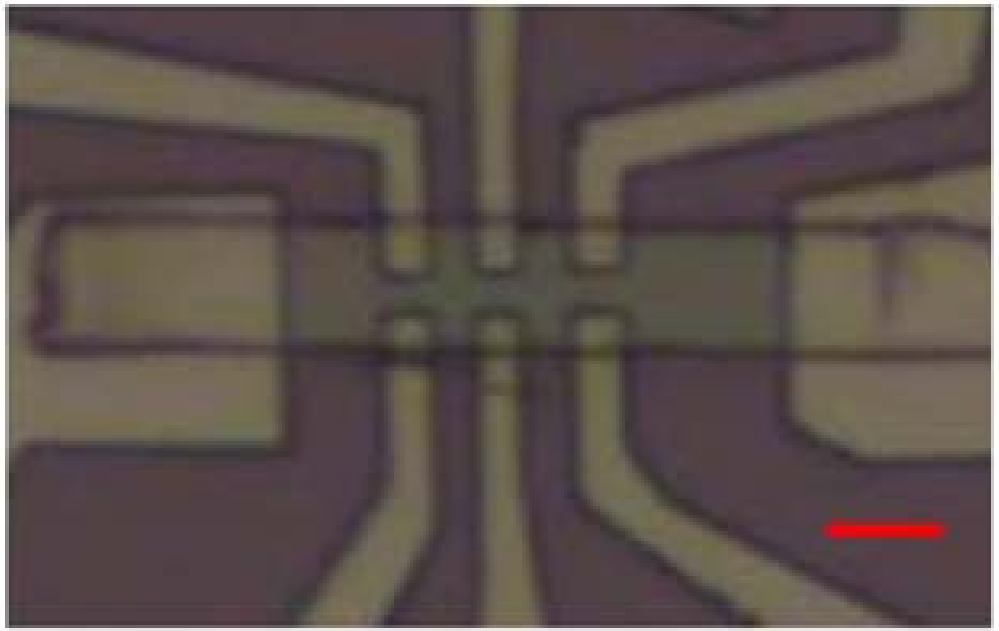
Outline –

- Quantum transport studies in $ZrTe_5$
  - Growth and characterization
  - Photocurrent
  - Quantum oscillations at fractional Landau index

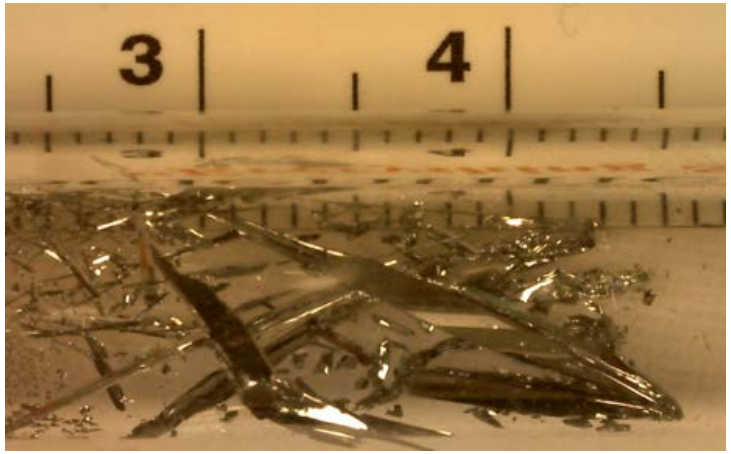
- Quantum transport studies in Cd_3As_2
  - Quantum oscillations and Berry phase
  - Proximity induced superconductivity in Josephson junctions

$ZrTe_5$

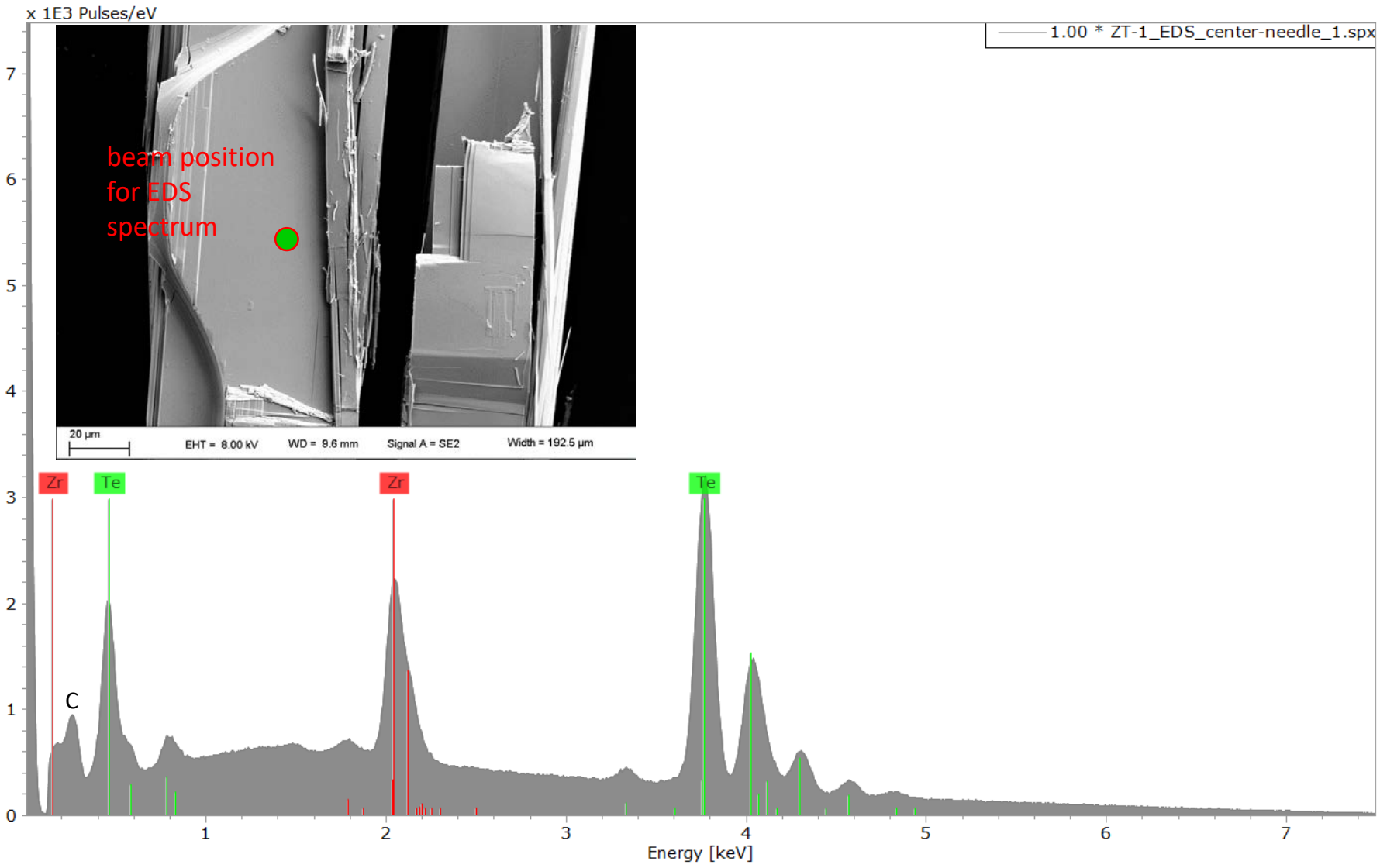




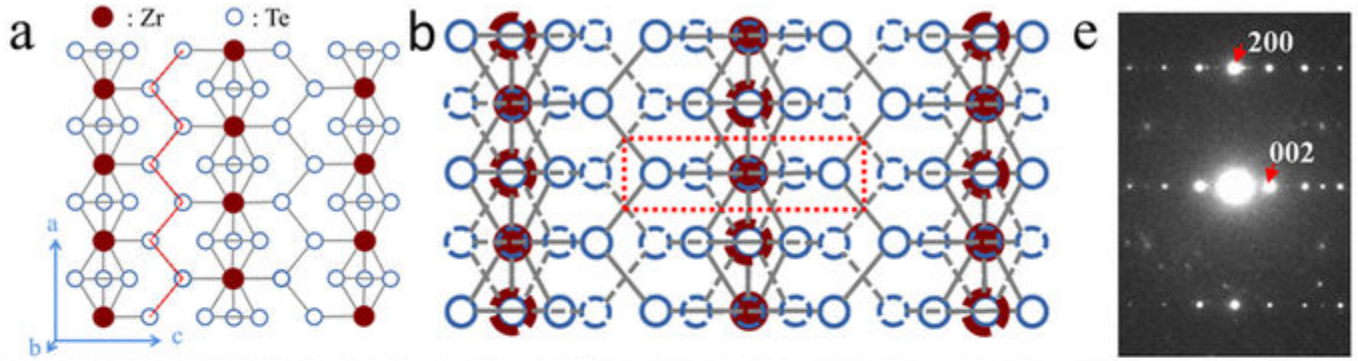
vapor transport growth

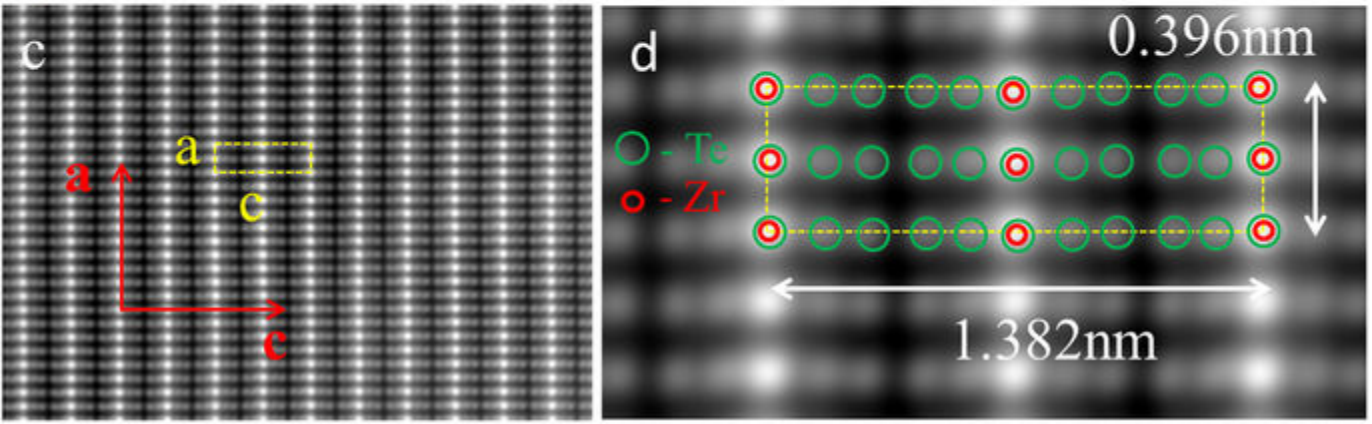


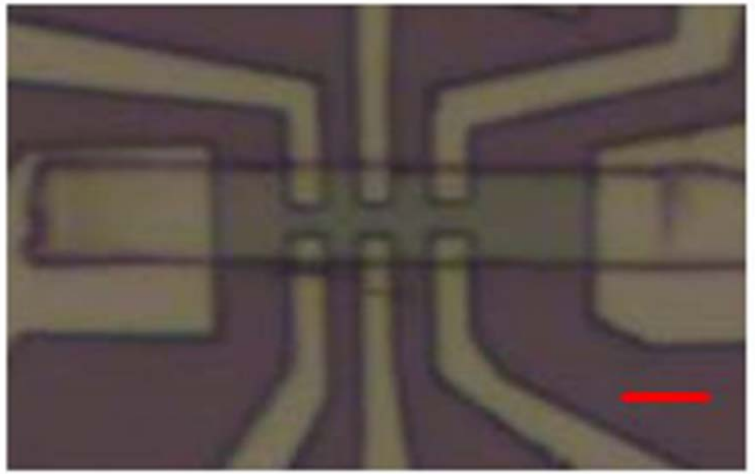
XRD

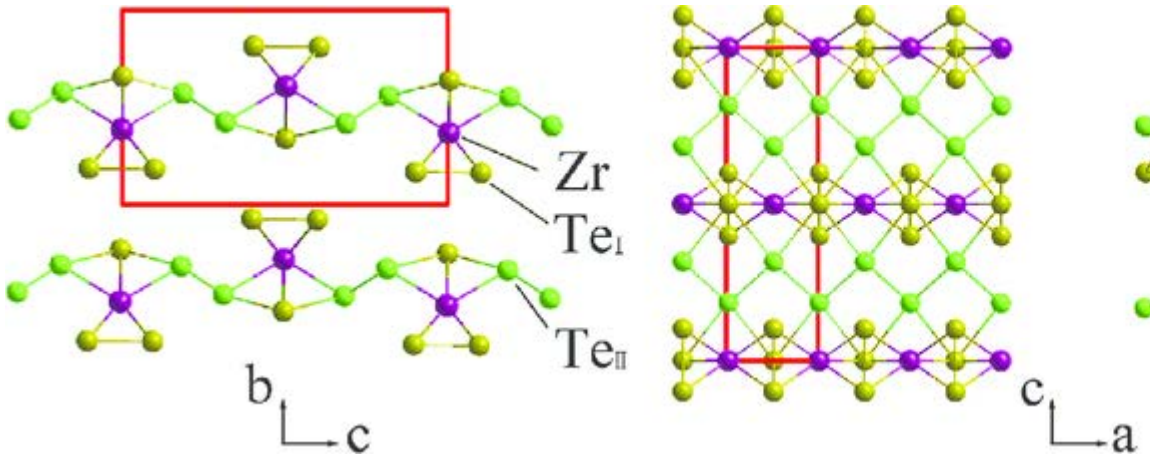

x 1E3 Pulses/eV
1.00 * ZT-1_EDS_center-needle_1.spx
beam position for EDS spectrum
20 µm
EHT = 8.00 kV
WD = 9.6 mm
Signal A = SE2
Width = 192.5 µm
Zr
Te
Zr
Te
C
0
1
2
3
4
5
6
7
Energy [keV]

AC-STEM









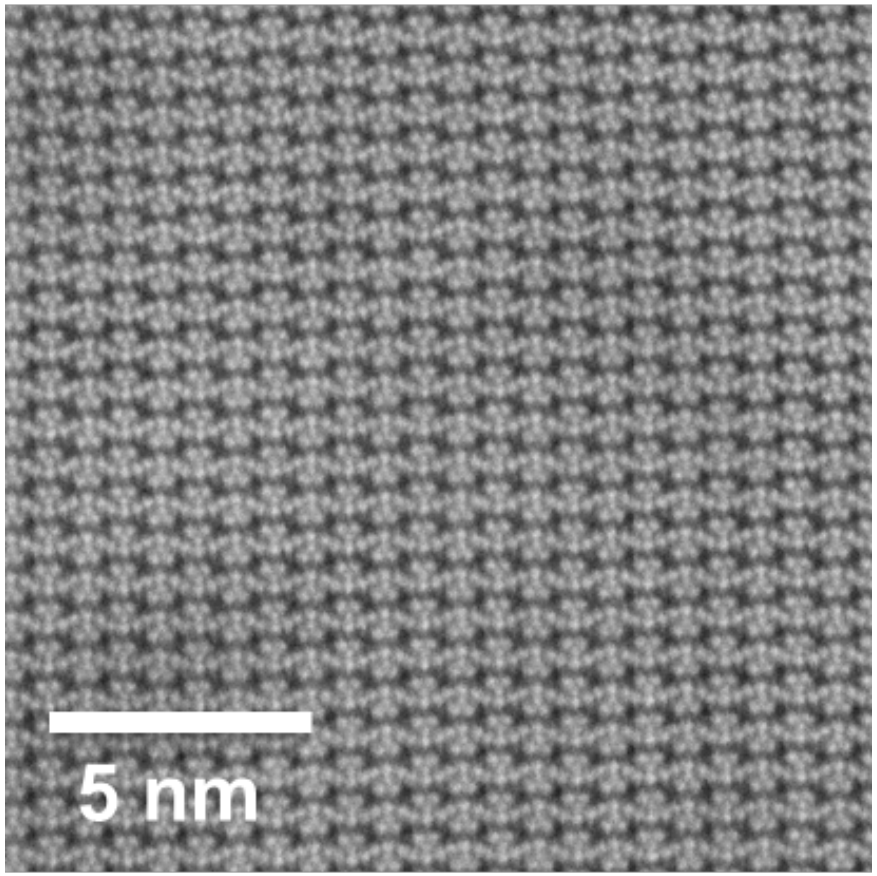
W. Yu, *et al. Scientific Reports,* **6**,35357 (2016)

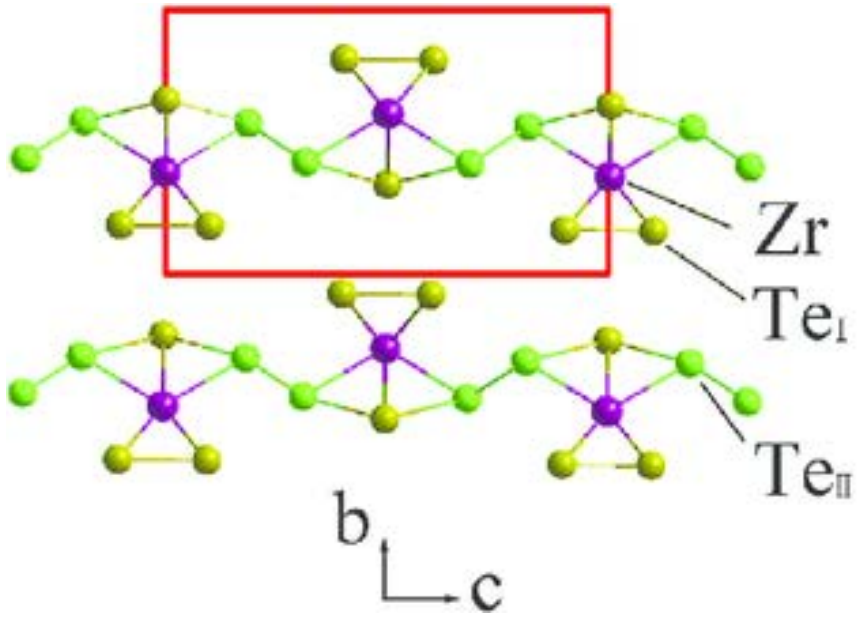
Spacegroup: Cmcm (#63)

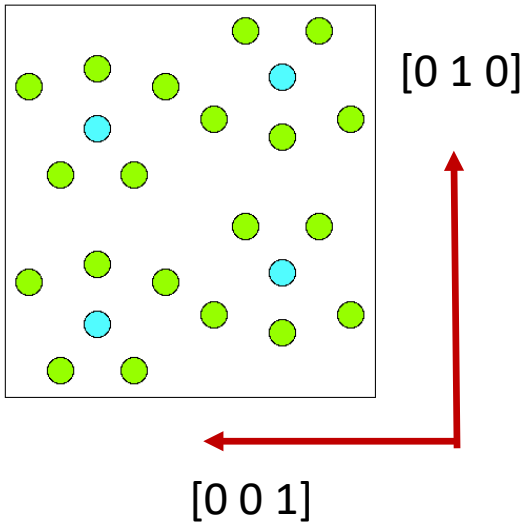
a=3.9875Å, b=14.530Å, c=13.724Å

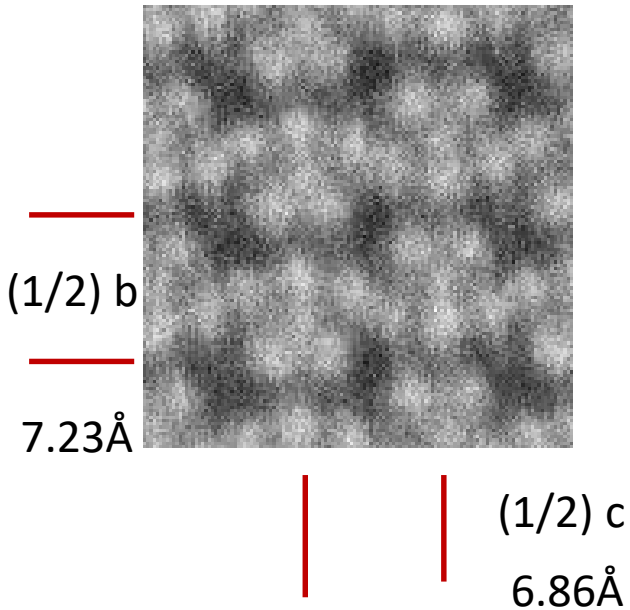
H. Fjellvåg, A. Kjekshus, Solid State Communications, 60 (2) (1986) 91-93

HAADF-STEM





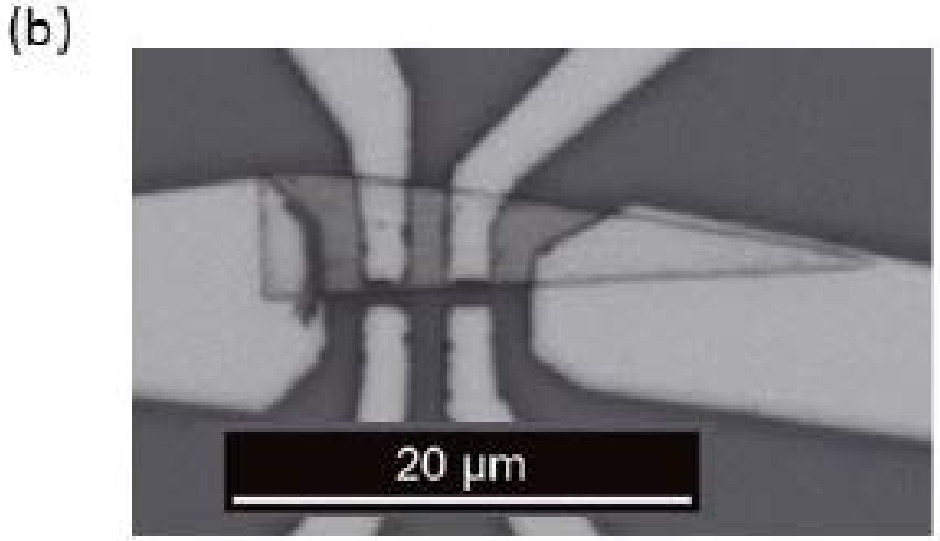


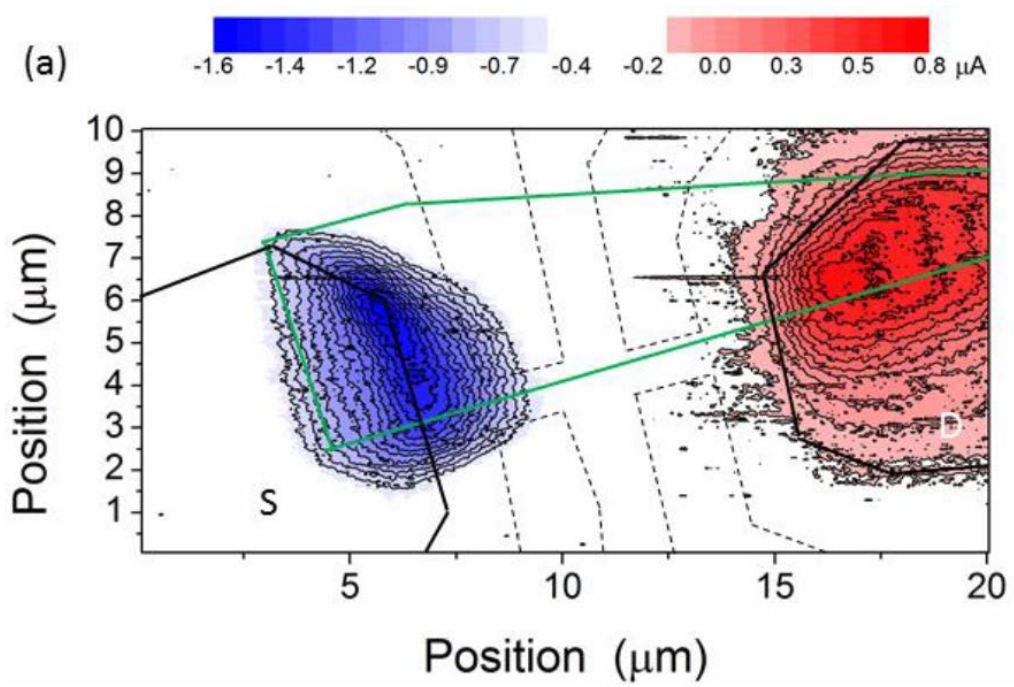


Spacegroup: Cmcm (#63)

a=3.9875Å, b=14.530Å, c=13.724Å

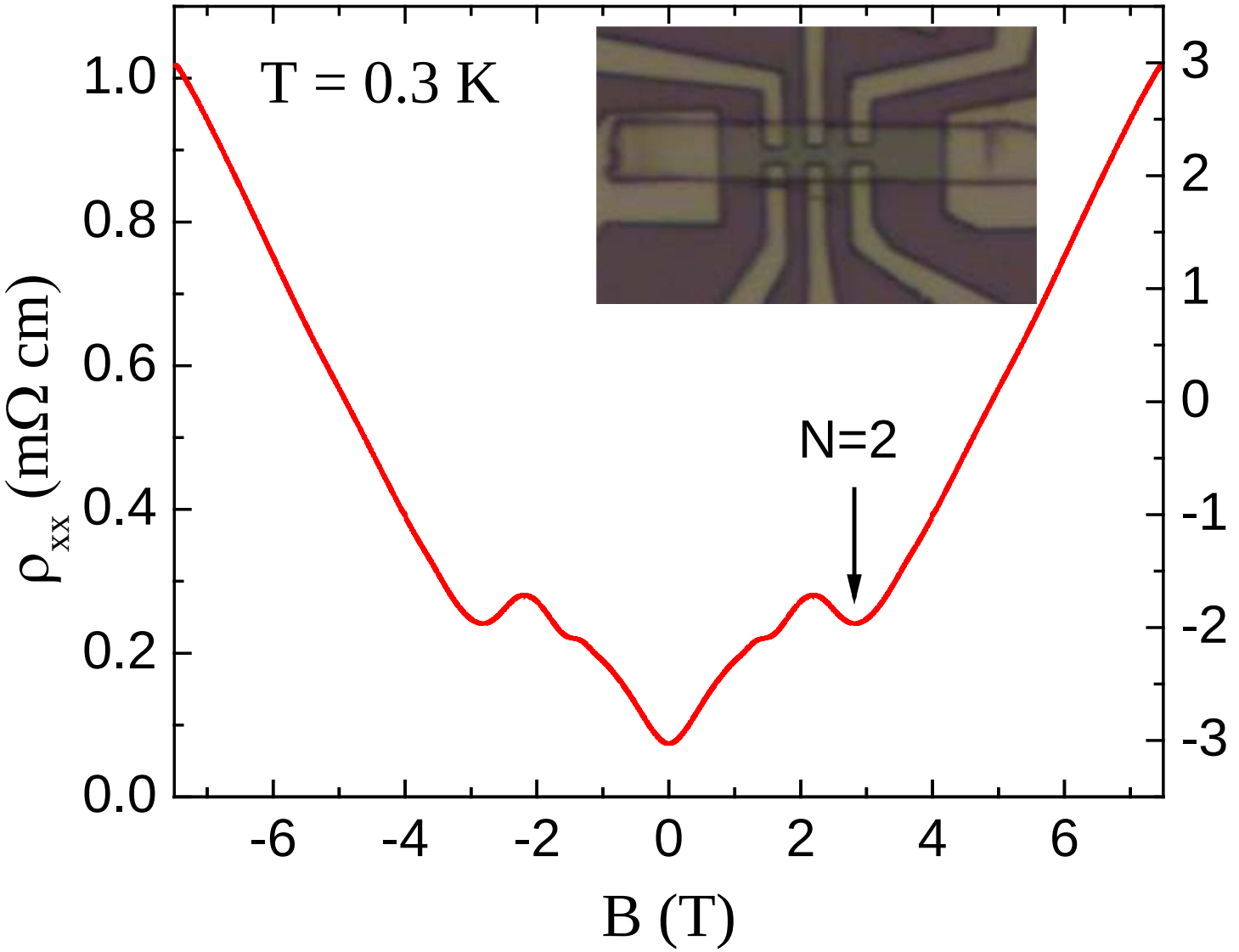
scanning photocurrent microscopy

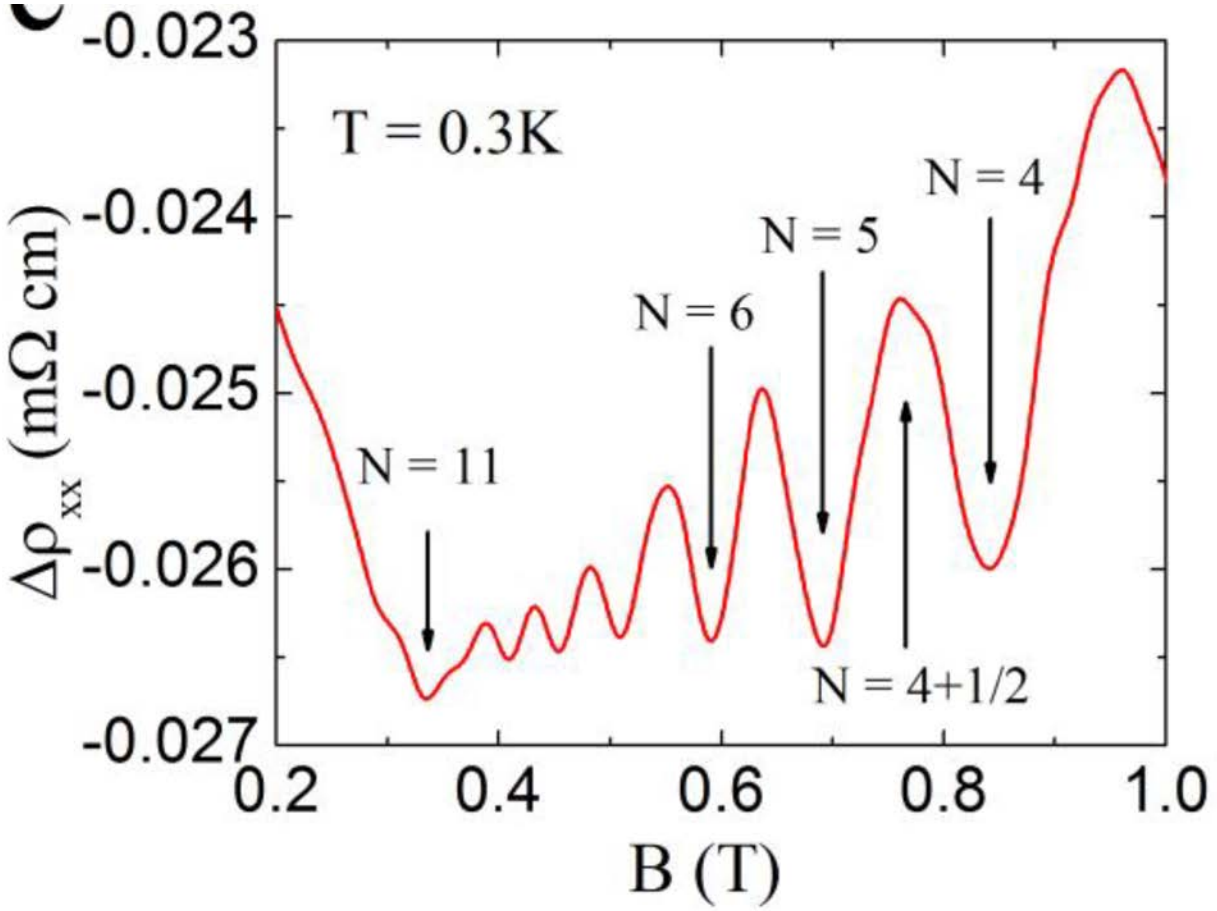


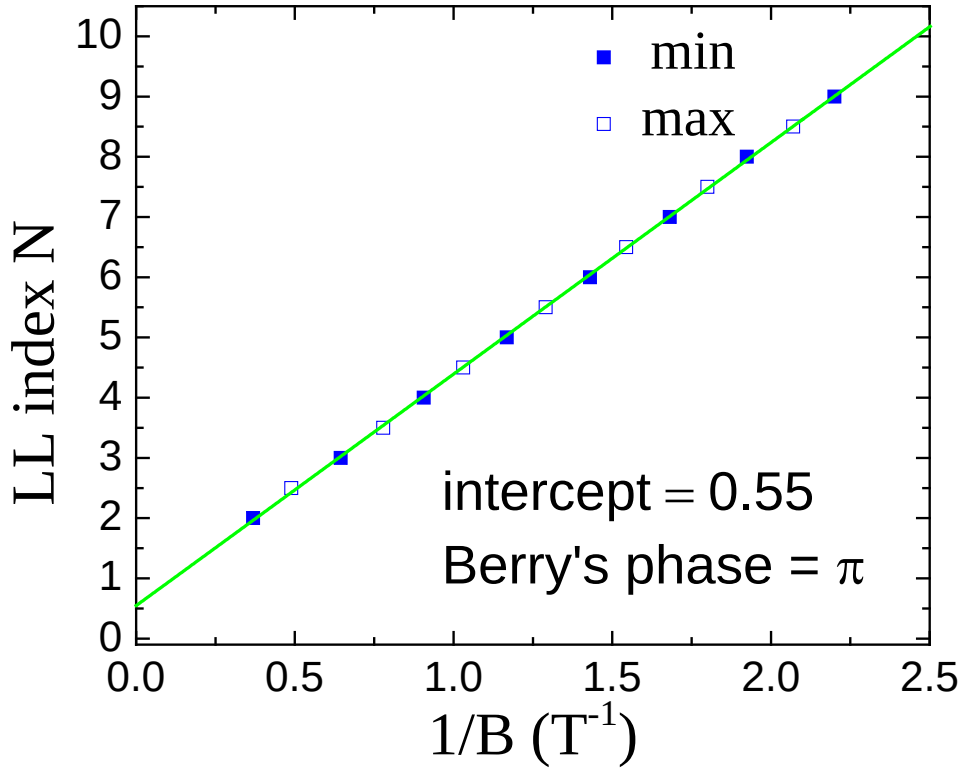


- a very strong photothermoelectric response under visible light illumination
- a responsivity as high as 74 V/W and a Noise-Equivalent Power as low as 42 $pW/Hz^{1/2}$ at room temperature.
- ZrTe5 a promising material to realize high performance, room-temperature, broadband, photodetectors.

Quantum oscillations in ZrTe5

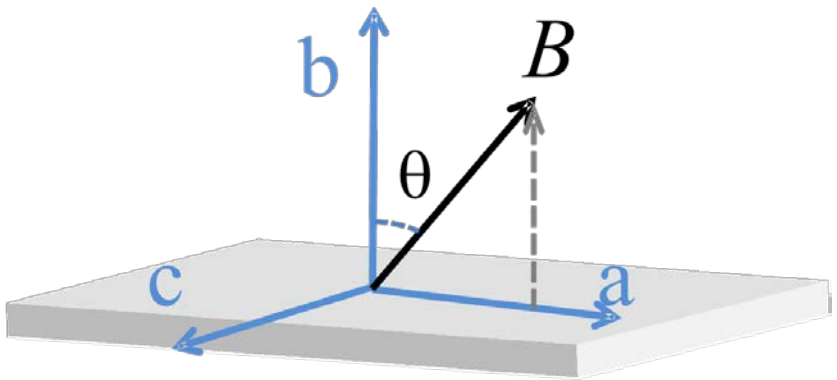




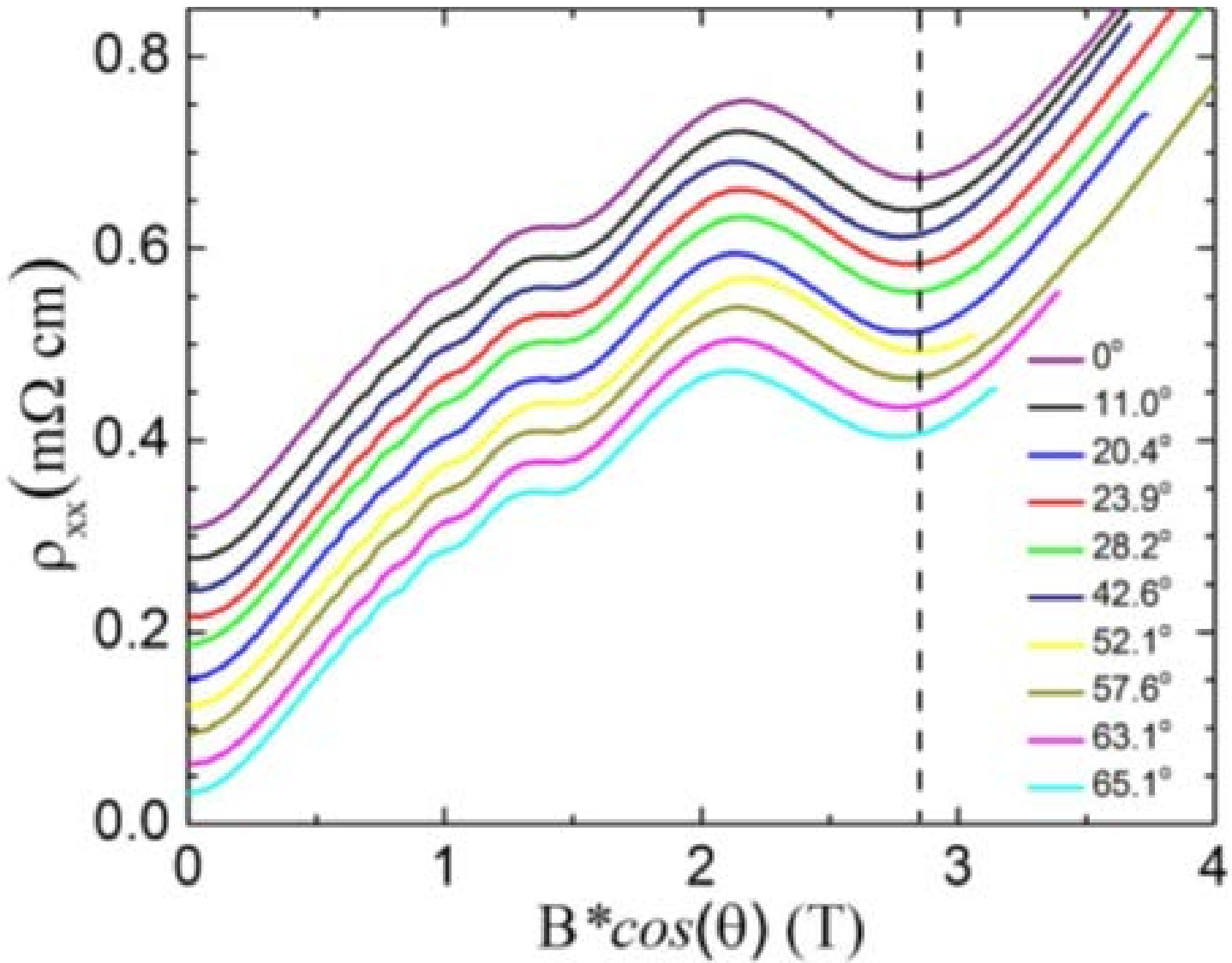


1. $\mu_q = 1/\mathrm{B} = 2.5 \times 10^4\ \mathrm{cm^2 V^{-1} s^{-1}}$

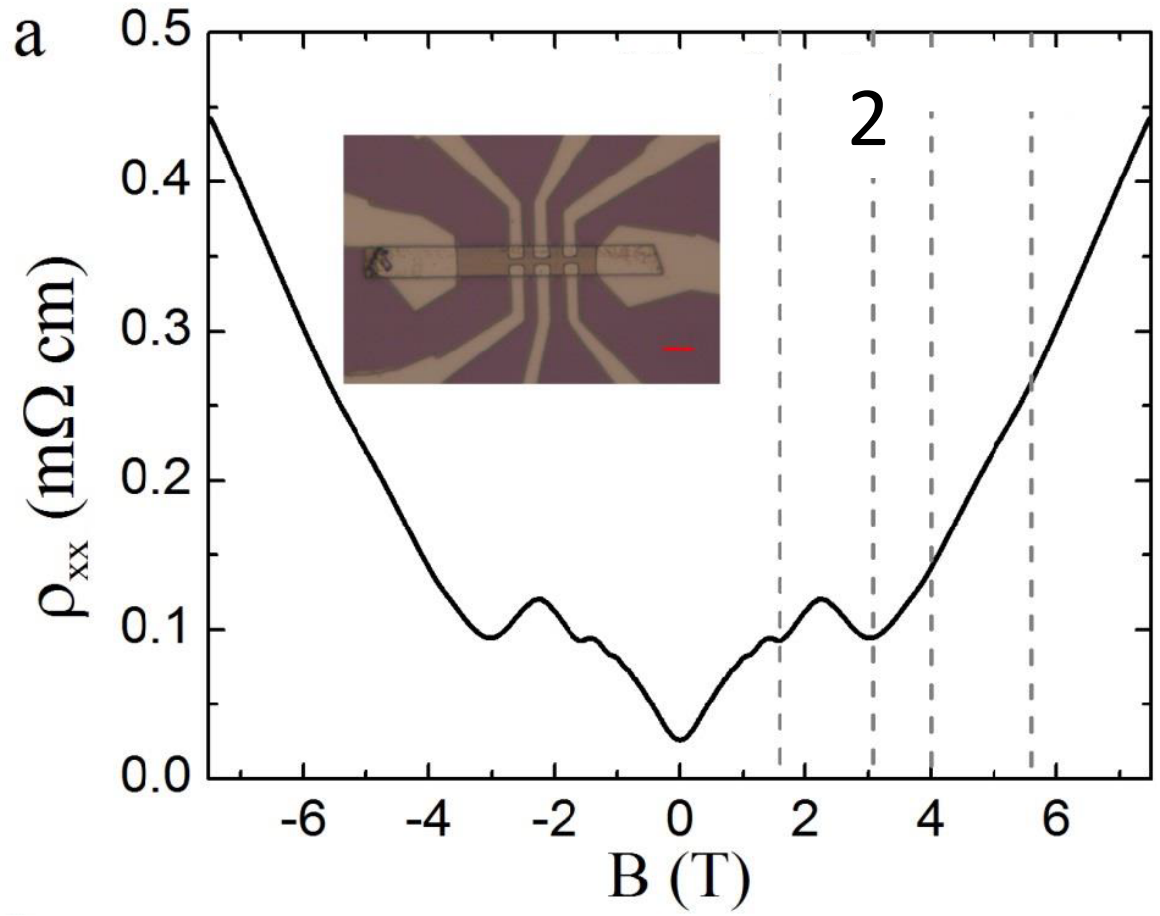
2. $n^{\mathrm{SdH}} = \frac{2e}{h}\frac{\mathrm{N}}{1/B} = 1.86 \times 10^{11}\ \mathrm{cm^{-2}}$

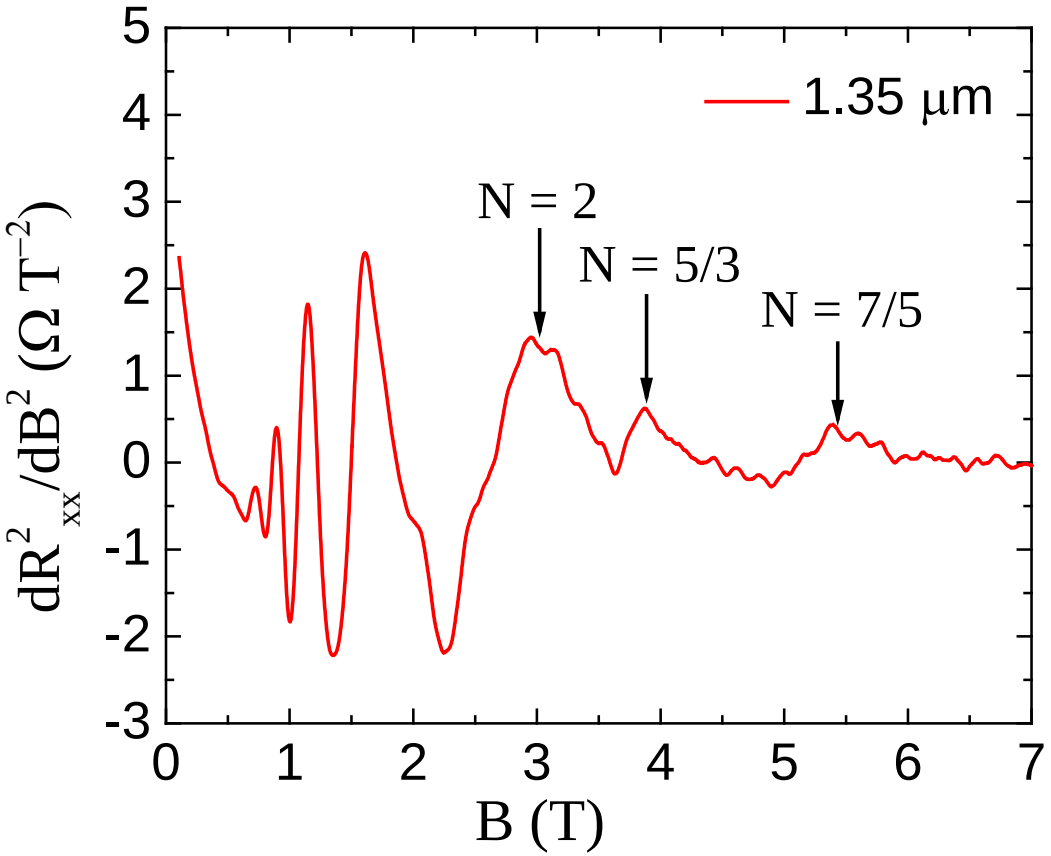


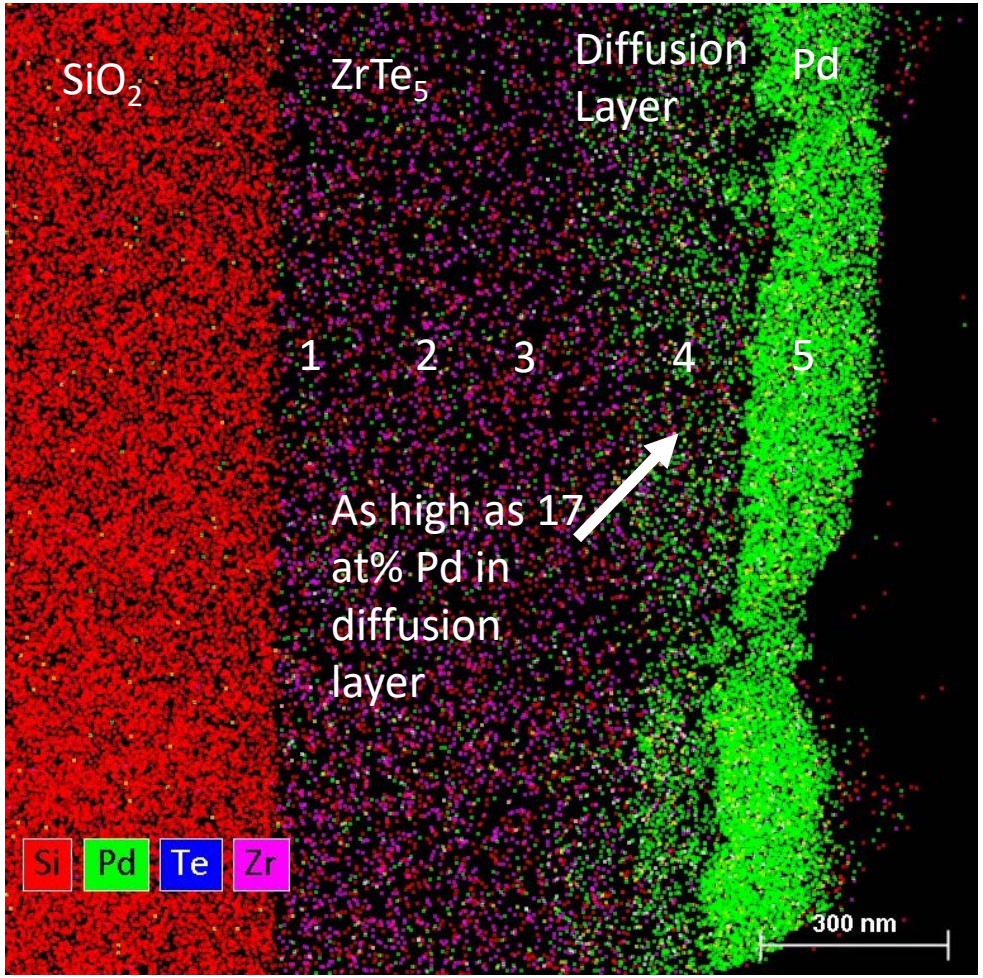
$B\perp = B * \cos(\theta)$



Quantum Oscillations at Fractional Landau levels





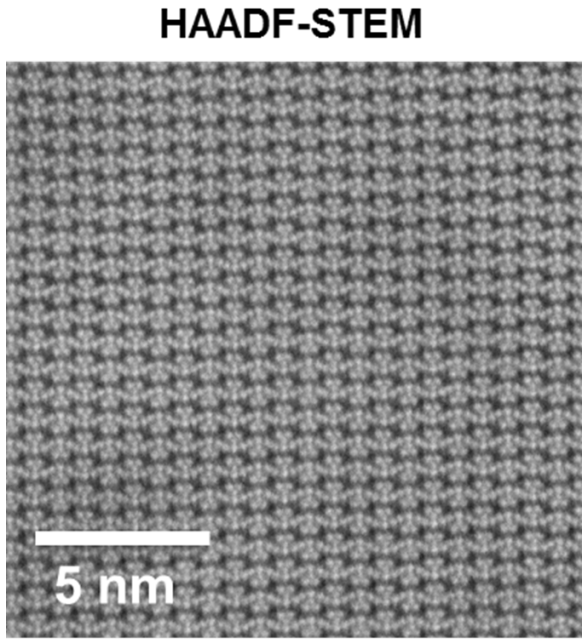


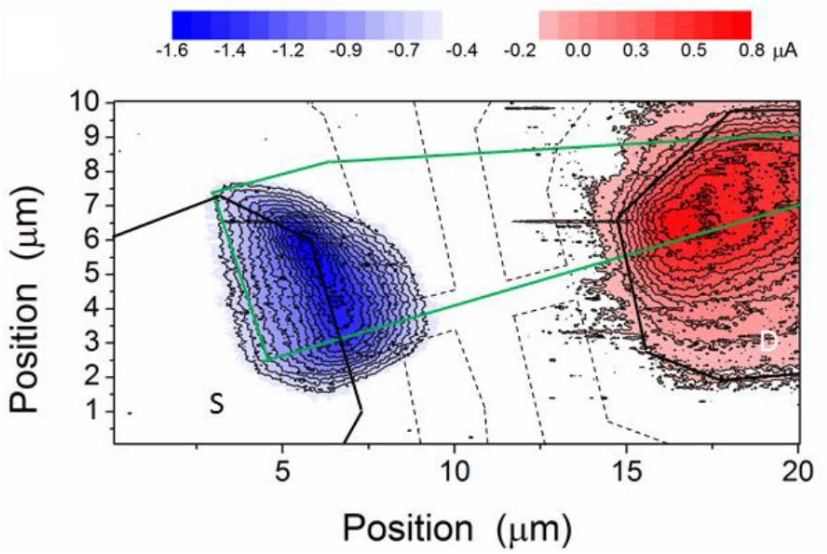
Pd–containing ZrTe5 does not show evidence for additional phases (from diffraction studies), consistent with Pd diffusing in based on our DFT calculations.

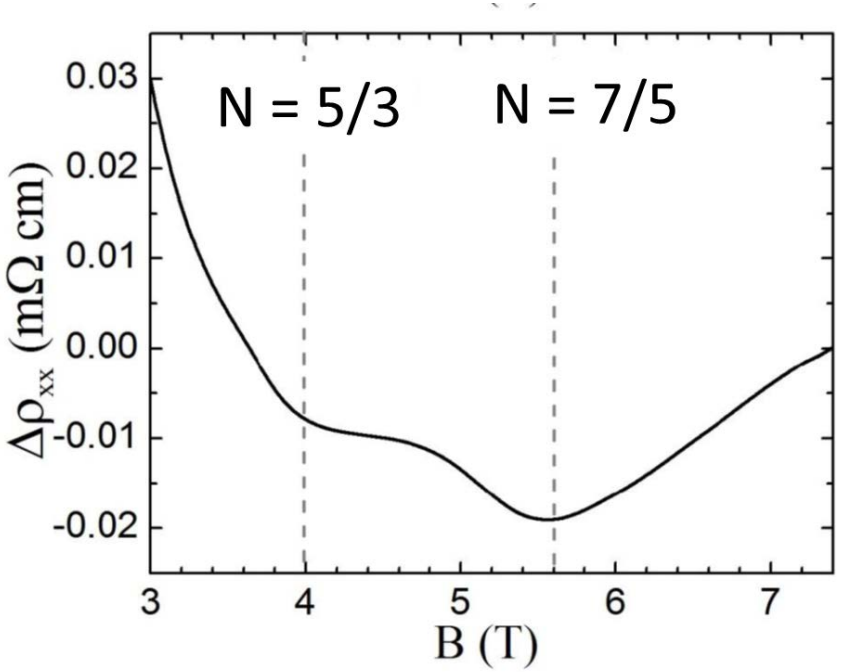
DFT calculations:

- No evidence of Pd reacting with ZrTe5
- Suggestions of Pd diffusing into ZrTe5
- Ionic radius of Pd^{+2} ~ 86-100 pm

Summaries of experimental results in $ZrTe_5$







Quantum transport studies in Cd_3As_2

PHYSICAL REVIEW B VOLUME 15, NUMBER 8 15 APRIL 1977

Band structure of cadmium arsenide at room temperature*

M. J. Aubin, L. G. Caron, and J.-P. Jay-Gerin†
Groupe de Recherche sur les Semiconducteurs et les Diélectriques et Département de Physique, Université de Sherbrooke, Sherbrooke, Québec, Canada, J1K 2R1
(Received 5 October 1976)

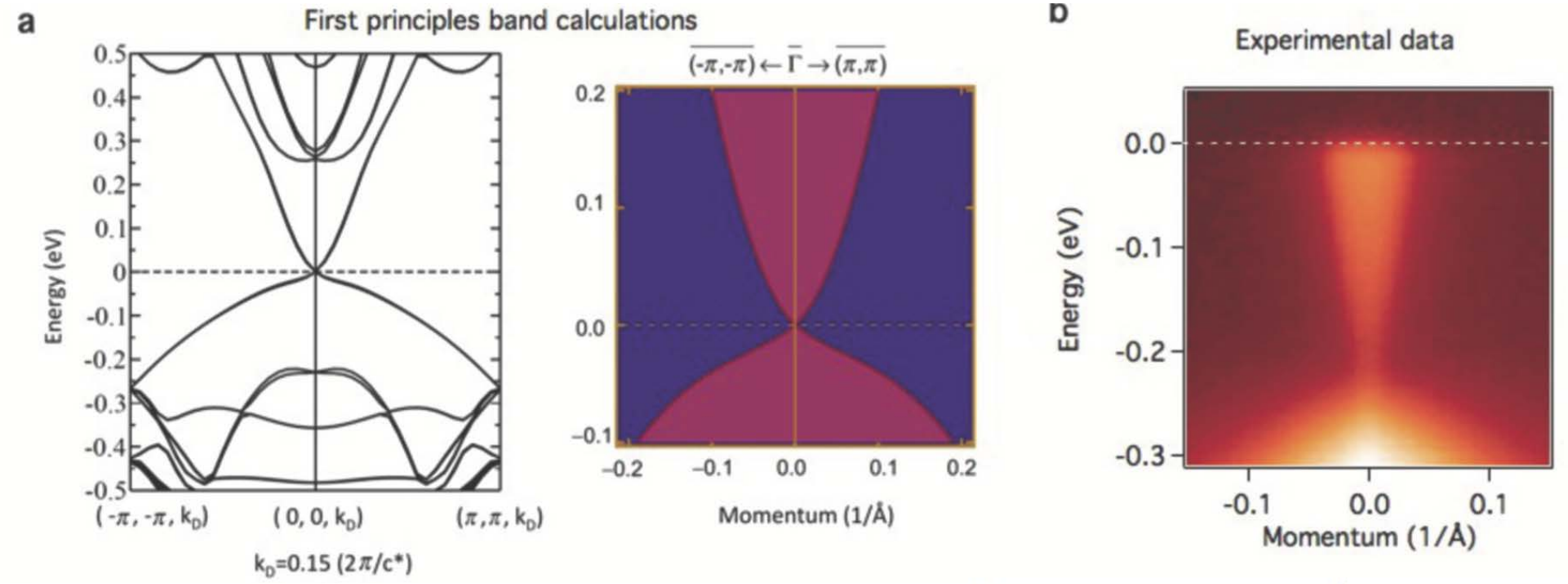
I. INTRODUCTION

Cadmium arsenide (Cd_3As_2) has long been considered an unusual semiconductor because of its high electronic mobility and the large number of carriers always present. At room temperature, mobilities of 10 000 cm^2/V sec have been reported[1-13] with 2×10^{18} electrons/cm^3. An impressive amount of data on this compound has accumulated in the literature over the years, but a convincing model for the band structure which would satisfy all these data and all workers involved has not been forthcoming. The situation has been com-

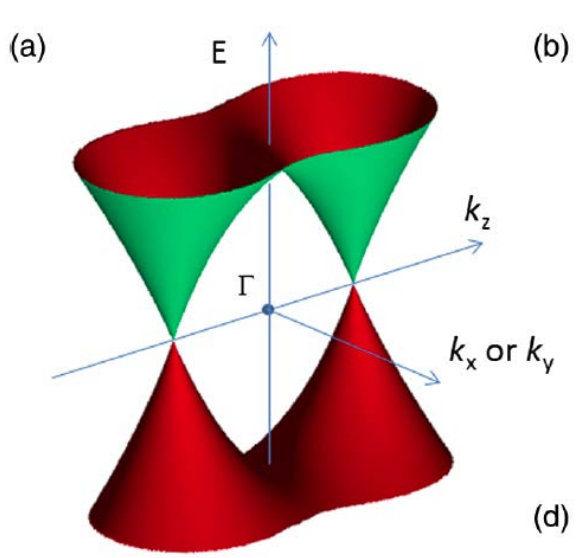
Wang et al. Three-dimensional Dirac semimetal and quantum transport in Cd3As2. Phys. Rev. B 88, 125427 (2013).

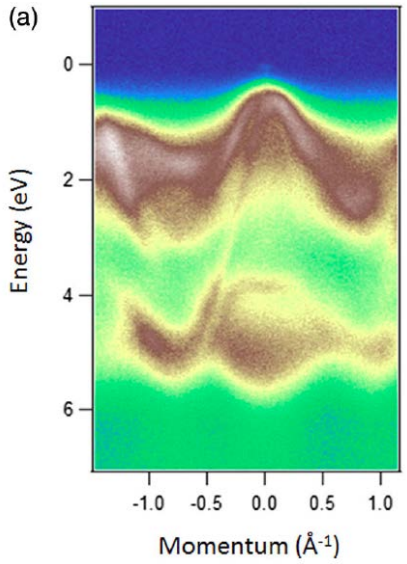
Cd_3As_2 is a 3D Dirac semimetal, protected by the C4 symmetry and spin-orbit coupling.

Neupane et al Nature Commun. 5, 3786 (2014).

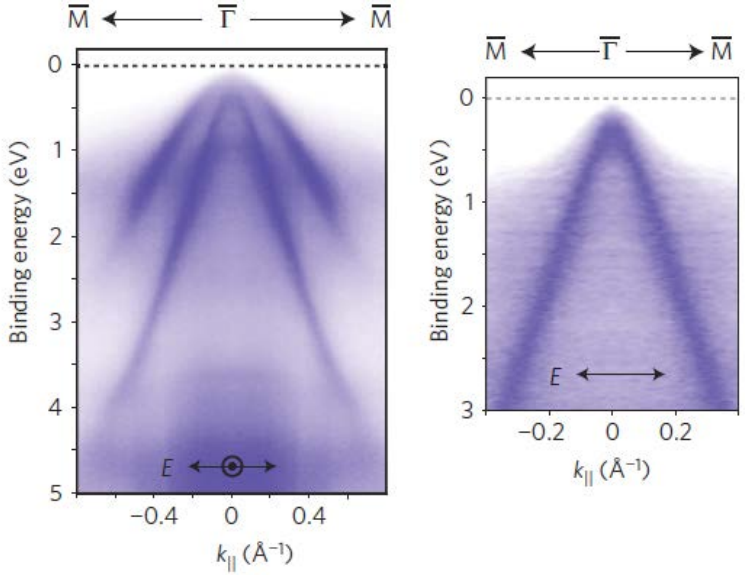


Borisen et al, PRL 113m 027603 (2014)

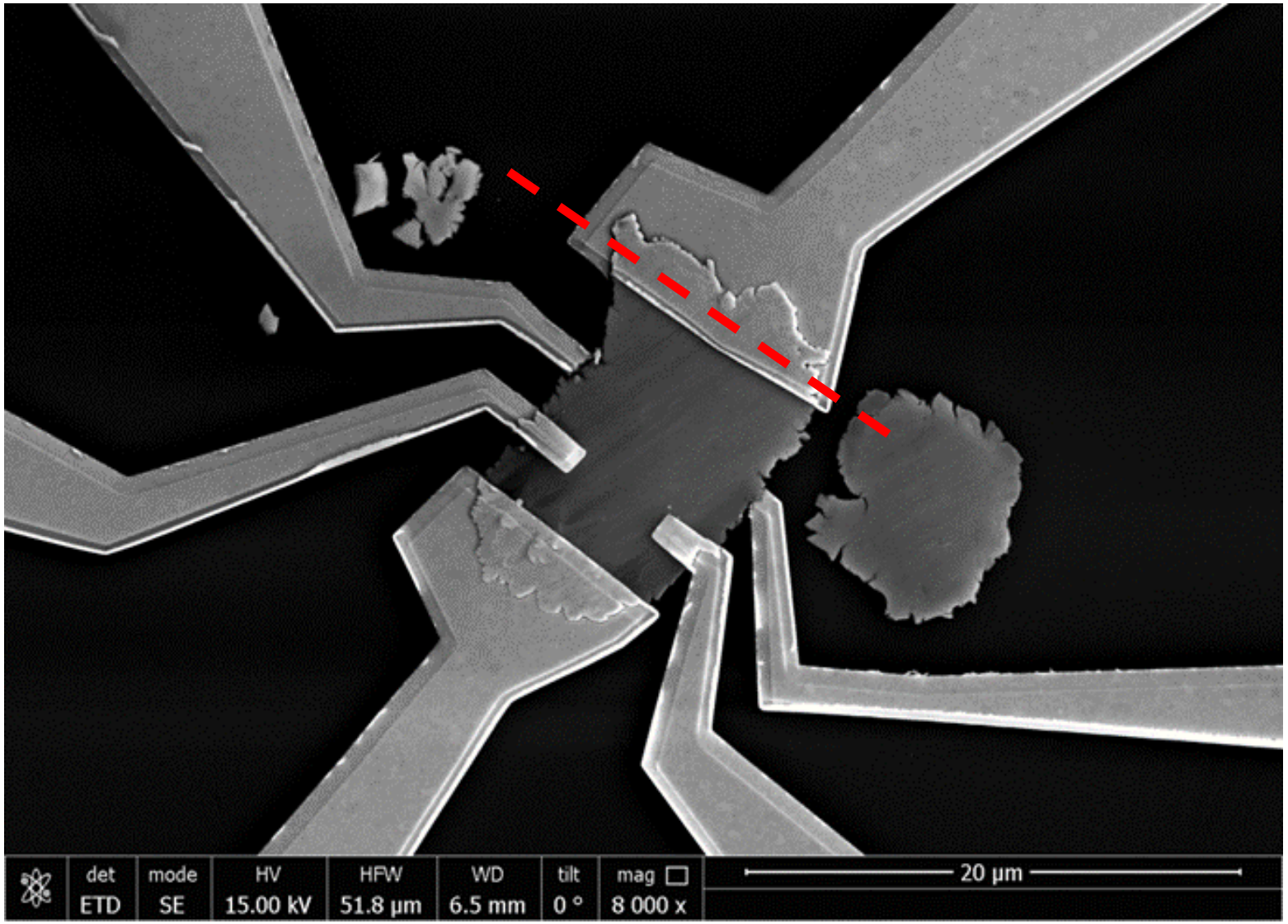




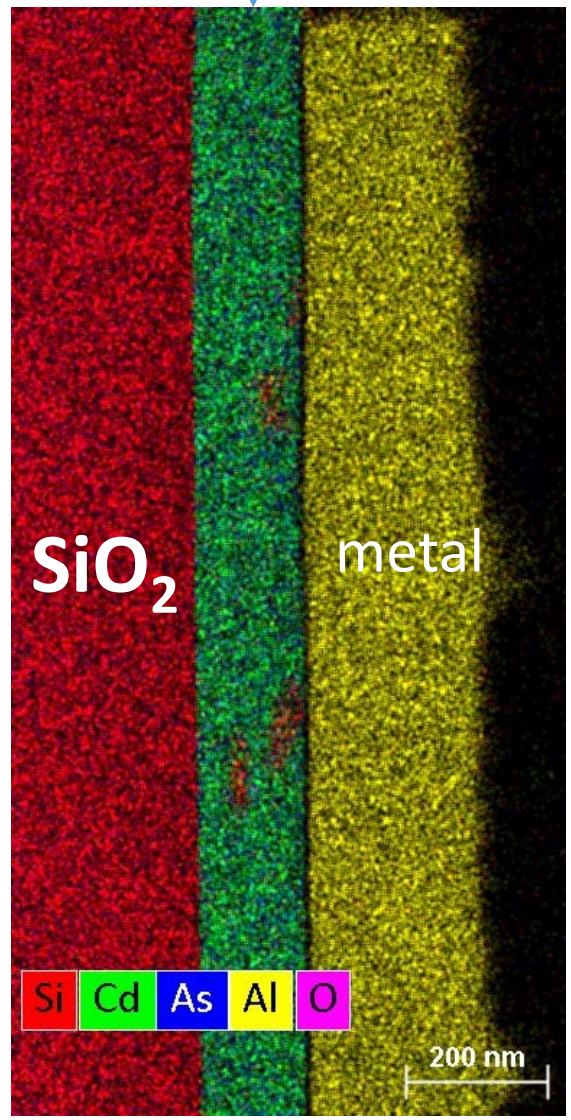
Liu et al, Nature Mat. (2014).



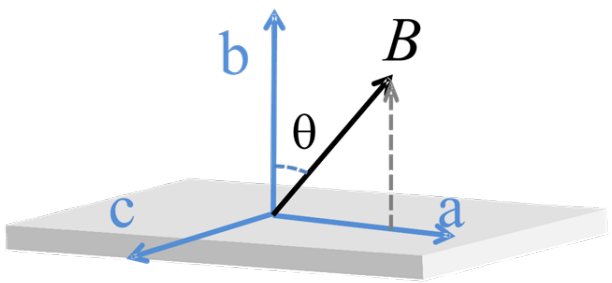
micro-platelet device



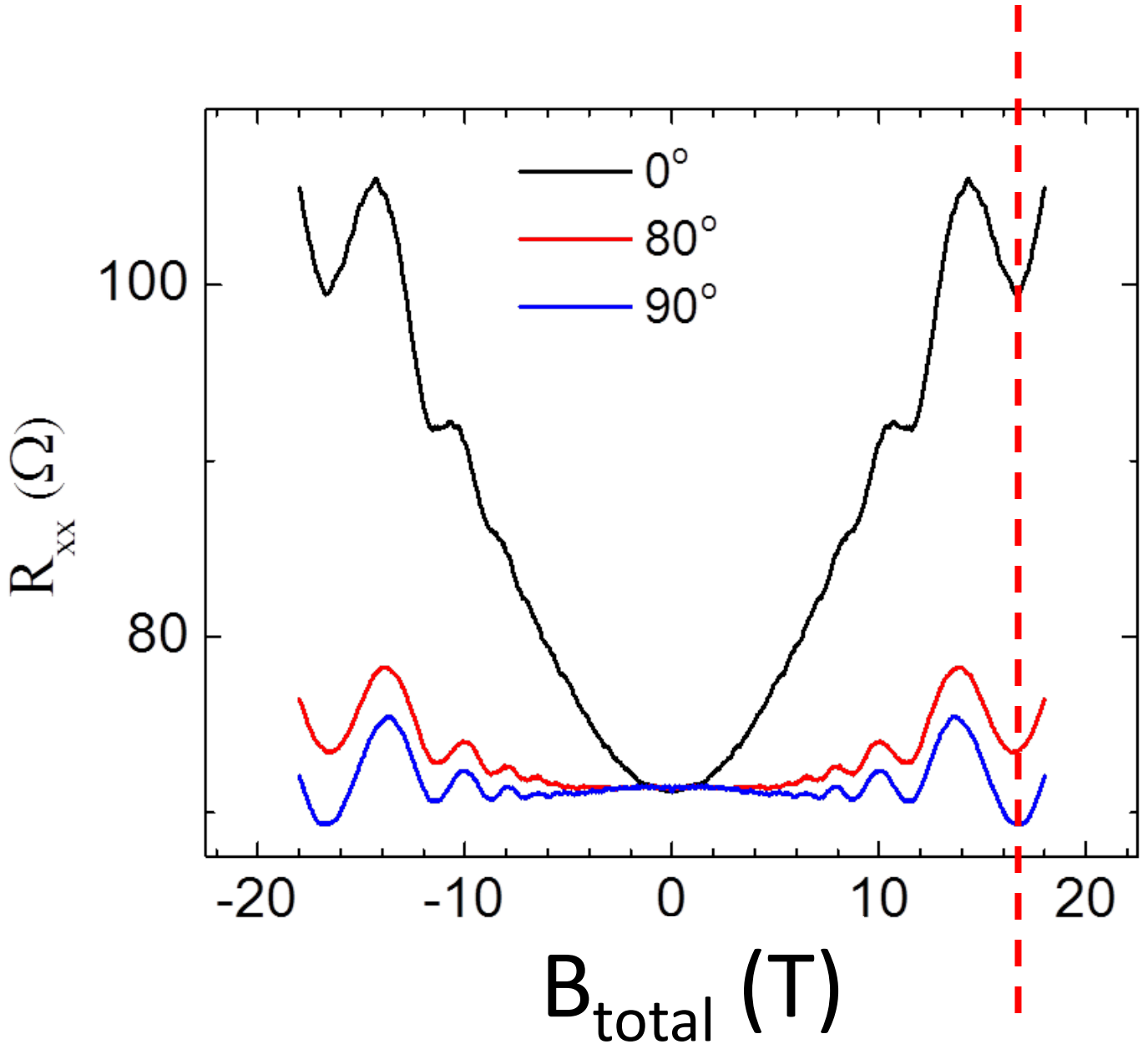
Cd_3As_2

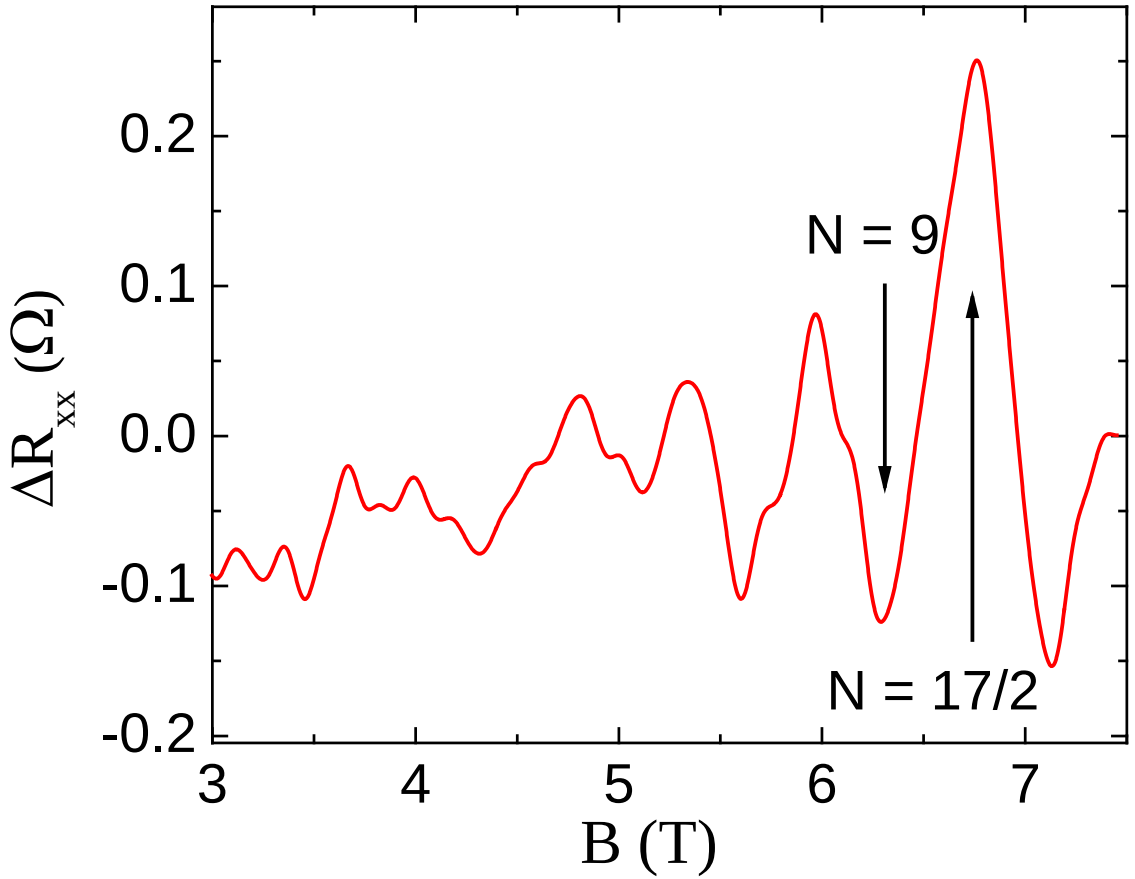


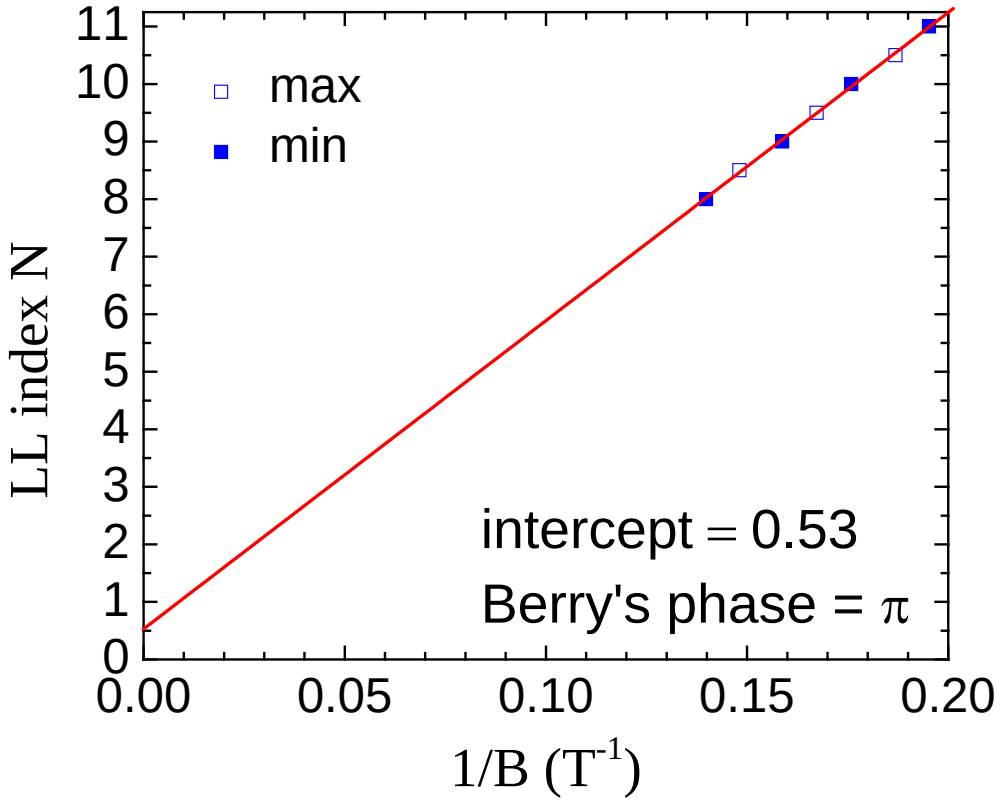
3D nature

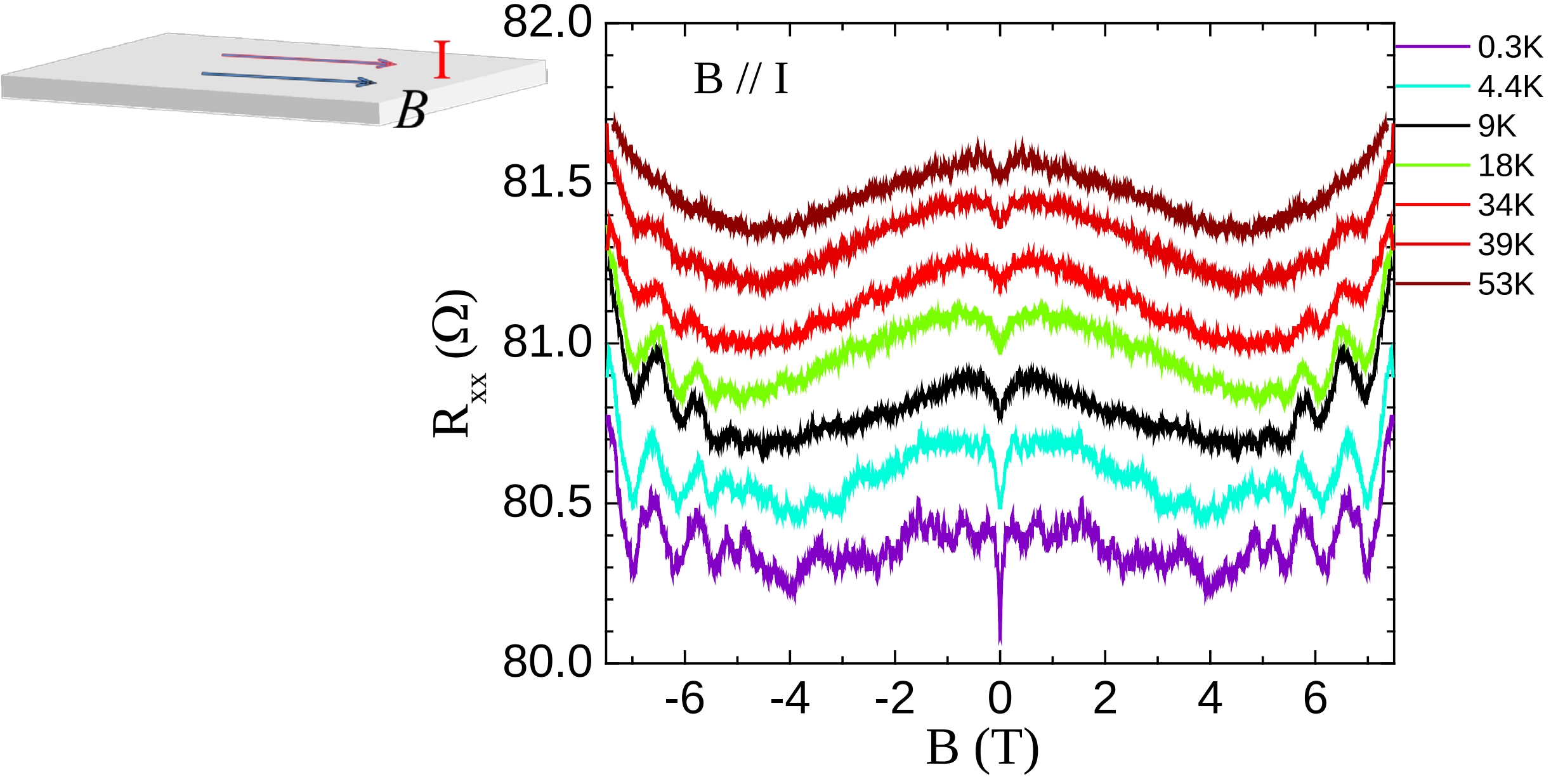


$B\perp = B * \cos(\theta)$

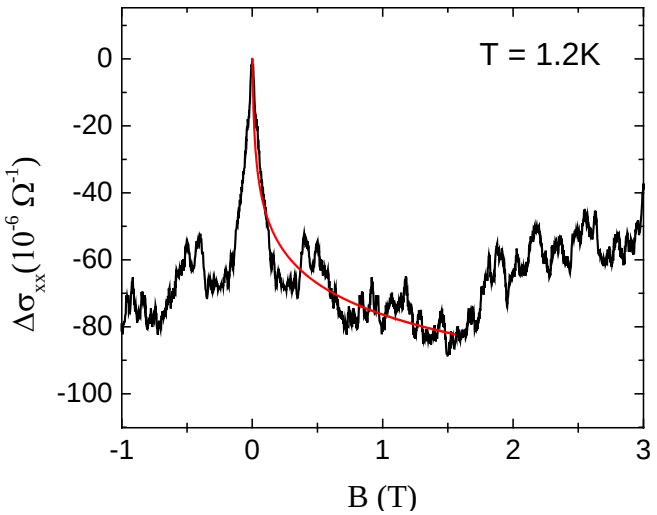


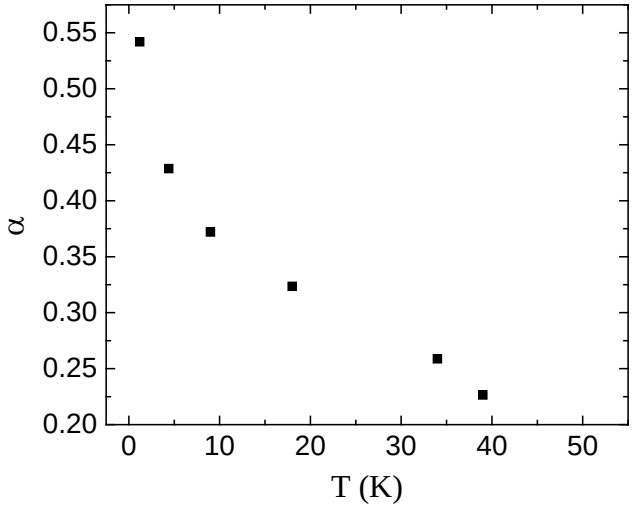

0.2
0.1
0.0
-0.1
-0.2
ΔR_xx (Ω)
N = 9
N = 17/2
3
4
5
6
7
B (T)


11
10
9
8
7
6
5
4
3
2
1
0
LL index N
max
min
intercept = 0.53
Berry's phase = π
0.00
0.05
0.10
0.15
0.20
1/B (T^-1)


I
B
B // I
82.0
81.5
81.0
80.5
80.0
R_{xx} (Ω)
-6
-4
-2
0
2
4
6
B (T)
0.3K
4.4K
9K
18K
34K
39K
53K

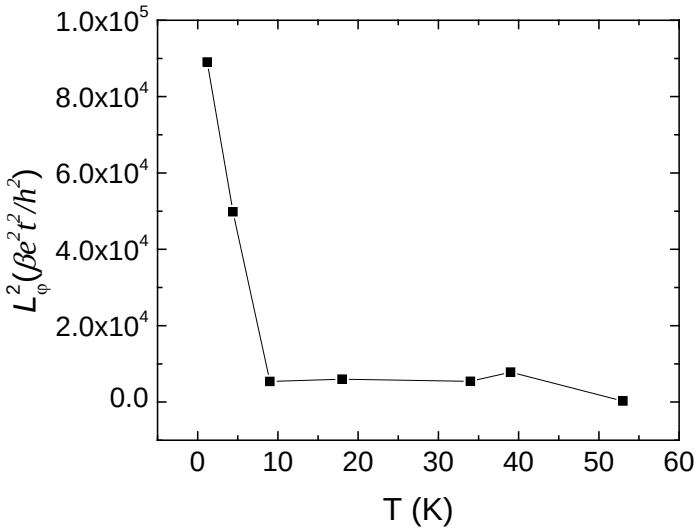
Weak anti-localization





$$\Delta\sigma_{||}(B) \cong \alpha\frac{-e^2}{2\pi^2\hbar}\ ln\left(1+\beta\frac{et^2}{4\hbar B_\varphi}B^2\right)$$

$$B_\varphi = \hbar/\left(4eL_\varphi^2\right)$$



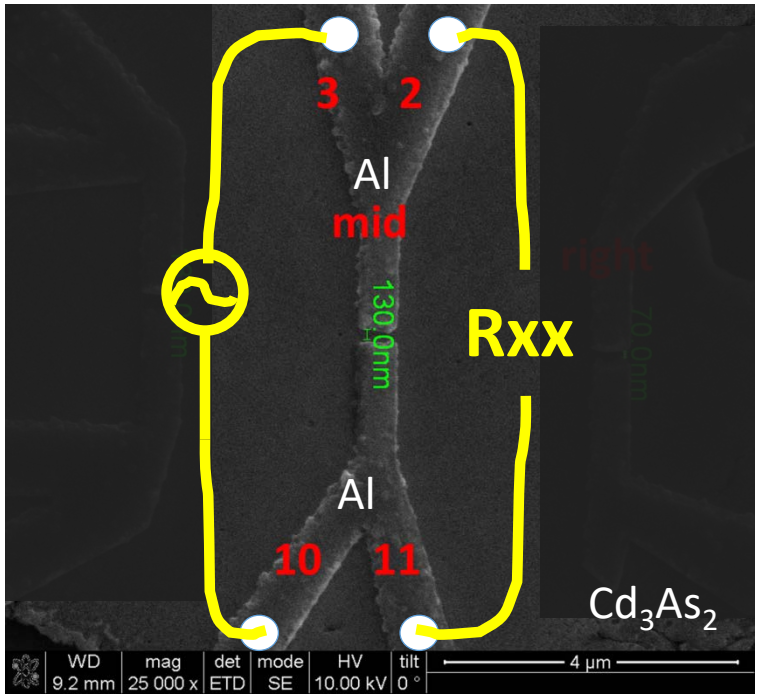
Conventional materials: $\alpha = -1$

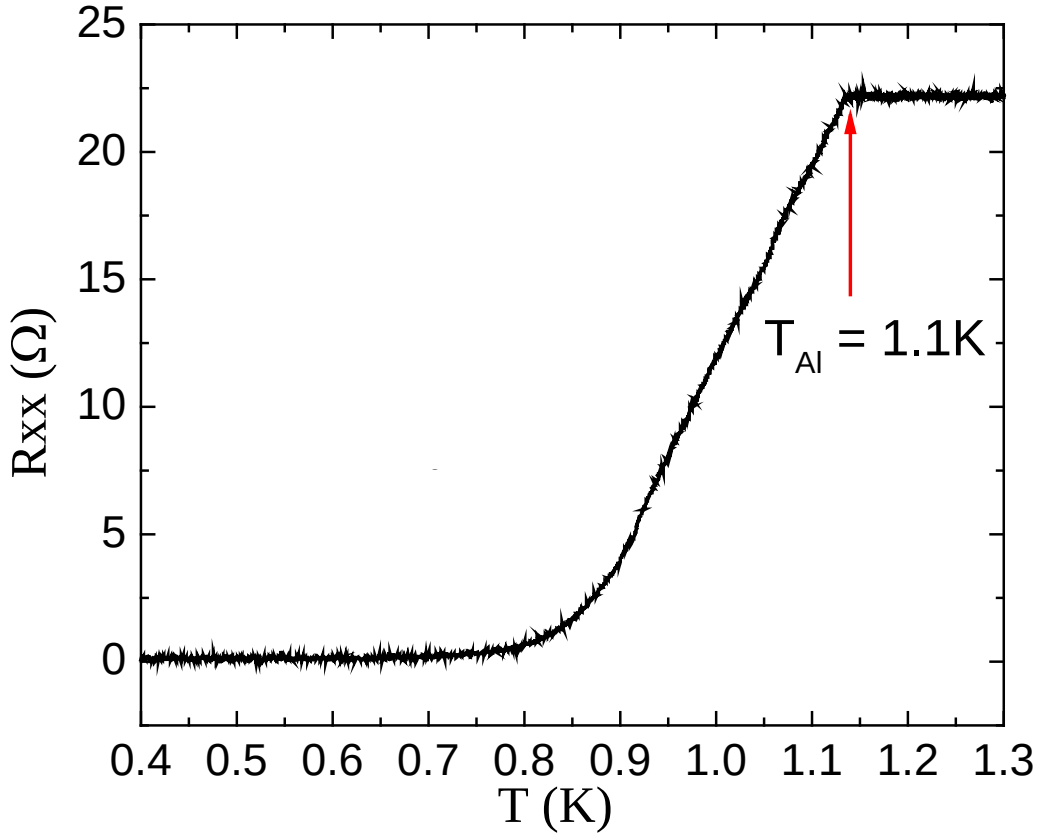
Dirac materials: $\alpha = 0.5$

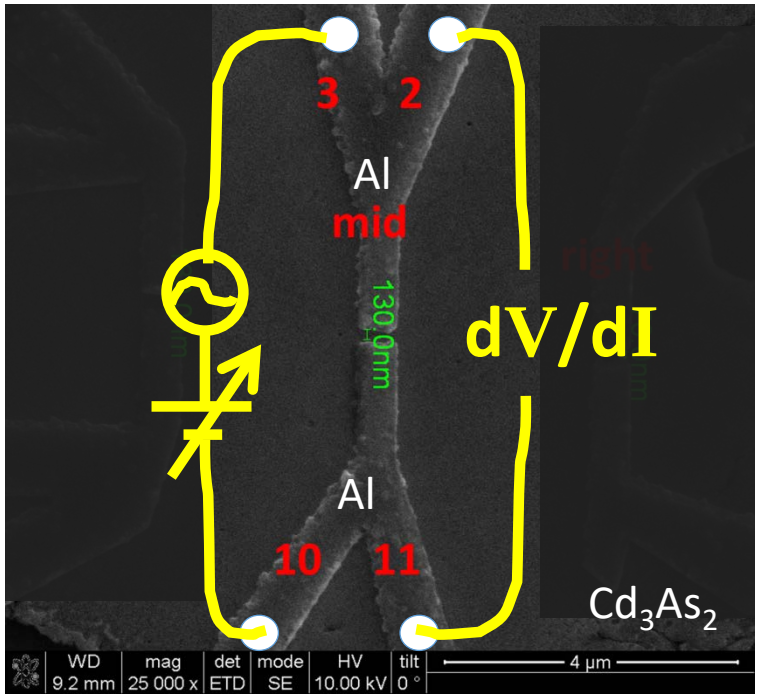
Zhao, B. *et al. Scientific Reports* **6**, 22377,(2016)

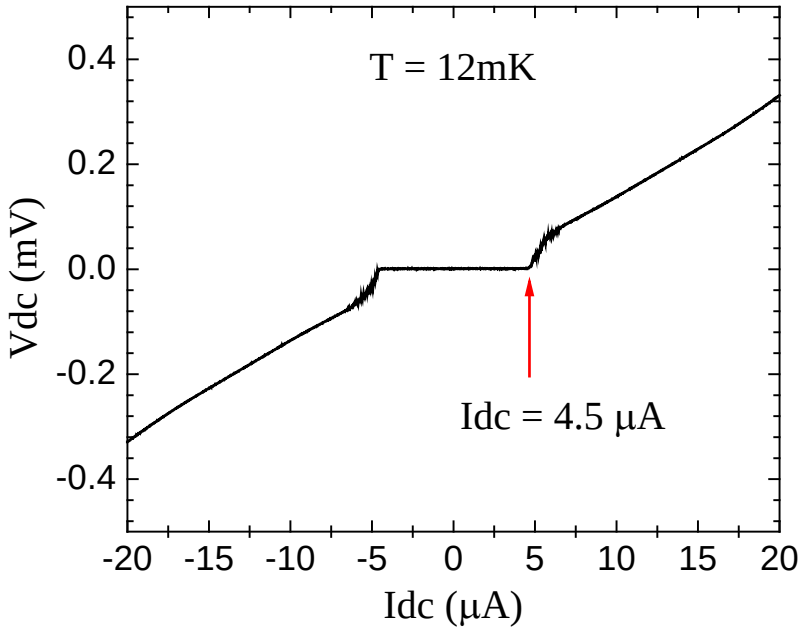
Proximity induced superconductivity in Cd_3As_2

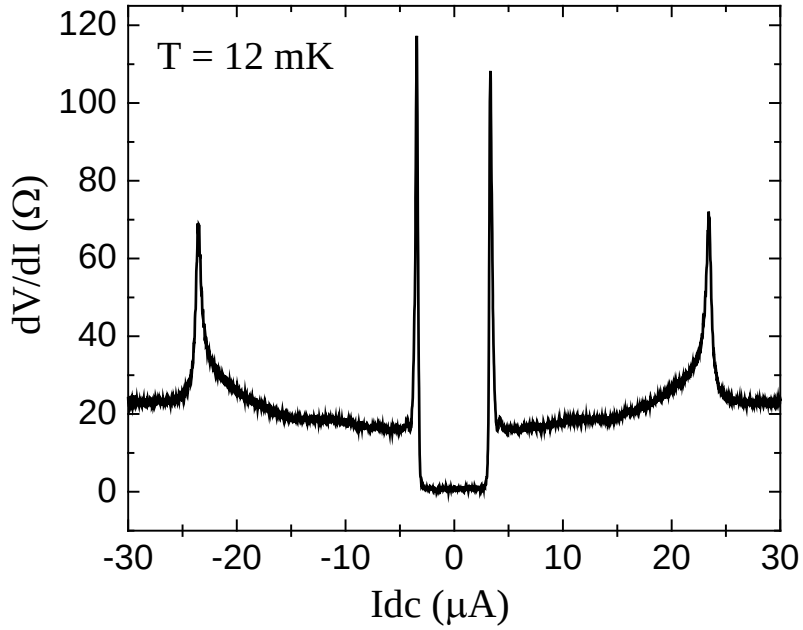
L. Fu and C.L. Kane,
Superconducting Proximity Effect and Majorana Fermions at the Surface of a Topological Insulator,
Physical Review Letters 100, 096407 (2008).

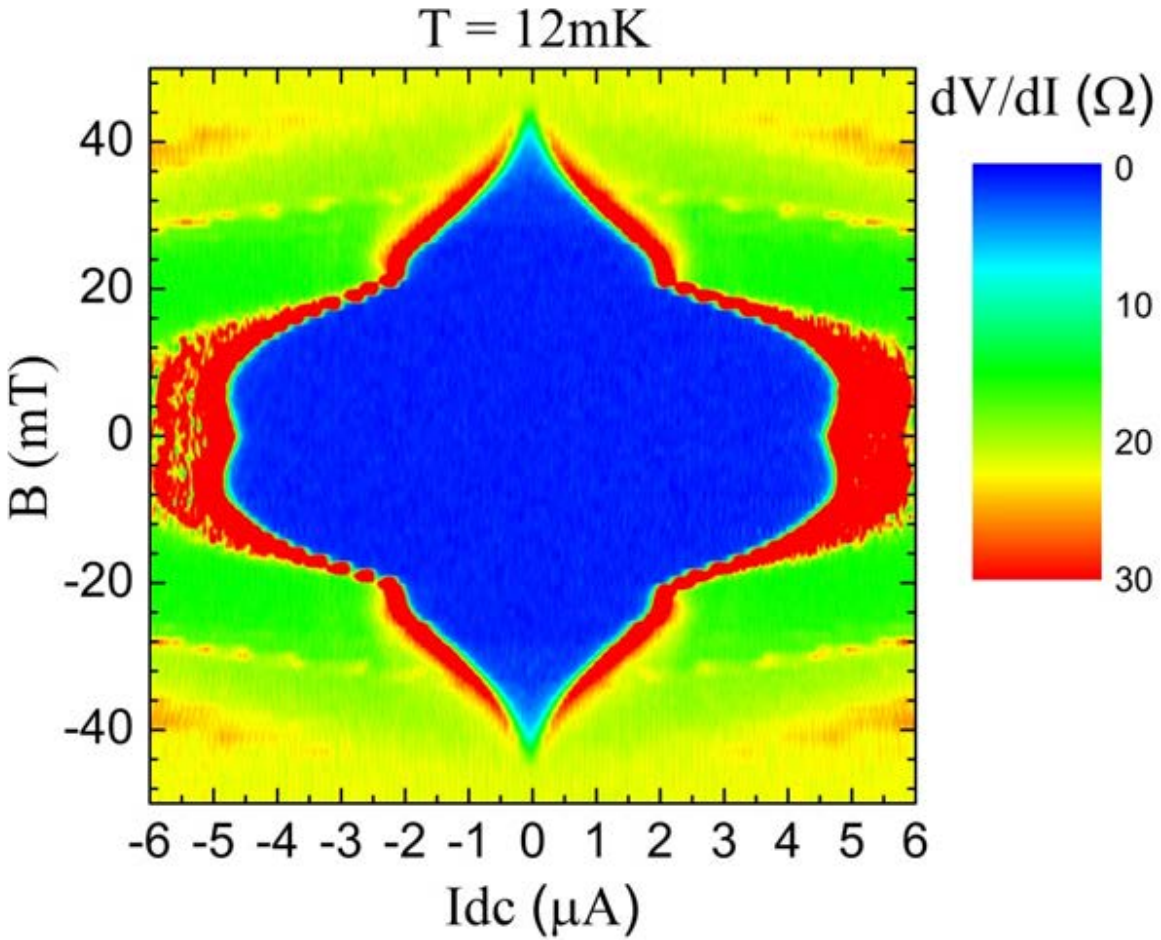

3
2
Al
mid
130.0nm
Rxx
Al
10
11
Cd3As2
WD
9.2 mm
mag
25 000 x
det
ETD
mode
SE
HV
10.00 kV
tilt
0 °
4 µm

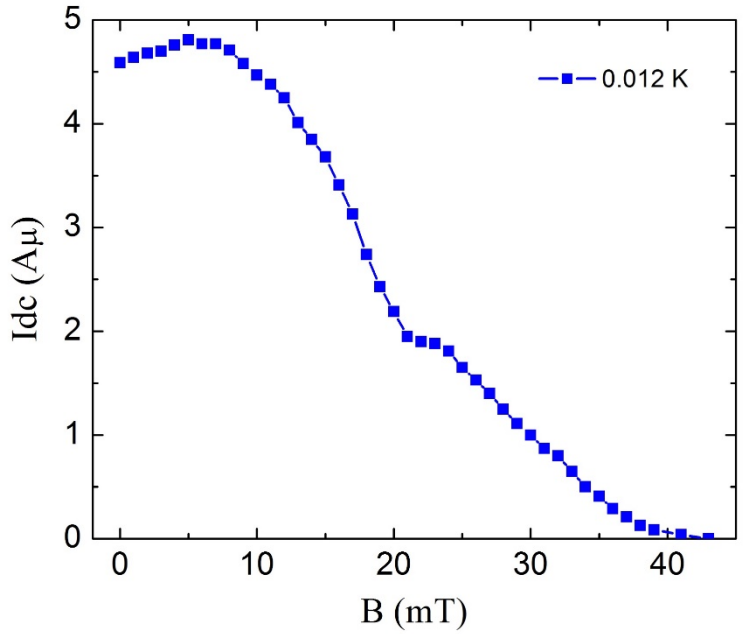

25
20
15
10
5
0
Rxx (Ω)
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
T (K)
T_Al = 1.1K

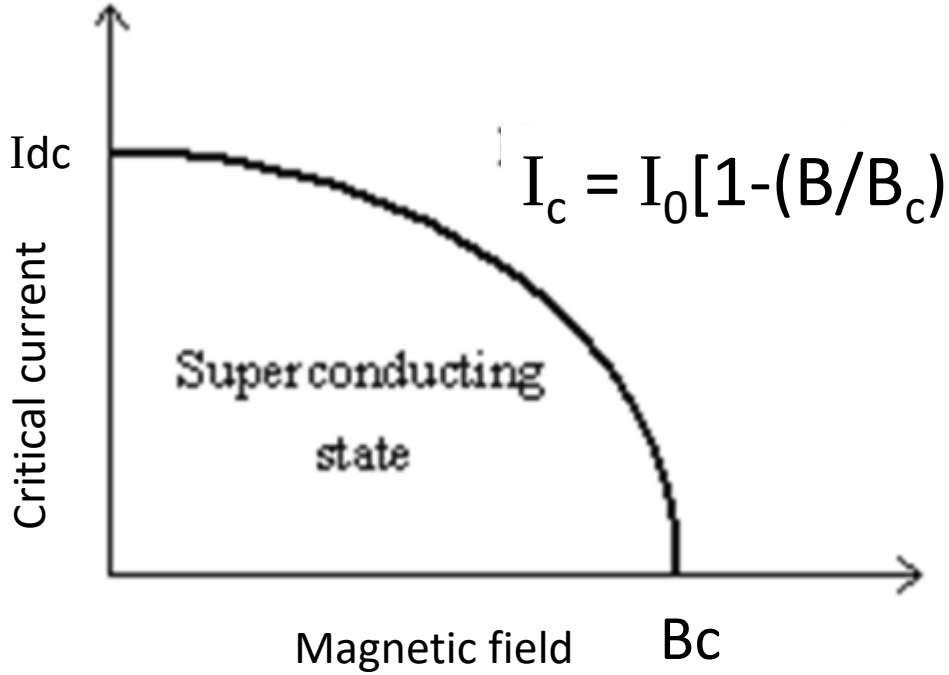

3
2
Al
mid
130.0nm
dV/dI
Al
10
11
Cd3As2
WD 9.2 mm
mag 25 000 x
det ETD
mode SE
HV 10.00 kV
tilt 0 °
4 µm


T = 12mK
Idc = 4.5 µA
Vdc (mV)
Idc (µA)
0.4
0.2
0.0
-0.2
-0.4
-20
-15
-10
-5
0
5
10
15
20


T = 12 mK
dV/dI (Ω)
Idc (µA)
120
100
80
60
40
20
0
-30
-20
-10
0
10
20
30

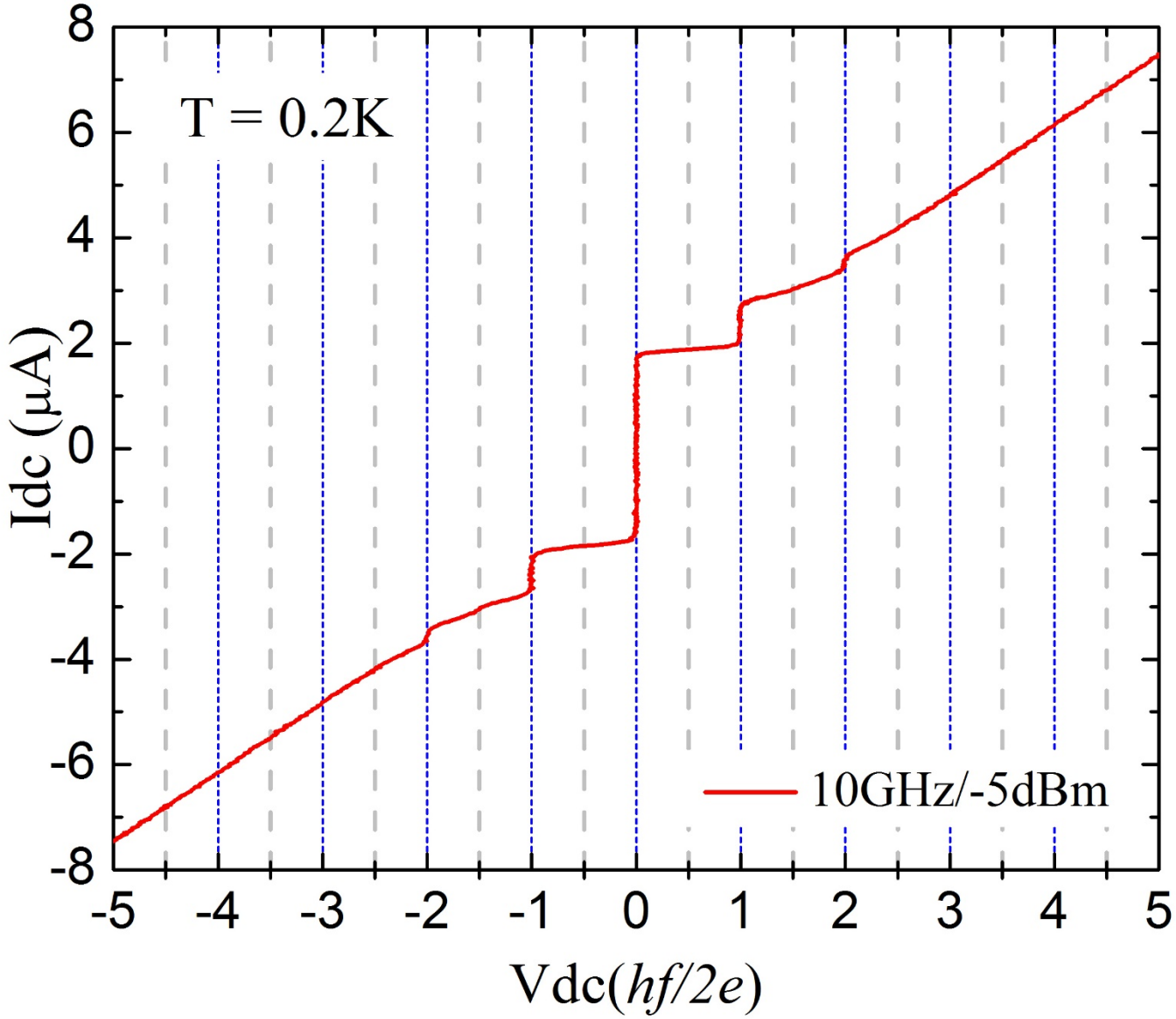

T = 12mK
dV/dI (Ω)
0
10
20
30
B (mT)
40
20
0
-20
-40
-6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6
Idc (μA)


0.012 K
Idc (Aμ)
5
4
3
2
1
0
0 10 20 30 40
B (mT)


Idc
Critical current
Superconducting
state
Magnetic field
Bc

$$I_c = I_0[1-(B/B_c)^2]$$

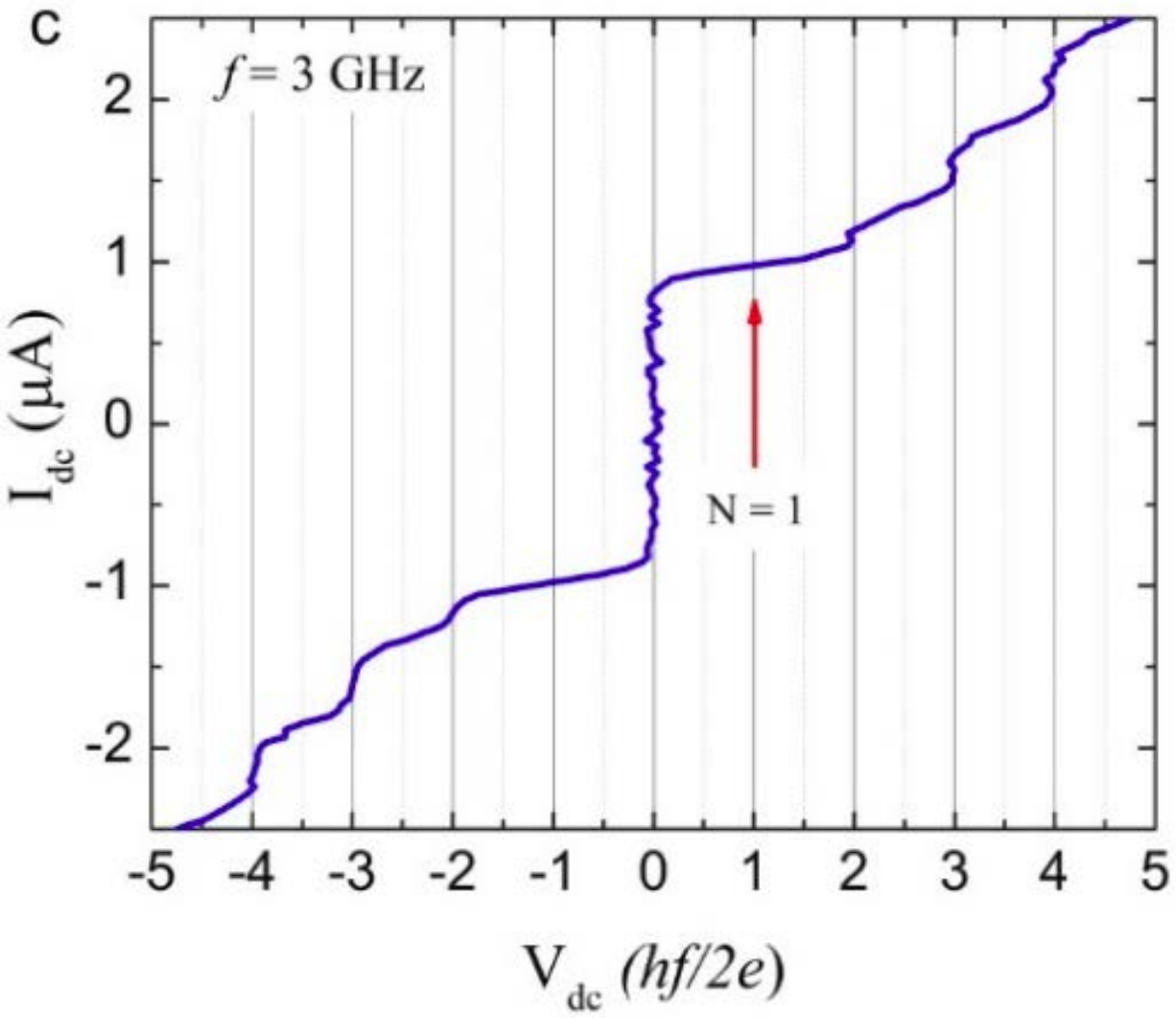
AC Measurements

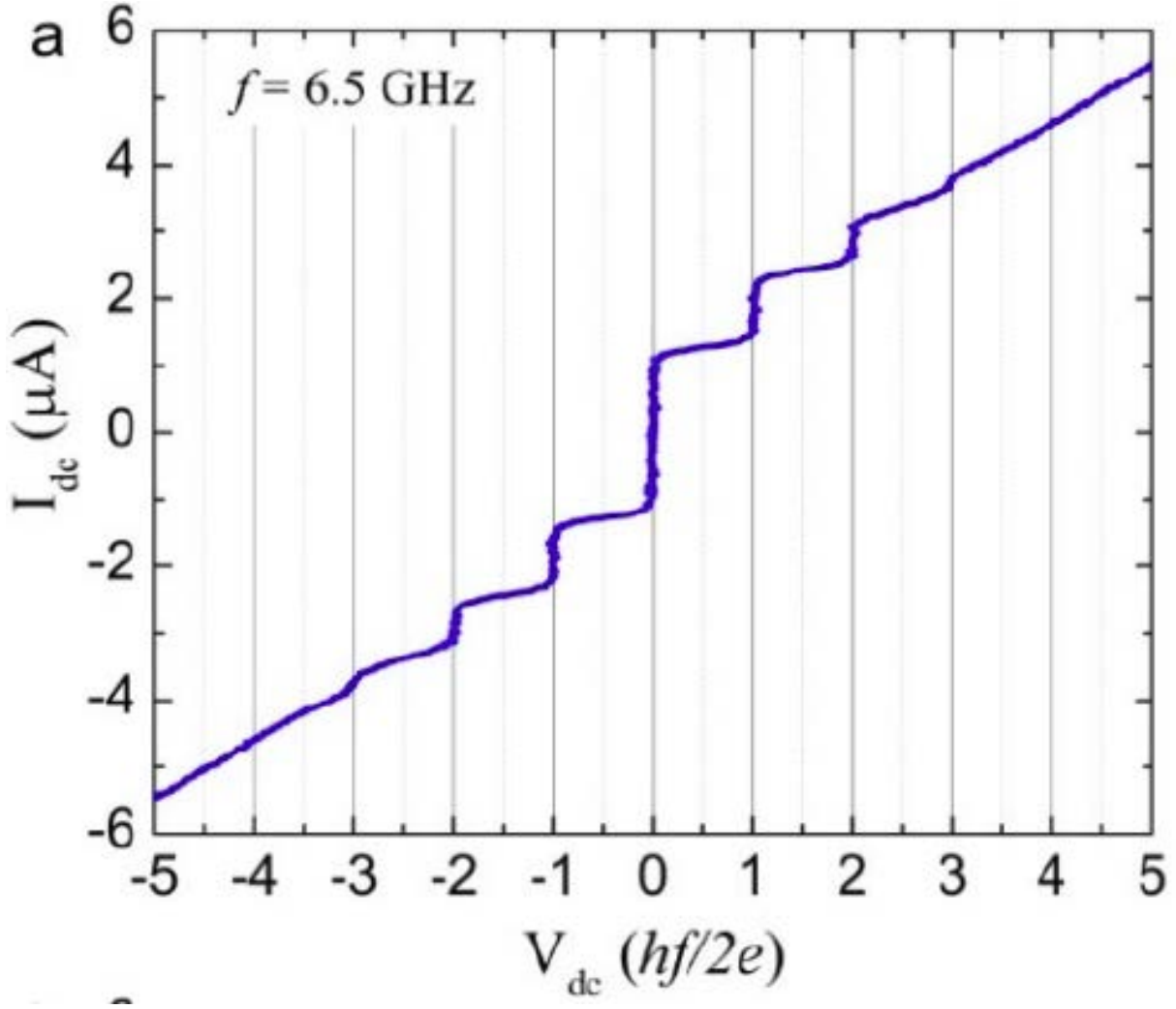


Shapiro steps:

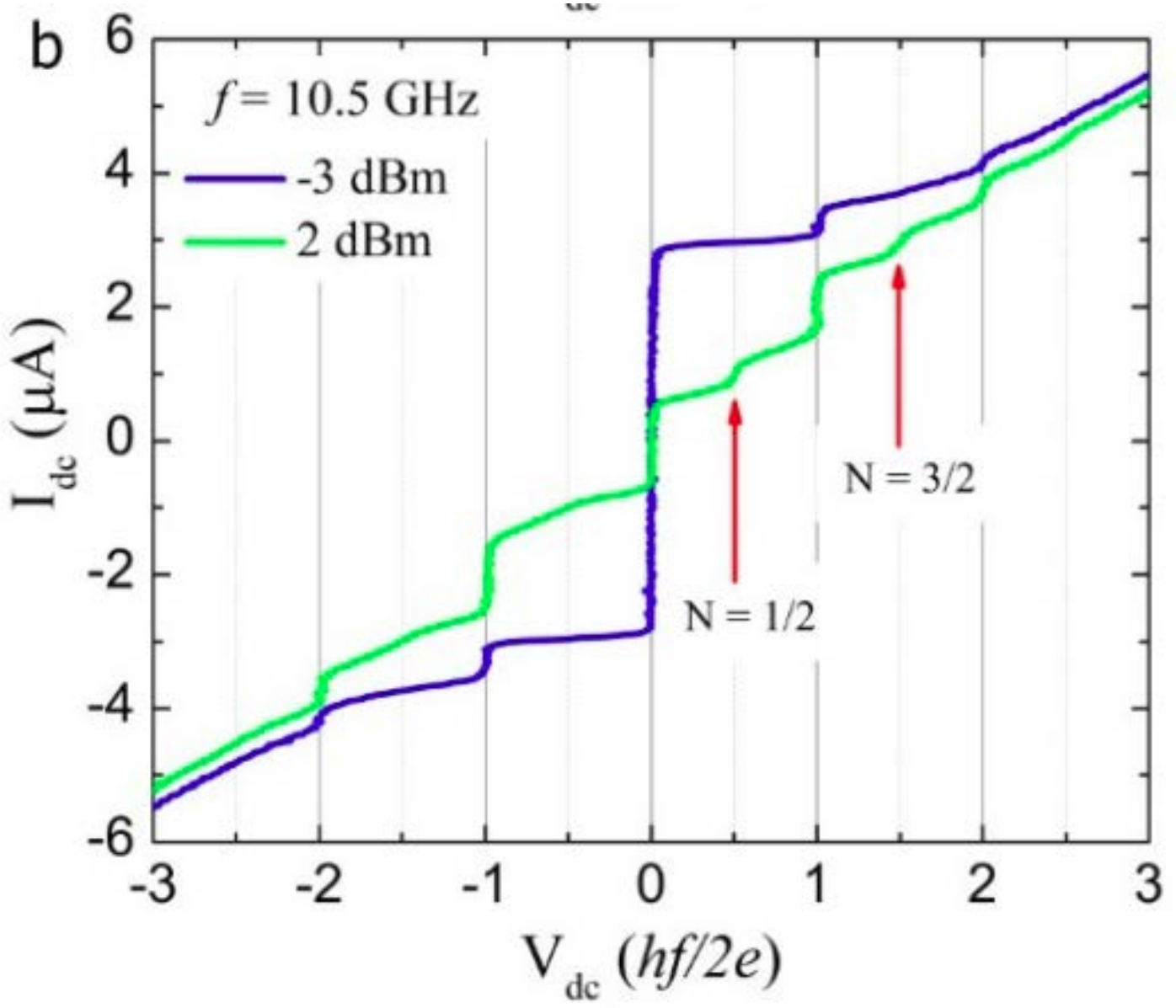
$$V_n = nhf/2e$$

Missing the first Shapiro Steps





Half-Integer Shapiro Steps



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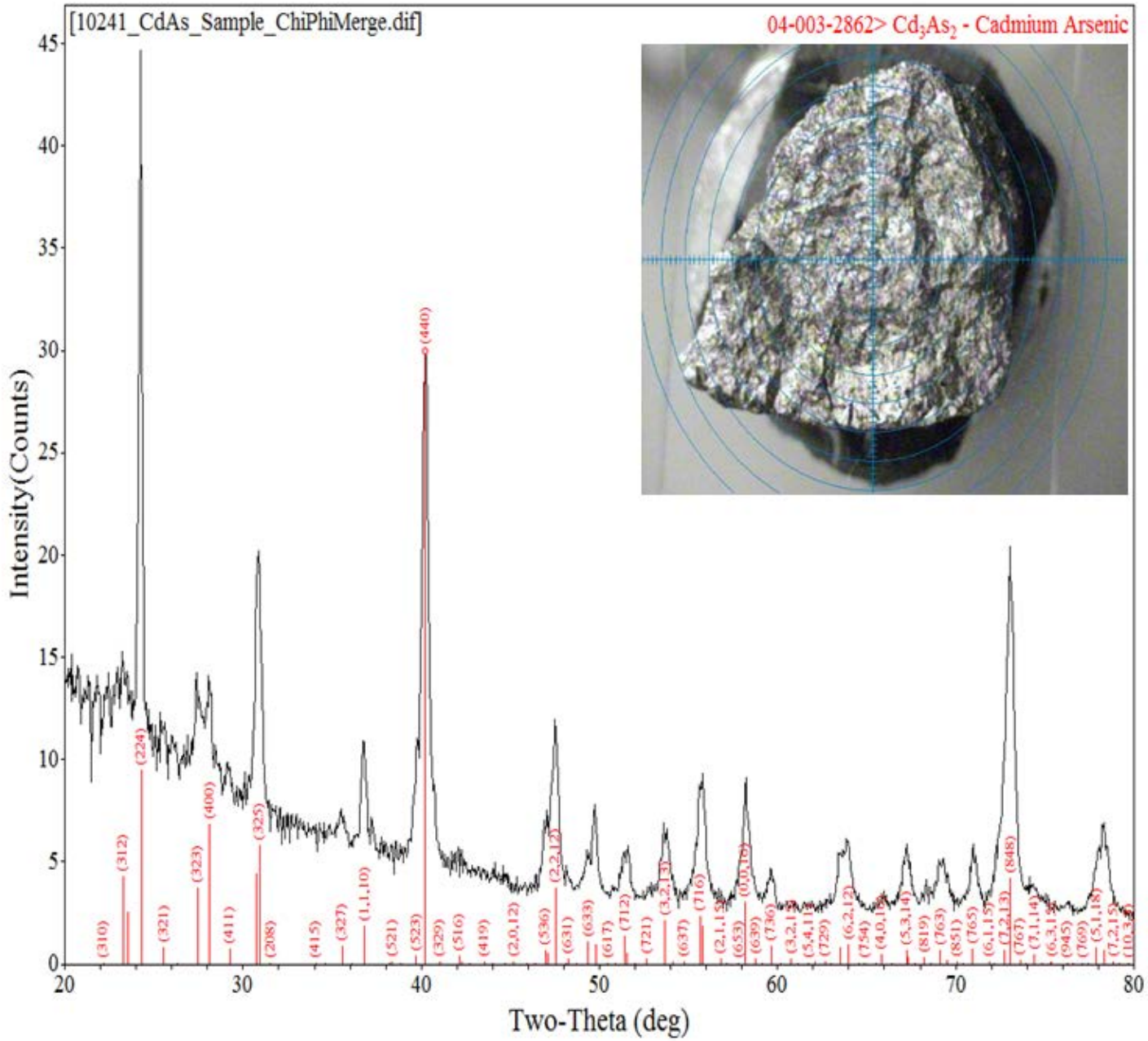
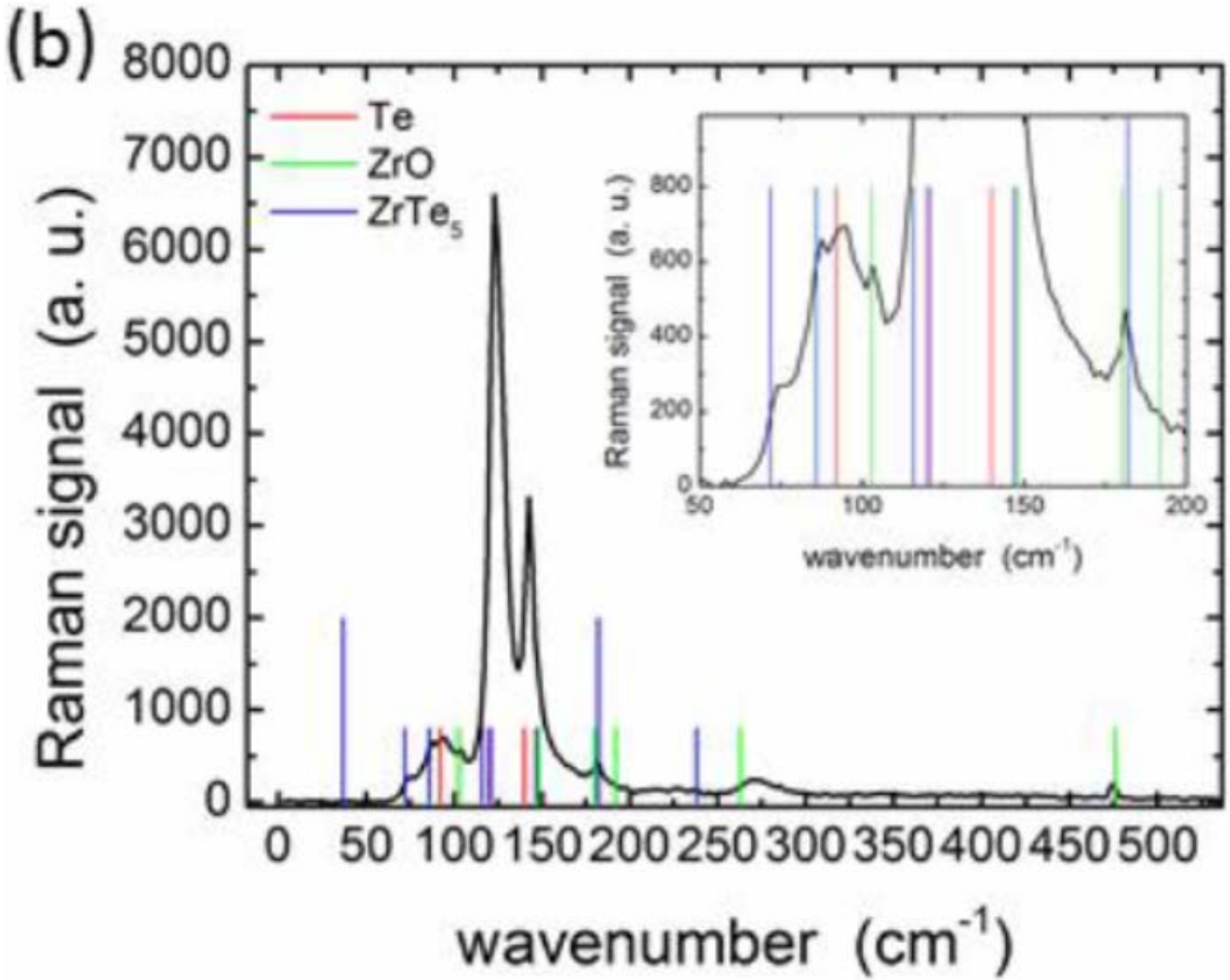
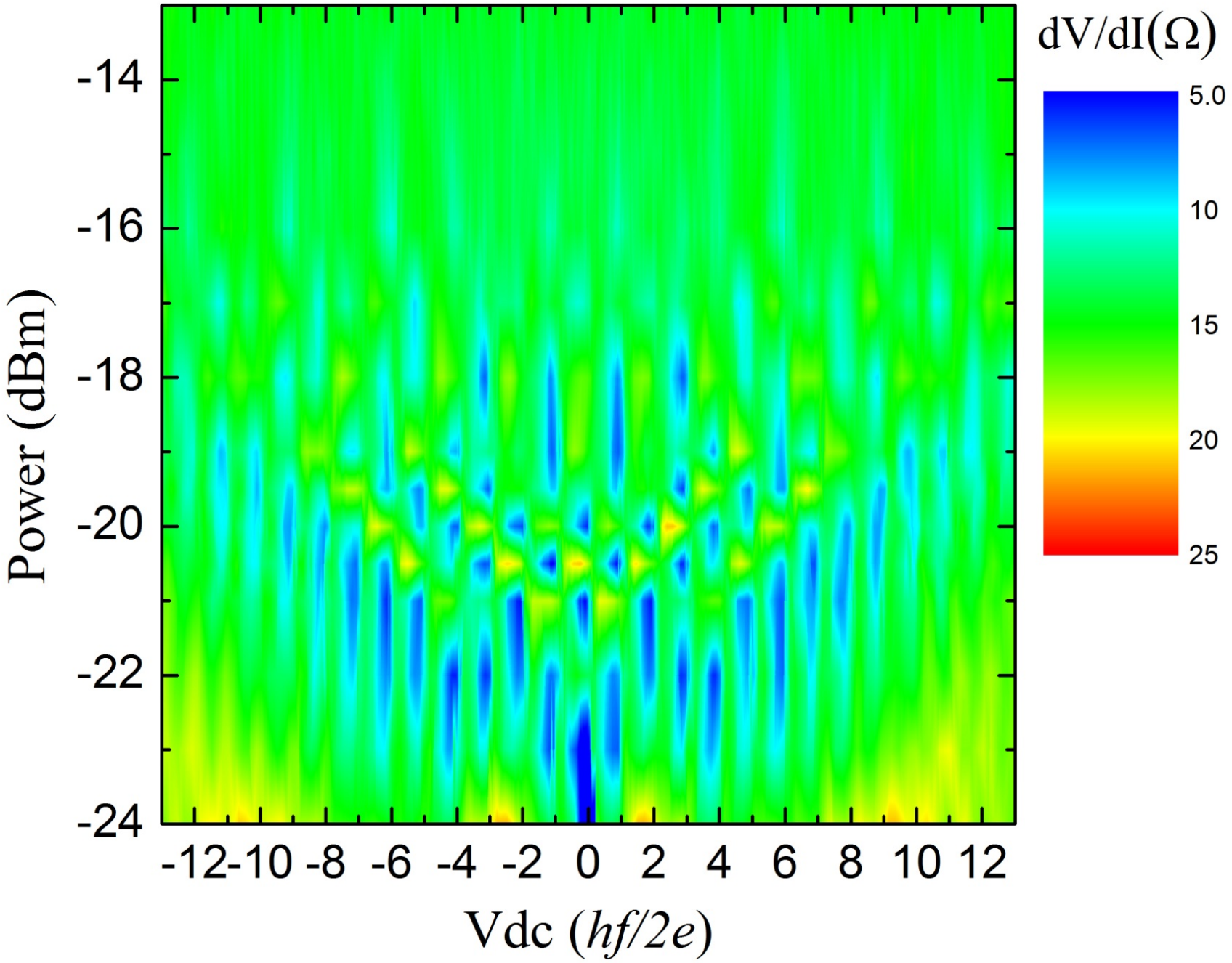

[10241_CdAs_Sample_ChiPhiMerge.dif]
04-003-2862> Cd_3As_2 - Cadmium Arsenic
Intensity(Counts)
Two-Theta (deg)
0
5
10
15
20
25
30
35
40
45
20
30
40
50
60
70
80
(440)
(224)
(312)
(400)
(325)
(323)
(321)
(411)
(208)
(415)
(327)
(1,1,10)
(521)
(523)
(329)
(516)
(419)
(2,0,12)
(536)
(2,2,12)
(631)
(633)
(617)
(712)
(721)
(3,2,13)
(637)
(716)
(2,1,15)
(653)
(0,0,16)
(639)
(736)
(729)
(6,2,12)
(754)
(5,3,14)
(819)
(763)
(851)
(765)
(6,1,15)
(7,2,13)
(848)
(767)
(7,1,14)
(945)
(769)
(5,1,18)
(7,2,15)

(Francois Leonard)



2GHz


dV/dI(Ω)
5.0
10
15
20
25
Power (dBm)
-14
-16
-18
-20
-22
-24
-12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12
Vdc (hf/2e)