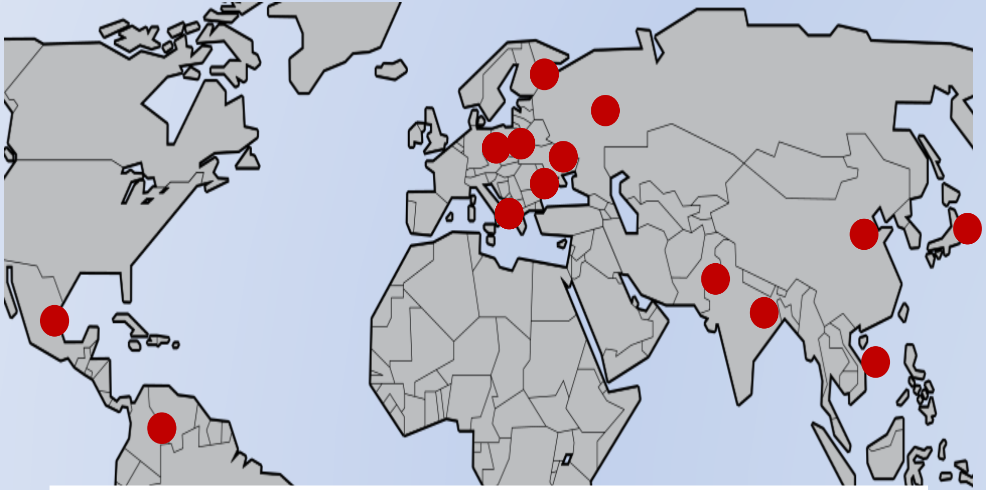
Tomasz Dietl

International Research Centre for Interfacing Magnetism and Superconductivity with Topological Matter „MagTop”
at the Institute of Physics, Polish Academy of Sciences, Warsaw

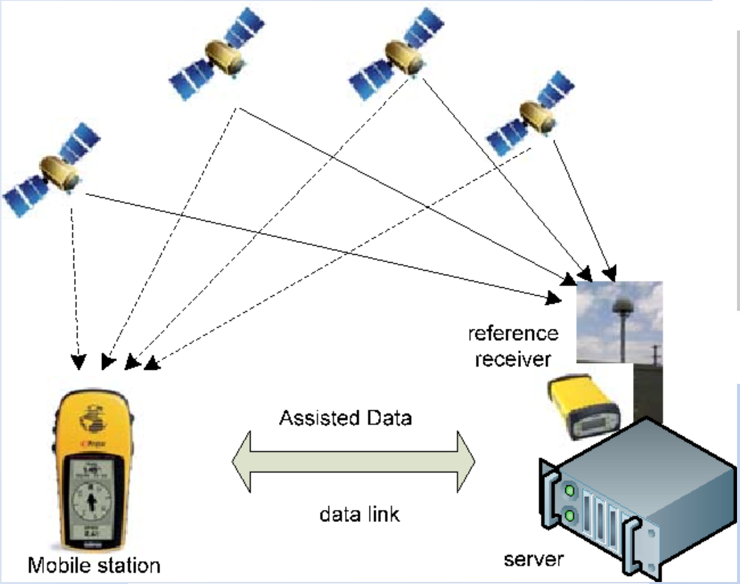
On the way to quantum ampere and quantum kilogram



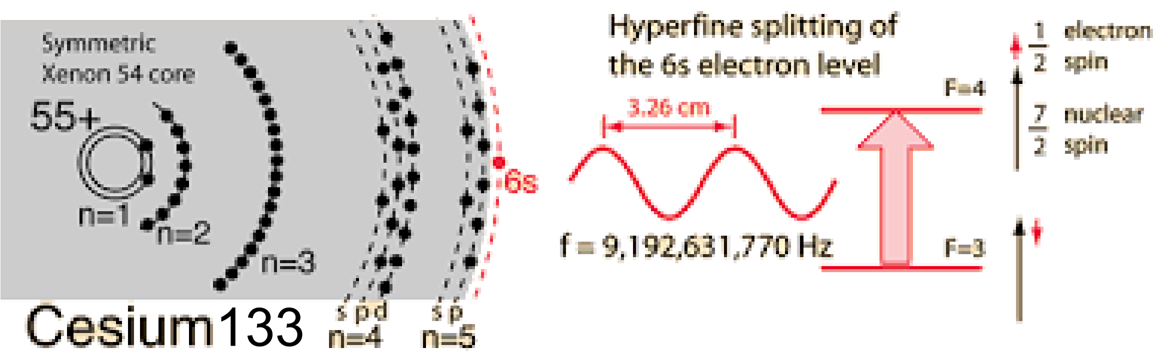
European Funds Smart Growth
Republic of Poland
FNP Foundation for Polish Science
European Union European Regional Development Fund

atomic clock

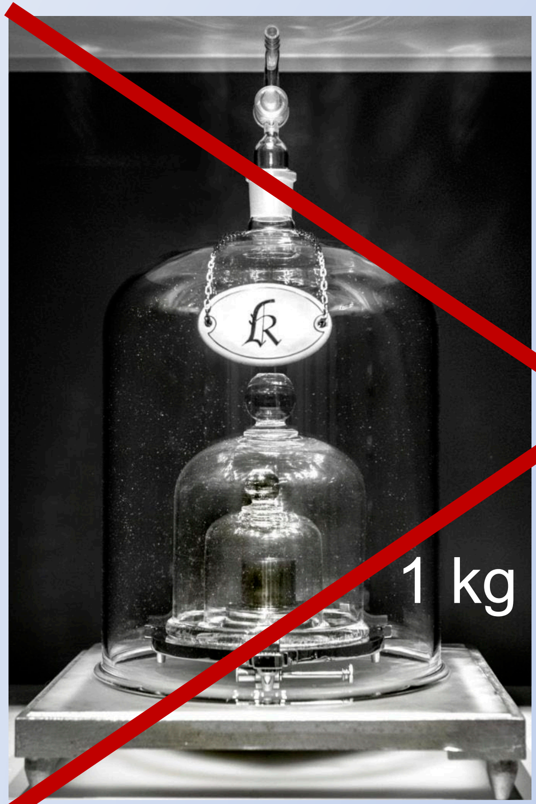
quantum meter – since 1983

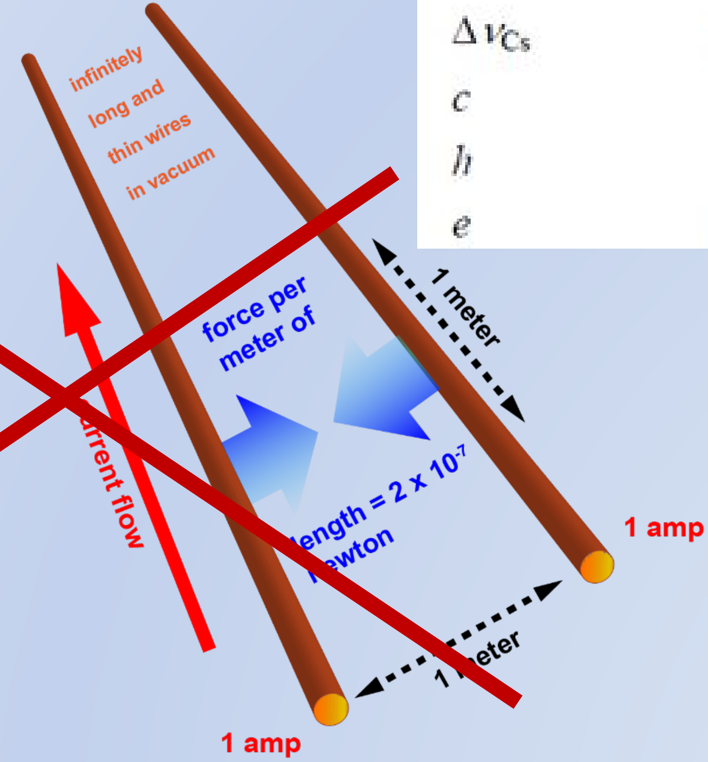


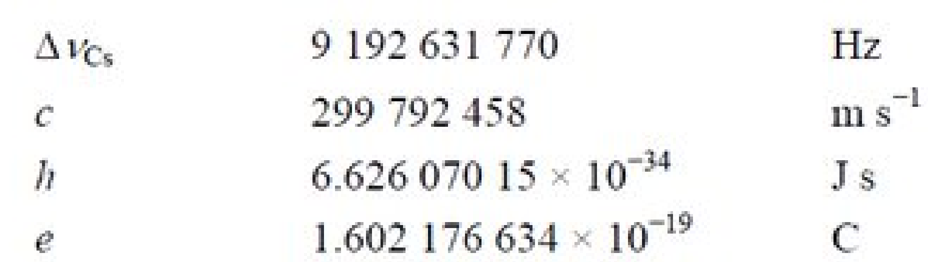
$\Delta t = 10^{-8}$ s → $\Delta r = 5$ m



quantum ampere and kilogram – since 2019







$\Delta\nu_{Cs}$	9 192 631 770	Hz
c	299 792 458	m s^{-1}
h	$6.626\,070\,15 \times 10^{-34}$	J s
e	$1.602\,176\,634 \times 10^{-19}$	C

$K_J = h/2e$ [V/s]

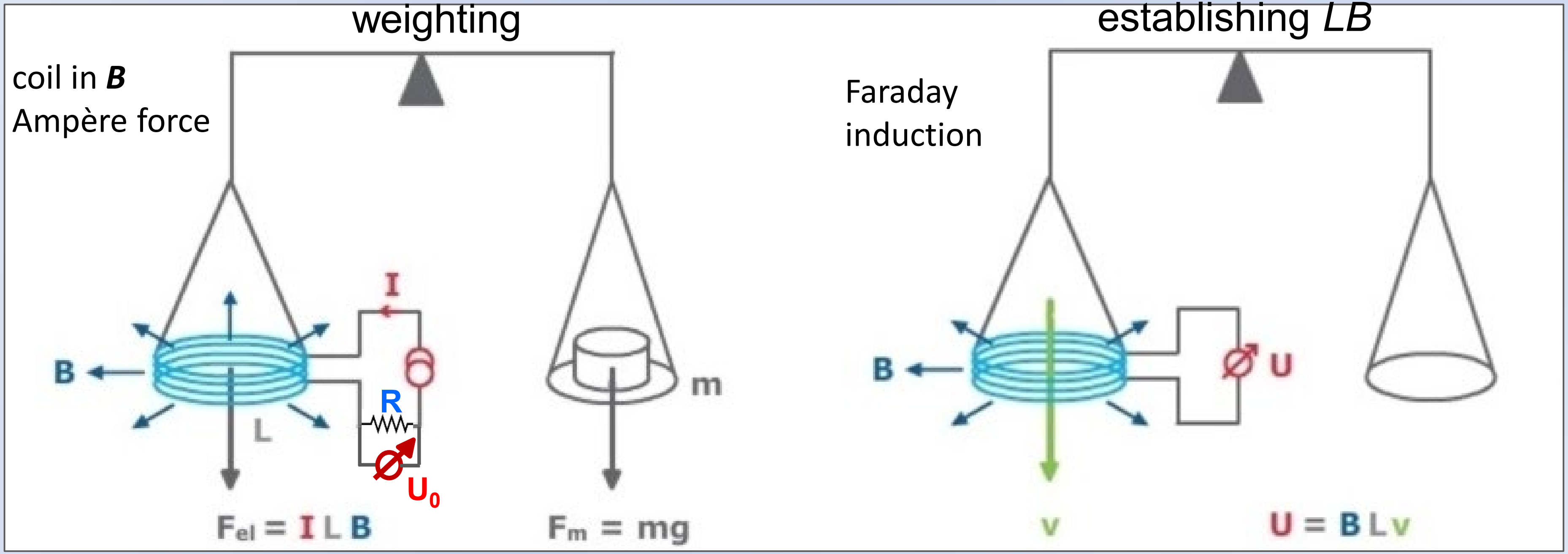
$R_K = h/e^2$ [Ω]

A = [V/Ω]

kg = [(s/m)^{2}V^2/Ω]

Kibble balance

kilogram standard – Kibble balance



weighting

coil in ***B***
Ampère force

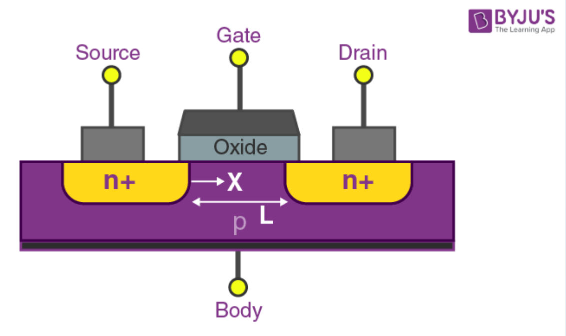
establishing *LB*

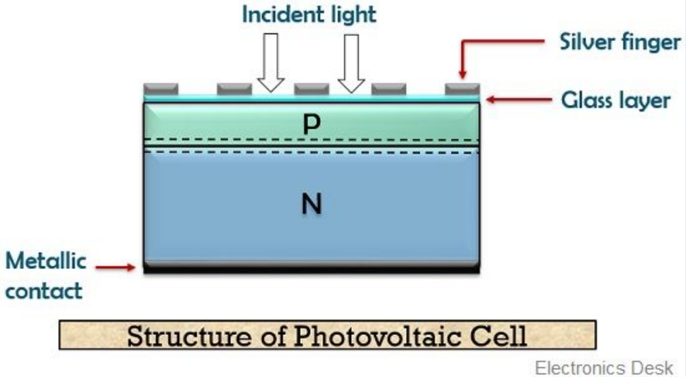
Faraday
induction

$m = UU_0/Rvg$ (accuracy $2 \cdot 10^{-8}$)

semiconductors

semiconductors in ICT and new energy technologies



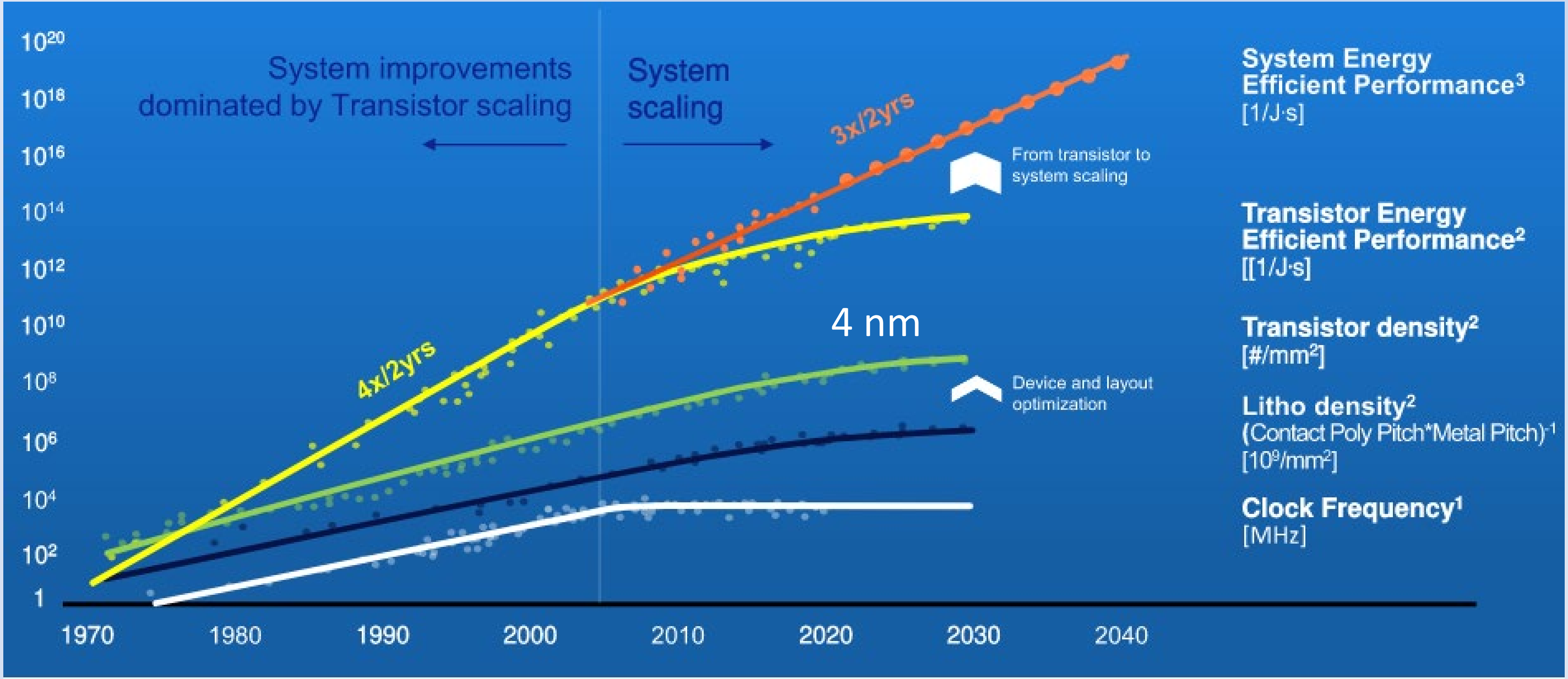


Structure of Photovoltaic Cell

Electronics Desk

gating and doping

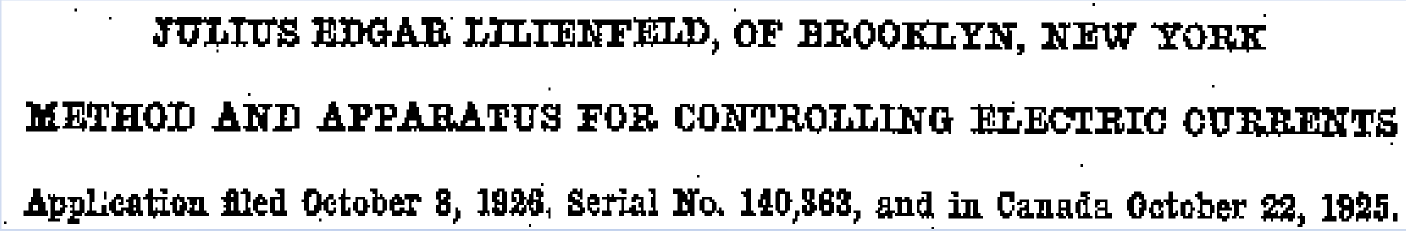
Moore’s law



Sources: ¹Karl Rupp, ²ASML data and projection using Rupp, ³Mark Liu, TSMC, normalized to transistor EEP in 2005.

Public

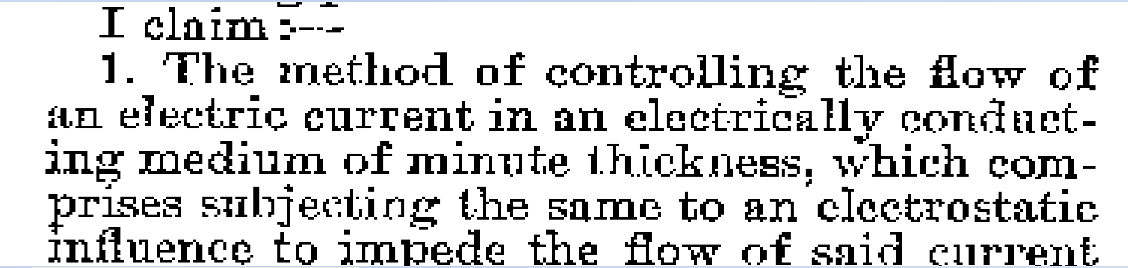
gating



JULIUS EDGAR LILIENFELD, OF BROOKLYN, NEW YORK

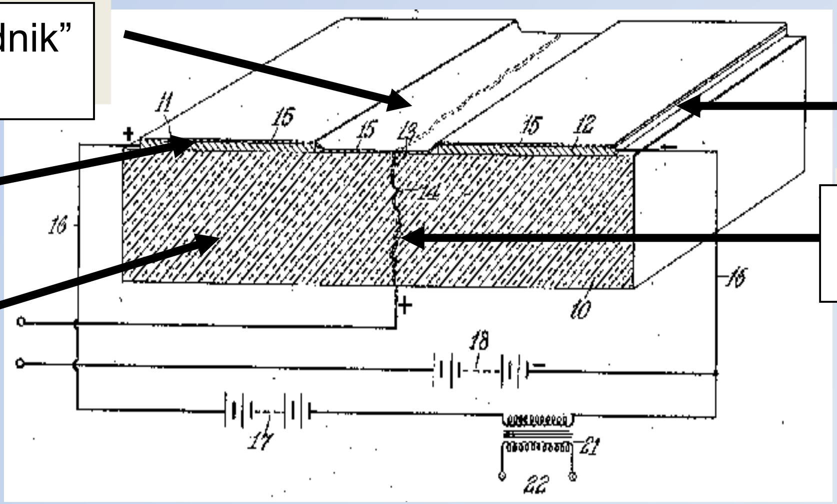
METHOD AND APPARATUS FOR CONTROLLING ELECTRIC CURRENTS

Application filed October 8, 1926, Serial No. 140,363, and in Canada October 22, 1925.



I claim:—

1. The method of controlling the flow of an electric current in an electrically conducting medium of minute thickness, which comprises subjecting the same to an electrostatic influence to impede the flow of said current



„półprzewodnik”
Cu$_2$S

źródło, Al

podłoże
szkło

dren, Al

bramka
folia Al

Canada, Patent Office, 1925

MES FET

Juliusz Lilienfeld to Maria Skłodowska-Curie

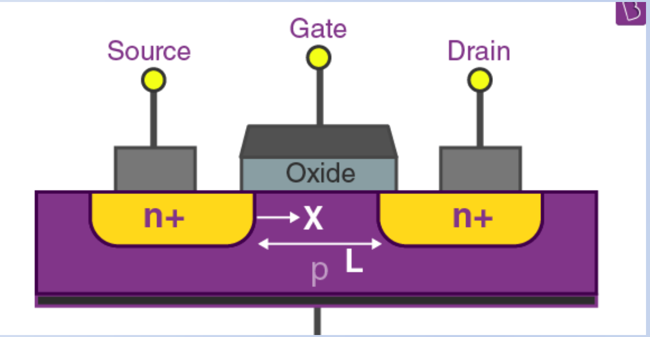
Lipsk, 3 maja 1921

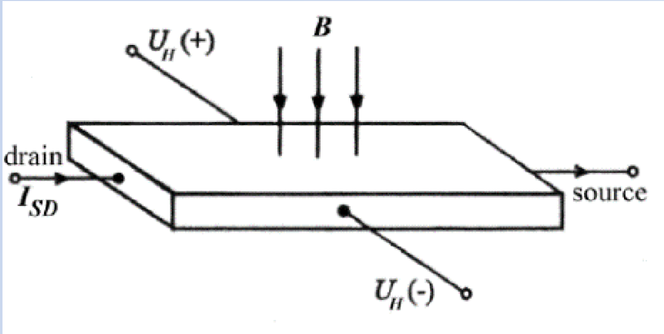
Wielce Szanowna Pani

Pozwalam sobie wręczyć ogłoszenie serii nowo rozpoczętej pracy z zapytaniem czy dana byłaby możliwość zademonstrowania odnośnych zjawisk przed publicznością francuską. Sytuacja Polaka w Niemczech jest taka, że o rozwój stanowiska naukowego trudno – do Polski przenieść się znaczyłoby zrzec się na kilka lat naukowej pracy...

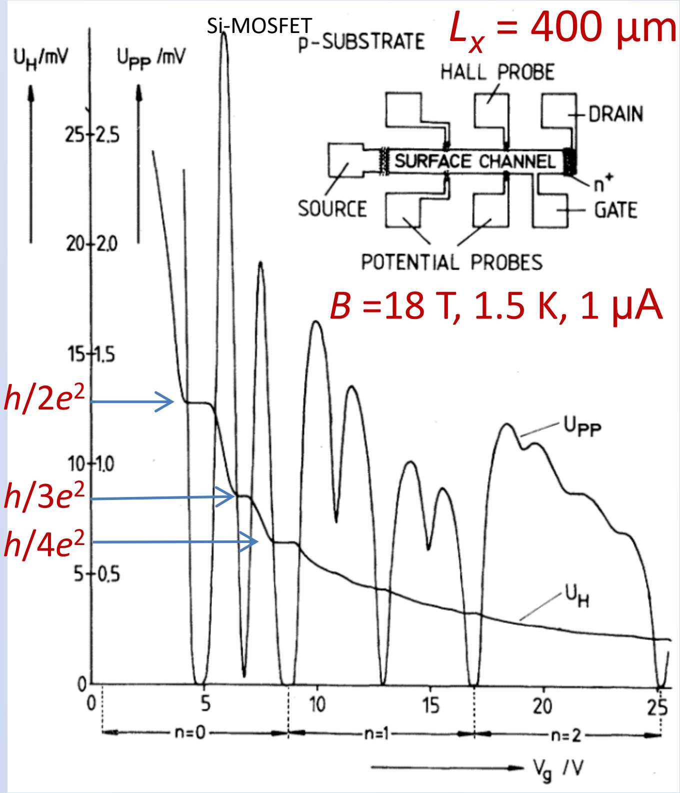
Archiwum Muzeum MSC, M/320

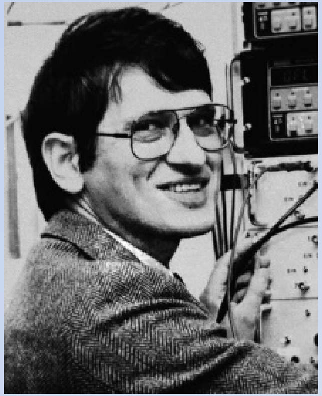
quantum Hall effect





quantized Hall resistance in MOS-FET transistor in high magnetic fields





K. v. Klitzing et al.
[Wuerzburg, Grenoble] PRL'1980
Nobel Prize 1985

$R_{xy} = U_H/I = h/ie^2$

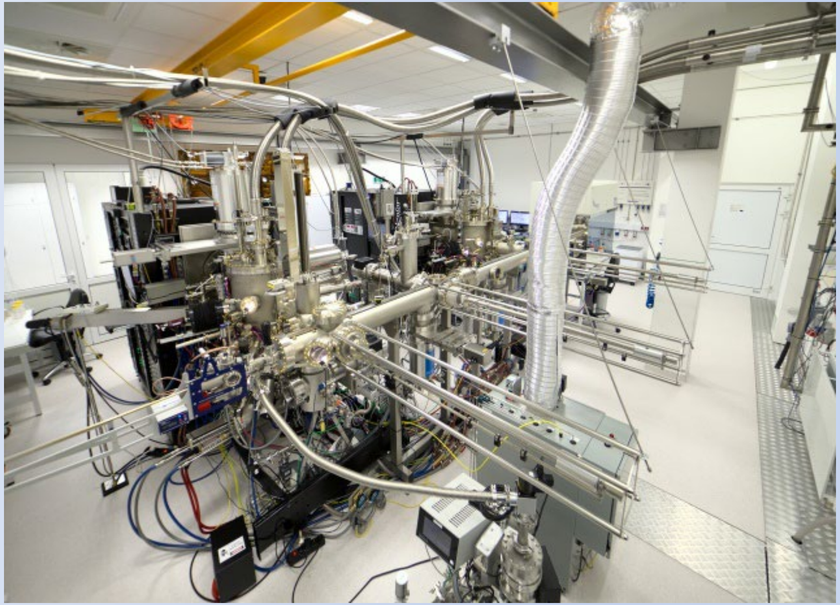
$i = 1, 2, 3, 4$

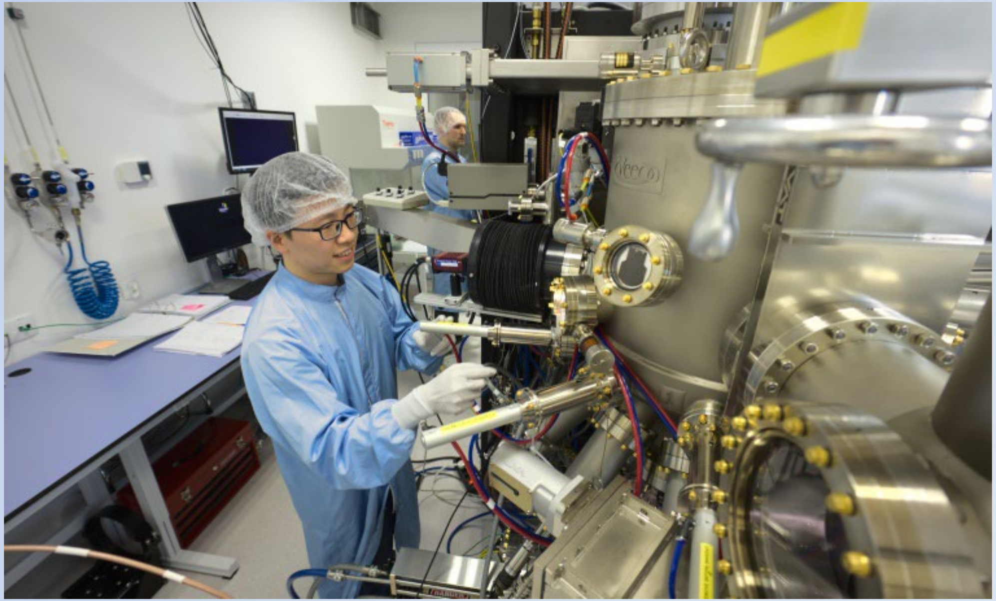
accuracy 10^{-10}

$R_K = h/e^2\ [\Omega]$
since 2019 fixed

molecular beam epitaxy

vacuum 10^{-14} atm

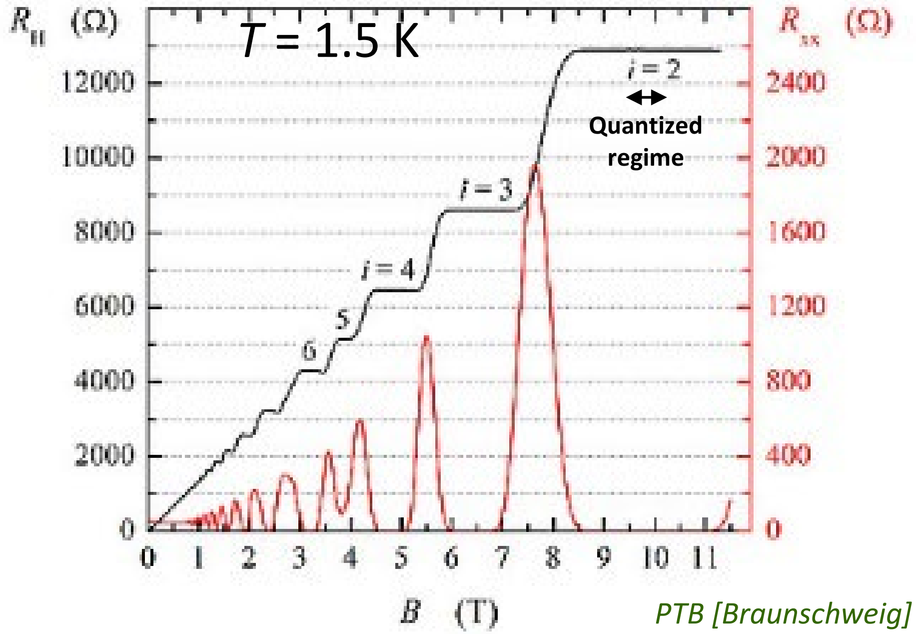




Wojtowicz-Wojciechowski MagTop’s MBE lab

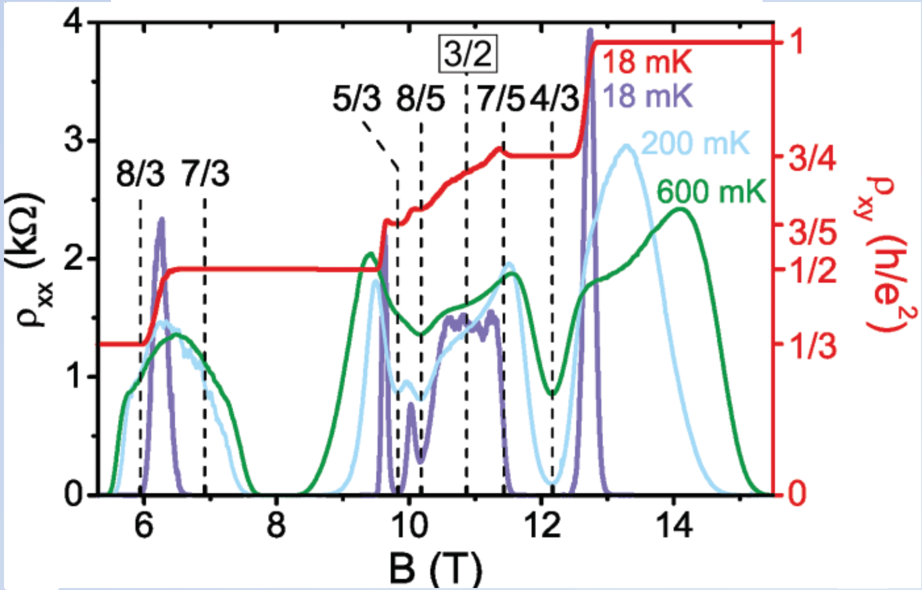
state of the art since the 1990s

GaAs/AlGaAs:Si



PTB [Braunschweig]

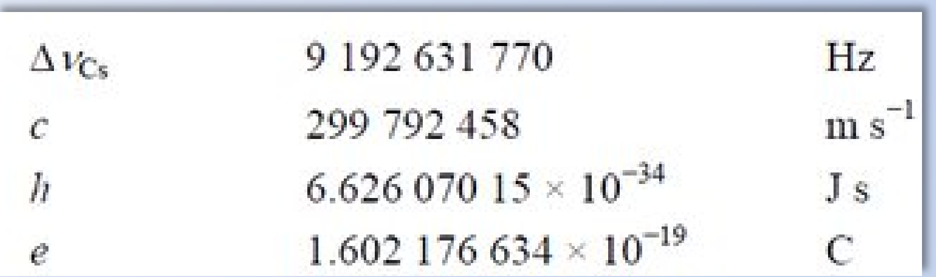
same in (Cd,Mn)Te/(Cd,Mg)Te:I



C. Betthausen et al. [Regensburg,Grenoble,IFPAN] PRB’2014

also GUM

quantum ampere and kilogram – since 2019



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c	299 792 458	$m\ s^{-1}$
h	$6.626\ 070\ 15 \times 10^{-34}$	J s
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$K_J = h/2e$ [V/s]

$R_K = h/e^2$ [Ω]

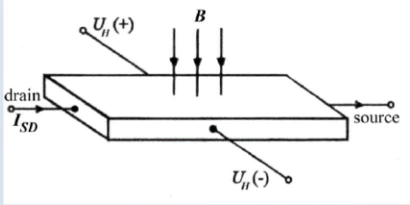
A = [V/Ω]

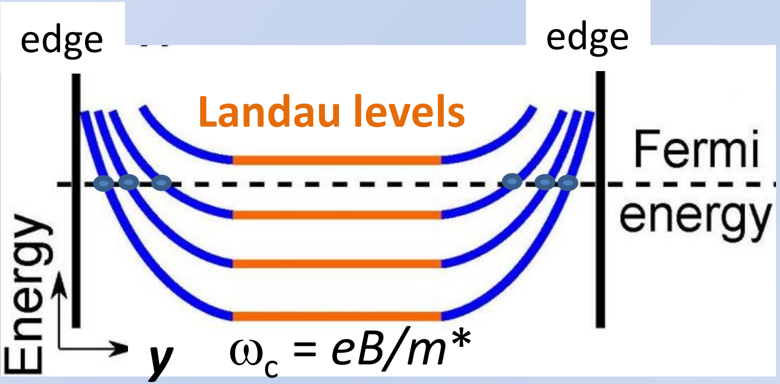
kg = [(s/m)²V²/Ω]

Kibble balance

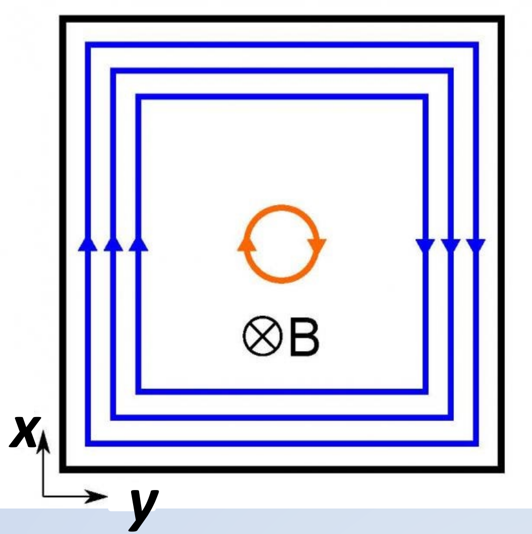
ideally: integrated standard at 4.2 K, $B \rightarrow 0$

origin of quantized resistance in 2D systems in high magnetic fields





$\omega_c = eB/m^*$

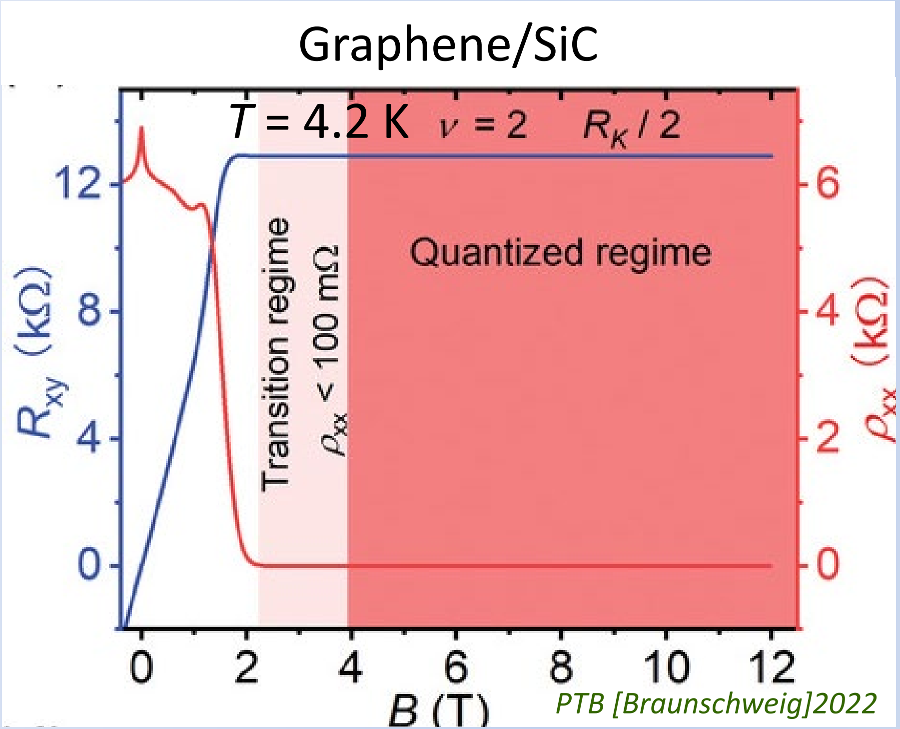


- bulk insulating
- 1D edge conducting channels (number *i*)
- group velocity $v_g = \hbar^{-1}d\varepsilon/dk$
- in 1D, DOS $\nu(\varepsilon) = (2\pi d\varepsilon/dk)^{-1}$
- if *no* backscattering $I = nev_g \nu eU$
- → $R = h/ie^2$ independently of shape, ….
- i – topological invariant

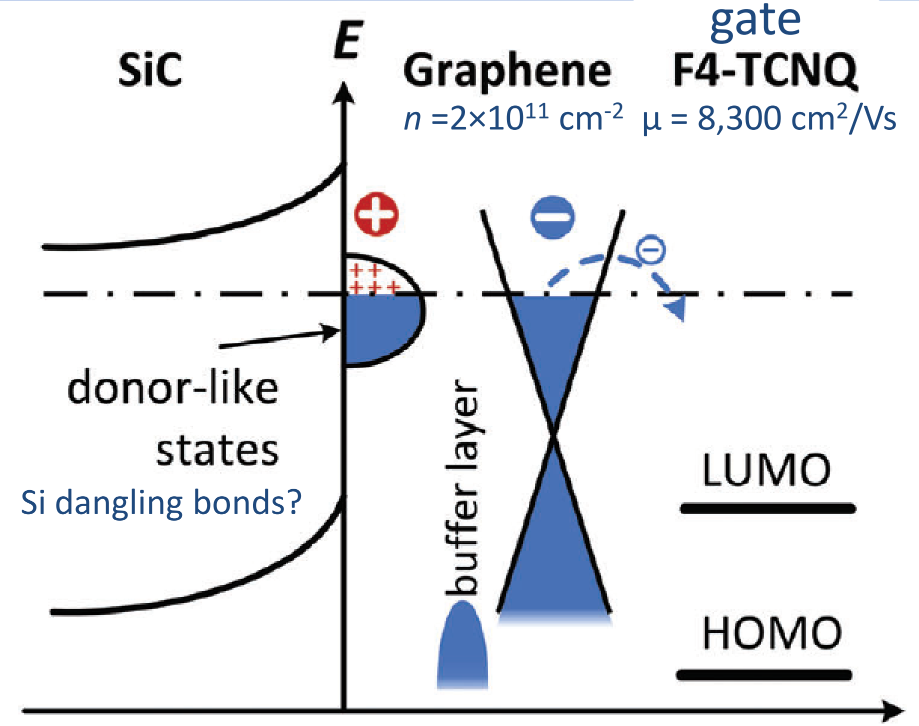
David Thouless

Nobel Prize 2016

QHE in Graphene – Dirac cones and defects



PTB [Braunschweig]2022



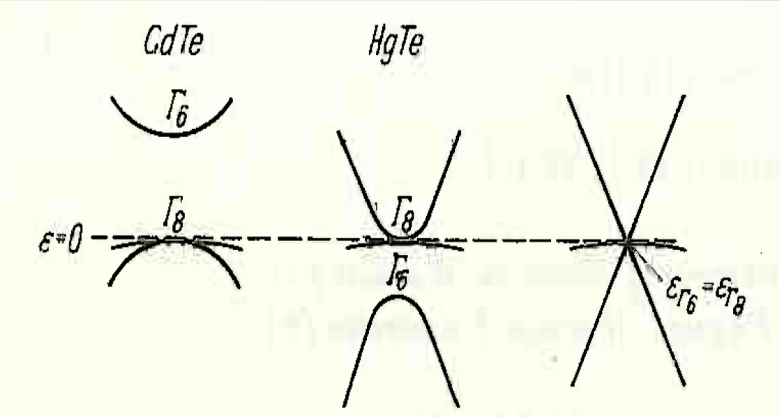
$n = 2\times10^{11}$ cm^{-2} $\mu = 8{,}300$ cm^2/Vs

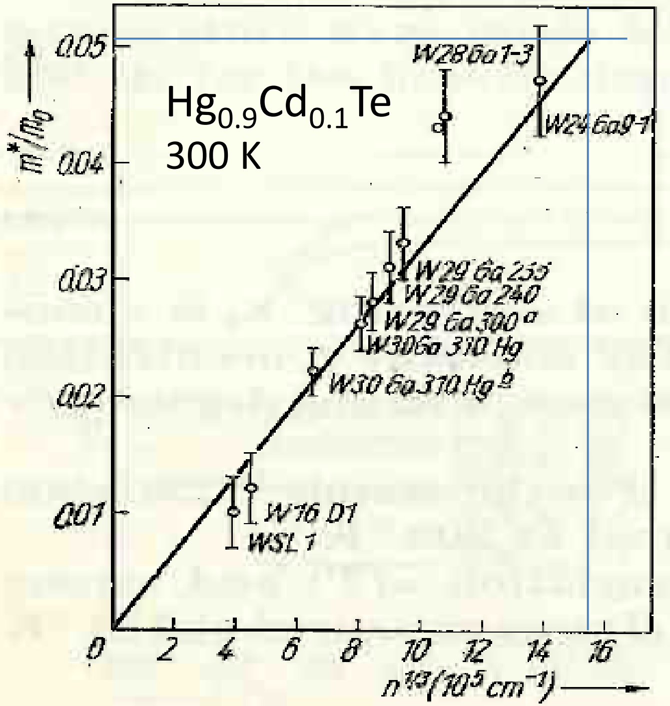
Si dangling bonds?

- wide plateau $\Delta V_g = en_d/C$ 🙂
- low mobility $\mu \sim 1/n_d$ 😟

3D Dirac cone in Hg$_{0.9}$Cd$_{0.1}$Te

Experimental dependence of the effective mass on $n^{1/3}$ (in the case of strong degeneracy $n^{1/3} \sim k$)





$m^*(k) = \hbar k/v_f$
$v_f = 1.1\text{x}10^6$ m/s

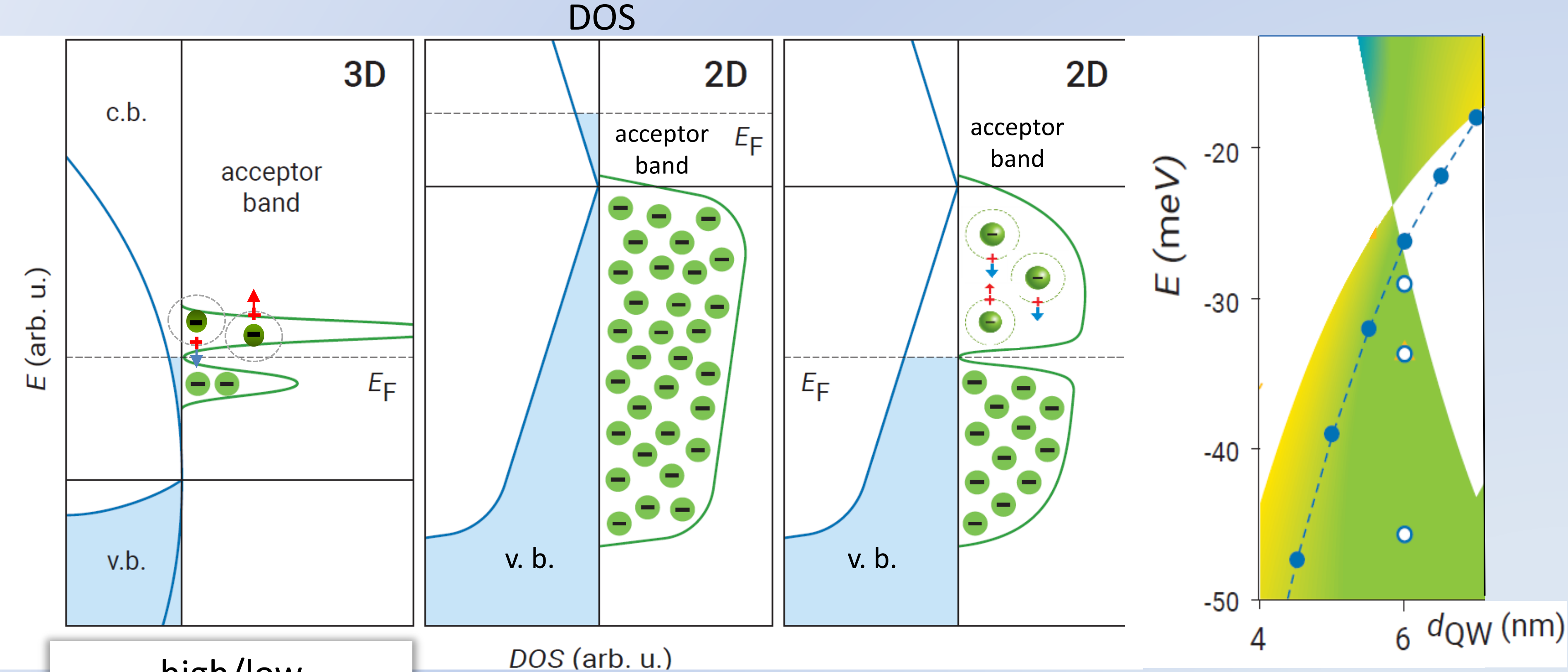
$v_f = 1.0\text{x}10^6$ m/s graphene
$v_f = \sim 0.6\text{x}10^6$ m/s Bi$_2$Te$_3$, (Pb,Se)Te


(1937–2021)


(1911–1986)

R. R. Gałązka and L. Sosnowski [FPAN] phys. stat .sol.' 1967

density of states in Dirac bulk (Hg,Cd)Te and HgTe quantum well (6 nm)



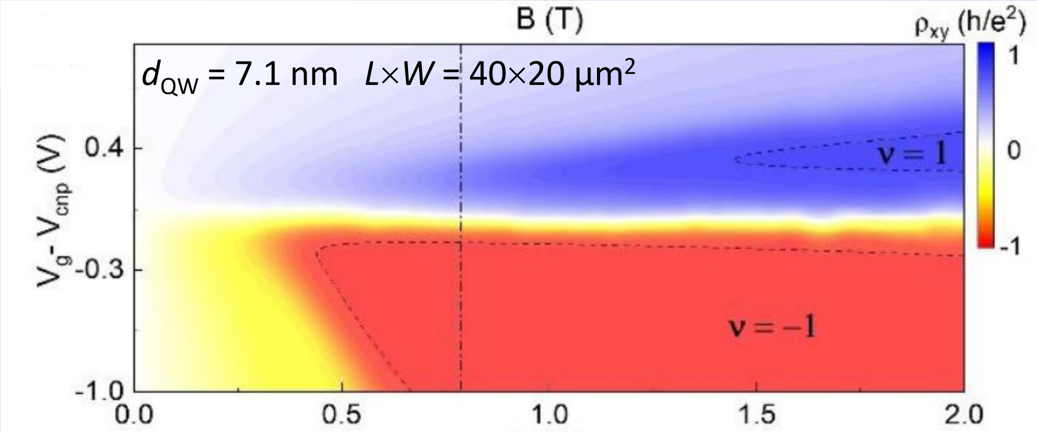
high/low electron/hole mobility

low electron mobility

high hole mobility

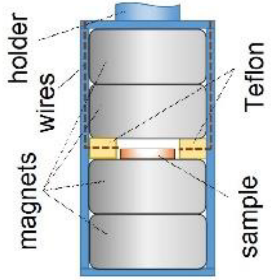
T. D. [IFPAN] PRL'2023

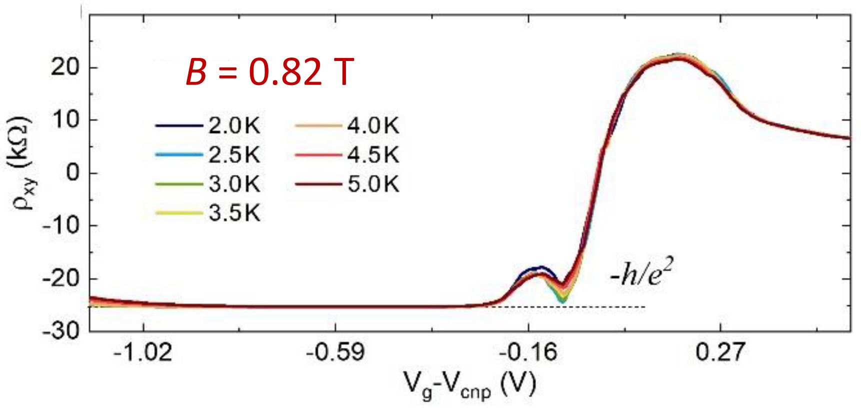
QHE in HgTe Dirac QW at ^{4}He and in permanent magnets



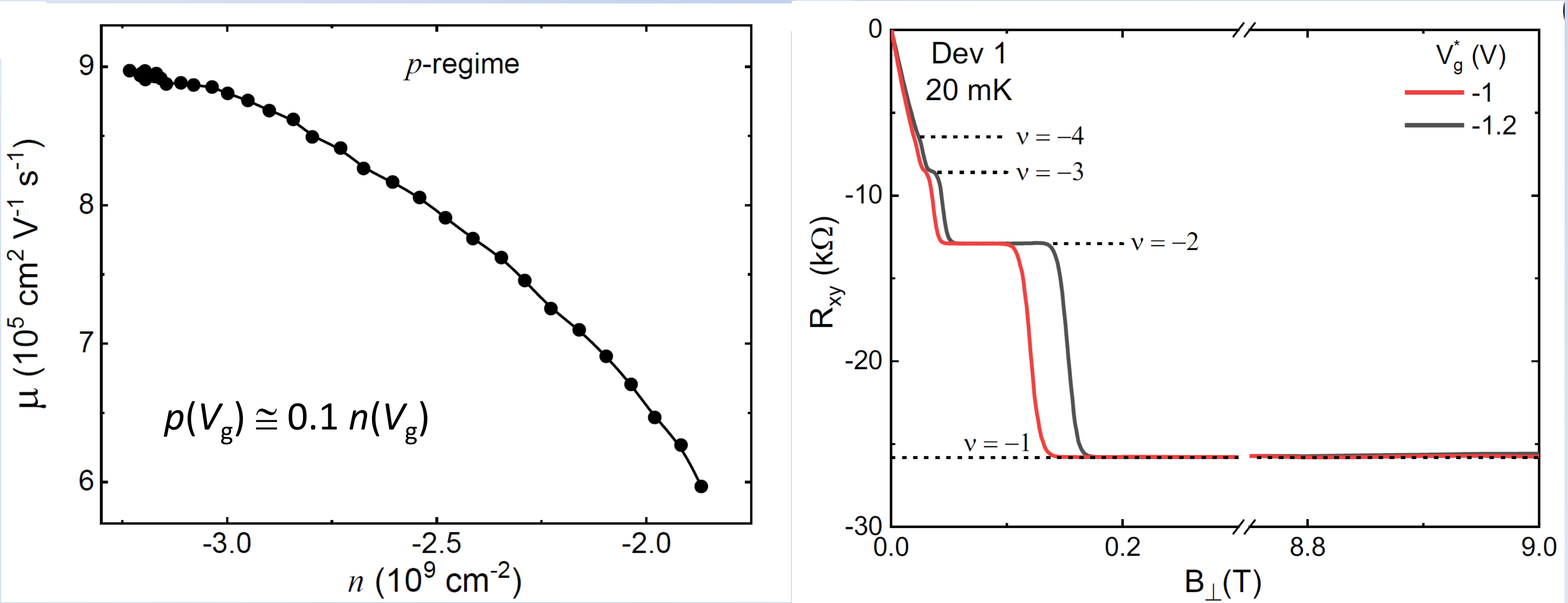
I. Yahniuk , … T.D. , W. Knap [Warsaw, Montpellier, Novosibirsk]
npj Quant. Mater.'2019; arXiv:2111.07581

cf. M. Koenig et al. [Würzburg] Science'2007
B. Büttner et al. [Würzburg] Nat. Phys.'2011





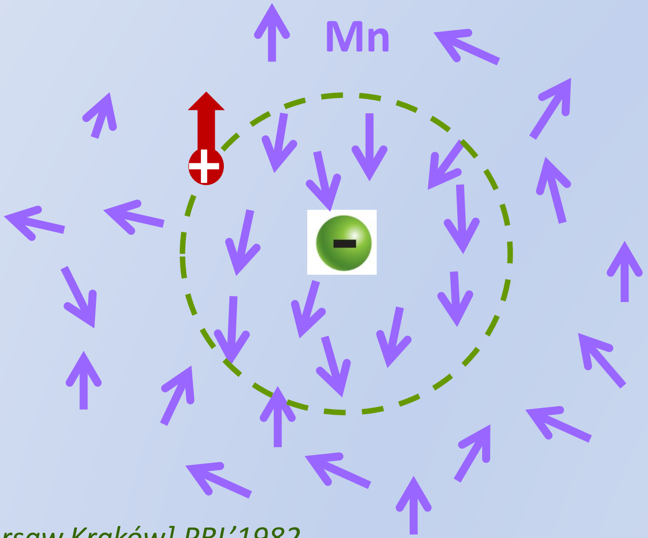
high mobility and QHE of holes in Dirac $Hg_{0.976}Mn_{0.024}Te$ QW at $E_g \cong 0$

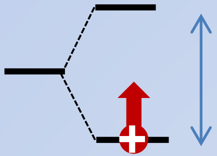


better characteristics compared to HgTe QWs

S. Shamim et al. [Würzburg] Sci. Adv.'2020

acceptor bound magnetic polaron in QW with magnetic ions



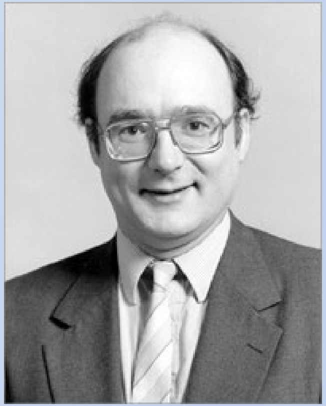


ω_s increases with lowering T enhancing Coulomb gap

T.D, J. Spałek [Warsaw,Kraków] PRL'1982
J. Jaroszyński, T.D. [Warsaw] PB'1983

for $Hg_{0.988}Mn_{0.012}Te$ QW, $\omega_s > k_B T$ at $T < 3.5$ K

quantized resistance possible in $H = 0$



Duncan Haldane

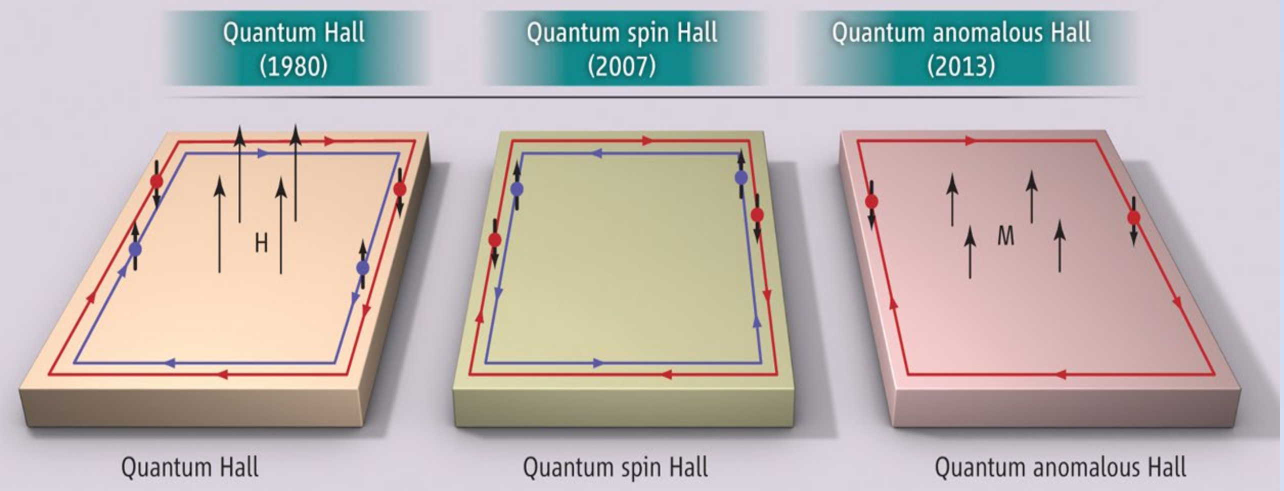
Nobel Prize 2016

Charles Kane

Shoucheng Zhang

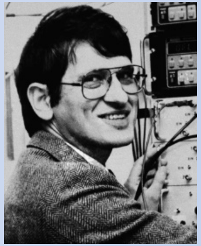
(1963-2018)

family of quantum Hall effects



$R = h/ie^2$

Klaus von Klitzing

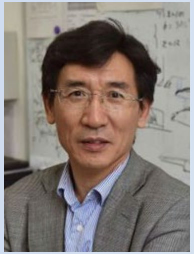


$R = h/2e^2$

Laurens Molenkamp

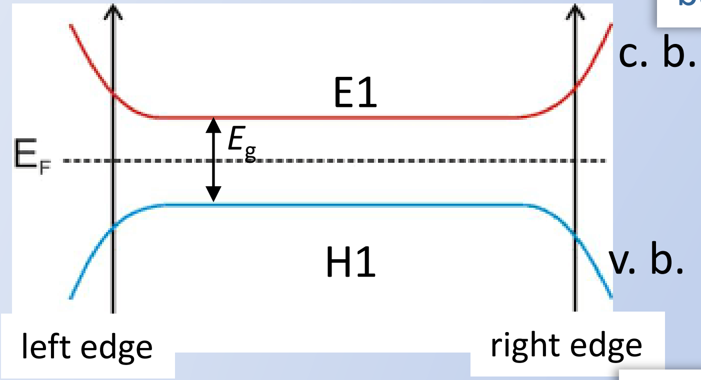
$R = h/e^2$

Qi-Kun Xue

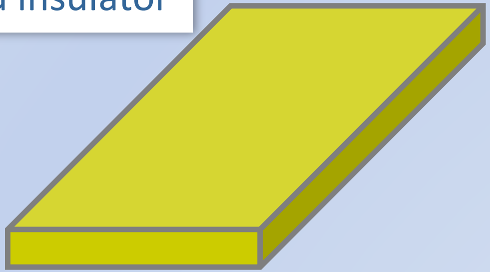


quantum spin Hall effect

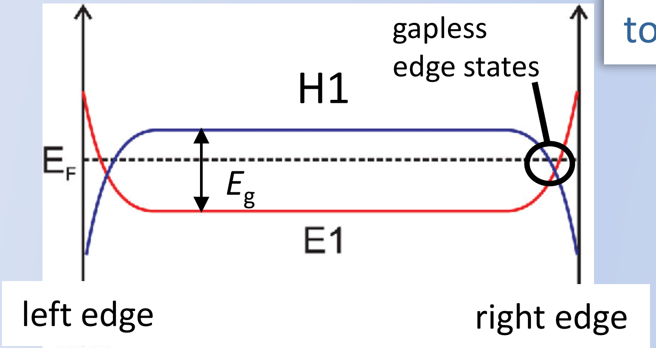
origin of edge states in topological QW

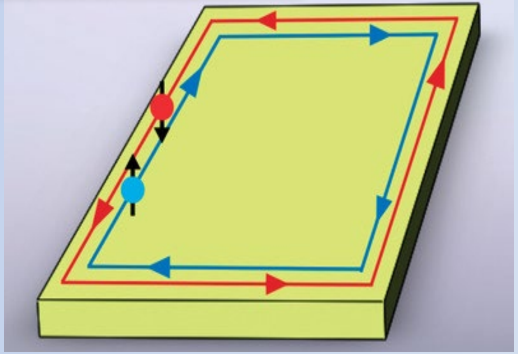


normal QW
band insulator

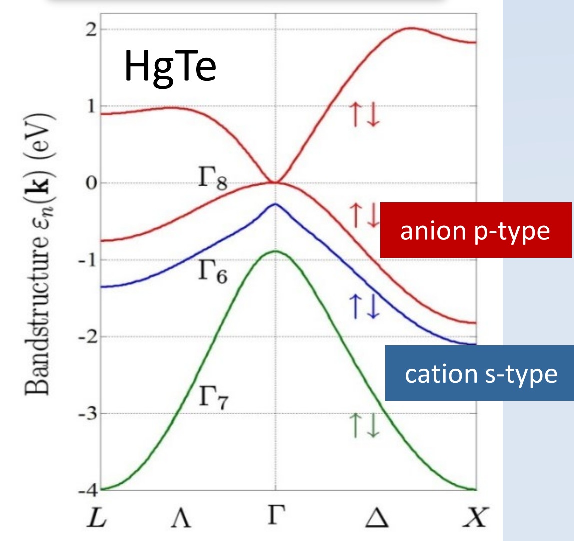


topological QW
topological insulator



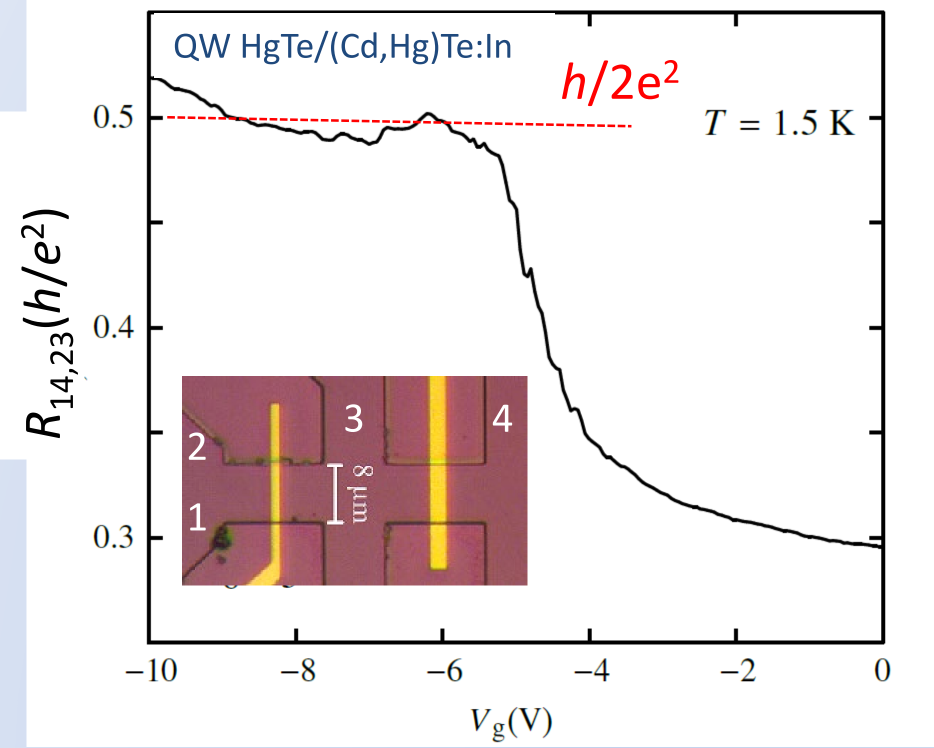


inverted band order

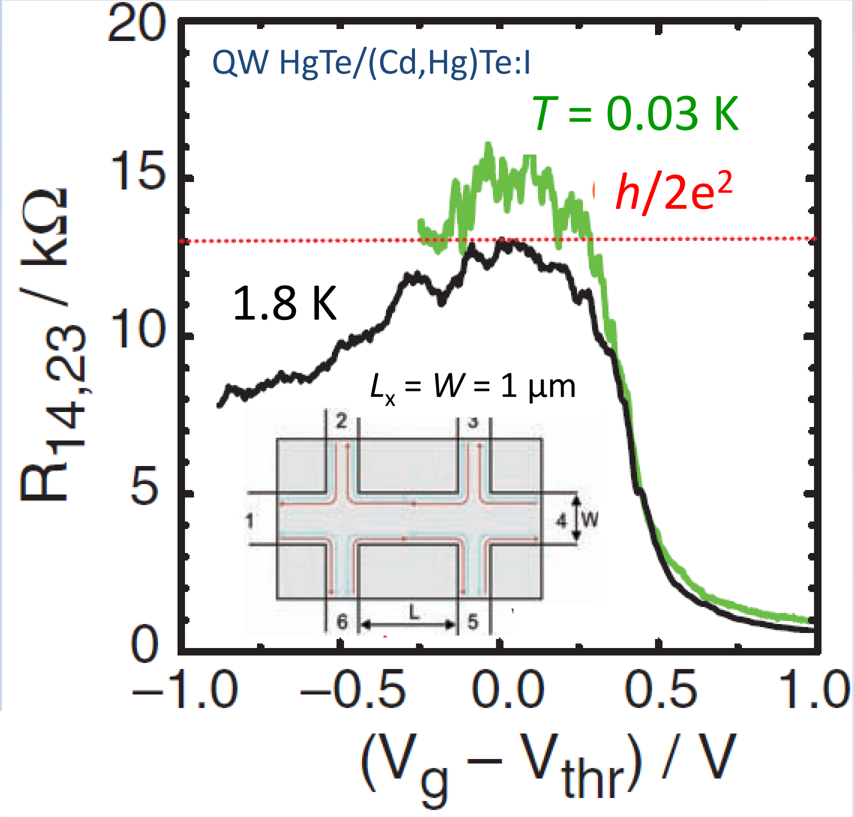


B. A. Bernevig et al. [Stanford] Science'2006

edge channels’ resistance in HgTe QWs



M. Majewicz [IFPAN] Ph.D. Thesis’2018

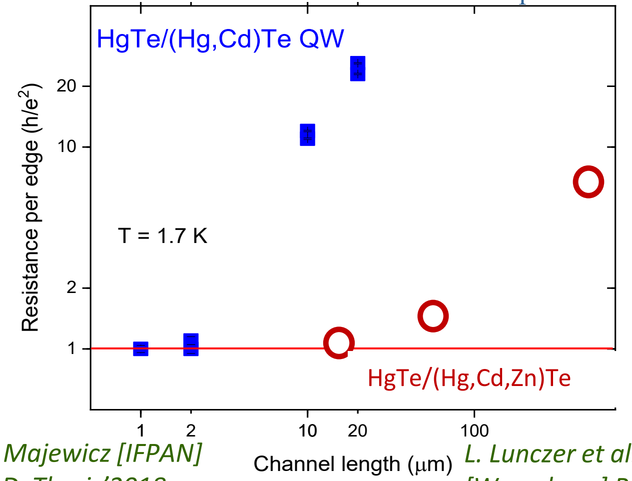


M. Koening et al. [Wuerzburg,Stanford] Science’2007

key role of in-gap acceptor impurity states

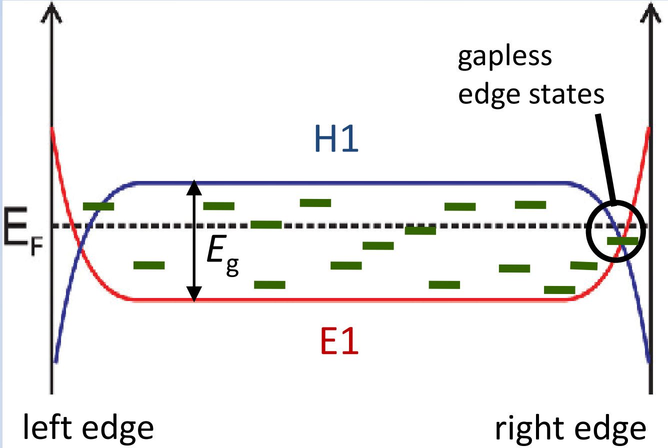
- pin E_F in gap leading to non-zero plateau width
  $\Delta V_g = eN_a/C$ 🙂
- allow for backscattering between helical states
  leading to $R > h/e^2$ 😟

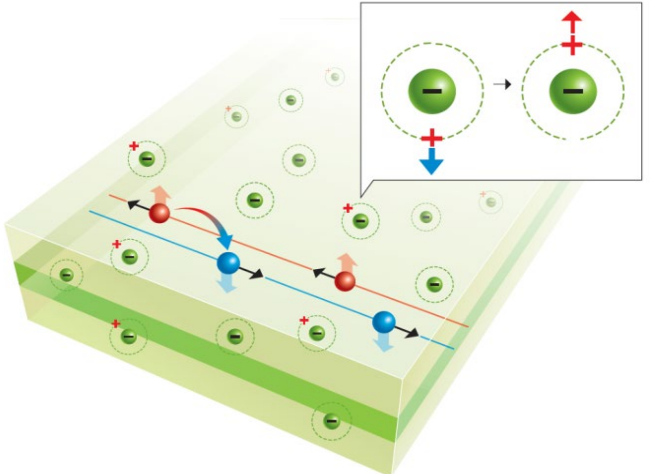
$R = (h/2e^2)(1 + L_x/L_{tp})$



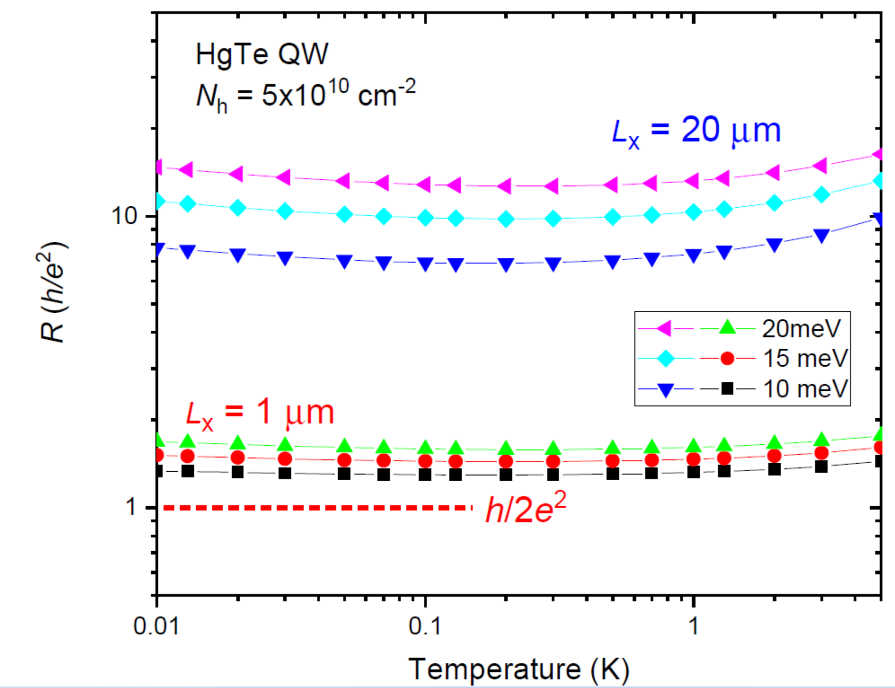
M. Majewicz [IFPAN] Ph.D. Thesis'2018

L. Lunczer et al. [Wuerzburg] PRL'2019



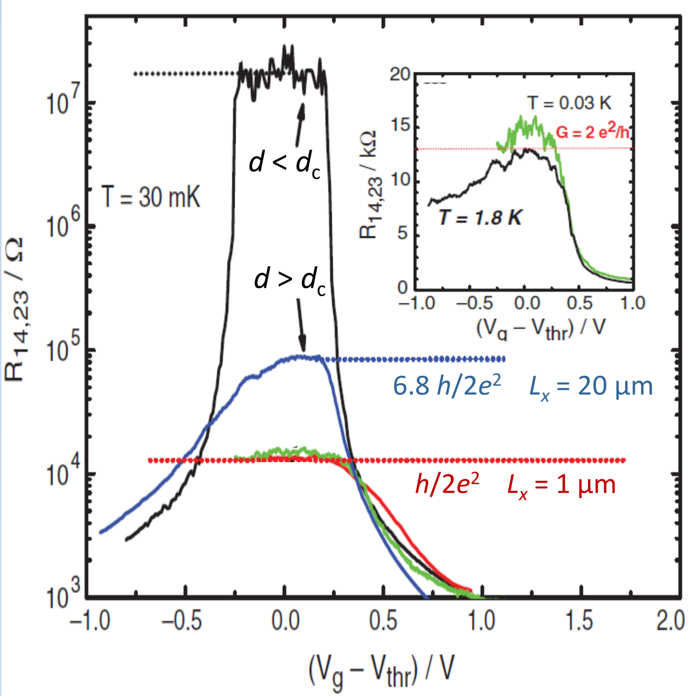


edge’s resistance vs. T and L_x



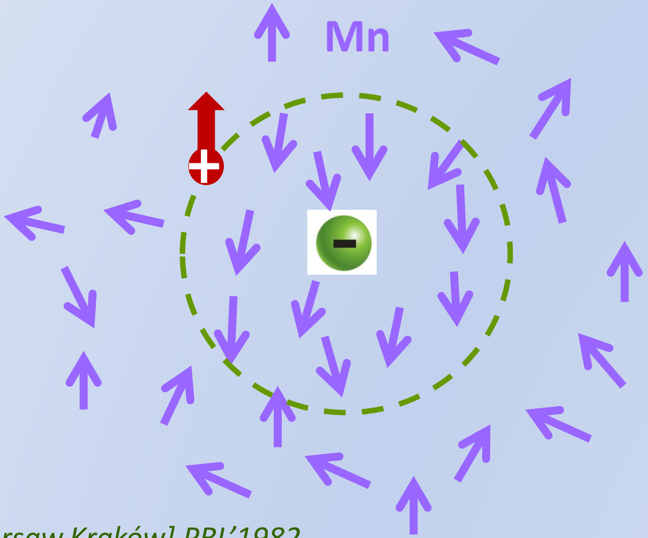
no adjustable parameters

T. D. [IFPAN] PRL’2023; PRB’2023



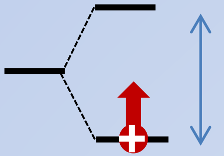
M. Koening et al. [Würzburg, Stanford] Science’2007

killing of Kondo effect by BMP formation in DMS QW

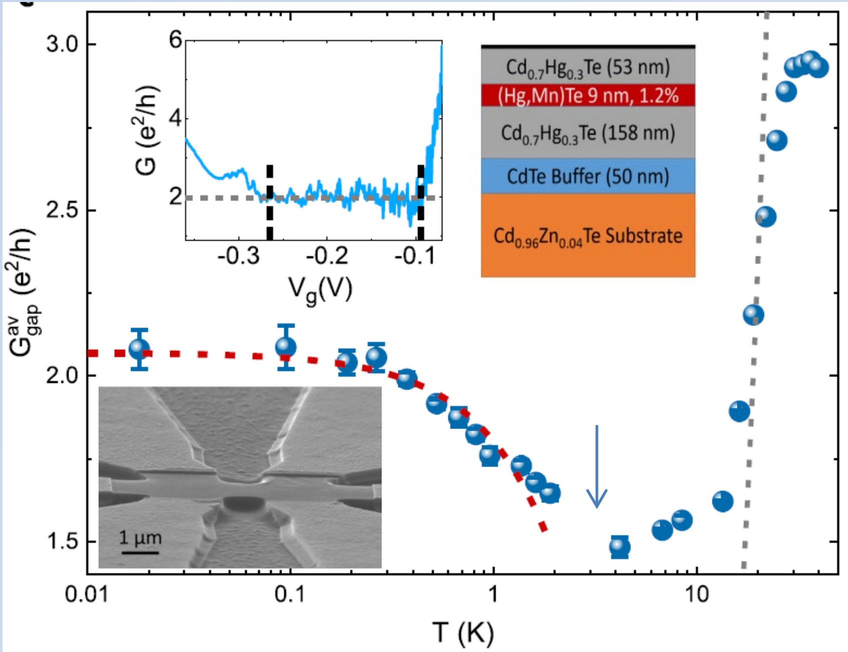


T.D, J. Spałek [Warsaw,Kraków] PRL'1982
J. Jaroszyński, T.D. [Warsaw] PB'1983

for $Hg_{0.988}Mn_{0.012}Te$ QW, $\omega_s > k_B T$ at $T < 3.5$ K



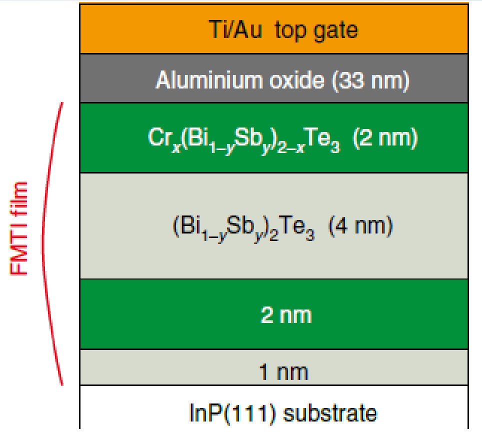
ω_s increases with lowering T
diminishing Kondo effect

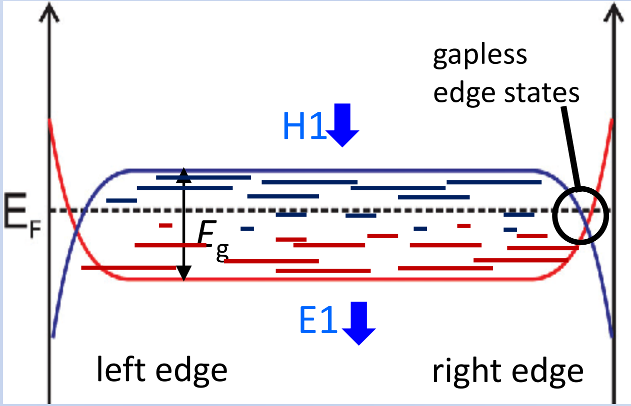


S. Shamim et al. [Wuerzburg] Nat. Commun.'2021

quantum anomalous Hall effect

QAHE in (Bi,Sb,Cr)$_2$Te$_3$ - accuracy 10^{-8}

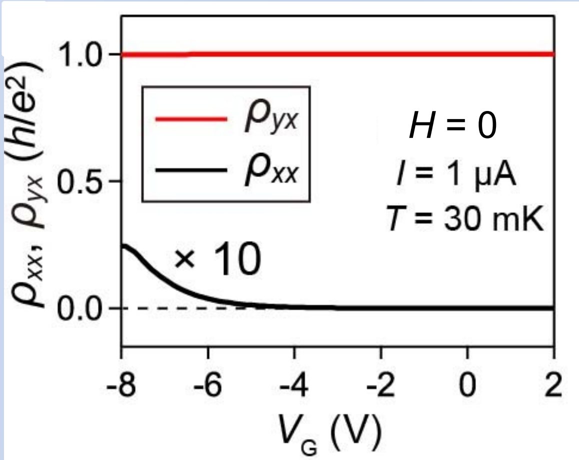


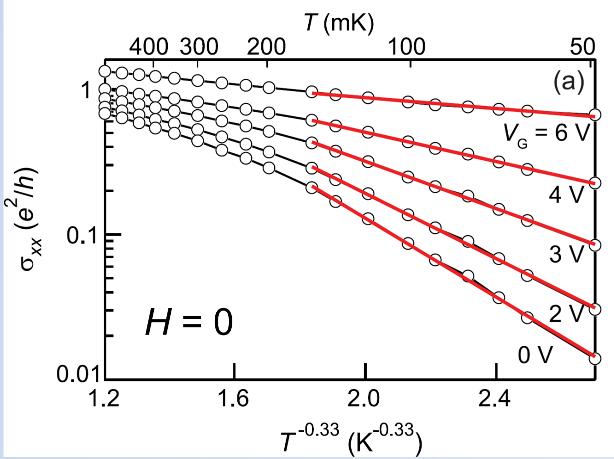


- large density of in-gap states
  $\Delta V_g = e\Delta n/C \rightarrow \Delta n = 5\times10^{12}$ cm^{-2}
  → wide plateau 🙂
- large hopping conductivity
  → limits T and I 😟

→ less defected compound needed

Y. Okazaki et al. [NMIJ, RIKEN] Nat. Phys.'2022

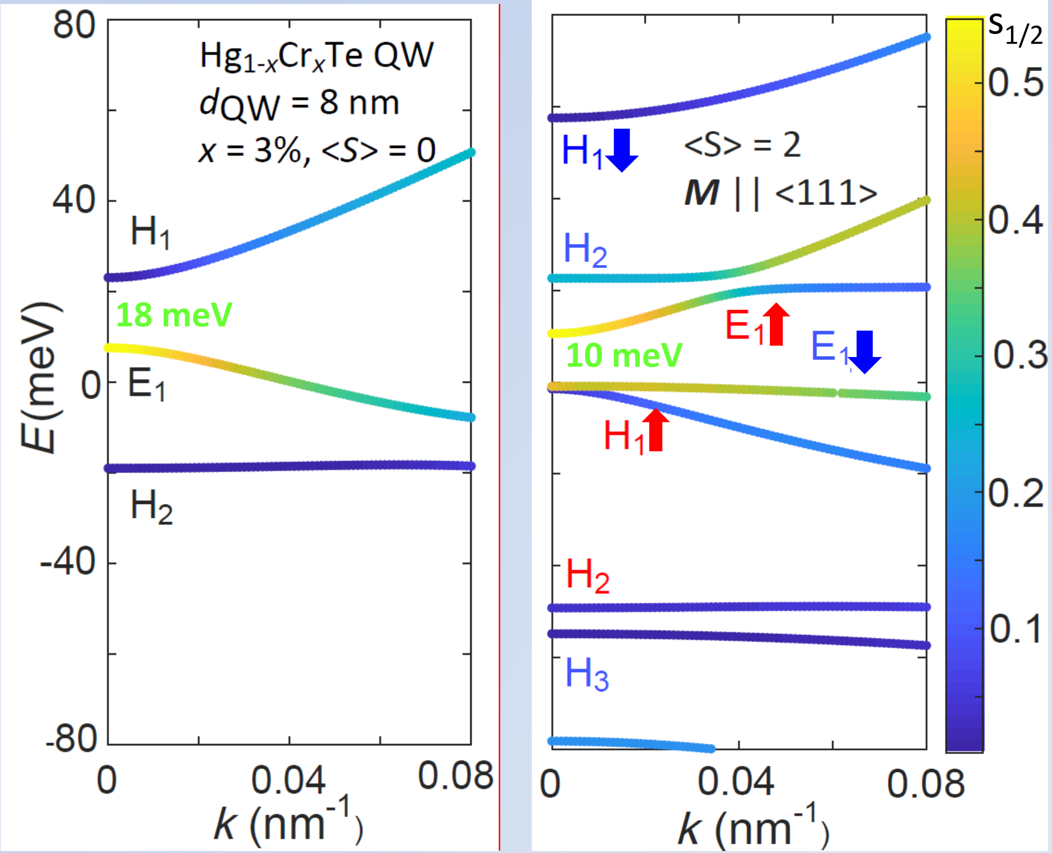




prospects for QAHE in (Hg,Cr)Te

(Hg,Cr)Te compared to (Hg,Mn)Te

- harder to introduce Cr
  but FM (Zn,Cr)Te grown by MBE
  R. Watanabe [RIKEN] APL'2019



C. Śliwa, T. D. [Warsaw] arXiv:2310.19856
cf. C.-X. Liu et al. [Beijing, Stanford] PRL'2008

outlook

dilute magnetic semiconductors on the way to quantum ampere and kilogram

- QHE in (Hg,Mn)Te QWs superior to Graphene
- QAHE in (Hg,Cr)Te QWs superior to $(Bi,Sb,Cr)_2Te_3$

Mn and Cr effusion cells installed in Rzeszów University Hg-MBE