Metal-insulator transition and ion implantation doping in semiconductor devices

Shamashis Sengupta

Astroparticles Solid-State Detectors,
IJCLAB, Orsay

Journées MOSAIC,
IJCLAB,
September 26, 2024

Acknowledgements

Solid-state devices

Claire Marrache-Kikuchi
Le Hong Hoang To
Louis Dumoulin
Shamashis Sengupta

Implantation and microscopy

Jérome Bourçois
Florian Pallier
Silvin Herve
Cedric Baumier
Cyril Bachelet
Stéphanie Jublot-Leclerc
Aurélie Gentils

C2N, Palaiseau

Léonard Desvignes
Francesca Chiodi
Dominique Debarre

LPS, Orsay

Miguel Monteverde

Project CP-Insulators

Project SEMISURF

Metals and insulators

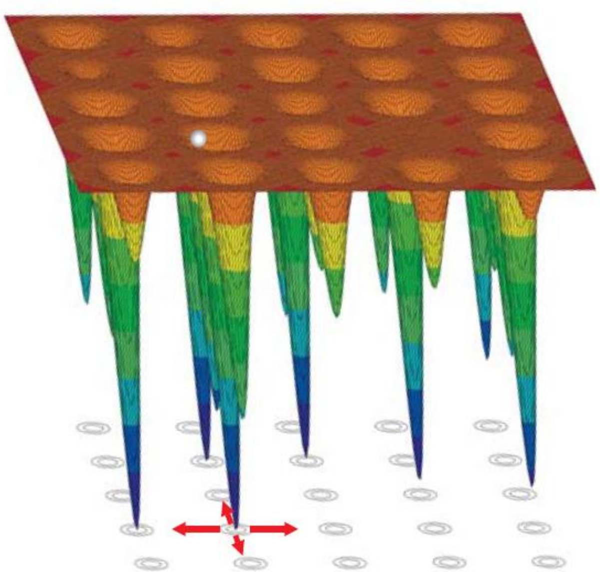
Parameters to describe metallic conductors

Conductivity $\sigma = ne\tau/m$

τ : Relaxation time

Mean free path $\ell = v_F \tau$

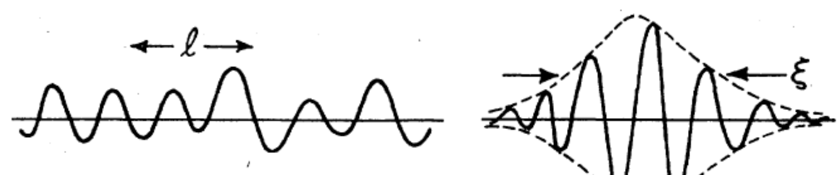
'Free' electron in a disorder potential



Fifty years of Anderson localization
Physics Today 62, 24 (2009)

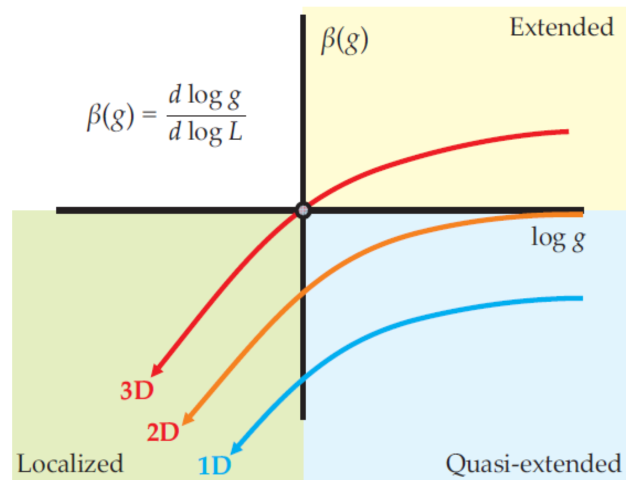
Absence of Diffusion in Certain Random Lattices
P. W. Anderson, Phys. Rev. (1958)

Beyond a critical limit of disorder, extended wavefunctions cease to exist. Electrons are localized.



Rev. Mod. Phys. 57, 287 (1985)

Scaling Theory of Localization: Absence of Quantum Diffusion in Two Dimensions
Abrahams et al., Phys. Rev. Lett. 42, 673 (1979)



Temperature variation of resistance

Arrhenius or activated behaviour

$$R = R_0 \ \exp\left(\frac{T_0}{T}\right)$$

T_0 is related to the band gap or nearest neighbour hopping

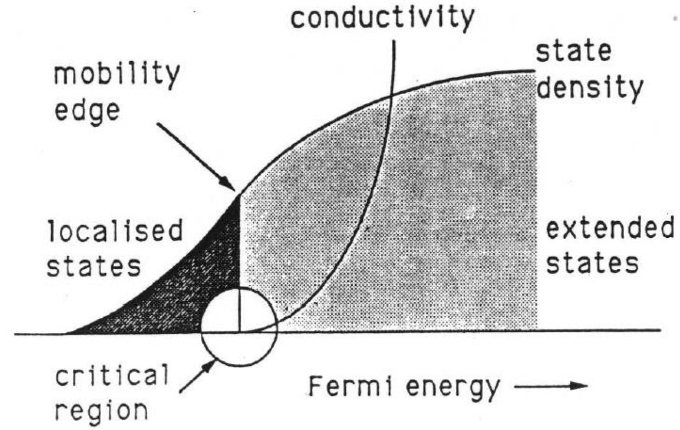
Variable range hopping (VRH)

$$R = R_0 \ \exp\left(\frac{T_0}{T}\right)^{\alpha} \qquad \alpha = D/(D+1)$$

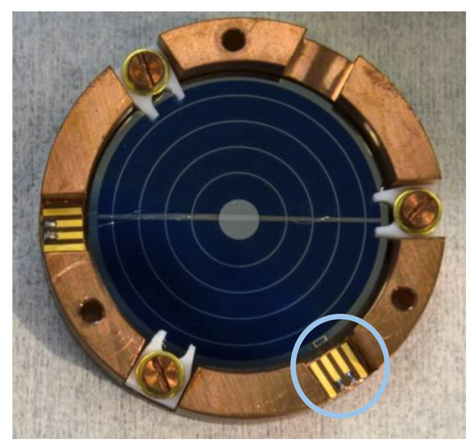
Electrons hop further if they find a suitable energy state.

α = 0.5 independent of dimensionality, with Coulomb interactions

Efros and Shklovskii, J. Phys. C 8, L49 (1975)



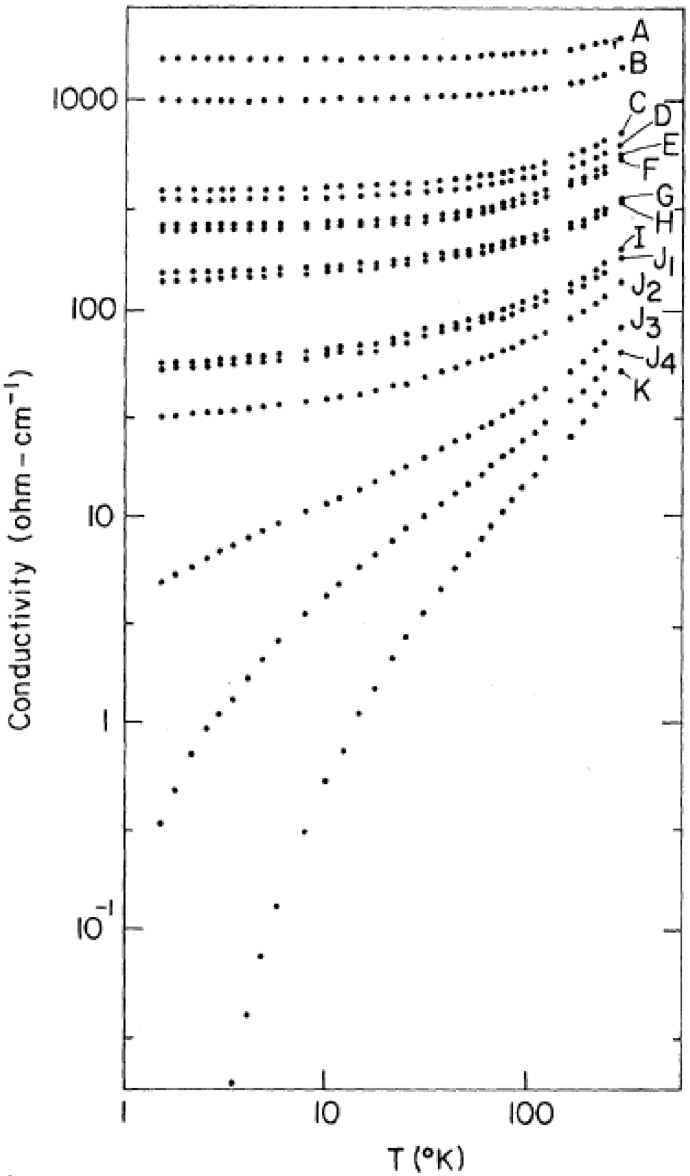
N. F. Mott,
Journal of Non-Crystalline Solids
(1968)



Valentina Novati, PhD thesis, 2018

Light detector with Ge absorber

Metal-insulator transition in disordered alloys



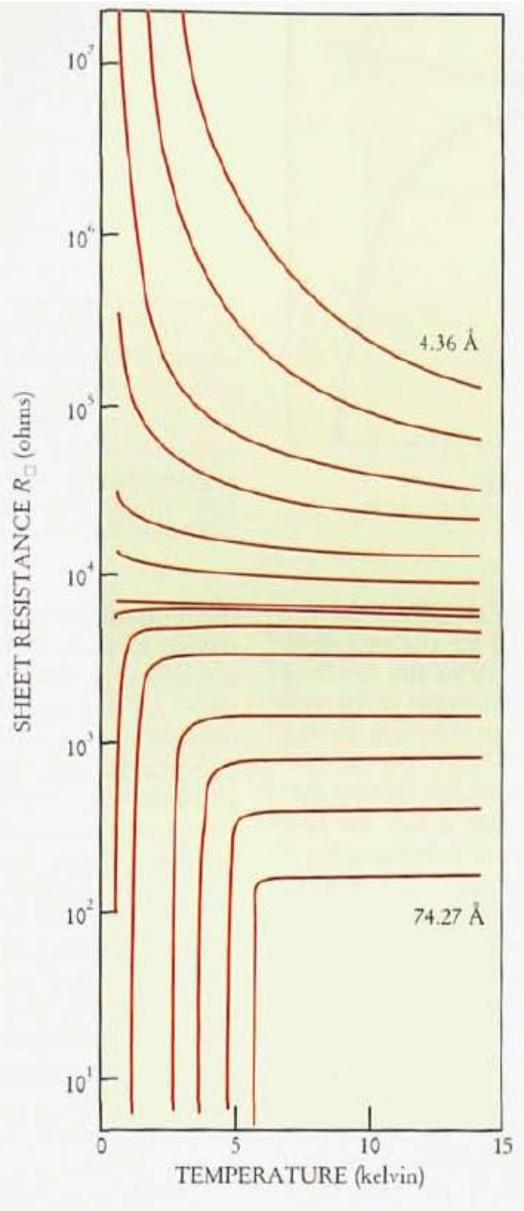
Ge-Au alloy

Dodson et al.,

Phys Rev. Lett. 46, 46 (1981)

FIG. 2. Conductivity vs temperature for amorphous $Ge_{1-x}Au_x$; decreasing conductivity generally corresponds to decreasing x. For curve A, $x = 0.24$ at.%; curve B, 0.20; curve C, 0.18; curve D, 0.12; curve E, 0.14; curve F, 0.14; curve G, 0.10; curve H, 0.10; curve I, 0.09; curves J_1–J_4, 0.08; and curve K, 0.06. The curves J_1–J_4 are produced by slight heating below 80 C to produce gold clustering.

Superconductor-Insulator transition (SIT)



SIT in bismuth films

PRL 67, 2068 (1991)

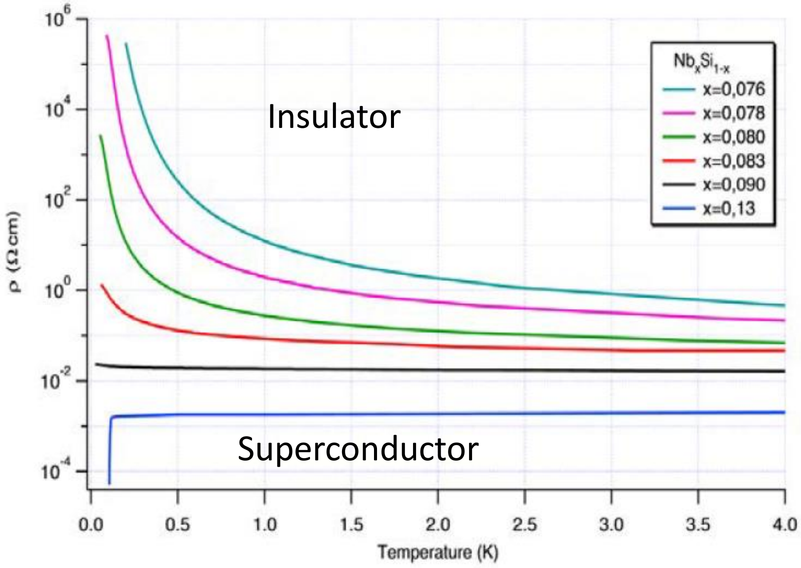
Physics Today 51, 39 (1998)

Is the insulating state fermionic or bosonic?

Is the electronic state homogeneous or granular?

Superconductor–insulator quantum phase transition
Gantmakher and Dolgopolov, **Phys.-Usp. 53, 1 (2010)**

Quantum breakdown of superconductivity in low-dimensional materials
Sacépé, Feigel'man and Klapwijk , **Nature Physics 16, 734 (2020)**

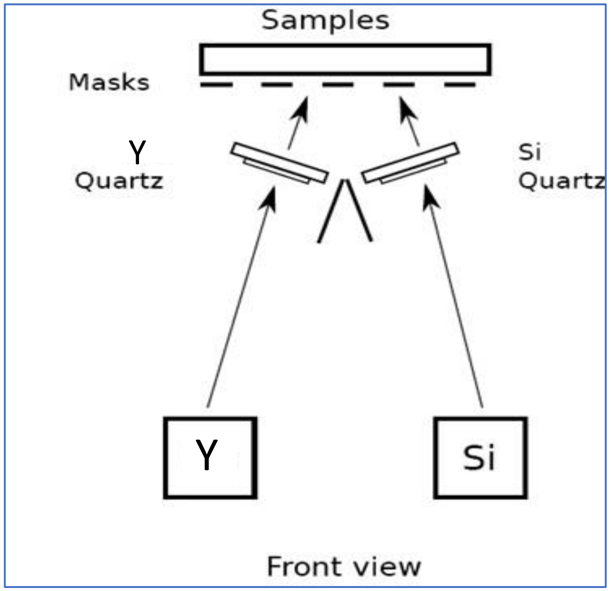


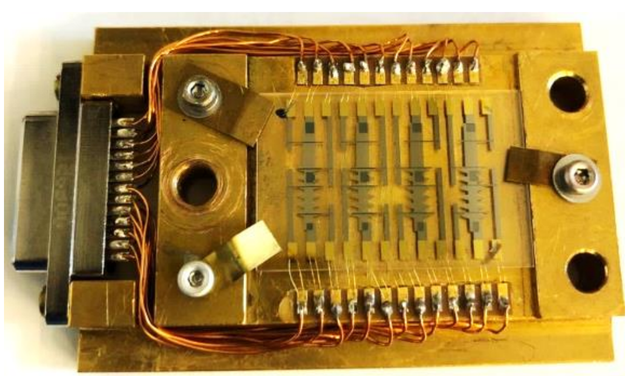
Stefanos Marnieros, PhD thesis, 1998

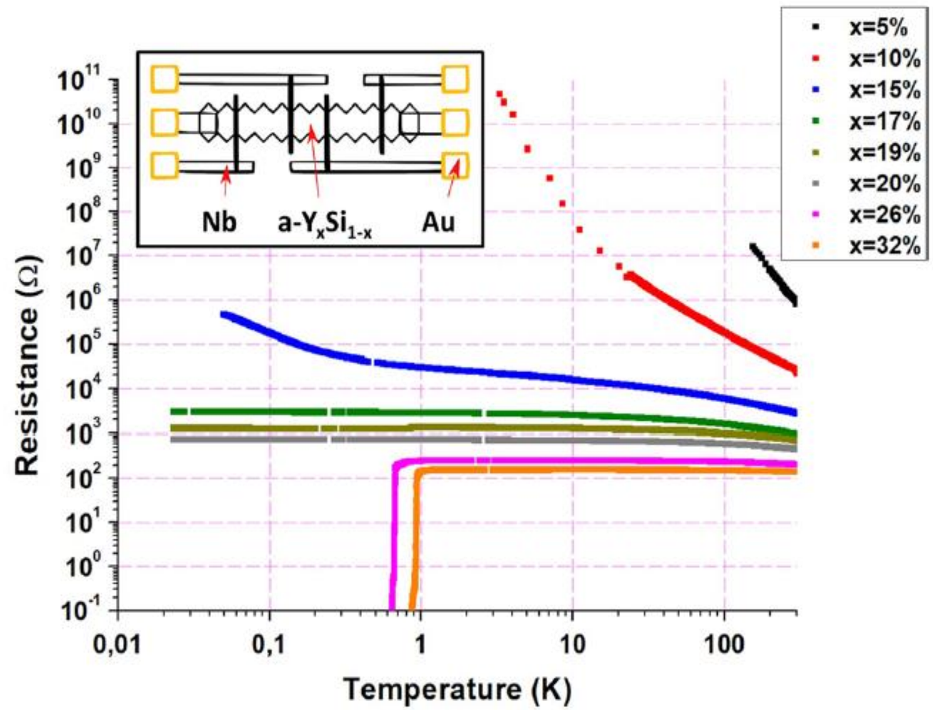
Different ways to tune T_c :
Film thickness,
composition,
annealing temperature

Superconductor-Insulator transition in Y_xSi_{1-x}

Preparation of thin films with co-evaporation







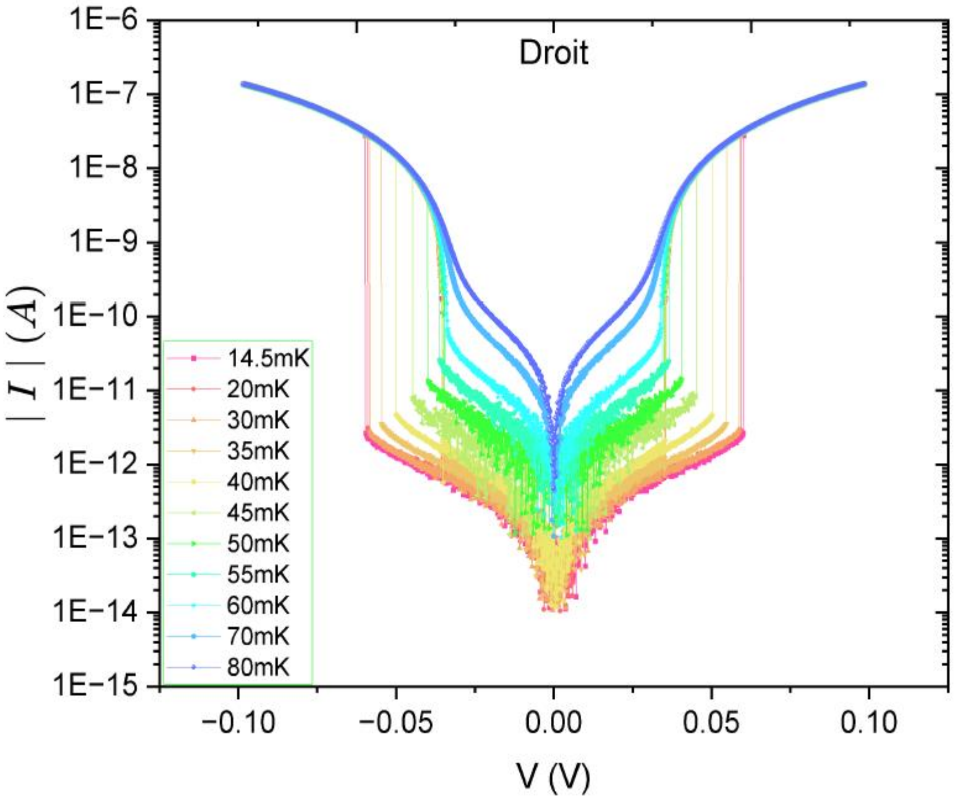
Hoang To et al.,
Journal of Low Temperature Physics 209, 1104 (2022)

Current jumps in $Y_{15}Si_{85}$

Heat balance equation

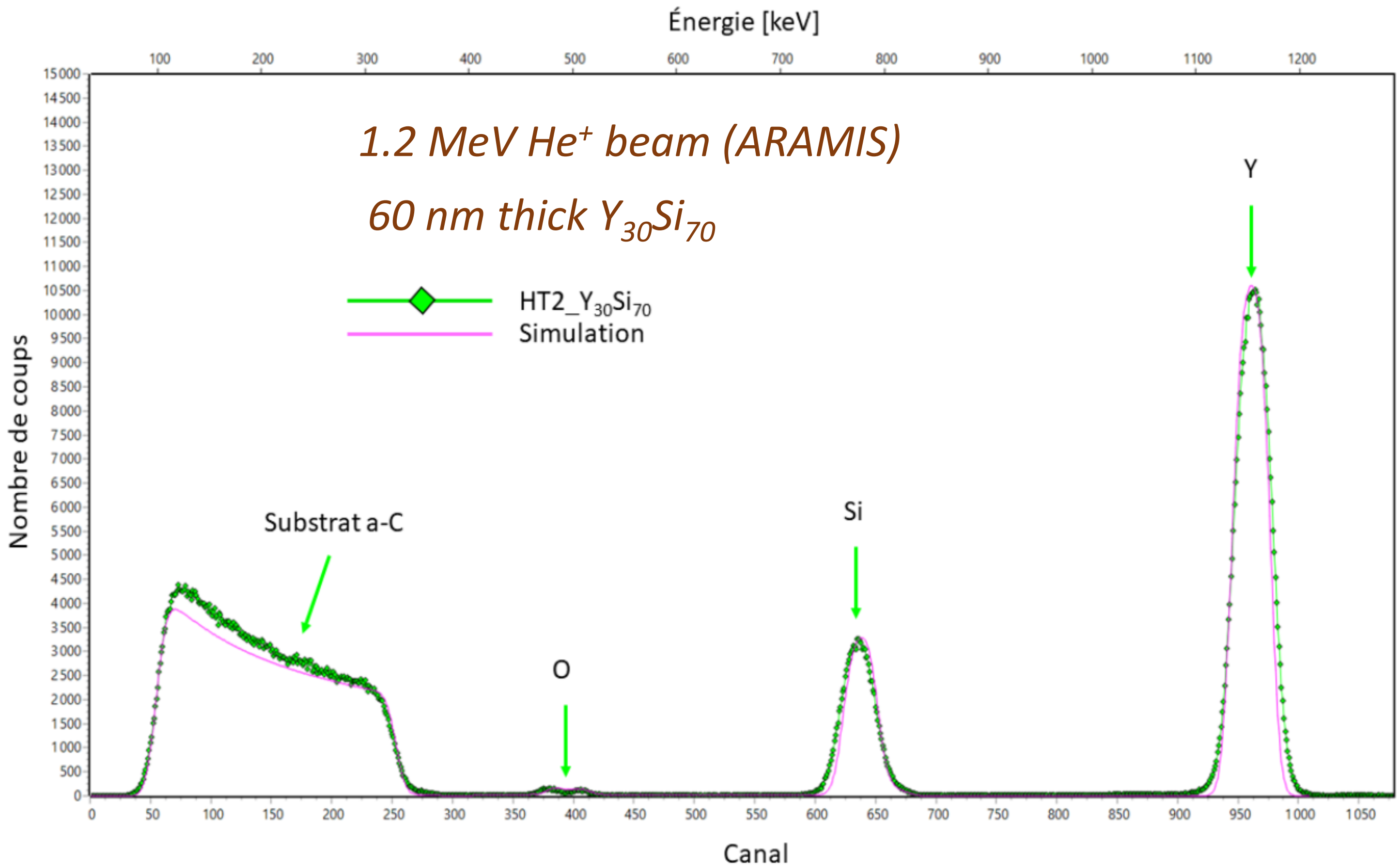
$$P = \Gamma_{e-\mathrm{ph}} \Omega (T_{\mathrm{el}}^{\beta} - T_{\mathrm{ph}}^{\beta})$$

Several orders of magnitude change in conductivity beyond a threshold voltage: Signature of electron-phonon decoupling



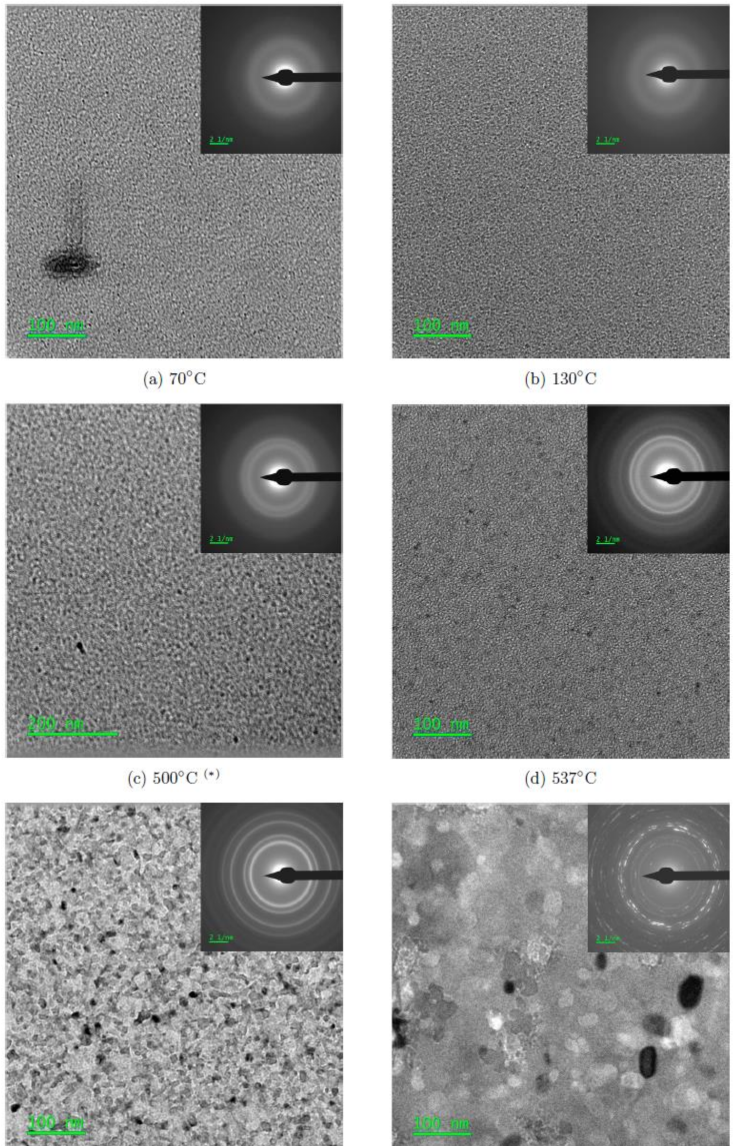
Le Hong Hoang To, PhD thesis, 2023

Rutherford Backscattering Spectrometry (RBS)



Experiments and analysis:
Jerome Bourçois
Hoang To
Claire Marrache-Kikuchi

Trasmission Electron Microscopy

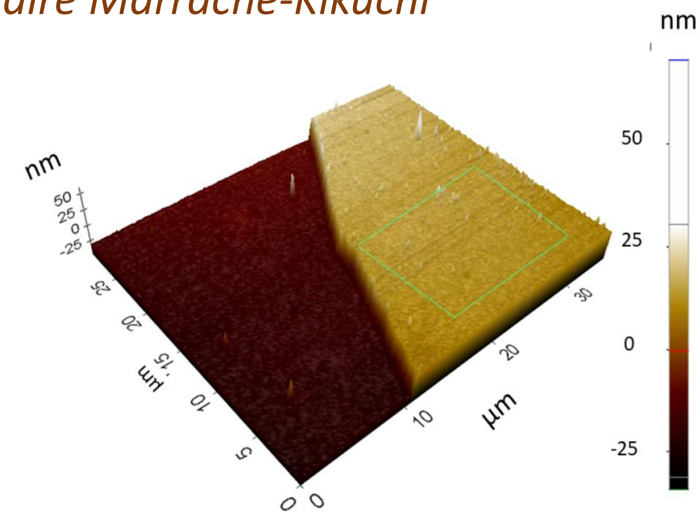


(a) 70°C (b) 130°C (c) 500°C (*) (d) 537°C (e) 770°C (f) 790°C

Evolution of film structure with annealing

30 nm thick $Y_{15}Si_{85}$ film on Si_3N_4 membrane

Experiments:
Cedric Baumier
Florian Pallier
Hoang To
Claire Marrache-Kikuchi

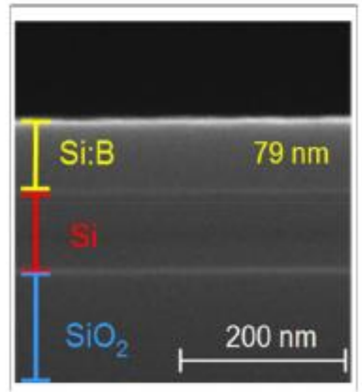


Si:B with gas immersion laser doping (GILD)

Direct band gap of Si: 3.5 eV
$\lambda = 308nm \Leftrightarrow E = hc/\lambda \simeq 4eV$

25 ns pulse

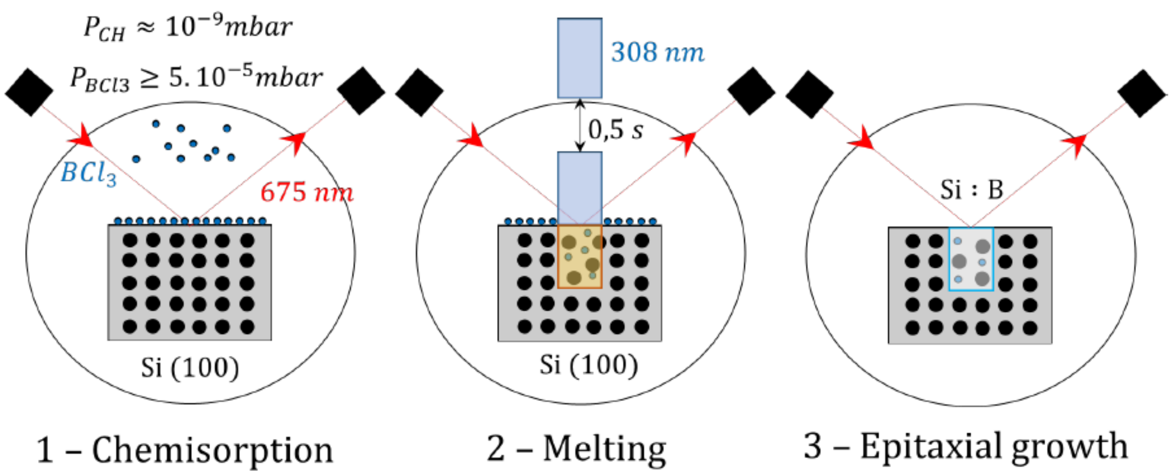
Hall measurements:
30 nm samples 10^{20} cm^{-3}

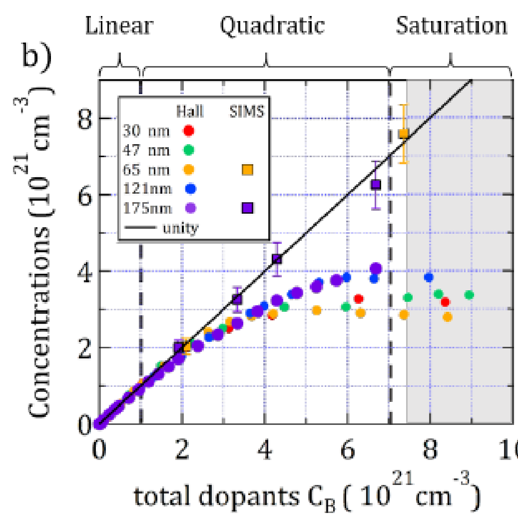


Léonard Desvignes
PhD thesis, 2023

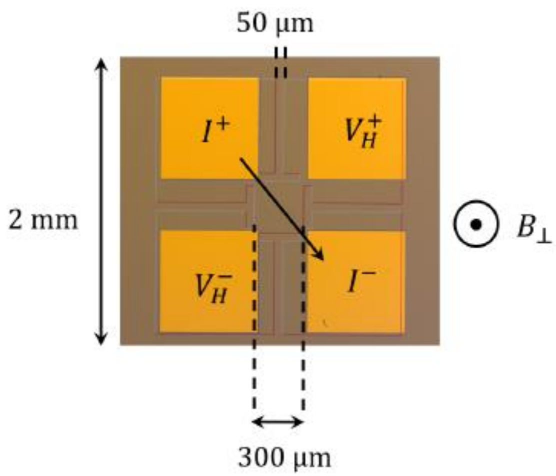
C2N

Léonard Desvignes
Francesca Chiodi
Dominique Debarre

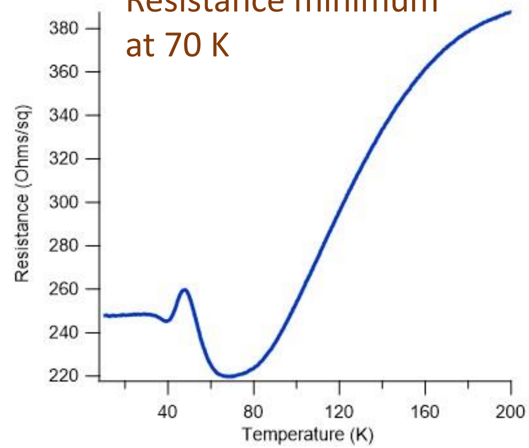


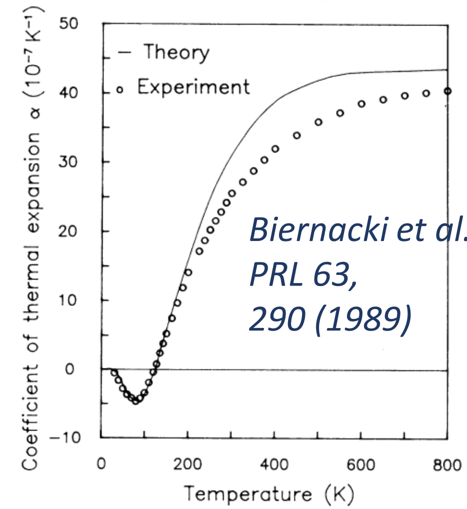


Si:B with gas immersion laser doping (GILD)



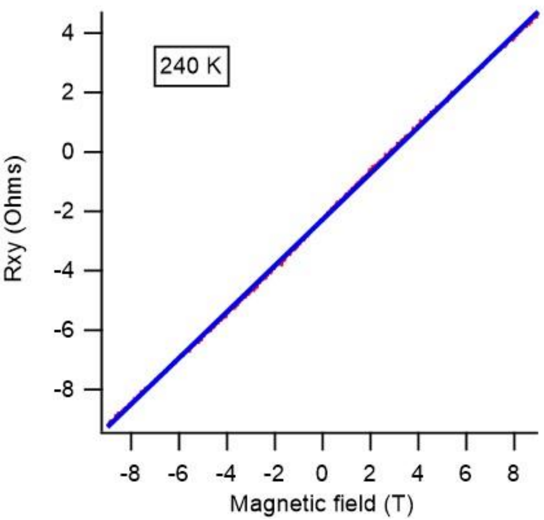
Resistance minimum at 70 K

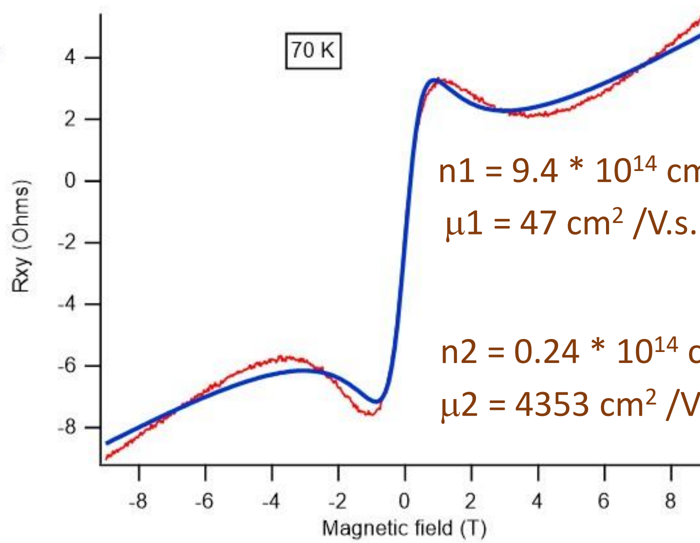




Biernacki et al., PRL 63, 290 (1989)

n = 8.3 * 10^{14} cm^{-2}

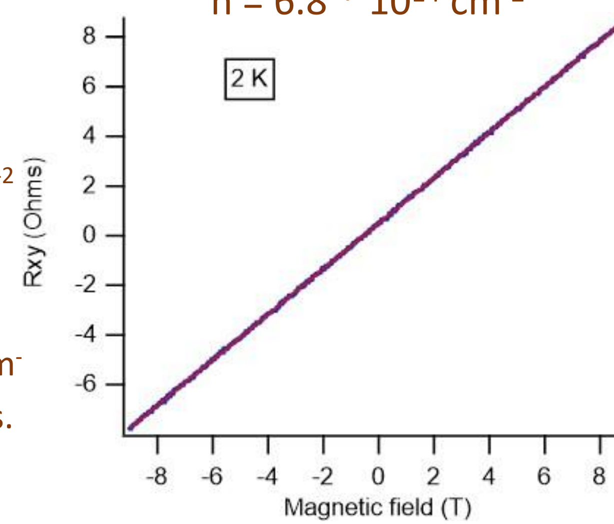




n1 = 9.4 * 10^{14} cm^{-2}
µ1 = 47 cm^2 /V.s.

n2 = 0.24 * 10^{14} cm^{-}
µ2 = 4353 cm^2 /V.s.

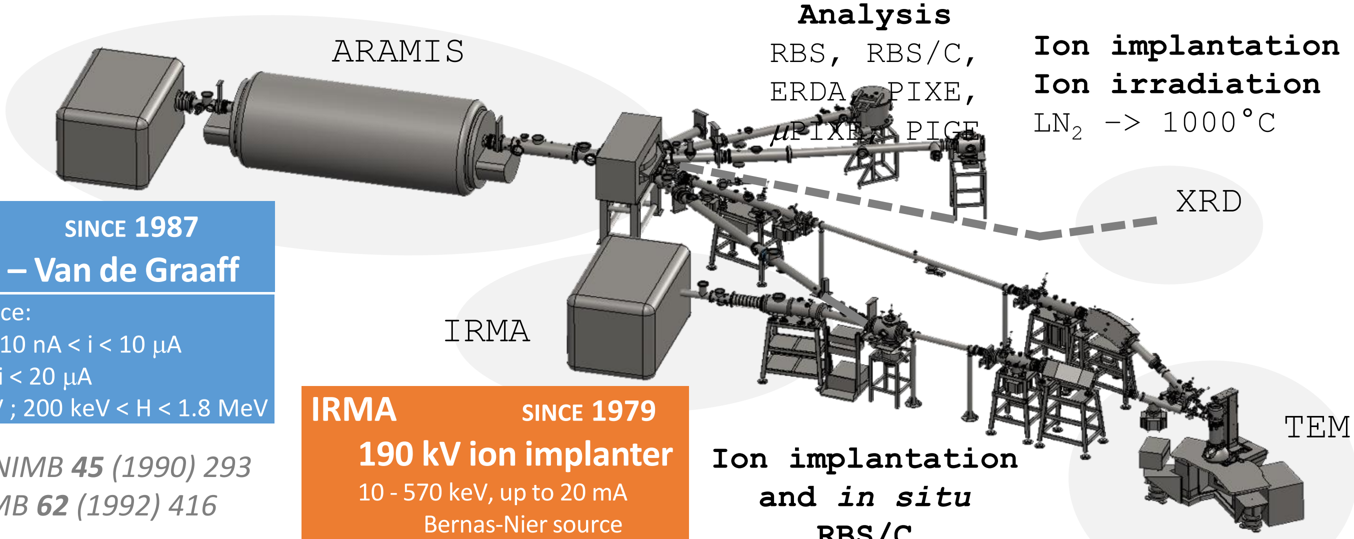
n = 6.8 * 10^{14} cm^{-2}



Hall effect reveals two types of carriers at 70 K.

Ion implantation

The JANNuS-Orsay experimental hall :
ARAMIS, IRMA, *in situ* TEM



ARAMIS SINCE 1987
2 MV Tandem – Van de Graaff

SNICS negative ion source:
500 keV < E < 11 MeV ; 10 nA < i < 10 μA
Penning source @ HV : i < 20 μA
200 keV < He < 3.6 MeV ; 200 keV < H < 1.8 MeV

*E. Cottereau et al., NIMB **45** (1990) 293*
*H. Bernas et al., NIMB **62** (1992) 416*

IRMA SINCE 1979
190 kV ion implanter
10 - 570 keV, up to 20 mA
Bernas-Nier source

*J. Chaumont et al., NIMB **198** (1981) 193*

***IN SITU* DUAL ION BEAM TRANSMISSION ELECTRON MICROSCOPE**
SINCE 1980 UPDATED IN 1994, 2007

*M.-O. Ruault et al., J. Mater. Res. **20** (2005) 1758*
*A. Gentils et al., NIMB **447** (2019) 107*

Ion implantation

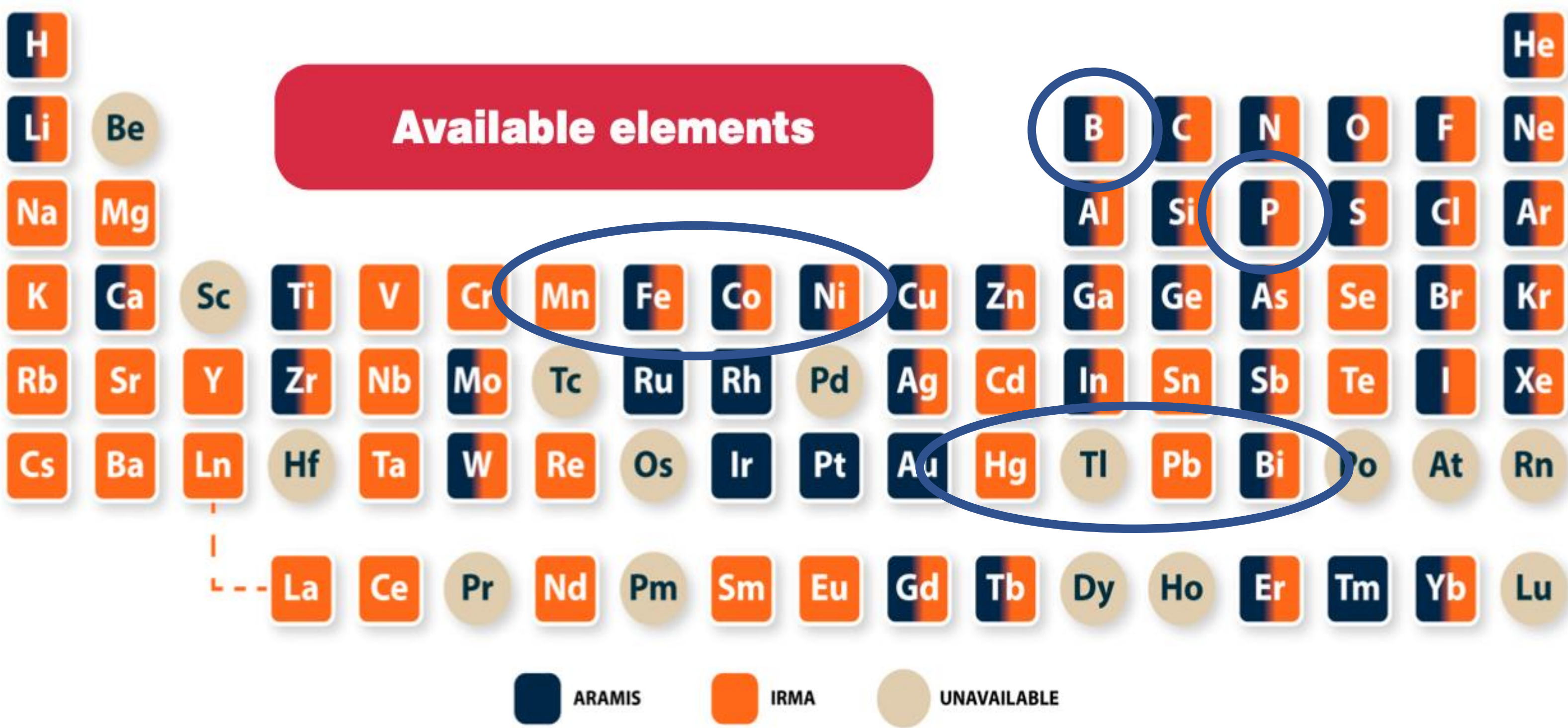
2 MV
ARAMIS

190 kV
IRMA

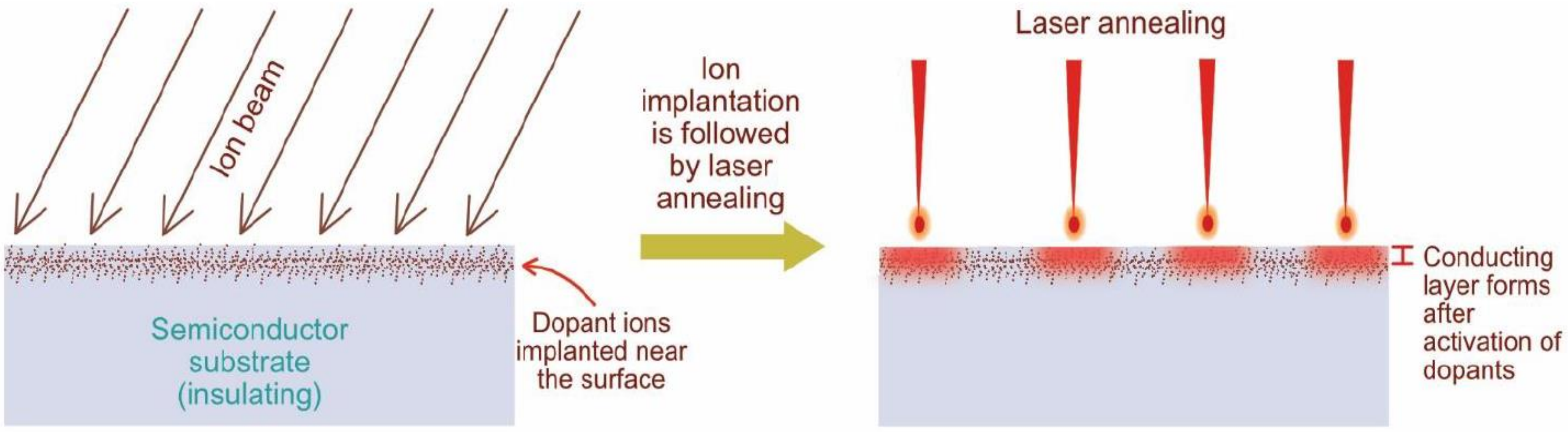
40 kV
SIDONIE

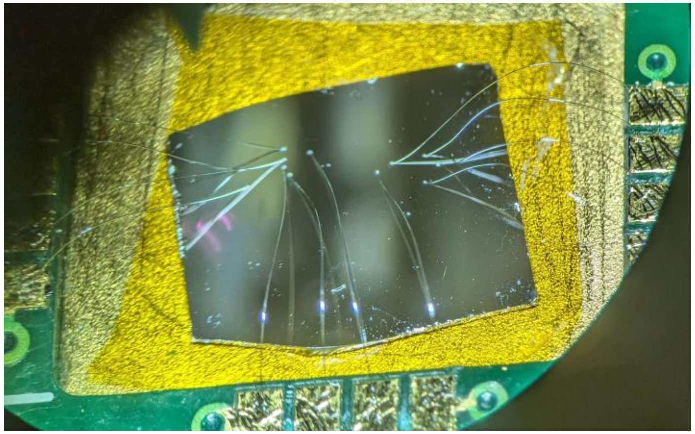
Choice of dopants

More than 70 elements available



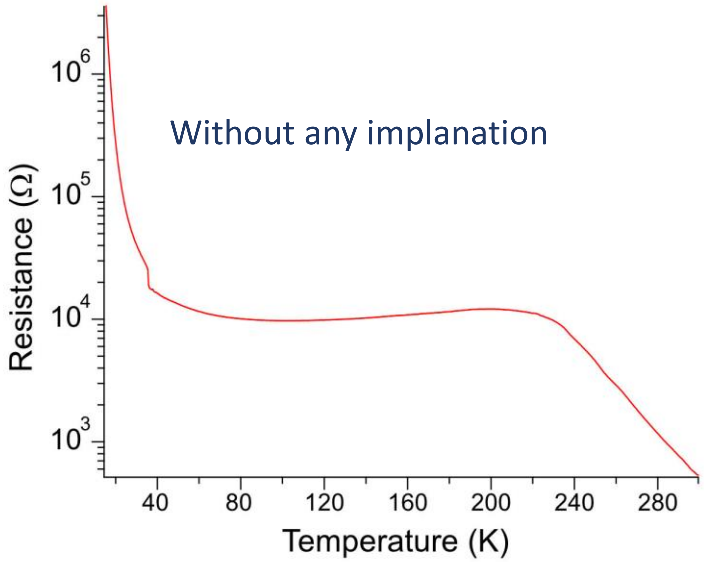
Ion imlantation doping

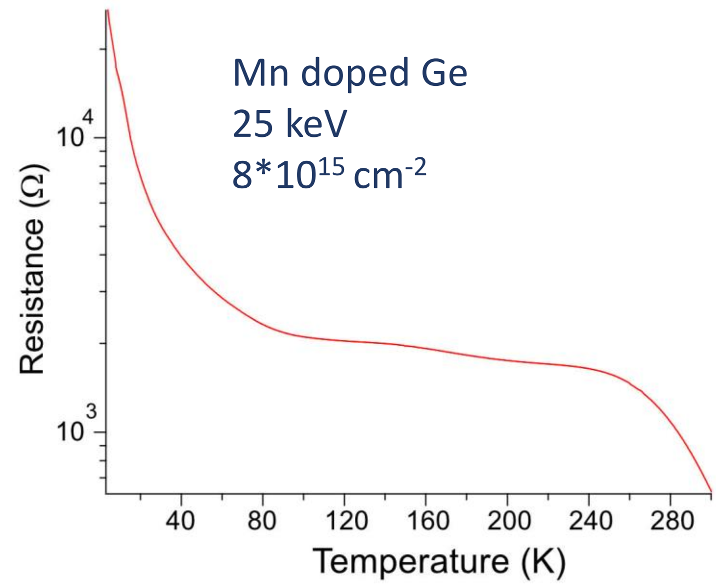


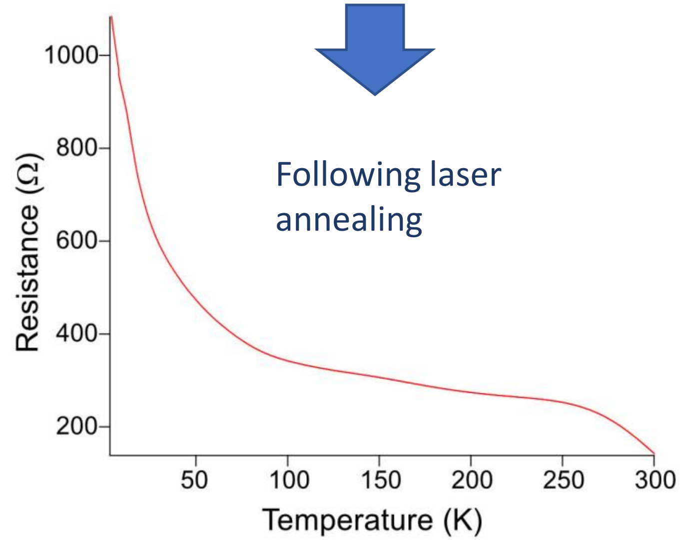


Mn-doped Si

Mn-doped Ge



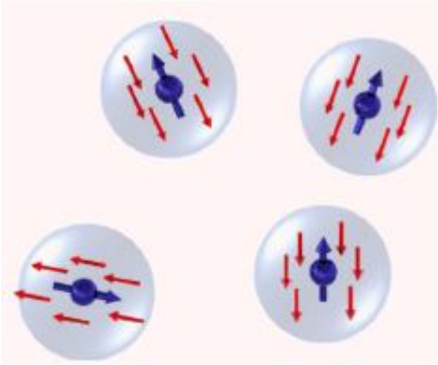




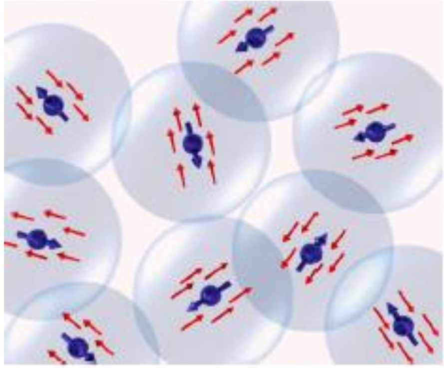
Implantation:
Jérome Bourçois
Silvin Herve

Magnetic impurities in Si

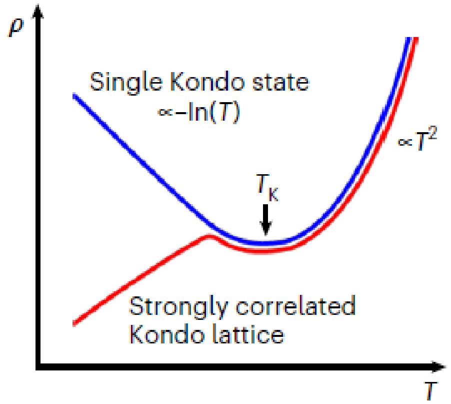
Kondo cloud

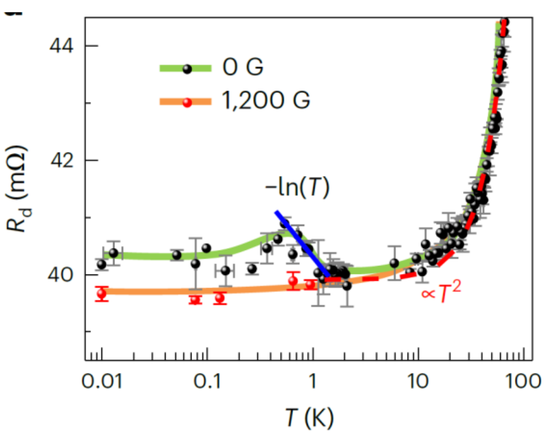


Kondo condensation



Im et al., Nat. Phys. 19, 676 (2023)

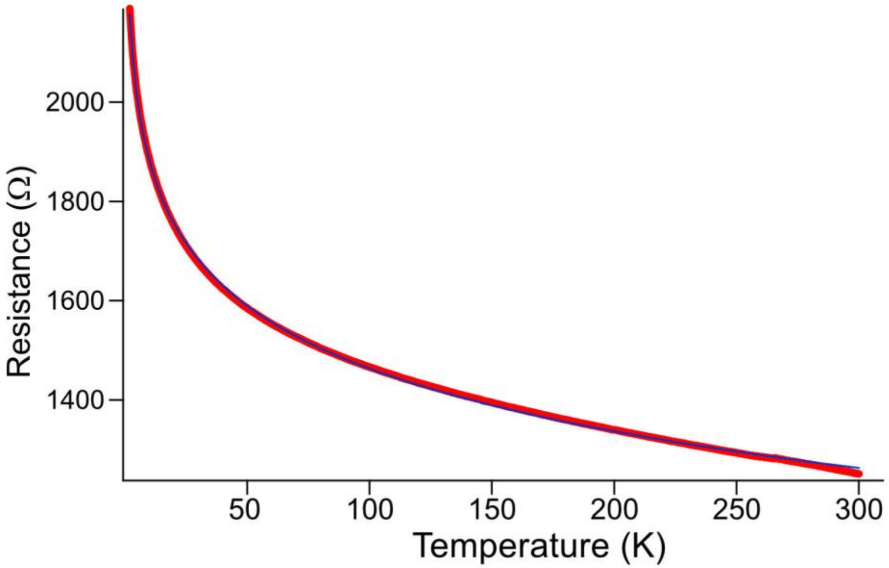


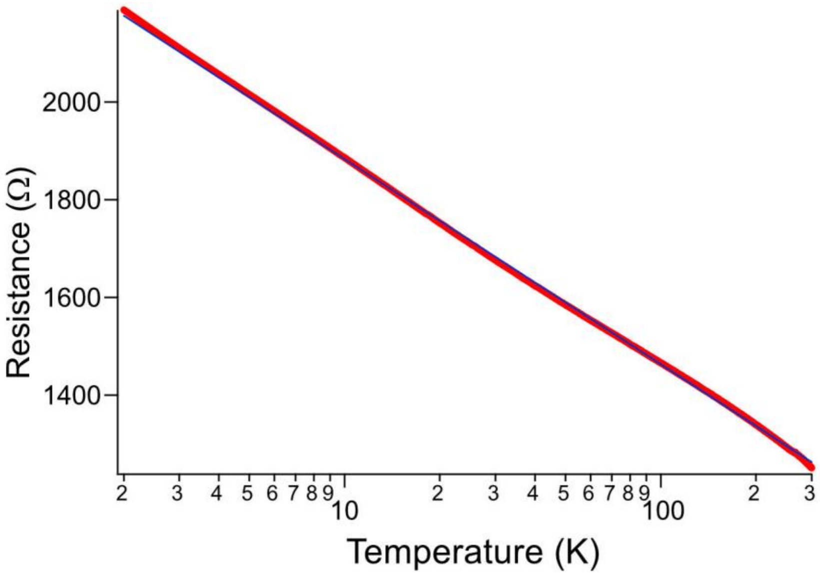


P-doped Si

Mn-doped Si

Mn doped Si
25 keV
$8*10^{15}$ cm^{-2}





ln (1/T) dependence over a large range of temperatures: weak localization in 2D

Future objectives

- Engineering electronic states with magnetism and spin-orbit interactions on semiconductor surfaces
- Explore the physics of metal-insulator transitions, superconductivity and device applications

Thank you!