Condensed Matter Seminar
(Korea University)

Doping in semiconductors &
New magnetic phase transitions in P-doped metallic Si

2016. 03. 23.

임 현식

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Brief introduction

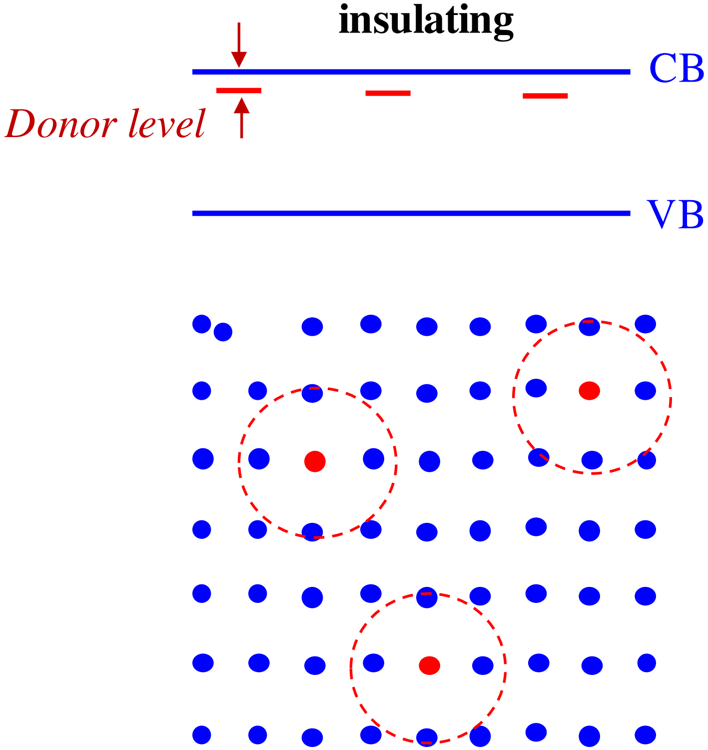
- **Doping in semiconductors: Metal insulator transition (MIT)**
- **Single-particle DOS gap near the MIT region**

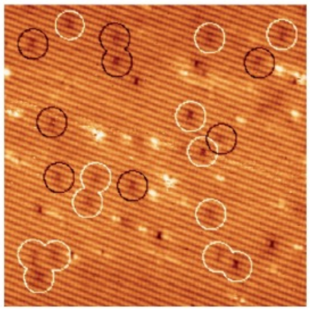
Results and discussion

- **Novel quantum phases and quantum phase transitions**
  in quasi-degenerate metallic Si:P

Impurity band in P-doped silicon (Si:P)

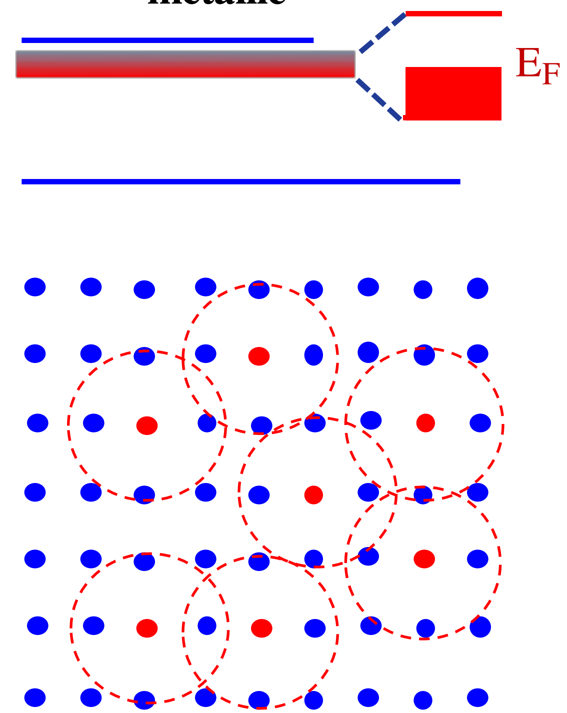
$N < N_C$
insulating





Si:P (6×10^{19}/cm^3)

$N > N_C$
metallic



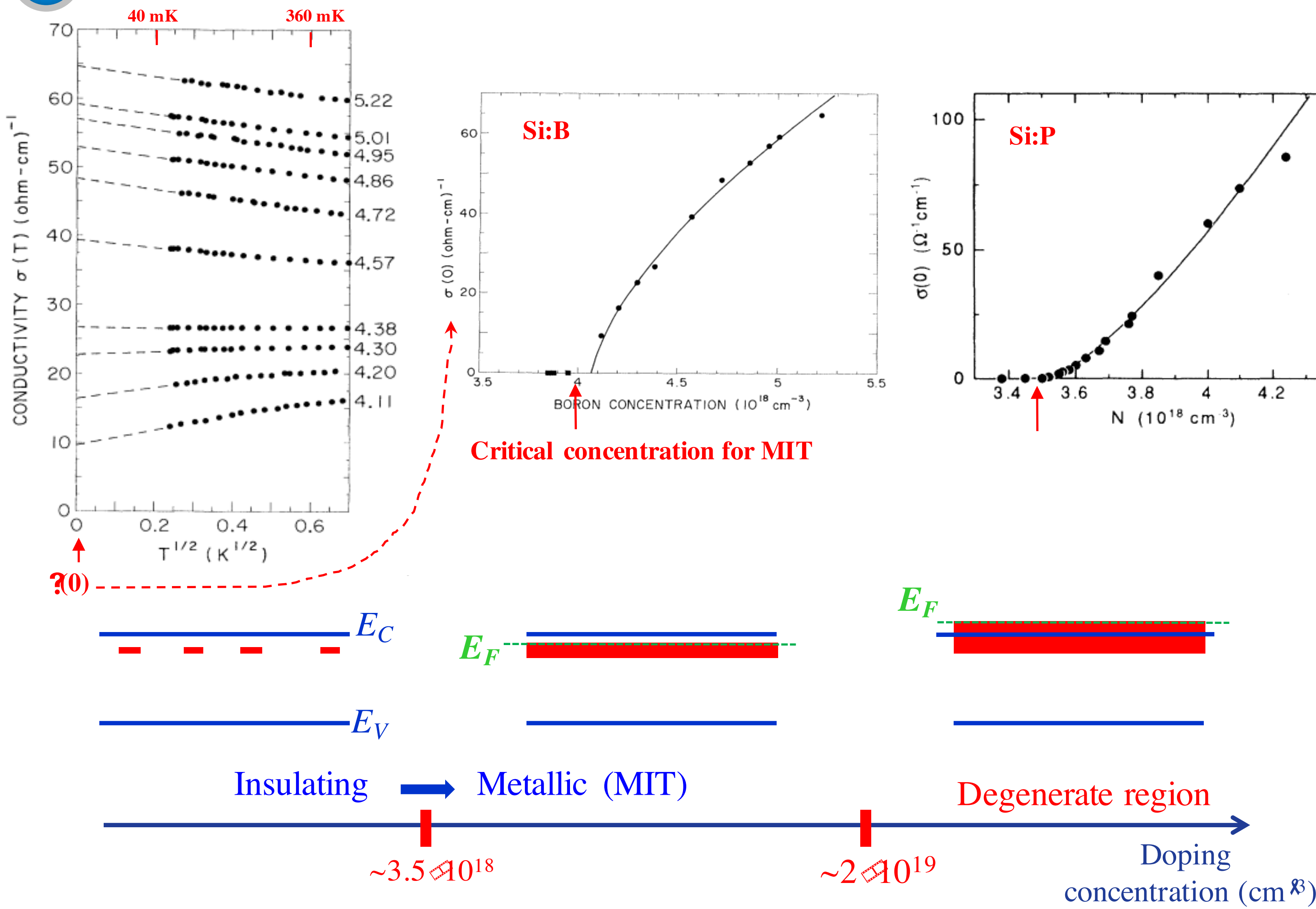
Isolated impurity level

Localized moments

Impurity band

Disorder
Coulomb correlations

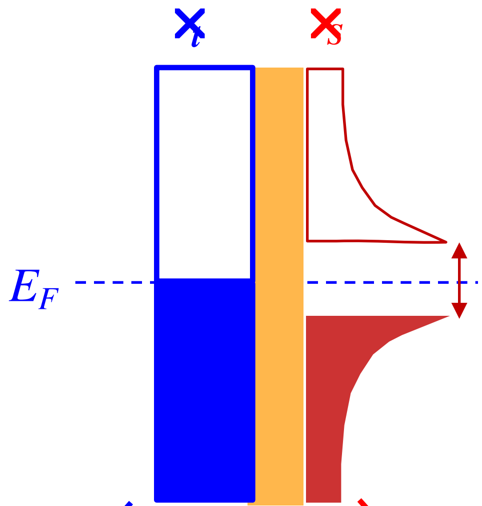
Metal Insulator Transition (MIT) in Si



Tunneling DOS spectroscopy

Tunneling current

$$I \propto \int_0^{eV} \rho_s(E)\rho_t(-eV+E)dE$$



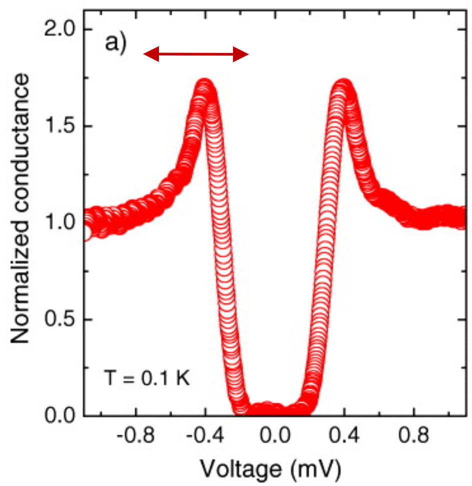
Reference material (i.e. metal) Constant DOS near E_F

Tunnel barrier

Interesting material

Tunneling conductance $\propto$ DOS

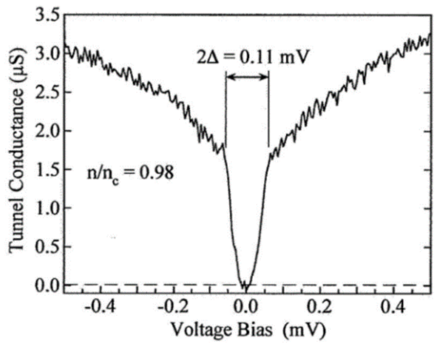
$$\frac{dI}{dV} \propto \rho_s(E_F - eV)$$



DOS gap in Si:B

Gap in the single particle DOS in Si:B (p-type) near the MIT

(*e-e* interaction and disorder)



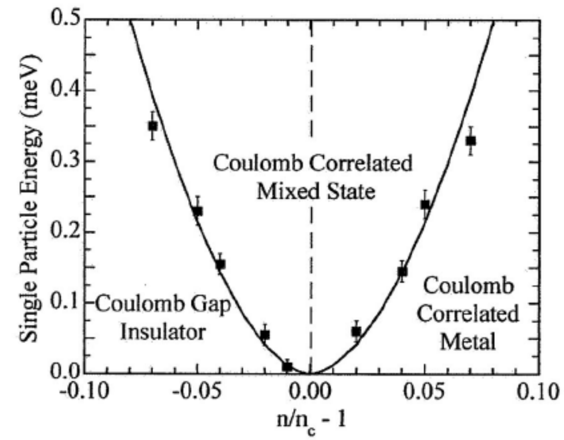
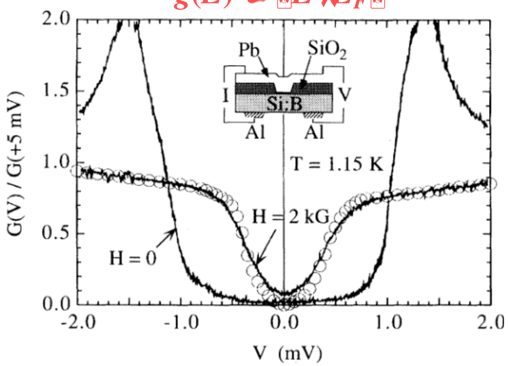


FIG. 4. Zero temperature phase diagram of Coulomb correlations through the MIT in the single-particle energy vs reduced density plane. The data points plotted are Δ for insulators and Δ' for metals. The blue curve is a guide-to-the-eye representation of the phase boundary $\epsilon^*(|n/n_c - 1|)$. As drawn, $\epsilon^* \sim |n/n_c - 1|^\gamma$ with $\gamma = 1.7$, but any value of γ between 1.5 and 2 can yield a reasonable fit.

Efros & Shklovskii: Coulomb gap

(Soft gap)

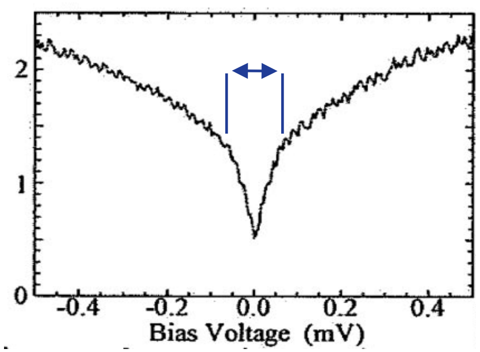
$g(E) \propto |E - E_F|^2$



Altshuler, Aronov, McMillan:

Zero-bias anomaly (ZBA)

$[g(E) - g(0)] \propto |E|^{0.5}$



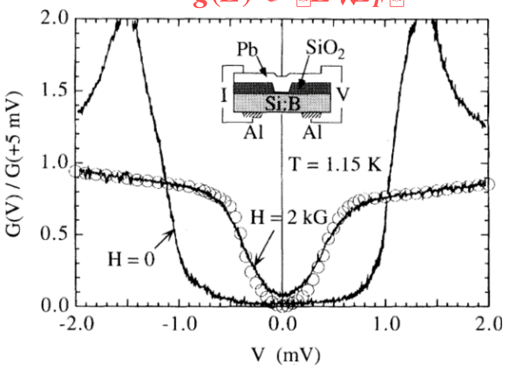
Insulating side ***Metallic side***

3.4×10^{18} for Si:B (MIT)

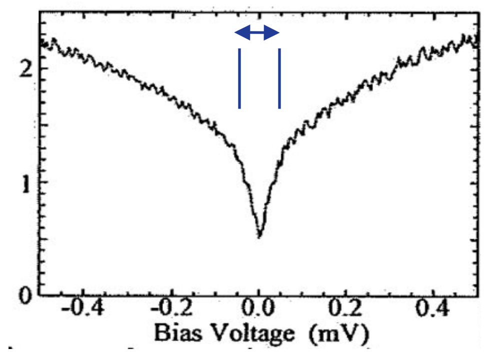
Something new in the quasi-degenerate metallic region?

Non-magnetic

Efros & Shklovskii: Coulomb gap
(Soft gap)
$g(E) \propto |E - E_F|^2$



Altshuler, Aronov, McMillan:
Zero-bias anomaly (ZBA)
$\delta g(E)/g(0) \propto |E|^{0.5}$



Insulating side

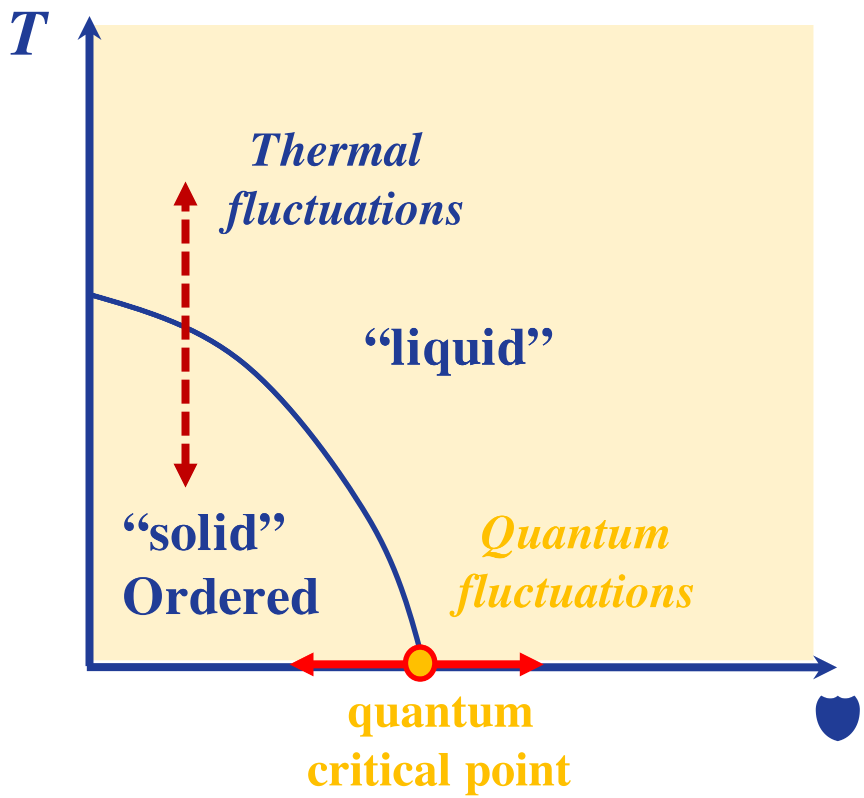
Metallic side

?

Interesting comment:
The single-particle DOS in Si:P (n-type) has not been reported yet.

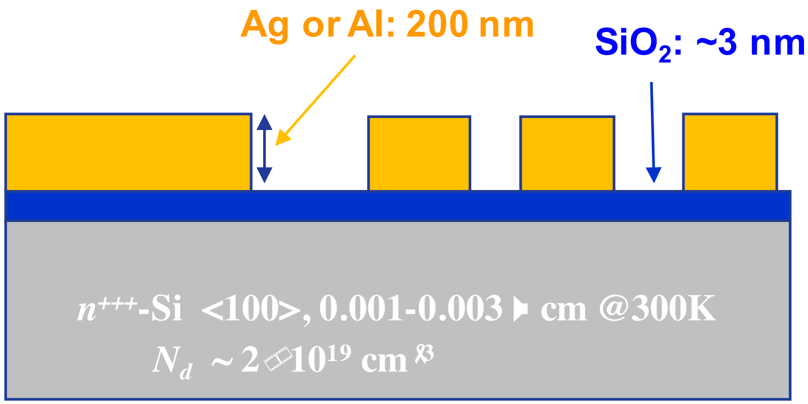
Quantum Phase Transition (QPT)

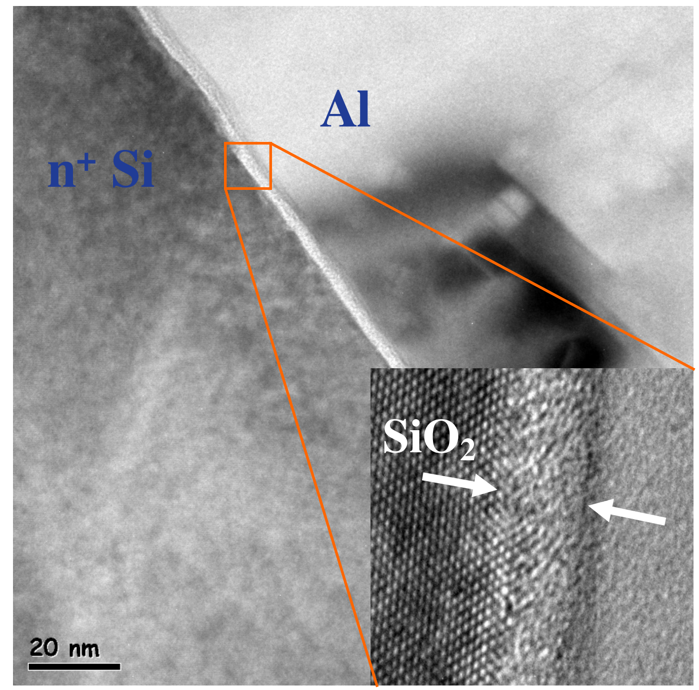
Phase transition between different phases of matter at absolute zero temperature (*T*) by varying a physical parameter (, *B*, *P* or composition, etc).



In this work, different phases of Si:P are assessed by measuring the DOS as a function of *B* at various temperatures.

Tunneling devices



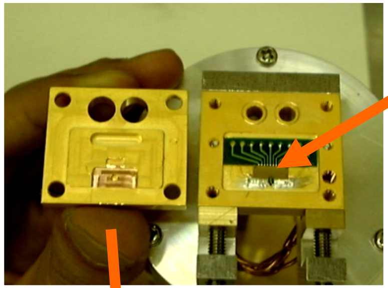


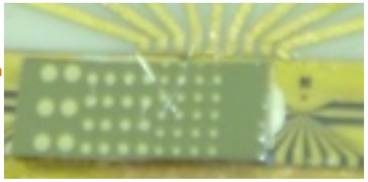
Oxidation:

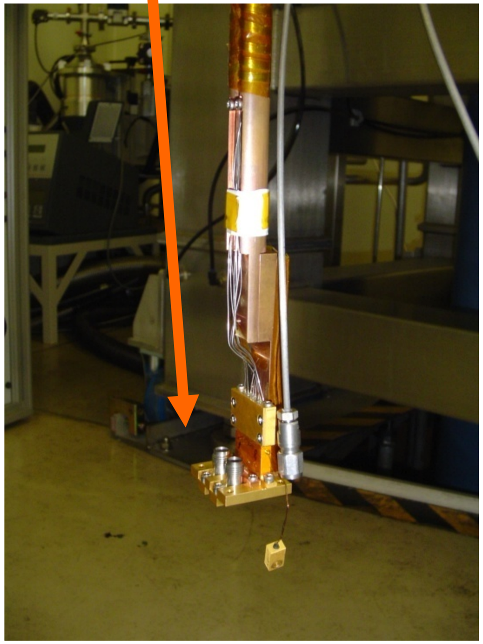
O_2: 100 Pa, Substrate T: 1000 °C, 17 min

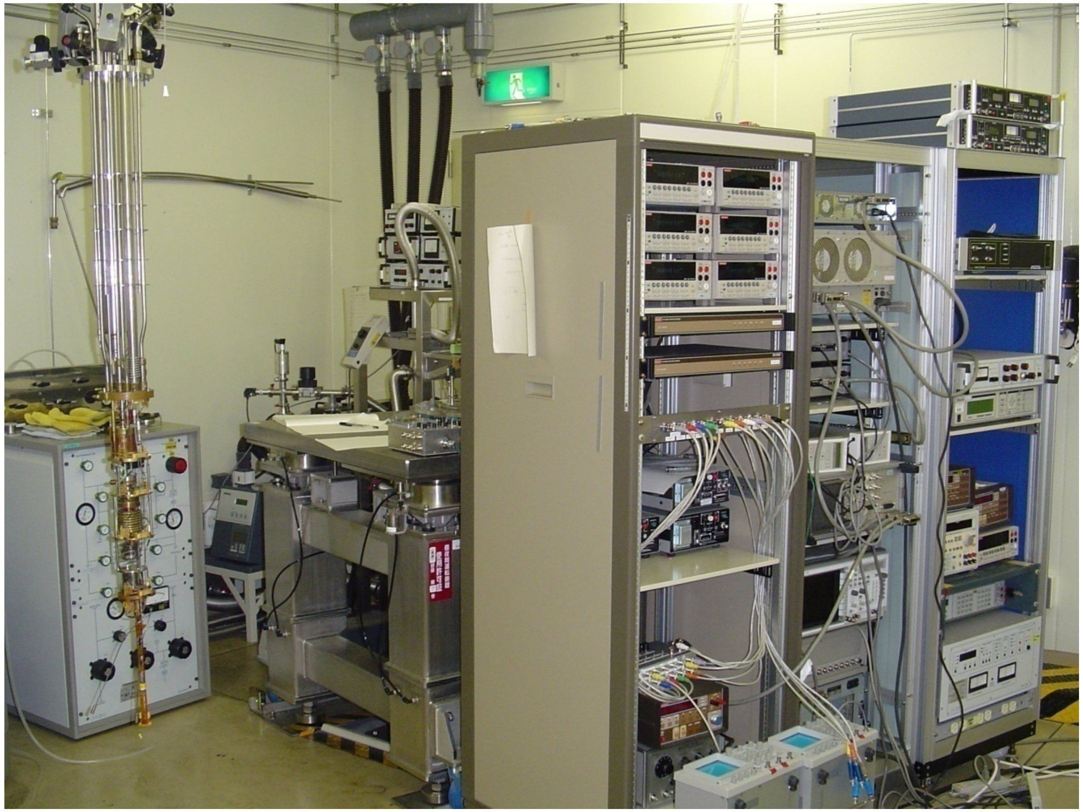
Transport measurement at dilution temperatures

@ NEC/RIKEN (Japan) & KRISS (Korea)



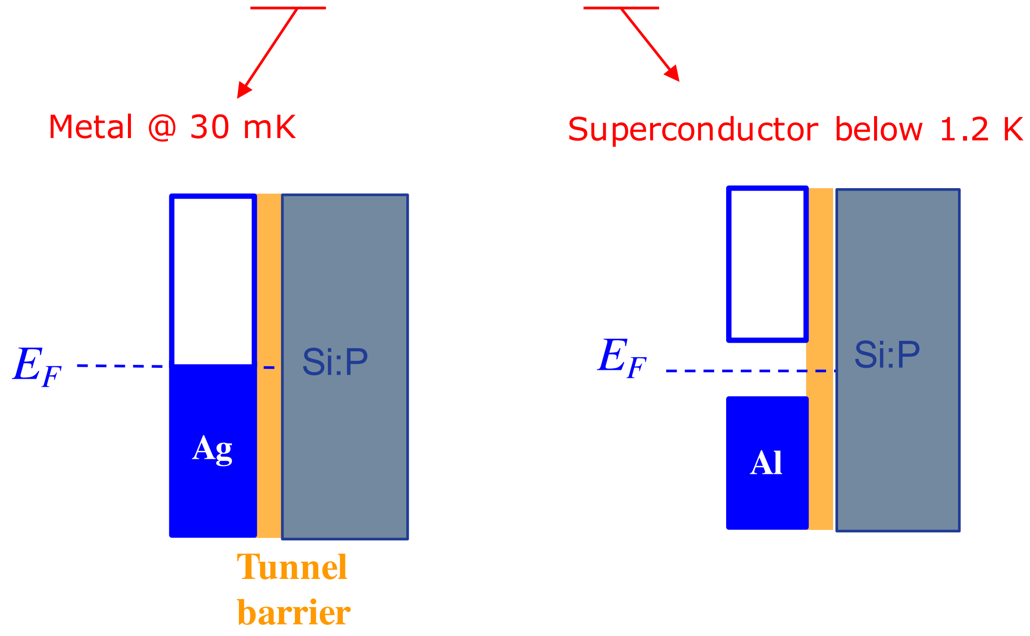






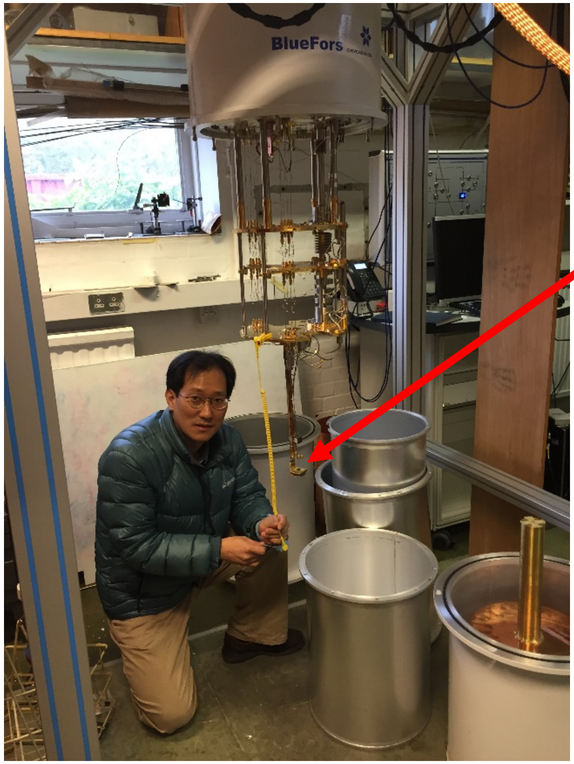
Tunneling DOS spectroscopy *in quasi-degenerate P-doped silicon (Si:P)*

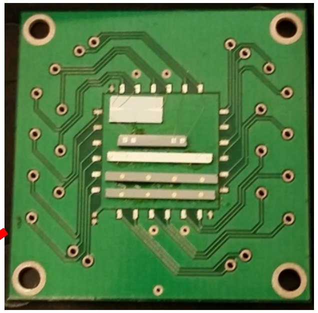
Two different samples: Ag-SiO_2-Si:P & Al-SiO_2-Si:P

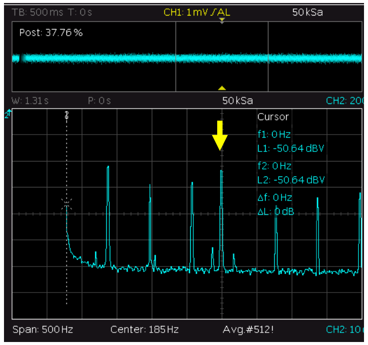


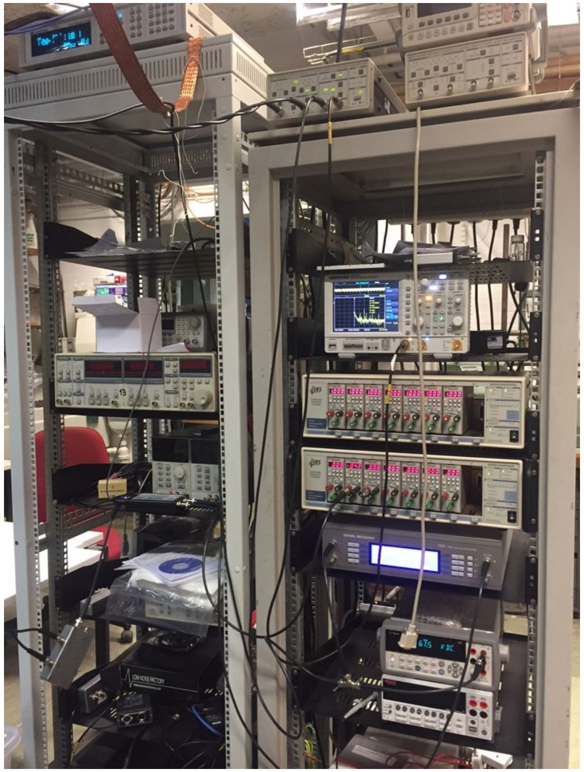
Novel magnetic quantum phases & Magnetic field driven quantum phase transition

4 points conductance measurements @ Quantum technology center at Lancaster Univ.

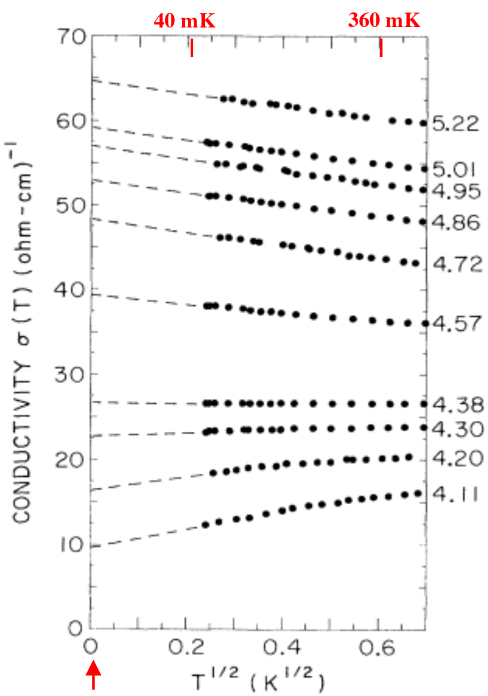


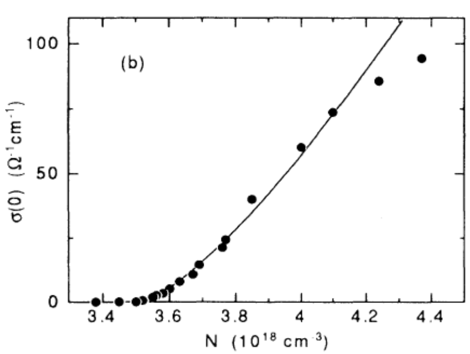


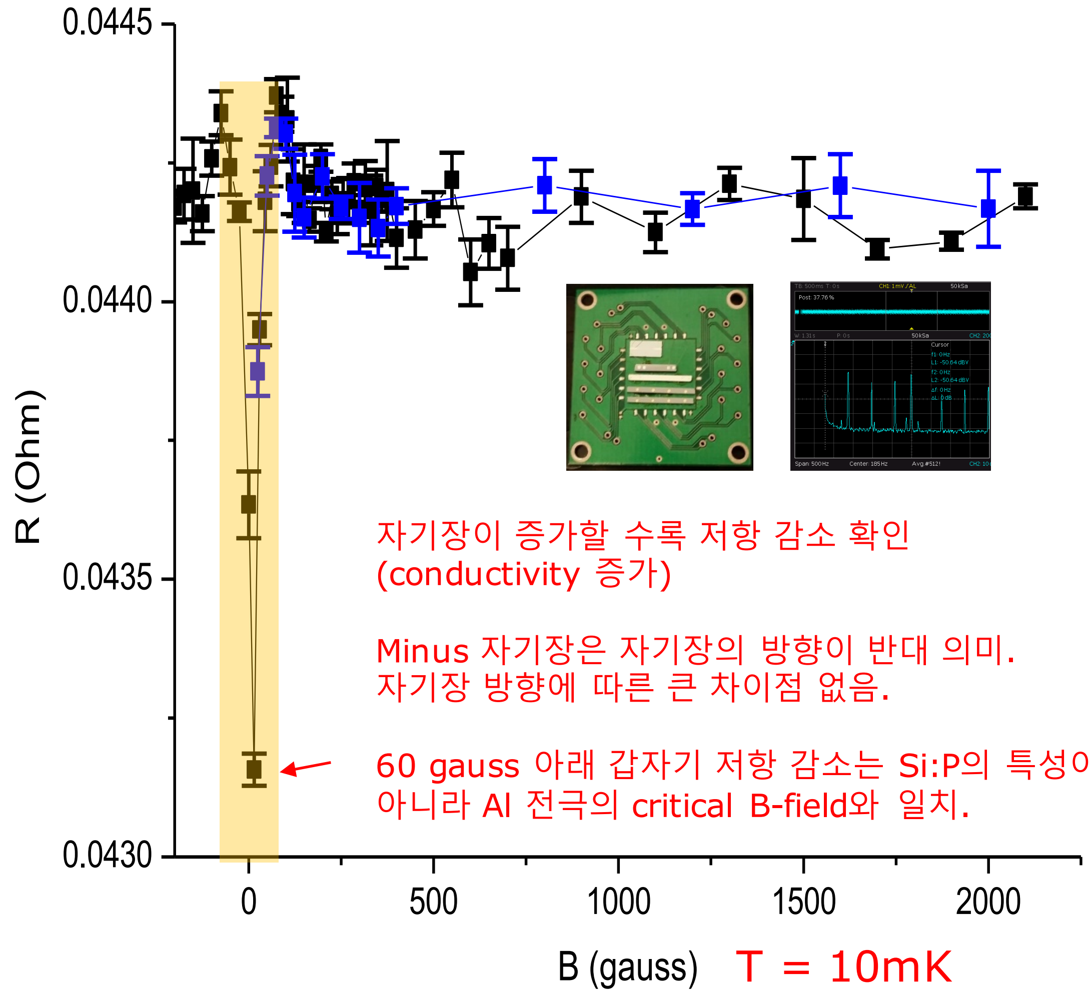




Bulk conductivity for Si:P (> $10^{19}/cm^3$)



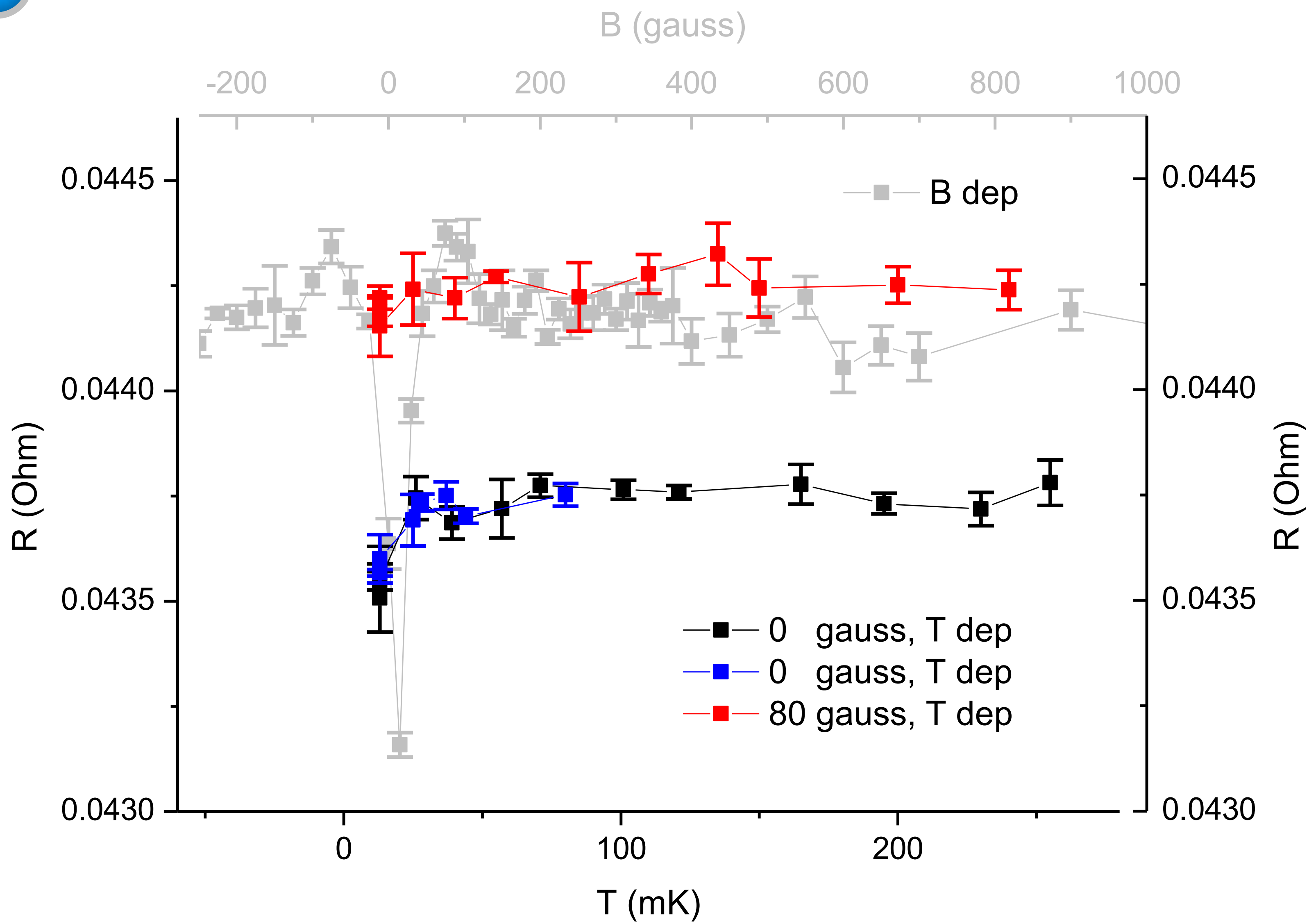




자기장이 증가할 수록 저항 감소 확인
(conductivity 증가)

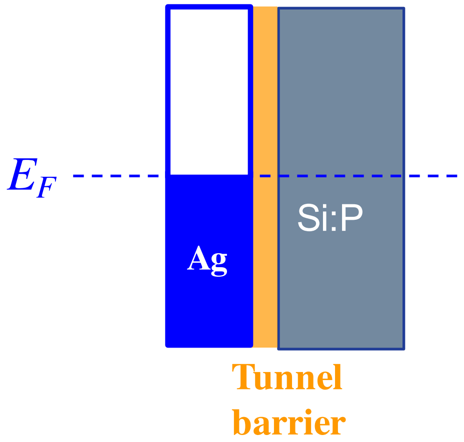
Minus 자기장은 자기장의 방향이 반대 의미.
자기장 방향에 따른 큰 차이점 없음.

60 gauss 아래 갑자기 저항 감소는 Si:P의 특성이
아니라 Al 전극의 critical B-field와 일치.

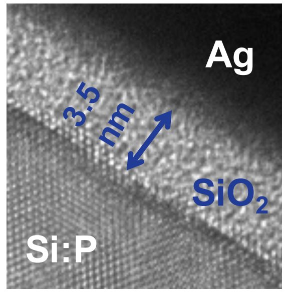


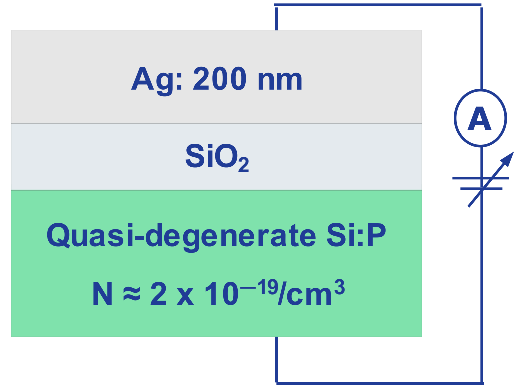
B (gauss)
-200
0
200
400
600
800
1000
0.0445
0.0440
0.0435
0.0430
R (Ohm)
B dep
0 gauss, T dep
0 gauss, T dep
80 gauss, T dep
0
100
200
T (mK)

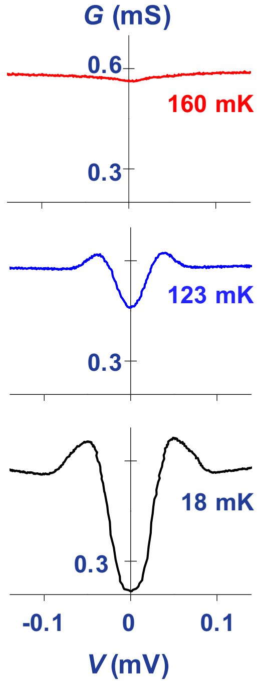
Tunnelling spectroscopy for Ag-SiO_2-Si:P



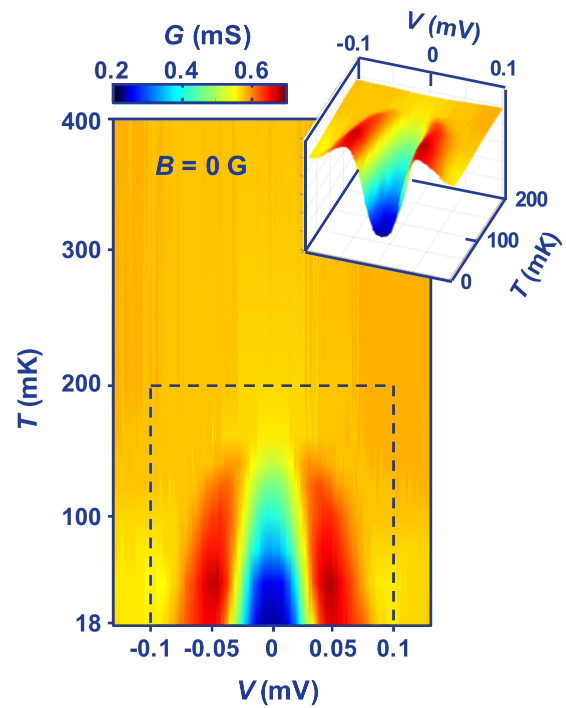
T-dependent tunneling conductance, $G(T, B=0)$



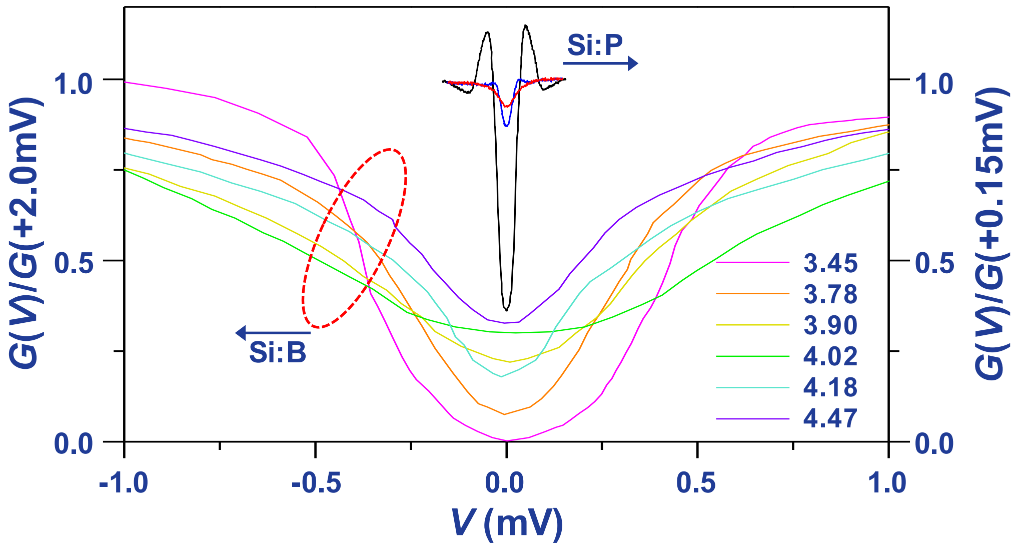




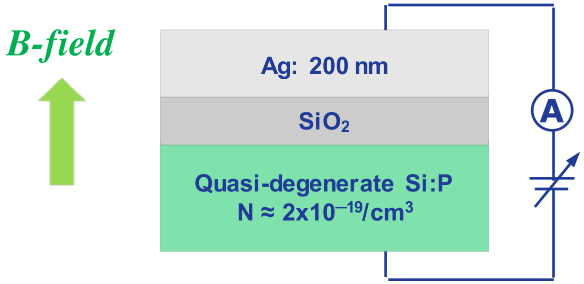
Single-particle DOS structure in Si:P

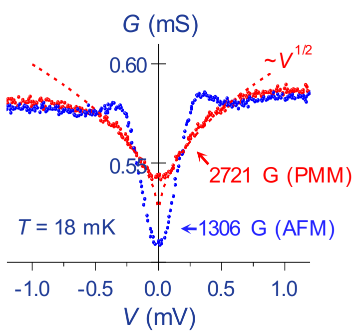


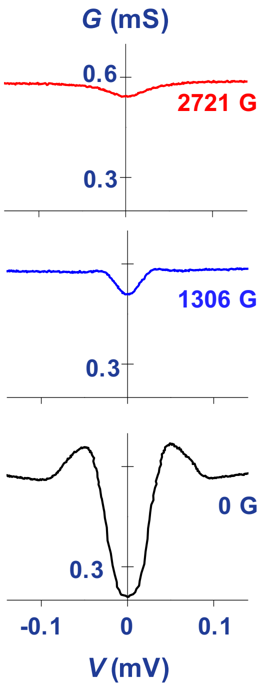
Comparison: *Coulomb gap near the MIT and our results*

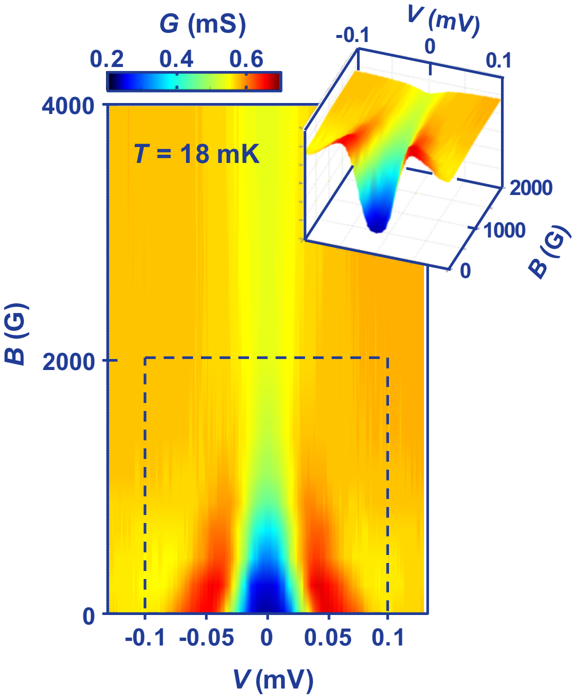


B-dependent tunneling conductance, *G*(*T*=20*mK*, *B*)

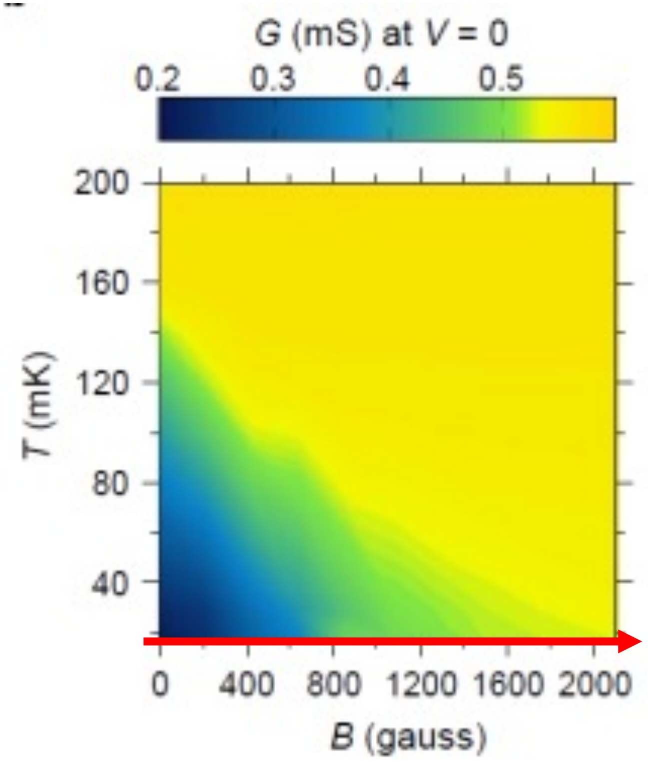




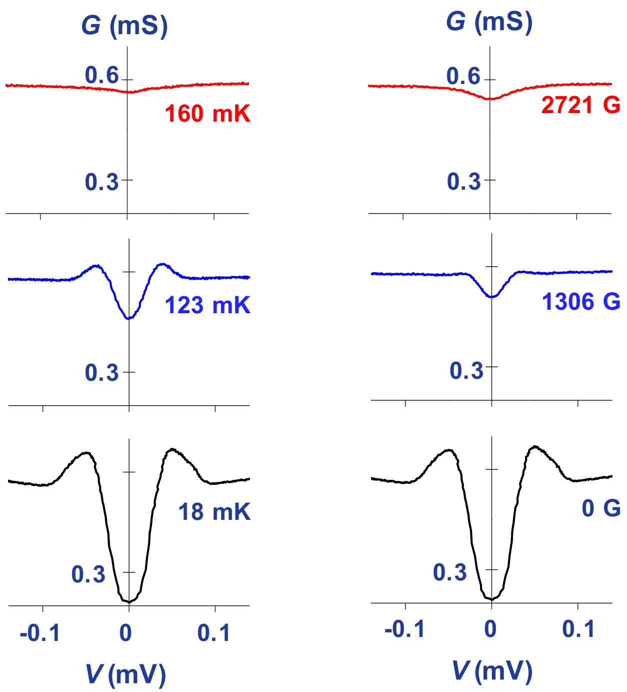




Quantum phase diagram in Si:P



Intensity plot for the DOS at E_F in Si:P
(Quantum phase diagram)

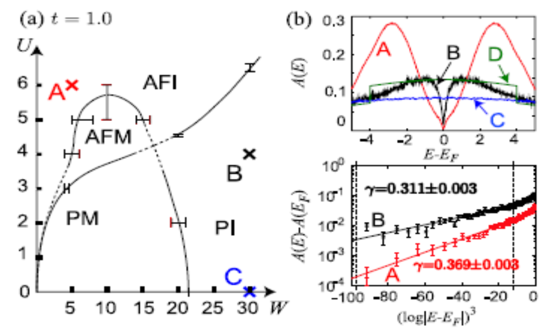


T-dependence @ B=0 *B*-dependence @ 30mK

Disordered Hubbard model and Phase diagram

PRL 102, 016404 (2009) PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2009

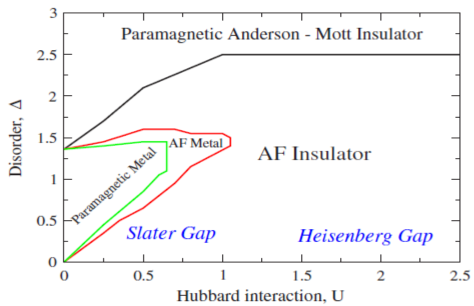
Soft Hubbard Gaps in Disordered Itinerant Models with Short-Range Interaction

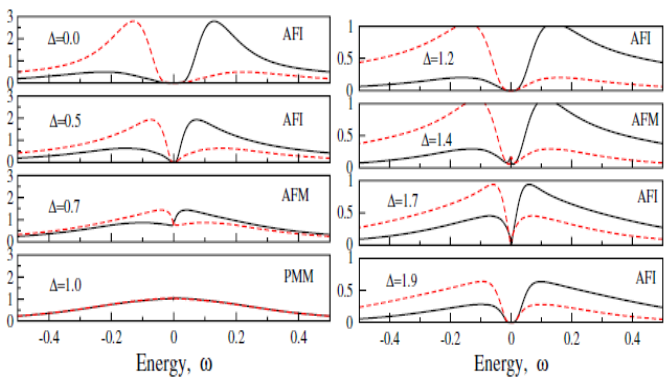


PRL 102, 146403 (2009) PHYSICAL REVIEW LETTERS week ending 10 APRIL 2009

Competition between Anderson Localization and Antiferromagnetism in Correlated Lattice Fermion Systems with Disorder

Krzysztof Byczuk,[1,2] Walter Hofstetter,[3] and Dieter Vollhardt[1]





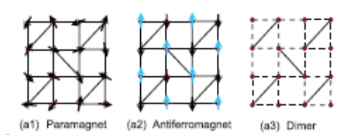
SCIENTIFIC REPORTS

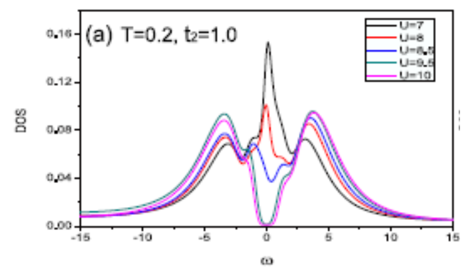
OPEN

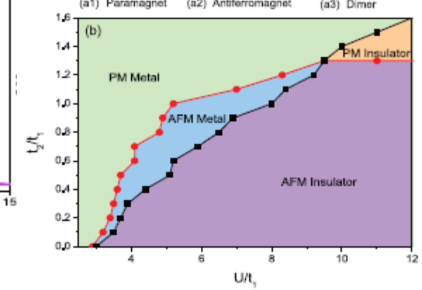
SUBJECT AREAS: PHASE TRANSITIONS AND CRITICAL PHENOMENA

Antiferromagnetic Metal and Mott Transition on Shastry-Sutherland Lattice

Hai-Di Liu, Yao-Hua Chen, Heng-Fu Lin, Hong-Shuai Tao & Wu-Ming Liu







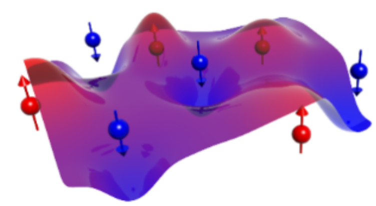
Hubbard model including spin-spin (RKKY) interaction

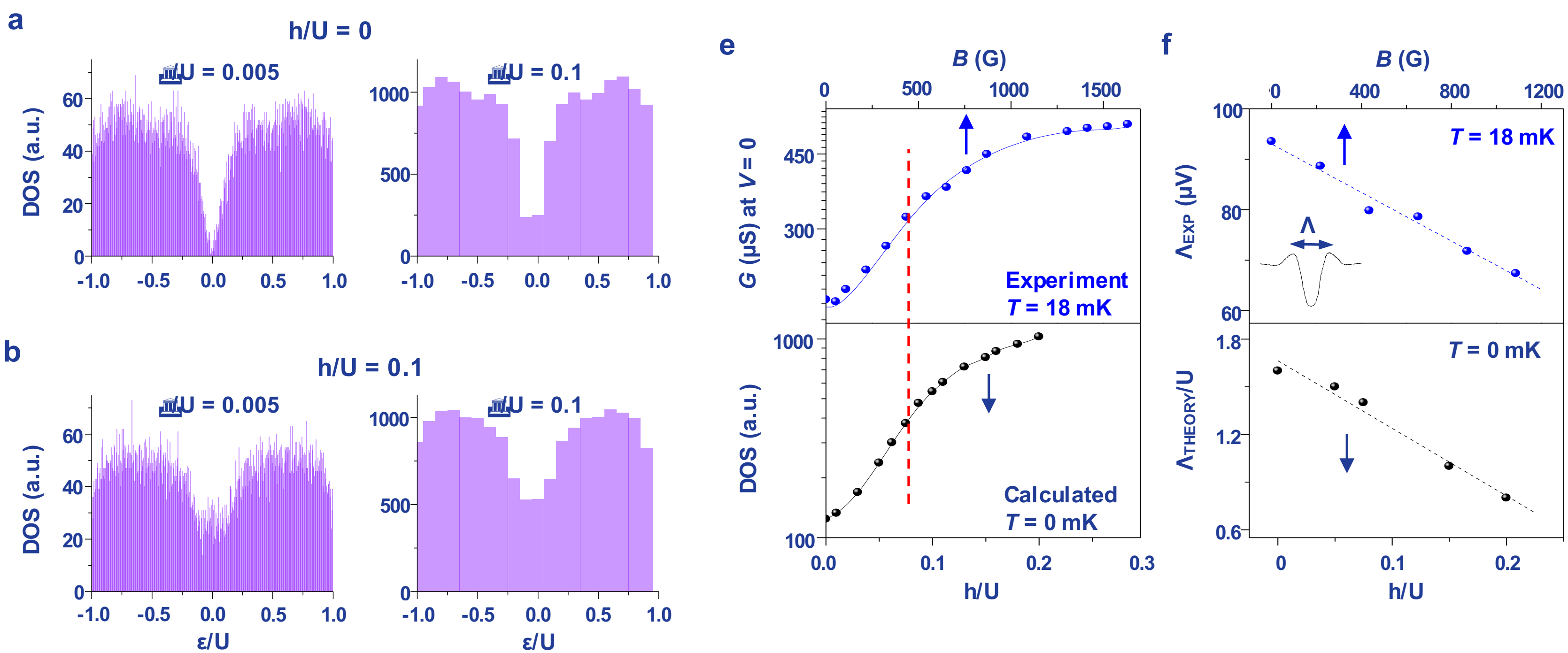
(Eric Yang & GS Jeon)

External B-field

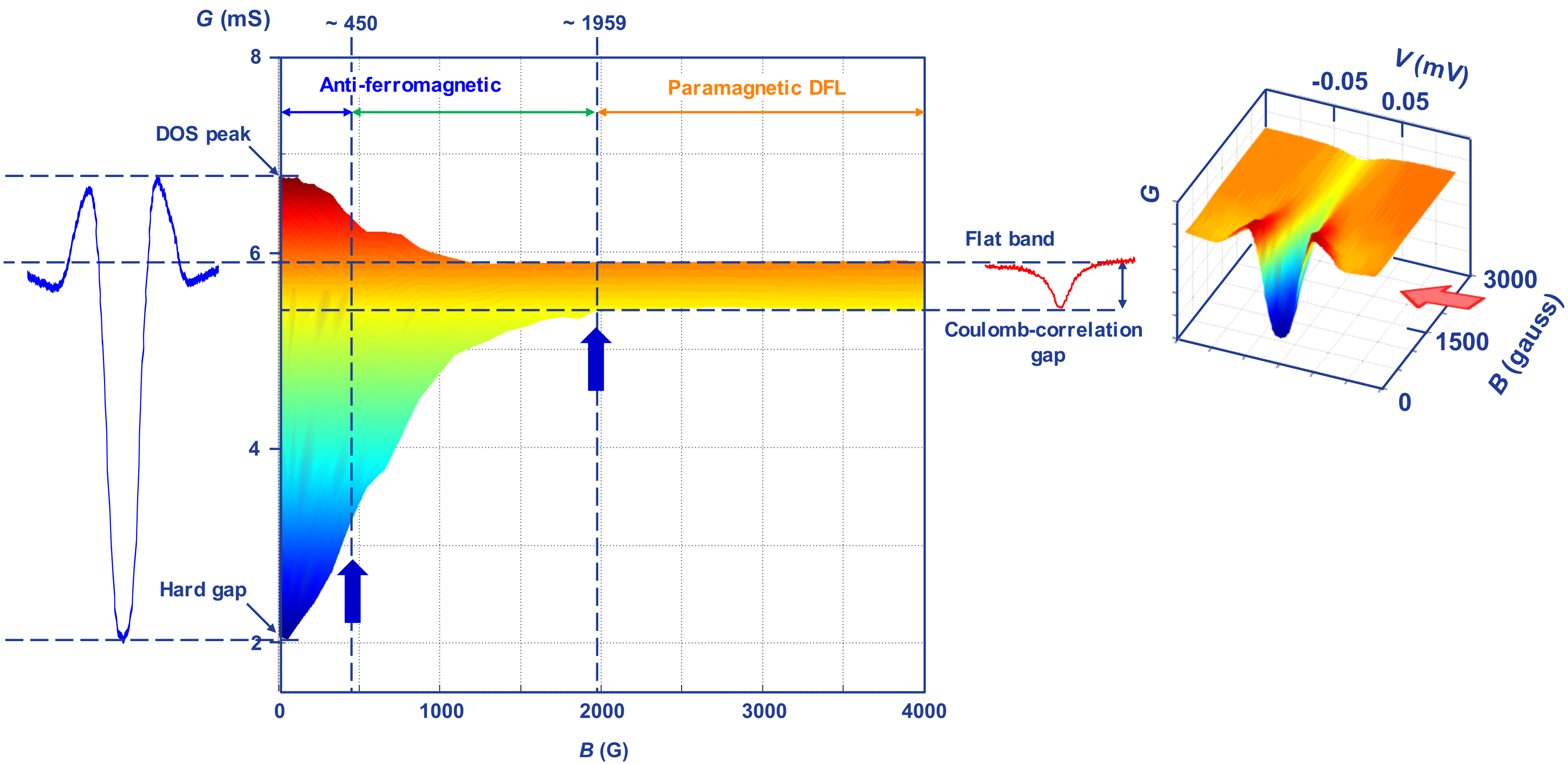
$$H = -t\sum_{\langle i,j\rangle,\sigma} c^{\dagger}_{i\sigma}c_{j\sigma} + \sum_{i,\sigma}\left(\varepsilon_{i\sigma}-\mu\right)c^{\dagger}_{i\sigma}c_{i\sigma} - \vec{h}\cdot\sum_{i}\vec{\sigma}_i - \sum_{i>j}J_{ij}\vec{\sigma}_i\cdot\vec{\sigma}_j$$

Long-range
anti-ferromagnetic coupling
(RKKY spin-spin interaction)

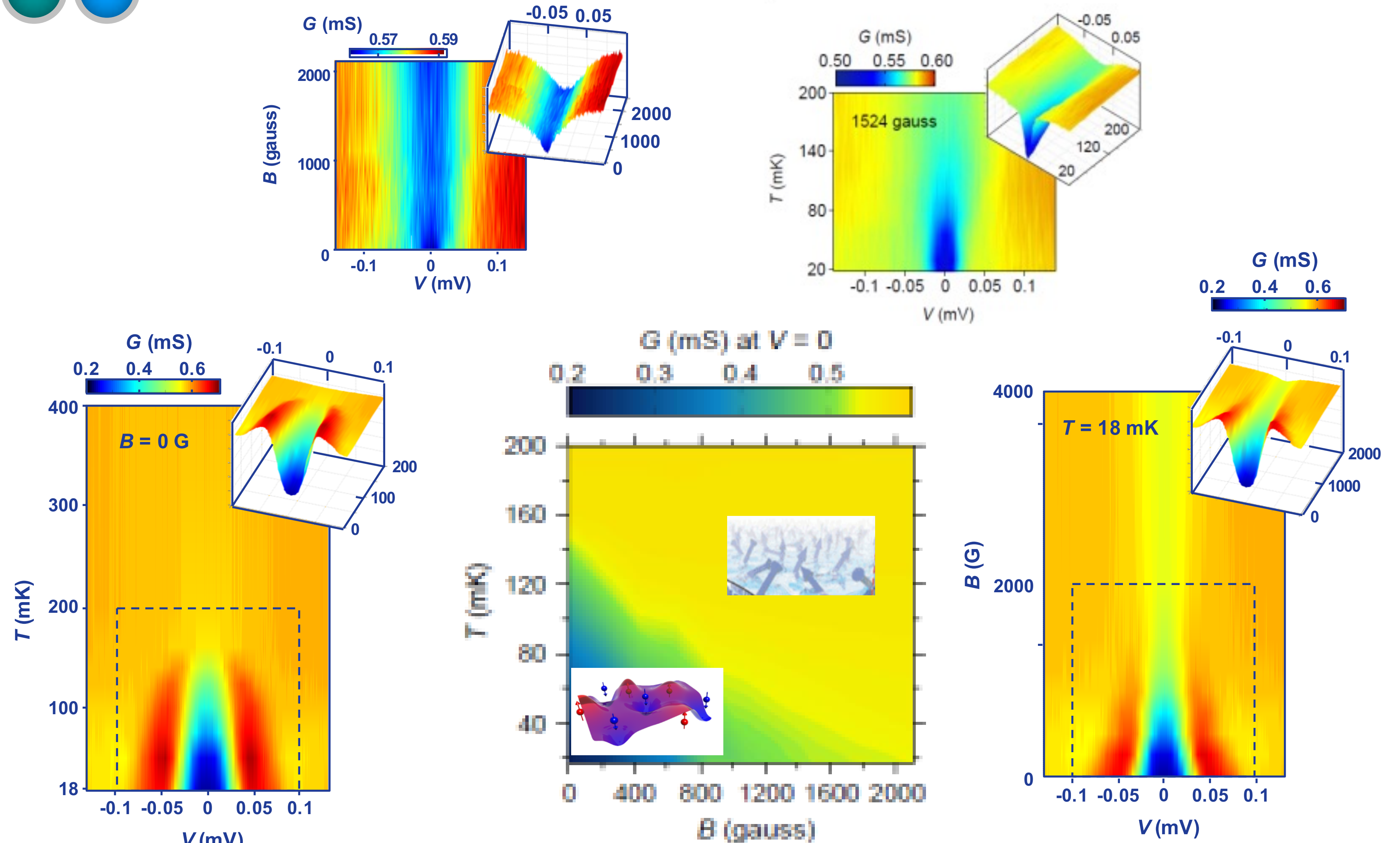




Determining Phase boundary (magnetic & non-magnetic)



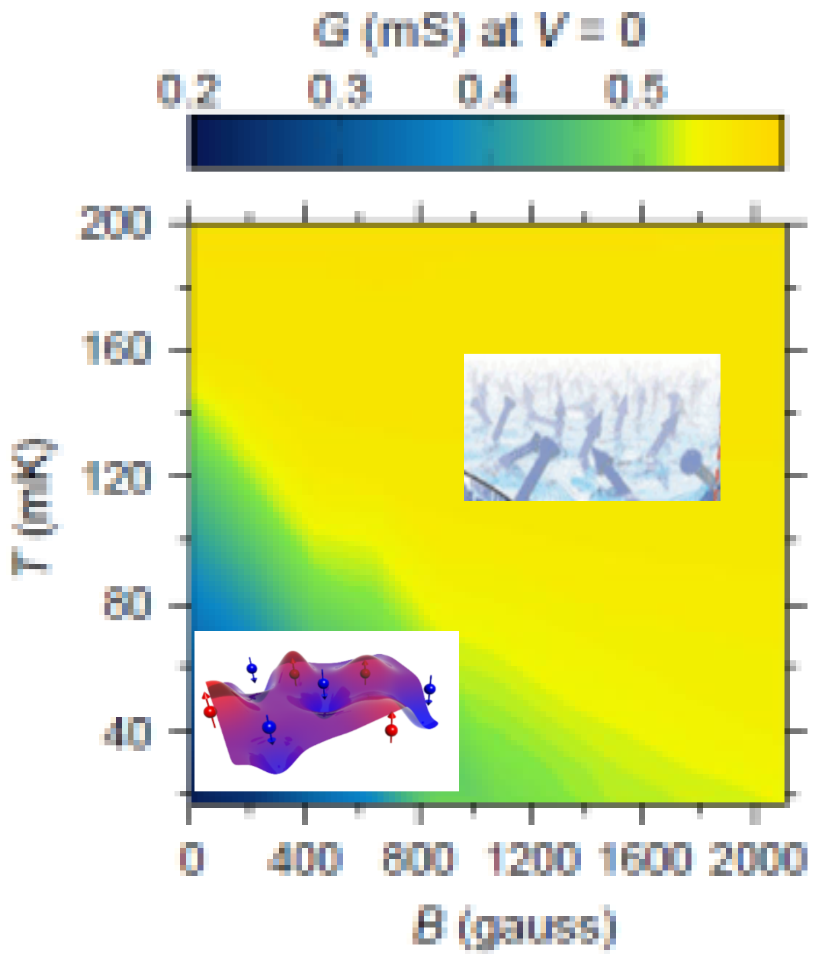
Quantum Phase diagram



Quantum Phase Transition

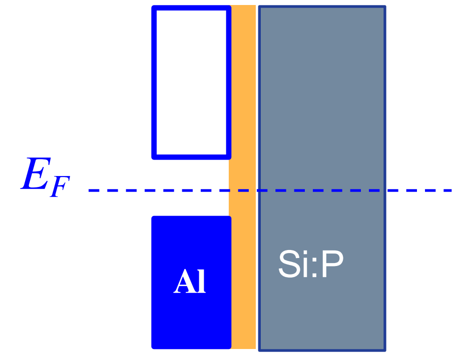
Origin of insulating phase in Si:P

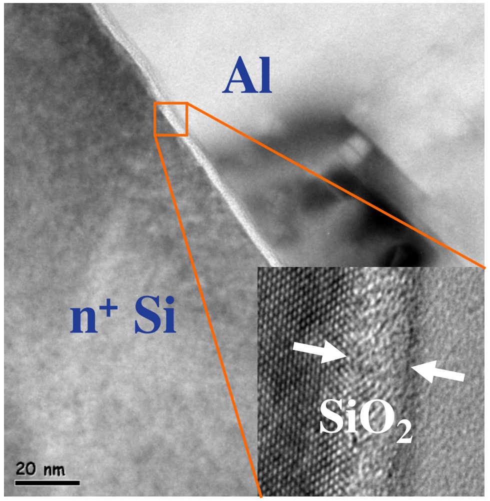
Interplay between disorder, on-site repulsion, spin-spin interaction

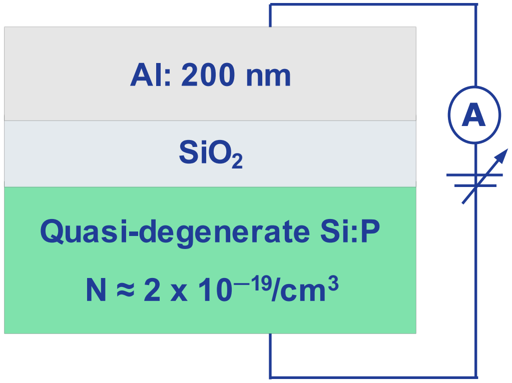


Tunnelling spectroscopy for Al-SiO_2-Si:P

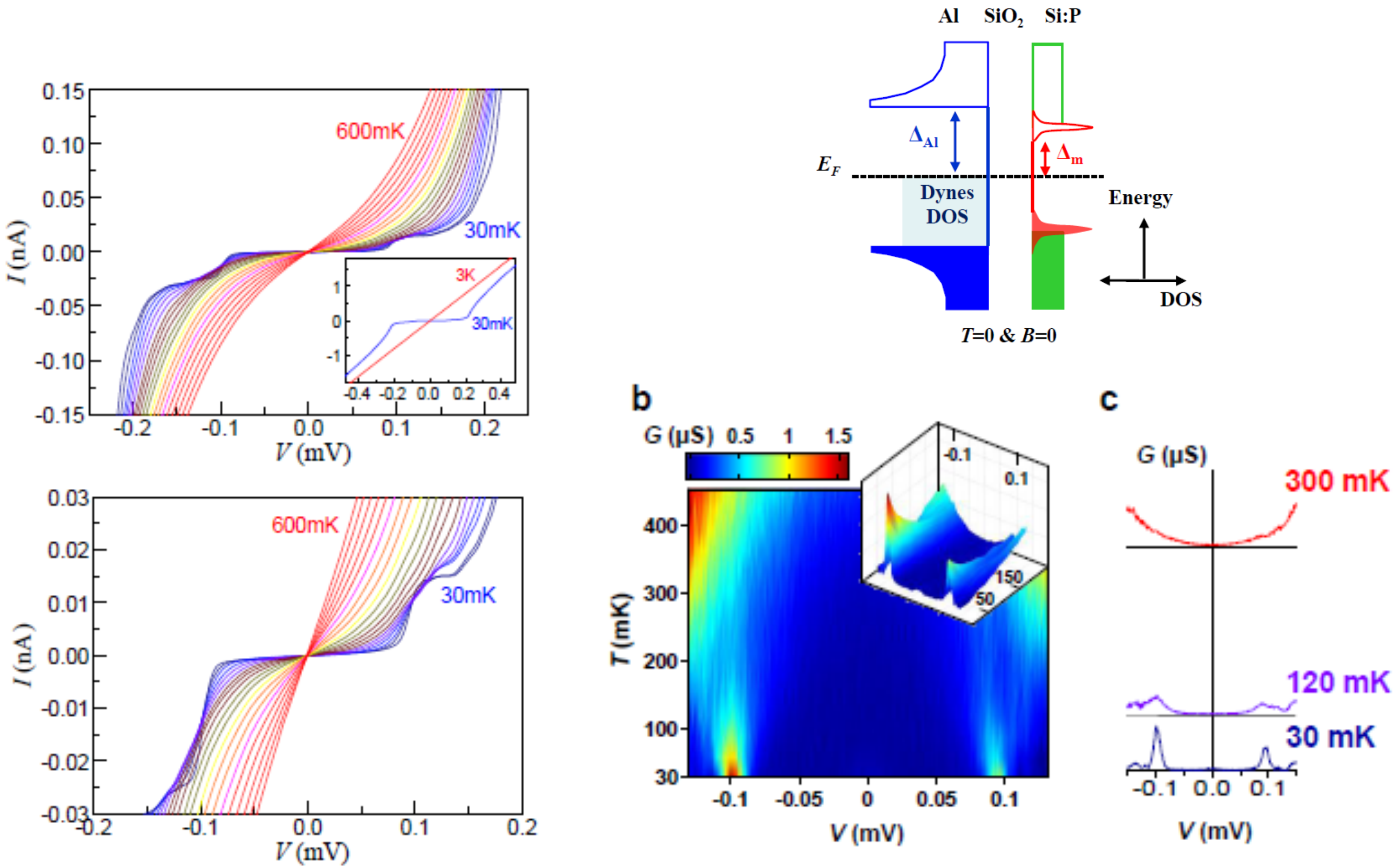
Note that Al is a superconducting electrode.



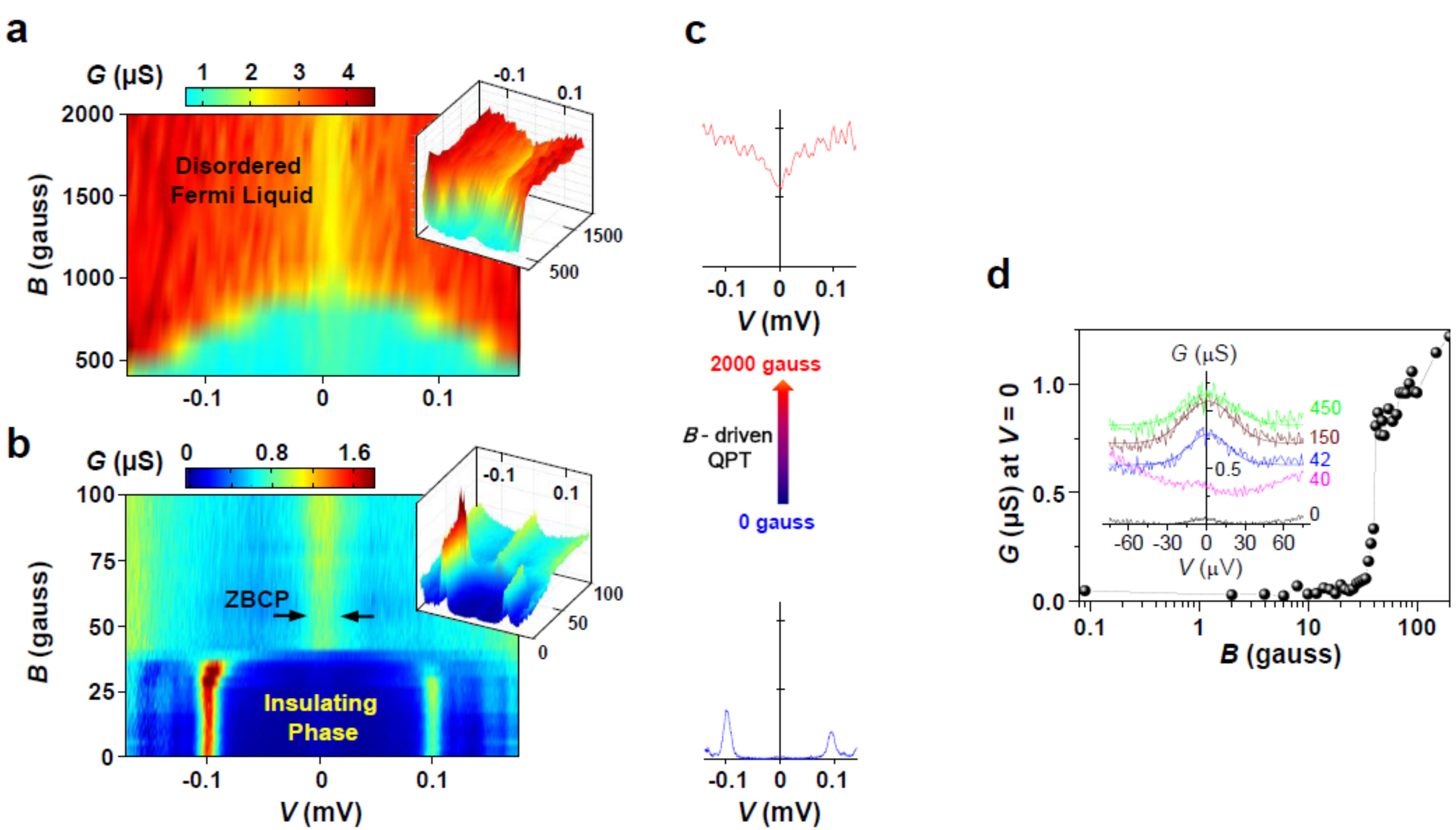




T-dependent tunneling conductance, $G(T, B=0)$

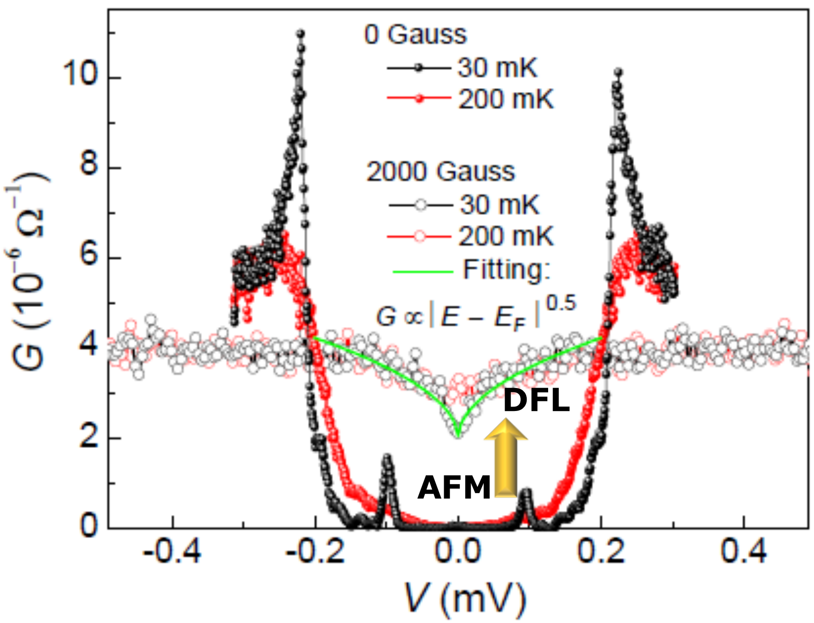


B-dependent tunneling conductance, $G(T = 30mK, B)$

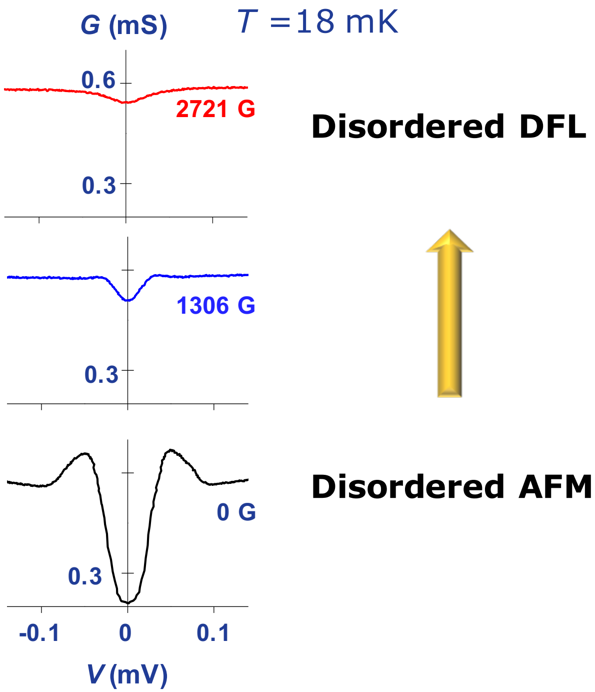


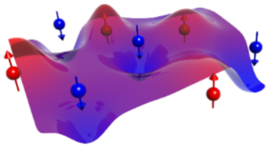
B-driven quantum phase transition

Al-SiO_2-Si:P



Ag-SiO_2-Si:P

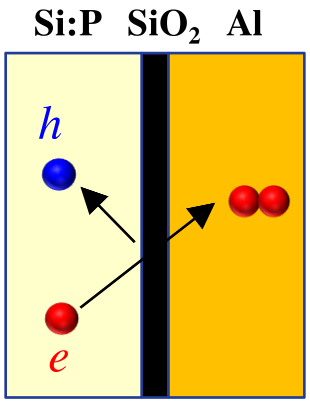


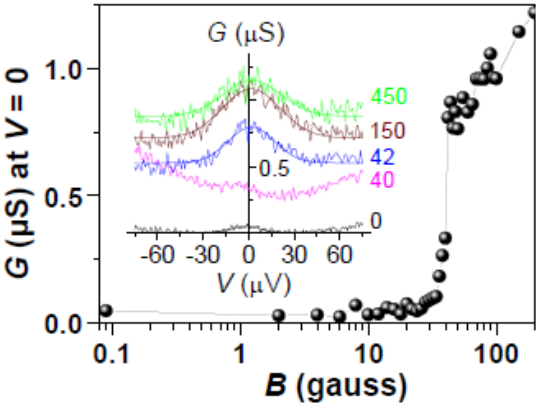


Disordered Antiferromagnetic Insulator (AFM) → Disordered Fermi Liquid (DFL)

Role of superconductor electrode Al in QPT ?

- Andreev reflection causes hole injection into Si:P.





Open question :

What happens if holes are present in Si:P ?

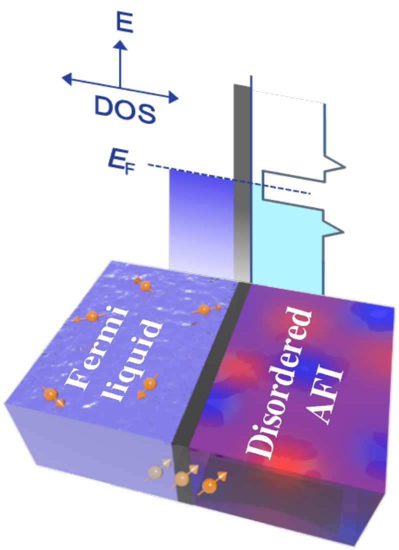
Summary

- We have used tunneling DOS spectroscopy to study the nature of various disordered electronic systems in quasi-degenerate metallic Si.

- Our data are consistent with the *B*-driven Quantum phase transitions from the disordered AFM to the paramagnetic DFL phases (for the Ag-SiO_2-Si:P sample).

  For the Al-SiO_2-Si:P sample, the observed QPT is under analysis.

- The various physical properties of these new phases result from the delicate interplay between disorder, on-site repulsion, weak magnetic field, and spin-spin (RKKY) interaction.



Challenging issues

- ***Thermodynamic DOS versus Single particle tunneling DOS***
- ***Direct detection of Spin Density Wave (Neutron scattering)***
- ***Scalability***

Collaborators

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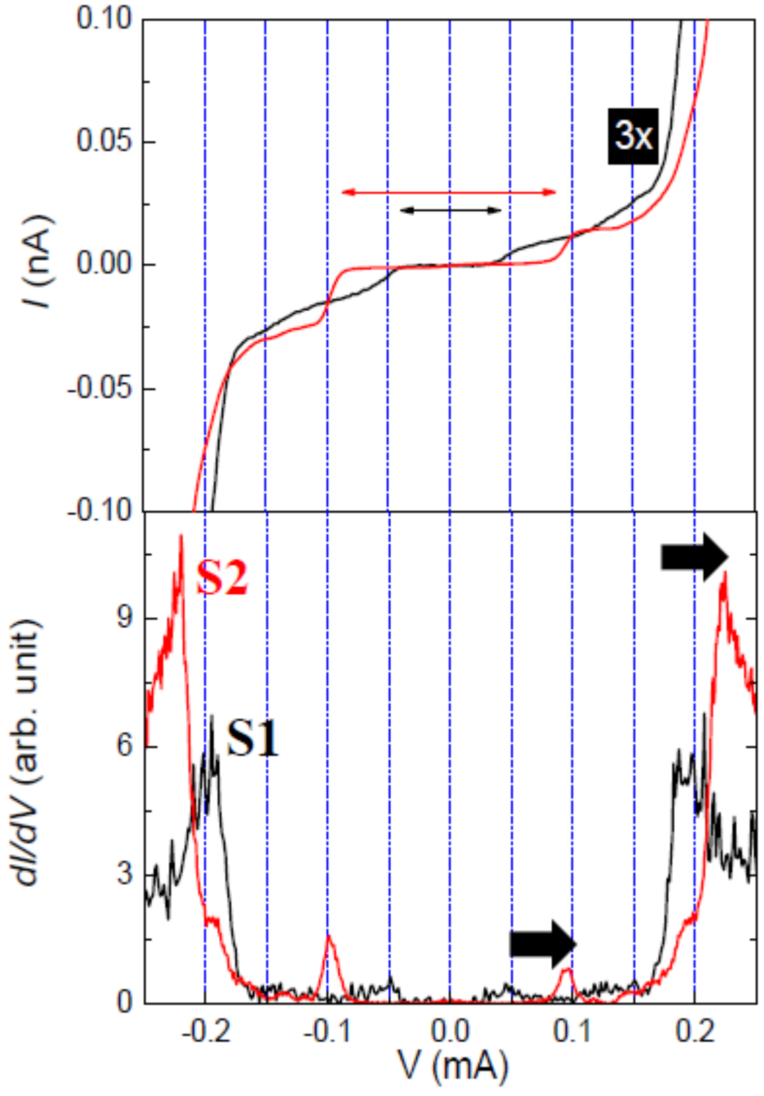
Shen Tsai (RIKEN in Japan)

Thank you for your attention

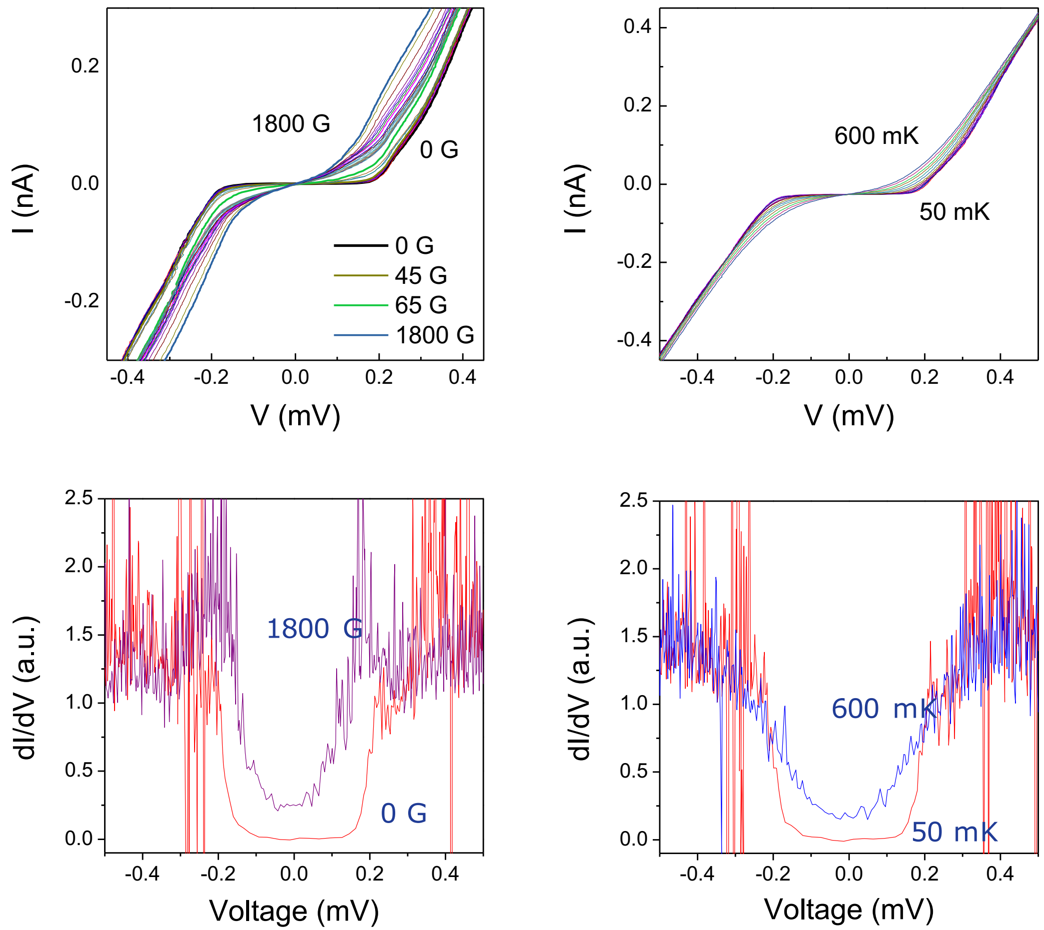
Long-range and short-range *e*-*e* interactions in Si:P

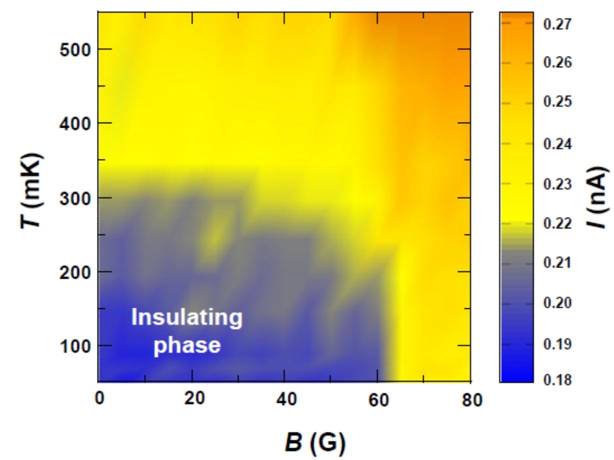
long-range	loss of screening due to diffusive electron motion arising from disorder metal: Altshuler-Aronov anomalies in DOS and $\sigma(T)$ insulator: soft Coulomb gap, Efros-Shklovskii VRH Anti-ferromagnetic spin-spin interaction (RKKY interaction): Our case
short-range	on-site Hubbard U metal: formation of magnetic moments, Kondo effect insulator: Hubbard splitting of $1s(A_1)$ impurity band

Superconductor gap voltage (Δ_{Al}/e) shifts due to the DOS gap in Si:P



Another Al device 1





Another Al device 2