System:

CVD graphene grown on top of SiC

Al electrodes in a

Superconductor/ Graphene /Superconductor

coplanar **Josephson Junction** structure

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Natal, March 27,2017

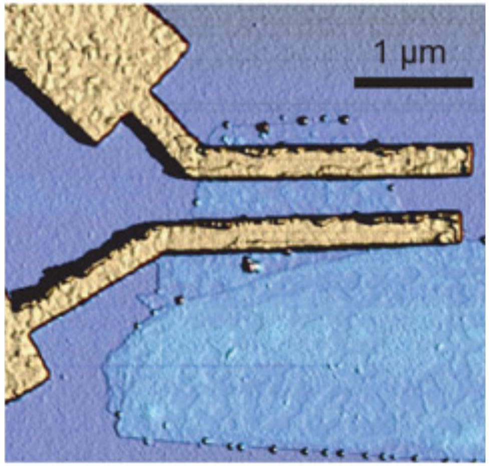
D. Massarotti, B. Jouault, V. Rouco, S. Charpentier, T. Bauch, A. Michon, A. De Candia, P. Lucignano, F. Lombardi, F. Tafuri, and A. Tagliacozzo, Phys. Rev. B 94, 054525 (2016)

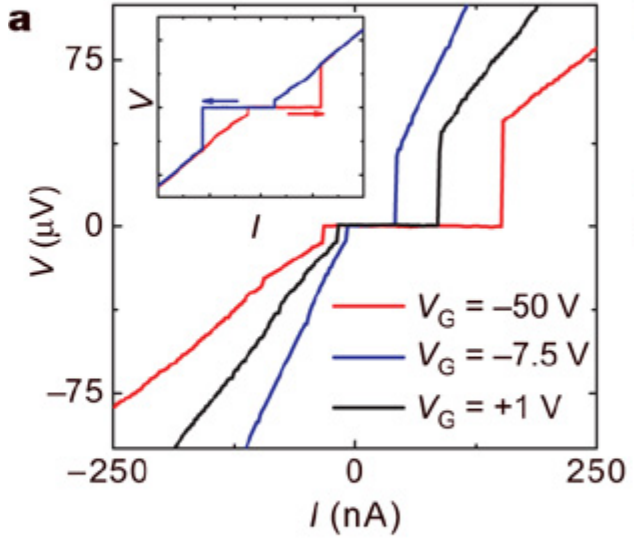
B. Jouault, S. Charpentier, D. Massarotti, A. Michon, M. Paillet, J.-R. Huntzinger, A. Tiberj, A.-A. Zahab, T. Bauch, P. Lucignano, A. Tagliacozzo, F. Lombardi, F. Tafuri, Journal Superconductivity and Novel Magnetism 29,1145 (2016)

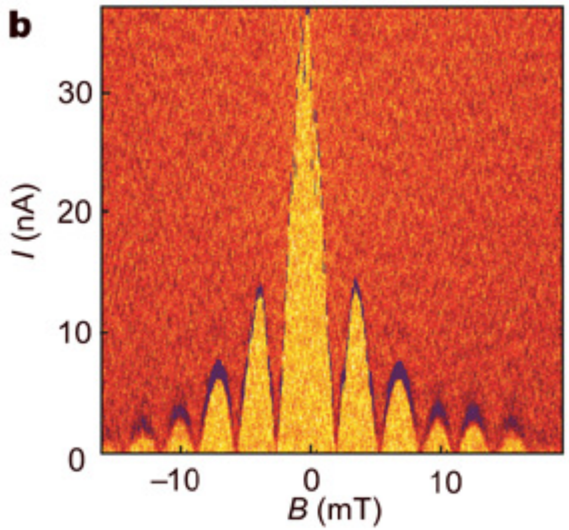
D. Massarotti, B. Jouault, V. Rouco, G. Campagnano, D. Giuliano, P.Lucignano, D. Stornaiuolo, G. P. Pepe, F. Lombardi, F. Tafuri, A. Tagliacozzo, J Supercond Nov Magn 30, 5 (2017).

Graphene Josephson Junctions (GJJ)

first GJJ exfoliated graphene on SiO_2... H. B. Heersche *et al.*, Nature **446**, 56 (2007)

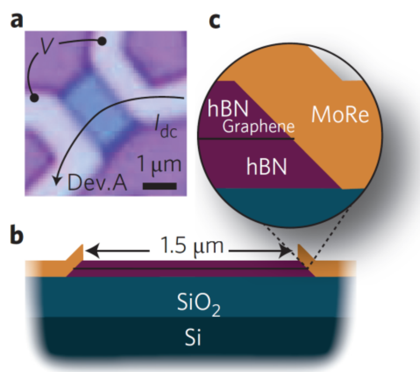




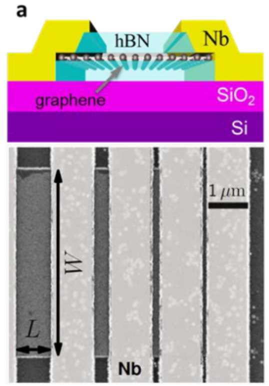


Lots of experimental efforts devoted to the realization of ballistic devices,

N. Mizuno *et al.*, Nature Comm. **4**, 2716 (2013)



V. E. Calado *et al.,* Nature Nano **10**, 761 (2015)



M. Ben Shalom *et al.*, Nature Physics 12 (4), 318 (2016)

CVD graphene on SiC

Limit of exfoliated graphene:

-Small devices only (no SQUID, no Voltage Standards…),

-geometry hard to control/reproduce

Solution? CVD graphene

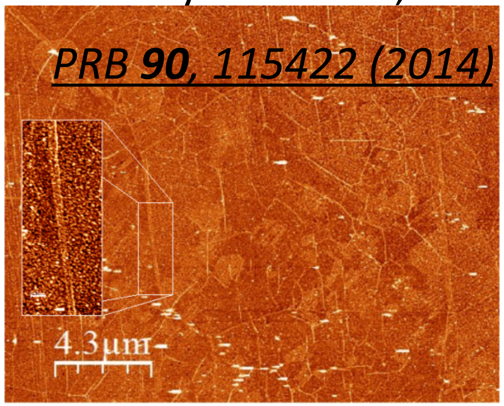
Very large surface = reproducibility and scalability

many junctions built on the same graphene/same lithography:

electrodynamics can be studied without ambiguity

CVD graphene on metals

Pros: any substrate, *Cons*: transfer!



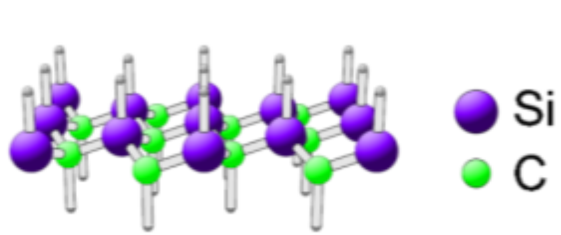
CVD graphene on SiO_x

Tianyi Li *et al, arXiv 1703.06049*

(CVD, sublimated) graphene on SiC

Pros: No transfer

Cons: substrate is SiC! (low mobility)



This is the way we study here

Incipient Berezinskii Kosterlitz and Thouless transition in 2D coplanar Al contacted graphene junctions

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Natal, March 27, 2017

Outline

Prerequisites

1) Graphene on SiC: characterization
2) Lithography

First results

1) V(I) curves, Josephson critical current, I_cR_N product

Applied Magnetic field

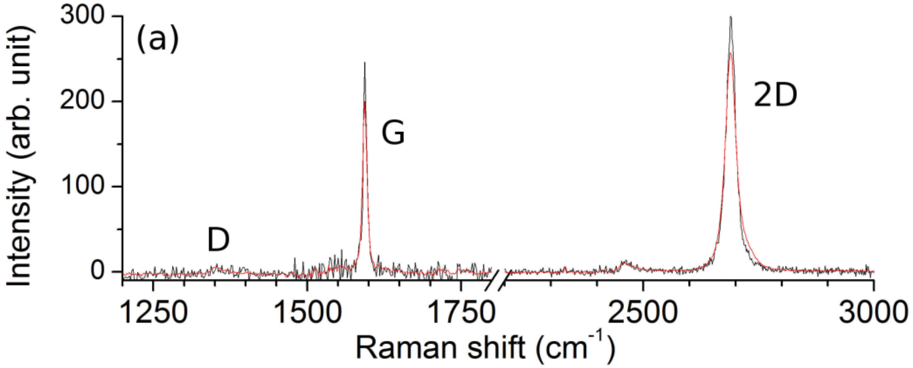
1) magnetic field fingerprint
2) Collapse and revival of the Josephson current
3) Fraunhofer pattern

R(T): fit with Berezinskii-Kosterlitz-Thouless theory for thin films

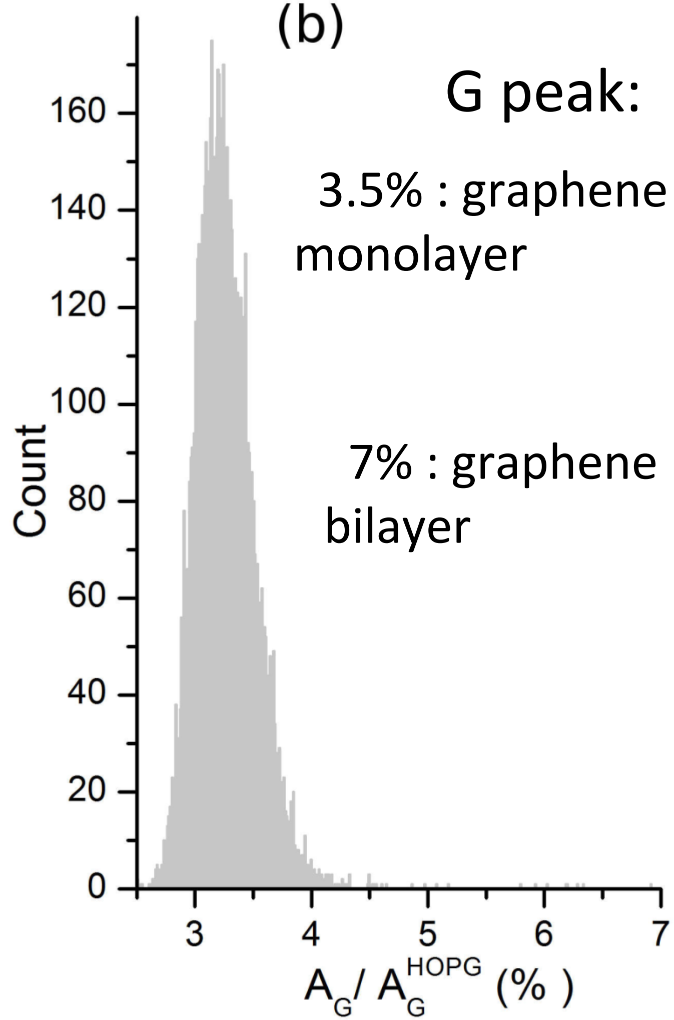
Proposed interpretation: **incipient BKT transition in form of coexistence of flux flow superconductivity with Josephson current**

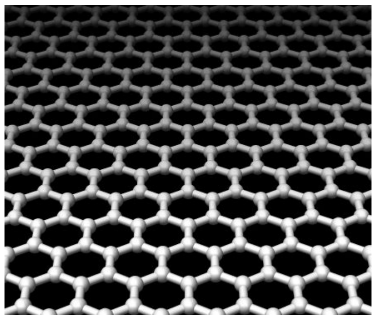
CRHEA sample, Raman analysis

Analysis of a 24 µm × 24 µm area



Small D peak: few defects





μ ~ 1,100 cm²/Vs

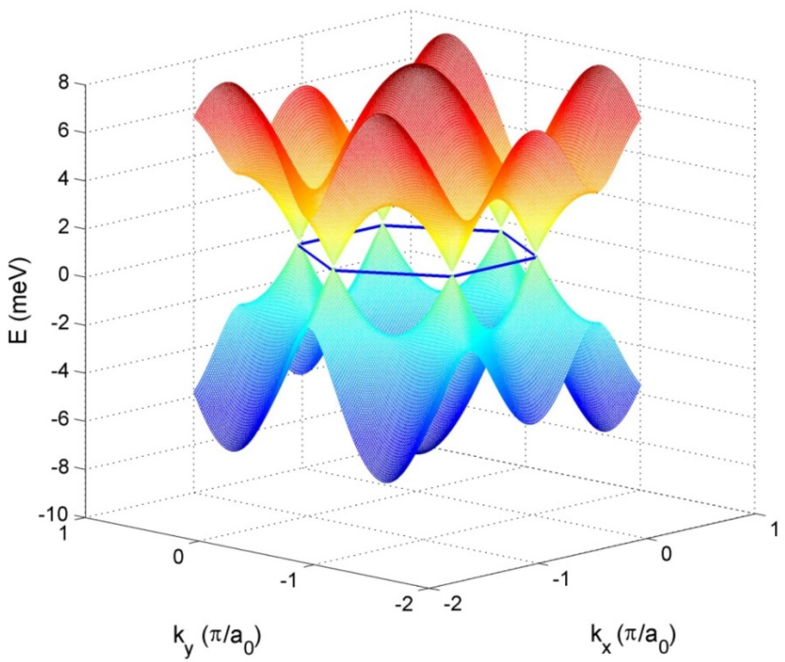
low mobility

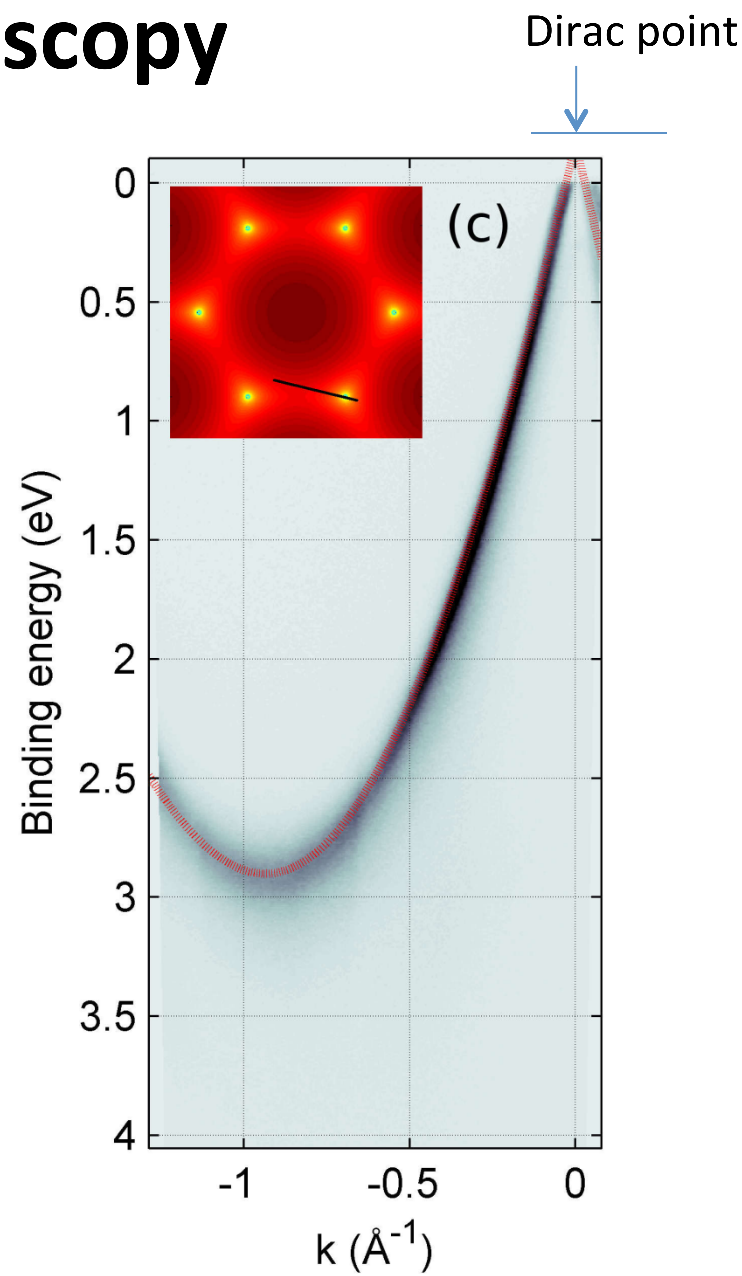
This sample is a homogeneous graphene monolayer

ARPES Spectroscopy

Monolayer graphene, p-doped,
$p \approx 5 \times 10^{12}$ cm^{-2}

Perfect fit (red line) with the predicted graphene band structure:





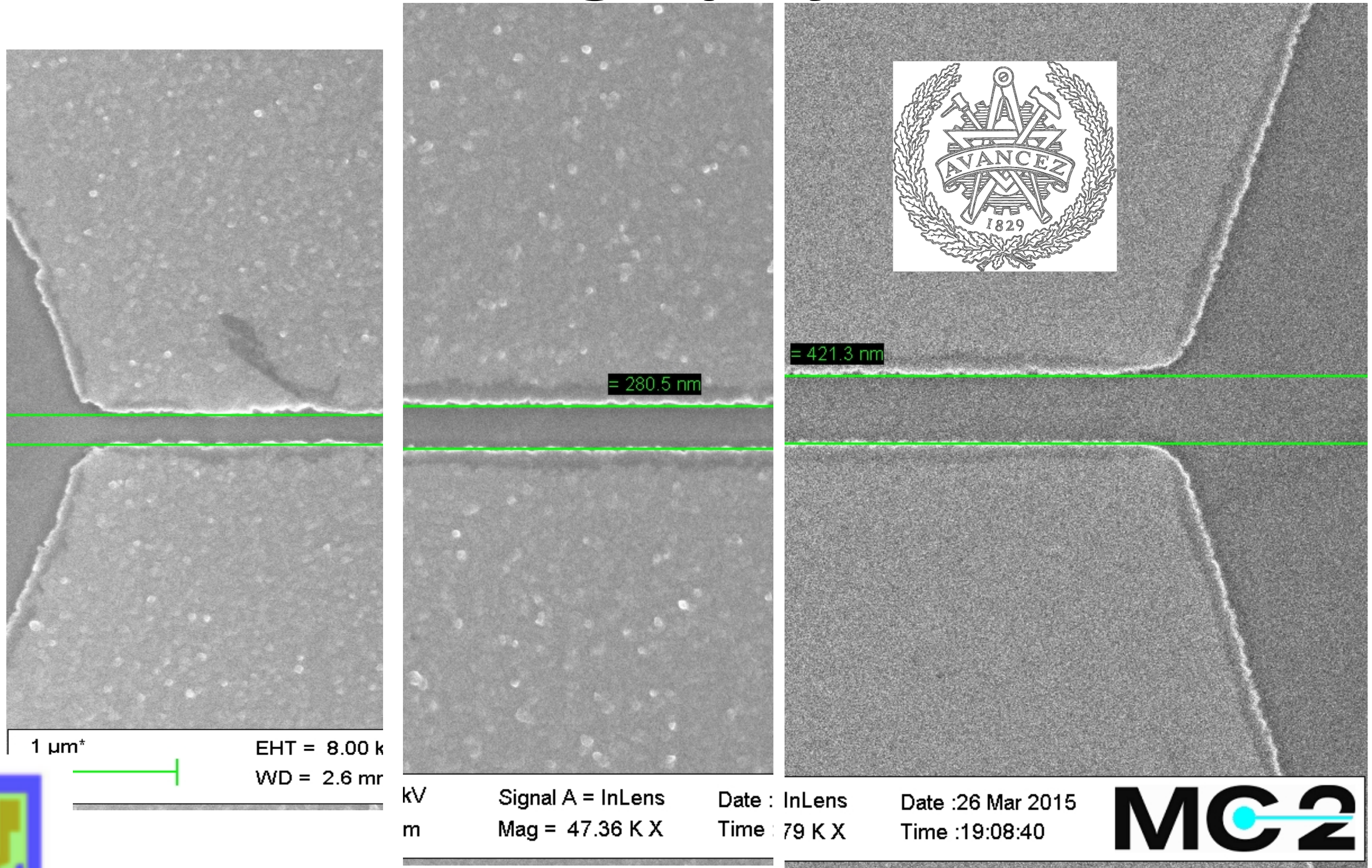
A. H. Castro-Neto *et al.*, RMP **81**, 101 (2009)

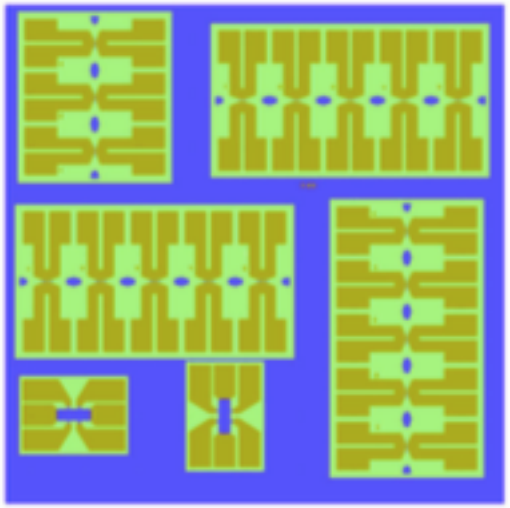
E-beam lithography

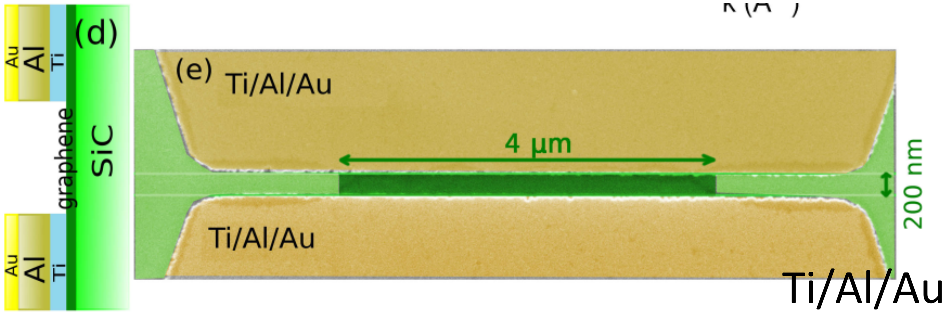
No gate at this stage
μ ~ 1,100 cm^2/Vs

O_2 plasma etching

Many junctions on the same graphene sheet

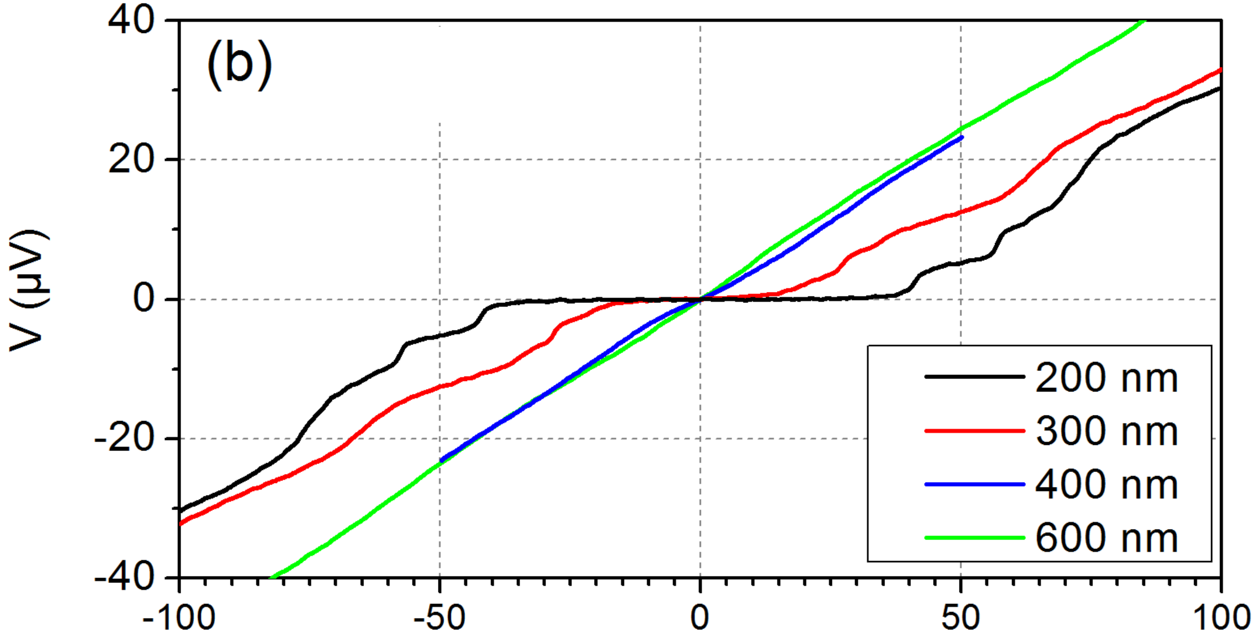




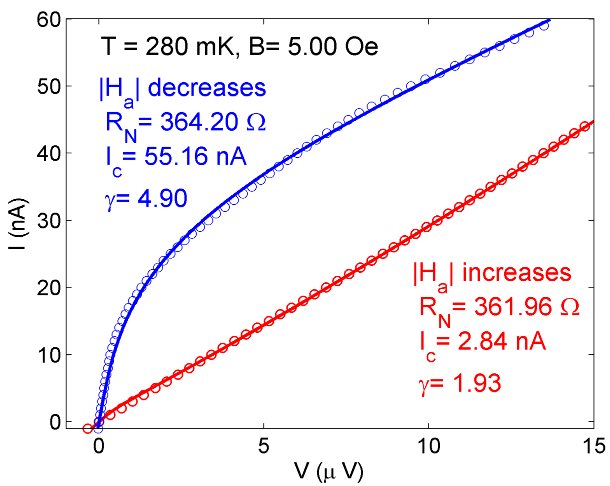


Ti/Al/Au contacts
5/80/3 (nm)

V(I) curves at 280 mK



RSJ classical model



ℓ ~ 50 nm: all junctions **diffusive**.
Al gap Δ ~ 100 µeV, coherence length ξ_0 ~ 300 nm:
Expected and observed crossover between short and long junction limits at L ~ ξ_0 ~300 nm.

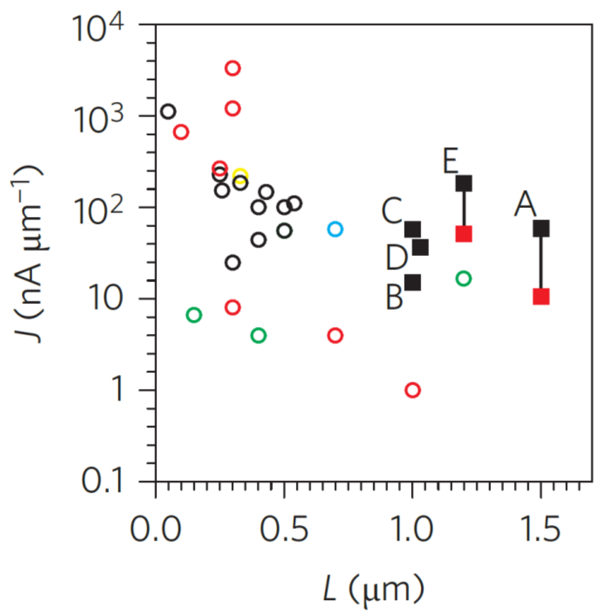
L ≈ 200 nm, W ≈ 4μm   Our R_N ≈400 Ω

At the Dirac point $R_N \sim \frac{h}{e^2}\frac{L}{W} \approx$ 920 Ω

$\frac{eI_cR_N}{\Delta} \sim$ 0.09 <0.66

eI_cR_N/Δ ~ 0.09, smaller than its theoretical estimate 0.66 : either bad contacts or underestimation of I_c (as T ~0.3 T_c for Al only), but

$J_c = I_c/W$ ~ 10 nA μm^{-1} at L =200 nm : in the literature, J_c between 1 and 100 nA μm^{-1}



$$L \leq \xi_0 = \sqrt{\frac{\hbar D}{\Delta}} \sim 300nm$$

$$\Rightarrow \quad E_{Th} = \frac{\hbar D}{L^2} \sim \Delta$$

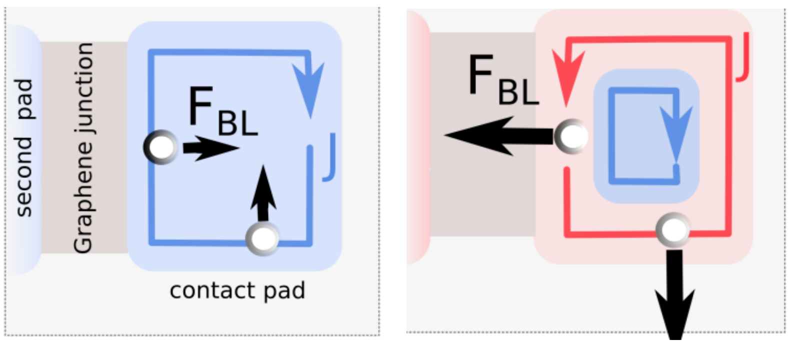
Magnetic field hysteresis

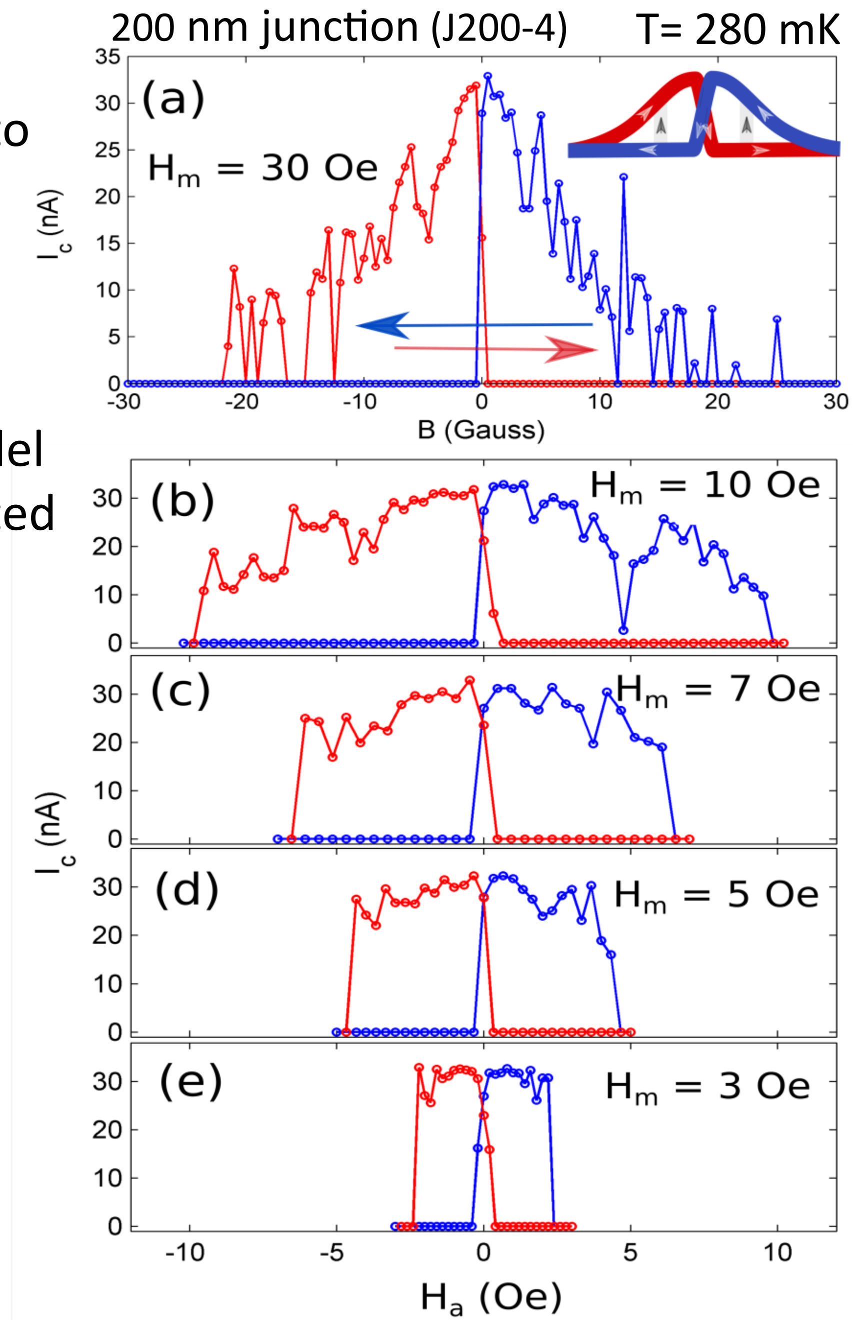
-Magnetic field hysteresis persists up to 30 Oe

-Observed on all measured junctions

-should not be so large in 2L-CSM model
-anomalous M(B) curves often attributed to Bean-Livingstone (BL) barrier

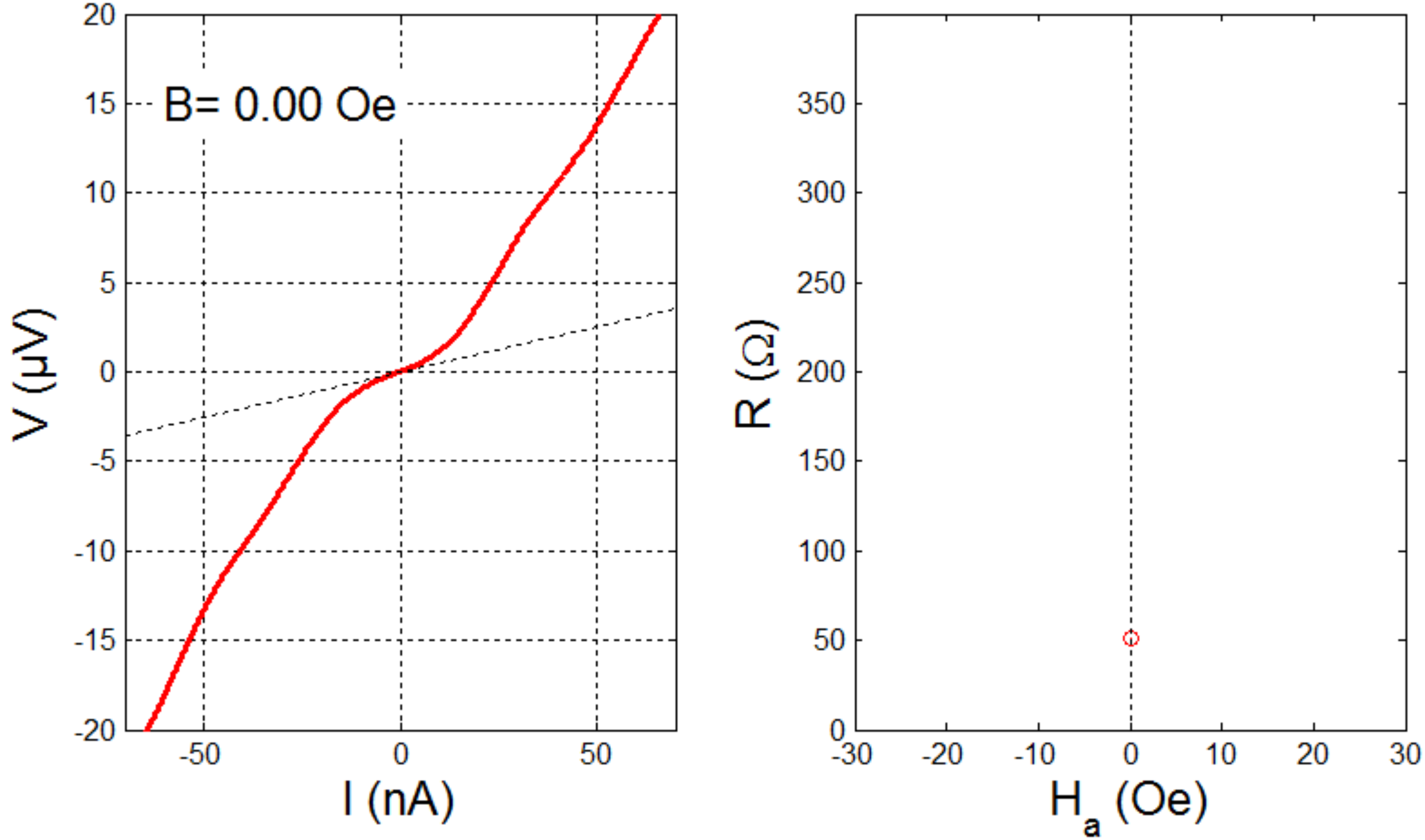
BL barrier= sum of image and screening forces





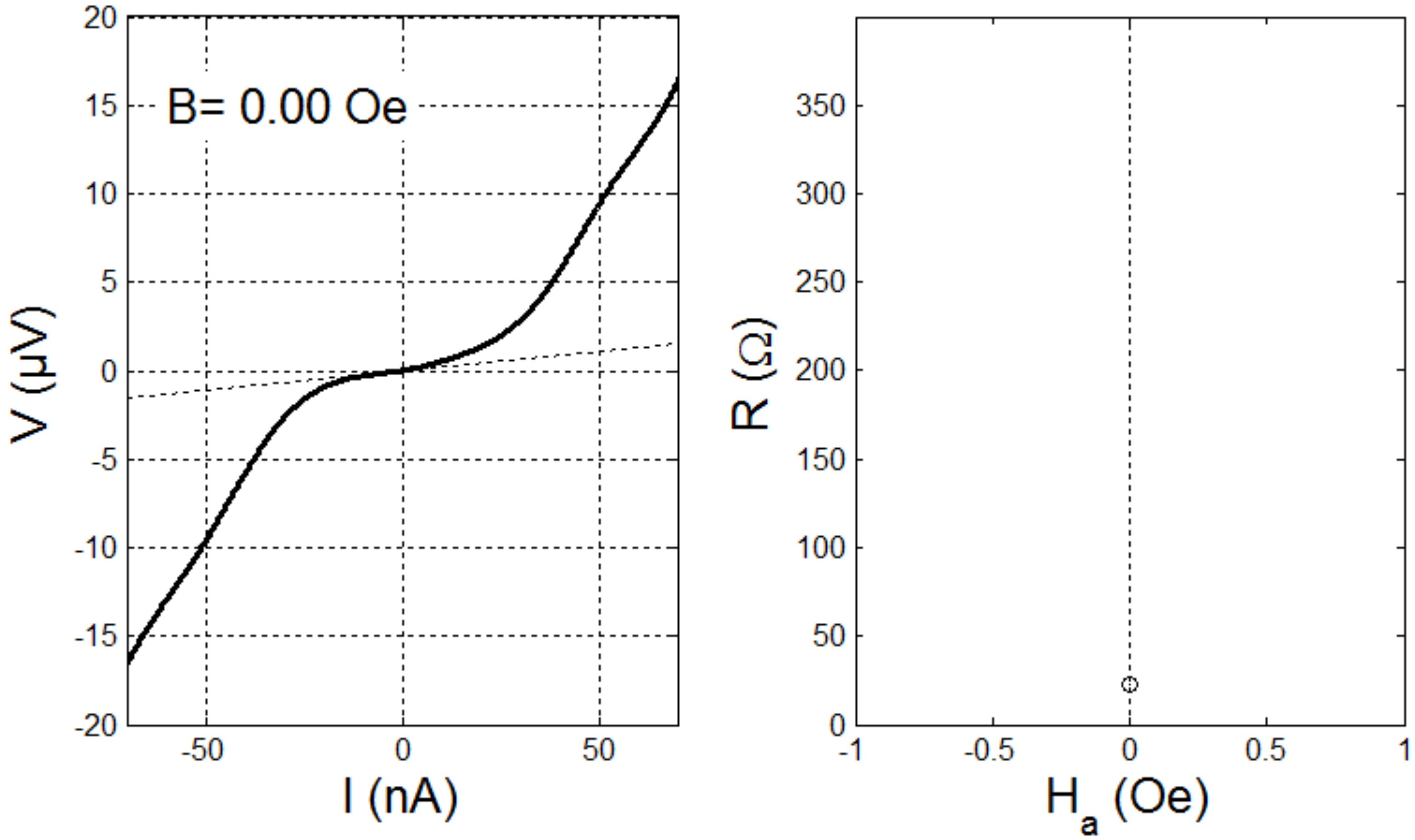
Magnetic field signature

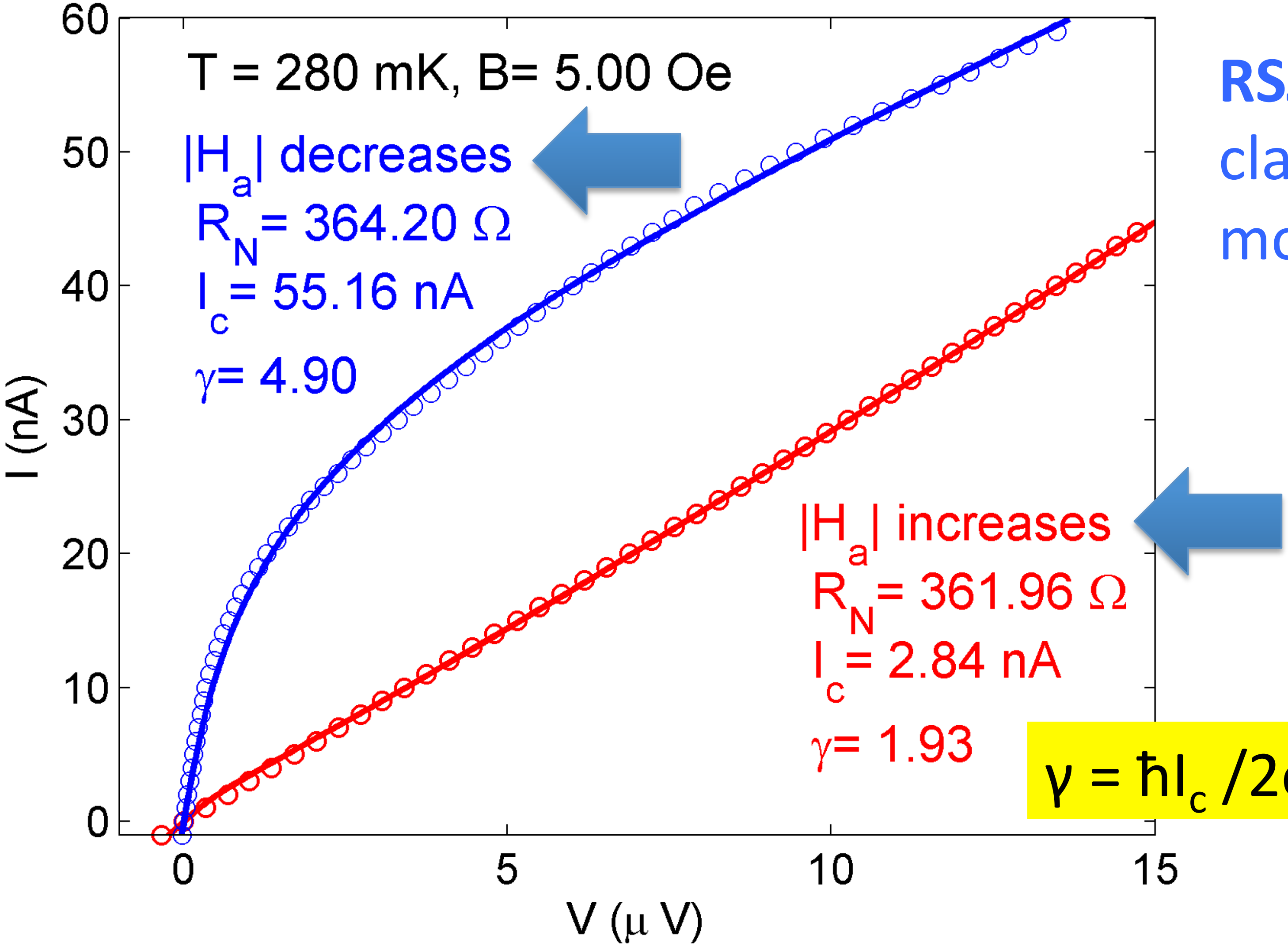
200 nm junction (J200-4)   T= 280 mK



Magnetic field hysteresis persists up to 30 Oe

Inverted hysteresis below 1 Gauss





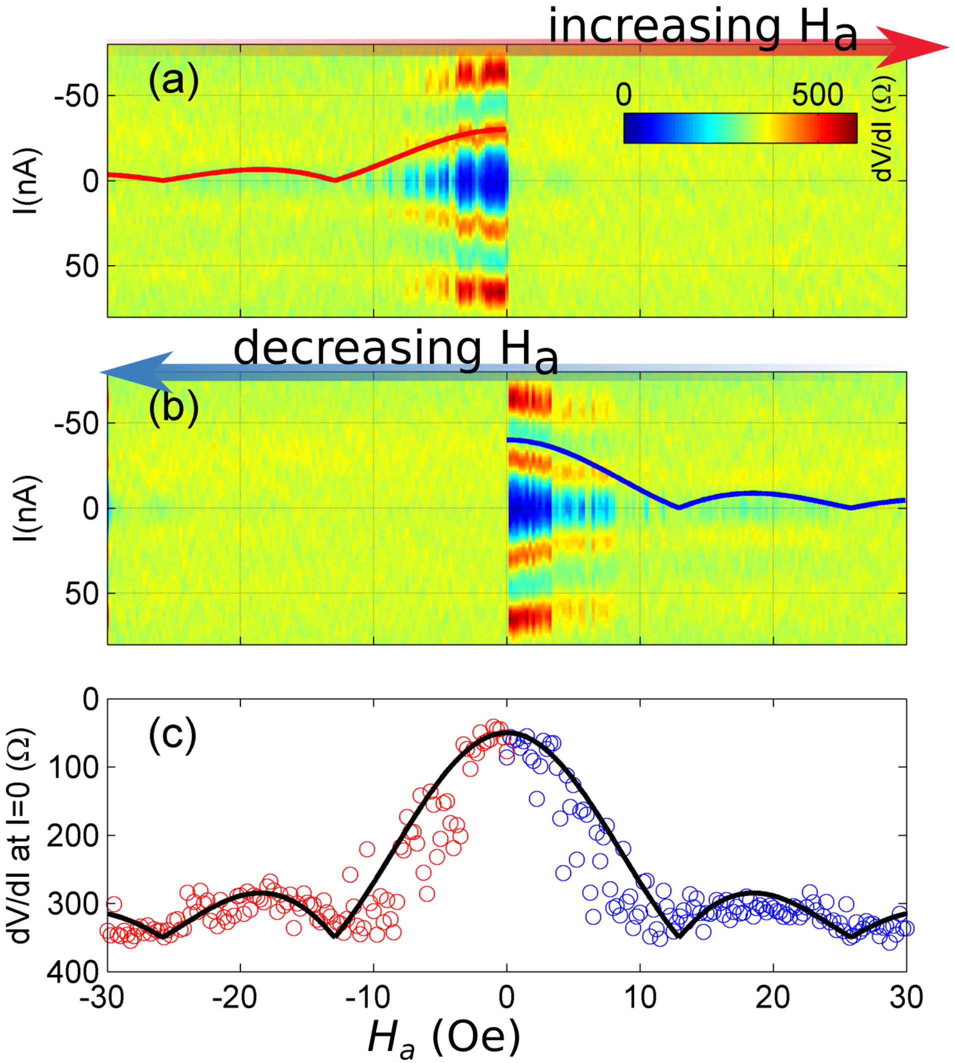
RSJ
classical
model

$\gamma = \hbar I_c / 2ek_B T$

RSJ model for phase diffusion: unable to describe hysteresis

Magnetic field signature

By combining the decreasing |Ha| parts (the revival)



Fraunhofer pattern (FP) retrieved

but…

FP is only the envelope of faster oscillations :

ΔH ~ 1-3 Oe

effective area S_{eff} ~ 9 µm ²

nominal junction area is WL ~ 1 µm²

Magnetic flux below and inside Al contacts

Weak screening ($\lambda > 1$ µm)

(typical of coplanar junctions)

first model: Rosenthal model

P. A. Rosenthal *et al.*, APL **59**, 3483 (1991):
$\delta B \propto w^2$ in thin-film grain boundary junctions.

Assuming London penetration length λ=1 µm,
we solve the London equation :

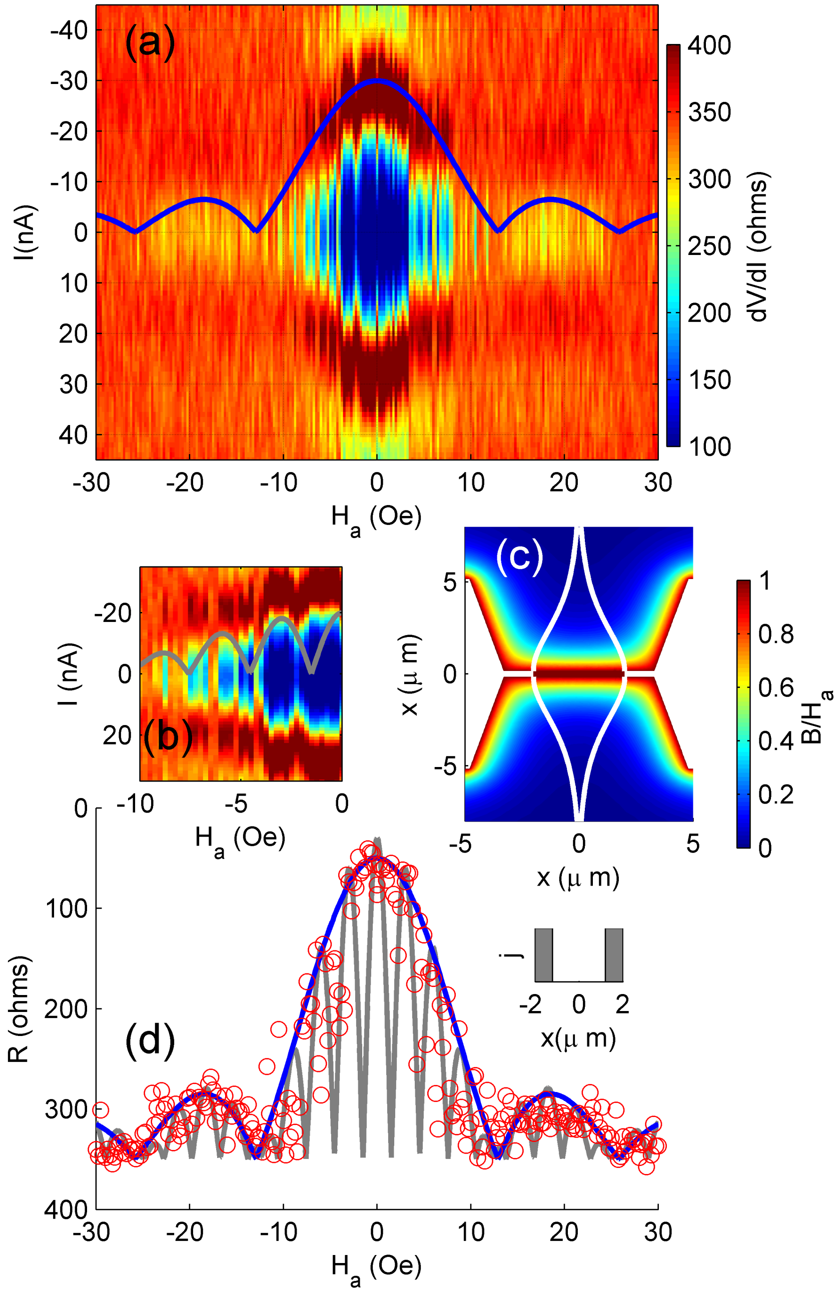
$$\boxed{\nabla^2 J - \frac{1}{\lambda^2} J = 0}$$

In the London Gauge:

$\nabla \cdot \boldsymbol{A} = 0$, $\boldsymbol{A} \cdot n = 0$, $A = -\frac{\mu_0 J}{\lambda^2}$

The phase can then be recalculated via:

$$\Delta\varphi = 2e/\hbar \int A \bullet dl$$



i) The fast oscillations easily reproduced

ii) their aperiodicity is not reproduced

iii) Fraunhofer envelope reproduced only by introducing additional inhomogeneous current distribution in the graphene junction.

…The model is not the full story **but it signals the presence of flux entering and exiting the contacts**

Inverted hysteresis

typical of type-II granular superconductor

hysteretic

inverted hysteresis

with 2 anomalous features:

when| H increases

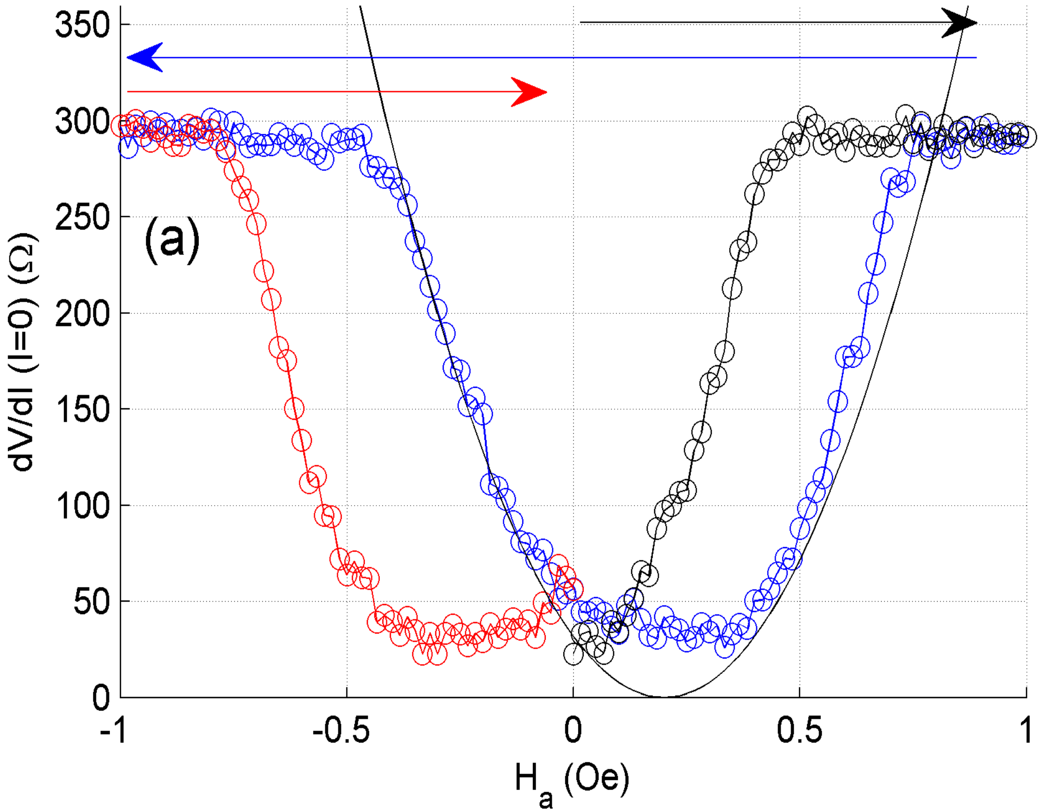
>

when |H_a decreases

has a minimum

at 0.3 Oe

before |$H_a$reaches 0



below 1 Gauss

<u>signature of flux trapping</u>

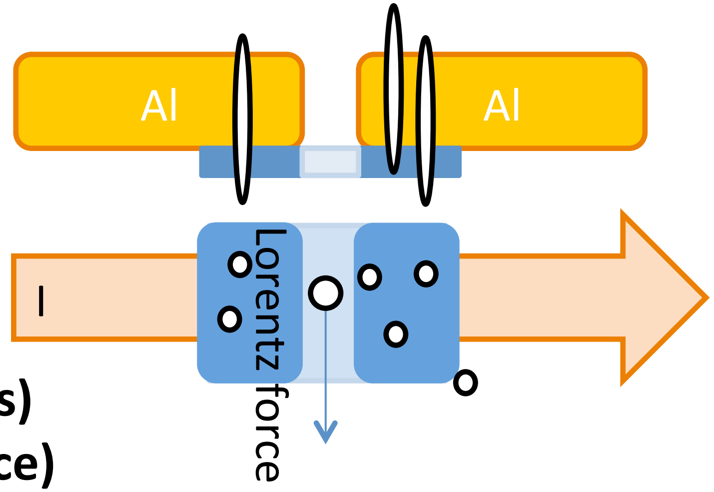
Two-level critical state model *vortices*

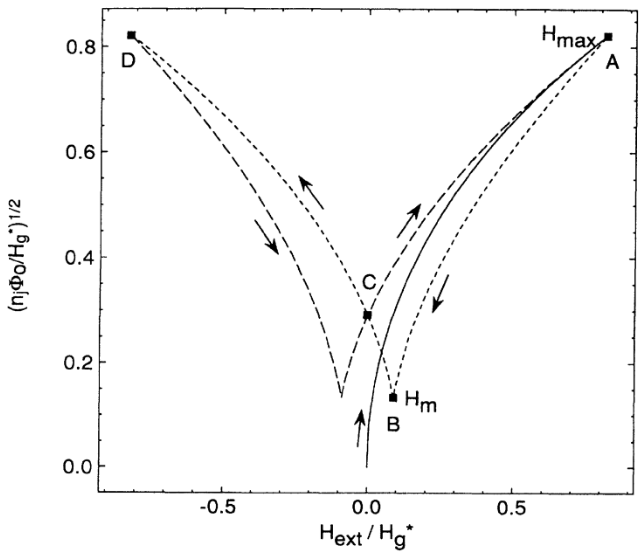
L. Ji *et al.*, PRB **47,** 470 (1993)

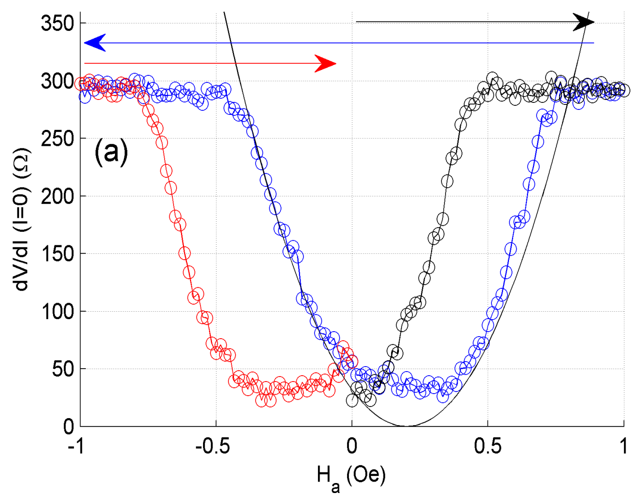
explain the anomalous hysteresis of granular superconductors

Implies the existence of

1) **Grain-pinned vortices** **(pinning, hysteresis)**
2) **Grain-boundary vortices** **(electrical resistance)**







Next question: what about the (bounded) parabolic shape ?

Bean-Livingstone (BL) barrier?

BL appropriate to explain asymmetric hysteresis

BL barrier to introduce or expel vortices inside the type II superconductor

(a) increasing $|H_a|$

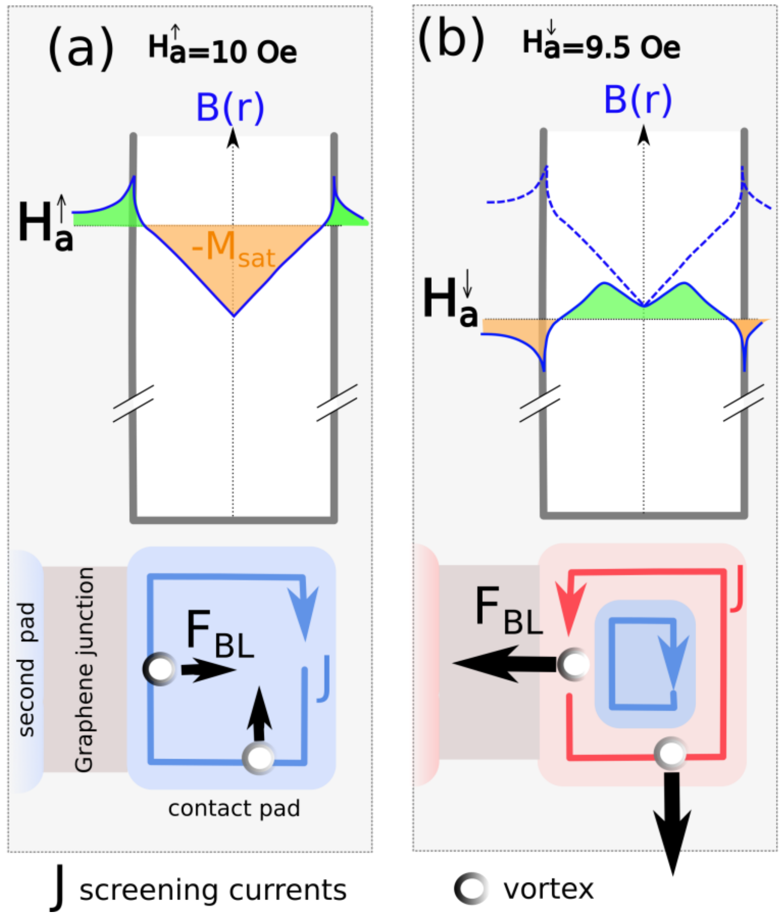
image and screening forces are opposite
Vortex driving force moderate

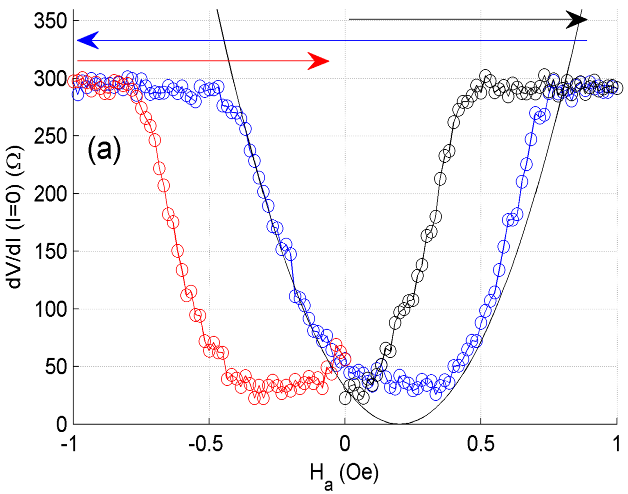
(b) decreasing $|H_a|$, screening current reversed

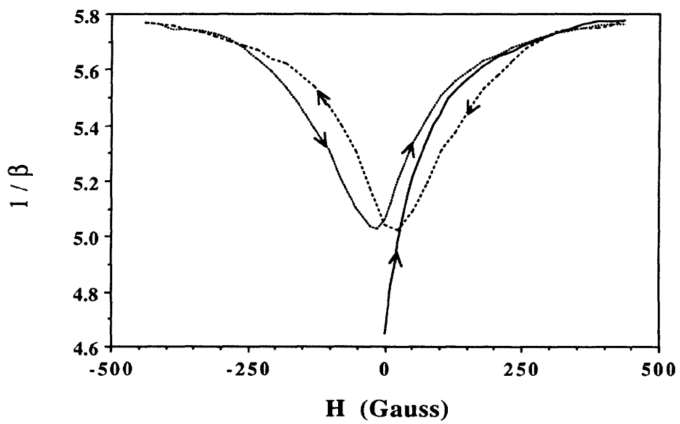
image and screening forces both expel vortices
only strongly pinned vortices are not expelled

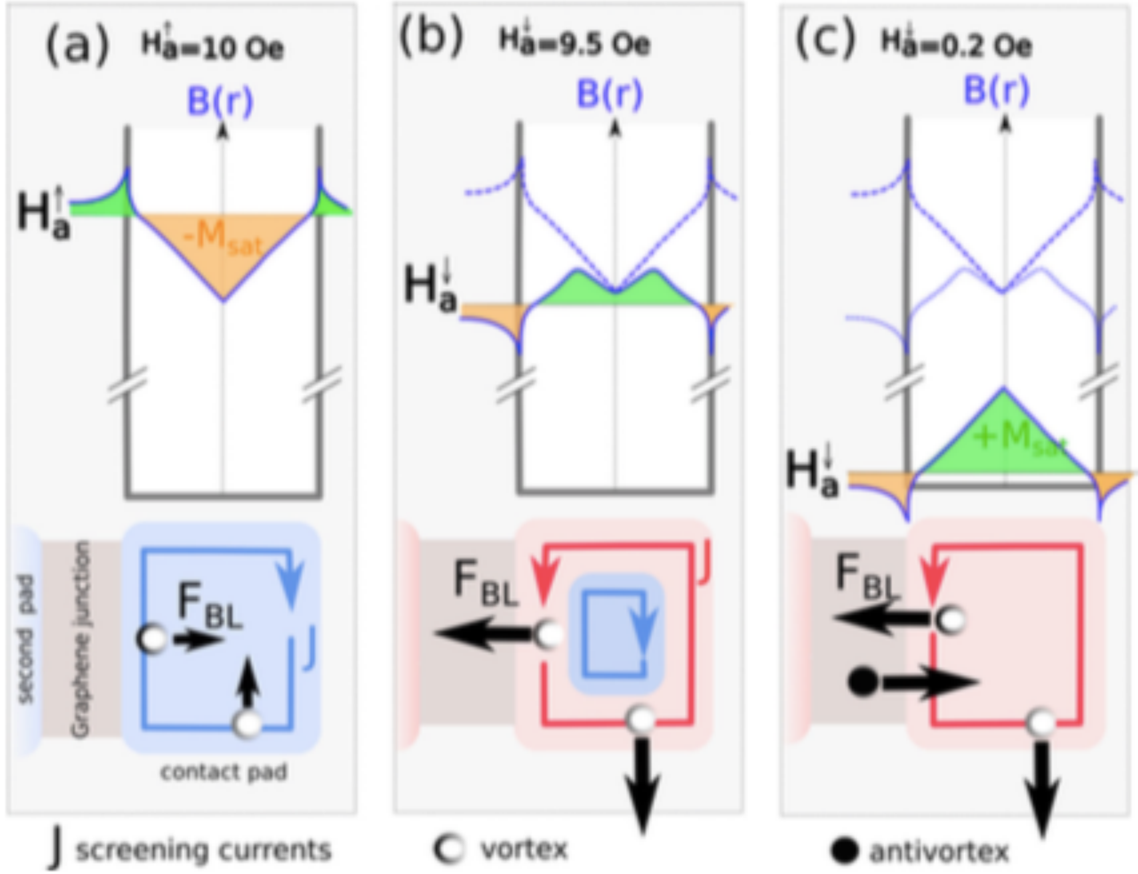
In the CSM, pinning force

Dissipation possibly reduced at the graphene junction barrier




(a)
dV/dI (I=0) (Ω)
H_a (Oe)
350
300
250
200
150
100
50
0
-1
-0.5
0
0.5
1


1 / β
H (Gauss)
5.8
5.6
5.4
5.2
5.0
4.8
4.6
-500
-250
0
250
500


(a) H↑a=10 Oe
B(r)
H↑a
-Msat
(b) H↓a=9.5 Oe
B(r)
H↓a
(c) H↓a=0.2 Oe
B(r)
H↓a
+Msat
second pad
Graphene junction
FBL
J
contact pad
J screening currents
vortex
antivortex

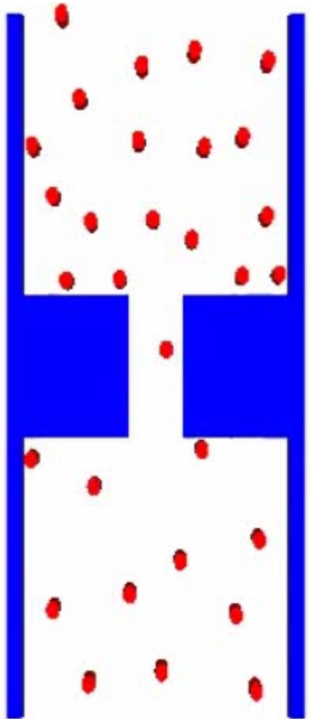
R(H): classical simulations

N=2048 2D disks
Interaction potential is
$u(r)= (\sigma/r)+ e^{-r^2/\lambda^2}$
σ = 1 μm, λ = 8 μm

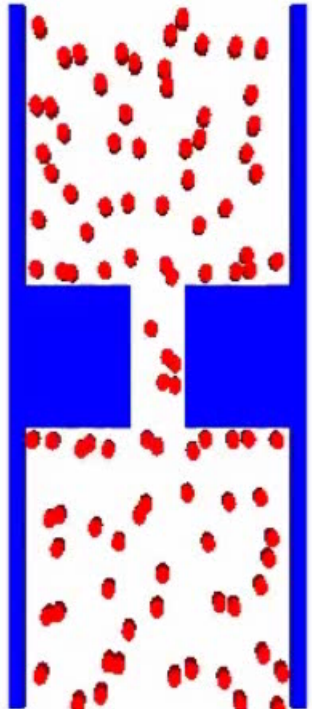
Vortex density = H/ϕ_0
Number of vortices $N=\rho L^2$

Viscosity η = inverse of diffusion coefficient D

$R \propto E/j_{ext} \propto Hv/\eta v \propto \rho/\eta$



H= 0.7 Oe



H= 2.5 Oe

Vortex diameter = 0.5 μm

R(H): classical simulations

Flux flow resistance

$$\rho_f = \frac{E}{j_{ext}} = H \frac{\phi_o}{\eta c^2}.$$

N= 2048 2D disks

Interaction potential is

$u(r)= \sigma^2/r^2 + exp[-r^2/\lambda^2]$

σ =1 μm, λ=8 μm

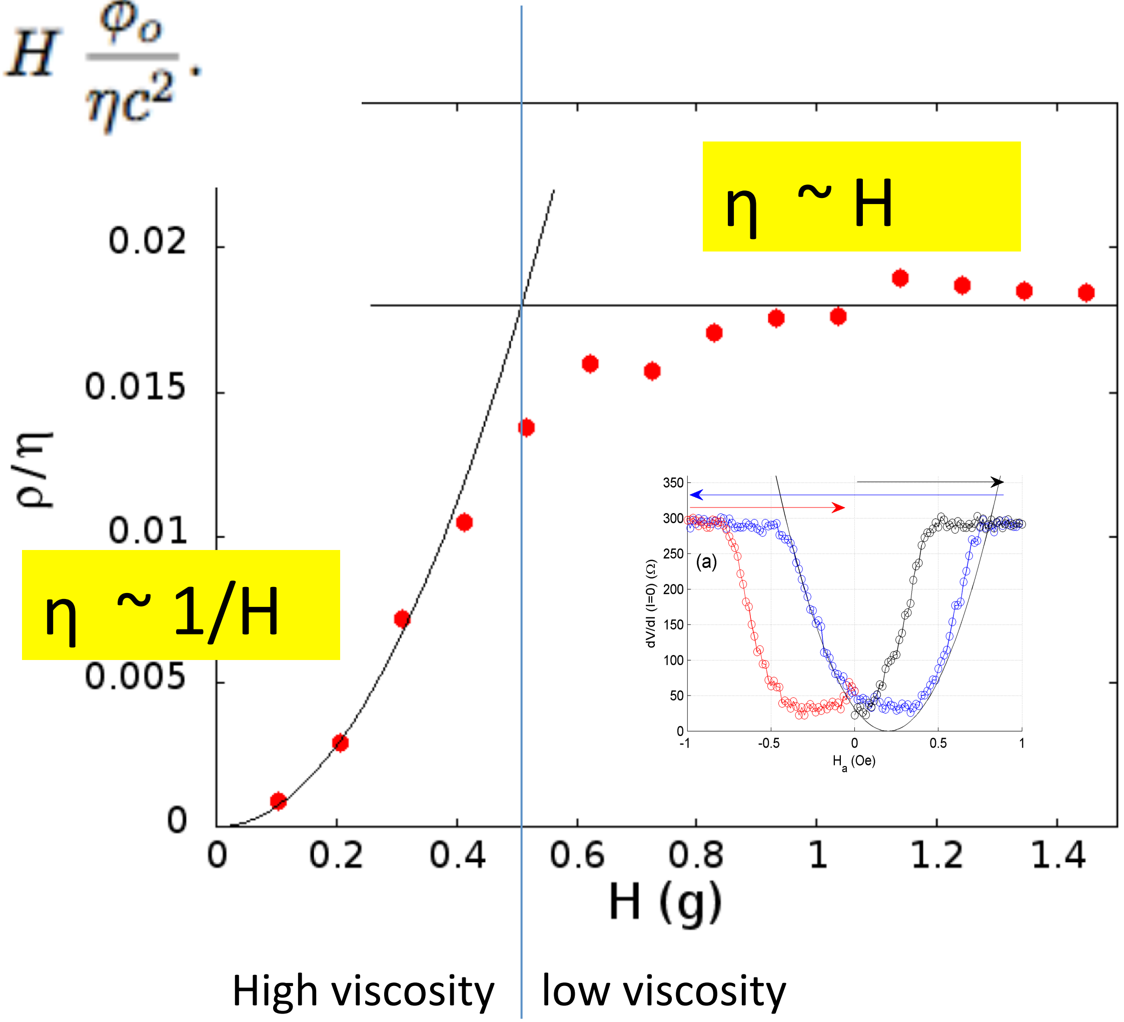
Vortex density $\rho = H / \phi_0$

Number of vortices $N = \rho L^2$

Viscosity η ~ inverse of

Diffusion coefficient *D*

$R \sim E / j_{ext} \sim Hv/ \eta v \sim \rho / \eta$



High viscosity | low viscosity

Long range interaction | short range interaction

solid | liquid

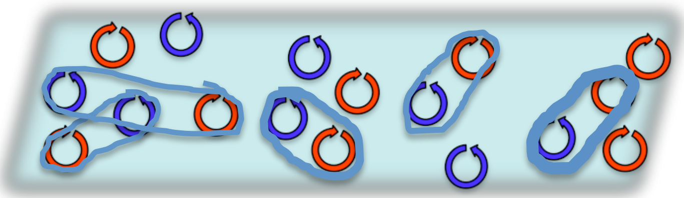
Incipient BKT transition

$T>T_{c0}$

Paraconductivity : Aslamasov-Larkin

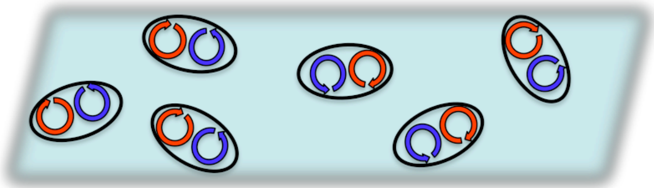
Low $T < T_{c0}$ =500mK : R(T) compatible with vortex/ antivortex pair formation

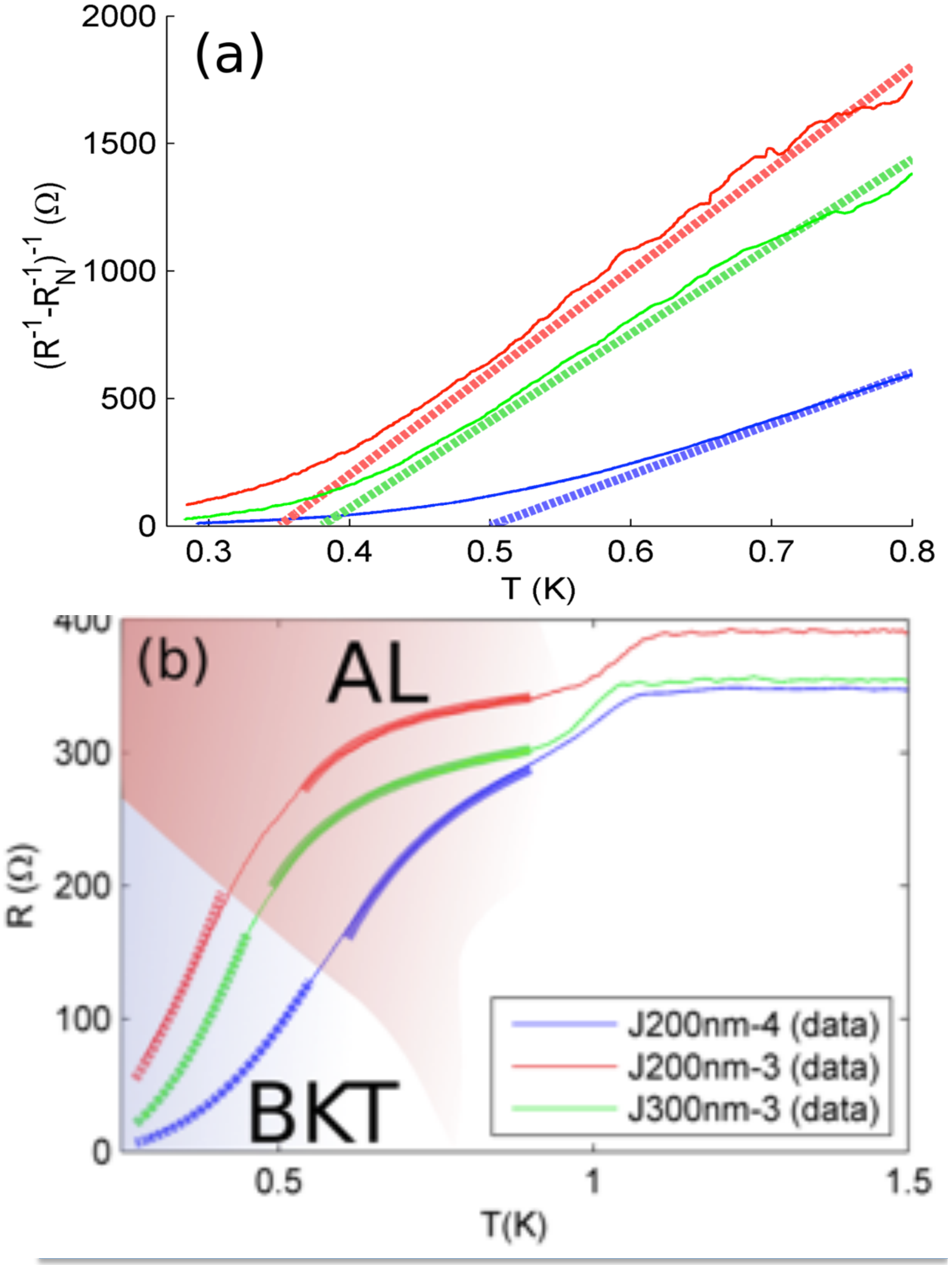
$T>T_{BKT}$



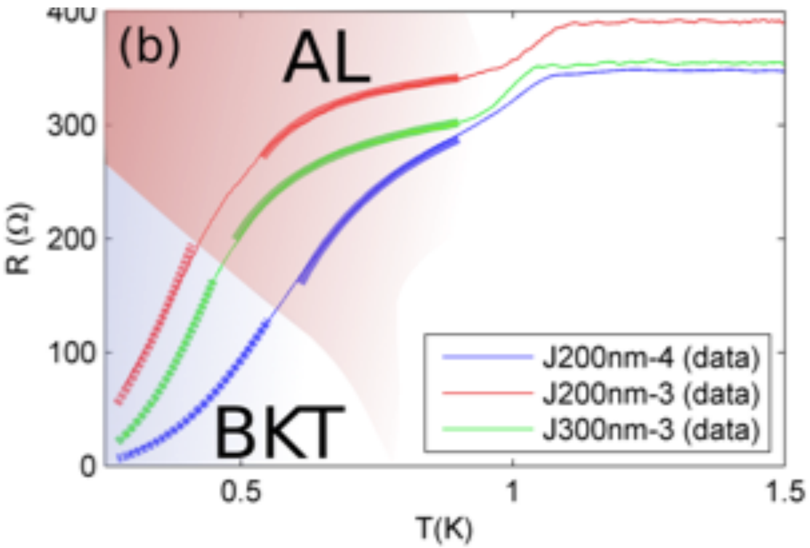
$T > T_{BKT}$ ~50 mK : breaking of vortex/antivortex pairs

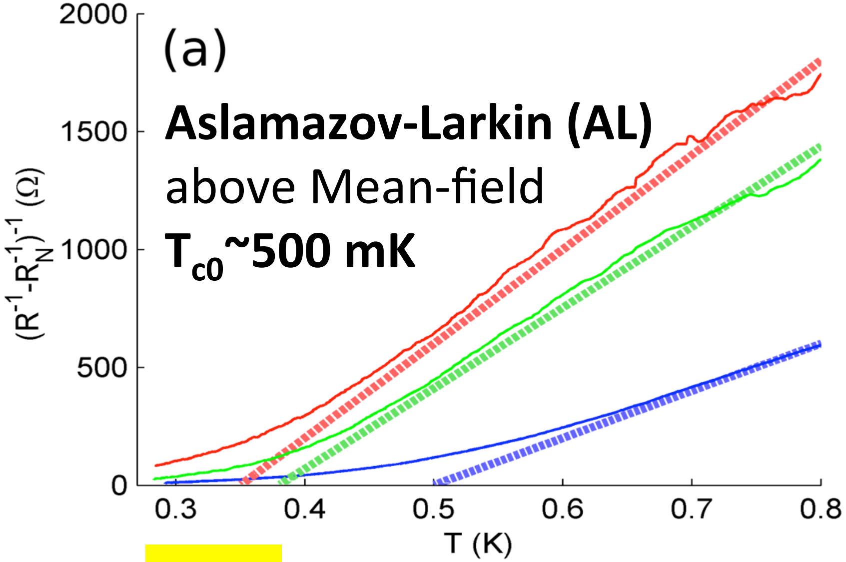
$T<T_{BKT}$



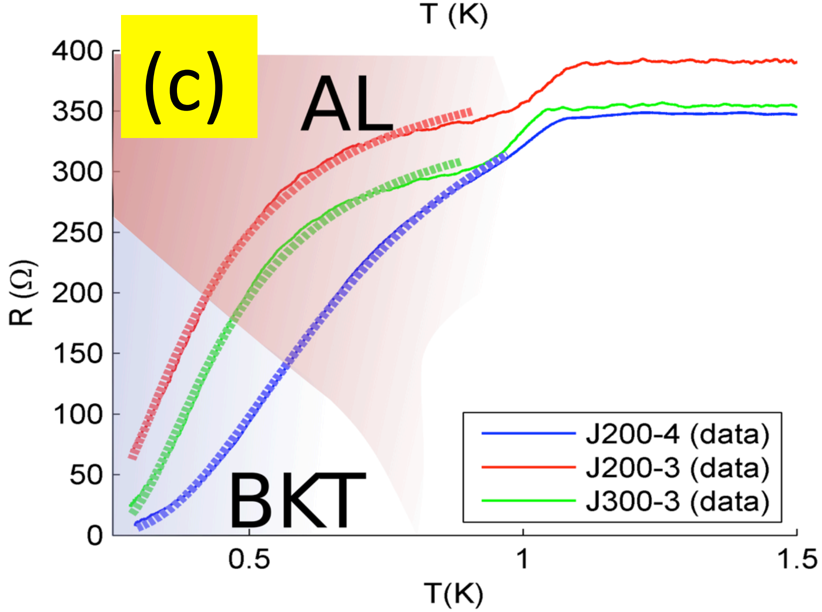


R(T) transition





Berezinskii-Kosterlitz-Thouless (BKT) fit **50 mK ~T_{BKT} < T<T_{c0}**



$$R(T)^{-1} = \frac{0.37}{b} R_N^{-1} \sinh^2\left(\frac{bt_c}{t}\right)^{1/2}$$

Halperin-Nelson crossover fit for R(T) at T_{BKT} < T
(1979)

$t=(T-T_{BKT})/T_{BKT}$; $t_c=(T_{c0}-T_{BKT})/T_{BKT}$

name	L nm	R_N Ω	I_c nA	R_0 Ω	T_{c0} K	T_{BKT} mK	b
J200-1	200	720	4	8,500	0.23		
J200-2	200	425	5				
J200-3	200	370	10	1,400	0.43	45	5.22
J200-4	200	410	50	1,000	0.5	60	9.3
J300-3	300	350	30	1,300	0.38	80	8.7
J400-1	400	650	0	16,000	0.285		
J600-1	600	440	0				

Aslamasov-Larkin

$R_0 = 16\hbar/e^2 \sim 65$ kΩ

TABLE I. Main parameters for the investigated devices: name, length L, normal resistance R_N, critical current I_c at $T = 280$ mK, mean field resistance R_0, mean field critical temperature T_{c0}, BKT temperature, dimensionless parameter b of Eq. (2).

Large *b*, large T_{c0} - T_{BKT}

Condensation energy loss in vortex core

>> Superconducting stiffness

Berezinskii-Kosterlitz-Thouless (BKT)

as in 2D-XY model

!

Conclusion

Josephson supercurrent observed in Al/G/Al diffusive junctions
G on SiC: a way towards more complex Graphene-based superconducting devices

Hysteretic collapse and revival of the Josephson current:
Unique manifestation of Josephson effect
(no other example known up to date)

Vortices are present in the devices (not only in the Al itself)
at the Al/G interface
Multiple hints of BKT: hysteresis in R(H), R(T) fits, shape of R(H),…

GRAPHENE FLAGSHIP