Electric current crowding in nanostructured conductors

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LABORATORY OF PHYSICS OF NANOSTRUCTURED MATERIALS

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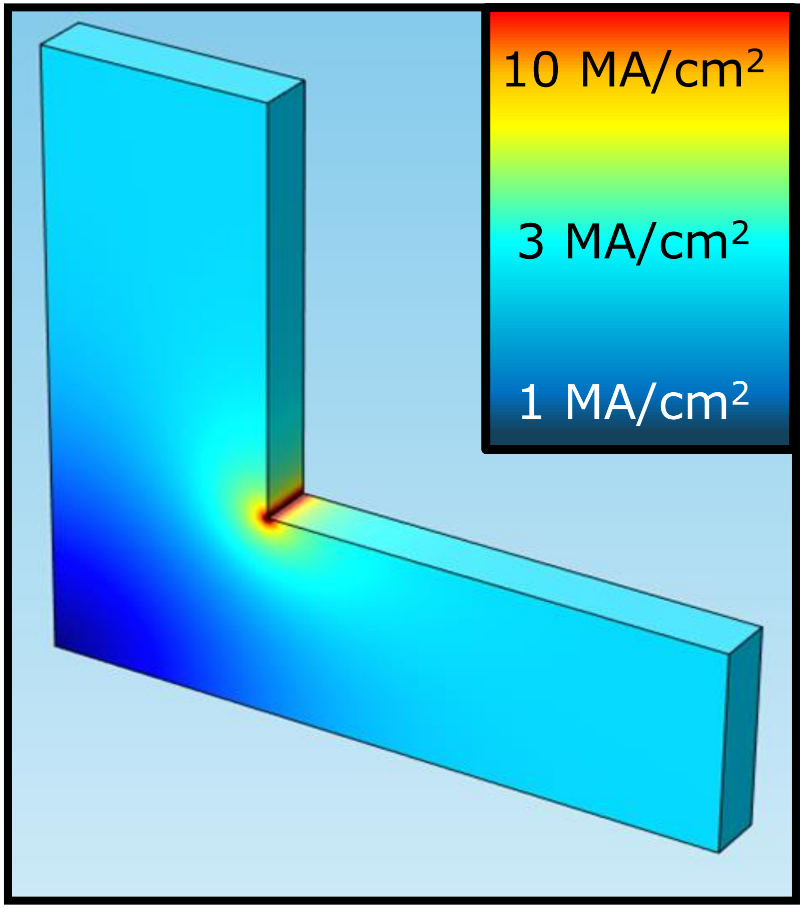
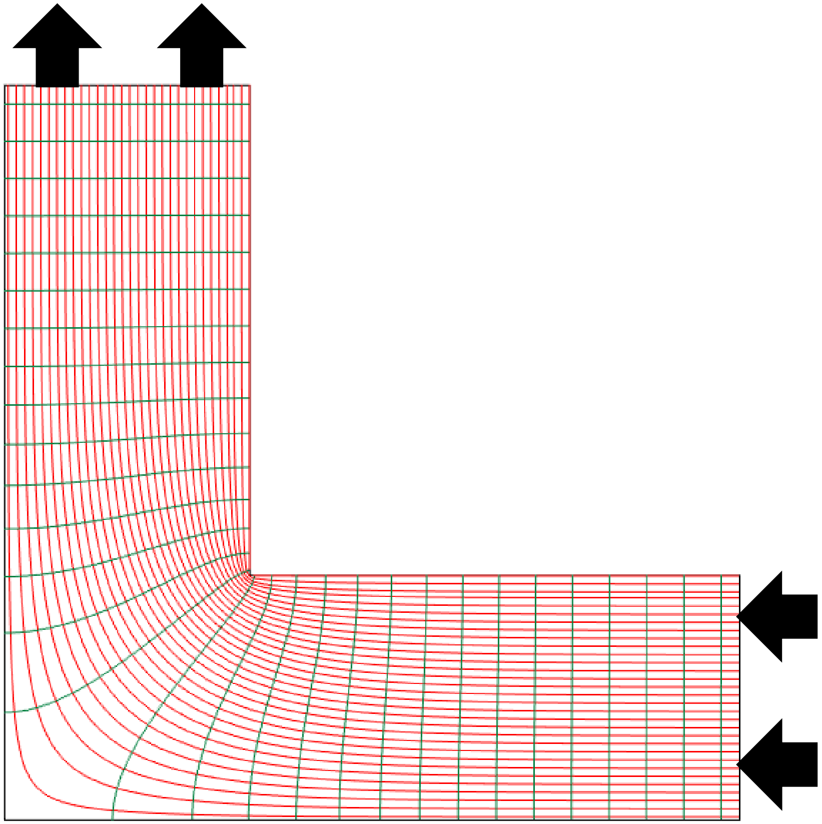
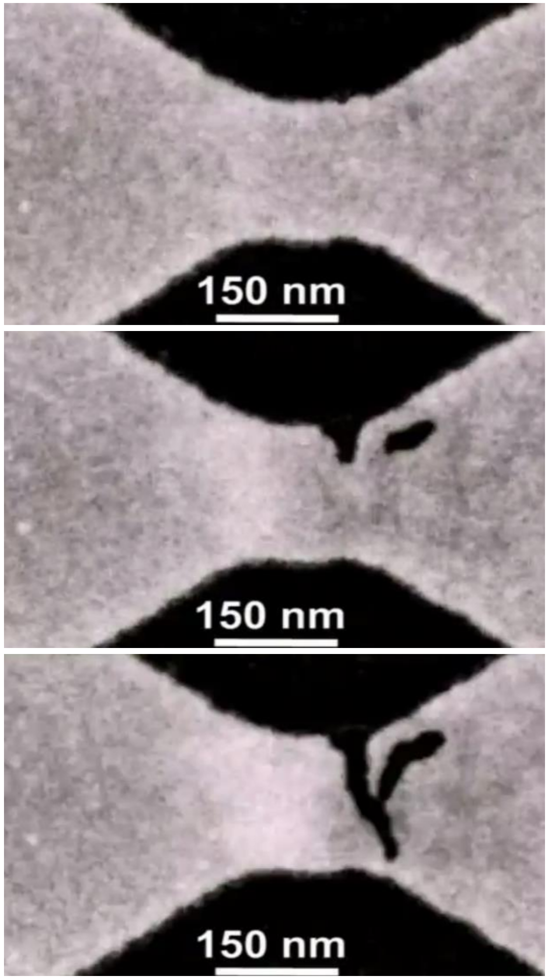
What is current crowding ?



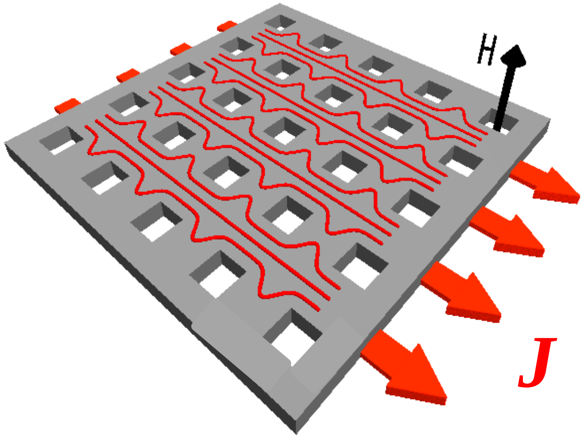


Why is it important ?

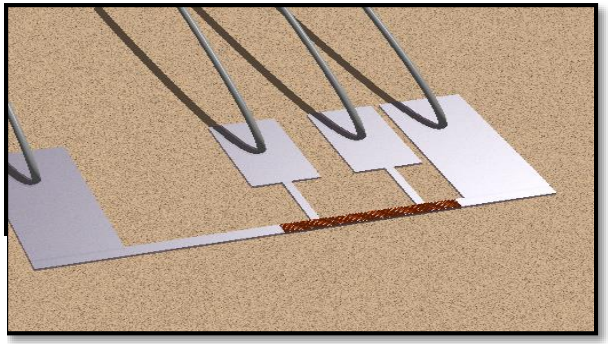
Electromigration



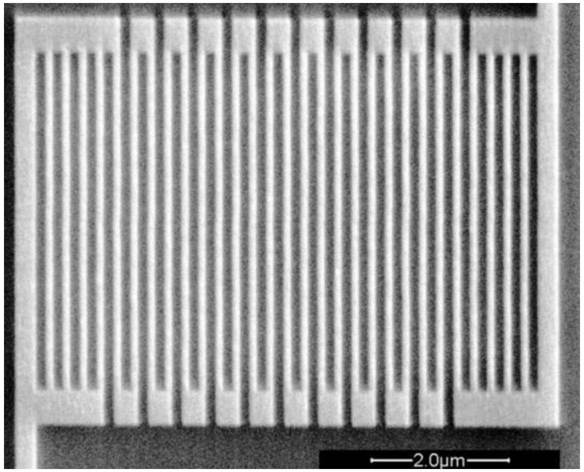
Nanostructured superconductors



Kelvin probe bridges



Single photon detectors



T. Taychatanapat et al., NanoLetters 7, 652 (2007)

Outline

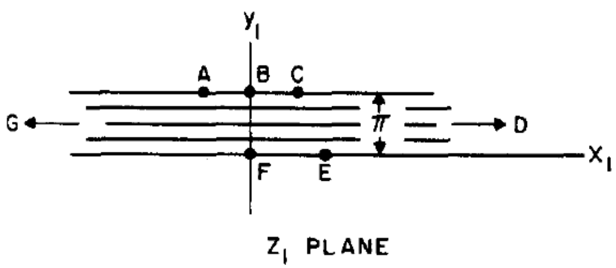
- CURRENT CROWDING IN NORMAL METALS
- CURRENT CROWDING IN SUPERCONDUCTORS
    - SHARP BENDS
    - SURFACE INDENTATIONS
    - MAGNETIC FLUX AVALANCHES
- NANOSTRUCTURING VIA CURRENT CROWDING
- CONCLUSION

Pre-history: normal conductors

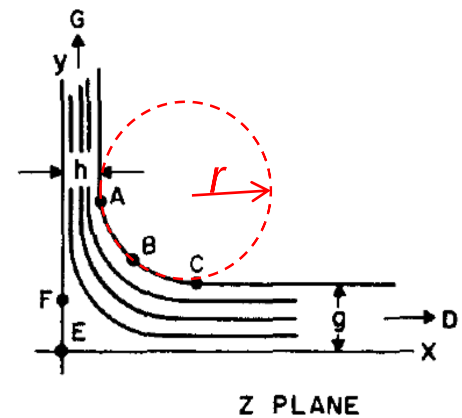
JOURNAL OF APPLIED PHYSICS VOLUME 34, NUMBER 1 JANUARY 1963

Right-Angle Bends in Thin Strip Conductors

F. B. HAGEDORN AND P. M. HALL
Bell Telephone Laboratories, Inc., Murray Hill, New Jersey
(Received 25 June 1962)



conformal mapping

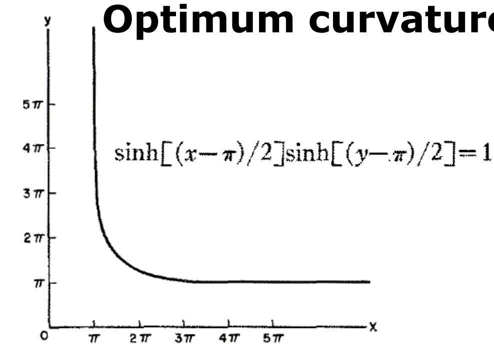


$$i_{ABC} \approx \left(\frac{g}{r}\right)^{1/3} i_0$$

i_0 is the asymptotic current density in the leg

The perturbations of the current crowding propagate about three strips widths into the legs

Optimum curvature



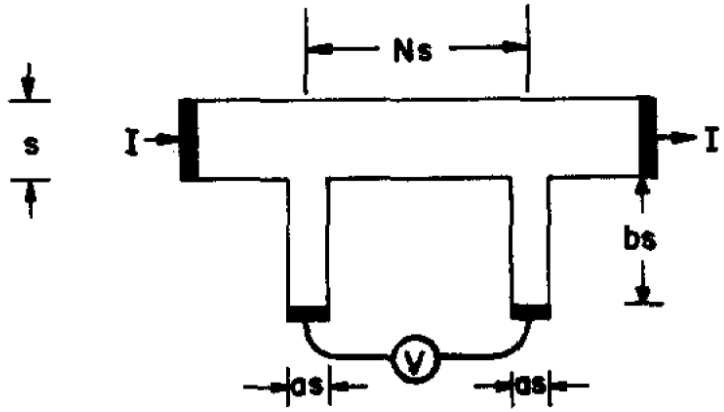
Pre-history: normal conductors

RESISTANCE CALCULATIONS FOR THIN FILM PATTERNS

P. M. HALL

Thin Solid Films, 1 (1967/68) 277–295

Bell Telephone Laboratories, Inc., Allentown, Pa. (U.S.A.)



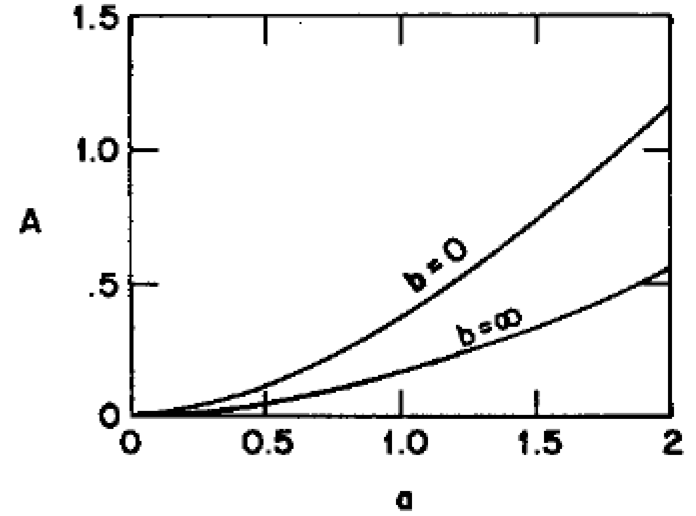
if $b >> a$ and $N >> 1$

$$R = \frac{\rho}{t}\left[N + \frac{2}{\pi}\ln\left(\frac{a^2}{4}+1\right) - \frac{2a}{\pi}\tan^{-1}\left(\frac{a}{2}\right)\right] = \frac{\rho}{t}[N - A]$$

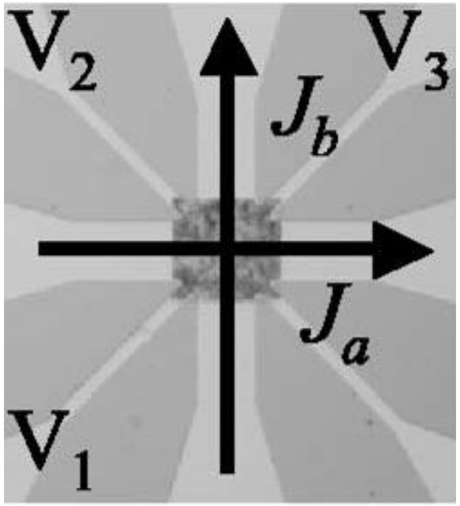
__a__ as small as possible

and

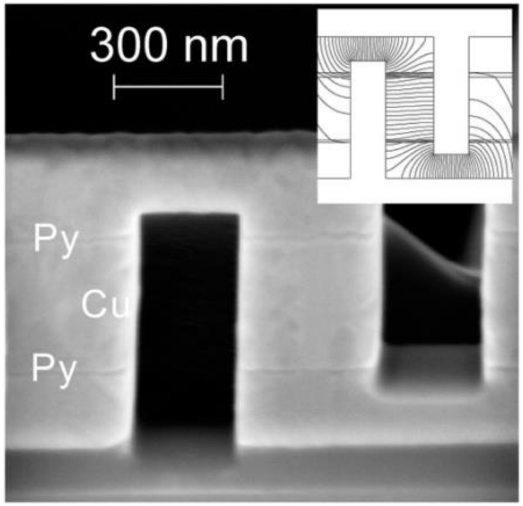
__b and N__ as large as possible



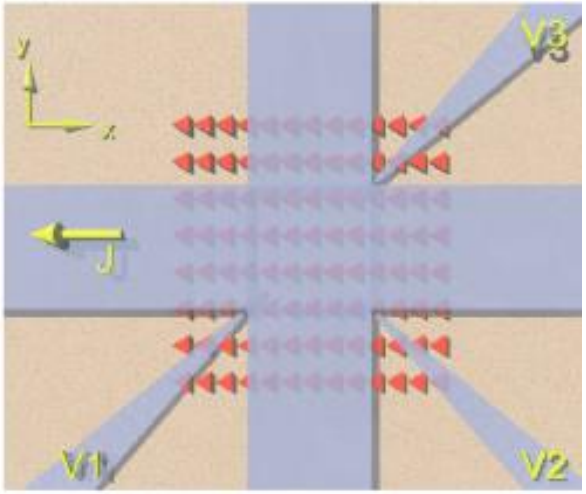
History: superconductors



Villegas *et al.* (2005)
Phys. Rev. B **72**, 064507



A Palau *et al.* (2007)
Phys. Rev. Lett. **98**, 117003



Silhanek *et al.* (2008)
Appl. Phys. Lett. **92**, 176101

…substantial deformation of the current-voltage characteristic when the voltage pads are attached close to the vertices.

Superconductors (vortex nucleation)

PHYSICAL REVIEW B **84**, 174510 (2011)

Geometry-dependent critical currents in superconducting nanocircuits

John R. Clem
Ames Laboratory and Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011-3160, USA

Karl K. Berggren
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA and Kavli Institute of Nanoscience, Delft University of Technology, Lorentzweg 1, NL-2628CJ Delft, The Netherlands

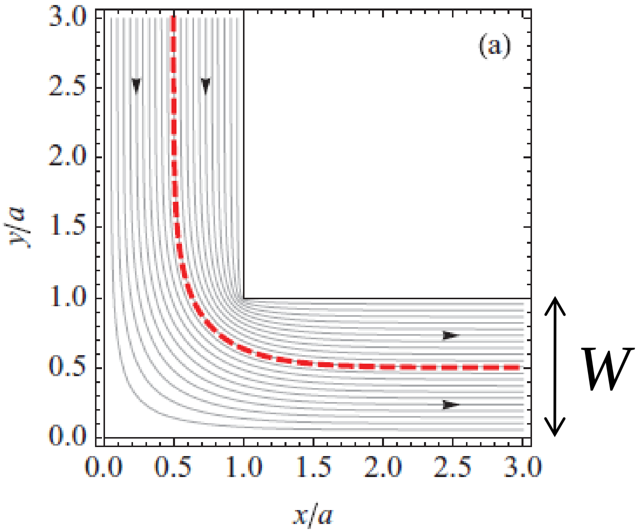
$$\xi << W << 2\lambda^2 / d$$

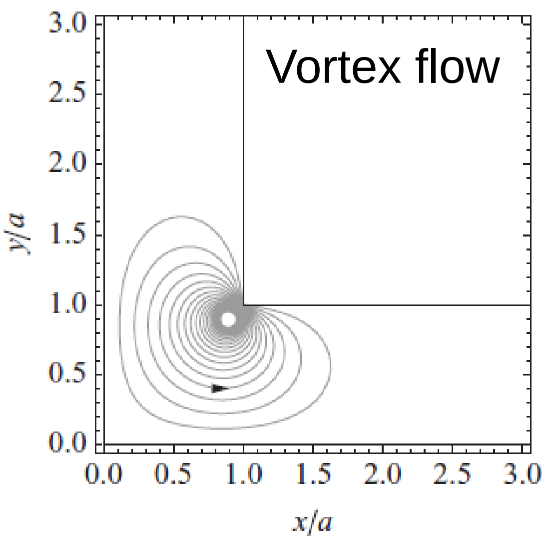
Definition of J_c…current at which a nucleating vortex surmounts the Gibbs-free-energy barrier at the wire edge and then is driven entirely across the strip

$$J_c = R\, J_0 \qquad R < 1$$

J_0 the critical current of a superconducting strip

Comparison superconductors vs metals





$J_c = R\,J_0$

$$R \xrightarrow[r\to 0]{} \frac{3}{2}\left(\frac{\pi\xi}{4W}\right)^{1/3}$$

Clem-Berggren
(superconductor)

$$R \xrightarrow[r\to 0]{} \left(\frac{r}{W}\right)^{1/3}$$

Hagedorn-Hall
(normal metal)

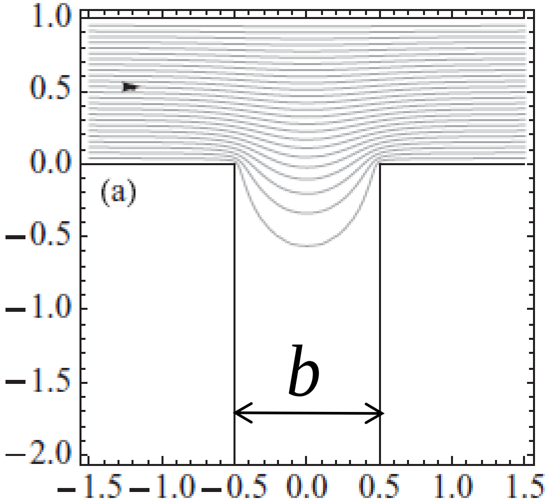
λ does not play a role
The critical current of a right-angle bend is finite

There is an optimum curvature which permits to avoid current crowding. The minimum radius being 1.27 *W*

Clem and Berggren, Phys. Rev. B **84**, 174510 (2011)

CC in voltage and current leads

Voltage Contact

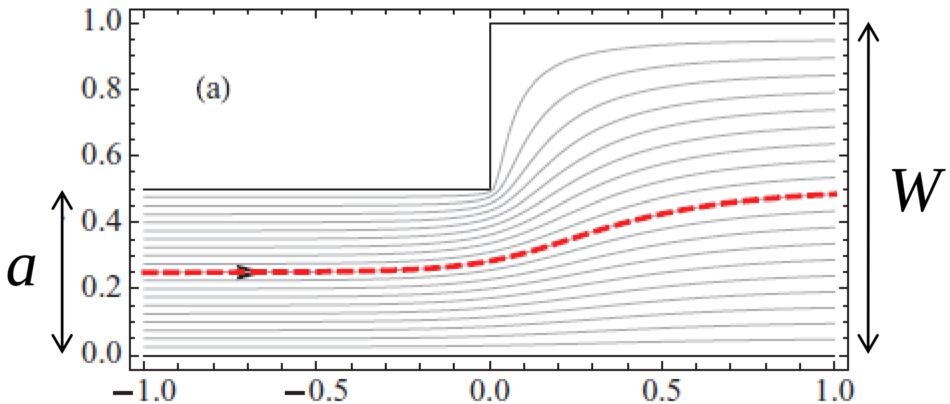


$$C = \frac{3}{2}\left(\frac{\pi\xi}{b}\right)^{1/3} \quad \text{if} \quad \xi < b << W$$

$$C \approx 1 \quad \text{if} \quad b < \xi$$

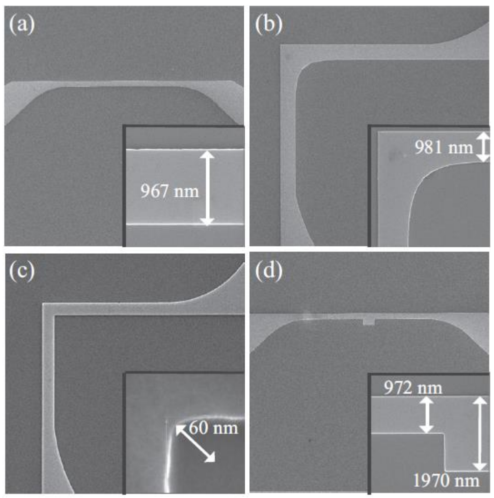
Current Contact

$$C = \frac{3}{2}\left(\frac{\pi W^2 \xi}{(W^2 - a^2)a}\right)^{1/3}$$



Clem and Berggren, Phys. Rev. B **84**, 174510 (2011)

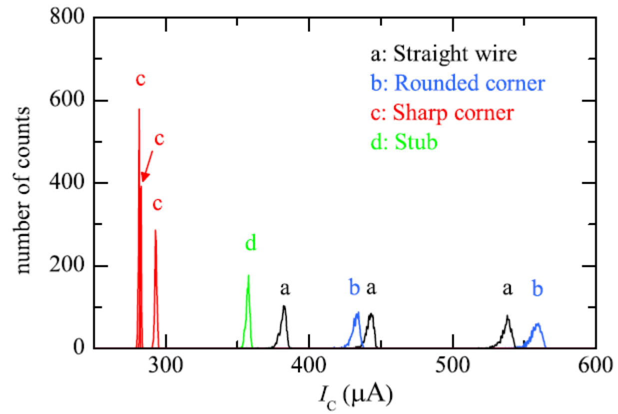
Supporting experimental evidence



H. L. Hortensius *et al.* Appl. Phys. Lett. **100**, 182602 (2012)

NbTiN

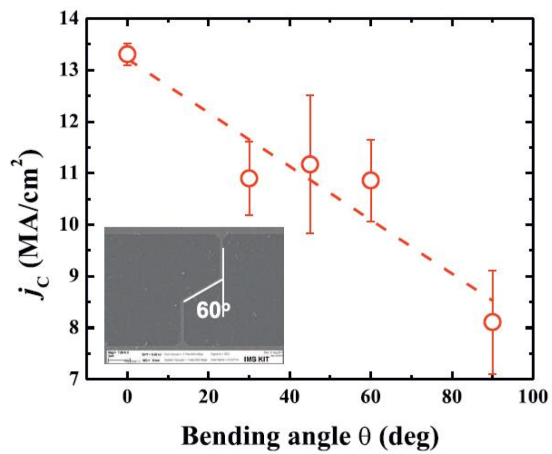
ξ ~ 7 nm
Λ ~ 20 μm
W ~ 1 μm

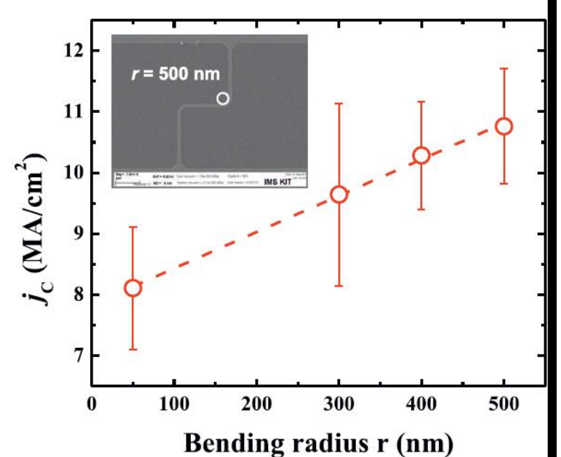


D. Henrich *et al.*, Phys. Rev. B **86**, 144504 (2012)

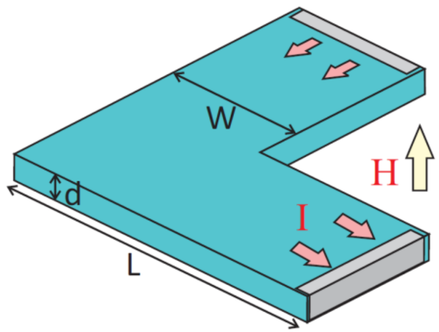
NbN

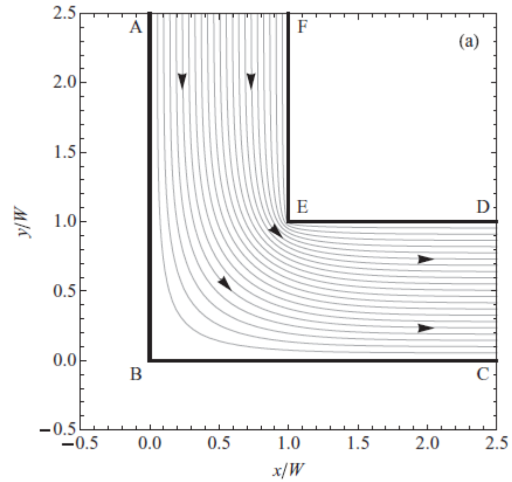
ξ ~ 5 nm
Λ >> W
W ~ 0,3 μm

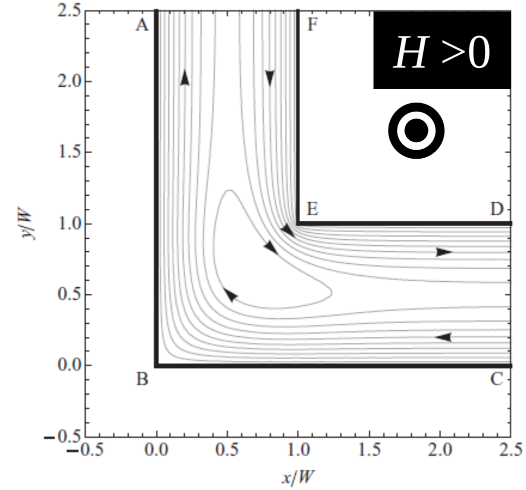


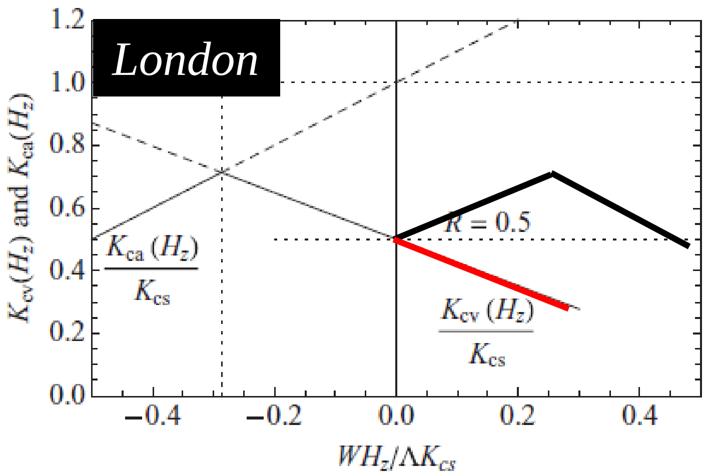


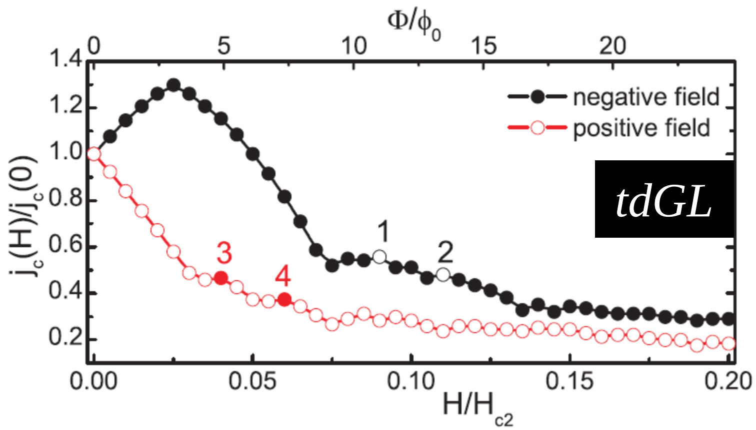
Field dependence

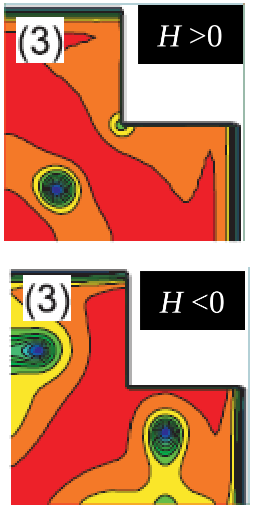








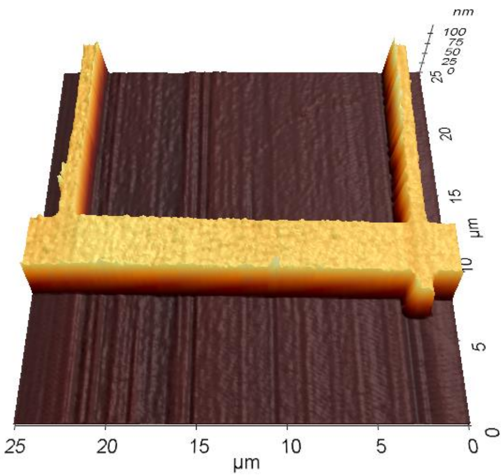




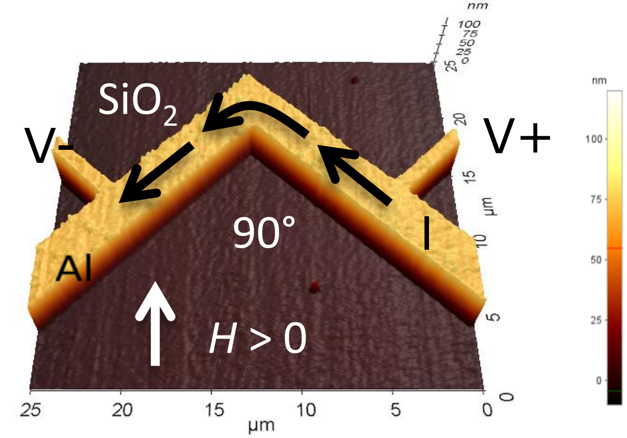
Compensation effect between the field induced stream-lines and the externally applied current at the current crowding point

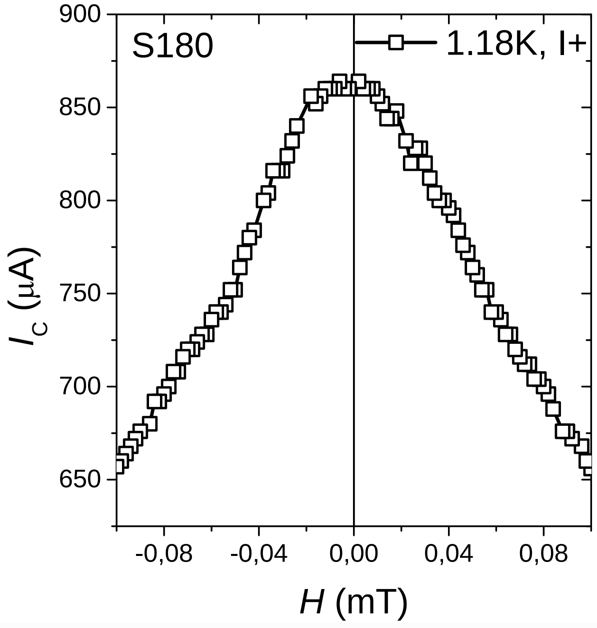
Clem *et al.*, Phys. Rev. B **85**, 144511 (2012)

Experimental confirmation

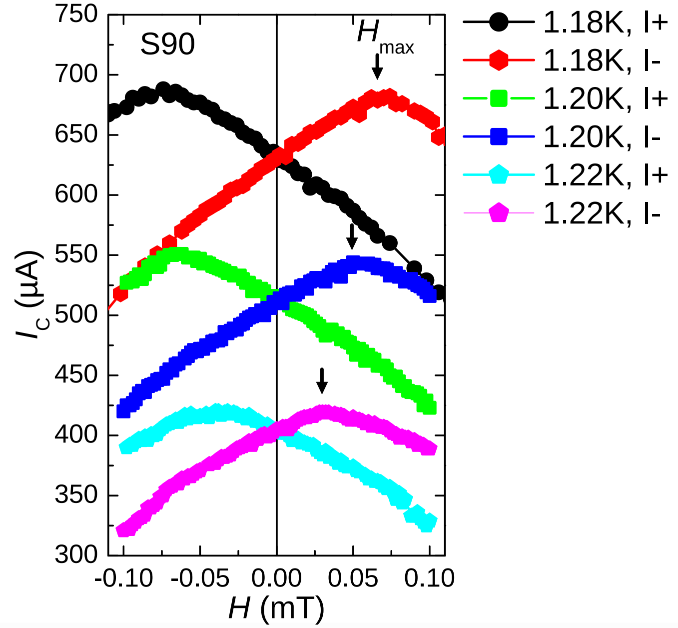


Al
$\xi(0)$ ~ 120 nm
Λ(1,22 K) ~ 8,3 μm
W ~ 3,3 μm



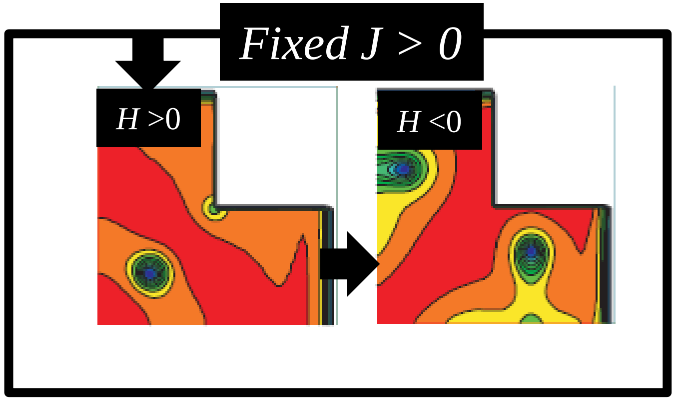


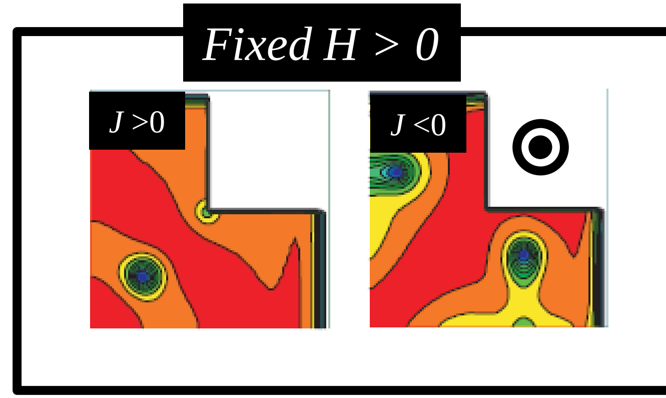
$$H_{\mathrm{max}} \propto \frac{1}{\xi(T)}$$

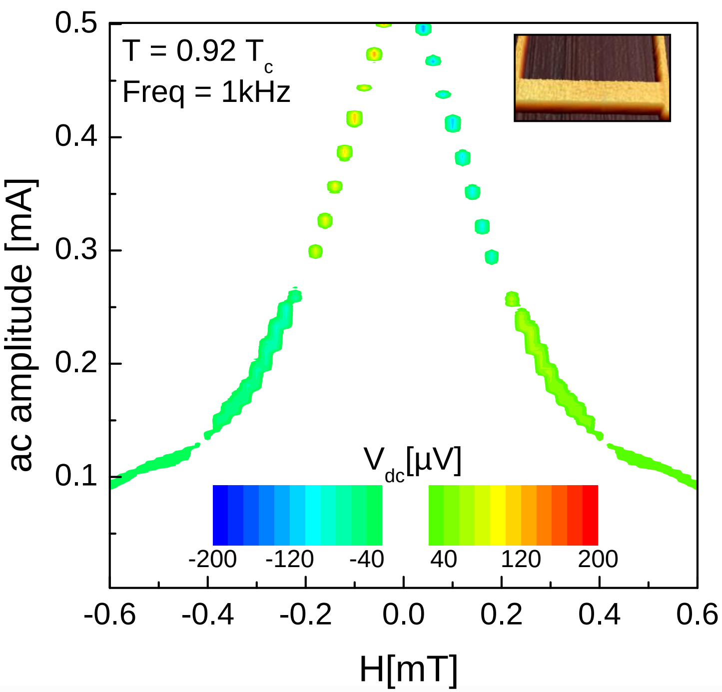


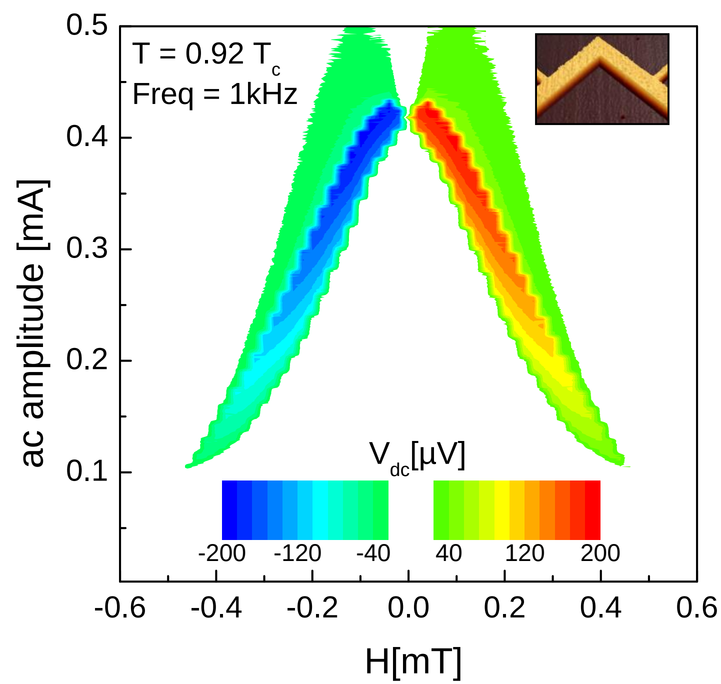
Adami *et al.*, Appl. Phys. Lett. **102**, 052603 (2013)

Rectified motion of vortices



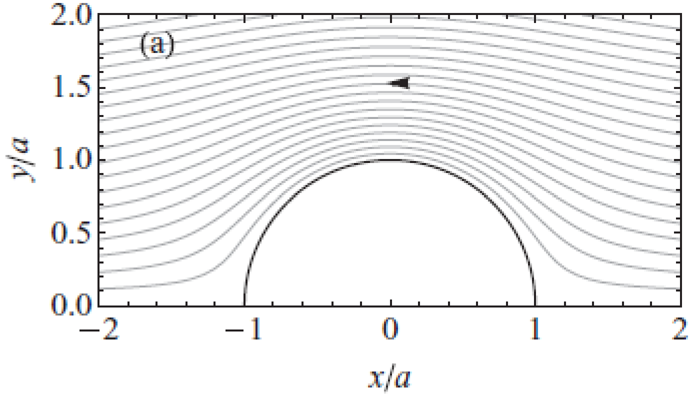




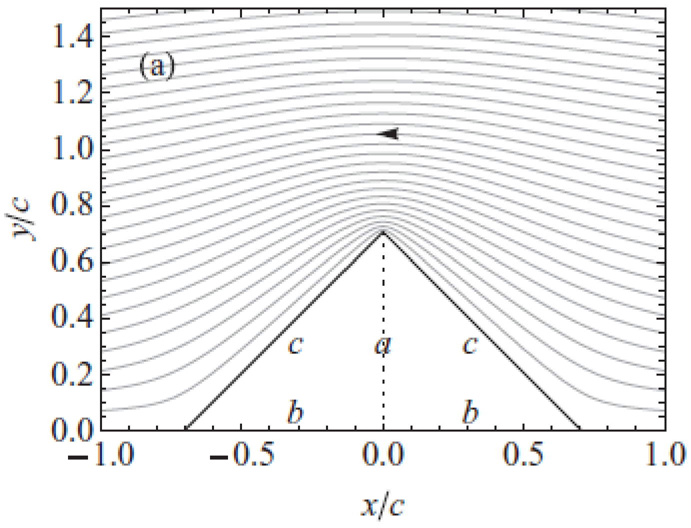


Adami *et al.*, Appl. Phys. Lett. **102**, 052603 (2013)

Surface indentations



$$C \approx \frac{1}{2}$$

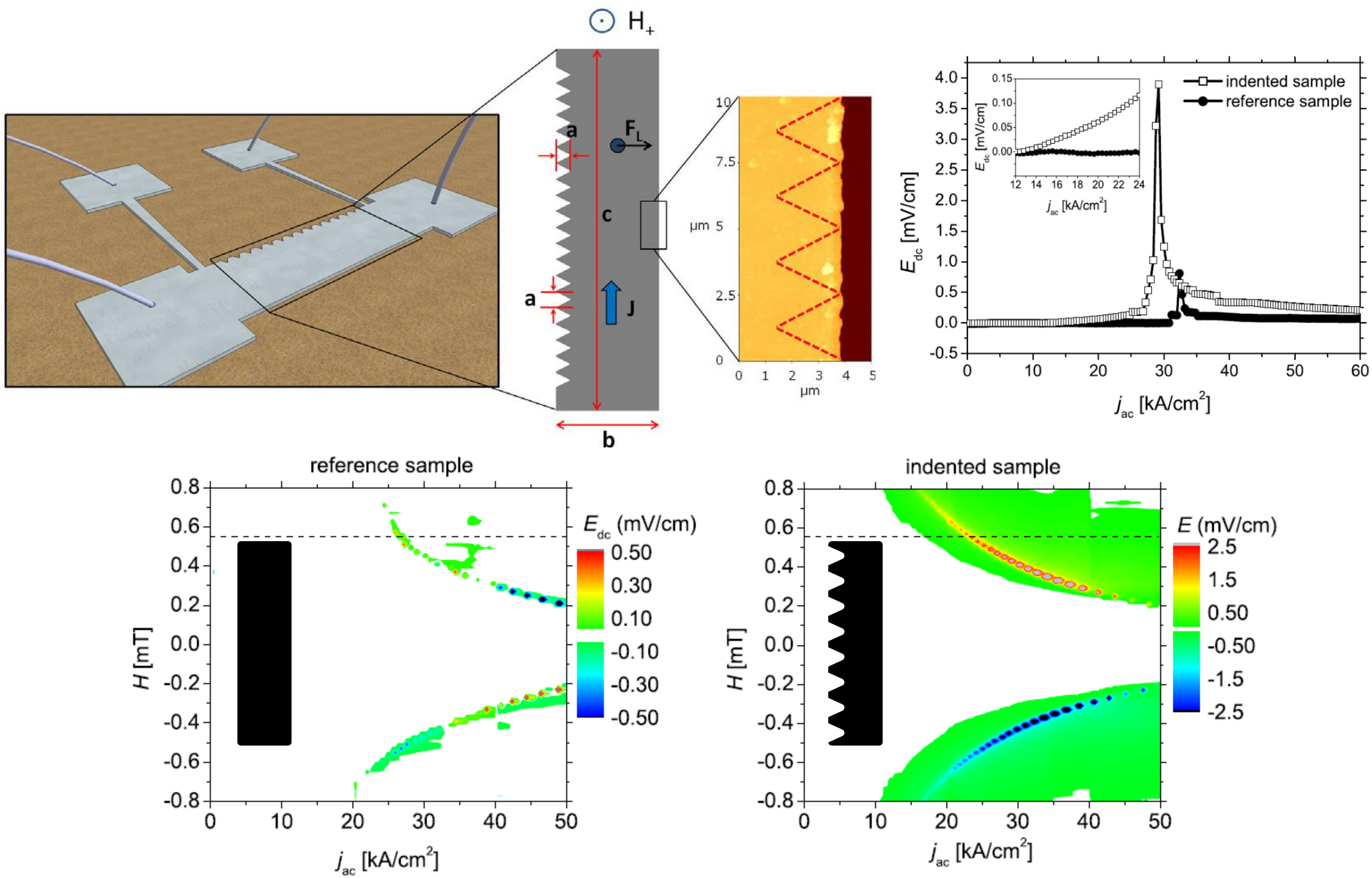


$$C \approx \left(\frac{\xi}{a}\right)^{1/3} \quad \text{if} \quad \theta = 90^\circ$$

Current crowding is more important for the triangular indentation

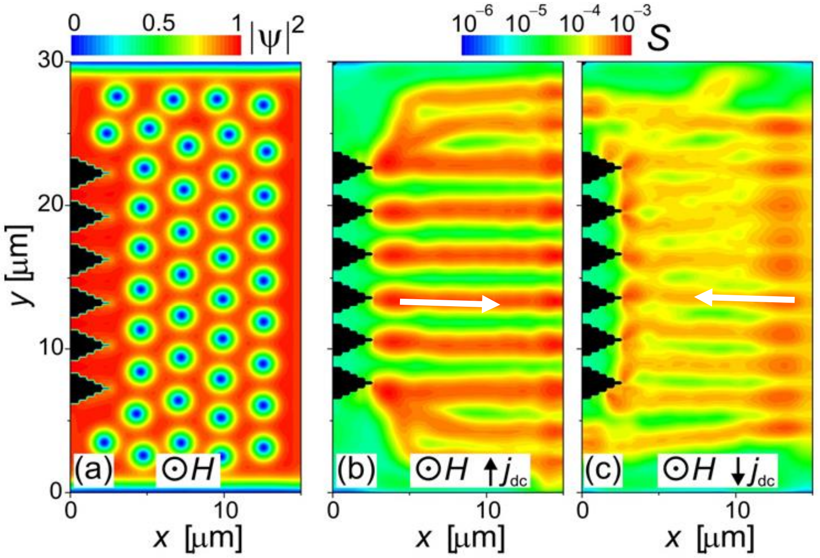
Clem *et al.*, Phys. Rev. B **84**, 174510 (2011)

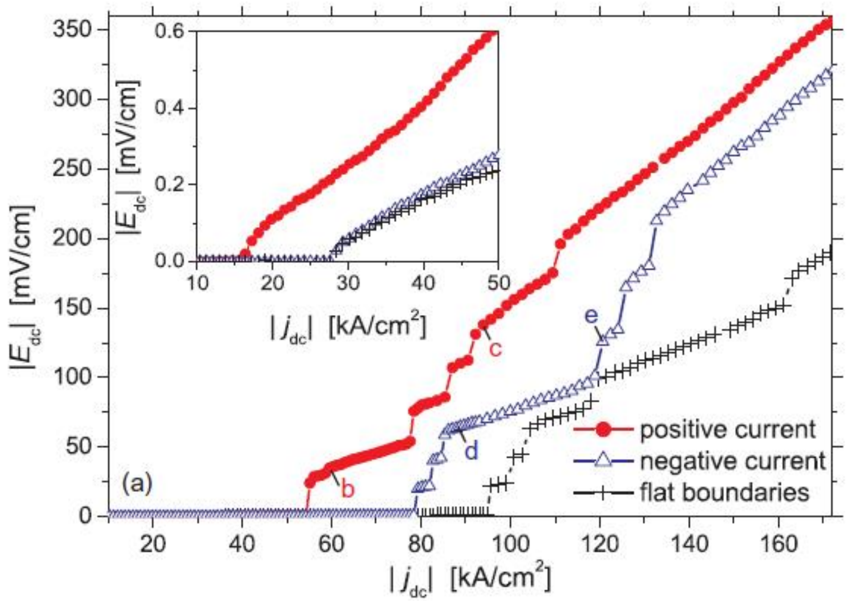
Surface indentations



Cerbu *et al*. New J. Phys. **15**, 063022 (2013)

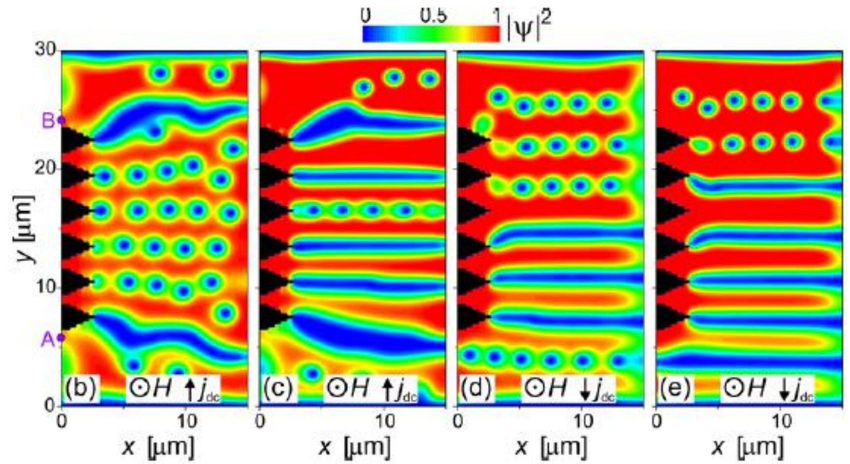
Surface indentations





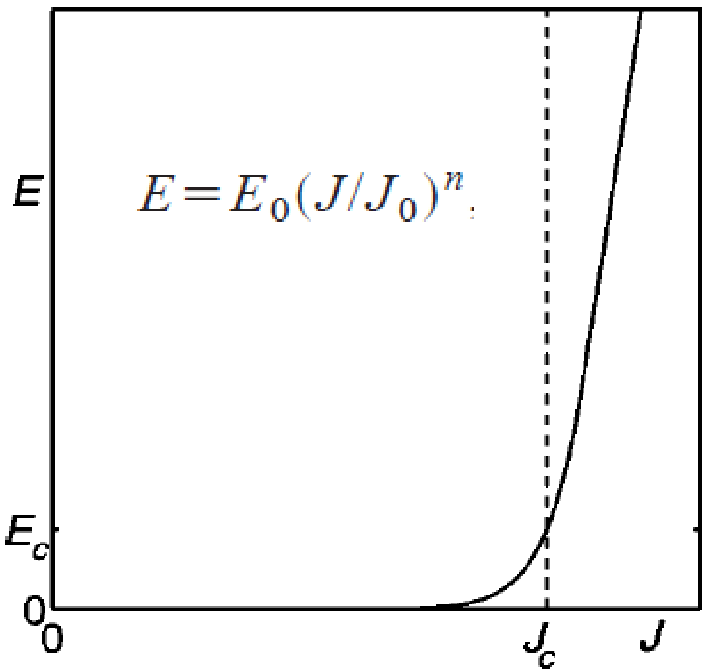
The onset of the resistive regime is mainly determined by the properties of the 'inlet' boundary of the strip.

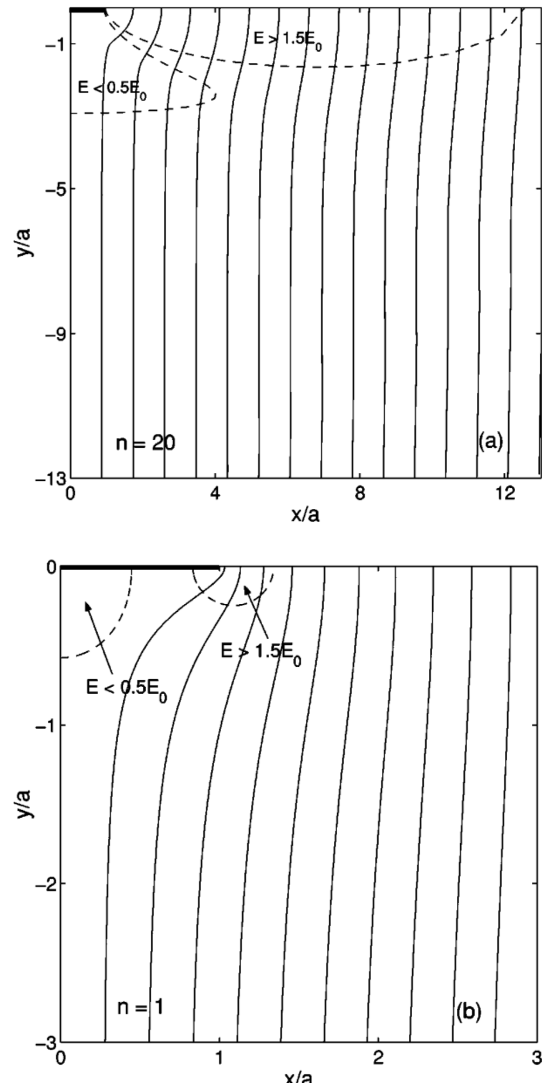
The effect due to patterning of the 'outlet' boundary facilitates the formation of PSLs



Cerbu *et al*. New J. Phys. **15**, 063022 (2013)

High field behavior



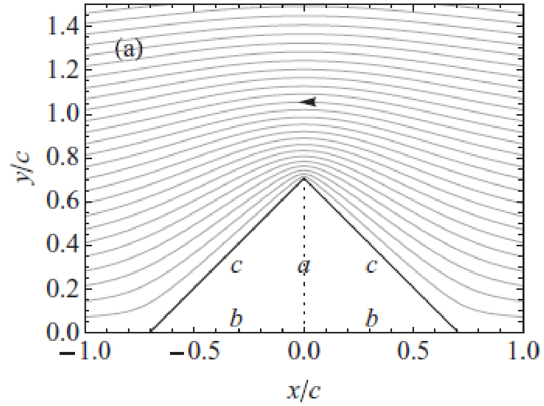


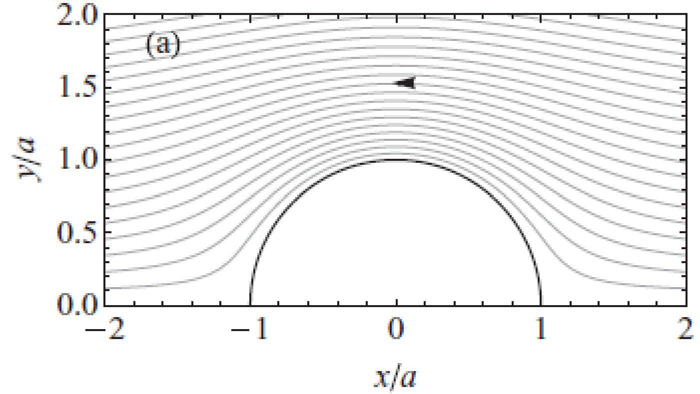
$$L_\perp \sim an$$

$$L_\parallel \sim a\sqrt{n} \gg a$$

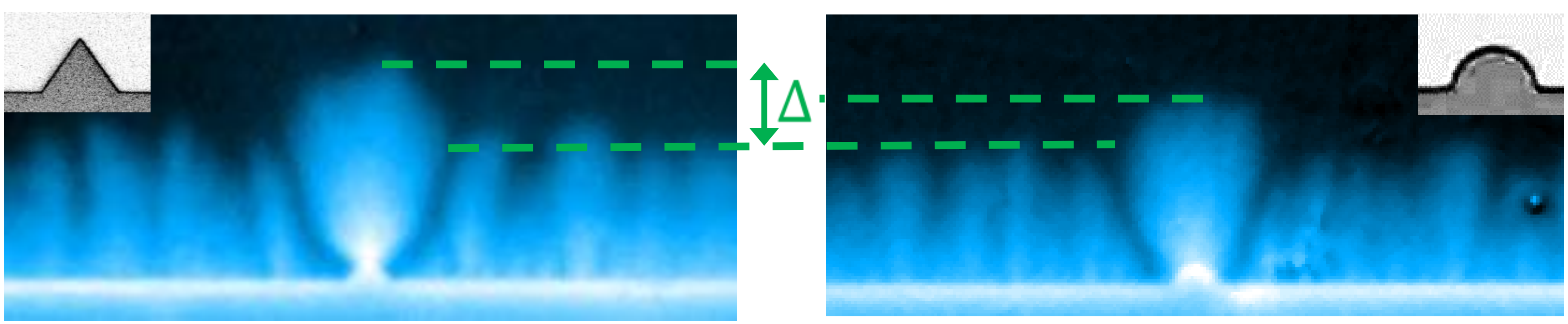
M. Friesen and A. Gurevich, Phys. Rev. B **63**, 064521 (2001)

Surface indentations (many vortices)





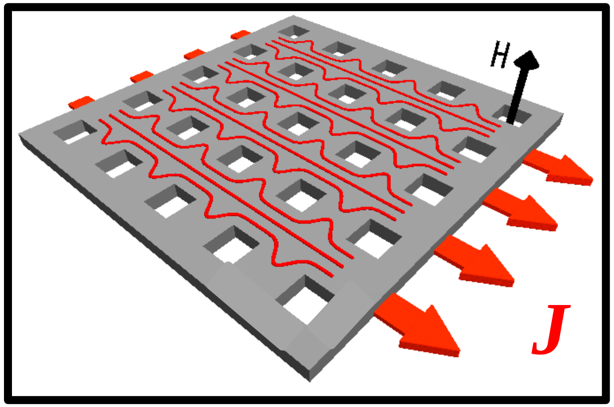
J. I. Vestgården *et al.*, PRB 76, 174509 (2007) → Meissner currents concentrate in front of the indentation where their density reaches *jc* and hence lead to even deeper flux penetration. This is why the flux front near the indentation advances faster than in the rest of the film.

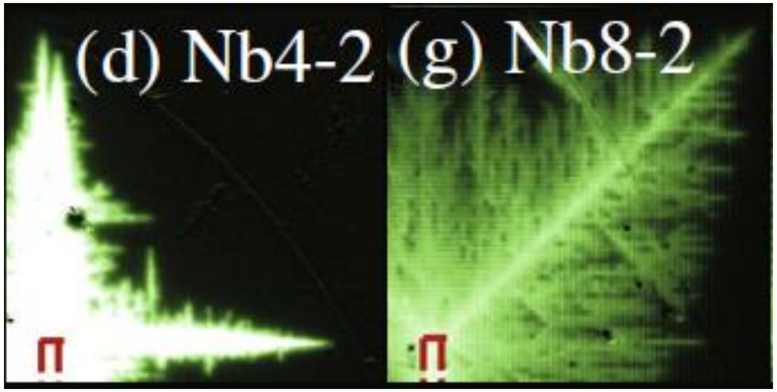


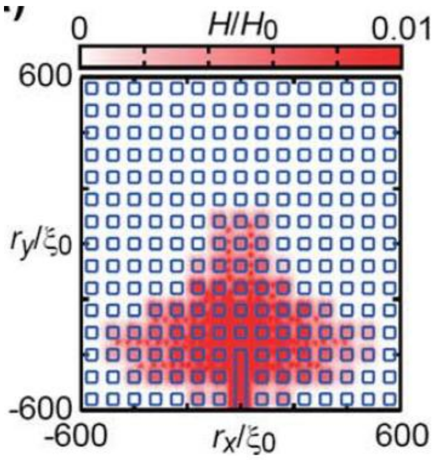
Nb, H=2 mT, T=4K

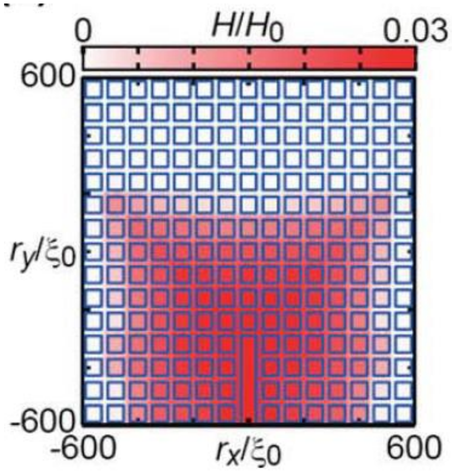
Brisbois *et al.*, unpublished

CC in nanostructured superconductors





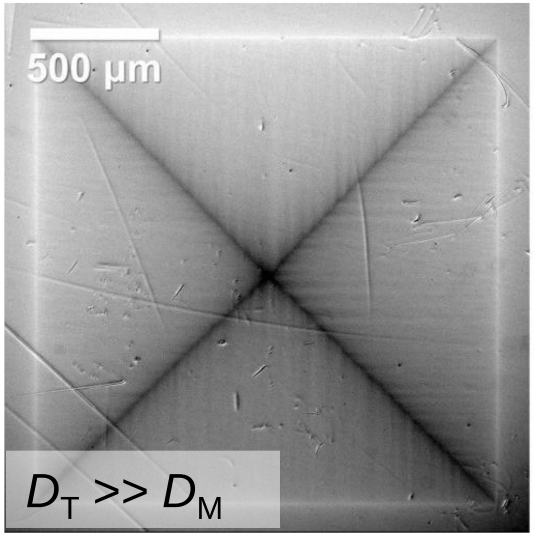


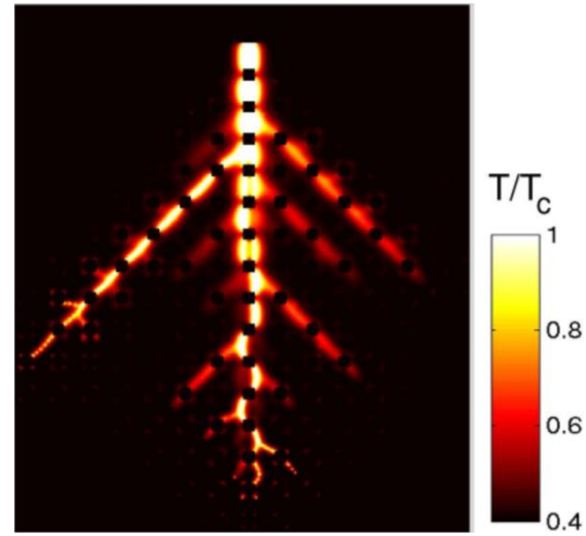


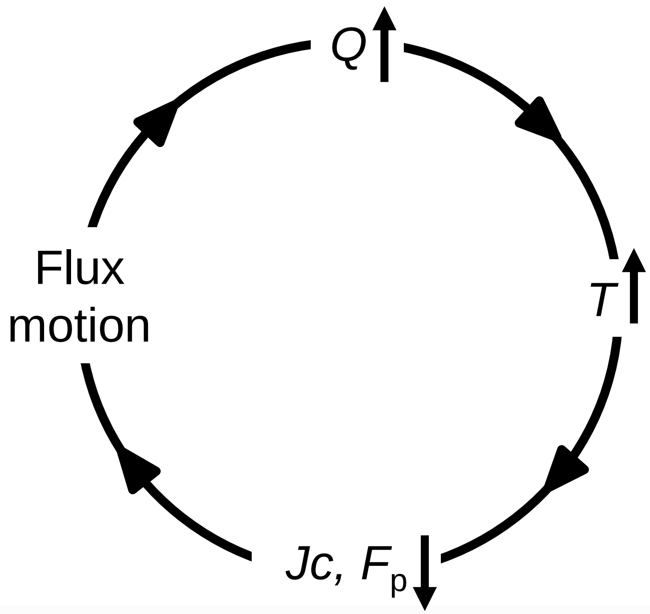
Nakai & Machida Physica C **470** 1148 (2010)

Tsuchiya *et al.* Physica C **470** S788 (2010)

Magnetic flux avalanches







Adiabatic conditions, $\Delta T = Q/C(\mathrm{T})$

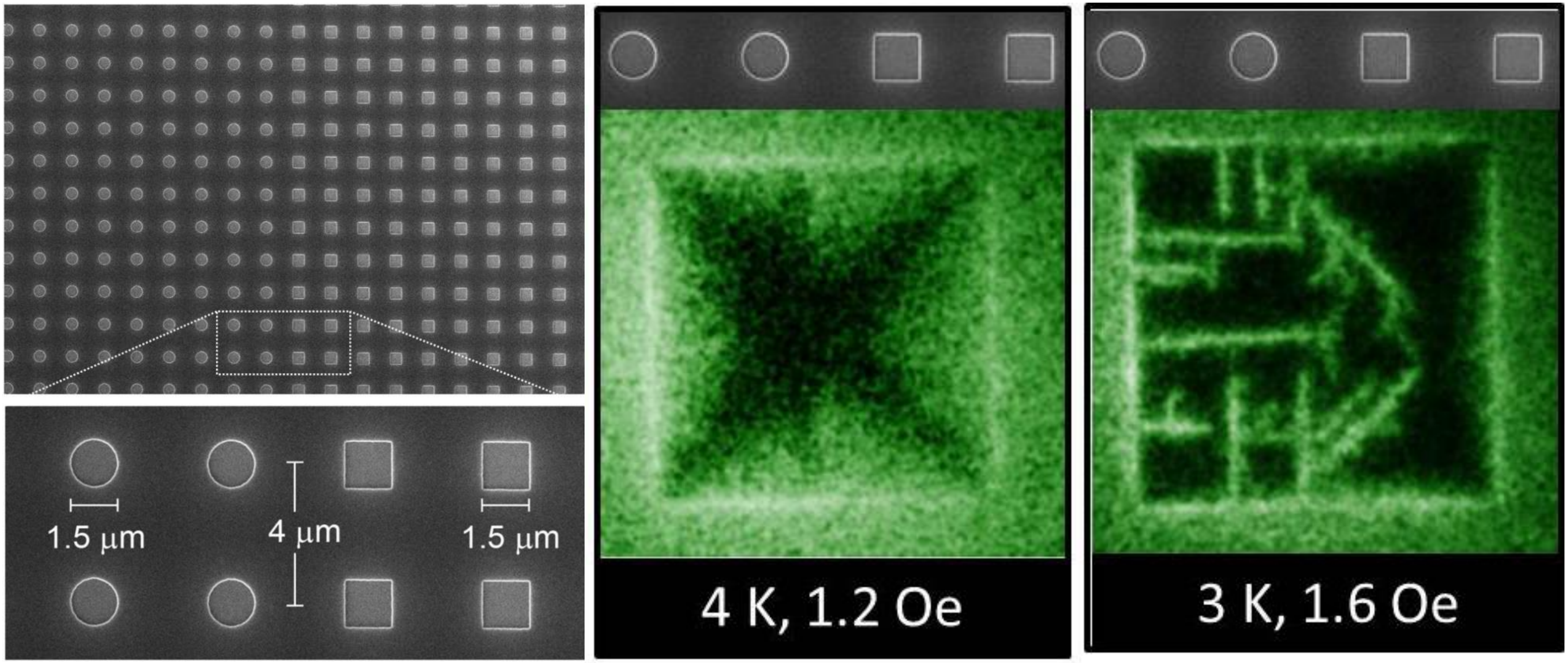
v>10 km/s > sound velocity 3 km/s

$v_{Abrikosov} << 1$ *km/ s*

$v_{kinematics} \sim 1\text{-}10$ *km/ s*

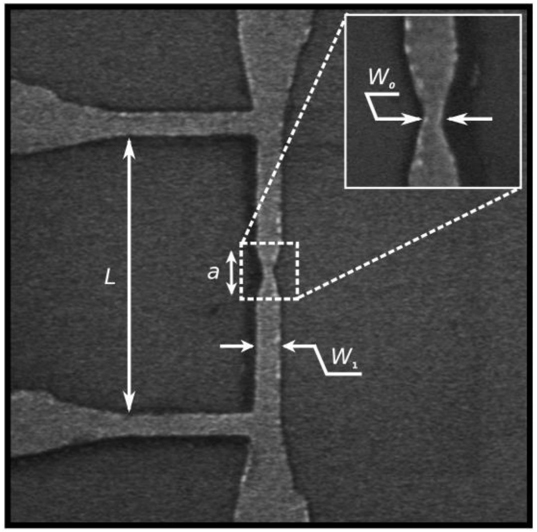
R. G. Mints and A. L. Rakhmanov, *Rev. Mod. Phys.* **53**, 551 (1981)

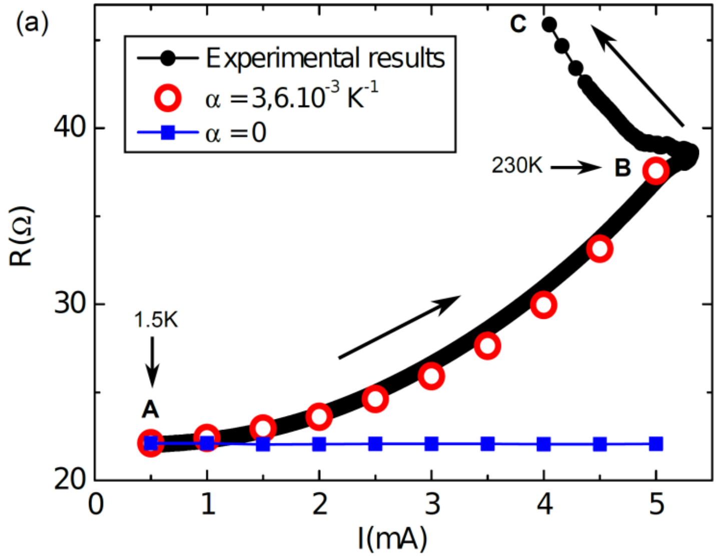
Magnetic flux avalanches

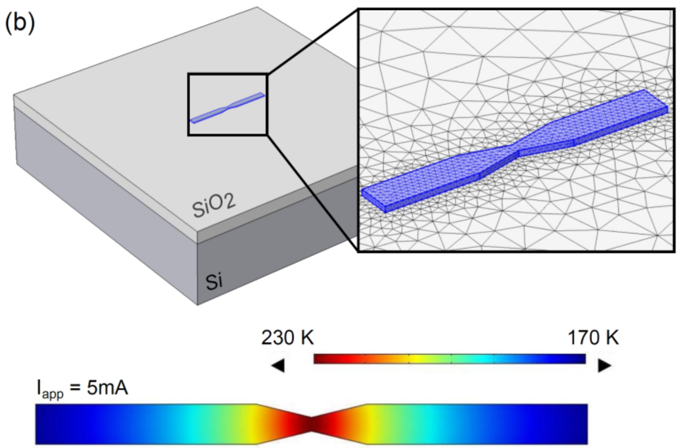


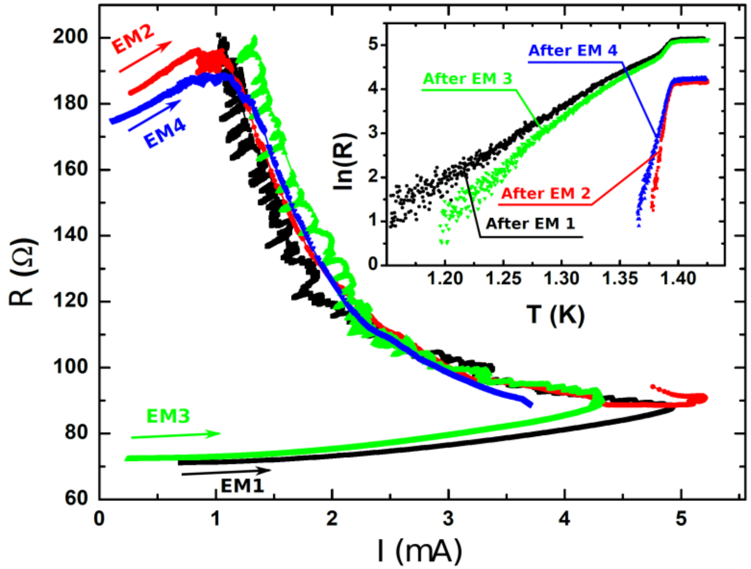
Motta *et al.* Phys. Rev. B 89, 134508 (2014)

Electromigration









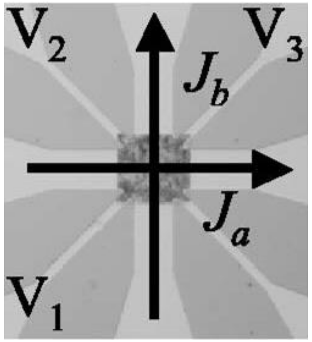
Baumans *et al.* unpublished

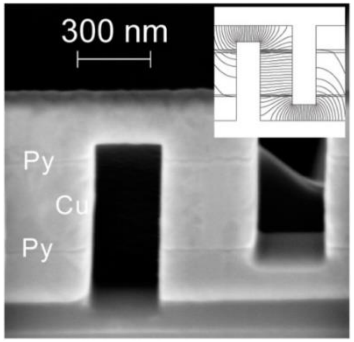
Conclusion

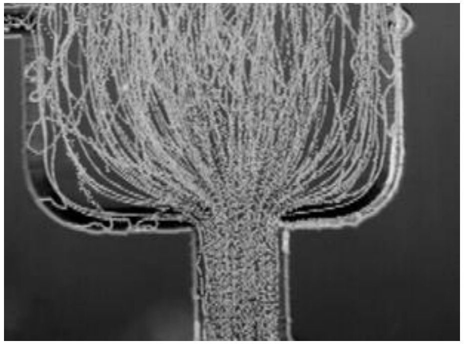
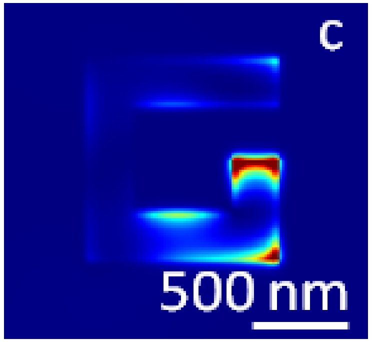
In the same way that magnetic field lines lead to demagnetization effects, deformation of current stream lines lead to current crowding.

This effect have important consequences on

- the resistance calculation in normal metals
- V(I) characteristics in superconductors
- unwanted ratchet signal
- hot spots (joule heating)
- reduction of the critical current





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