Vortices in superconductors: III. Nanostructured SC films

François Peeters

Outline

1. Manipulating vortices: fluxonic cellular automata
3. Vortex lattices: Novel commensurability effects.
4. Critical parameter of perforated SC films
   - Influence of temperature
   - Influence of material properties
5. Ordered vortex structures in superconducting films with arrays of blind holes and pillars
6. Interaction of a single vortex with a circular cavity in a superconducting film

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• Vortex structure of a perforated SC square with two/four antidots
  • symmetry supported vortex states
  • H-T boundary and comparison with experiment

Considered geometry

Reference sample  2 antidots  4 antidots

The free energy and the magnetization

Reference sample

Two-antidot sample

Vortex configurations
The free energy and the magnetization

Reference sample

Four-antidot sample

Stability of the vortex states

Vortex structure of a perforated SC square with two/four antidots

- symmetry supported vortex states
- H-T boundary and comparison with experiment

- SC square with 2x2 blind holes as a logic device
  - basic principles
  - possible experiment

Cellular automata


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Switching

a=3.0 μm
a_0=0.35 μm
a_i=0.85 μm
d=150 nm
d_i=15 nm
R=0.6 μm
ξ(0)=120 nm
ξ(0)=140 nm

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The switching process “1” to “0”

Majority gate

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Pinning of vortices

- Array of pinning centers in a superconducting film.
- Vortex lattices.

Vortices in applied current

Lorentz force pushes vortices - dissipation of energy - resistance - increase of temperature.
Pinning of vortex lattice

- Mixed state: the resistance is only zero if the vortices do not move, i.e. are pinned
  
  Current + B-field (from vortices) $\rightarrow$ Lorenz force on vortices $\rightarrow$ flow of normal electrons (in vortex core) $\rightarrow$ resistance
  
- $H_{irr}$: irreversibility field
  
  when $H > H_{irr}$ (or $J > J_c$): vortices start to move and a finite resistance develops
  
- $J_c$: critical current

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Antidot lattice


AFM picture of a [Pb(100Å)Ge(50Å)]$_2$ multilayer with a triangular lattice of submicron antidots (period $d = 1\mu m$, radius $r = 0.22\mu m$).
Arrays of antidots – matching effects

Stable vortex configurations at matching fields lead to enhancement of the critical current


Pinning of vortices

O. Daldini et al., PRL 32 (1974) 218
A.F. Hebard et al., IEEE T. Magn. 13 (1977) 589
B. Pannetier et al., PRL 53 (1984) 1845
M. Baert et al., PRL 74 (1995) 3269
U. Welp et al., PRB 66 (2002) 212507
PS nanospheres
AAO (d=100nm)
AAO (d=50nm)
**Vortex lattice**

- **Abrikosov lattice in type II (hard) superconductors**
  A.A. Abrikosov, Soviet Phys. JETP 5, 1174 (1957)
- **First experimental observation**: through neutron diffraction
  D. Cribier et al, Phys. Lett. 9, 106 (1964)
- **Earliest visualization**: through Bitter patterning

**Wigner crystal**

**Ground state of the electron gas in metals**

*E. Wigner, Physical Review 46, 1002 (1934)*

If the electrons had no kinetic energy, they would settle in configurations which correspond to the absolute minima of the potential energy. These are close-packed lattice configurations, with energies very near to that of the body-centered lattice....

- 2D electrons on liquid helium
  C.C. Grimes and G. Adams, PRL 42, 795 (1979)
- Colloidal particles on surfaces or interfaces
Commensurability effects

Add an underlying lattice structure which is different

Nanostructuring of the B-field

V.V. Moshchalkov et al.,

Nanostructuring of the SC

M.J. VanAlsen et al.,

Integer and half-integer matching \((H_a=H_n)\)
small size of the antidots

K. Harada et al.,
Science 274, 1167 (1996)
Commensurability effects


MD-simulations: London approximation

Influence of the parameters

R-large: \( N_h = n \), no interstitial vortices
R-small: \( N_h = 1, n-1 \) interstitial vortices

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The phase diagram at $H=H_4$

$n_s = R/2\xi(T)$

G.S. Mkrtchyan and V.V. Schmidt, Sov. Phys. JETP 34, 195 (1972).
Influence of geometrical parameters (half-integer matching fields)

\[ H_a = \frac{H}{2} \]

\[ d / \xi = 0.1, \quad \kappa = 0.45 \]

Influence of temperature

Multi- to giant vortex transition at \( H_a = \frac{H}{4} \)

Multi- to vortex-antivortex transition at \( H_a = \frac{H}{2} \)

\[ P_b, \quad W = 1 \mu m, \quad R = 0.2 \mu m, \quad d = 0.02 \mu m, \quad \kappa = 0.45 \]
How to measure the VAV state?

Micro-Hall probe simulation
Magnetization calculated as expelled flux:
\[ 4M = \langle h \rangle - H \]
over 1µm x 1µm effective area.

\[ M = \frac{\langle h \rangle - H}{1\mu m \times 1\mu m \text{ effective area.}} \]

W=1µm, R=0.2µm, d=0.02µm, \( \kappa = 0.45 \), \( T/T_c = 0.96 \), \( H=H_{9/2} \)

Evolution of the vortex structure as a function of current

Magnetization as a function of applied current

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Vortex structure – influence of the GL parameter

W=6\xi, R=1.2\xi.

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The phase diagram for two different $\kappa$

$\kappa^*=0.1$

$\kappa^*=10$

Influence of current

$H=H_1$

$J_c$ : motion of vortices out of anti-dot

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Influence of current: *interstitial vortices*

- $H = H_2$
- $H = H_3$
- $H = H_4$

$J_c$: motion of interstitial vortices

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Influence of current *giant vortices*

- $H = H_4$

- $R$: $1 \xi \rightarrow 1.3 \xi$
- $n_0$: $1 \rightarrow 2$
- Interstitial: MVS $\rightarrow$ GVS

- Current induced GVS $\rightarrow$ MVS transition
- $\rightarrow$ no MVS $\rightarrow$ GVS transition
- $n_0$, independent of $j$

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Critical current (the influence of antidot density)

The critical current has pronounced maxima at integer $H_1, H_2, H_3$ and at some fractional matching fields, confirming that the antidot array provides a strong pinning potential for the vortices.

Due to the appearance of interstitial vortices, the critical current drops sharply immediately after the first matching field.

Small inter-hole distances affect the hole occupation number – additional vortices outside $H_1$ are still captured by the holes – and, consequently, the critical current in this case is higher for smaller periodicity.

The critical current of the superconducting film with circular holes for two values of the lattice period $W$.

The critical current – influence of the parameters

Critical current (the influence of temperature)

Period: \( W = 1.5 \mu m \), antidot size: \( a = 0.5 \mu m \),
film thickness: \( d = 50 \text{nm} \), and \( \xi(0) = 40 \text{nm} \), and \( \lambda(0) = 42 \text{nm} \).

\[
H = H_3, n_{\text{anti-dot}} = 2, n_{\text{interstitial}} = 1 \\
H = H_2, n_{\text{anti-dot}} = 1, n_{\text{interstitial}} = 1 \\
\rightarrow J_c(H_3) > J_c(H_2)
\]

Caging-effect

\( H - T \) phase diagram – the experiment

Critical field of Pb film with an array of antidots at 10\% of \( R_n \) (period 1 \( \text{mm} \), size 0.4 \( \text{mkm} \)).


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Vortex structures in superconducting films with arrays of blind holes and pillars


- the vortex structure inside the cavities becomes visible (as opposed to the antidot case)

Ordered vortex configurations

The ground state vortex lattice at $H=H_2$ as a function of blind hole radius $R$ and period $W$.

Molecular dynamic simulations

Transition from shell structure to Abrikosov lattice

The ground state vortex configurations in a superconducting film (thickness $d=0.1\xi$) with a square array of blind holes (radius $R=15\xi$, period $W=32\xi$ and thickness $d_b=0.01\xi$) for $n_s=47$ (a), $n_s=50$ (b), $n_s=55$ (c), $n_s=58$ (d), $n_s=66$ (e), $n_s=69$ (f), $n_s=80$ (g), $n_s=85$ (h).

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Vortex shells outside the blind holes

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Pillars: vortex rings

Vortex structure in the pillars
Conclusions

- Two/four antidots square
  - symmetry supported vortex states
  - H-T boundary and comparison with experiment
  - Cellular automata
- New vortex lattice configurations
  - Giant interstitial vortices
  - Vortex / anti-vortex
  - Fractional matching fields: GVS + MVS (or VAV) co-exist
- Current driven GVS $\rightarrow$ MVS
- Caging effect: $J_c(H_3) > J_c(H_2)$
- Blind holes (and pillars):
  - dimer, trimer, and composite states. Ring configurations
  - Shell structure