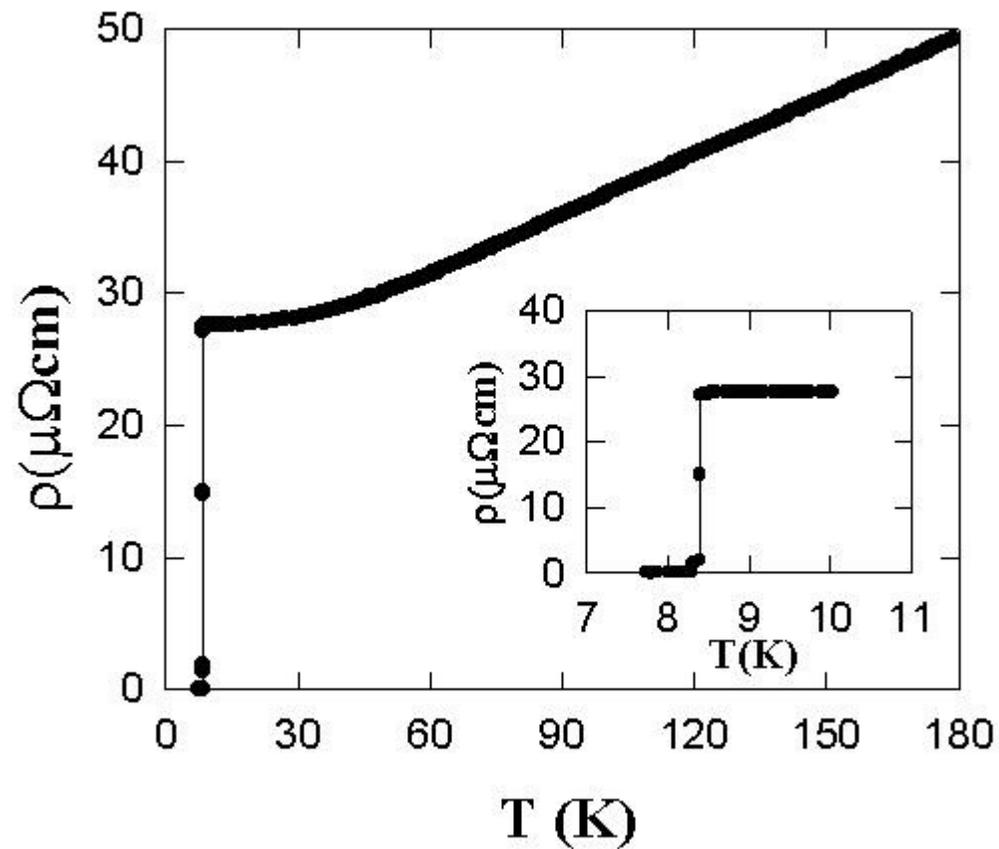


Avances en Superconductores y sus Aplicaciones

J. I. Martín

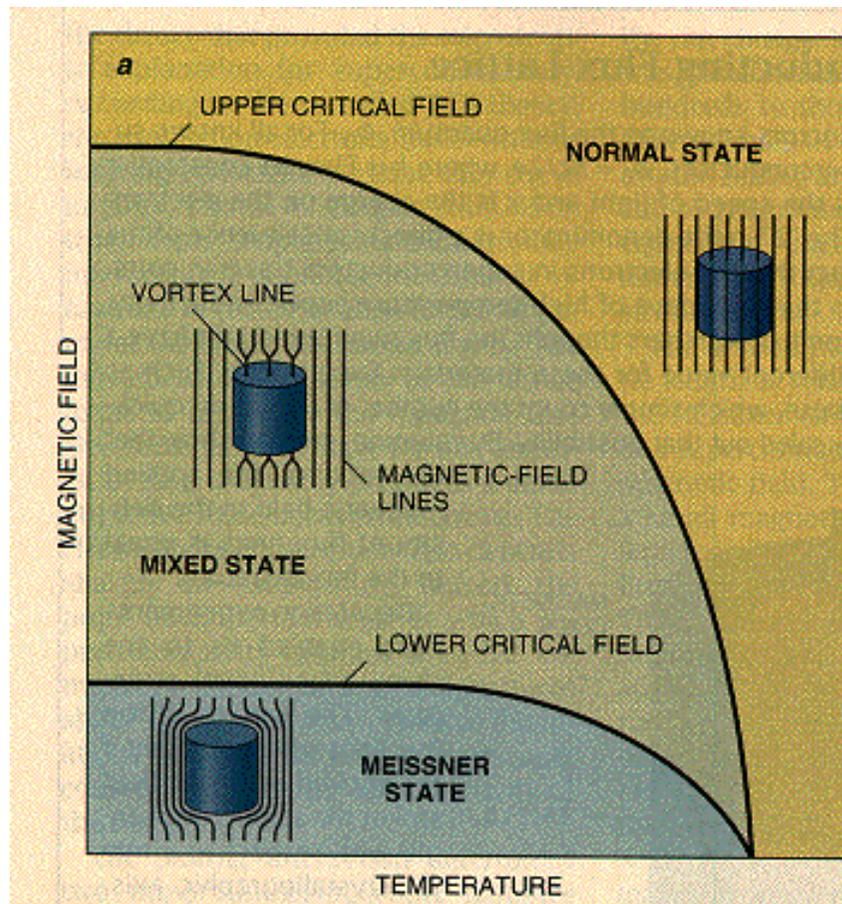
Universidad de Oviedo

Superconductividad es algo más que $R = 0$

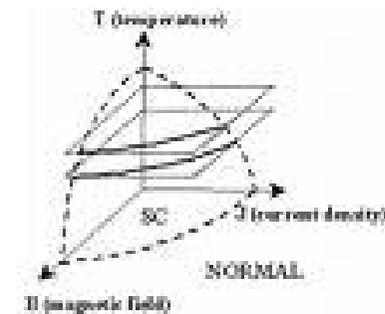


Nb

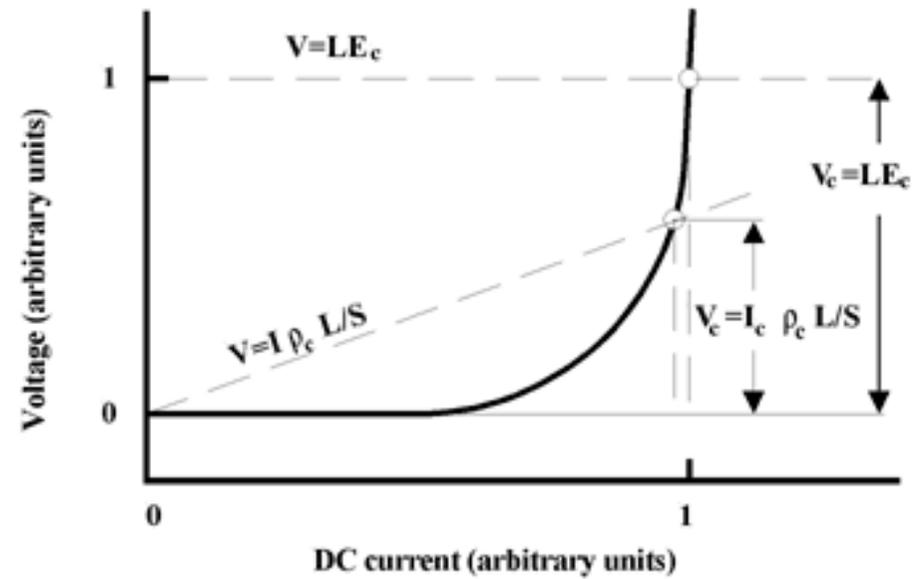
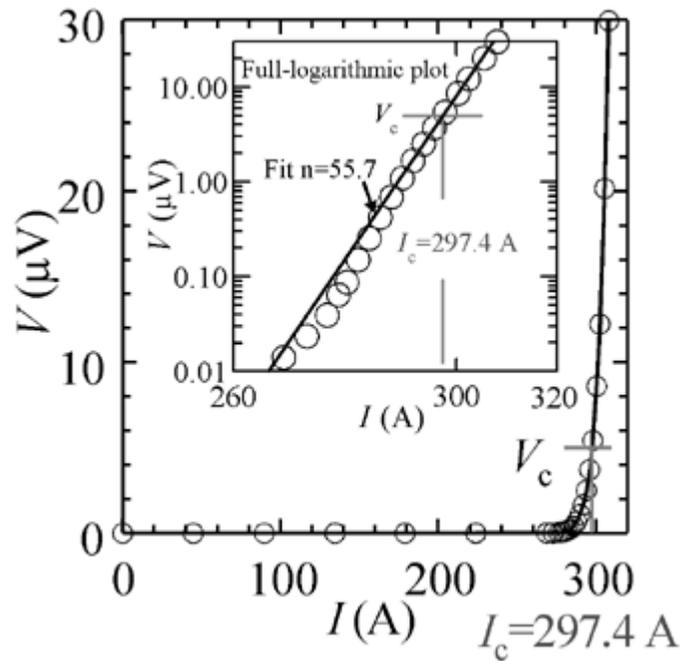
Diagrama de Fases de un superconductor Tipo II



Hay un tercer eje



Corriente crítica



Aplicaciones

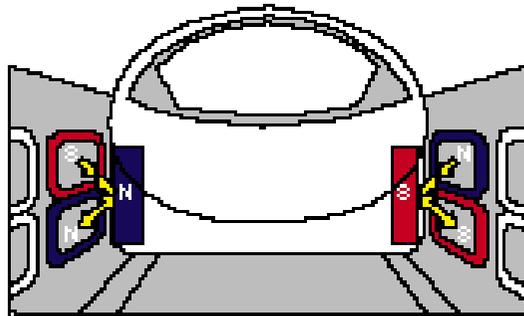
Efecto Meissner



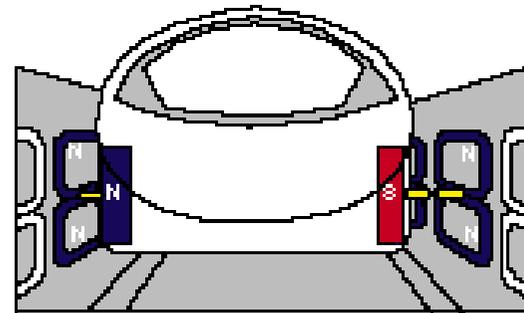
Tren MAGLEV

Aplicaciones

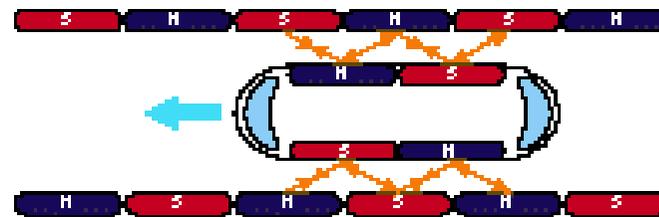
Tren MAGLEV



Levitación



Guía



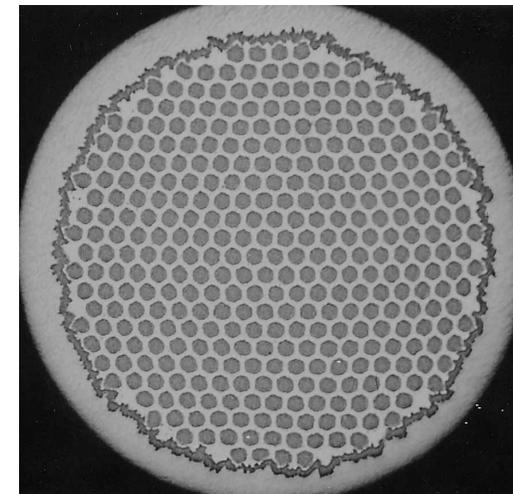
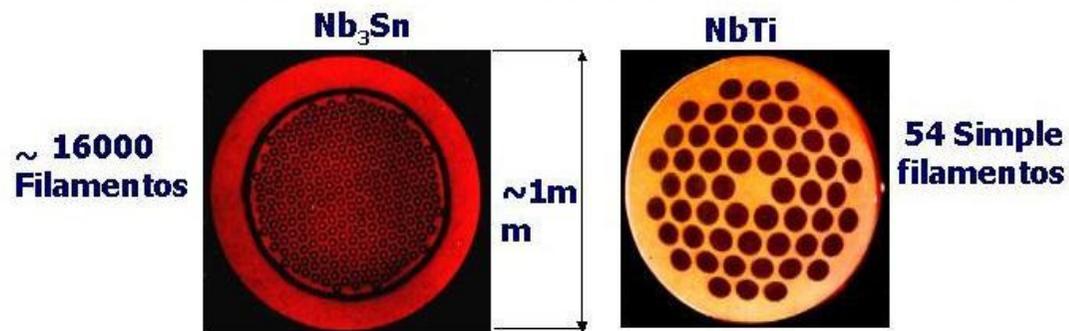
Propulsión

Efecto Meissner

Aplicaciones

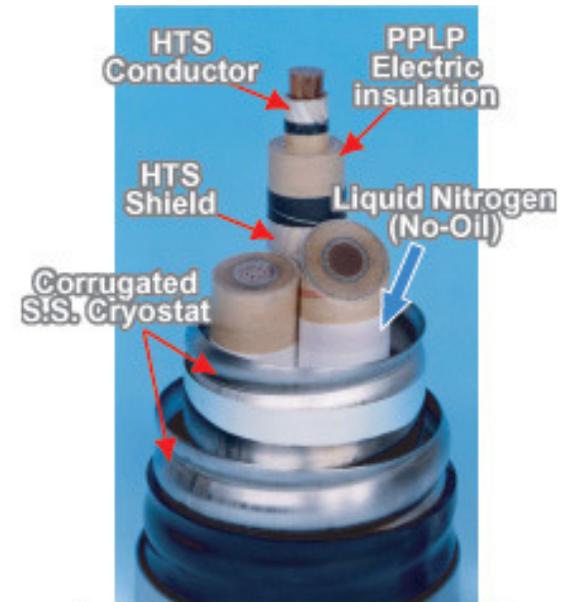
Conducción eléctrica

Dimensiones de los cables

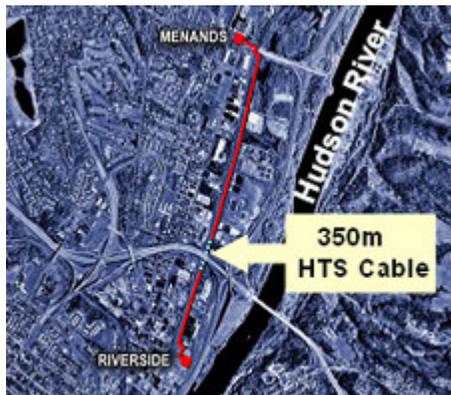


Aplicaciones

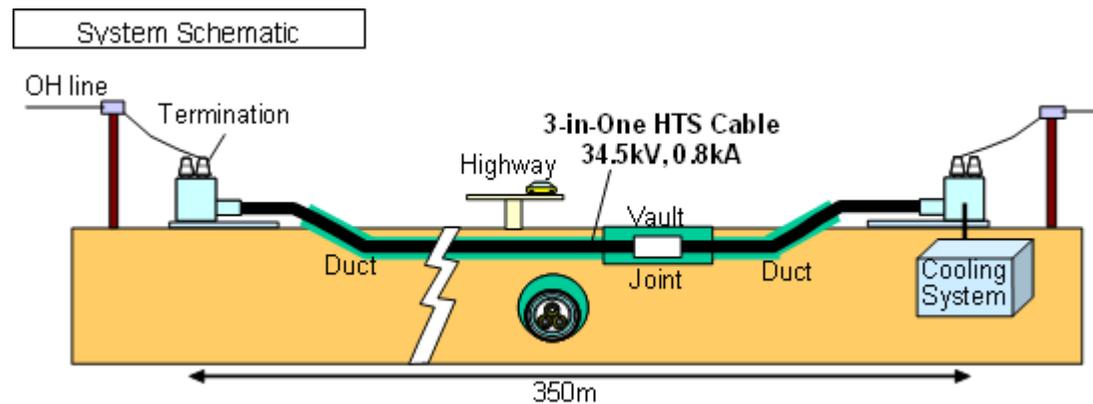
Conducción eléctrica HTS



Structure of "3-in-One" Superconducting Cable

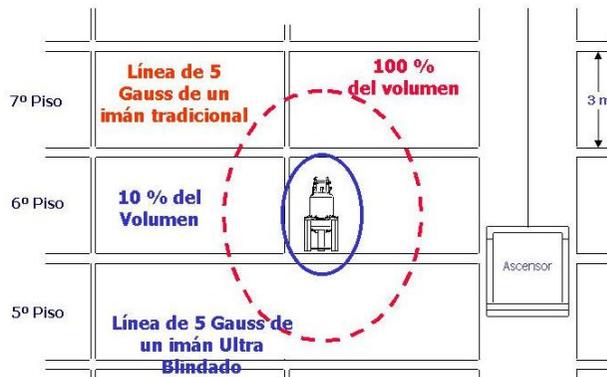
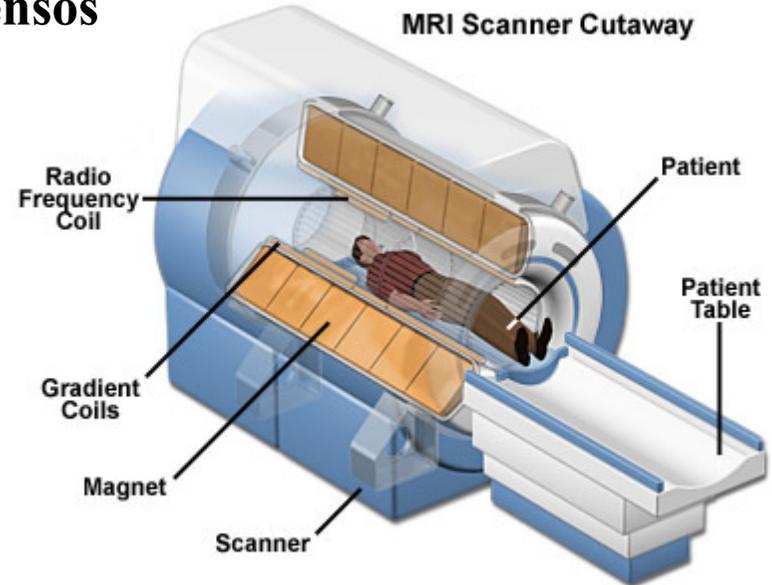
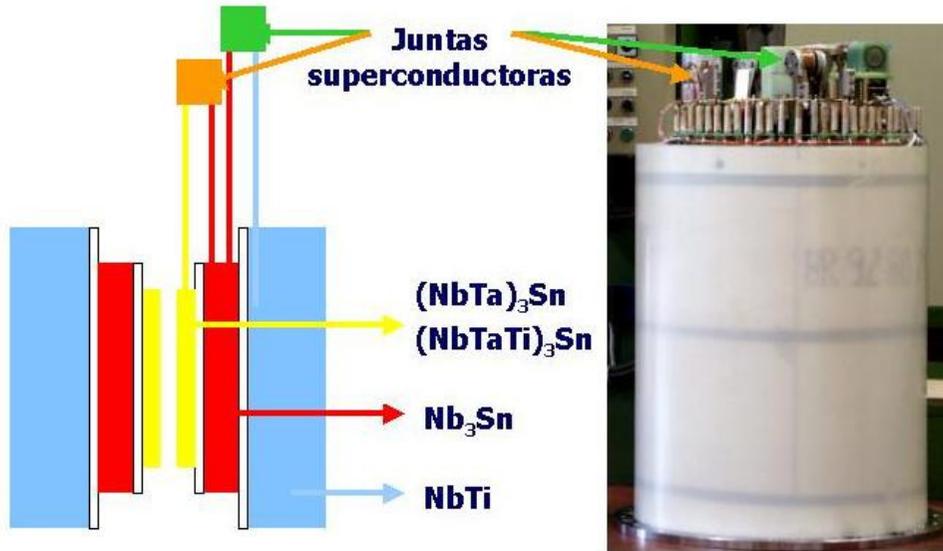


Nueva York



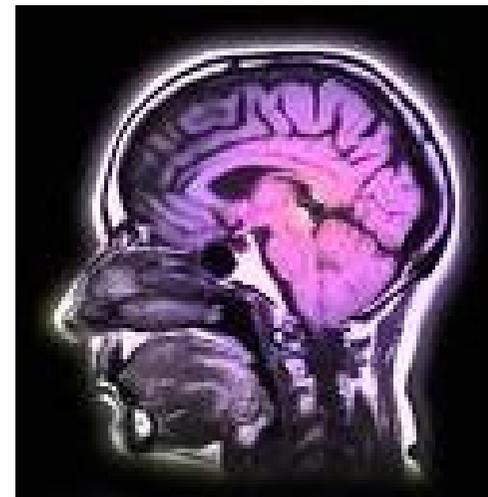
Aplicaciones

Campos magnéticos intensos



RMN

MRI



(Campos magnéticos intensos – acumuladores de energía)

Josephson Effect

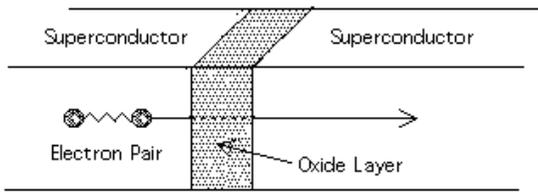
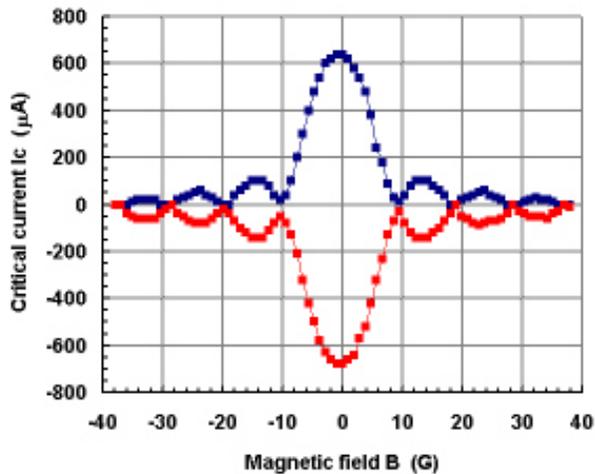
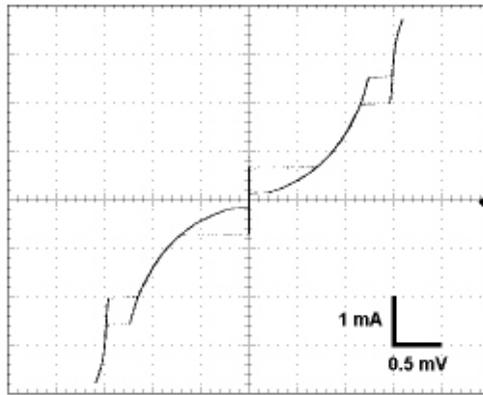


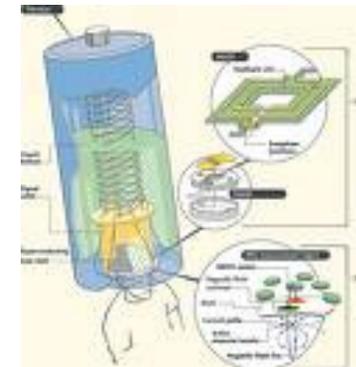
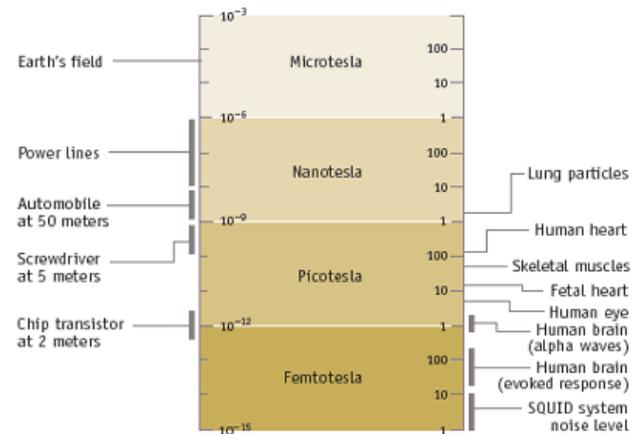
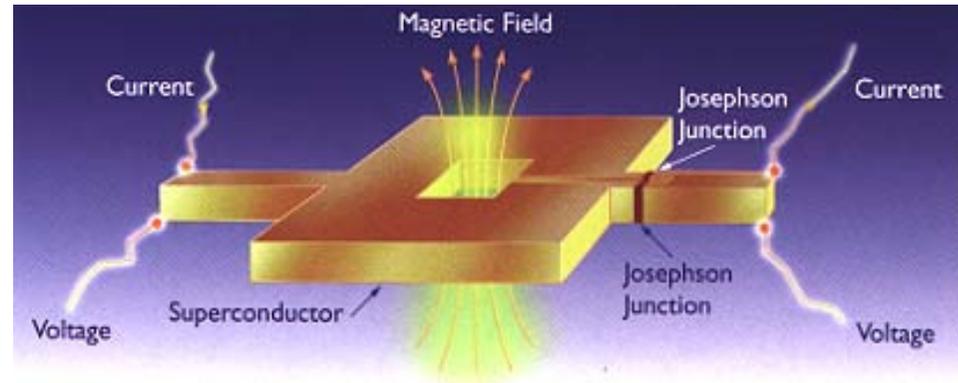
Fig. 13



Aplicaciones

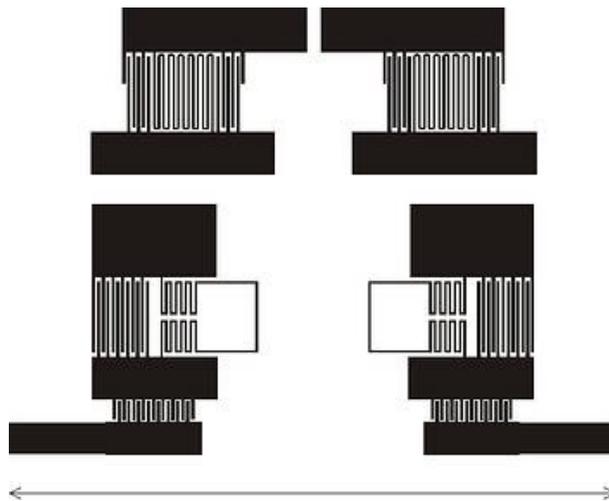
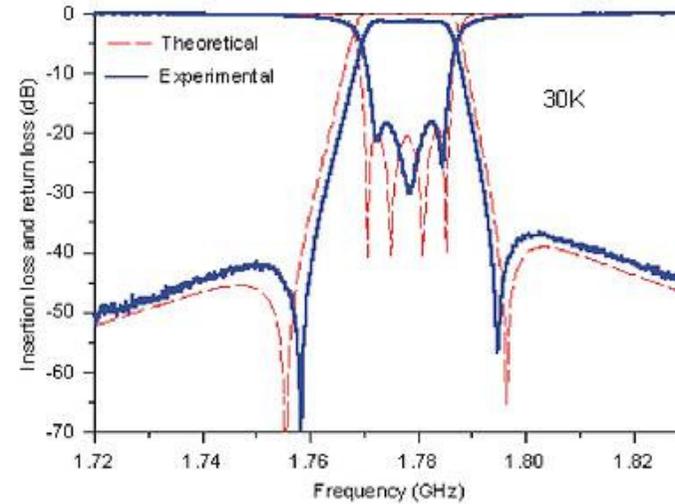
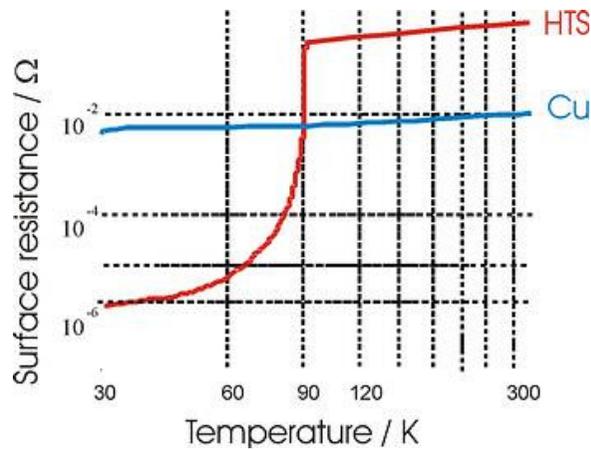
Efecto Josephson

SQUID



Aplicaciones

Filtros



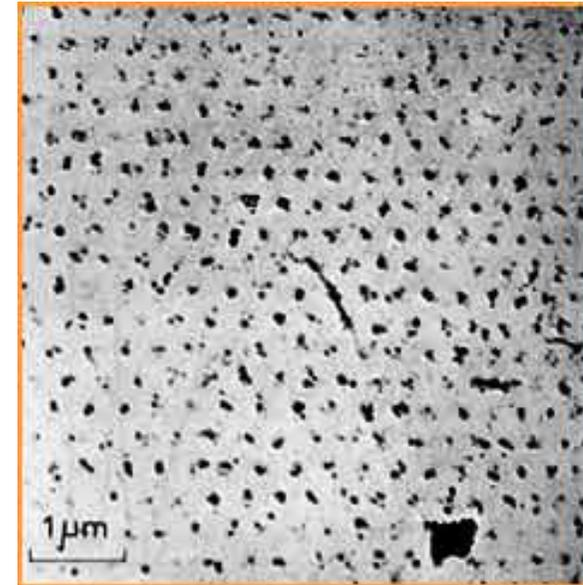
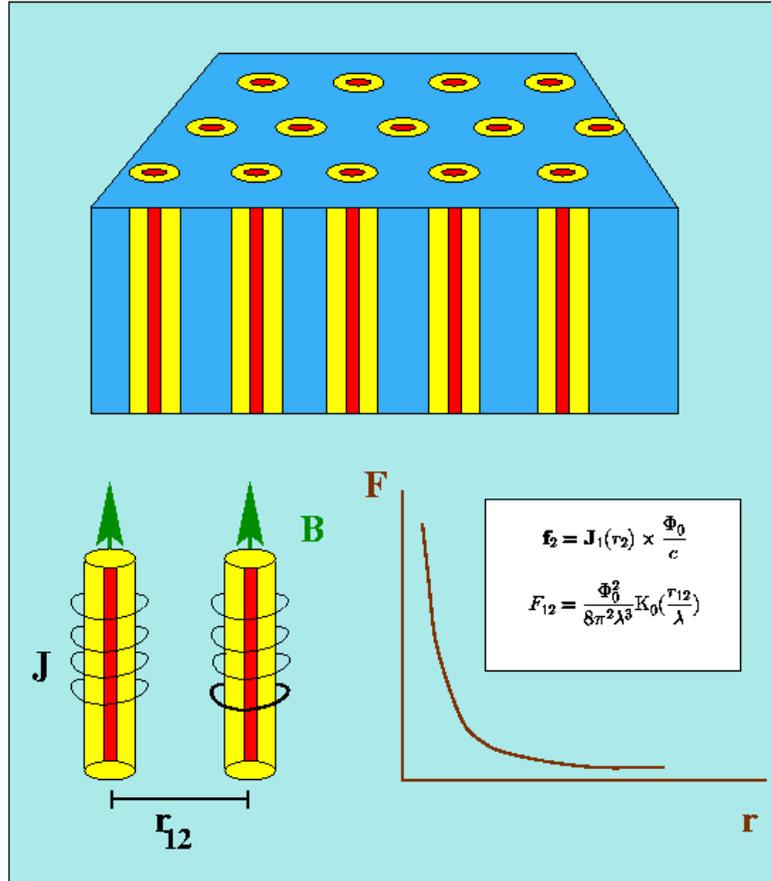
Normal: R Superc: L

$$\omega_0 = R/L$$

$$10^{11} \text{ Hz}$$

$$Q = 10^{10}$$

Red de vórtices



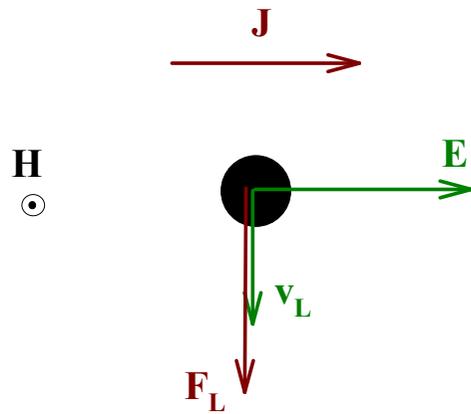
Red de vortices en Pb-4%at, 1.1 K
U. Essman and H. Trauble, 1967

Red de Abrikosov:

- hexagonal
- $a_0 = 1.075 (\Phi_0/B)^{1/2}$
- núcleo $\sim \xi$ (long. coherente)
- $J \sim \lambda$ (long. penetración)

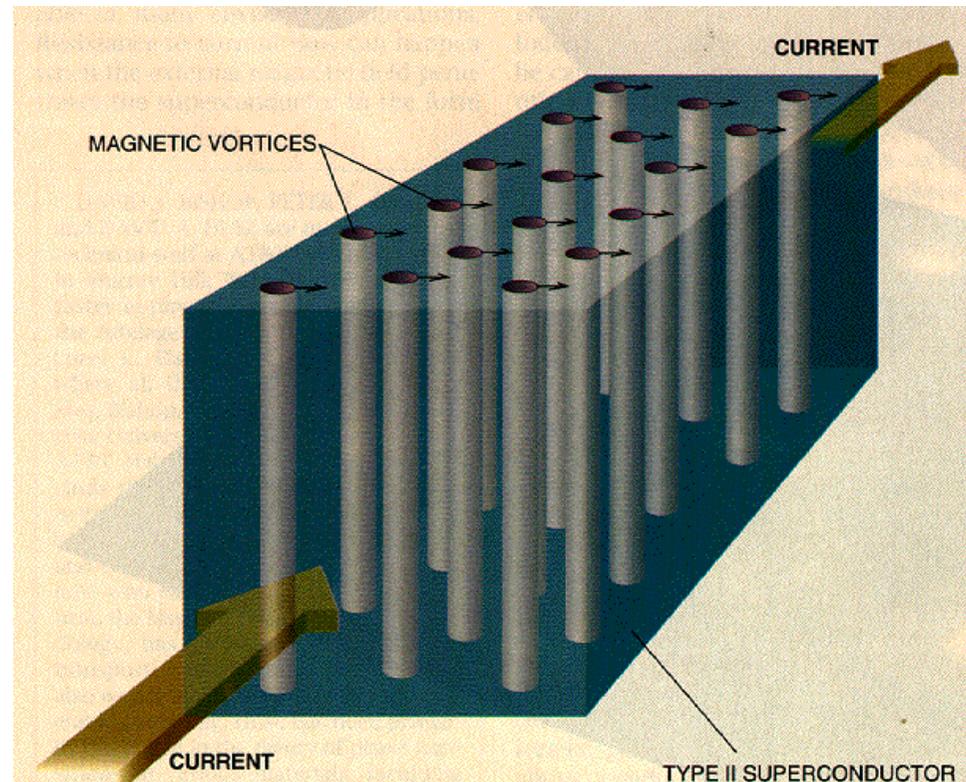
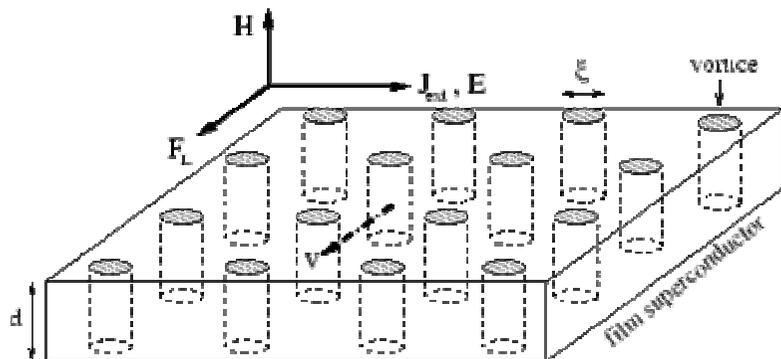
$$\Phi_0 = 2.07 \times 10^{-15} \text{ Wb}$$

Resistencia en el estado mixto: movimiento de vórtices



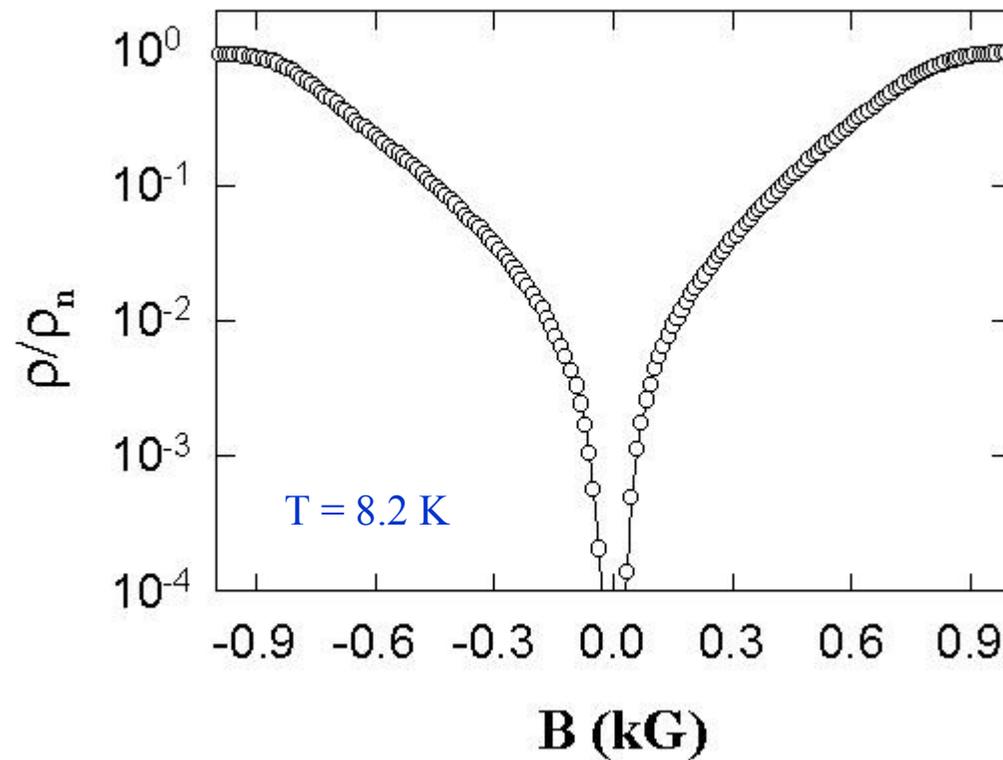
$$\mathbf{E} = -\mathbf{v}_L \times \mathbf{H} / c$$

Josephson (1965)



$$\mathbf{F}_L = \mathbf{J} \times \mu_0 \mathbf{H}$$

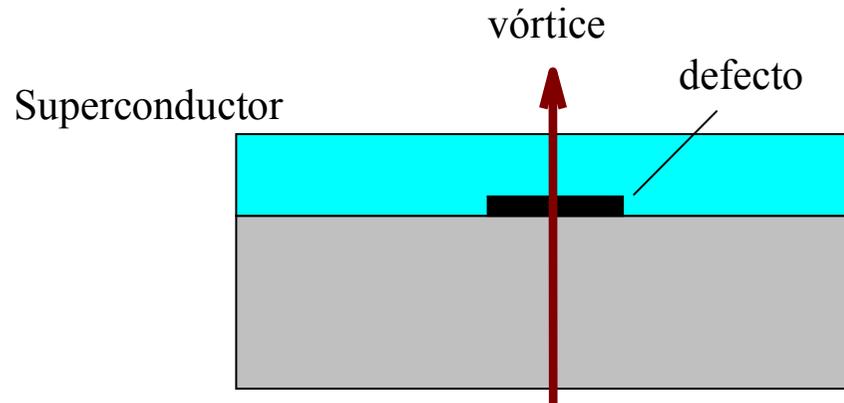
Disipación por movimiento de vórtices



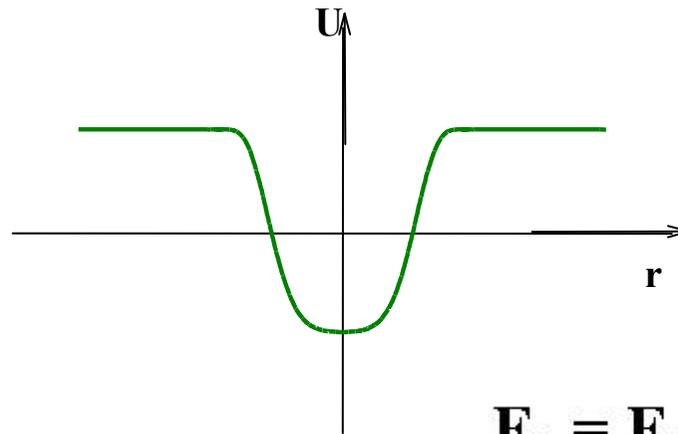
$R \neq 0$

si $J > J_C$

Anclaje de vortices por defectos



Tamaño óptimo defecto $\sim \xi \lambda$



$$\mathbf{F}_P = \mathbf{F}_L = \mathbf{J}_C \times \mu_0 \mathbf{H}$$

**PROXIMIDAD
LONGITUD
CARACTERÍSTICA**

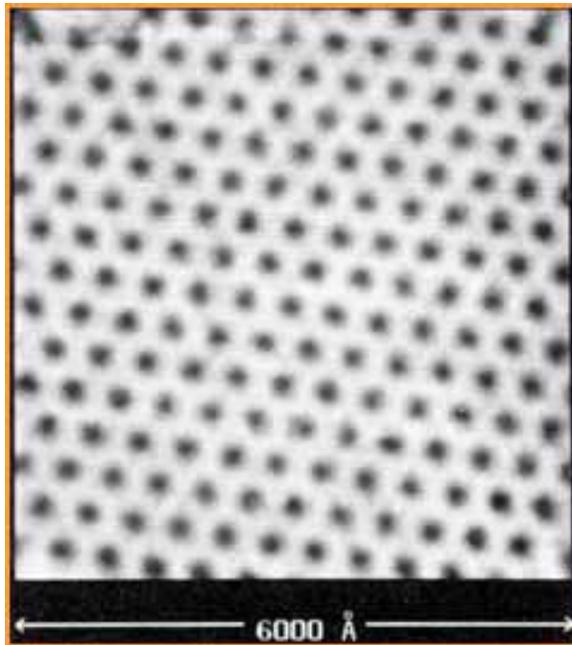
**NANOESTRUCTURAS
MAGNÉTICAS**



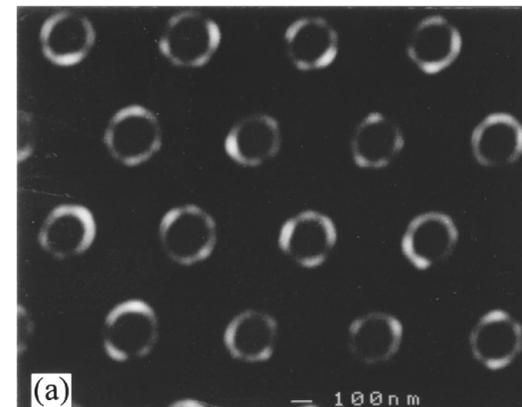
SUPERCONDUCTOR

Nanoestructuras magnéticas:

redes ordenadas de defectos submicrométricos



Red de vórtices en NbSe₂ (1.8 K, 1T)
Hess et al (1989)



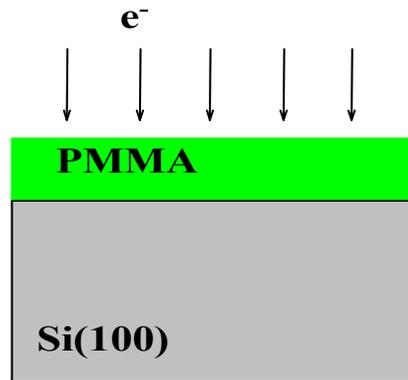
Red Triangular de puntos de Ni, $d = 410$ nm
Martín, Vélez, Nogués y Schuller, PRL (1997)

Procesos de fabricación de nanoestructuras

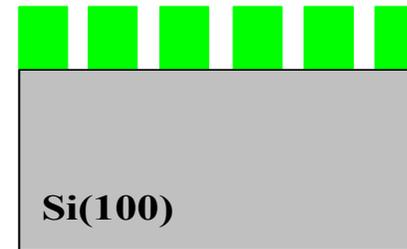
- Litografía Óptica
- Litografía por Rayos-X
- Litografía por Interferometría Láser
- Litografía por Haz de Electrones
- Litografía por Haz de Iones
- Nanoimpresión
- Litografía por Barrido de Punta (STM/AFM)
- Sistemas Autoorganizados

Litografía por haz de electrones

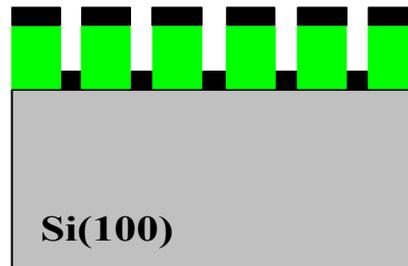
escritura con el haz de e^-



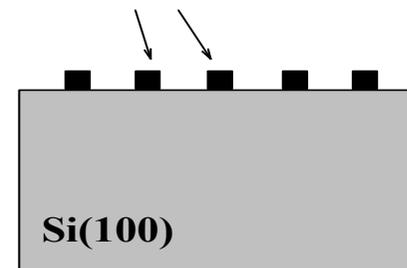
Revelado



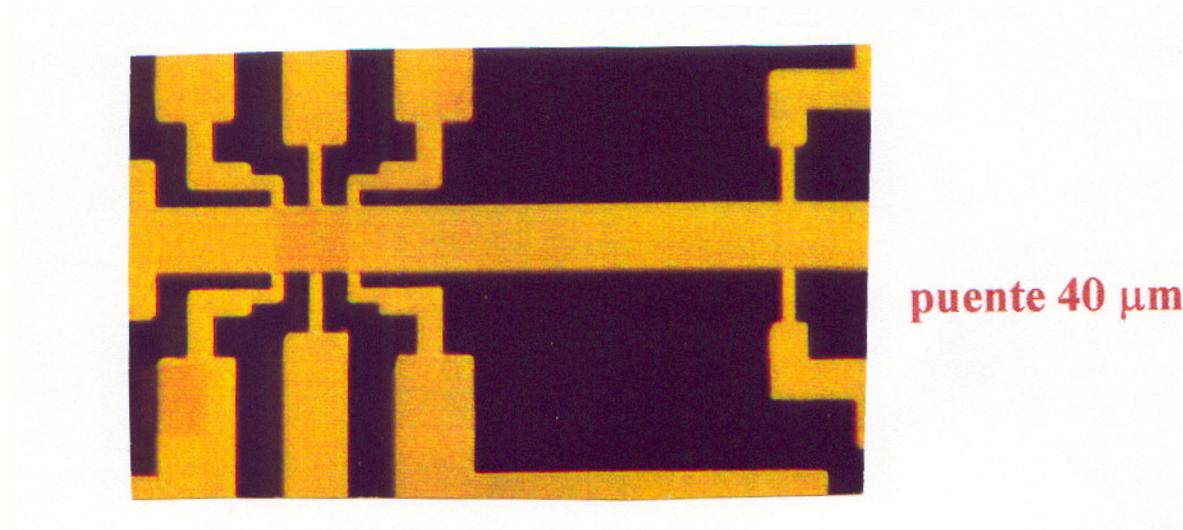
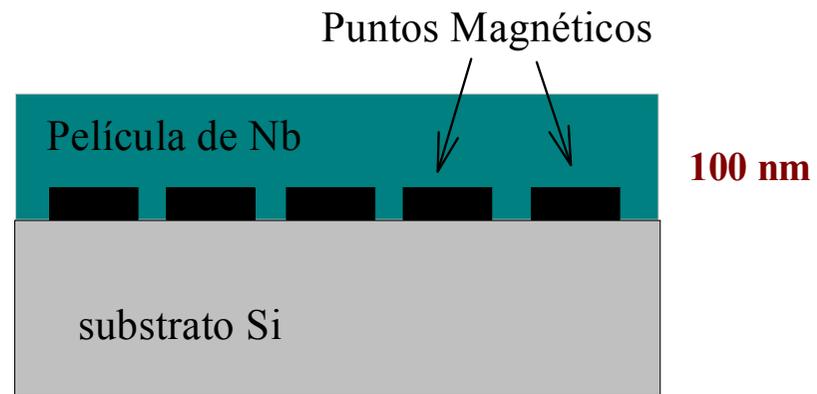
Crecimiento de Co, Ni, Fe



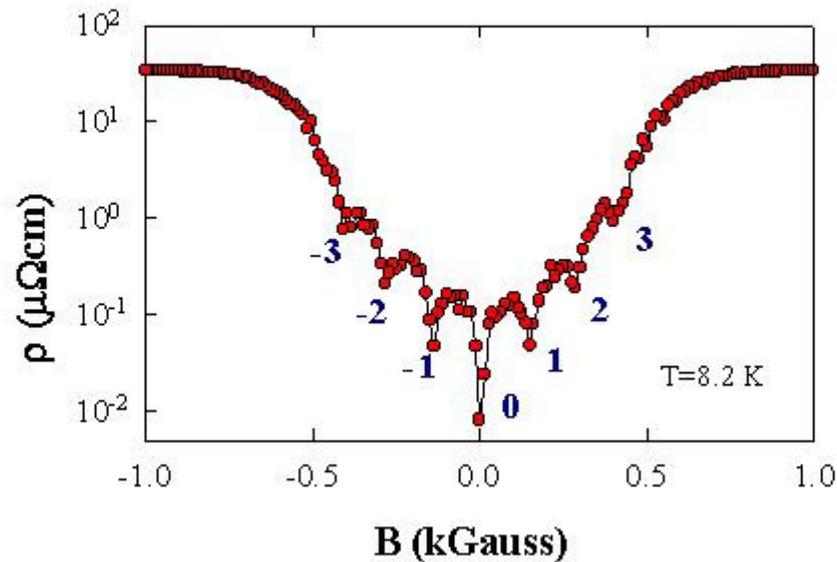
Lift-off
Puntos
Magnéticos



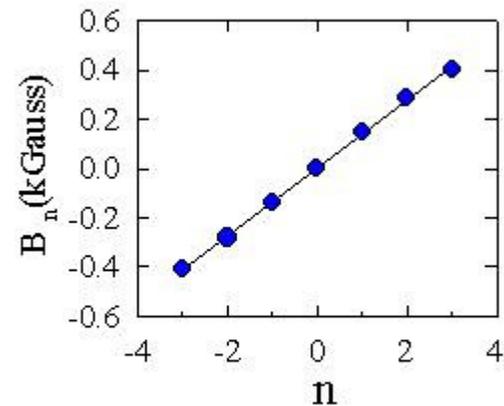
Película de Nb + Red de puntos magnéticos



Película de Nb con una red triangular de puntos de Ni



$$a_0 = 1.075 (\Phi_0/B)^{1/2}$$



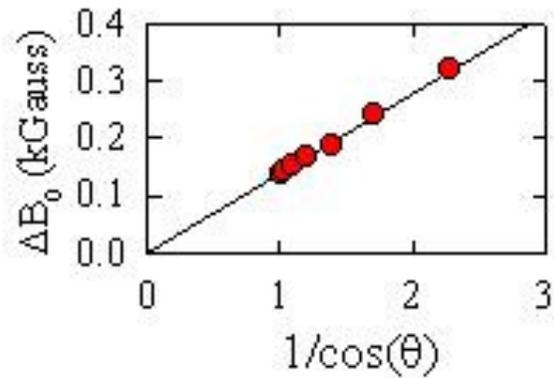
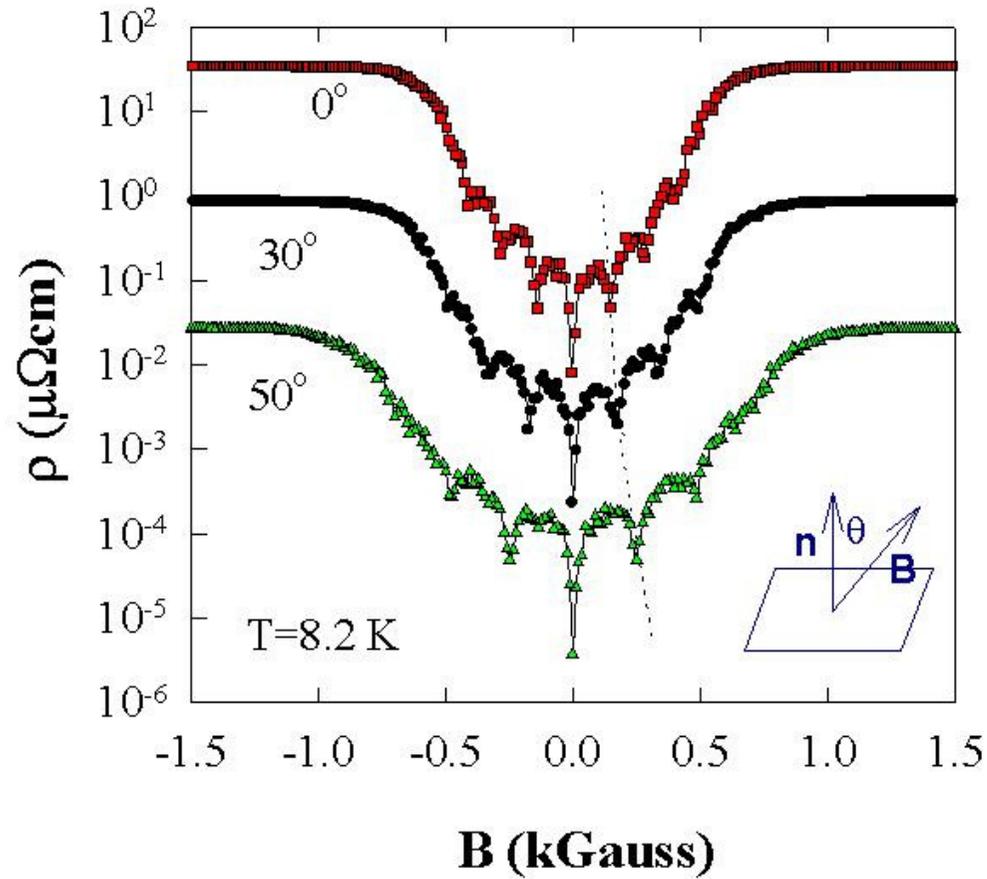
$$\Delta B_0 = 141 \pm 4\text{ G}$$

$$a_0 = 413 \pm 6\text{ nm}$$

$$d = 410 \pm 10\text{ nm}$$

Anclaje para $a_0 = d$

Martín, Vélez, Nogués y Schuller, PRL (1997)



$$\Delta B_0 = 138 \text{ G}/\cos(\theta)$$



Componente perpendicular del campo aplicado

Anclaje sincronizado en distintas geometrías: *distorsiones en la red de vórtices*

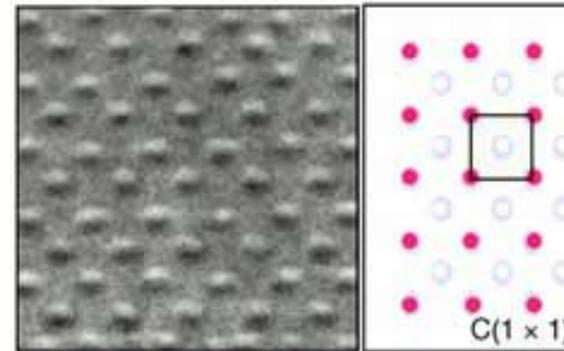
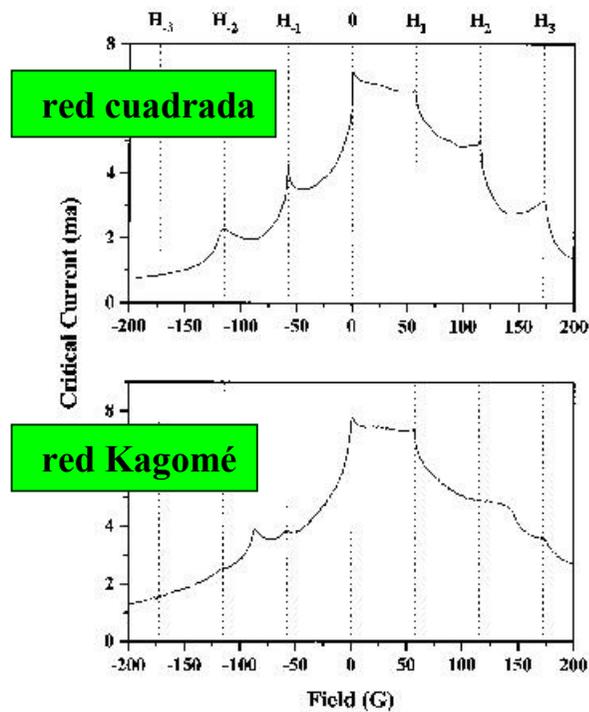
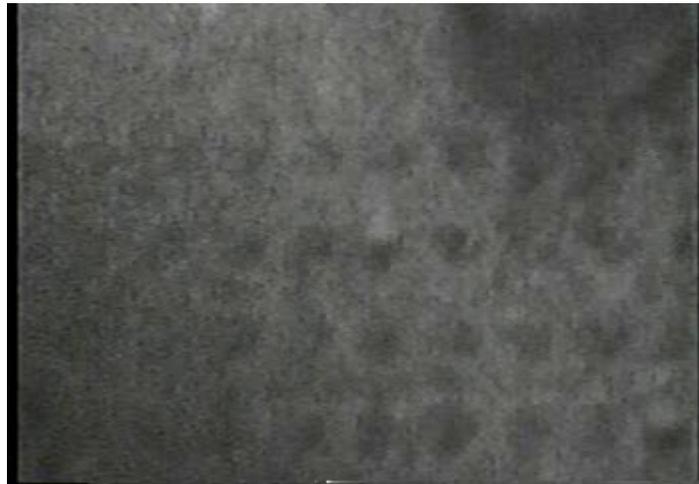


Imagen de microscopía Lorentz de vórtices sobre una red cuadrada de defectos

Harada et al, Science 1996

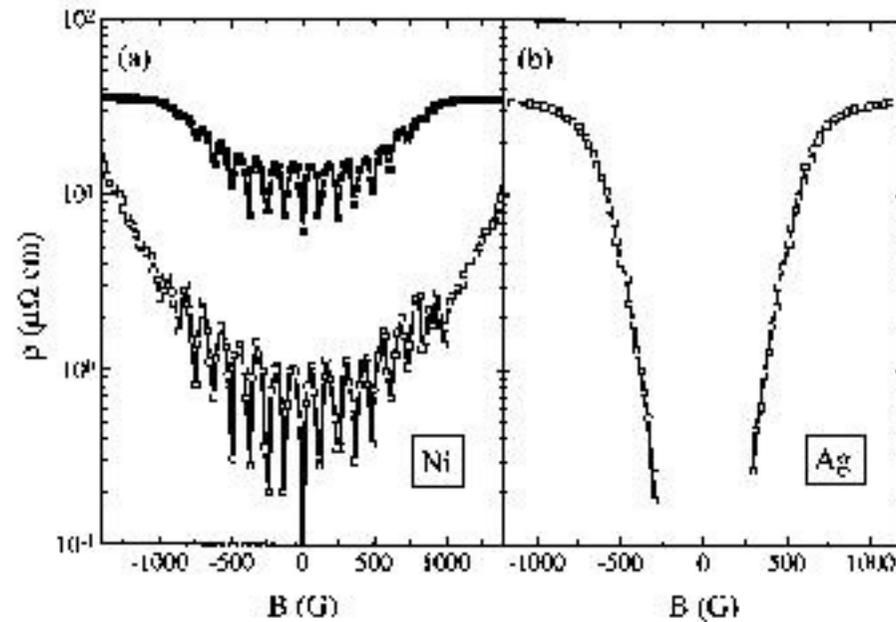
Redes de cilindros de Ni en una lámina de Nb
Morgan y Ketterson, PRL (1998)

Movimiento de vórtices en presencia de una red cuadrada de defectos



Harada et al, Science 1996

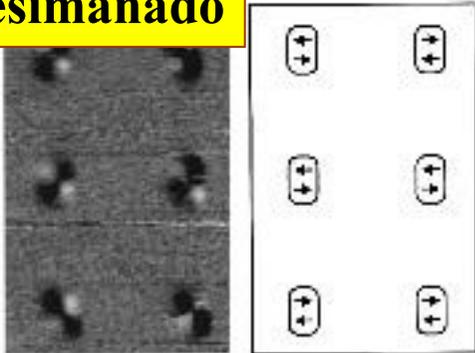
Puntos magnéticos vs. Puntos no magnéticos



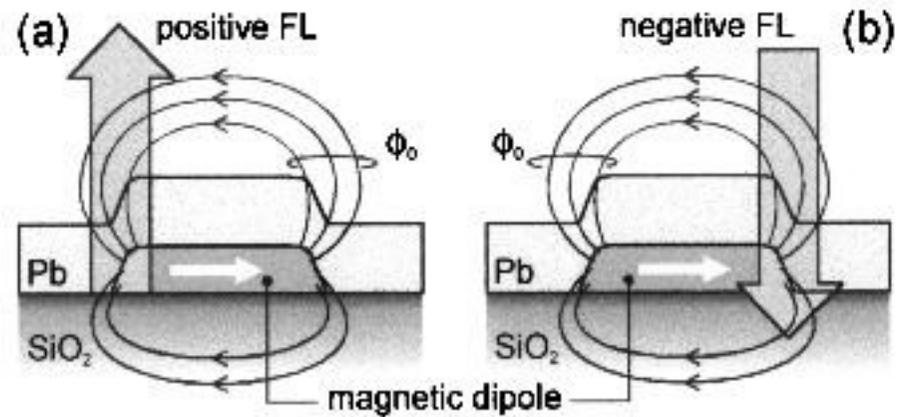
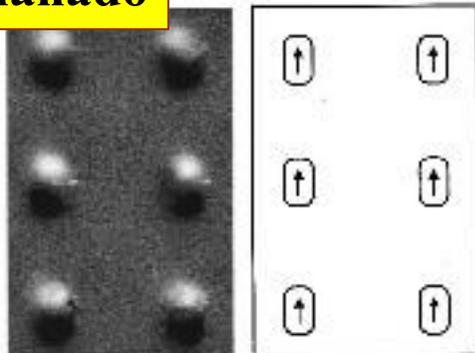
Redes de puntos de Ni y Ag en una lámina de Nb
Jaccard, Martín, Cyrille, Vélez, Vicent y Schuller, PRB (1998)

Estado de imanación de los puntos magnéticos

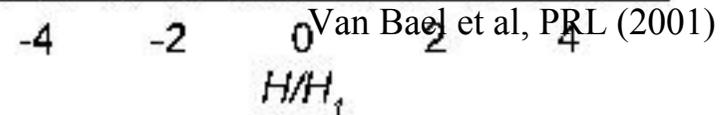
Desimanado



Imanado



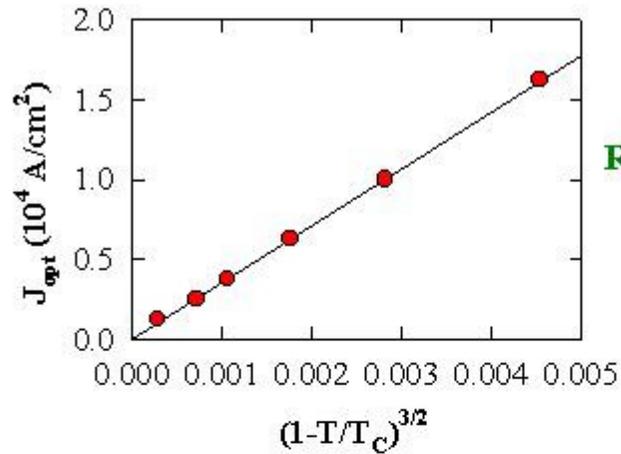
Anclaje por el campo de fugas de los puntos magnéticos



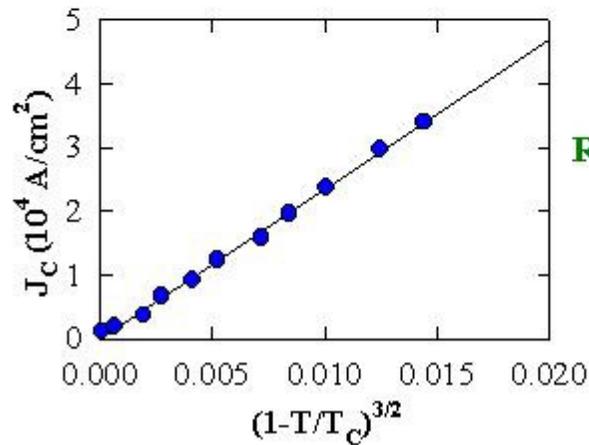
Red triangular de puntos de Co en una lámina de Pb
 Van Bael, Temst, Moschakov y Bruynseraede, PRB (1999)

Puntos de Co, $d = 1 \mu\text{m}$

Mecanismos de anclaje



Red cuadrada



Red rectangular

Interacción con el momento magnético del dot

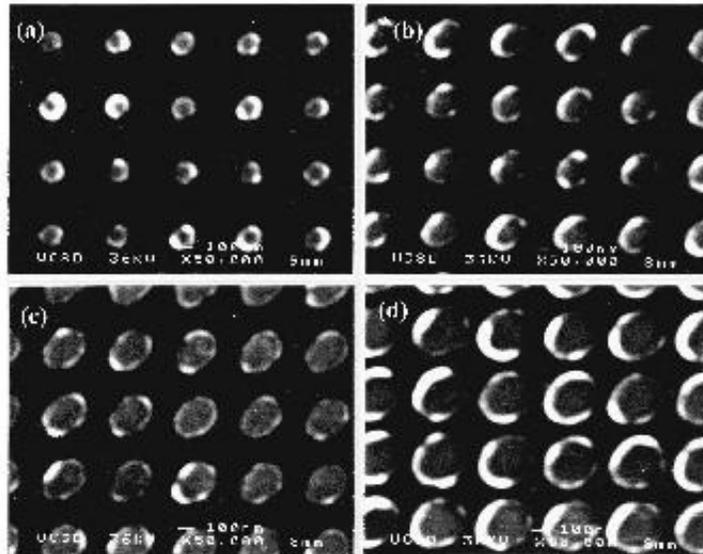
$$F_P = \Phi_0 m_z / 2\pi\mu_0 \xi \lambda^2 \sim (1-T/T_C)^{3/2}$$

Efecto de proximidad

$$F_P = \Phi_0^2 t / 16\pi\kappa^2 \mu_0 \xi^3 \sim (1-T/T_C)^{3/2}$$

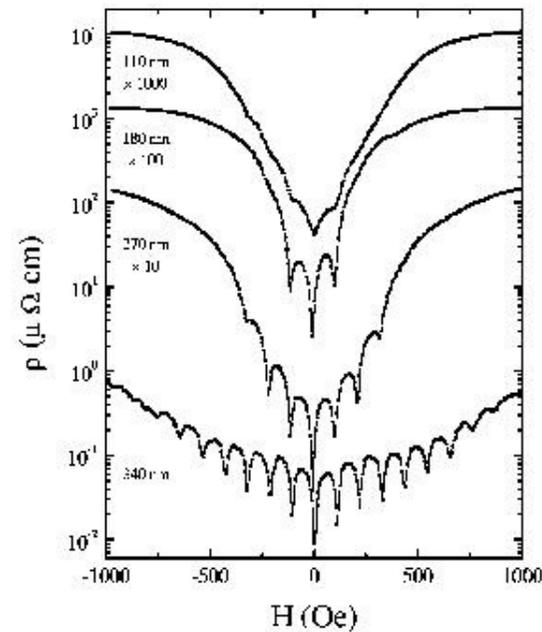
Martín, Vélez, Hoffmann, Schuller y Vicent, PRB (2000)

Efectos de *Tamaño/Separación* de los puntos magnéticos



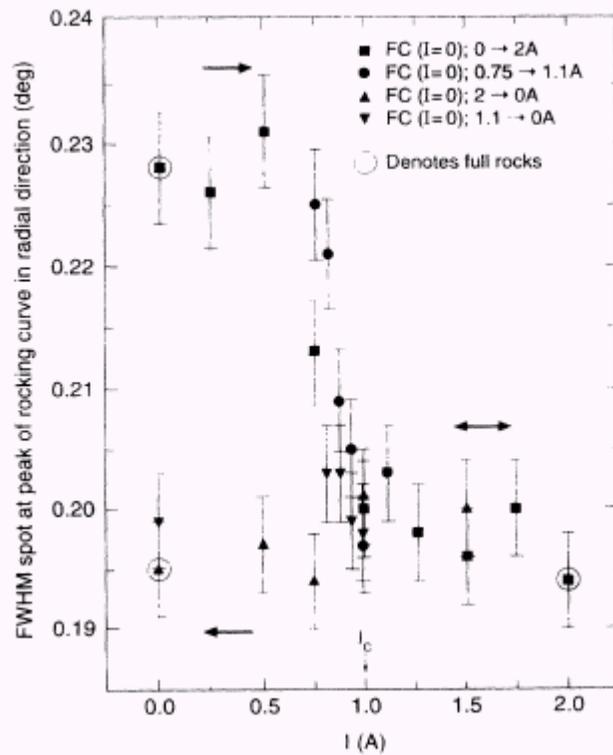
Redes de puntos de Ni de distintos tamaños en una película de Nb

Hoffmann, Prieto y Schuller, PRB (2000)

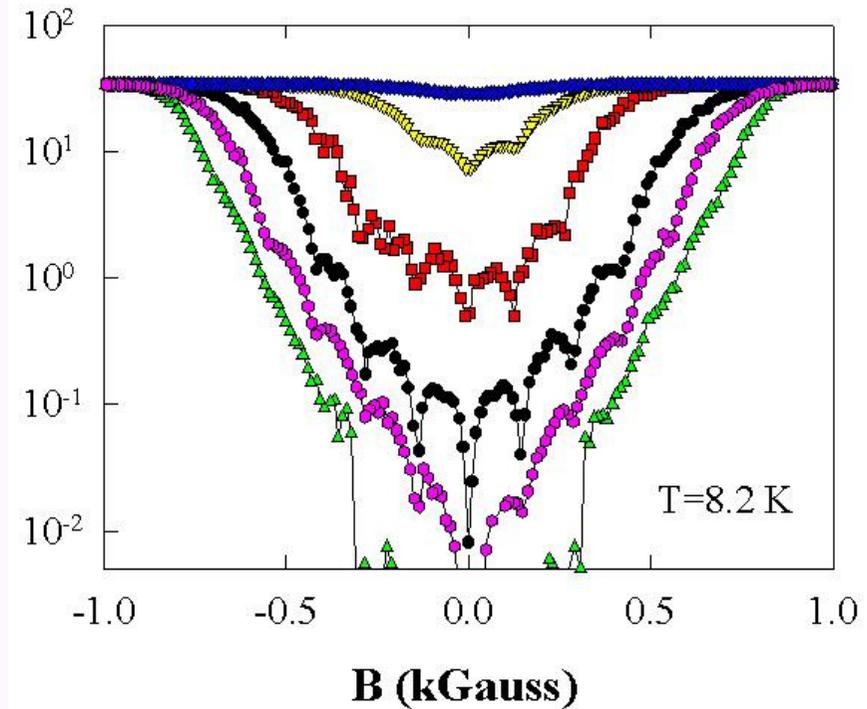


Anclaje débil \longrightarrow Red de hilos Superconductores (SWN)

Velocidad óptima de anclaje

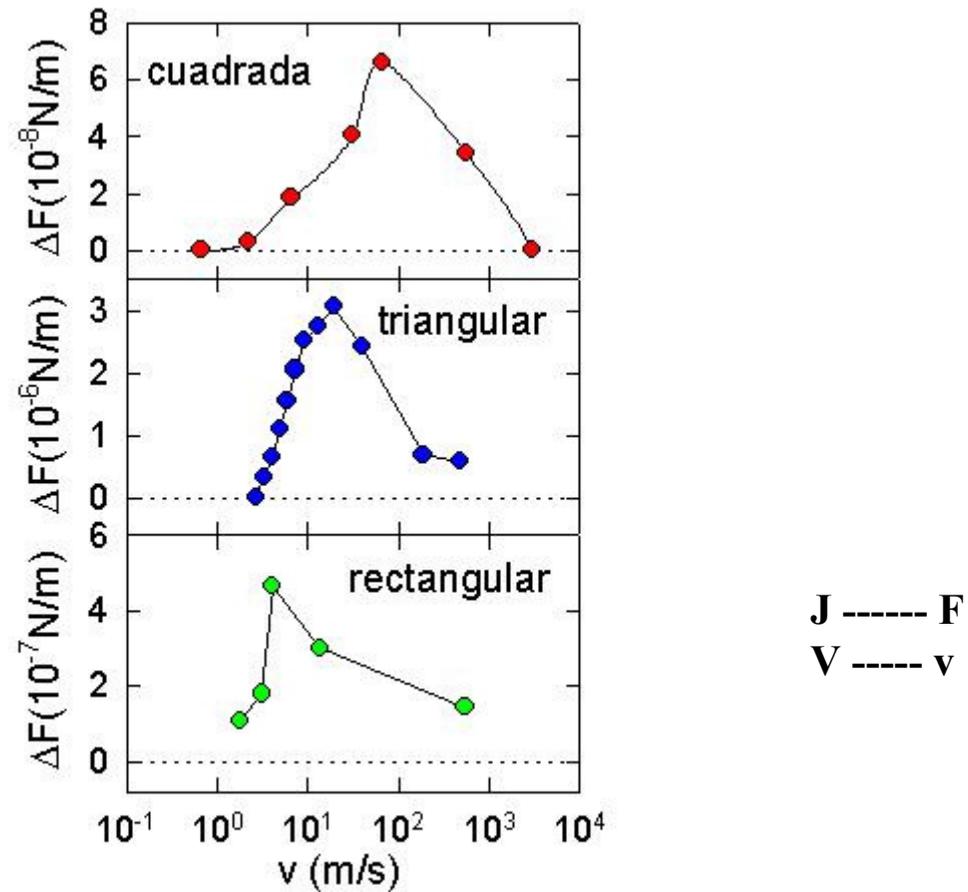


Yaron et al, PRL (1994)



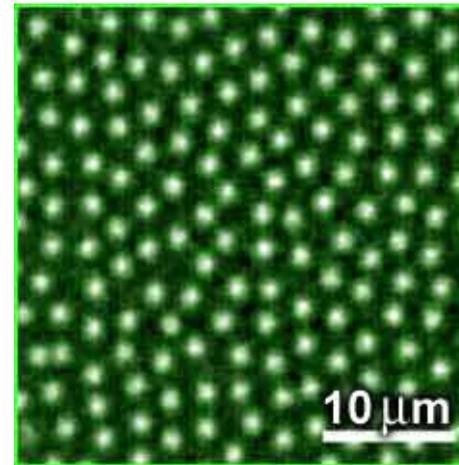
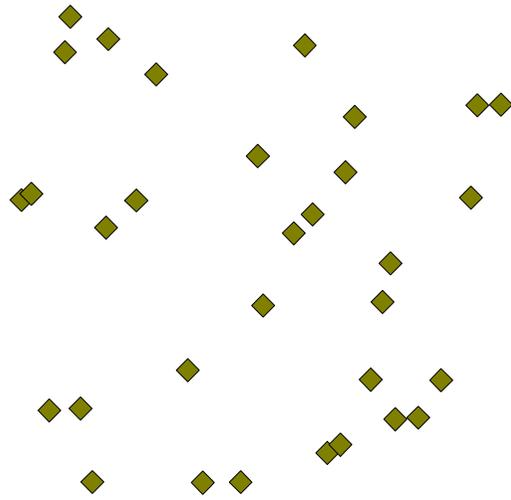
- ◆ $J=7.5 \cdot 10^4$ A/cm²
- ▼ $J=5.6 \cdot 10^4$ A/cm²
- $J=5.0 \cdot 10^4$ A/cm²
- $J=2.5 \cdot 10^4$ A/cm²
- ◆ $J=1.25 \cdot 10^4$ A/cm²
- ▲ $J=2.5 \cdot 10^3$ A/cm²

Velocidad óptima de anclaje



Defectos aleatorios vs. Redes ordenadas

Defectos naturales aleatorios

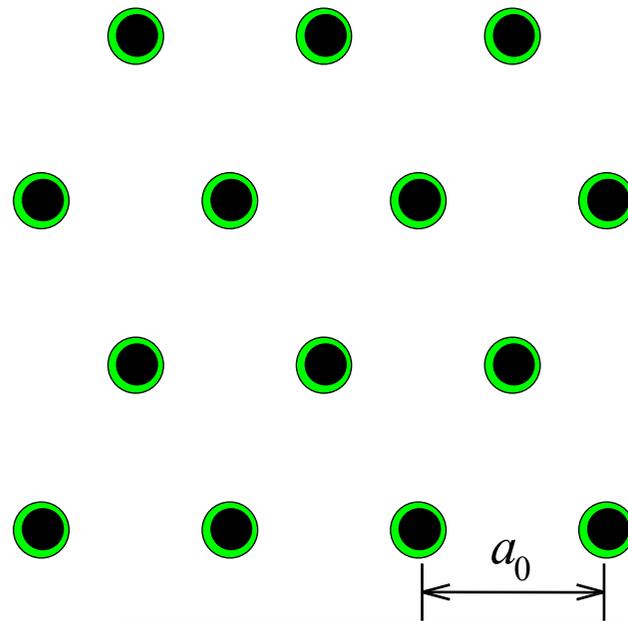


Baja velocidad →

$$v_L < 1 \text{ m/s}$$

- Red de vórtices desordenada
- Anclaje por defectos naturales aleatorios

Defectos aleatorios vs. Redes ordenadas



Velocidad Intermedia

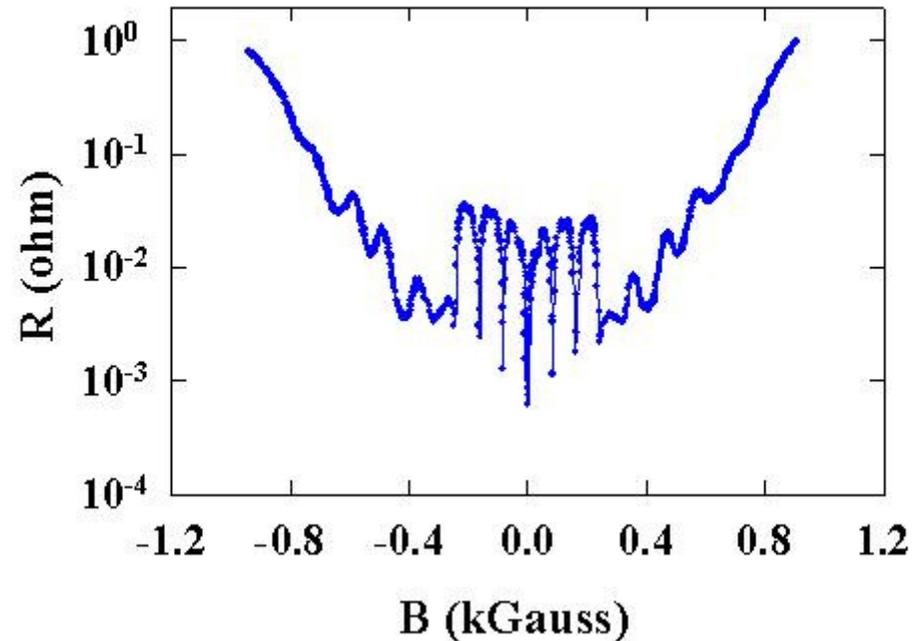
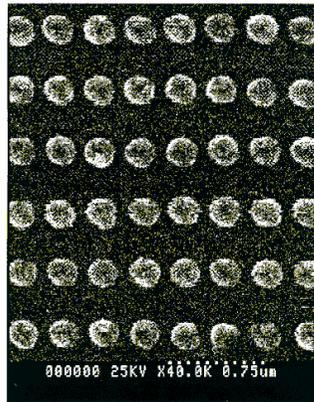


$$1 \text{ m/s} < v_L < 100 \text{ m/s}$$

- Red de vórtices ordenada
- Anclaje sincronizado por red ordenada de puntos

Redes rectangulares: *Reconfiguración*

Red de puntos de Ni (625 nm × 400 nm) en una lámina de Nb



Experimental

$$\Delta B_{\text{low}} = 81 \pm 2 \text{ G}$$

$$\Delta B_{\text{high}} = 112 \pm 5 \text{ G}$$

Teórico

$$\Delta B^{\text{rect}} = 83 \pm 2 \text{ G}$$

$$\Delta B^{\text{cuad}} = 129 \pm 5 \text{ G}$$

Martín, Vélez, Hoffmann, Schuller y Vicent, PRL 1999

Balance de Energías en la reconfiguración rectangular-cuadrada

$$\Delta E_{\text{Pinning}} = \Delta E_{\text{Elastica}}$$

$$\Delta E_{\text{elastica}} = E_{\text{rect}} - E_{\text{cuad}}$$

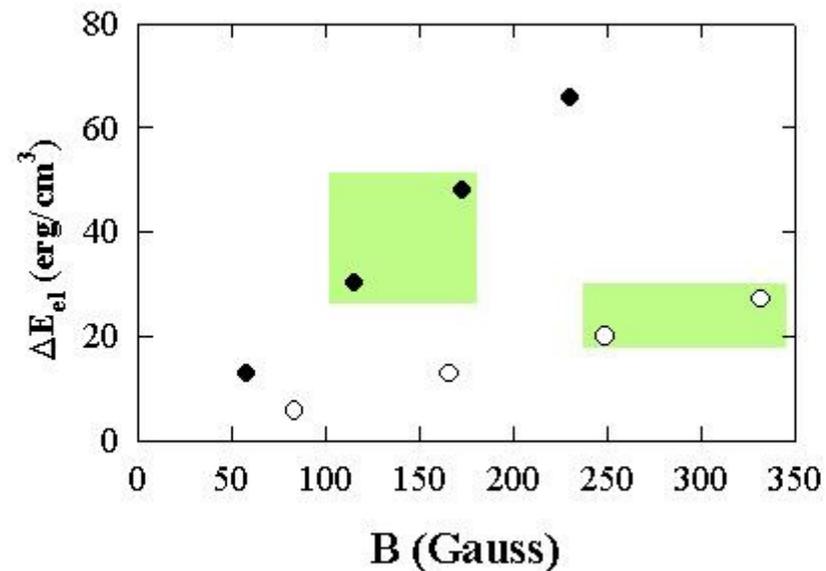
Energía libre de Gibbs

$$\Delta G = \epsilon_1 \mathbf{B} / \Phi_0 + \sum_{i>j} \mathbf{F}_{ij} - \mathbf{B}H / 4\pi$$

Término de interacciones

$$\sum_{i>j} \mathbf{F}_{ij} = (\Phi_0^2 / 8\pi^2 \lambda^2) \sum_{i>j} K_0(r_{ij} / \lambda)$$

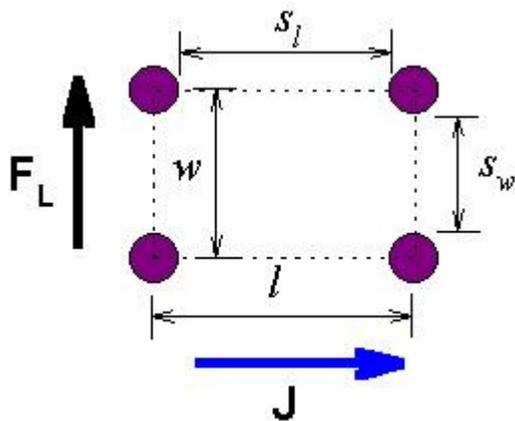
$$\Delta E_{\text{elastica}} = \sum_{i>j} \mathbf{F}_{ij \text{ rect}} - \sum_{i>j} \mathbf{F}_{ij \text{ cuad}}$$



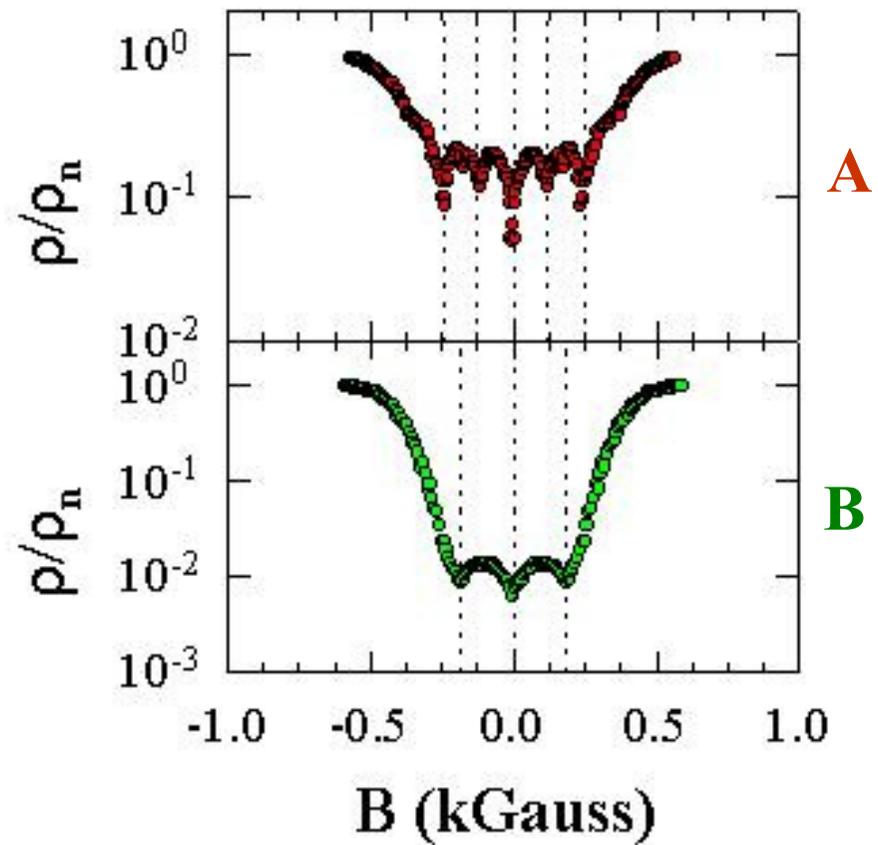
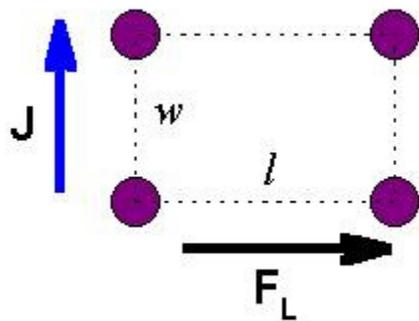
Reconfiguración → Energía anclaje por punto: 0.6 eV

Anisotropía según la dirección de la fuerza de Lorentz

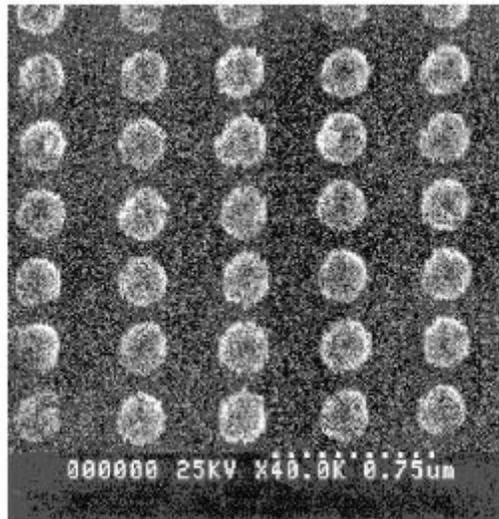
Geometría A



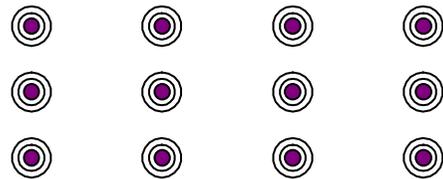
Geometría B



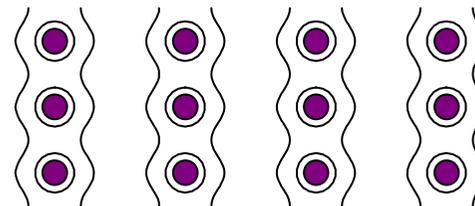
Channeling



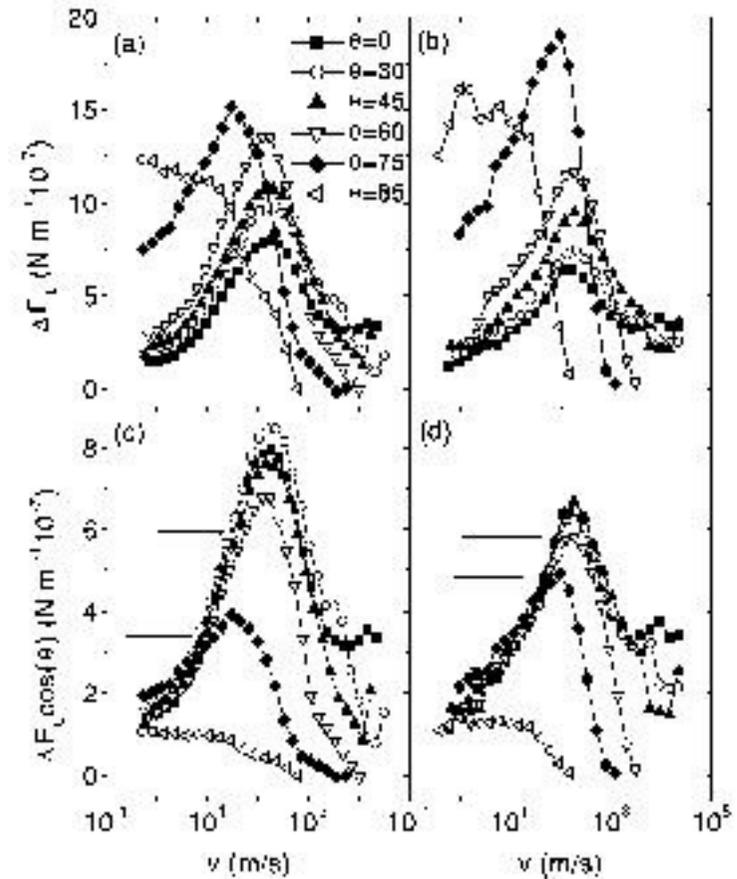
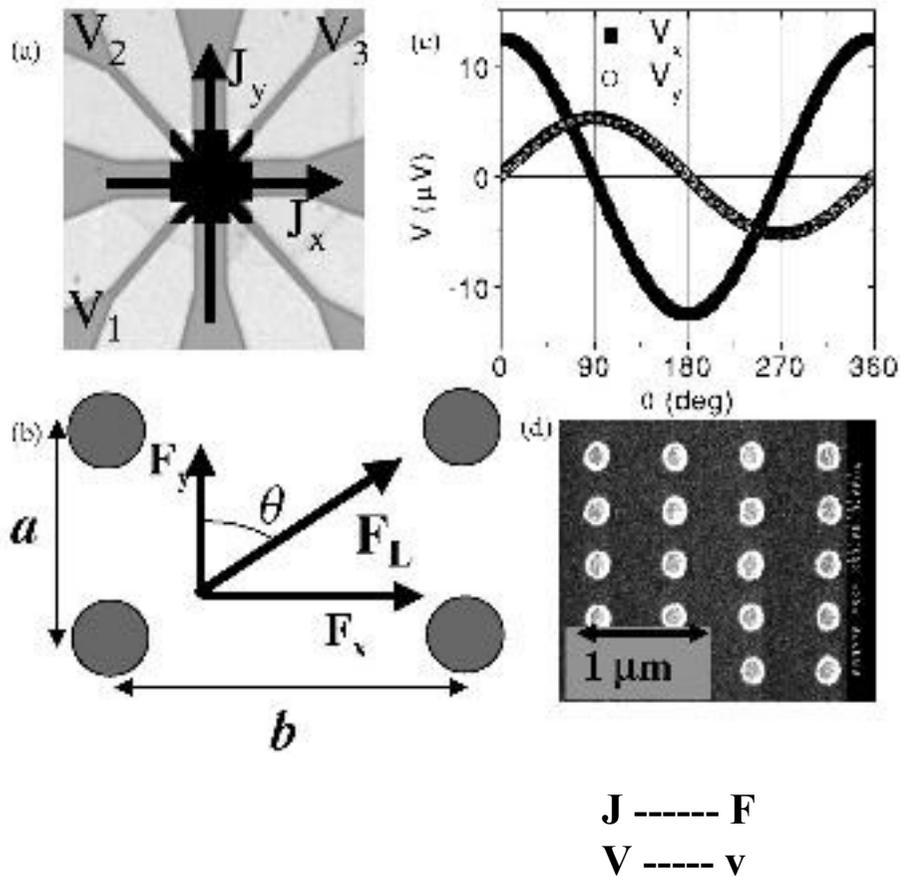
Centros puntuales



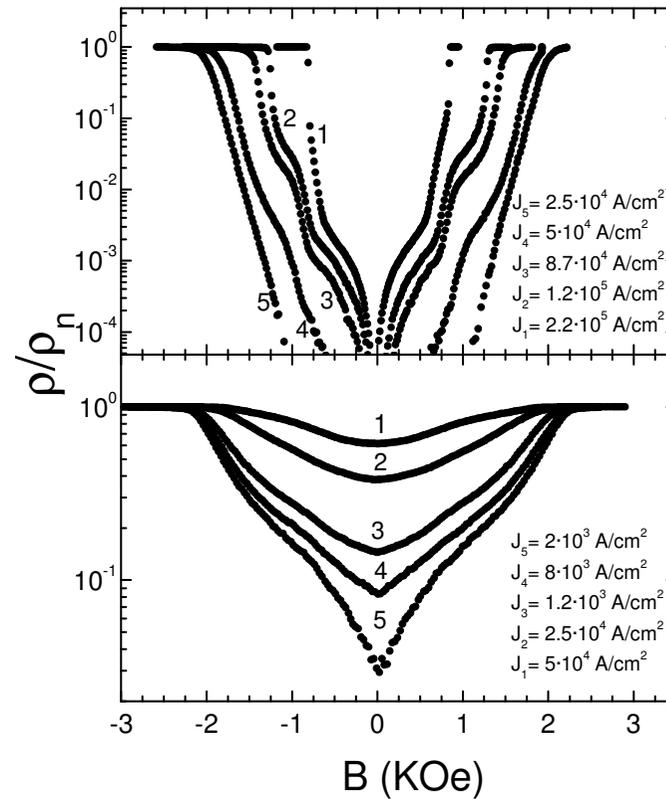
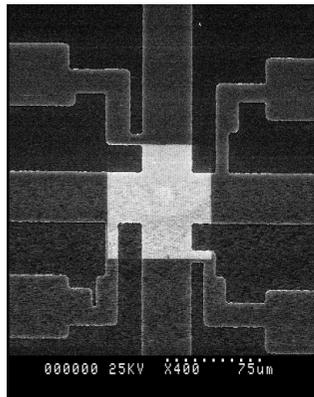
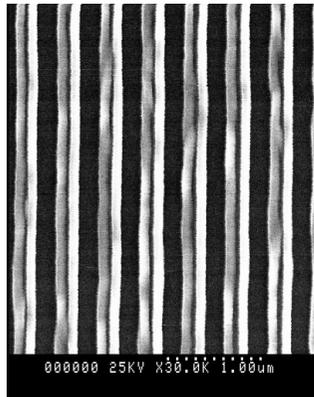
Canales para el flujo de vórtices



Movimiento de guiado de vórtices

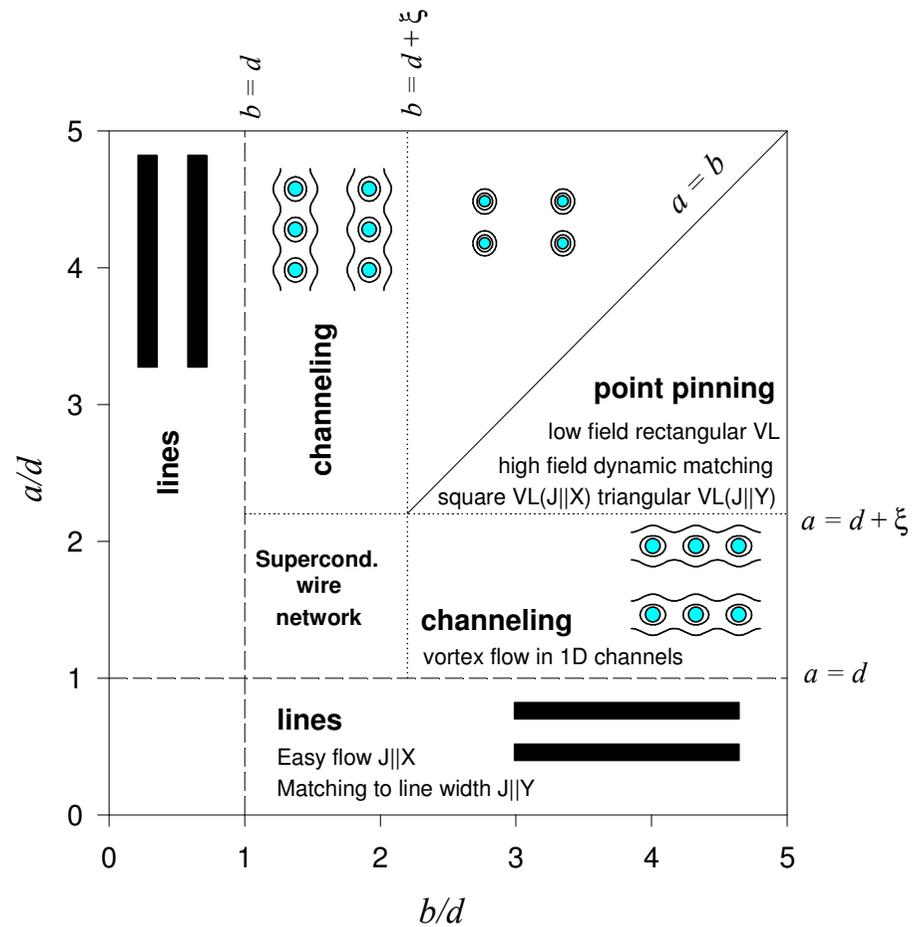


Redes de líneas de Ni

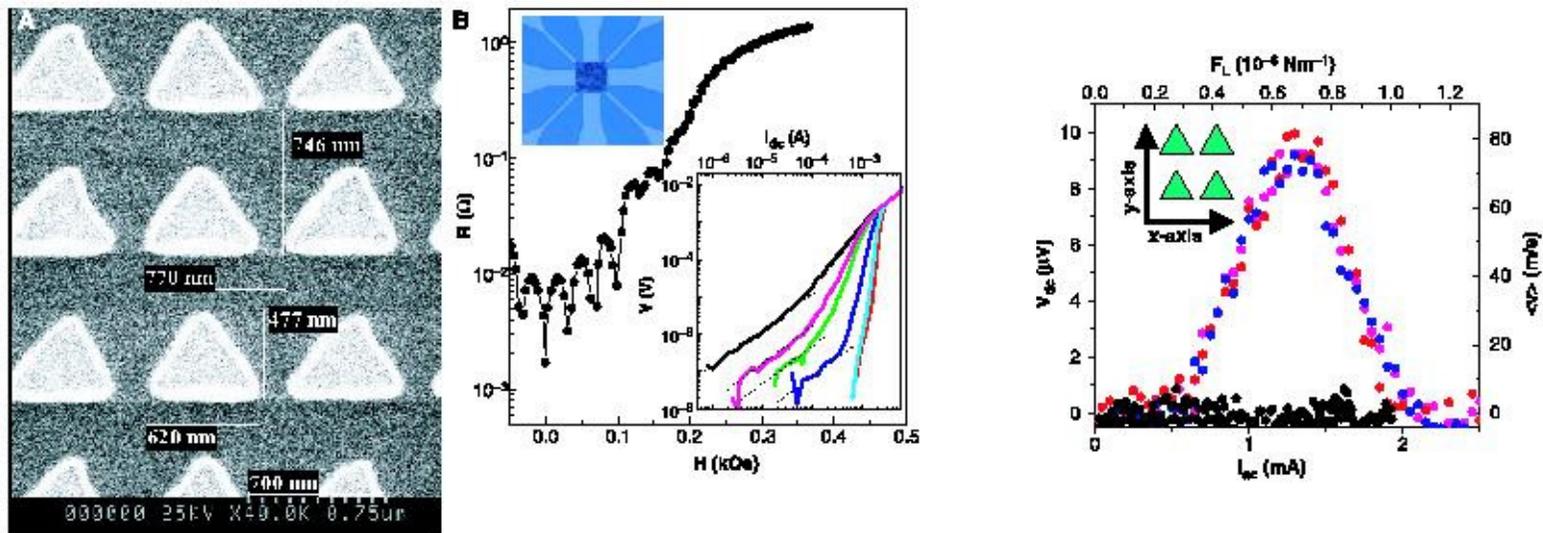


Jaques, González, Martín, Anguita y Vicent, APL 2002

Anclaje periódico en redes rectangulares

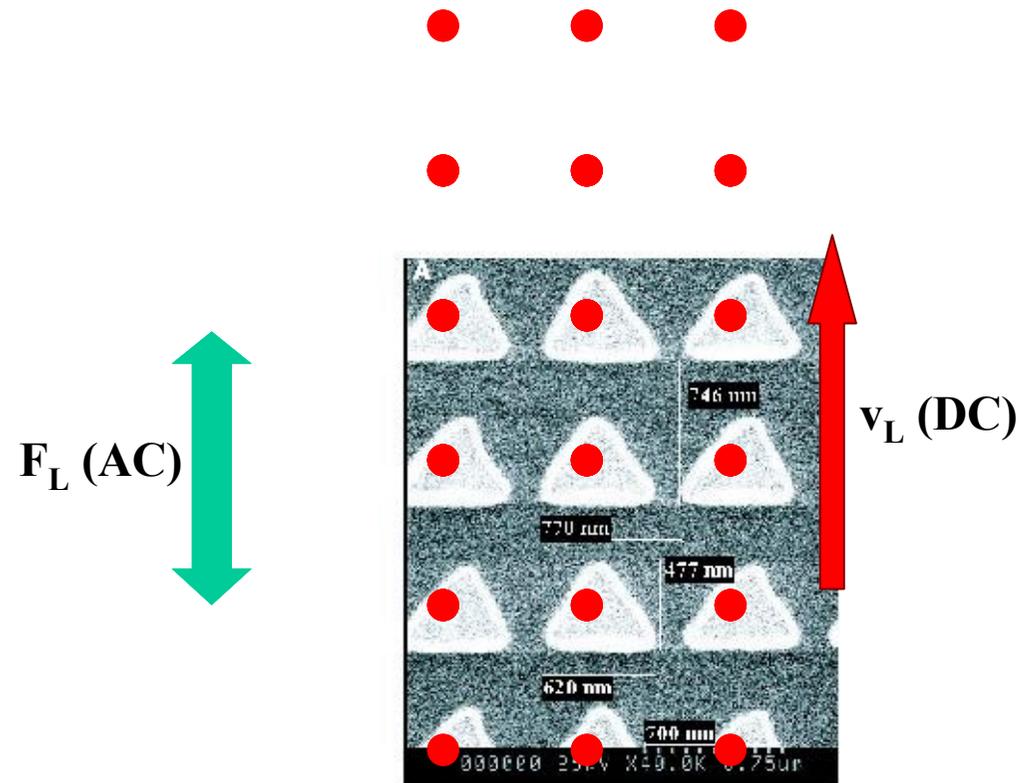


Redes de triángulos: efecto ratchet



Villegas, Savel'ev, Nori, González, Anguita, García y Vicent, Science 2003

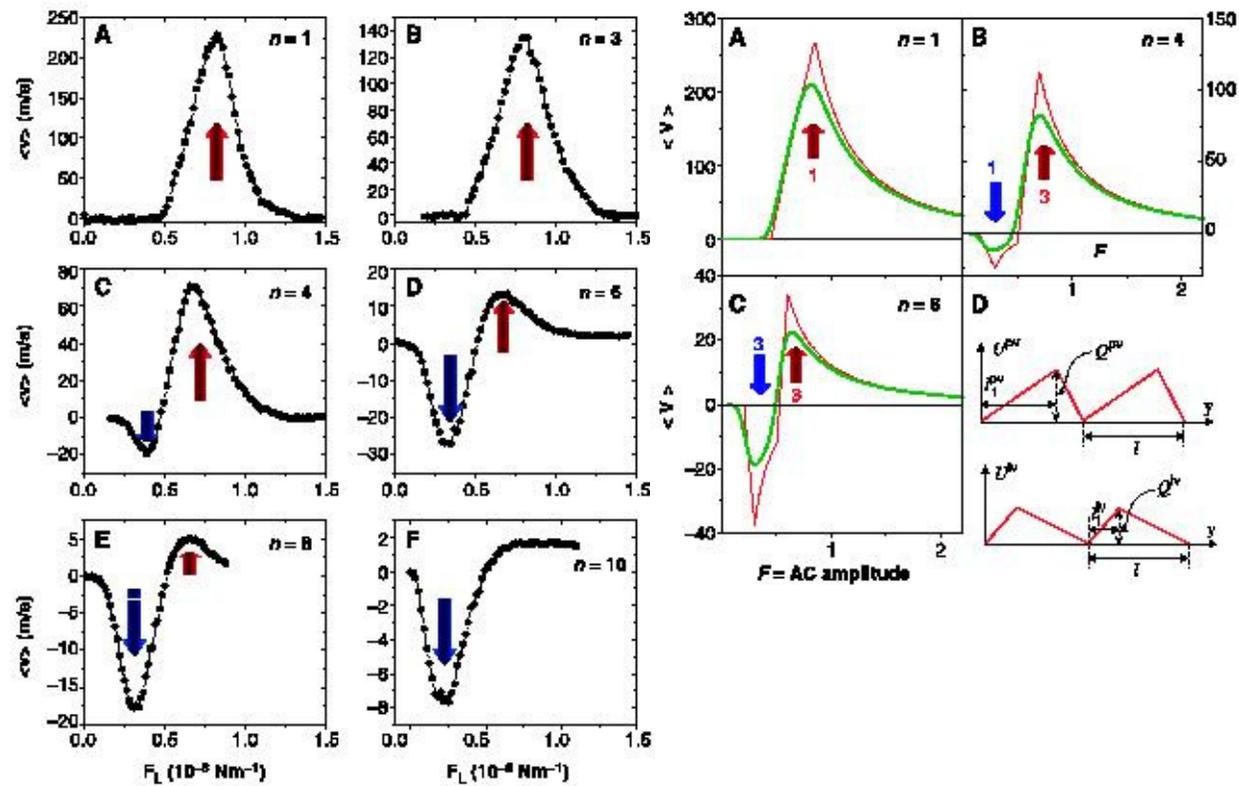
Rectificador de vórtices



Villegas, Savel'ev, Nori, González, Anguita, García y Vicent, Science 2003

Villegas, González, González, Anguita, y Vicent, PRB 2005

Efecto ratchet: *vortices anclados vs intersticiales*



Propiedades de los vórtices controladas por las nanoestructuras magnéticas

- ✓ **Anclaje de la red de vórtices**
- ✓ **Ordenación de la red con la velocidad**
- ✓ **Elasticidad de la red de vórtices**
- ✓ **Guías de vórtices**
- ✓ **Rectificador de vórtices**
- ✓ **.... y más por conocer**

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