The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

International Atomic Energy Agency

SMR.1664 - 14

Conference on Single Molecule Magnets and Hybrid Magnetic Nanostructures

27 June - 1 July 2005

Nanostructures:
Confinement Proximity Induced Phenomena

Ivan K. SCHULLER
University of California, San Diego
Department of Physics
9500 Gilman Drive
La Jolla, CA 92093-0319
U.S.A.

NANOSTRUCTURES:
CONFINEMENT
PROXIMITY
INDUCED PHENOMENA

Ivan K. Schuller

University of California
San Diego

Jose-Luis Vicent

Universidad Complutense-Madrid

Hybrid Magnetic-Superconducting

Periodic pinning by arrays of nanostructured magnetic dots

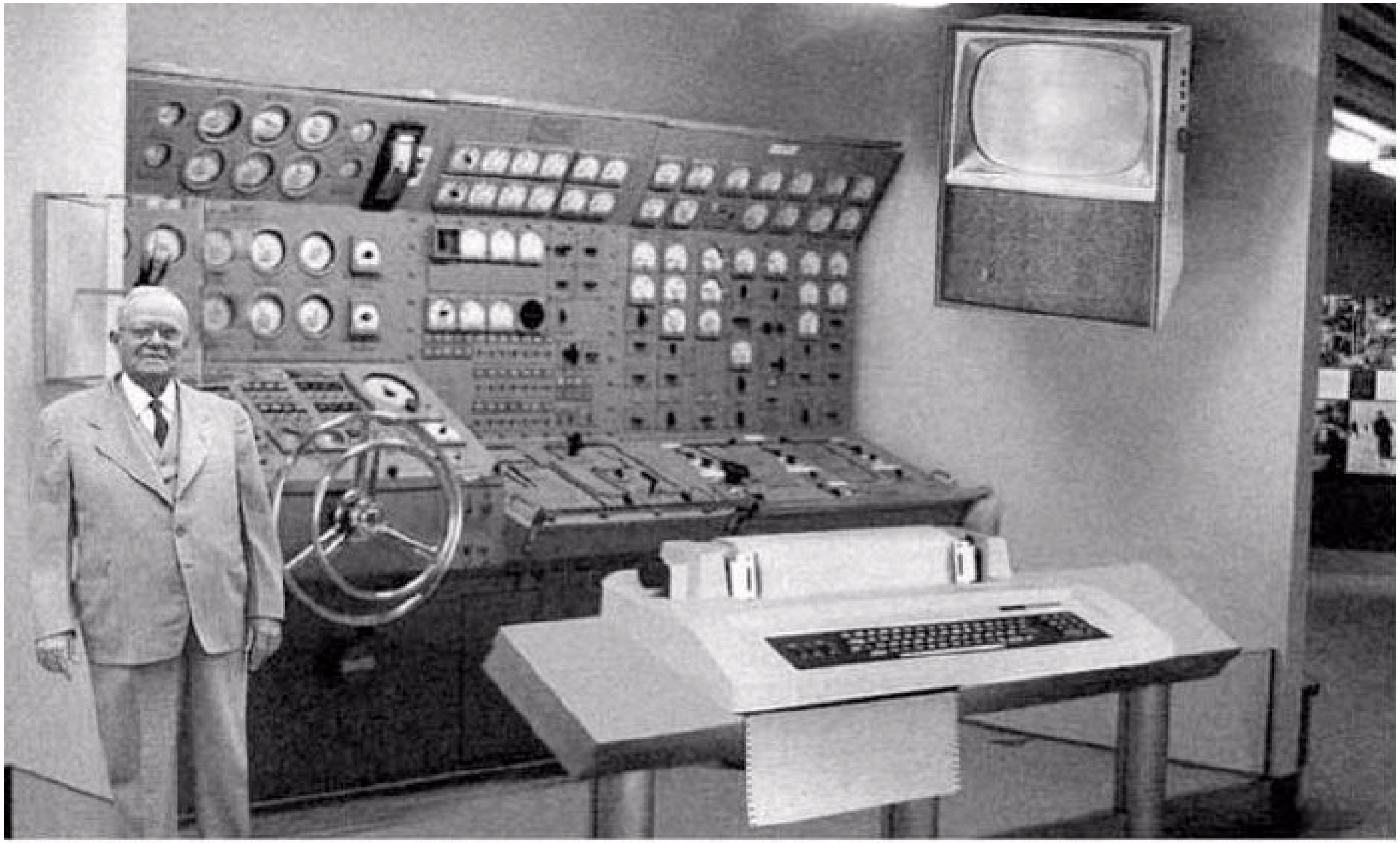
SURPRISING AND INTERESTING

FUNDING

- *US-NSF*
- *SPAIN-DGICYT*

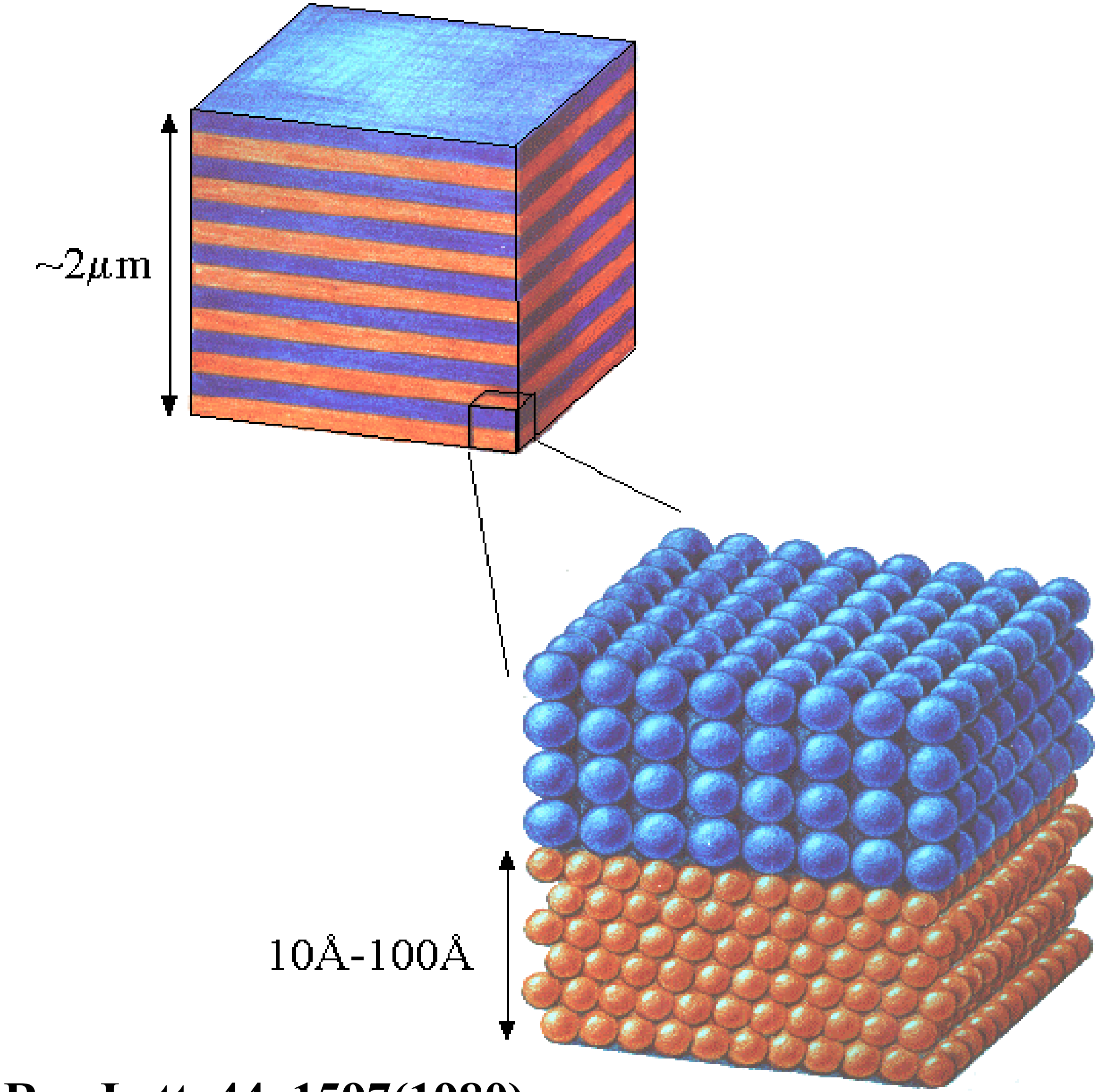
(Ramon Areces, Ramon & Cajal)

Targeted Research



*Scientists from the **RAND** Corporation have created this model to illustrate how a "home computer" could look like in the year 2004. However the needed technology will not be economically feasible for the average home. Also the scientists readily admit that the computer will require not yet invented technology to actually work, but 50 years from now scientific progress is expected to solve these problems. With teletype interface and the Fortran language, the computer will be easy to use.*

SCIENCE DRIVEN RESEARCH



I.K.Schuller, Phys.Rev.Lett. 44, 1597(1980)

AIP Conference Proceedings
Series Editor: Hugh C. Wolfe
Number 53

Modulated Structures–1979
(Kailua Kona, Hawaii)

Editors
J.M. Cowley, Arizona State University
J.B. Cohen, Northwestern University
M.B. Salamon, University of Illinois
B.J. Wuensch, Massachussetts Institute of Technology

American Institute of Physics
New York
1979

TRANSPORT PROPERTIES OF THE COMPOSITIONALLY MODULATED ALLOY Cu/Ni*

Ivan Schuller, Charles M. Falco
Argonne National Laboratory, Argonne, Illinois 60439

J. Hilliard, J. Ketterson, B. Thaler
Northwestern University, Evanston, Illinois 60201

R. Lacoe, R. Dee
University of California, Los Angeles, California 90024

ABSTRACT

We report preliminary transport measurements; electrical resistivity, thermopower, Hall effect and magnetoresistance, of a number of Cu/Ni composition modulated alloy films over the temperature range 10-300°K and for magnetic field up to 70 kGauss.

The results indicate non-monotonic dependence of the transport properties on the modulation amplitude. The Hall coefficient saturates around 40 kGauss in contrast to the transverse magnetoresistance which does not show evidence for saturation up to 70 kGauss.

INTRODUCTION

Recently there has been extensive interest in the properties of Composition Modulated Alloys[1] (CMA). This has been motivated by elastic constant measurements which show an anomalous enhancement of the biaxial modulus as a function of modulation wavelength λ for a number of CMA's. Recent ferromagnetic resonance experiments indicate that the magnetization of Ni in the Cu/Ni CMA is larger below 200°K than the zero temperature magnetization of pure Ni. It was suggested that these results could be an indication of large changes in the band structure of CMA's as a function of wavelength and composition amplitude (A_1). Motivated by these results we undertook preliminary transport merasurements on the Cu/Ni CMA to study the effect of composition modulation on the electronic properties of such systems.

The resistivity and thermopower measurements were performed over the temperature range 10-300°K using a closed cycle refrigerator system. The magnetic transport measurements were performed in liquid helium at 4.2°K using a superconducting magnet.

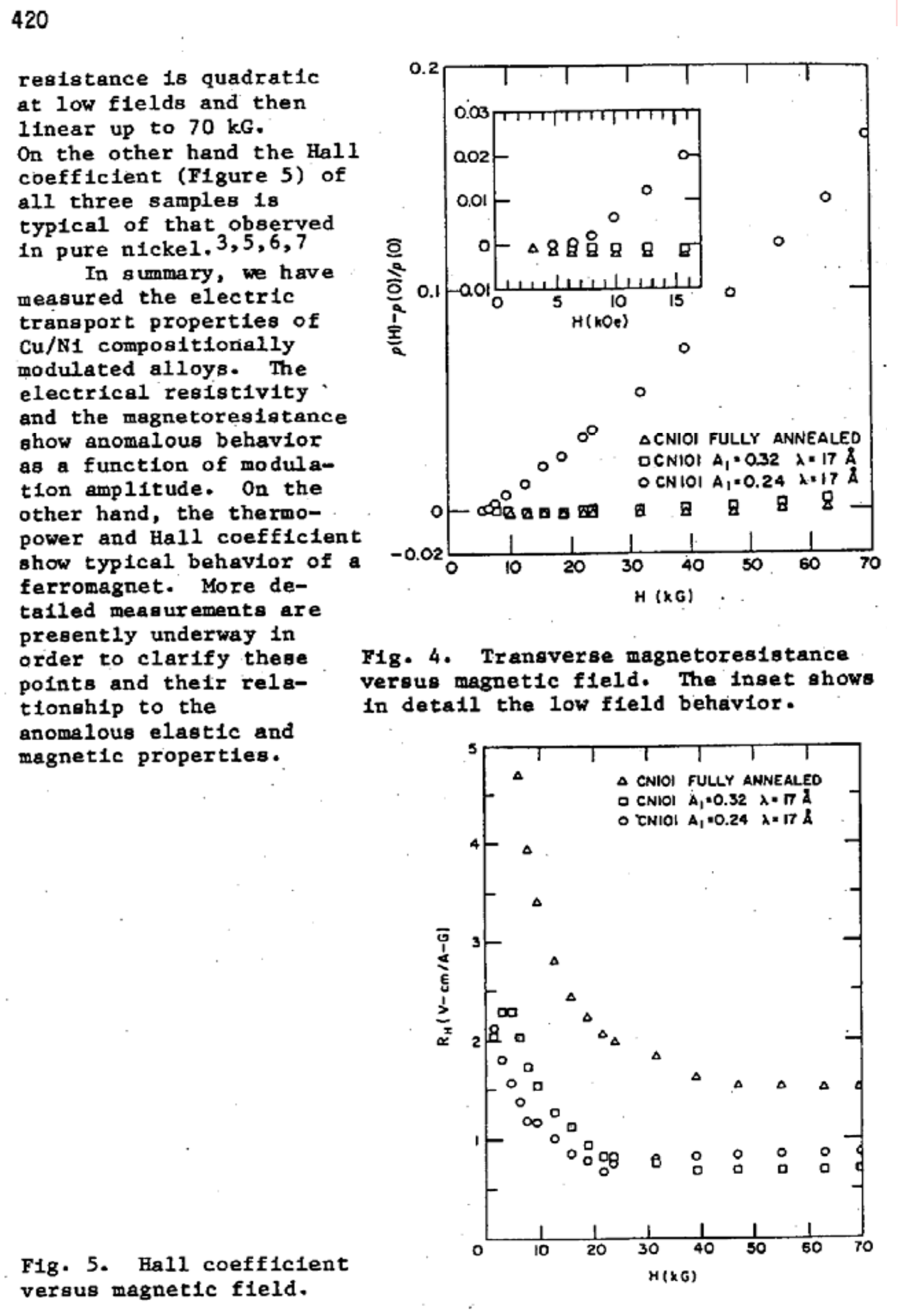
All of the samples were cut from a master CMA, annealed if necessary, x-rayed and attached to the sample holders using GE 7031 varnish to improve thermal contact. Some of the samples were also x-rayed after the measurements were performed to assure

---

*Work performed under the auspices of U.S.D.O.E., the Northwestern Materials Research Center under NSF Grant DMR-76-80847-801, and by NSF Grant DMR 78-12000, University of California.

ISSN:0094-243X/79/530417-05$1.50

...magnetoresistance shows anomalous behavior......

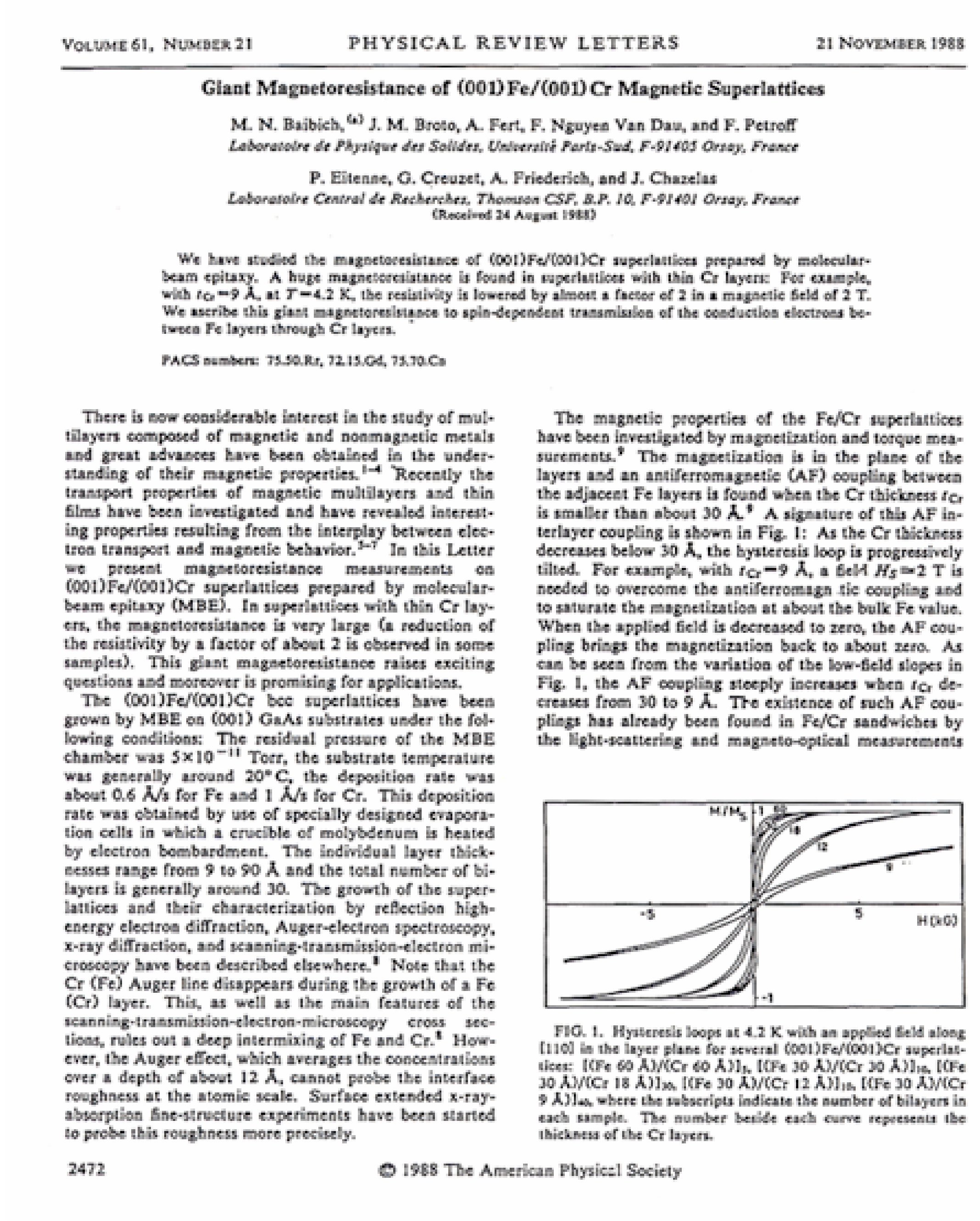


resistance is quadratic at low fields and then linear up to 70 kG. On the other hand the Hall coefficient (Figure 5) of all three samples is typical of that observed in pure nickel.[3,5,6,7]

In summary, we have measured the electric transport properties of Cu/Ni compositionally modulated alloys. The electrical resistivity and the magnetoresistance show anomalous behavior as a function of modulation amplitude. On the other hand, the thermopower and Hall coefficient show typical behavior of a ferromagnet. More detailed measurements are presently underway in order to clarify these points and their relationship to the anomalous elastic and magnetic properties.

Fig. 4. Transverse magnetoresistance versus magnetic field. The inset shows in detail the low field behavior.

Fig. 5. Hall coefficient versus magnetic field.



VOLUME 61, NUMBER 21 PHYSICAL REVIEW LETTERS 21 NOVEMBER 1988

Giant Magnetoresistance of (001)Fe/(001)Cr Magnetic Superlattices

M. N. Baibich,[a] J. M. Broto, A. Fert, F. Nguyen Van Dau, and F. Petroff
Laboratoire de Physique des Solides, Université Paris-Sud, F-91405 Orsay, France

P. Eitenne, G. Creuzet, A. Friederich, and J. Chazelas
Laboratoire Central de Recherches, Thomson CSF, B.P. 10, F-91401 Orsay, France

(Received 24 August 1988)

We have studied the magnetoresistance of (001)Fe/(001)Cr superlattices prepared by molecular-beam epitaxy. A huge magnetoresistance is found in superlattices with thin Cr layers: For example, with $t_{Cr} = 9$ Å, at $T = 4.2$ K, the resistivity is lowered by almost a factor of 2 in a magnetic field of 2 T. We ascribe this giant magnetoresistance to spin-dependent transmission of the conduction electrons between Fe layers through Cr layers.

PACS numbers: 75.50.Rr, 72.15.Gd, 75.70.Cn

There is now considerable interest in the study of multilayers composed of magnetic and nonmagnetic metals and great advances have been obtained in the understanding of their magnetic properties.[1-4] Recently the transport properties of magnetic multilayers and thin films have been investigated and have revealed interesting properties resulting from the interplay between electron transport and magnetic behavior.[5-7] In this Letter we present magnetoresistance measurements on (001)Fe/(001)Cr superlattices prepared by molecular-beam epitaxy (MBE). In superlattices with thin Cr layers, the magnetoresistance is very large (a reduction of the resistivity by a factor of about 2 is observed in some samples). This giant magnetoresistance raises exciting questions and moreover is promising for applications.

The (001)Fe/(001)Cr bcc superlattices have been grown by MBE on (001) GaAs substrates under the following conditions: The residual pressure of the MBE chamber was 5×10^{-11} Torr, the substrate temperature was generally around 20 °C, the deposition rate was about 0.6 Å/s for Fe and 1 Å/s for Cr. This deposition rate was obtained by use of specially designed evaporation cells in which a crucible of molybdenum is heated by electron bombardment. The individual layer thicknesses range from 9 to 90 Å and the total number of bilayers is generally around 30. The growth of the superlattices and their characterization by reflection high-energy electron diffraction, Auger-electron spectroscopy, x-ray diffraction, and scanning-transmission-electron microscopy have been described elsewhere.[8] Note that the Cr (Fe) Auger line disappears during the growth of a Fe (Cr) layer. This, as well as the main features of the scanning-transmission-electron-microscopy cross sections, rules out a deep intermixing of Fe and Cr.[8] However, the Auger effect, which averages the concentrations over a depth of about 12 Å, cannot probe the interface roughness at the atomic scale. Surface extended x-ray-absorption fine-structure experiments have been started to probe this roughness more precisely.

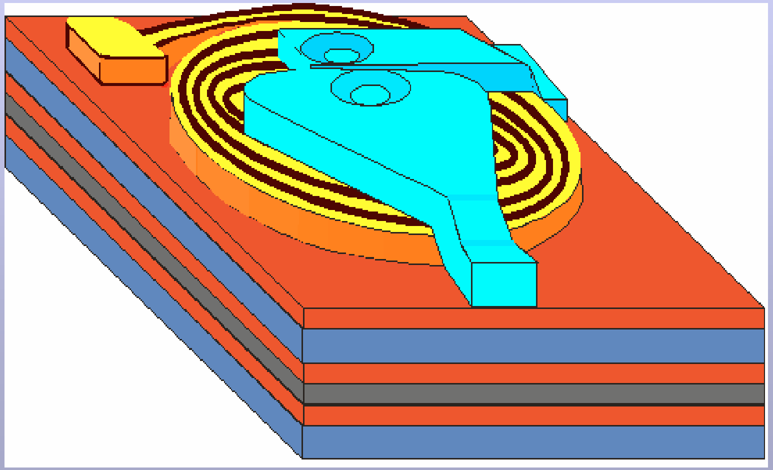
The magnetic properties of the Fe/Cr superlattices have been investigated by magnetization and torque measurements.[9] The magnetization is in the plane of the layers and an antiferromagnetic (AF) coupling between the adjacent Fe layers is found when the Cr thickness t_{Cr} is smaller than about 30 Å.[9] A signature of this AF interlayer coupling is shown in Fig. 1: As the Cr thickness decreases below 30 Å, the hysteresis loop is progressively tilted. For example, with $t_{Cr} = 9$ Å, a field $H_S = 2$ T is needed to overcome the antiferromagnetic coupling and to saturate the magnetization at about the bulk Fe value. When the applied field is decreased to zero, the AF coupling brings the magnetization back to about zero. As can be seen from the variation of the low-field slopes in Fig. 1, the AF coupling steeply increases when t_{Cr} decreases from 30 to 9 Å. The existence of such AF couplings has already been found in Fe/Cr sandwiches by the light-scattering and magneto-optical measurements

FIG. 1. Hysteresis loops at 4.2 K with an applied field along [110] in the layer plane for several (001)Fe/(001)Cr superlattices: $[(\mathrm{Fe}\ 60\ \text{Å})/(\mathrm{Cr}\ 60\ \text{Å})]_5$, $[(\mathrm{Fe}\ 30\ \text{Å})/(\mathrm{Cr}\ 30\ \text{Å})]_{10}$, $[(\mathrm{Fe}\ 30\ \text{Å})/(\mathrm{Cr}\ 18\ \text{Å})]_{30}$, $[(\mathrm{Fe}\ 30\ \text{Å})/(\mathrm{Cr}\ 12\ \text{Å})]_{10}$, $[(\mathrm{Fe}\ 30\ \text{Å})/(\mathrm{Cr}\ 9\ \text{Å})]_{40}$, where the subscripts indicate the number of bilayers in each sample. The number beside each curve represents the thickness of the Cr layers.

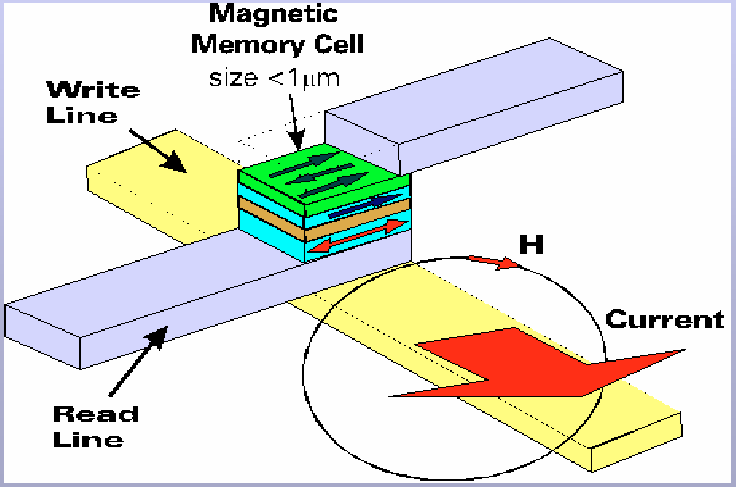
UNEXPECTED

WITHIN 15 YEARS

Read Head



Magnetic RAM



Basic Research Pays !!!

Where ??????

Plan

- **Introduction-**
  - Preparation
  - Superconductivity
- **New Functionalities-**
  - Confinement X
  - Proximity Effect
  - Induced Phenomena
- **Summary-** Unexpected and Interesting
- **Future-** Nano+Proximity+Induced
- **Interesting questions**
- **Relevance to other fields**

DRIVING FORCE

SHOULD BE

- Interesting Physics
- Interesting Materials or Devices

SHOULD NOT BE

- Applications
- Big Machine

Many Surprises

Physics Driving Force

DISORDER

- **Surfaces**
- **Quantization**

NANO, nano, nano, nano

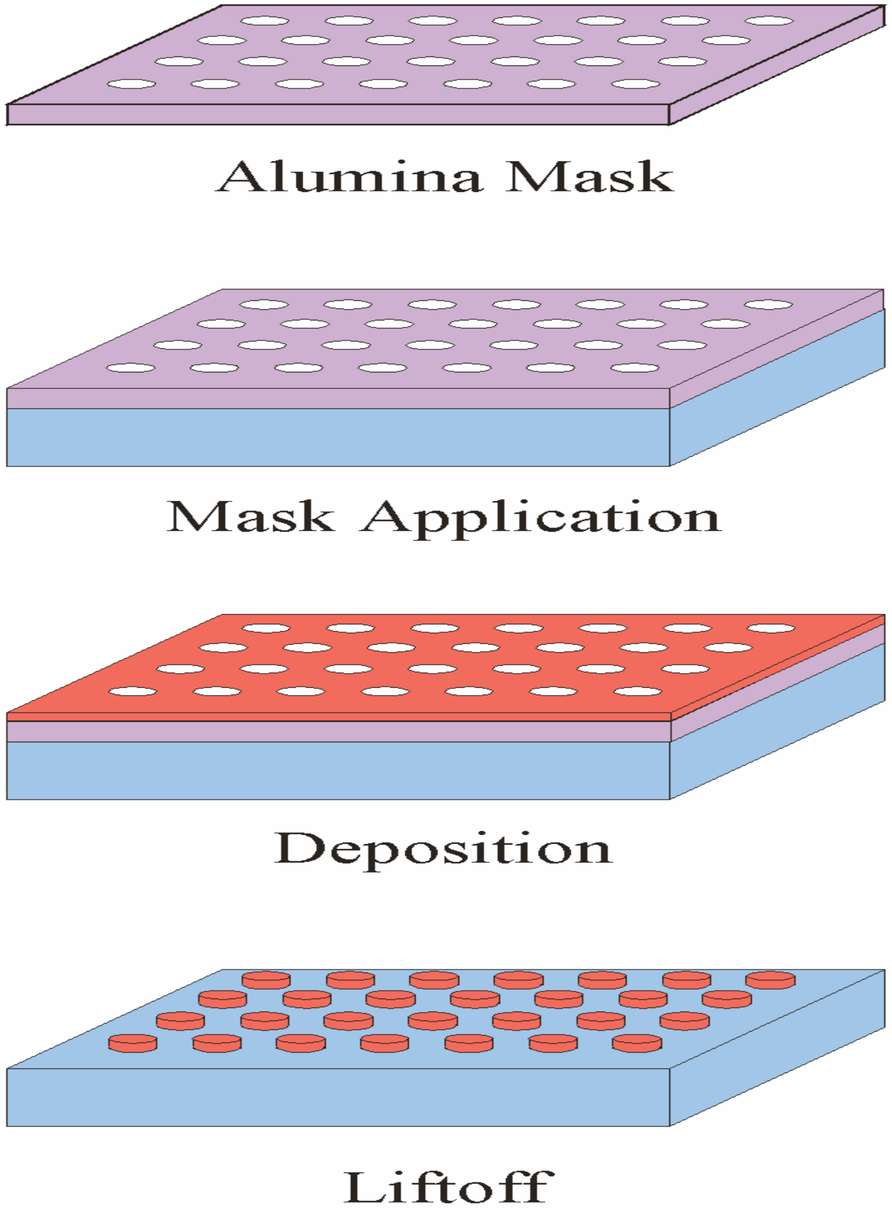
- **Extension of Ψ**
- **Extension of M**

Proximity

New Paradigm Needed

FABRICATION

Shadow Mask



ChangPeng Li
Igor Roshchin
Xavier Batlle

NAN0-FABRICATION

- **Lithography, high technology:**

  electron and ion beams,

  X-ray,

  Scanning Tunneling Microscope

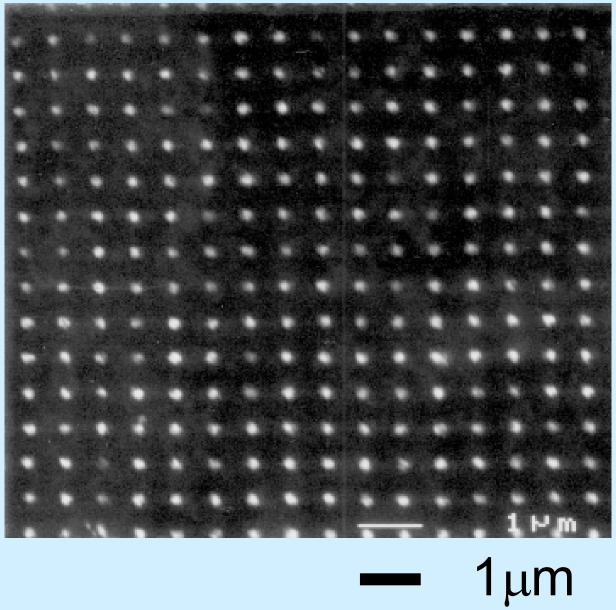
- **Self Assembly :**

  chemical

  biological

NOT PERFECT

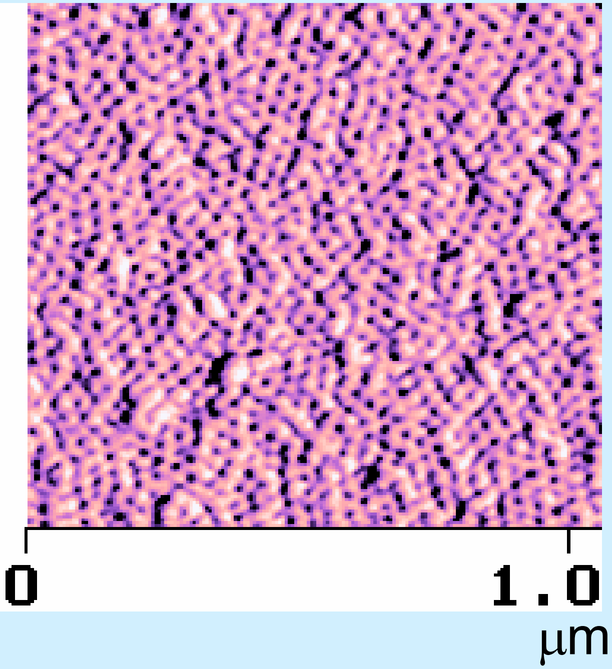
E-beam



Small area:

100µm x 100µm

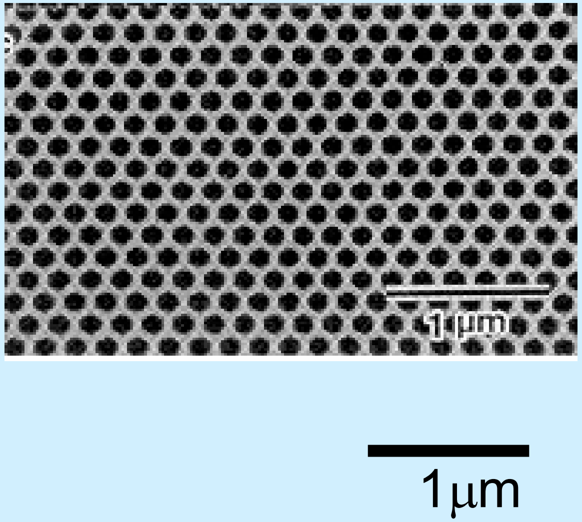
Diblock copolymer



Macroscopic area

M.Park, C.Harrison, P.Chaikin, R.A.Register, D.H.Adamson, *Science* **276**, 1401 (1997)

Anodized alumina



Macroscopic area

H. Masuda et al., Appl. Phys. Lett. **71**, 2770 (1997).

NEW FUNCTIONALITIES

- **Confinement**
- **Proximity Effect**
- **External Stimulii**

PROXIMITY

PROXIMITY EFFECT

“ Nanostructures are always in contact with something “

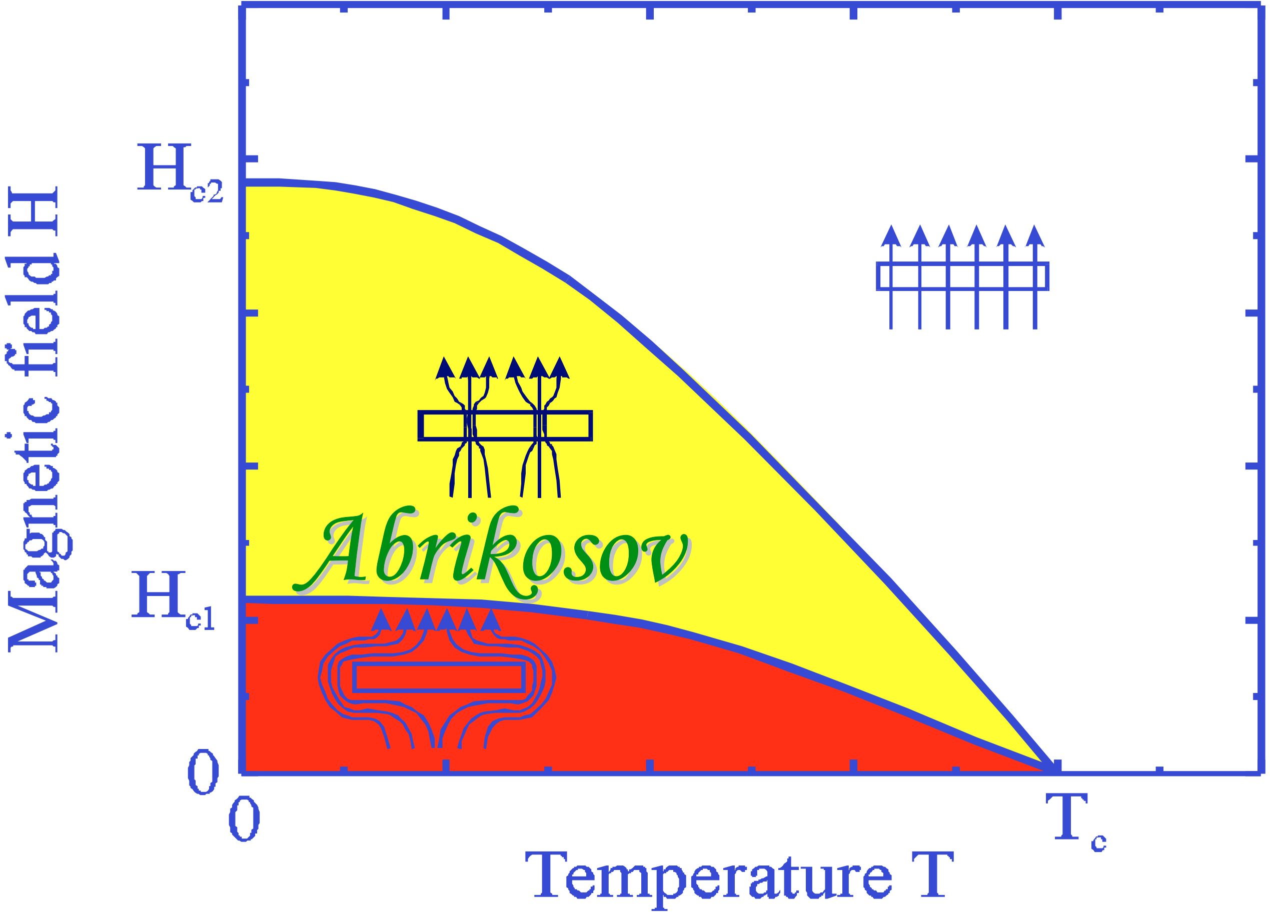
- Modify the properties of the **SOMETHING**
- Modify the properties of the **NANOSTRUCTURE**

Nano History
Nano Magnetic-Superconductors

- **Proximity Effect-1D** (Tedrow-Meservey-1968)
  - Tunneling Spin Glasses-1976
- **Superlattices-1D**
  - Critical Fields Ni/V-1981
  - 1D-2D Transitions Nb/Cu-1984
- **Nanostructures-2D** (Martinoli-1974, Moshchalkov-Bruynseraede-1992)
  - Pinning with Nanomagnets-1997

Magnetic Phase Diagram
Type II Superconductor

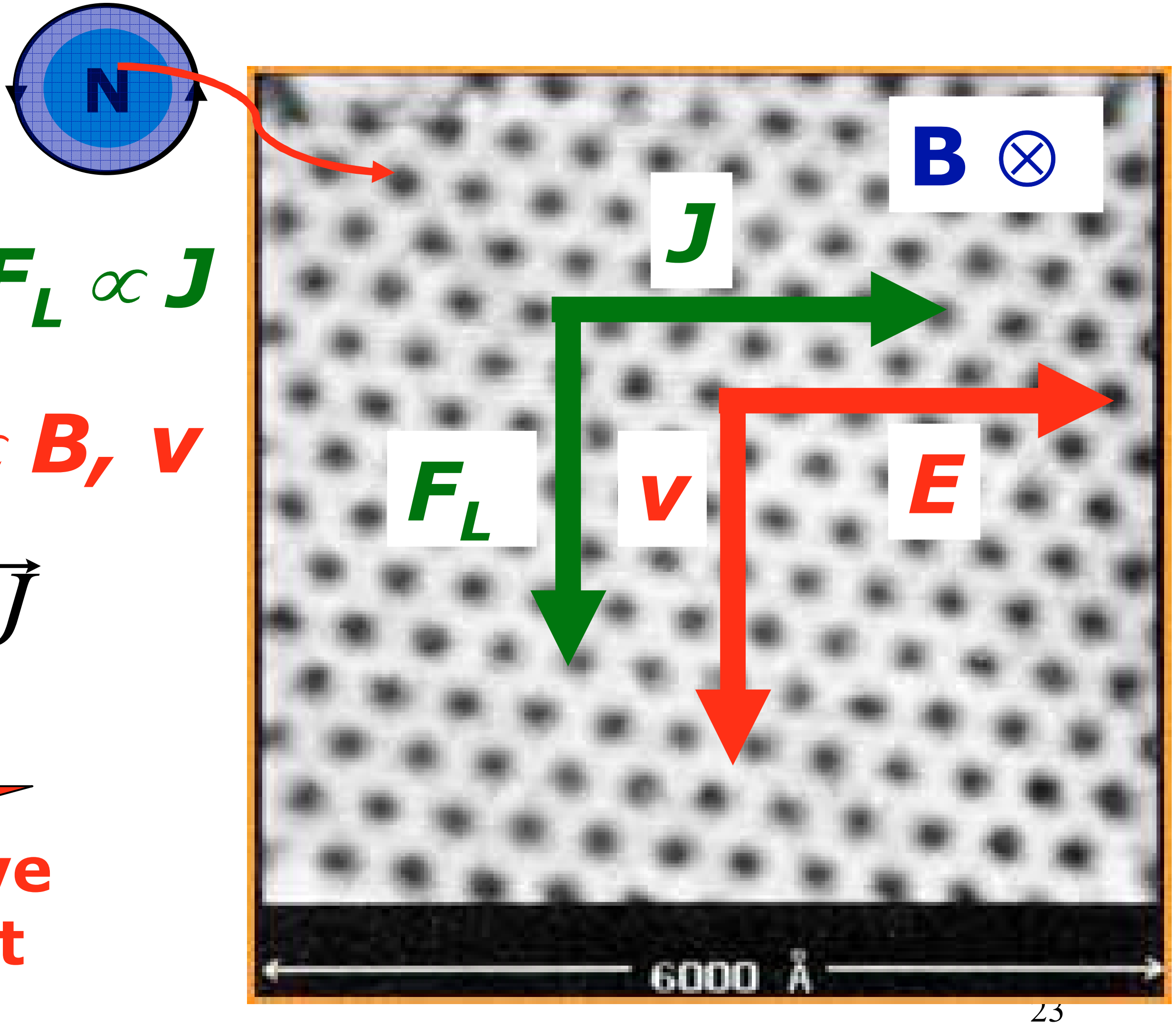
2003
Nobel



Vortex Density

$$\frac{1}{a_0^{\,2}} \approx \frac{B}{\phi_0}$$

Vortex-vortex Interaction → **Abrikosov Lattice**



H.F. Hess *et al. PRL* (1989)

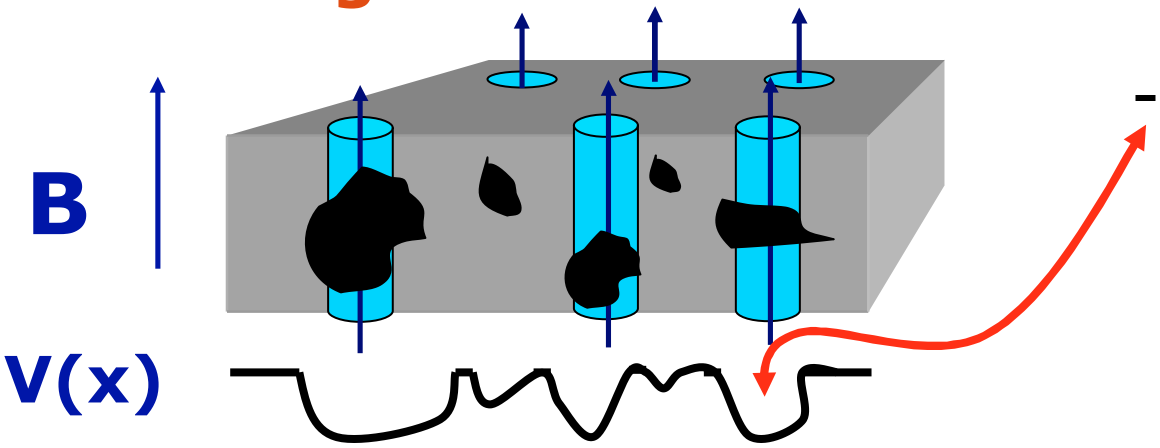
$$\vec{F}_L = \vec{J} \times \vec{B} \qquad F_L \propto J$$

$$\vec{E} = \vec{B} \times \vec{v} \qquad E \propto B, v$$

$$\vec{E} = \rho \vec{J}$$

Dissipative transport

Pinning

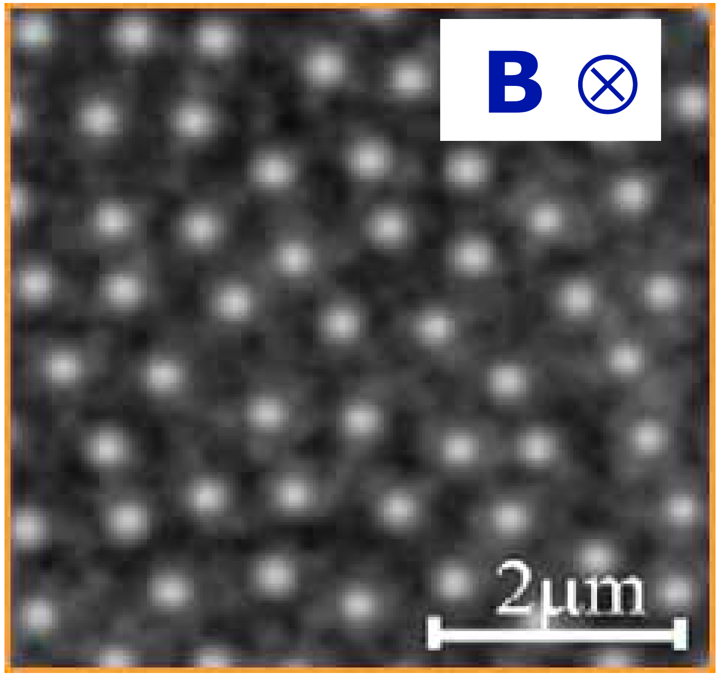


$-dV/dx = F_p$

$F_L < F_P$ ($J < J_c$)

$\rho = 0$

Intrinsic



A. Volodin *et al.*, EPL 2002

Artificial
Size?

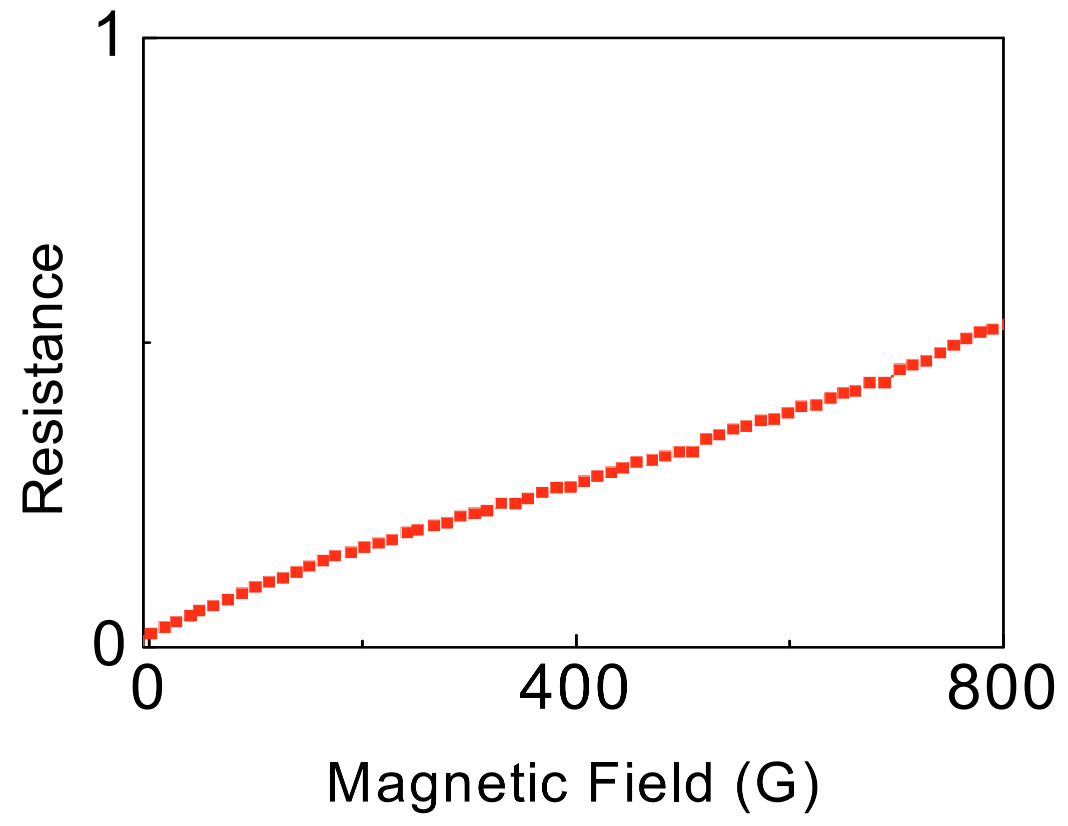
ξ, λ

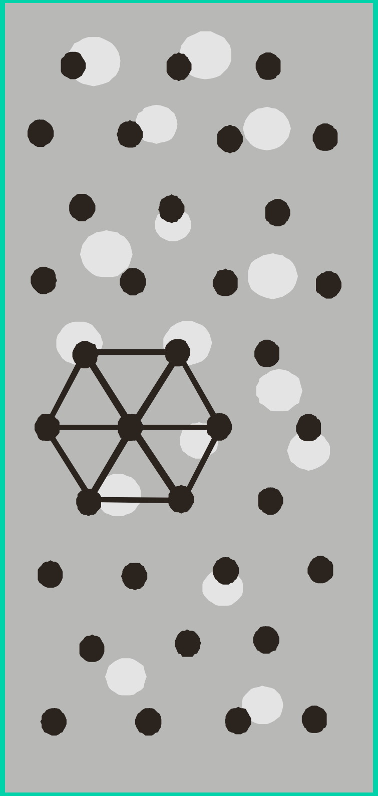
10-100 nm

What to Expect ???

Natural Impurities:
Random Pinning

Nb Film





I wonder what happens if the pinning sites Are periodic ??????

Piero Martinoli-1974

THE NEW YORK TIMES, TUESDAY, APRIL 27, 2004

The Biggest Jolt to Power Since Franklin Flew His Kite

By BARNABY J. FEDER

SCHENECTADY, N.Y. — In a one-time printing plant on the edge of this tattered manufacturing city, a small company named Superpower churns out sample after sample of what looks like shiny metal tape.

The tape has five layers. The middle one, a ceramic film one-tenth as thick as a human hair, exhibits one of nature's most tantalizing tricks. At very low temperatures, the ceramic abruptly loses all resistance to electrical current.

That free-flowing current generates a strong magnetic field, a feature that Superpower technicians demonstrate by showing visitors how a thumbnail-size magnet floats half an inch or so above a ribbon of chilled tape.

Superconductivity, as the phenomenon is known, has fascinated and baffled scientists since its discovery in 1911. Even now, they have yet to develop a comprehensive theory to explain its appearance in materials as diverse as metal and ceramics.

Such scientific conundrums are of only passing interest at Superpower, a four-year-old subsidiary of Intermagnetics General, and at other companies like it. After years of false starts and setbacks, these companies say they are closing in on the goal of producing relatively inexpensive superconducting wire for power generators, transformers and transmission lines.

Success requires making yard after yard of wire, and eventually mile after mile. The focus at the companies, at national laboratories and at many universities is on questions that call for a genius more like Edison than Einstein.

"We are finding out what works and going with that," said Dr. Jodi L. Reeves, a senior materials scientist at Superpower.

Success could spring superconduc-

High-Speed Tape? Try This

Several companies are trying to cut the costs of making superconducting tape-like wire (right), which is wound into cable. Here is one approach.

PRESENT VERSION Now used in commercial products and prototype electrical applications.

NEWER WIRE Cheaper, with potential for higher performance using nanodots.

DESIGNED TO INCREASE FLOW Magnetic fields surround all electric current. As current increases, these "flux lines" impede the path of electricity.

"Nanodots," each about 100 atoms [illegible] non-superconducting particles tha[illegible] flux lines and hold them in place. [illegible] lines pinned, current can flow unrestricted.

Source: American Superconductor Corp.

Bill Marsh/The New York Time

low zero Fahrenheit. To reach that point, they have to be cooled by liquid helium, which is expensive to make and manage.

By contrast, ceramic superconductors work at temperatures above minus 321 Fahrenheit, allowing them to be cooled by liquid nitrogen, an inexpensive industrial refrigerant. For that reason, they are called high-temperature superconductors, though they are still far from the dream of a room-temperature superconductor.

The first reports of ceramic superconductors, in 1986, touched off a global research race to understand them and find others. The excitement peaked at the annual meeting of the American Physical Society in March 1987, when thousands of researchers crowded into a hastily organized midnight presentation.

ness. Experts from Intermagnetics General, a manufacturer of superconducting metals that was spun out of General Electric in 1971, immediately began work on the materials.

"Superconductivity was guaranteed to be a field where everything you did would be new," said Dr. Venkat Selvamanickam, who joined the first wave of research as a graduate student at the University of Houston, home to one of the leading

On the verge of making electricity leaner and meaner

the magnetic field drift through the superconducting layers of the tape like swirling weather systems through the atmosphere. Figuring how to immobilize [illegible] magnetic vortices, an atomic-scale process called pinning, has emerged as a crucial area for research.

Early ceramic compounds were based on bismuth. The complexity of manufacturing and the need to rely on silver substrates to provide a workable mix of strength and stability to the bismuth compounds kept costs so much higher than standard copper wires that companies lost confidence that they could compete [illegible] mass markets.

Although bismuth-based wires have been useful for research and in a few products that help stabilize power grids, the spotlight has shifted to another compound, a mixture of

The last steps will not be easy While the semiconductor industry works on improving technology t produce ever thinner films, superconductivity companies chase th opposite goal, making thicker film to carry more current.

The best available process for depositing YBCO involves blasting chunk of it in a vacuum chambe with high-energy laser pulses an running the tape through the resulting plume. But pulsed lasers use to much time and money to produc large quantities of wire. So companies are looking for other methods.

"There's probably a dozen ways t deposit the superconductor," sai Dr. Dean Peterson, head of the research program at the Los Alamo National Laboratory, which has bee researching the alternatives an how to improve them

NANODOTS

Figuring how to immobilize the magnetic vortices,
an atomic scale process called pinning,
has emerged as a crucial area of research

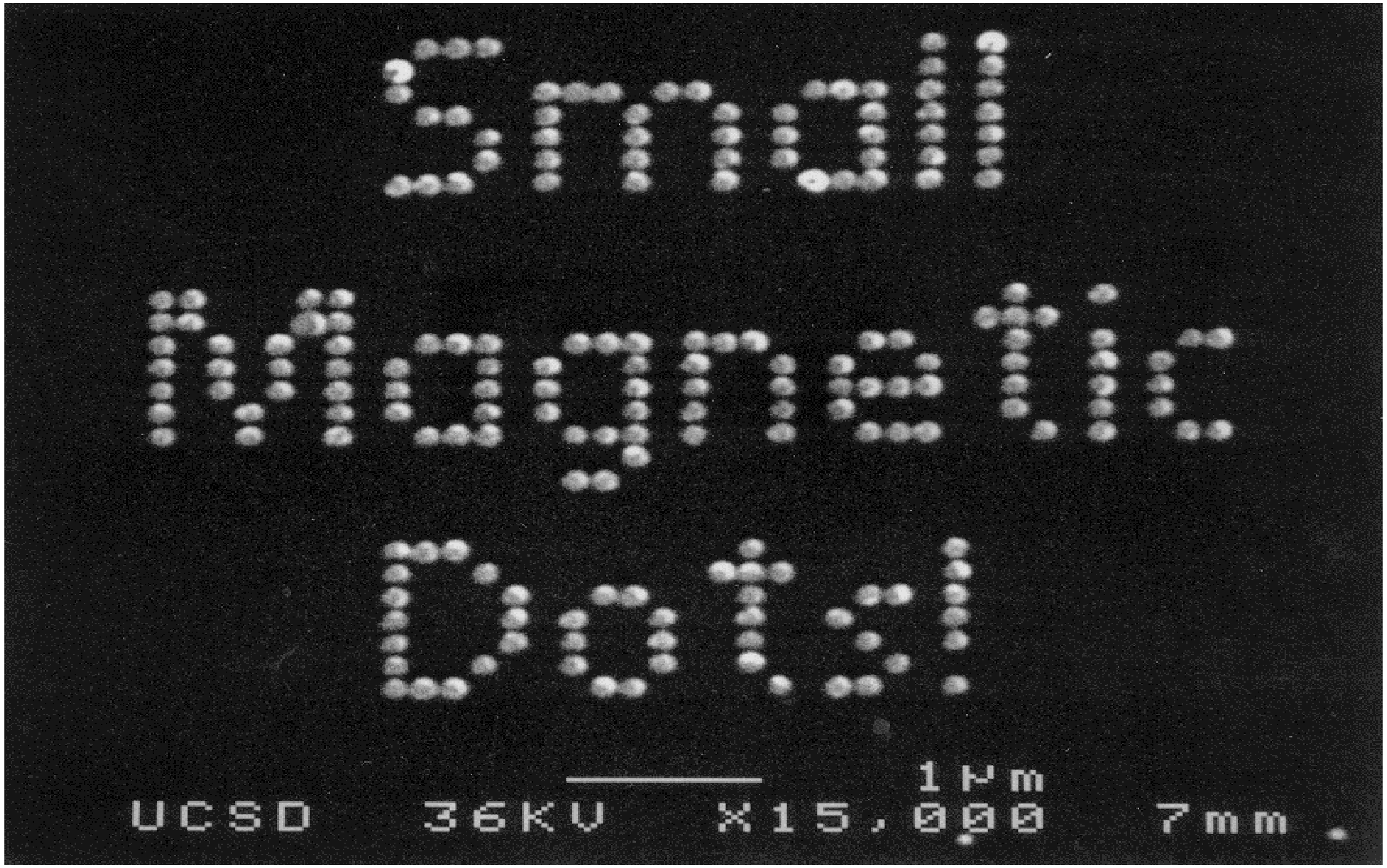
DESPINA E DON ALFONSO
In poch'ore, lo vedrete,
Per virtù del magnetismo,
Finirà quel parossismo

DESPINA AND DON ALFONSO
In a few hours, you will see
The power of magnetism
Will end this…

(Passion, Excitement, Tumult, Orgasm,…)

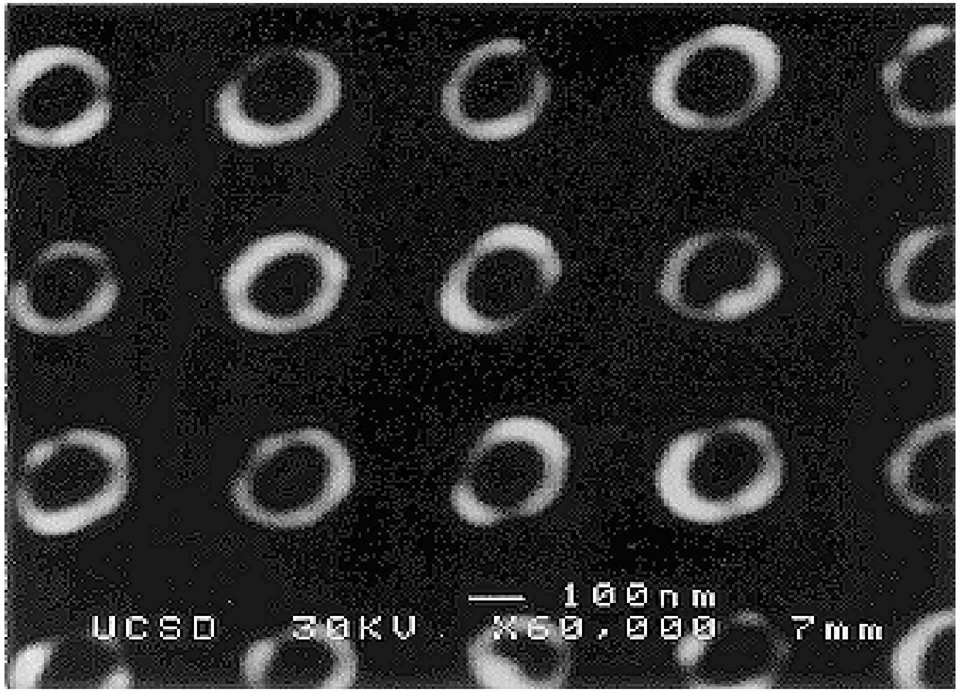
Cosi fan tutte
W. A. Mozart-1790

Periodic Vortex Pinning with



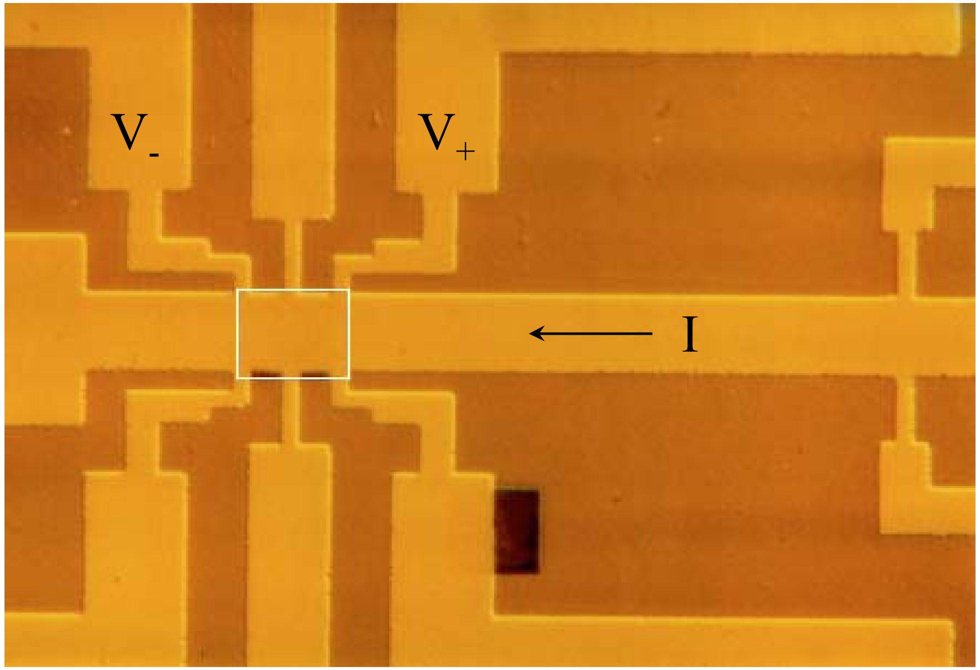
**Maribel Montero, Jose Martin, Javier Villegas,
Pilar Gonzalez, Elvira Gonzalez
Jose L. Vicent, Ivan K. Schuller**

Nanostructures



Magnetic Dots

Microstructures

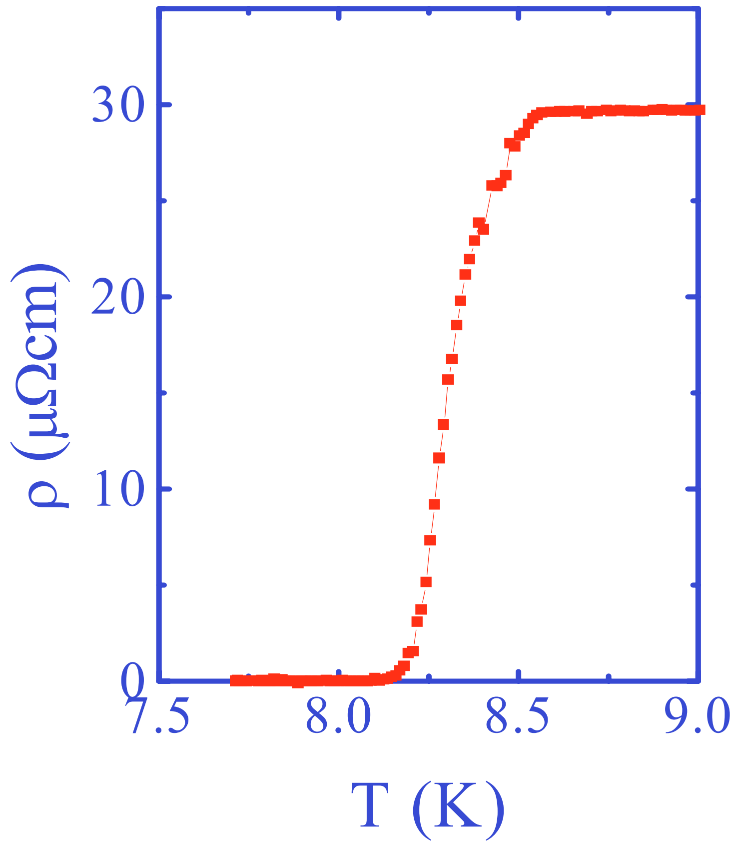


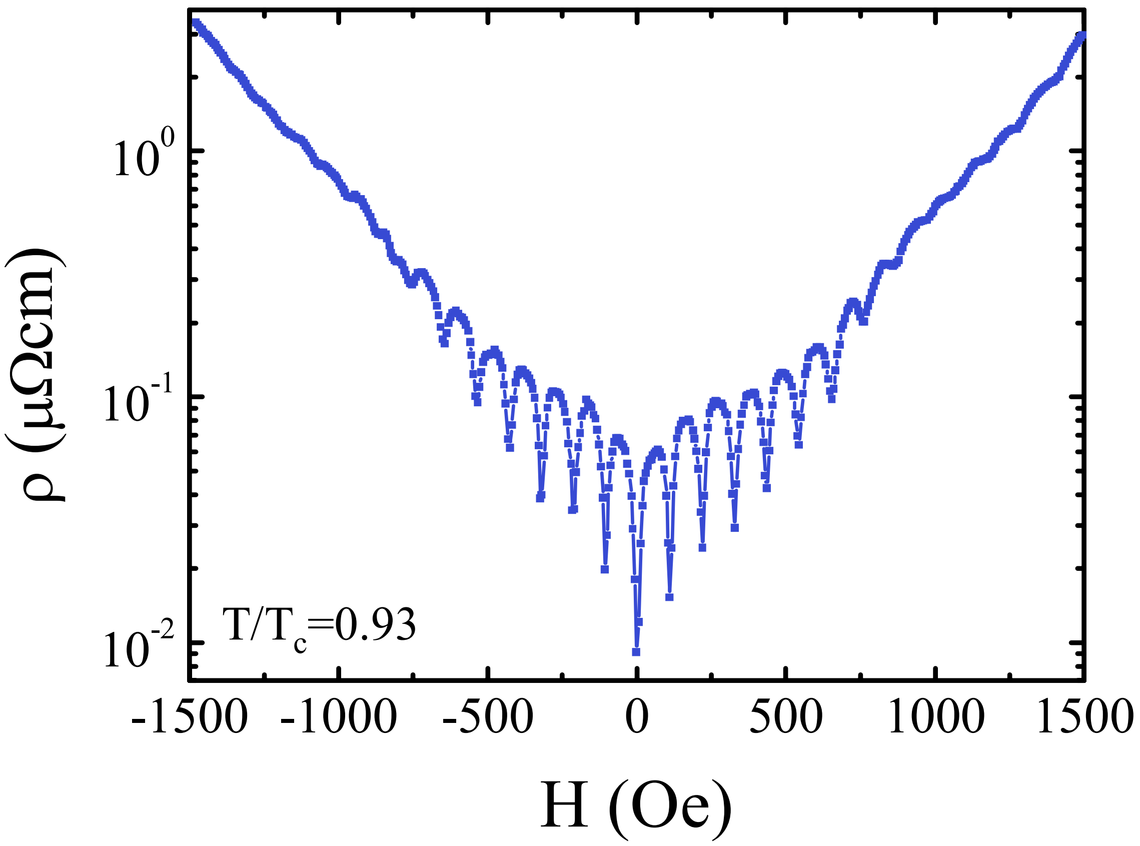
Nb Film

SURPRISE

Magnetoresistance

(Dynamic)

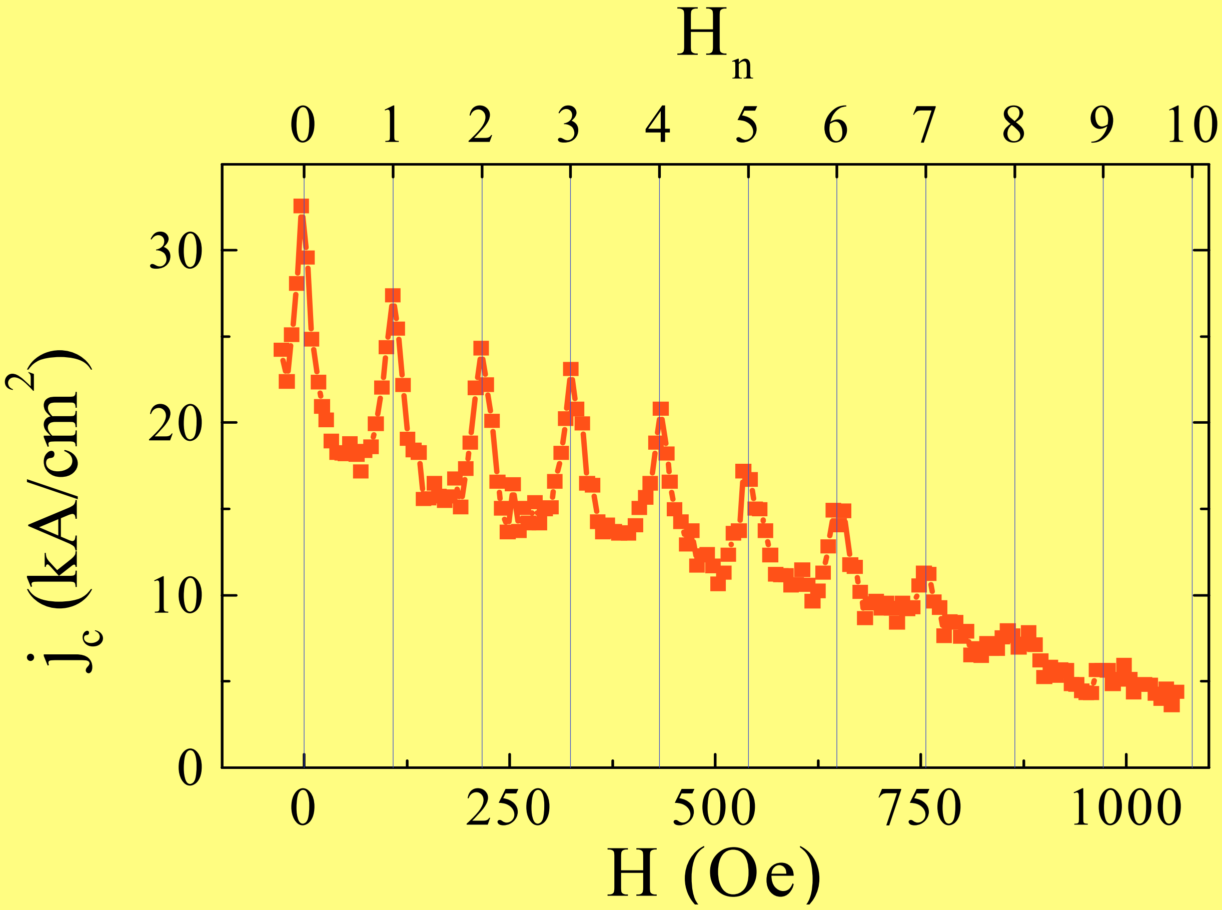




- up to 8th order peaks!
- square lattice of Ni dots (∅ 340 nm)

Critical Current

(Static)



Matching Field:

$$H_1 = \frac{\Phi_0}{a^2}$$

a: lattice parameter

$\Phi_0 = 20.7\ \mathrm{G\mu m^2}$

REMEMBER

$\mathcal{H}$ proportional
to
number of vortices

n=1 implies 1 vortex/plaquette
n=2 implies 2 vortices/plaquette

……………………

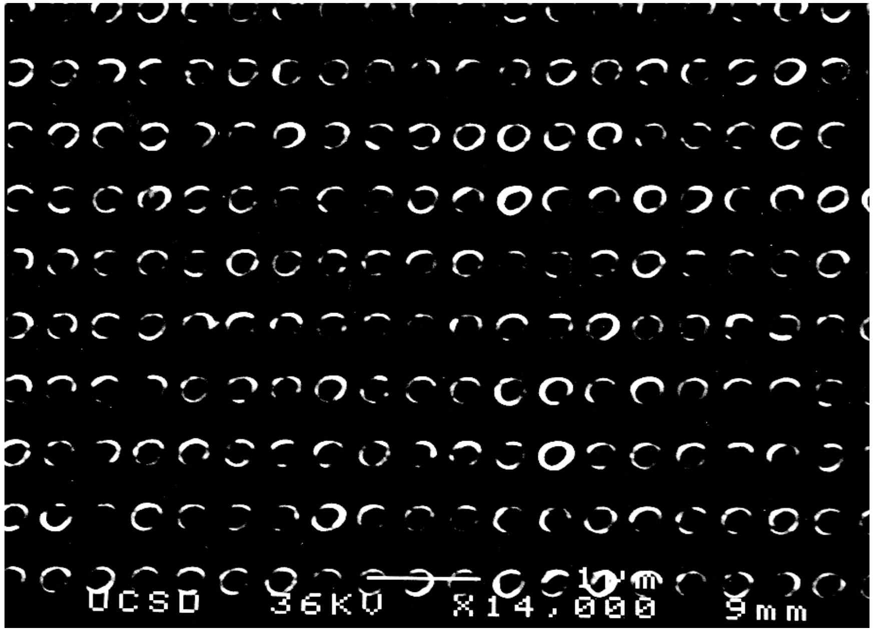
Rectangular Arrays

Pinning vs. Elastic Energy

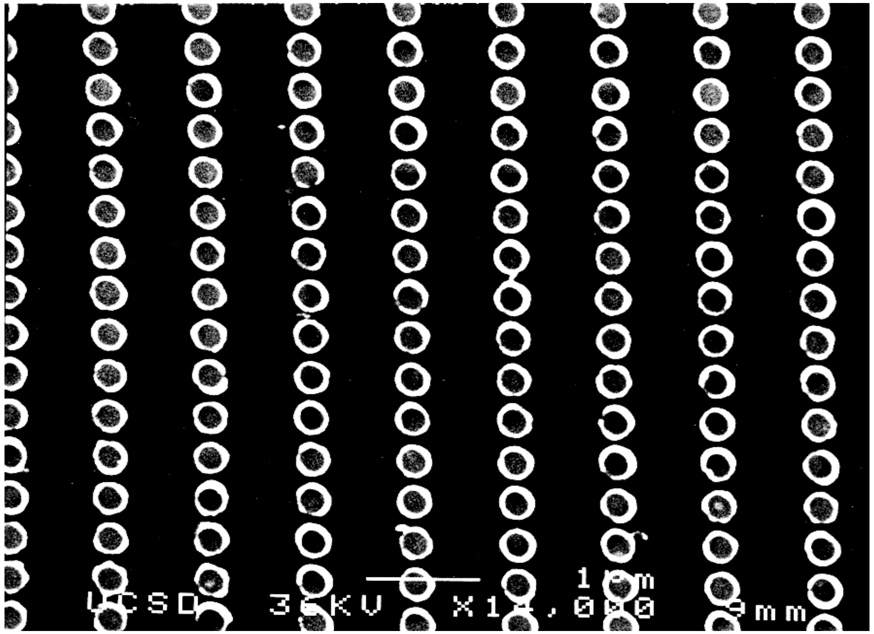
Interaction
Vortex + Pinning Center

Interaction
Vortex + Vortex

Rectangular Arrays



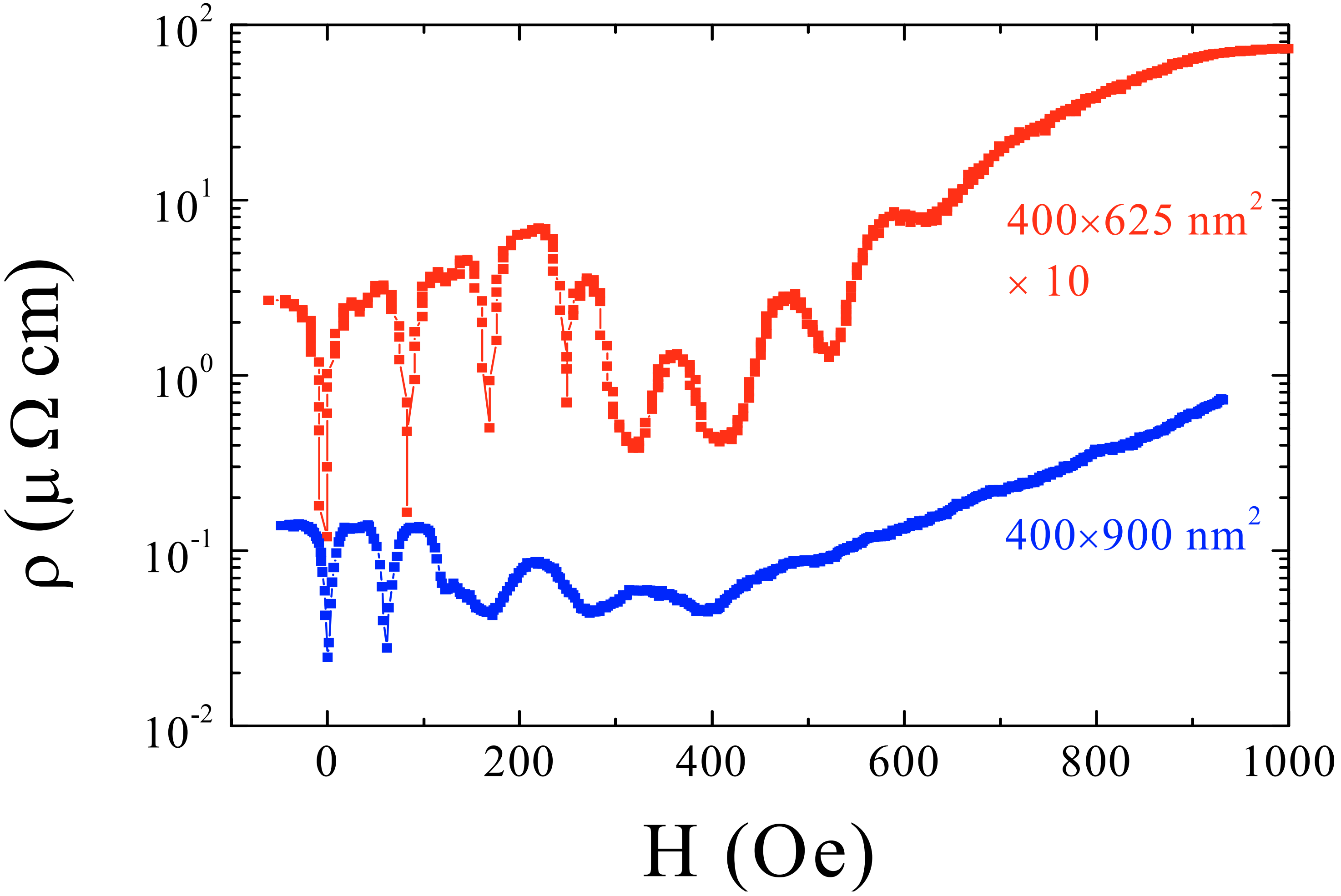
a = 400 nm
b = 625 nm



a = 400 nm
b = 900 nm

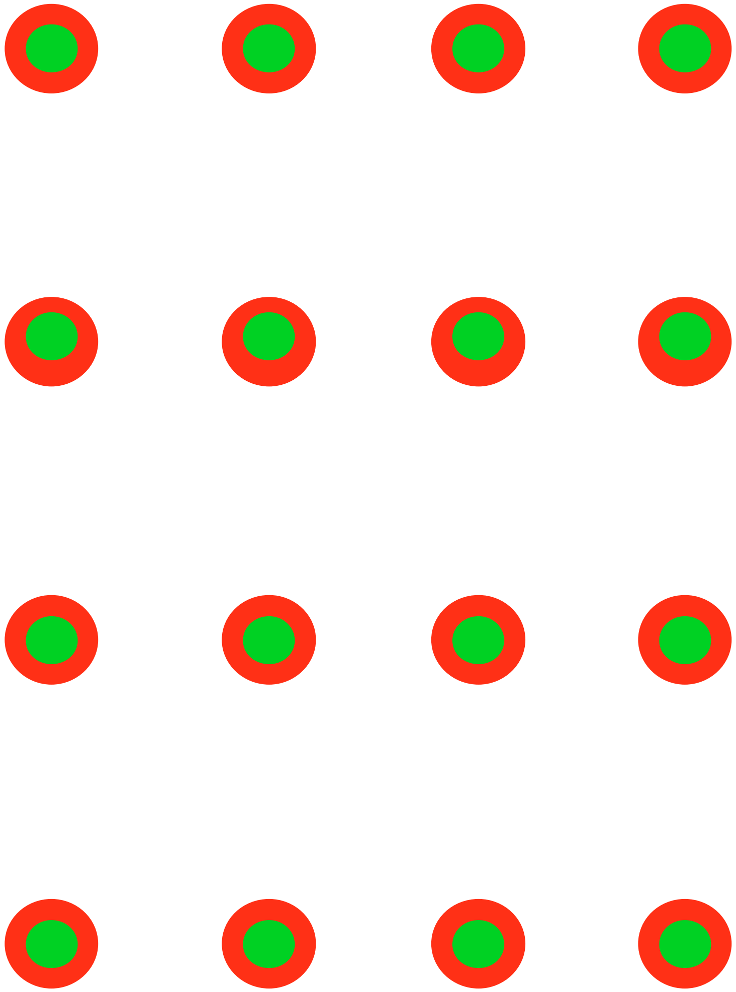
SURPRISE

Magnetoresistance



2 different periodicities !

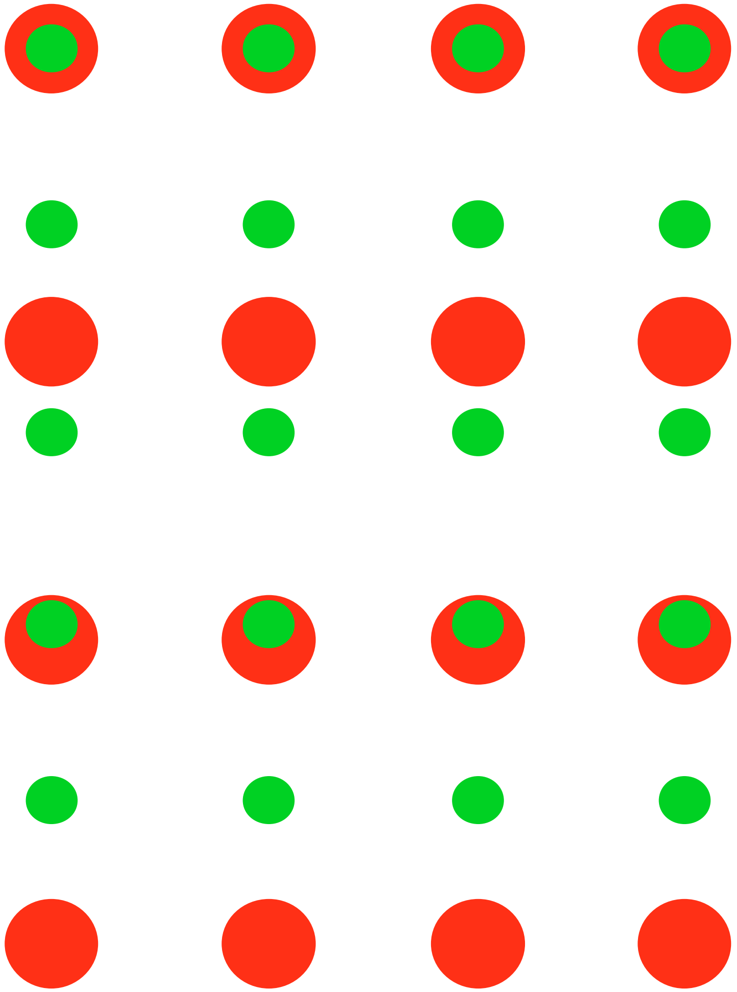
Low Fields



- Geometric matching

🔴 Dot 🟢 Vortex

High Fields



- **Reconfiguration to square lattice**
- **Matching along direction of motion**

Experiment: ΔH = **112, 115 Oe**

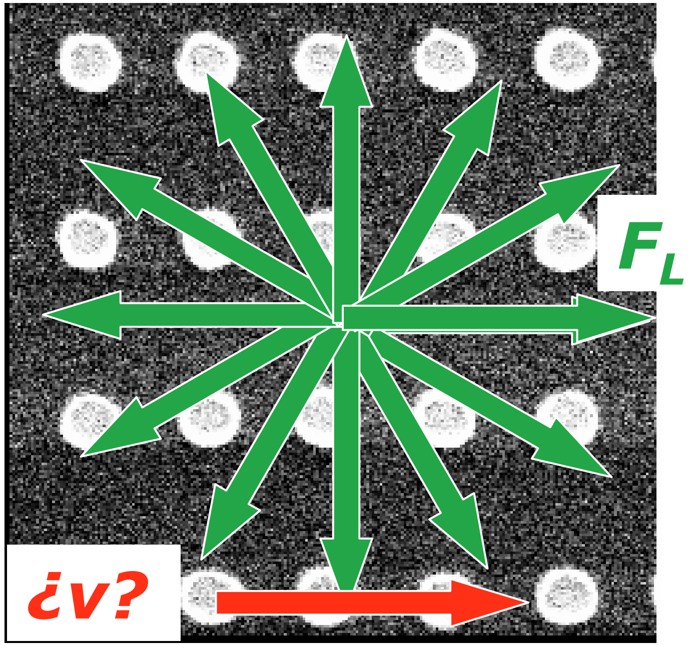
Theory: ΔH = **129 Oe**

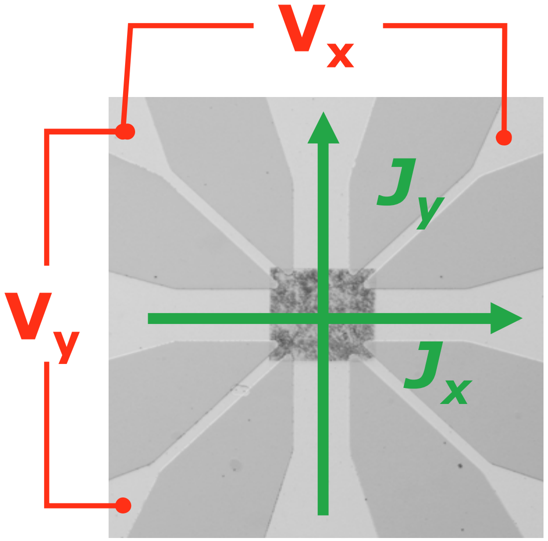
Vortex Motion →

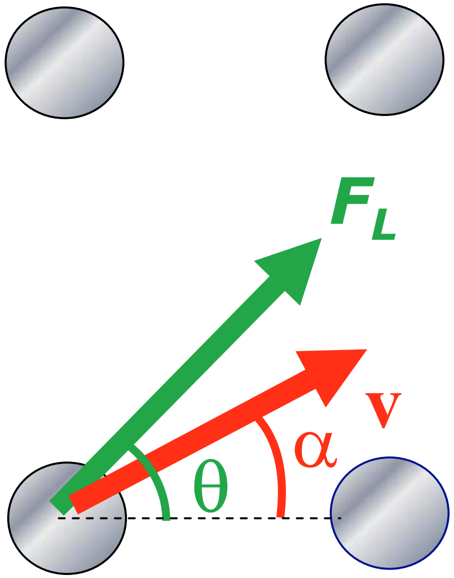
Elastic vs. Pinning Energy

- Crossover: $E_{Pinning} = E_{Elastic}$
- $E_{Elastic}$ can be calculated
- Allows to determine $E_{Pinning}$
- $E_{Pinning} \approx$ 0.6 eV/Dot

Varying Force Direction







$$F_L \propto J$$

$$V \propto v$$

$$F_L = \sqrt{F_x^{\,2} + F_y^{\,2}}$$

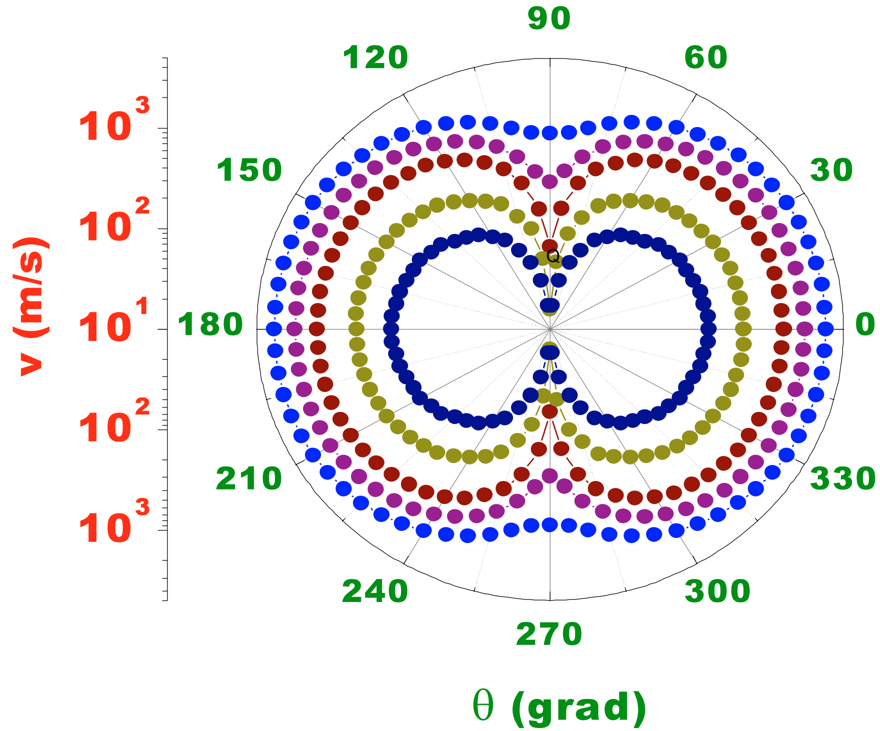
$$\theta = \arctan(F_x / F_y) = \arctan(J_y / J_x)$$

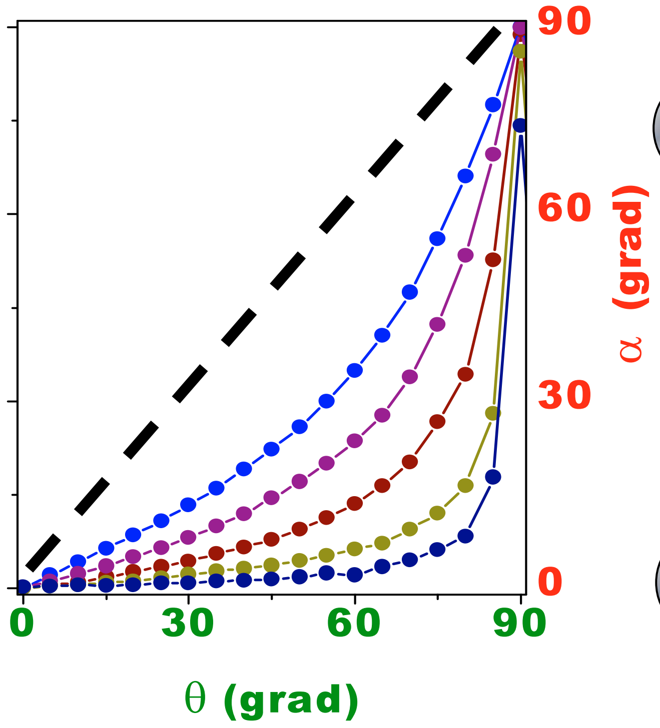
$$v = \sqrt{v_x^{\,2} + v_y^{\,2}}$$

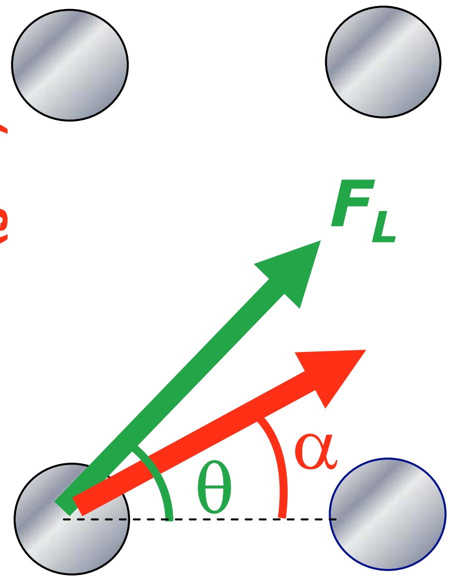
$$\alpha = \arctan(v_x / v_y)$$

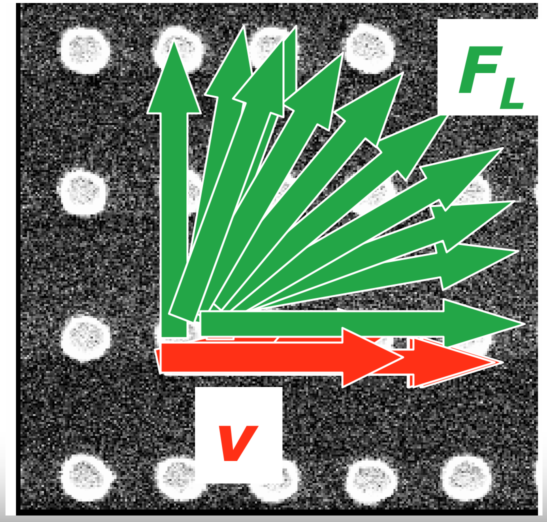
SURPRISE

Channeling









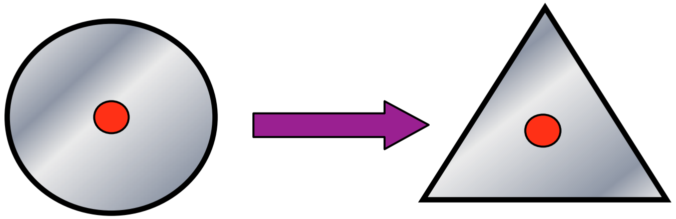
- Small distance → easy axis

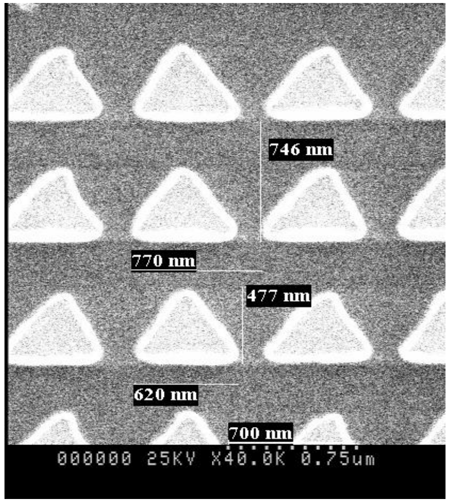
- Very Anisotropic Resistance

- Guided motion

INDUCED PHENOMENA

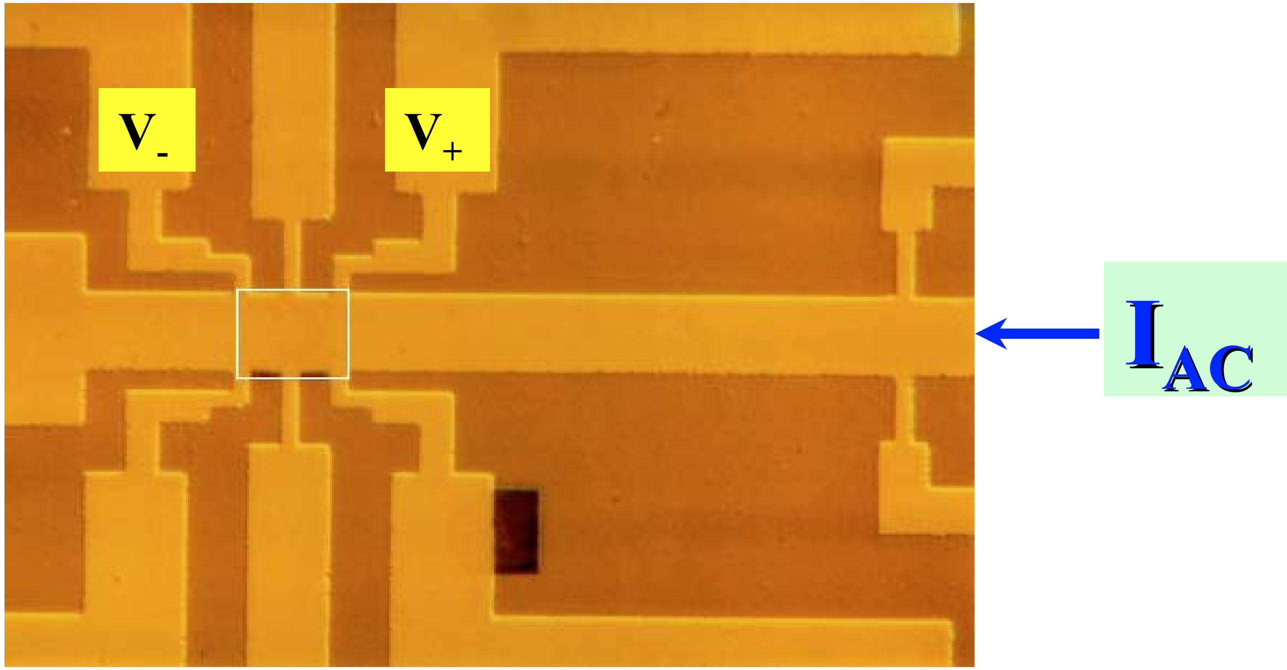
Asymmetric





AC drive

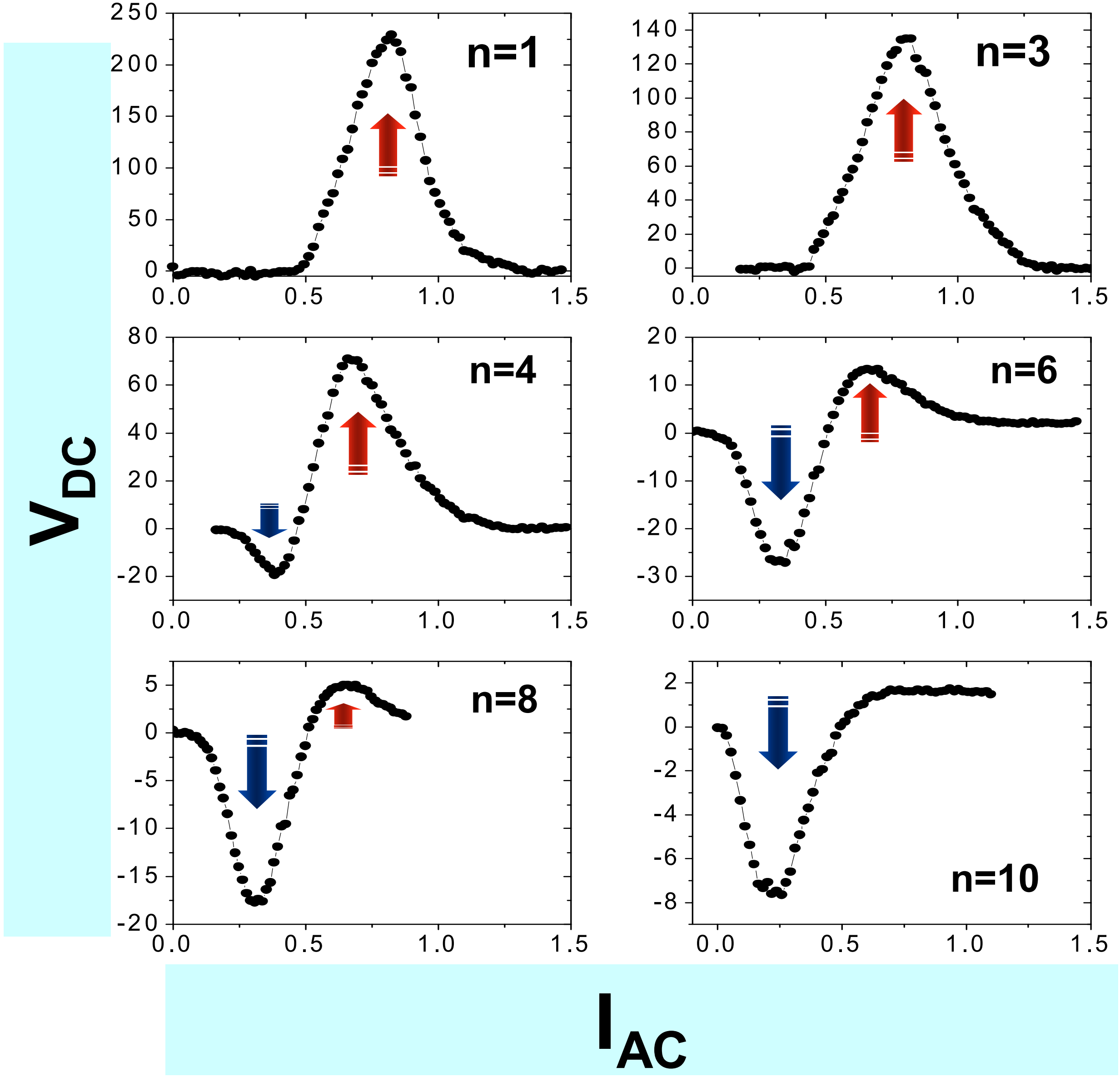
Measure DC

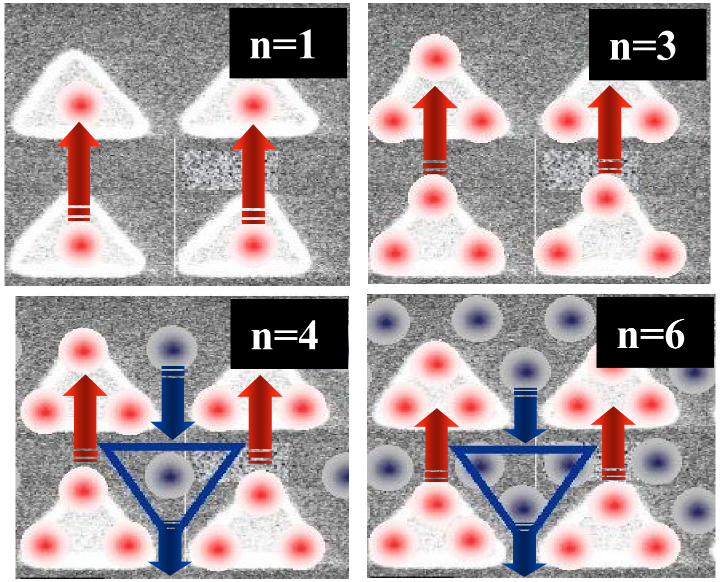


What to Expect ? **NIENTE**

SURPRISE

J. E. Villegas, J. Vicent *et al.* **Science 302,** 1189 (2003)





n number of vortices per unit cell

$T = 0.98T_c$

$F = 10$ kHz

Amplitude Controlled Rectification

UNEXPECTED

- **Periodic Pinning**

  Martin, IKS-Phys. Rev. Lett.

- **Channeling**

  Villegas, Vicent, Montero,IKS- Phys. Rev.

- **Rectification with Triangular “Dots”**

  Villegas, Gonzalez, Vicent- Science

NEW FUNCTIONALITIES

- **Confinement**
- **Proximity Effect**
- **External Stimulii**

Geometry
Dissimilar, *1-3 D*
E, B, light,….

Together Very Interesting

SUMMARY

Periodic pinning by arrays of nanostructured magnetic dots

- Maxima and minima in R, Jc
- Magnetic effects
- Structural effects
- Unexpected

Elastic , Channeling, Ratchet

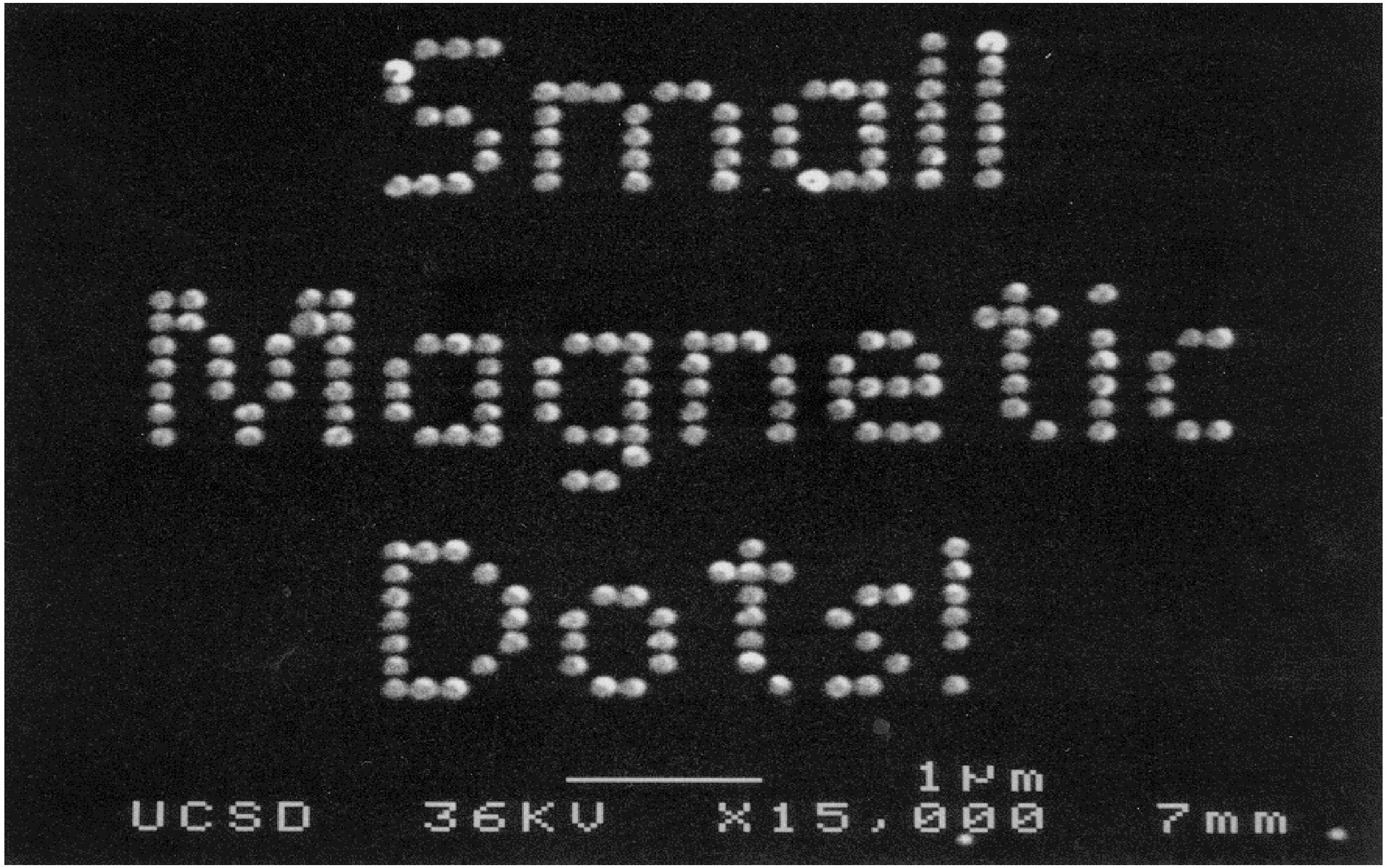
OPEN ISSUES

- Position of vortices ?
- Triangular vs Square ?
- Novel Josephson Effect
- Noise
- Devices
- Quantum Computing
- Unexpected

Ongoing Experiments

- Nb Thickness
- Location of vortices
- Asymmetric empty triangles
- Self assembled dots
- Exchange biased dots
- Angular dependence
- Disorder
- Noise

Periodic Vortex Pinning with



CONNECTIONS

INTERACTIONS OF TWO PERIODS

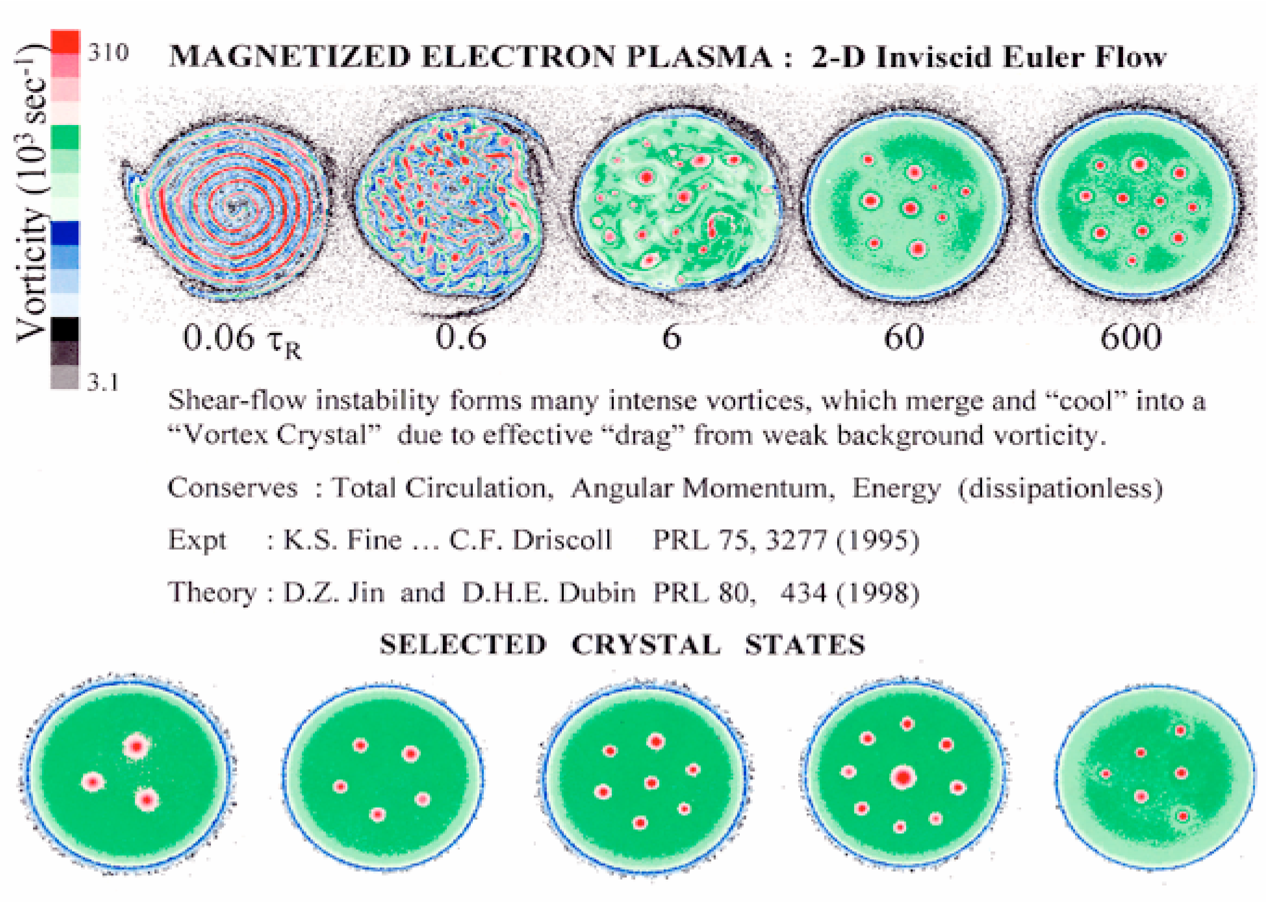
1.	EPITAXIAL GROWTH	Soft on Rigid Lattices
2.	2 D MELTING	Noble Gases on Graphite
3.	PLASMA PHYSICS	Vortices in Charged Plasmas

INDIRECT

1.	PROBE MAGNETIC STATE	Nanomagnetism
2.	MODEL SYSTEM	Ratchet (Biology)

APPLICATIONS

1.	NOVEL JOSEPHSON	H dependent υ
2.	NOISE REDUCTION	SQUIDS



MAGNETIZED ELECTRON PLASMA : 2-D Inviscid Euler Flow

Shear-flow instability forms many intense vortices, which merge and "cool" into a "Vortex Crystal" due to effective "drag" from weak background vorticity.

Conserves : Total Circulation, Angular Momentum, Energy (dissipationless)

Expt : K.S. Fine … C.F. Driscoll PRL 75, 3277 (1995)

Theory : D.Z. Jin and D.H.E. Dubin PRL 80, 434 (1998)

SELECTED CRYSTAL STATES

Relevance to this conference

Any thing interesting in superconductor ?

- Critical field
- T_c
- J_c
- Driven states

- Any thing interesting in ferromagnet ?

- Ferro State Different ?
- Scattering times
- Spin splitting
- Coulomb blockade
- Inelastic e-tunneling

Representative Publications from UCSD

- **New Josephson-like Effect in a Superconducting Transformer**
  A. Gilabert, Ivan K. Schuller, V.V. Moshchalkov and Y. Bruynseraede
  Appl. Phys. Lett. **64**, 2884 (1994).
- **Flux Pinning in a Superconductor by an Array of Submicrometer Magnetic Dots**,
  J.I. Martin, M. Velez, J. Nogues and Ivan K. Schuller
  Phys. Rev. Lett. **79**, 1929 (1997).
- **Artificially Induced Reconfiguration of the Vortex Lattice by Arrays of Magnetic Dots**
  Jose I. Martin, M. Velez, A. Hoffmann, Ivan K. Schuller, and J.L. Vicent
  Phys. Rev. Lett. **83**, 1022 (1999).
- **Individual and Multi Vortex Pinning in Systems with Periodic Pinning Arrays**
  C. Reichhardt, C.T. Zimanyi, R.T. Scalettar, A. Hoffmann and Ivan K. Schuller
  Phys. Rev. B **64**, 052503 (2001).
- **Nanostructures and Proximity Effect**
  M.I. Montero, Kai Liu, O.M. Stoll, A. Hoffmann, Ivan K. Schuller, Johan J. Åkerman, J.I.Martin, J.I. Vicent, S.M. Baker, T.P. Russell, C. Leighton and J. Nogues
  J. Phys. D 35, 2398 (2002).
- **Directional Vortex Motion Guided by Artificially Induced Mesoscopic Potentials**
  J.E. Villegas, E.M. Gonzalez, M.I. Montero, Ivan K. Schuller and J.L. Vicent,
  Phys. Rev. B **68**, 224504 (2003).
- **Mechanism of Periodic Pinning in Superconducting Thin Films**
  M.I. Montero, O.M. Stoll, and Ivan K. Schuller
  Eur. Jour. Phys. B. (2005-In Press).

http://ischuller.ucsd.edu

Fini-End-Fin-Ende