SCHULLER GROUP

- **Nanoscience**: Thin Film, Lithography
- **Magnetism**: Exchange Bias, Tunneling, Transport
- **Superconductivity**: Pinning, Photoinduced, Search
- **Superlattices**: Metal, Organic, Oxides, Semicond.
- **Organics**: Metallo-Phthalocyanines
- **Oxides**: Transition Metals, Perovskites
- **Applications**: Sensors, Storage, Magnetic devices
- **Movies and Plays**

http://ischuller.ucsd.edu
Enjoy the Process

• Caminante no hay camino, se hace el camino al andar.

Antonio Cipriano José María y Francisco de Santa Ana Machado y Ruiz
(26 July 1875 – 22 February 1939)

• Wanderer, there is no road, the road is made by walking.
Proximity Between Dissimilar Magnets

$T_N << T_C$

**Anomalous Spontaneous Reversal in Magnetic Heterostructures,**
PLEASE ASK QUESTIONS

WHY?

- Keeps you focused
- Keeps you awake
- You learn more
- Develop interest

Feed Back Please
35 Years of Metallic Superlattices

IEEE Distinguished Lecturer

IVAN K. SCHULLER

University of California
San Diego

DOE
NSF, AFOSR, ONR
• IEEE Magnetics Society Home Page: www.ieeemagnetics.org
  – 3000 full members
  – 300 student members

• The Society
  – Conference organization (INTERMAG, MMM, TMRC, etc.)
  – Student support for conferences
  – Large conference discounts for members
  – Graduate Student Summer Schools
  – Local chapter activities
  – Distinguished lectures

• IEEE Transactions on Magnetics
  – ~2000 peer reviewed pages each year
  – Electronic access to all IEEE Transactions on Magnetics papers

• Online applications for IEEE membership: www.ieee.org/join
  – 360,000 members
  – IEEE student membership  IEEE full membership
IEEE MAGNETICS LETTERS

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Thank you
1970s

RADIATION-HARD ALLOYS
Understanding the role that composition and precipitates play in determining materials properties leads to a new family of low-swelling stainless-steel alloys with improved performance in radiation environments.

METALLIC SUPERLATTICES
Sputtering techniques lead to the development of metallic superlattices and thus to new materials with novel magnetic and electronic properties.

CROSSED MOLECULAR BEAMS
The use of crossed molecular beams provides significant advances in the study of chemical reaction dynamics.

ELECTRONIC STRUCTURE OF METALLIC ALLOYS
The Kramers-Kahn Rostoker coherent potential approximation method brings about a new era in alloy theory that would allow calculation of physical and metallurgical properties based on the underlying electronic structure.

NMR STUDIES OF SURFACES AND CATALYSIS
Researchers develop new methods using nuclear magnetic resonance, which are a major stimulus to the study of surfaces and catalysis.

MIRROR CONFINEMENT
At Livermore, physicists explore the efficacy of the linear approach to plasma confinement with devices that include the 2DII-B and the Baseball II Magnet Mirror Machine.
35 years of METALLIC Superlattices
# JUNIOR

## UCSD
- Jose Colino
- Kai Liu
- Marie-Claire Cyrille
- Arjang Fartash
- Iatneng Chan
- Alberto Fernandes
- Eric Fullerton
- José M. Gallego
- Doris Girata
- Elvira Gonzalez
- Julio Guimpel
- Sihong Kim
- David Lederman
- Chris Leighton
- José I. Martín
- Tim Moran
- Osamu Nakamura
- María Vélez
- Josep Nogués

## ARGONNE LABS
- Cornell Chun
- Hitoshi Homma
- Indrajit Banerjee
- M.R. Khan
- Yves Lepetre
- J. Murduck
- T.R. Werner
- Q.S. Yang
- G.-G. Zheng
- Jia-Qi Zheng
- Eric Ziegler

## BELGIUM
- Kristian Temst
- Hans Vanderstraeten
- M. Gijs
- J.-P. Locquet
- W. Sevenhans

# LONG TERM

## Yvan Bruynseraede
- Ricardo Ramirez
- Miguel Kiwi
- Jose Vicent
- K.V. Rao
**EXCHANGE BIAS**

![Graph showing exchange bias with Hc values of 0.5, 2.0, and 5.0 kOe, and states of +1, 0, and -1.]

**APPLICATIONS**

- **Hard disk drives**
- **MRAM**
- **Sensors**

**GMR**

- Graph showing resistance ratio R / R(H=0) with states and magnetic field (kOe).

**SPIN TORQUE**

- Diagram showing spin torque with Co and Cu layers.

**SCIENCE**
Total # of records: 7174

Unemployment Solved

IN 2050 EVERYBODY WILL BE WORKING ON EXCHANGE BIAS

Source: ISI Web of Knowledge, July 8, 2011
PLAN

• Introduction and History

• Characterization

• Interface Effects:

  Structural length scale different from magnetic

  • Long Length Scales- Superlattice Effect:
    Collective Magnons in M/N

  • Short Length Scales- Superlattice effects:
    Oscillations in Resistivity

• Future
Why do all this?

Many layers, \( N \)

Three layers

Two layers

One layer

Superlattice effects

Coupling

Dimensional transitions

Spin transmission

Interfaces

Electron transfer

Strains

Proximity effects

Disorder

Confinement

Lower dimensionality
Double Unit Cell

Consequence of the Periodicity

Metal

Insulator
**VO₂**

Dimers to Single

*Peierls*

~ 0.32% Volume Change

**V₂O₃**

AFM to Para

*Slater*

1.4% Volume Change

![Graphs showing temperature vs. resistance for VO₂ and V₂O₃ films](image-url)
DICTIONARY

• Heterostructure (incoherent)
• Multilayer (long wavelength coherence)
• Superlattice (atomic scale coherence)
ATOMS → SOLIDS

DUE TO THE ADDED PERIODICITY
NEW EFFECTS APPEAR IN THE
ELECTRONIC PROPERTIES

FILMS → SUPERLATTICES

SUPERLATTICE EFFECTS!
Superlattice Effect

$E\text{ (eV)}$

$\pi/a$

$\pi/b$

$E_F$

$E\text{ (eV)}$

$K(\text{Å}^{-1})$

$\pi/c$

$\pi/2c$

$K(\text{Å}^{-1})$
In 4 or 5 years, this will be THE field in materials science.

...superlattices may lead to a new breed of electronic devices.

metal superlattices... for use in computer memories.
METALLIC SUPERLATTICE

WHY CARE ABOUT STRUCTURE?
STRUCTURE vs. PROPERTIES

• POSTULATE
  Properties of a solid are given by the atomic locations

• SMALL STRUCTURAL CHANGES
  Large effects on Physical Properties

• EXAMPLE
  2% expansion in lattice $\Rightarrow$ 100% change in elastic constant

CHARACTERIZE QUANTITATIVELY AT THE ATOMIC SCALE
MAGNETISM

Untwinned

Twinned

In-plane polycrystalline

ALL 110 FeF$_2$
EXCHANGE BIASED Fe/FeF2

\[ \text{Intensity (arb. units)} \]

\[ \log_{10}(\text{Intensity}) \]

\[ 10^{6} \]

\[ 10^{5} \]

\[ 10^{4} \]

\[ 10^{3} \]

\[ 10^{2} \]

\[ 10^{1} \]

\[ 1 \]

\[ 2 \]

\[ 3 \]

\[ 4 \]

\[ 2 \theta \text{ (deg)} \]

\[ \text{FeF}_2(110)/\text{Fe} \]

\[ T_s = 200^\circ\text{C} \]

\[ \sigma = 0.6 \text{ nm} \]

\[ T_s = 250^\circ\text{C} \]

\[ \sigma = 1.4 \text{ nm} \]

\[ T_s = 300^\circ\text{C} \]

High Frequency Peaks = FeF$_2$ ($\sim$ 90 nm)

Low Frequency Peaks = Fe ($\sim$ 13 nm)


29
STRUCTURE

“DETERMINE THE POSITIONS OF ALL THE ATOMS IN THE MATERIAL”

Find out: - Expansions
- Interdiffusion
- Roughness
- etc.

• ELECTRON MICROSCOPY
• DIFFRACTION
WHY CARE ABOUT STRUCTURE?

• Nothing is Perfect nor As Expected
• Small structural changes give BIG effects in the Physical Properties
STRUCTURAL MEASUREMENTS

Must Measure AFTER Synthesis

MANY RED HERRINGS
Py-V$_2$O$_3$ Bilayer

Field Cooling 1000 Oe
Field Cooling 1000 Oe

Kerr Effect

Py (30 nm)  V$_2$O$_3$ (100 nm)  Py (30 nm)

MOKE (arb. units)

H (Oe)

MOKE (arb. units)

H (Oe)
STRUCTURE IS IMPORTANT

**X-Ray Intensity**

Py (30nm) / V$_2$O$_3$ (100 nm)
Ni (30nm) / V$_2$O$_3$ (100 nm)

* V$_2$O$_3$
▼FM (Py or Ni)
• New Phase

**Unexpected FeO phase**
NOTHING IS PERFECT
ALL HAVE DISORDER

IF YOU MEASURE THEM PROPERLY
Merci-Pierre Dhez
<table>
<thead>
<tr>
<th>Capability</th>
<th>Neutrons</th>
<th>Synchrotron</th>
<th>Electron Micr</th>
<th>Scanning Probe</th>
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<td>☺</td>
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<tr>
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<td>☺</td>
<td>☺☺☺</td>
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## Sample Viewpoint

<table>
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<th>E- microscopy</th>
<th>Scanning Probe</th>
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</thead>
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<tr>
<td>Destructive</td>
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<td>☺☺☺</td>
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<tr>
<td>Smallest size</td>
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<td>☺☺☺</td>
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<tr>
<td>Interfaces</td>
<td>☺☺☺</td>
<td>☻</td>
<td>☺</td>
<td>☺</td>
</tr>
</tbody>
</table>
REFINEMENT

Somewhere, something went terribly wrong

SUPREX:
http://ischuller.ucsd.edu
How well do we need to know the structure???

Compare to Physical Length Scale and .........

Always remember limitations
PHILOSOPHY

Effects are interesting either if they:

- Cannot be explained as disorder
- Or
- Connected quantitatively to the structure
Physics Driving Force

DISORDER

• Surfaces
• Quantization

\[ \text{NANO, Nano, nano, nano} \]

• Extension of \( \Psi \)
• Extension of \( M \)

Proximity

New Paradigm Needed
STRUCTURAL DETERMINATION

- Quantitative
- Appropriate Length Scale

SMALL CHANGES IN THE STRUCTURE CAN PRODUCE LARGE EFFECTS IN THE PHYSICS

Remember limitations of techniques
Magnetic & Nonmagnetic Roughness
Mo/Ni Superlattices

Collaborators
J. Cable, ORNL
M. Khan, G. Felcher, ANL
Polarized Neutron Scattering

Mo/Ni Superlattices

- Square Modulation
- All possible models
- Experimental Flipping Ratio
Mo/Ni Superlattices

“A comparison of X-ray and neutron diffraction implies that the magnetic profile in the superlattice is more perfect than the chemical profile.”

Element Specific Magnetization of Buried Interfaces Probed by Diffuse X-Ray Resonant Magnetic Scattering

J. F. MacKay, C. Teichert, D. E. Savage, and M. G. Lagally

University of Wisconsin, Madison, Wisconsin 53706
(Received 18 January 1996)

The magnetization of buried interfaces and its relationship to interfacial roughness is probed for Co films and Co/Cu multilayers using diffuse x-ray resonant magnetic scattering, a method in which the average diffusely scattered x-ray intensity is compared with the component that reflects magnetic scattering. The comparison demonstrates that the boundary between magnetic and nonmagnetic layers is smoother than the interfacial roughness, with short-wavelength roughness less effective in magnetic scattering than longer-wavelength roughness. [S0031-9007(96)01572-4]

...the boundary between magnetic and nonmagnetic layers is smoother than the interfacial roughness.

FIG. 3. $\Delta f(M, \Omega)$ and $I_{\text{mvs}}(\Omega)$ transverse scans of a Co(2.0 nm)/Cu(1.0 nm)/Co(2.0 nm) sandwich capped with 2.0 nm of Al grown on Si(100). The diamonds are $I_{\text{mvs}}(\Omega)$ and the circles are $\Delta f(M, \Omega)$. The best fit to $I_{\text{mvs}}(\Omega)$ gives an rms roughness of $\sigma = 0.30$ nm and a correlation length $\xi = 13 \pm 1$ nm. The best fit to $\Delta f(M, \Omega)$ gives an rms roughness of the magnetic boundary of $\sigma = 0.15$ nm and a correlation length $\xi = 19 \pm 6$ nm.
So six blind men of Hindustan disputed loud and long,
Each in his own opinion exceeding stiff and strong;

Though each was partly in the right,
they all were in the wrong!
SYSTEMATIC STUDIES ESSENTIAL

- **Quantitative** (Structure,.....)
- **Systematic** (One parameter at a time)
- **Different** measurements on **same** samples
- **Reevaluate** (Even well accepted “facts”)

Many Surprises
A member of my crew must be tough, ruthless and never give up, even when things look completely hopeless!

What makes you think you qualify?

I worked for Ivan Schuller
WHY DO ALL THIS?

Many layers, N

Three layers

Coupling
Dimensional transitions
Spin Transmission

Two layers

Interfaces
Electron transfer
Strains
Proximity effects

One layer

Disorder
Confinement
Lower dimensionality

Superlattice effects
Exchange Bias

Free FM
- Exchange field $H_E=0$
- Small coercivity $H_C$
- Symmetric
- Uniform

Pinned FM
- Large $H_E$
- Large $H_C$

\[ H - H_E - 2H_C \]
AntiFerromagnet
SURFACE OR BULK

Confirmed by Mossbauer, Synchrotron,\textsuperscript{59}Neut
**FM/AF/FM**

**Parallel**

![Py](#) FeF$_2$  
Ni

**Anti-parallel**

![Py](#) FeF$_2$  
Ni

200 nm

**Graph**

- **H$_{EB}$ (Oe)**
  - 400
  - 300
  - 200
  - 100
  - 0

- **T (K)**
  - 20
  - 40
  - 60
  - 80
  - 100

- **T (K)**
  - 20
  - 40
  - 60
  - 80
  - 100

**Ni**
Radiation Damage

Magnetic Field (kOe)

T=10K

M/M_S

-2 -1 0 1 2

-1.0 -0.5 0.0 0.5 1.0

H^B_EB =66.5mT
H^D_EB =40.9mT

He^+
Ferromagnet-Oxide
\( \textbf{VO}_2 \) 

\( \textbf{V}_2\text{O}_3 \)

\( R (\Omega) \)

\( \text{Temperature (K)} \)

\( \sim 0.32\% \text{ Volume Change} \)

\( 1.4\% \text{ Volume Change} \)
Interface Coupling in Ni/V\textsubscript{2}O\textsubscript{3}

Metal Insulator Transition + Structural Phase Transition

Change of M and H\textsubscript{c} at MIT and SPT
WHY DO ALL THIS?

Many layers, $N$  
Superlattice effects

Three layers  
Coupling  
Dimensional transitions  
Spin Transmission

Two layers  
Interfaces  
Electron transfer  
Strains  
Proximity effects

One layer  
Disorder  
Confinement  
Lower dimensionality

- Interfaces
- Electron transfer
- Strains
- Proximity effects

- Disorder
- Confinement
- Lower dimensionality

- Coupling
- Dimensional transitions
- Spin Transmission

- Many layers, $N$
- Three layers
- Two layers
- One layer
Magnetotransport in Superlattices

Collaborators

C. Falco, ANL
J. Hilliard, J. Ketterson, B. Thaler, Northwestern
R. Lacoe, R. Dee, UCLA
In the Beginning ...

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, Massachusetts Institute of Technology

American Institute of Physics
New York 1979
TRANSPORT PROPERTIES OF THE COMPOSITIONALLY MODULATED ALLOY Cu/Wi*

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

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

R. Lacey, 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/Wi 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 (CMA). This has been motivated by elastic constant measurements which showed an anomalous enhancement of the biaxial modulus as a function of modulation wavelength $\lambda$ 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 measurements 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, anodized 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:0094-229X/79/530417-06$1.50 Copyright 1979 American Institute of Physics
GMR in Fe/Cr superlattices

2007 PHYSICS NOBEL

Grunberg

Fert
DON’T LET YOUR ELDERS DEPRESS YOU !!!!

• Pushing the Limits is Important
  • Make New Materials
  • Something will happen
WHY DO ALL THIS?

Many layers, N

Superlattice effects

Coupling
Dimensional transitions
Spin Transmission

Interfaces
Electron transfer
Strains
Proximity effects

Disorder
Confinement
Lower dimensionality

One layer

Two layers

Three layers
PROPERTIES WHICH DEPEND ON THE SUPERLATTICE NATURE?

Relevant Length scale?

1. X-rays \textit{Sensitive to disorder!}

2. Magnons \textit{Long length scale}
   \textit{Dipolar} \approx 200 \AA

3. Resistivity \textit{Very high compared to bulk}
   \textit{Monotonic vs. Periodicity (\Lambda)}

RESISTORS IN PARALLEL
SUPERLATTICE EFFECTS IN THE TRANSPORT PROPERTIES

COLLABORATORS
Sihong Kim
J.M. Gallego
D. Lederman

UCSD

Work supported by DOE
Why is this difficult?
TROUBLE

Interfacial Scattering Dominates

Figure 6. Resistivity of Nb/Cu LUCS versus inverse layer thickness.

Figure 2. The dependence of the room temperature resistivity on composition wavelength.

Nb/Cu

Nb/Ti
ATOMS → SOLIDS

DUE TO THE ADDED PERIODICITY
NEW EFFECTS APPEAR IN THE ELECTRONIC PROPERTIES

SUPERLATTICE EFFECTS!
SUMMARY

Do what you like,
but above all
like what you do

Francisco Schuller
WHY DO ALL THIS?

Many layers, N

Three layers

Two layers

One layer

Superlattice effects

Coupling
Dimensional transitions
Spin Transmission

Interfaces
Electron transfer
Strains
Proximity effects

Disorder
Confinement
Lower dimensionality
INTERESTING QUESTIONS

1. Extended Electronic States?
   • Signature

2. Interaction Effects?
   • $\pi$ Phase in Ferromagnetic/Superconducting

3. Confinement of Collective Excitations?
   • Magnons, Phonons, etc.

4. Proximity Effects?
   • Magnetism

5. Growth
   • Kinetics vs. Thermodynamics

6. Pinning

7. Spin Transport