In the initial phases, we showed that we can prepare self-supporting masks and that the concept of magnetic stabilization using exchange bias is feasible. We developed instrumentation for the preparation of porous alumina masks on a substrate and automated analysis methods for characterization of dot distribution. During the next phase, we started preparation and characterization of samples grown on Si substrates. Studies of the magnetic properties were started during the third phase. Further studies are needed to reach the terrabit-per-square inch goal.
FINAL REPORT
June 1, 2001-November 30, 2003

Nanostructured Magnetism for Super-Dense Memories
AFOSR – F49620-01-1-0393

(AWARD # FOR NEW GRANT PERIOD: FA9550-04-1-0160)

Prof. Ivan K. Schuller, P.I.
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9500 Gilman Drive
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1. OBJECTIVES

This proposal has been dedicated to the development of nanostructured medium for super-dense memory architecture. More specifically, we concentrated on the preparation, characterization and the study of the physical limitations of artificially nanostructured magnetic materials. These materials will be the building blocks for future ultra-high density patterned magnetic storage media. Under this project we developed self-assembly and electron beam lithography methods for the preparation of nanostructured magnetic arrays, characterize their physical and chemical properties quantitatively and solve the limitation imposed by the superparamagnetic limit.

2. STATUS OF EFFORT

In the initial phases, we showed that we can prepare self-supporting masks and that the concept of magnetic stabilization using exchange bias is feasible. We developed instrumentation for the preparation of porous alumina masks on a substrate and automated analysis methods for characterization of dot distribution. During the next phase, we started preparation and characterization of samples grown on Si substrates. Studies of the magnetic properties were started during the third phase. Further studies are needed to reach the terrabit-per-square inch goal.

3. ACCOMPLISHMENTS/NEW FINDINGS

The key for the development of super dense memories is the reproducible preparation of regular arrays of small (~100-200 Å) magnetic structures over macroscopic (cm x cm) areas on a substrate.

We have performed studies of the distribution and thermal stability of arrays of small (down to ~350 Å) magnetic dots on Si substrates using self assembled alumina as masks. We are able to prepare these arrays of nanodots over macroscopic (cm x cm) areas. The size and distribution of the mask and the arrays correlate well. The distribution width on the mask and array is of the order 10% so further improvements are needed. Improvements in the preparation of the alumina process are underway to decrease the size, to improve uniformity and to perfect array distribution. Further studies of the magnetic properties in an exchange biased and normal configuration are needed.

We are now concentrating on understanding the magnetic behavior of the dots we already prepared. Interestingly, we find below ~600 Å dot size a transition from single or multi-domain to vortex state to single domain with decreasing size. For Fe dots we find an unexpected exchange bias even for the dot arrays without an antiferromagnet deliberately added to the structure. We suspect that this "bonus" comes from a possible Fe oxide present, which provides the exchange bias. This is under investigation at the present time and needs further research.

To date the smallest sizes we can reproducibly prepare are close to 350Å with ~10% dispersion. Improvements in the preparation of the alumina process are underway to decrease the size, to improve uniformity and to perfect array distribution. Further studies of the magnetic properties in an exchange biased and normal configuration are needed.
4. PERSONNEL SUPPORTED

Postdoctoral Fellows:
Igor Roshchin
Maribel Montero
Johannes Eisenmenger (funded by von Humboldt foundation)

Graduate students:
Changpeng Li

Undergraduate Students:
Doug Bird
Nate Goldman (funded by NSF-REU program)

Visitors:
Waldemar Macedo (funded by Brazilian Government)
Jose Vicent (funded by Spanish sources)

Collaborators:
Kai Liu
Johan J. Åkerman
S.M. Baker
J. Nogues
K. Nishio
J.M. Slaughter
José Mejia-Lopez
J.A. Borchers
J.B. Kortright
M.F. Toney

O.M. Stoll
J.I. Martin
T.P. Russell
J. Guimpel
S. M. Baker
Renu Whig Dave
M.R. Fitzsimmons
G.P. Felcher
T.C. Schulthess
D. Weller

A. Hoffmann
J.L. Vicent
C. Leighton
H. Masuda
M. Tuominen
Dora Altbir
S.D. Bader
J.K. Furdyna
S.K. Sinha
S. Wolf

5. PUBLICATIONS

Papers
Published in Refereed Journals

1. Nanostructures and Proximity Effect

2. Hysteresis and Fractional Matching in Thin Nb Films with Rectangular Arrays of Nanoscaled Magnetic Dots
O.M. Stoll, M.I. Montero, J. Guimpel, Johan J. Åkerman and Ivan K. Schuller
3. **Fabrication and Thermal Stability of Arrays of Fe Nanodots**  

4. **Exchange Biased Magnetic Nanostructures**  

5. **Ordered Magnetic Nanostructures: Fabrication and Properties**  
   J.I. Martin, J. Nogues, Kai Liu, J.L. Vicent and Ivan K. Schuller  

6. **Origin of Temperature Dependence in Tunneling Magnetoresistance**  
   Johan J. Åkerman, Igor V. Roshchin, J.M. Slaughter, Renu Whig Dave and Ivan K. Schuller  

7. **Relaxation Times in Exchange-biased Nanostructures**  
   Jose Mejia-Lopez, Dora Altbir and Ivan K. Schuller  

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**Papers Submitted to Refereed Journals**  
(Not Yet Published)

1. **Neutron Scattering Studies of Nanomagnetism and Artificially Structured Materials**  

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**Invited Talks**  
(At National and International Meetings)

1. **Magnetic and Superconducting Nanostructures**  
   Ivan K. Schuller  
   Festkolloquium, "Solid State Physics: Origin of the Future Electronics"  
   Tuebingen, Germany, October 19, 2001.

2. **Nanolithography Using Electron Beam Writing and Self Assembly**  
   Ivan K. Schuller, M.I. Montero, O.M. Stoll, Kai Liu and Johan J. Åkerman  
   Materials Research Society, Fall 2001 Meeting  
3. Nanostructures,
Ivan K. Schuller
Simposio en Fisica de Materiales del CCMC, Ensenada,
Mexico, January 23-26, 2002.

4. Proximity Effect with Magnetic Nanostructures
J. Vicent, S.M. Baker, M. Tuominen and T.P. Russell
International Conference on Superconductivity, GMR & Related Materials: Novel
Trends, Giens, France, June 1-8, 2002.

5. Unusual Properties in Exchange Biased Bilayers
J. Nogues, C. Leighton, M. Fitzsimmons, A. Hoffmann, K. Liu, M. Pechan,
I.N. Krivorotov, E.D. Dahlberg and Ivan K. Schuller
IUMRS International Conference on Electronic Materials
Xian, China, June 10-14, 2002.

6. Proximity Effect and Magnetic Nanostructures
M.I. Montero, Kai Liu, O.M. Stoll, A. Hoffmann, Johan J. Åkerman, J.J. Martin,
Schuller
TNT 2002 Conference, Santiago de Compostela (Spain), September 9-13, 2002.

7. Adler Award Lecture: 25 Years of Metallic Superlattices
Ivan K. Schuller

8. Nanostructures: A Voyage from Three to Zero Dimensions
Ivan K. Schuller, M. Montero, I. V. Roshchin, J.J. Martin, M. Velez, J. Nogues,
Leighton, H. Masuda, and K. Nishio
Institute for Structural and Engineering Materials (ISEM), Nagoya, Japan, June

9. Stabilization of Magnetism in Ferromagnetic Dot Arrays Towards Terrabit
per Square Inch Storage
Igor V. Roshchin, C.P. Li, M. Viret, Kai Liu, J.J. Tores, A.H. Romero, K. Nishio,
H. Masuda, and Ivan K. Schuller, Non-Volatile Memory Technology Symposium

Invited Talks at Research Institutions

1. Artificially Prepared Nanostructures
Ivan K. Schuller, University Ulm, October 17, 2001.

2. Magnetic Nanostructures
Ivan K. Schuller, UCSD Chemistry Department, January 29, 2002.

3. Magnetic Nanostructures,
4. **Fabrication and Magnetism of Nanodots and Wires with Nanoconstrictions.**
   Igor V. Roshchin
   Special Condensed Matter Seminar. University of Illinois at Urbana-Champaign.

5. **Nanostructures and the Proximity Effect,**
   Ivan K. Schuller, Technische Hochschule, Aachen, June 17, 2002.

6. **Nanostructures and Proximity Effect**
   Ivan K. Schuller, Physics Department Colloquium, Ruhr-Universitat Bochum,
   July 8, 2002.

7. **Tunneling Criteria for Magnetic Tunnel Junctions**

8. **Nanostructures and the Proximity Effect**
   Ivan K. Schuller, Hamburg University, Hamburg, Germany, August 2, 2002.

9. **Magnetism in Nanostructures**
   Igor Roshchin
   Division Seminar, General Physics, Institute of Russian Academy of Sciences,
   Moscow, Russia, October 2, 2002.

10. **Nanotechnology and Magnetism**
    Igor Roshchin
    Special Interdepartmental Colloquium,
    Southern Ural State University, Chelyabinsk, Russia, October 8, 2002.

**Contributed Talks**

1. **Exchange Bias in Magnetic Nanostructures Over Macroscopic Area**
   Kai Liu, Ivan K. Schuller, S.M. Baker, and T. Russell

2. **Tailoring Exchange Bias with Magnetic Nanostructures**

3. **Magnetization Stabilization in Arrays of Fe Nanodots with Exchange Bias**
   Magnetism and Magnetic Materials Conference, Seattle, WA., November 13-16,

4. **Fabrication and Magnetization Stabilization in Arrays of Fe Nanodots with Exchange Bias**
   Londergan, C. Kubiak, K. Nishio, and H. Masuda
5. **Preparation of Nanoscopic Magnetic Structures in Exchange Biased Systems**  
Sarah Olmstead, Shenda Baker, Ivan Schuller, Kai Liu, and Thomas P. Russell  

6. **Exchange Biased Magnetic Nanostructures**  
T.P. Russell, H. Masuda and K. Nishio  
2002 International Symposium on Magnetoelectronics and Superconducting  
Electrical Engineering, Beijing, China, August 15-18, 2002.

7. **Magnetization Stabilization in Arrays of Fe Nanodots with Exchange Bias**  
Igor V. Roshchin, C.P. Li, Kai Liu, K. Nishio, H. Masuda and Ivan K. Schuller  

8. **Synthesis and Thermal Stability of Nanomagnets**  
Masuda, K. Nishio, I.V. Roshchin and Ivan K. Schuller, International  

9. **Size Effects in Exchange Biased Nanostructures**  
Johannes Eisenmenger, Zhipan Li, Oleg Petracic, Igor Roschin, Changpeng Li, Kai  

6. **HONORS AND AWARDS**

Ivan K. Schuller

2003 – American Physical Society Adler Award – “For research in metallic  
heterostructures and superlattices, communicated with unusual enthusiasm and  
eloquence”.

2003 – Materials Research Society - MRS Medal – “For innovative studies of  
exchange bias in magnetic heterostructures and nanostructures”.