

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

Public Reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comment regarding this burden estimates or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188,) Washington, DC 20503.

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE 13 May, 03

3. REPORT TYPE AND DATES COVERED
Final, 01 May 01 – 30 Apr 03

4. TITLE AND SUBTITLE

Novel approaches to the synthesis, processing and applications of nanocomposite magnets

5. FUNDING NUMBERS

DAAD 19-01-1-0546.

6. AUTHOR(S)

J.P. Liu, J.A. Barnard, J.S. Jiang, C. O'Connor, S.G. Sankar, S. Sun, N.N. Thadhani, Z.L. Wang, G. Zangari

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

PI organization: Department of Physics, University of Texas at Arlington, Arlington, TX 76019
Team members include Argonne National Lab, IBM T.J. Watson, Georgia Tech, U. Pitts, U. New Orleans, U. Virginia and Advanced Materials Corporation

8. PERFORMING ORGANIZATION
REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING
AGENCY REPORT NUMBER

42668-MS
06

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

An interdisciplinary research teamwork has been carried out under the DARPA Metamaterials program. Remarkable progress has been made to February 2003 which includes: 1. a new model analysis in exchange-coupled nanocomposite magnets was made which is in good agreement with the experimental data; 2. breakthrough was made in synthesis of hard and soft magnetic nanoparticles as well as their self-assembled nanocomposite; 3. a new solid-state reaction method to fabricate bulk nanomagnets was found; 4. bulk nanocomposite magnets produced by shock-compaction have been successfully fabricated.

14. SUBJECT TERMS

Metamaterials, exchange coupling, nanocomposites, permanent magnets

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION
OR REPORT

UNCLASSIFIED

18. SECURITY CLASSIFICATION
ON THIS PAGE

UNCLASSIFIED

19. SECURITY CLASSIFICATION
OF ABSTRACT

UNCLASSIFIED

20. LIMITATION OF ABSTRACT

UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. Z39-18
298-102

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

Summary

Exchange-coupled nanocomposite magnets have been studied worldwide for more than ten years. However, no breakthrough was made for a decade to enable production of bulk nanocomposite magnets with high energy products. This situation has been changing during the past year and a half since DARPA began investing in this area. We have made remarkable progress in gaining a better understanding of the exchange coupling and in finding novel approaches to the synthesis and processing of the nanocomposites:

Our theoretical modeling has revealed that the accepted condition for exchange-coupling— soft-phase dimension equal or smaller than twice the domain-wall thickness in the hard phase — derived by three groups in Europe, must be amended: the critical soft-phase dimension depends also on the soft phase itself. In experimental investigation, breakthroughs have been made by finding several novel approaches to materials synthesis and processing, including chemical synthesis of nanoparticles and their self-assembly into exchange-coupled nanocomposite magnets, solid-phase-reaction synthesis (eutectoid decomposition) of $L1_0$ phase-based nanocomposite, and dynamic compaction of nanoparticles. More effort in producing nanoparticles and bulk magnets is underway including electrochemical deposition of the hard-phase nanoparticles, anisotropic nanoparticles, extrusion of nanostructured magnets and field induced texture in nanocomposite magnets. These novel approaches show a great potential for mass production of bulk nanocomposite magnets with high energy products.

This project was terminated officially on Feb. 28, 2003 at Louisiana Tech University because the PI moved to University of Texas at Arlington (UTA). The project is continued at UTA.

Publications (peer reviewed):

- [1] S.-S. Yan, J.A. Barnard, F. Xu, J.L. Weston, and G. Zangari, “Critical Dimension of the Transition from Single switching to an Exchange Spring Process in Hard/Soft Exchange-Coupled Bilayers”, *Phys. Rev. B.* **64**, 184403 (2001).
- [2] S. Saha, C.J. Thong, M.Q. Huang, R.T. Obermyer, B.J. Zande, V.K. Chandhok, S. Simizu and S.G. Sankar, “Magnetic and mechanical proerties of (Fe,Co)-Pt bulk alloys prepared through various processing techniques”, *J. Appl. Phys.*, in press.
- [3] Hao Zeng, T.S. Vedantam, J.P. Liu, Z.R. Dai, Z.L. Wang and Shouheng Sun, “ Exchange-coupled FePt nanoparticles assembly, *Appl. Phys. Lett.*, 80 (2002), 2583-2585.
- [4] Hao Zeng, Jing Li, Zhong L. Wang, J. Ping Liu, and Shouheng Sun, “Interparticle Interactions in Annealed FePt Nanoparticle Assemblies”, *IEEE Trans. On Mag.* 38 (2002), 2598-2600.
- [5] Z. S. Shan, J. P. Liu, Vamsi M. Chakka, H. Zeng, J. S. Jiang , “Energy barrier and magnetic properties of exchange-coupled spring magnets”, *IEEE Trans. On Mag.* 38 (2002), 2907-2909.
- [6] D. Chumakov, R. Schäfer, D. Elefant, D. Eckert, L. Schultz, S.S. Yan and J.A. Barnard, “Magnetization process in SmFe-NiFe exchange spring films”, *Phys. Rev. B.* 66, 134409 (2002).

- [7] Zu Rong Dai, Zhong L. Wang and Shouheng Sun, "Shape, multiply twins and surface structures of monodispersive FePt magnetic nanocrystals", submitted to *Surface Science*, 505 (2002), 325-335.
- [8] Shouheng Sun and Hao Zeng, "Size-controlled synthesis of magnetite nanoparticles", *J. Am. Chem. Soc.* 124 (2002), 8204-8205.
- [9] Z. J. Guo, J. S. Jiang, J. E. Pearson, S. D. Bader, J. P. Liu, "Exchange-coupled Sm-Co/Nd-Co nanomagnets: correlation between soft phase anisotropy and exchange field", *Appl. Phys. Lett.*, 81 (2002), 2029-2031.
- [10] Robert Peterson, Mike Novikov, Jeff Hsu, Herb Gass, S.G. Sankar, Satoru Simizu, Rechar T. Obermyer, Brian Zande, V.K. Chandhok and Arkady Maygolin, "Design and construction of a linear actuator with NdFeB magnets for a high frequency motion simulator", an invited presentation at the *Proc. of the 17th Intl. Workshop on Rare Earth Magnets and Their Applications*, Eds. G.C. Hadjipanayis and M.J. Bonder, Rinton Press (2002), pp. 490-503.
- [11] Christina H. Chen, Steve Kodak, Michael H. Walmer, Sh-Fan Cheng, Matthew A. Willard and Vincent G. Harris, "Magnetic and structural properties of $\text{Sm}(\text{Co}_{1-x}\text{Fe}_x)\text{Z}$ based powders and spin cast ribbons", *Proc. of the 17th Intl. Workshop on Rare Earth Magnets and Their Applications*, Eds. G.C. Hadjipanayis and M.J. Bonder, Rinton Press (2002), pp. 844-852.
- [12] Hao Zeng, Jing Li, J. P. Liu, Zhong L. Wang and Shouheng Sun, "Exchange-coupled nanocomposite magnets via nanoparticle self-assembly", *Nature*, 420 (2002), 395-398.
- [13] T. S. Vedantam, J. P. Liu, H. Zeng, S. Sun, "Thermal stability of self-assembled FePt nanoparticles", *J. Appl. Phys.*, in press.
- [14] Christina H. Chen, Steve Kodat, and Michael H. Walmer, Shu-Fan Cheng, Matthew A. Willard, and Vincent G. Harris, "The Effects of Grain Size and Morphology on the Coercivity of $\text{Sm}_2(\text{Co}_{1-x}\text{Fe}_x)_{17}$ Based Powders and Spin Cast Ribbons", *J. Appl. Phys.*, in press.
- [15] S. Simizu, R.T. Obermyer, B. Zande, V.K. Chandhok, A. Margolin and S.G. Sankar, "Exchange Coupling in Fe-Pt Permanent Magnets", *J. Appl. Phys.*, in press.
- [16] Jing Li, Zhong Lin Wang, Hao Zeng, Shouheng Sun and J. Ping. Liu, "Interface Structures in FePt/Pe3Pt Hard-Soft Exchange-Coupled Magnetic Nanocomposites." *Appl. Phys. Lett.*, in press.
- [17] H. Zeng, Shouheng Sun, R.L. Sandstrom and C.B. Murray, "Chemical Ordering of FePt Nanoparticle self-Assemblies by RTA", *J. Magn. Magn. Mater.*, in press.

Submitted manuscripts:

- K. H. Chen, Z. Q. Jin, J. Li, G. Kennedy, H. Zeng, S.-F. Chen, Z. L. Wang, N. N. Thadhani and J. P. Liu, "Bulk Nanocomposite Magnets Produced by Dynamic Shock Compaction", submitted to *Nature Materials*.
- Vamsi M. Chakka, Z. S. Shan, and J. P. Liu, "Effect of coupling strength on magnetic properties of exchange-coupled spring magnets", submitted to *J. Appl. Phys.*
- J. Zhang, G. Zangari "Electrodeposition of Sm-Co nanoparticles from aqueous solutions" submitted to *Applied Physics Letters*

Oral presentations:

Special Colloquium at Argonne National Lab, by Dr. Shouheng Sun (IBM T. J. Watson Research Center), "Self-Assembling Magnetic Nanomaterials", Wednesday, January 23, 2002

Improving Exchange-Spring Magnets with Interfacial Modification, J. S. Jiang, J. E. Pearson, J. P. Liu and S. D. Bader, Proc. 17th International Workshop on Rare Earth Magnets and Their Applications, Edited by G. C. Hadjipanayis and M. J. Bonder, p. 727-737 (Rinton Press, Princeton, 2002).

Improved Exchange Spring Nanocomposites with Interfacial Modification (Invited), J. S. Jiang, 17th International Workshop on Rare Earth Magnets and Their Applications, University of Delaware, Newark, Delaware (August 18-22, 2002).

Magnetic interactions in FePt-based nanoparticle assembly (invited), H. Zeng and Shouheng Sun, Fourth International Conference on Fine Particle Magnetism, Pittsburgh, 2002

Exchange-coupled nanocomposite via self-assembly, H. Zeng, Shouheng Sun, J. Li, Z.L. Wang, and P. Liu, 47th Annual Conference on Magnetism & Magnetic Materials, Tampa, 2002.

Exchange-coupled FePt nanoparticle assembly, Hao Zeng, T. Vedantam, Z.R. Dai, Z.L. Wang, J.P. Liu, and Shouheng Sun, Annual American Physical Society March Meeting, Indianapolis, 2002

How to create self-assembled nanostructures, S. Sun, the 47th Annual Conference on Magnetism and Magnetic Materials, November 11-15, 2002, Tampa, Florida.

Exchange-spring nanocomposites via self-assembly, S. Sun, H. Zeng, J. Li, Z.L. Wang, and P. Liu, DOE CESP annual workshop on nanocomposite magnetic materials, October 20-22, 2002, Stony Brook, New York.

Nd-Co/Sm-Co Exchange-Springs: Correlation between Soft Phase Anisotropy and Exchange Field, J. S. Jiang, J. Pearson, S. D. Bader, Z. J. Guo, J. P. Liu, APS March Meeting, 2003

Magnetic nanocomposite materials-nanoparticle approach (invited) H. Zeng and Shouheng Sun, American Chemical Society NorthEastern Regional Meeting, Saratoga Springs, NY, 2003

Structures of Fe-Pt Magnetic Nanocrystal Self-Assembled Arrays and The Optimization of Magnetic Properties, Jing Li, Zhong Lin Wang, Hao Zeng, Shouheng Sun and J. Ping Liu, Invited presentation in 2003 MRS Spring Meeting, Apr. 21-25, 2003, San Francisco. Symposium P: Self-Assembled Nanostructured Materials, Apr. 25, 2003, 10:30 AM. *P10.6. Speaker: Professor Zhong Lin Wang.

Synthesis and Characterization of Monodisperse Magnetite & Cobalt Ferrite) Nanoparticles, H. Zeng, S. Sun, C. Black, R. Sandstrom, MRS Spring Meeting, San Francisco, CA, Apr. 21-25, 2003.

Shock-compression processing of Advanced Materials: Fabrication of Bulk Nanocomposite Magnetic Alloys, N.N. Thadhani, Invited presentation at Istanbul Technical University, Istanbul, Turkey, April 21-25, 2003.

Shock compaction of exchange-coupled nanocomposite magnets,

Z.Q. Jin, K.H. Chen, J. Li, G. Kennedy, H. Zeng, J.P. Liu, Z.L. Wang, N.N. Thadhani, to be presented at the APS Topical Group Meeting on Shock Compression of Condensed Matter, July 20-25, 2003, Portland, OR.

Dynamic shock compaction of nanocrystalline bulk magnetic and thermoelectric materials,

N.N. Thadhani, Invited paper to be presented at THERMEC International Conference, Madrid, Spain, July 7-11, 2003.

Synthesis and assembly of magnetic nanoparticles,

S. Sun, the 77th ACS Colloid and Surface Science Symposium, June 15-18, 2003, Atlanta, GA.

Self-assembled magnetic nanoparticle arrays,

S. Sun, Keynote Speaker, the 5th International Symposium on Magnetic Materials and Applications, SOMMA 2003, December 4-6, 2003, Daejeon, South Korea.

Disclosure:

“Magnetic Nanocomposites via Nanoparticle self-assembly”, YOR820020086, Feb. 2002.

Graduate students and postdoc's supported under the grant:

Mr. Zhihui Ban (UNO)

Ms. Daniela Caruntu (UNO)

Mr. V.M. Chakka (UTA)

Mr. T. Vandetam (UTA)

Dr. Min Chen (IBM)

Dr. Shishou Kang (U.Virginia)

Dr. Jing Li (GaTech)

Dr. Z.J. Guo (Argonne)

Dr. Vladimir Kolesnichenko (UNO)

Dr. Shibaji Saha (UPitt)

Dr. Shi-shen Yan (NHFML)

Dr. Minghui Yu (U.Maryland)

Dr. Hao Zeng (IBM)

Dr. Jianqi Zhang (Alabama)