

Springer Series in Materials Science

Volume 252

Series editors

Robert Hull, Charlottesville, USA

Chennupati Jagadish, Canberra, Australia

Yoshiyuki Kawazoe, Sendai, Japan

Richard M. Osgood, New York, USA

Jürgen Parisi, Oldenburg, Germany

Tae-Yeon Seong, Seoul, Korea, Republic of

Shin-ichi Uchida, Tokyo, Japan

Zhiming M. Wang, Chengdu, China

The Springer Series in Materials Science covers the complete spectrum of materials physics, including fundamental principles, physical properties, materials theory and design. Recognizing the increasing importance of materials science in future device technologies, the book titles in this series reflect the state-of-the-art in understanding and controlling the structure and properties of all important classes of materials.

More information about this series at <http://www.springer.com/series/856>

Arcady Zhukov
Editor

High Performance Soft Magnetic Materials

 Springer

Editor
Arcady Zhukov
Basque Country University
San Sebastian, Spain

ISSN 0933-033X ISSN 2196-2812 (electronic)
Springer Series in Materials Science
ISBN 978-3-319-49705-1 ISBN 978-3-319-49707-5 (eBook)
DOI 10.1007/978-3-319-49707-5

Library of Congress Control Number: 2016962022

© Springer International Publishing AG 2017

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Recent technological advances have been greatly affected by the development of advanced functional materials with improved physical properties. Advanced soft magnetic materials represent a key and fruitful area of research for functional materials. Many industrial sectors, such as magnetic sensors, microelectronics, security, automobiles, medicine, aerospace, energy harvesting and conversion, informatics, electrical engineering, magnetic recording, and medicine, demand magnetically soft materials with tuneable magnetic properties. These soft materials feature enhanced magnetic softness, giant magnetoimpedance effect, magnetic bistability, or inductive heating properties. Additionally, the miniaturization of modern magneto-electronic devices tends to stimulate rapid development of soft magnetic materials with reduced dimensionality. Consequently the development of novel soft magnetic materials in the form of ribbons, wires, microwires, and multilayered thin films has gained significant attention of the scientific community.

In the area of soft magnetic materials, the discovery of the so-called giant magnetoimpedance effect in these materials makes them very attractive for a wide range of high-performance sensor applications for use in engineering, magnetic sensors, industry, and biomedicine. On the other hand, amorphous magnetic wires present magnetically bistable characteristics associated with a large Barkhausen jump. The magnetization reversal of these microwires runs through the quite fast domain wall (DW) propagation. Engineering of domain wall (DW) dynamics in nano- and microwires has become a challenge for fundamental physics and technological applications related to magnetic recording and magnetic sensors.

Therefore progress in the development of soft magnetic materials with low dimensionality, like ribbons, films, or wires, has drawn significant industry attention.

In all of these cases, a comprehensive understanding of the processing-structure-property relationship is of critical importance. Consequently, great efforts have been and continue to be focused on the origins of materials properties and on the prediction of novel, unusual macroscopic properties based on nano- and microstructures.

The present book on soft magnets was inspired by the recent progress in the development of novel soft magnetic materials including amorphous, nanocrystalline, and nanostructured materials with improved magnetic and magneto-transport properties suitable for applications in various industrial sectors as well as in prospective applications.

The expert chapters from leading researchers from around the world cover a wide range of experimental and theoretical work highlighting the following main topics:

- Soft magnetic materials
- Amorphous and nanocrystalline magnetic materials
- Tailoring of soft magnetic properties
- Tuneable composites
- Applications

The aim throughout is to provide the latest advances on recent developments in the field of soft magnetic materials paying particular attention to the tailoring of soft magnetic materials and optimization of their properties for industrial applications.

I hope that this publication will stimulate further interest in soft magnetic materials research. Last but not least, I would like to acknowledge all the contributing authors for their invaluable time, great contributions, and assistance with this book. Without such efforts we would not be able to accomplish and bring this special volume to the interested readers.

San Sebastian, Spain

Arcady Zhukov

Contents

1 Amorphous and Nanocrystalline Glass-Coated Wires: Optimization of Soft Magnetic Properties	1
V. Zhukova, M. Ipatov, A. Talaat, J.M. Blanco, and Arcady Zhukov	
2 Tailoring of Soft Magnetic Properties and High Frequency Giant Magnetoimpedance in Amorphous Ribbons	33
L. González-Legarreta, V.M. Prida, A. Talaat, M. Ipatov, V. Zhukova, Arcady Zhukov, LI. Escoda, J.J. Suñol, J. González, and B. Hernando	
3 Melt Extracted Microwires	53
H. Wang, F.X. Qin, H.X. Peng, and J.F. Sun	
4 Giant Magneto-Impedance Effect in Amorphous Ferromagnetic Microwire with a Weak Helical Anisotropy	91
N.A. Usov and S.A. Gudoshnikov	
5 Tunable Magnetic Anisotropy and Magnetization Reversal in Microwires	111
A. Chizhik, A. Stupakiewicz, and J. Gonzalez	
6 Tunable Electric Polarization of Magnetic Microwires for Sensing Applications	131
Larissa V. Panina, Dmitriy P. Makhnovskiy, Abdukarim Dzhumazoda, and Svetlana V. Podgornaya	
7 Soft Ferromagnetic Microwires with Excellent Inductive Heating Properties for Clinical Hyperthermia Applications	151
Rupin Singh, Javier Alonso, Jagannath Devkota, and Manh-Huong Phan	

8 Magnetically Bistable Microwires: Properties and Applications for Magnetic Field, Temperature, and Stress Sensing 169
Rastislav Varga, Peter Klein, Rudolf Sabol, Kornel Richter,
Radovan Hudak, Irena Poláček, Dušan Praslicka,
Miroslav Šmelko, Jozef Hudak, Ivan Mikita,
Giovanni Andrea Badini-Confalonieri,
Rhimou El Kammouni, and Manuel Vazquez

Index 213

Contributors

Javier Alonso Department of Physics, University of South Florida, Tampa, FL, USA

BCMaterials Edificio No. 500, Parque Tecnológico de Vizcaya, Derio, Spain

Giovanni Andrea Badini-Confalonieri Instituto de Ciencia de Materiales de Madrid, CSIC, Cantoblanco, Madrid, Spain

J.M. Blanco Departamento de Física Aplicada, EUPDS, Basque Country University, UPV/EHU San Sebastian Spain, Bilbao, Spain

A. Chizhik Departamento Facultad de Química, Universidad del País Vasco UPV/EHU, San Sebastian, Spain

Jagannath Devkota Department of Physics, University of South Florida, Tampa, FL, USA

Abdulkarim Dzhumazoda National University of Science and Technology, MISIS, Moscow, Russian Federation

Rhimou El Kammouni Instituto de Ciencia de Materiales de Madrid, CSIC, Cantoblanco, Madrid, Spain

LI. Escoda Girona University, Girona, Spain

J. González Department of Materials Physics, University of the Basque Country, San Sebastián, Spain

L. González-Legarreta Department of Physics, University of Oviedo, Oviedo, Spain

J. Gonzalez Departamento Facultad de Química, Universidad del País Vasco UPV/EHU, San Sebastian, Spain

S.A. Gudoshnikov National University of Science and Technology “MISIS”, Moscow, Russia

Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences, IZMIRAN, Troitsk, Moscow, Russia

B. Hernando Department of Physics, University of Oviedo, Oviedo, Spain

Jozef Hudak Department of Aviation Technical Studies, Faculty of Aeronautics, Technical University of Košice, Košice, Slovakia

Radovan Hudak Department of Biomedical Engineering and Measurement, Faculty of Mechanical Engineering, Technical University of Košice, Košice, Slovakia

M. Ipatov Department of Material Physics, Basque Country University, UPV/EHU, San Sebastian, Spain

Departamento de Física Aplicada, EUPDS, Basque Country University, UPV/EHU San Sebastian Spain, Bilbao, Spain

Peter Klein Faculty of Science, Institute of Physics, UPJS, Košice, Slovakia

RVmagnetics s.r.o., Kosice, Slovakia

Dmitriy P. Makhnovskiy Robat Ltd., Macclesfield, UK

Ivan Mikita Department of Aviation Technical Studies, Faculty of Aeronautics, Technical University of Košice, Košice, Slovakia

Larissa V. Panina National University of Science and Technology, MISIS, Moscow, Russian Federation

Institute for Design Problems in Microelectronics, Moscow, Russian Federation

H.X. Peng Institute for Composites Science Innovation (InCSI), School of Materials Science and Engineering, Zhejiang University, Hangzhou, China

Manh-Huong Phan Department of Physics, University of South Florida, Tampa, FL, USA

Svetlana V. Podgornaya National University of Science and Technology, MISIS, Moscow, Russian Federation

Irenej Polaček Department of Biomedical Engineering and Measurement, Faculty of Mechanical Engineering, Technical University of Košice, Košice, Slovakia

Dušan Praslicka Department of Aviation Technical Studies, Faculty of Aeronautics, Technical University of Košice, Košice, Slovakia

V.M. Prida Department of Physics, University of Oviedo, Oviedo, Spain

F.X. Qin Institute for Composites Science Innovation (InCSI), School of Materials Science and Engineering, Zhejiang University, Hangzhou, China

Kornel Richter Faculty of Science, Institute of Physics, UPJS, Košice, Slovakia

Rudolf Sabol Faculty of Science, Institute of Physics, UPJS, Košice, Slovakia

RVmagnetics s.r.o., Kosice, Slovakia

Rupin Singh Department of Physics, University of South Florida, Tampa, FL, USA

Miroslav Šmelko Department of Aviation Technical Studies, Faculty of Aeronautics, Technical University of Košice, Košice, Slovakia

A. Stupakiewicz Laboratory of Magnetism, University of Bialystok, Bialystok, Poland

J.J. Suñol Girona University, Girona, Spain

J.F. Sun School of Materials Science and Engineering, Harbin Institute of Technology, Harbin, China

A. Talaat Department of Material Physics, Basque Country University, UPV/EHU, San Sebastian, Spain

N.A. Usov National University of Science and Technology “MISIS”, Moscow, Russia

Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences, IZMIRAN, Troitsk, Moscow, Russia

Rastislav Varga Faculty of Science, Institute of Physics, UPJS, Košice, Slovakia

RVmagnetics s.r.o., Kosice, Slovakia

Manuel Vazquez Instituto de Ciencia de Materiales de Madrid, CSIC, Cantoblanco, Madrid, Spain

H. Wang Institute for Composites Science Innovation (InCSI), School of Materials Science and Engineering, Zhejiang University, Hangzhou, China

Arcady Zhukov Department of Material Physics, Basque Country University, UPV/EHU, San Sebastian, Spain

Departamento de Física Aplicada, EUPDS, Basque Country University, UPV/EHU, San Sebastian, Spain

IKERBASQUE, Basque Foundation for Science, Bilbao, Spain

V. Zhukova Department of Material Physics, Basque Country University, UPV/EHU, San Sebastian, Spain

Departamento de Física Aplicada, EUPDS, Basque Country University, UPV/EHU San Sebastian Spain, Bilbao, Spain