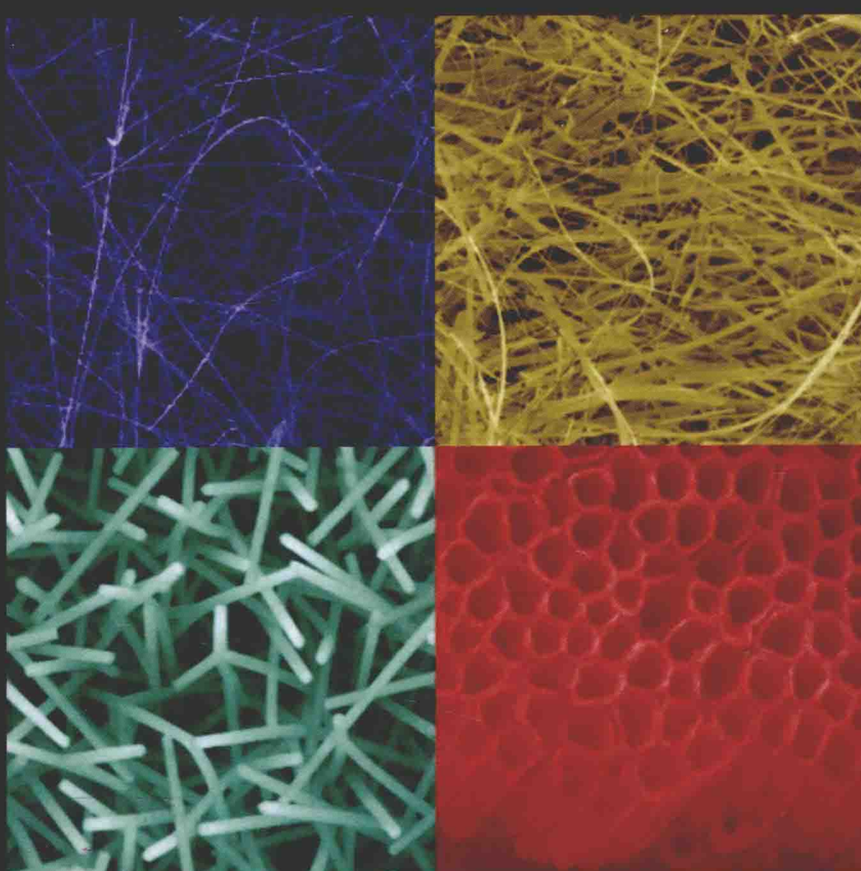
One-Dimensional Nanostructures

Principles and Applications

Edited by
Tianyou Zhai and Jiannian Yao



WILEY

ONE-DIMENSIONAL NANOSTRUCTURES

Principles and Applications

Edited by

TIANYOU ZHAI
JIANNIAN YAO

WILEY
A JOHN WILEY & SONS, INC., PUBLICATION

Cover illustrations: Courtesy of the authors

Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

Library of Congress Cataloging-in-Publication Data:

Zhai, Tianyou, 1980-
One-dimensional nanostructures: principles and applications / Tianyou Zhai, Jiannian Yao.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-118-07191-5 (hardback)
1. Nanowires. 2. Semiconductors–Materials. 3. One-dimensional conductors. 4. Nanostructured materials. I. Yao Jiannian, 1953- II. Title.
TK7874.85.Z43 2013
621.3815–dc23

2011049797

Printed in Singapore

10 9 8 7 6 5 4 3 2 1

ONE-DIMENSIONAL NANOSTRUCTURES

FOREWORD

Nanotechnology has had a profound impact on human economy and society in the twenty-first century that is perhaps comparable to the influence of information technology on human history. Science and engineering research in nanotechnology hold the key to breakthroughs in areas of materials and manufacturing, physics and chemistry, electronics, medicine, energy and the environment, biotechnology, information technology, and national security. It's widely believed that nanotechnology will be the driving force of the next industrial revolution.

One-dimensional (1D) nanostructures, such as nanowires, nanotubes, and nanobelts, constitute the fundamentals of nanoscience and nanotechnology. They have demonstrated their genius in wide applications such as electronics, optoelectronics, sensors, catalysts, energy conversion and storage, plasmonics, and spintronics. This book on the principles and applications of one-dimensional nanostructures, penetrates the tremendous worldwide interest in 1D nanostructures, ranging from the synthesis and properties to device applications of these structures. Prof. Tianyou Zhai and Prof. Jiannian Yao have harnessed their own knowledge and experience, and assembled internationally recognized authorities from 11 countries on four continents to contribute chapters covering a broad overview of important 1D nanostructure topics.

It is hoped that this book will provide an indispensable source of information for scientists, graduate students, engineers, industrial researchers, and other professionals working in the fields of nanomaterials, nanotechnology, materials science, chemistry, physics, polymer science, engineering and bioscience. It is also intended as an essential reference source for libraries in universities and industrial institutions, government laboratories and independent institutes, individual research groups, and scientists working in the field of nanoscience and nanotechnology.

I believe that this book will be useful in enabling readers to grasp the leading concepts of developments in this area, promoting cross-disciplinary integration, and enhancing original innovations.

CHUNLI BAI

President of the Chinese Academy of Sciences (CAS)

PREFACE

Since the revolutionary discovery of carbon nanotubes in 1991, one-dimensional (1D) nanostructures such as nanowires, nanobelts, and nanotubes have attracted tremendous attention due to their significance in basic scientific research and potential technological applications, based on their specific geometries and distinct properties. They are regarded as the most ideal systems for investigation of the dependence of electrical, optical, or mechanical properties on dimensionality and size reduction, and are expected to become the most promising building block for the next-generation nanoscale electronic and optoelectronic devices in the future. Nanocircuits built using semiconductor nanowires were declared as a "breakthrough in science" by *Science* magazine in 2001. *Nature* magazine published a report claiming that "Nanowires, nanorods or nanowhiskers. It doesn't matter what you call them, they're the hottest property in nanotechnology." There is no doubt that 1D nanostructures represent the most important yet controverzial field in nanoscience and nanotechnology because of their significant consequences.

This book, reflects the tremendous worldwide interest in 1D nanostructures. It covers the synthesis, properties, device applications, and major classes of 1D nanostructures, such as carbon nanotubes, semiconductor nanowires and nanotubes, organic molecule nanostructures, polymer nanofibers, peptide nanostructures, supramolecular nanostructures, and many other types of 1D nanomaterials. In addition, this book highlights various properties of 1D nanostructures such as optical, electronic, magnetic, catalytic properties as well as their advanced applications in photovoltaics, piezoelectrics, thermoelectrics, lithium ion batteries, field-effect transistors (FET), photodetectors, light emitting diodes (LED), lasers, field emitters (FE), waveguides, modulators, sensors, plasmonics, spintronics, and bioscience. This book contains 25 state-of-the art review chapters written by 68 internationally renowned experts in this field. The contents can be summarized as follows.

For the synthesis of 1D nanostructures (Chapters 1–5), Z. Zhang and S. Senz review their more recent efforts to control the growth of 1D semiconductor nanostructures with the assistance of porous templates. R. Mas-Ballesté and F. Zamora provide an overview of the construction of coordination polymers as 1D nanostructures. B. Korgel reports the fabrication of semiconductor nanowires through a supercritical fluid–liquid–solid process. Z. Li, G. Lu, and coworkers review the more recent progress of different types of colloidal nanowires produced from different wet-chemical approaches, including their optical, electronic, and magnetic properties, as well as their potential applications in the energy conversion and biomedical fields. Y. Chou and K. Tu discuss the core–shell effect on the nucleation and growth of nanoscale silicides.

For the properties of 1D nanostructures (Chapters 6–10), C. N. R. Rao and coworkers describe some of salient features of the electronic structure and properties (including Raman spectroscopy, chemical doping, electronic and magnetic properties, molecular charge transfer, and metal nanoparticle decoration) of carbon nanotubes and graphene. Q. Xiong and coworkers review the rational synthesis of various of 1D semiconductor nanowires and heterostructrues and systematically discuss the Raman scattering of 1D nanostructures of phonon confinement, radial breathing modes, surface optical phonons, the antenna effect, and stimulated Raman scattering. J. Zhang, Y. Li, and coworkers provide a brief overview of the synthesis, optical properties, charge carrier dynamics, and applications of 1D hematite nanostructures. B. Zou and coworkers investigate the doping effect on the novel optical properties of 1D semiconductor nanowires, and find that the confined elementary excitation in the 1D nanowire could be modified by minor doping, forming other quantum states and producing novel optical properties. G. Rosenman and N. Amdursky present the basic physics of quantum confinement phonomena and related optical effects in self-assembled biological fibrils and bioinspired peptide nanotubular materials.

For energy-related applications of 1D nanostructures (Chapters 11–13), Z. Fan and coworkers review advances in energy harvesting technologies utilizing 1D semiconductor nanowires and nanopillars. These materials are widely investigated as promising candidates for photovoltaics, piezoelectrics, and thermoelectrics. J. Luo and J. Zhu overview the fabrication and characteristics of $p-n$ junctions, and the photovoltaic applications of $p-n$ junction (including axial junction, radial junction, and individual junction) silicon nanowire arrays. H. Zhou and colleagues review the more recent development of nanomaterials for both cathodes and anodes in lithium ion batteries, focusing on 1D nanostructured metal oxides, which offer promise for higher energy density, higher performance rates, and longer lifecycles.

For applications in photonics and optoelectronics of 1D nanostructures (Chapters 14–18), Peng and coworkers report the controlled growth of carbon nanotube (CNT) arrays and their product electronic and optoelectronics devices, including field-effect transistors (FETs), photodetectors, and light emitting diodes (LEDs). J. Xu and colleagues give a brief survey of the application of scanning probe microscopy for investigation of local nanometer-scale electrical and optoelectrical properties of 1D nanostructures. L. Liao and X. Duan survey the more recent research on 1D metal oxide synthesis and their interesting applications in photonics and optoelectronics, including waveguides, light emitters, laser diodes, solar cells, and photodetectors. Y. Zhao and J. Yao describe more recent progress on the construction and unique optical and electronic properties of organic 1D nanostructures, as well as their applications as building blocks in optoelectronic functions and devices such as multicolor emission, tunable emission, optical waveguides, lasing, and modulators. W. Hu and colleagues review advances in the synthesis of 1D organic nanostructures in a wide range of organic functional materials ranging from polymers to small molecules, fabrication strategies of ordered 1D nanostructures, and their potential applications for optoelectronic devices, including photovoltaic cells, FETs, and photoswitches.

For applications in sensing, plasmonics, electronics, and biosciences of 1D nanostructures (Chapters 19–25), M. Razeghi and B. Nguyen present 1D physics of type II anotimonide-based superlattices and review the progress and performance of superlattice infrared photon detectors. A. Ponzoni, G. Sberveglieri, and coworkers review the use of metal oxide nanowires to prepare gas sensors based on conductometric, FET and optical (photoluminescence) devices. T. Qiu, P. Chu, and coworkers review the applications of 1D nanostructures to plasmonics, including plasmonic waveguides, surface-enhanced Raman scattering/fluorescence, and photovoltaics. M. Costache, S. Valenzuela, and colleagues discuss the theory of spin transport of 1D systems and describe several fabrication techniques for lateral spin devices. T. Zhai, Y. Bando, and coworkers, systematically and in detail, investigate factors affecting field emission (FE) performance, including nanostructure morphology (tip geometry, alignment, density, diameter, length); phase structure; temperature; effects of light, gas, substrate, gap, and composition; and the presence of hetero- and branched structures. J. Knoch presents 1D FETs, including the fundamentals of FETs and advantages of 1D nanostructures as FETs, and suggests that 1D nanostructures are a premier choice for high-performance, ultimately scaled FETs. B. Tian reports his work on nanowire FETs (NWFETs) for electrical interfacing with cells and tissue, and notes that NWFETs exhibit exquisite sensitivity in chemical and biological detection and can form strongly coupled interfaces with cell membranes.

The editors hope that this book will be a valuable reference source for scientists, graduate students, engineers, industrial researchers, and other professionals working in the fields of nanomaterials, nanotechnology, materials science, chemistry, physics, polymer science, engineering, and bioscience. This book is intended as a must-have handbook for university libraries, research establishments, government libraries, and high-tech companies engaged in research and developments of nanotechnology.

Finally, we would like to express our gratitude to all the authors for contributing comprehensive chapters, colleagues who offered invaluable advice to ensure the quality of this book, and the editorial staff of John Wiley & Sons, Inc. We expect that this book will stimulate further interest in this important new field, and that the readers of this book will find it useful.

Tianyou Zhai
Jiannian Yao

CONTRIBUTORS

Nadav Amdursky, Department of Materials and Interfaces, Faculty of Chemistry, Weizmann Institute of Science, Rehovot 76100, Israel (amdursky@Weizmann.ac.il)

Jin An, Department of Electronic Engineering, Materials Science and Technology Research Center, The Chinese University of Hong Kong, Shatin, N. T., Hong Kong SAR, China

Yoshio Bando, International Center for Materials Nanoarchitectonics (WPI-MANA), National Institute for Materials Science (NIMS), Namiki 1-1, Tsukuba, Ibaraki 305-0044, Japan

Yi-Chia Chou, Department of Materials Science and Engineering, Henry Samueli School of Engineering and Applied Science, University of California Los Angeles (UCLA), Los Angeles, California 90024

Paul K. Chu, Department of Physics and Materials Science, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, China (paul.chu@cityu.edu.hk)

Marius V. Costache, Catalan Institute of Nanotechnology (ICN), Campus UAB Bellaterra, Barcelona E-08913, Spain (mcostache@icn.cat)

Guozhang Dai, Micro-nano Technology Center, Beijing Institute of Technology, Beijing 100081, China

Huanli Dong, Beijing National Laboratory for Molecular Sciences, Key Laboratory of Organic Solids, Institute of Chemistry, Chinese Academy of Sciences, Beijing 100190, China

Xiangfeng Duan, Department of Chemistry and Biochemistry and California Nanosystems Institute, University of California, Los Angeles, California 90024 (xduan@chem.ucla.edu)

Guido Faglia, Department of Chemistry and Physics for Materials and Engineering, CNR-IDASC Sensor Laboratory and University of Brescia, Via Valotti 9, 25133 Brescia, Italy

Zhiyong Fan, Department of Electronic and Computer Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong SAR, China (eezfan@ust.hk)

Dmitri Golberg, International Center for Materials Nanoarchitectonics (WPI-MANA), National Institute for Materials Science (NIMS), Namiki 1-1, Tsukuba, Ibaraki 305-0044, Japan

A. Govindaraj, International Centre for Materials Science, Chemistry and Physics of Materials Unit, and CSIR Centre of Excellence in Chemistry, Jawaharlal Nehru Centre for Advanced Scientific Research, Jakkur P.O., Bangalore 560 064, India

Xuefeng Gu, Department of Physics, Southeast University, Nanjing 211189, China

Johnny C. Ho, Department of Physics and Materials Science, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong SAR, China

Wenping Hu, Beijing National Laboratory for Molecular Sciences, Key Laboratory of Organic Solids, Institute of Chemistry, Chinese Academy of Sciences, Beijing 100190, China (huwp@iccas.ac.cn)

Baoling Huang, Department of Mechanical Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong SAR, China

Lang Jiang, Beijing National Laboratory for Molecular Sciences, Key Laboratory of Organic Solids, Institute of Chemistry, Chinese Academy of Sciences, Beijing 100190, China

Joachim Knoch, RTWH Aachen University, 52074 Aachen, Germany (knoch@iht.rwth-aachen.de)

Brian A. Korgel, Department of Chemical Engineering, Texas Materials Institute, Center for Nano- and Molecular Science and Technology, The University of Texas at Austin, Austin, Texas 78712 (korgel@che.utexas.edu)

De Li, Energy Technology Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Umezono 1-1-1, 305–8568 Tsukuba, Japan

Huiqiao Li, Energy Technology Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Umezono 1-1-1, 305–8568 Tsukuba, Japan

Liang Li, International Center for Materials Nanoarchitectonics (WPI-MANA), National Institute for Materials Science (NIMS), Namiki 1-1, Tsukuba, Ibaraki 305-0044, Japan

Yan Li, Key Laboratory for the Physics and Chemistry of Nanodevices and College of Chemistry and Molecular Engineering, Peking University, Beijing 100871, China

Yat Li, Department of Chemistry and Biochemistry, University of California, 1156 High Street, Santa Cruz, California 95064 (yli@chemistry.ucsc.edu)

Zhen Li, ARC Center of Excellence for Functional Nanomaterials, Australian Institute for Bioengineering and Nanotechnology, The University of Queensland, Queensland 4072, Australia (zhenli76@hotmail.com)

Lei Liao, Department of Chemistry and Biochemistry and California Nanosystems Institute, University of California, Los Angeles, California 900924

Yichuan Ling, Department of Chemistry and Biochemistry, University of California, 1156 High Street, Santa Cruz, California 95064

Ruibin Liu, Micro-nano Technology Center, Beijing Institute of Technology, Beijing 100081, China

Gaoqing (Max) Lu, ARC Center of Excellence for Functional Nanomaterials, Australian Institute for Bioengineering and Nanotechnology, The University of Queensland, Queensland 4072, Australia (m.lu@uq.edu.au)

Jun Luo, Beijing National Center for Electron Microscopy, Laboratory of Advanced Materials, State Key Laboratory of New Ceramics and Fine Processing, Department of Materials Science and Engineering, Tsinghua University, Beijing 100084, China

Rubén Mas-Ballesté, Departamento de Química Inorgánica, Universidad Autónoma de Madrid, 28049 Madrid, Spain (ruben.mas@uam.es)

H. S. S. Ramakrishna Matte, International Centre for Materials Science, Chemistry and Physics of Materials Unit, and CSIR Centre of Excellence in Chemistry, Jawaharlal Nehru Centre for Advanced Scientific Research, Jakkur P.O., Bangalore 560 064, India

Binh-Minh Nguyen, Center for Quantum Devices, Northwestern University, Evanston, Illinois 60208

Lian-Mao Peng, Key Laboratory for the Physics and Chemistry of Nanodevices and Department of Electronics, Peking University, Beijing 100871, China (lmpeng@pku.edu.cn)

Andrea Ponzoni, Department of Chemistry and Physics for Materials and Engineering, CNR-IDASC Sensor Laboratory and University of Brescia, Via Valotti 9, 25133 Brescia, Italy (andrea.ponzoni@ing.unibs.it)

Teng Qiu, Department of Physics, Southeast University, Nanjing 211189, China (tqiu@seu.edu.cn)

C. N. R. Rao, International Centre for Materials Science, Chemistry and Physics of Materials Unit, and CSIR Centre of Excellence in Chemistry, Jawaharlal Nehru Centre for Advanced Scientific Research, Jakkur P.O., Bangalore 560 064, India (cnrrao@jncasr.ac.in)

Manijeh Razeghi, Center for Quantum Devices, Northwestern University, Evanston, Illinois 60208 (razeghi@eecs.northwestern.edu)

Gil Rosenman, School of Electrical Engineering, Iby and Aladar Fleischman Faculty of Engineering, Tel Aviv University, Tel Aviv 69978, Israel (gilr@eng.tau.ac.il)

Giorgio Sberveglieri, Department of Chemistry and Physics for Materials and Engineering, CNR-IDASC Sensor Laboratory and University of Brescia, Via Valotti 9, 25133 Brescia, Italy

Stephan Senz, Max Planck Institute of Microstructure Physics, Halle D-06120, Germany

Sean C. Smith, Centre for Computational Molecular Science, Australian Institute for Bioengineering and Nanotechnology, The University of Queensland, Queensland 4072, Australia

K. S. Subrahmanyam, International Centre for Materials Science, Chemistry and Physics of Materials Unit, and CSIR Centre of Excellence in Chemistry, Jawaharlal Nehru Centre for Advanced Scientific Research, Jakkur P.O., Bangalore 560 064, India

Qiao Sun, Centre for Computational Molecular Science, Australian Institute for Bioengineering and

Nanotechnology, The University of Queensland, Queensland 4072, Australia

Bozhi Tian, Department of Chemistry, the James Franck Institute and the Institute for Biophysical Dynamics, the University of Chicago, Chicago, Illinois 60637 (btian@uchicago.edu)

King-Ning Tu, Department of Materials Science and Engineering, Henry Samueli School of Engineering and Applied Science, University of California Los Angeles (UCLA), Los Angeles, California 90024 (kntu@ucla.edu)

Sergio O. Valenzuela, Institució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona E-08010, Spain; Catalan Institute of Nanotechnology (ICN) and Universitat Autónoma de Barcelona, Campus UAB Bellaterra, Barcelona E-08913, Spain.

Bart J. van Wees, Physics of Nanodevices, Zernike Institute for Advanced Materials, University of Groningen, Groningen, The Netherlands

Sheng Wang, Key Laboratory for the Physics and Chemistry of Nanodevices and Department of Electronics, Peking University, Beijing 100871, China

Xi Wang, International Center for Materials Nanoarchitectonics (WPI-MANA), National Institute for Materials Science (NIMS), Namiki 1-1, Tsukuba, Ibaraki 305-0044, Japan

Damon A. Wheeler, Department of Chemistry and Biochemistry, University of California, 1156 High Street, Santa Cruz, California 95064

Jian Wu, Department of Electrical Engineering, 121 Electrical Engineering East, The Pennsylvania State University, University Park, Pennsylvania 16802

Wei-Guang Xie, Department of Electronic Engineering, Materials Science and Technology Research Center, The Chinese University of Hong Kong, Shatin, N. T., Hong Kong SAR, China

Qihua Xiong, Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, 637371; Division of Microelectronics, School of Electrical and Electronic Engineering, Nanyang Technological University, 639798, Singapore (Qihua@ntu.edu.sg)

Jian-Bin Xu, Department of Electronic Engineering, Materials Science and Technology Research Center, The Chinese University of Hong Kong, Shatin, N. T., Hong Kong SAR, China

Jiannian Yao, Beijing National Laboratory for Molecular Sciences, CAS Key Laboratory of Photochemistry, Institute of Chemistry, Chinese Academy of Sciences, Beijing 100190, China (jnyao@iccas.ac.cn)

Félix Zamora, Departamento de Química Inorgánica, Universidad Autónoma de Madrid, 28049 Madrid, Spain (felix.zamora@uam.es)

Tianyou Zhai, Department of Materials Science and Engineering, Tsinghua University, Beijing 100084, P. R. China (zhai.tianyou@gmail.com)

Jin Zhong Zhang, Department of Chemistry and Biochemistry, University of California, 1156 High Street, Santa Cruz, California 95064 (zhang@chemistry.ucsc.edu)

Jun Zhang, Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, 637371, Singapore

Zhang Zhang, The School of Physics & Telecommunication Engineering, South China Normal University, Guangzhou, China, 510631; Max Planck Institute of Microstructure Physics, Halle D-06120, Germany (zzhang@scnu.edu.cn)

Zhiyong Zhang, Key Laboratory for the Physics and Chemistry of Nanodevices and Department of Electronics, Peking University, Beijing 100871, China

Yong Sheng Zhao, Beijing National Laboratory for Molecular Sciences, CAS Key Laboratory of Photochemistry, Institute of Chemistry, Chinese Academy of Sciences, Beijing 100190, China (yszhao@iccas.ac.cn)

Haoshen Zhou, Energy Technology Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Umezono 1-1-1, 305–8568 Tsukuba, Japan (hs.zhou@aist.go.jp)

Jing Zhu, Beijing National Center for Electron Microscopy, Laboratory of Advanced Materials, State Key Laboratory of New Ceramics and Fine Processing, Department of Materials Science and Engineering, Tsinghua University, Beijing 100084, China (jzhu@mail.tsinghua.edu.cn)

Zhonghua Zhu, School of Chemical Engineering, The University of Queensland, Queensland 4072, Australia

Bingsuo Zou, Micro-nano Technology Center, Beijing Institute of Technology, Beijing 100081, China (zoubs@bit.edu.cn)

CONTENTS