SYNTHESIS, CHARACTERIZATION AND MODELLING OF NICKEL NANOWIRES SYNTHESIZED VIA TEMPLATE-ASSISTED ELECTRODEPOSITION

NURHANIS SOFIAH BT ABD GHAFAR

Master of Science

UNIVERSITI MALAYSIA PAHANG

SUPERVISOR'S DECLARATION

We hereby declare that we have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science in Mechanical Engineering

_____

(Supervisor's Signature)

Full Name : Dr. Mahendran A/L Samykano

Position : Senior Lecturer

Date : 4 AUGUST 2017

_____

(Co-supervisor's Signature)

Full Name : Dr. Devarajan A/L Ramasamy

Position : Senior Lecturer

Date : 4 AUGUST 2017

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

_____

(Student's Signature)

Full Name : NURHANIS SOFIAH BT ABD GHAFAR

ID Number : MMM16004

Date : 4 AUGUST 2017

SYNTHESIS, CHARACTERIZATION AND MODELLING OF NICKEL NANOWIRES SYNTHESIZED VIA TEMPLATE-ASSISTED ELECTRODEPOSITION

NURHANIS SOFIAH BT ABD GHAFAR

Thesis submitted in fulfillment of the requirements
for the award of the degree of
Master of Science

Faculty of Mechanical Engineering

UNIVERSITI MALAYSIA PAHANG

AUGUST 2017

ACKNOWLEDGEMENTS

In the name of Allah S.W.T, the Most Beneficent and the Most Merciful. The deepest sense of gratitude to the Almighty for the strength and ability to complete this study.

I would like to express my sincere appreciation to my main supervisor, Dr. Mahendran Samykano, for his support, encouragement, and supervision throughout the period of this study, which has enabled me to complete my work successfully. I also would like to thank Dr. Devarajan Ramasamy as my co-supervisor.

My deepest appreciation goes to my supportive husband, Mohd Faizal bin Mohd Yusof, my beloved parents, Hj Abd Ghafar bin Awang and Hjh Rosiah bt Jusoh, and my siblings, Izzati, Mubasyir, Akilah and Amni whom had always supported me morally and been giving me their never-ending motivations to ensure that I complete this study successfully.

I would like to greatly thank the Ministry of Higher Education (MOHE) and Universiti Malaysia Pahang (UMP) for all the support throughout me completing this study.

Finally, thank you to all group members, friends and everyone that had been helping me, directly or indirectly, to complete my study.

TABLE OF CONTENT

DECLARATION

TITLE PAGE

ACKNOWLEDGEMENTS **ii**

ABSTRAK **iii**

ABSTRACT **iv**

TABLE OF CONTENT **v**

LIST OF TABLES **ix**

LIST OF FIGURES **x**

LIST OF SYMBOLS **xii**

LIST OF ABBREVIATIONS **xiii**

CHAPTER 1 INTRODUCTION **1**

1.1 General Introduction 1

1.1.1 Research Background 1

1.2 Problem Statement 4

1.3 Research Objectives 5

1.4 Research Scopes 5

1.5 Thesis Organization 6

CHAPTER 2 LITERATURE REVIEW **8**

2.1 Introduction to Metallic Nanowires 8

2.2 Synthesis of Metallic Nanowires 9

2.2.1 Template-assisted Electrodeposition 11

2.2.2 Growth Mechanism of Nanowire 14

2.2.3 Etching Process 16

2.2.4 Summary of other synthesis techniques of MNW 17

2.3 Metallic Nanowire Characterization 19

2.3.1 Physical Characterization of Metallic Nanowires 19

2.3.2 Nano Tensile Characterization and Testing 23

2.3.3 Mechanical Characterization of MNWs based on Bending and Flexural Loading 25

2.3.4 Mechanical Resonance Test 26

2.3.5 Compression Testing and Characterization of MNWs 28

2.4 Modeling of Metallic Nanowires 29

2.4.1 Molecular Dynamic (MD) Simulation 30

2.5 Overview of Metallic Nanowire Applications 34

2.6 Summary 36

CHAPTER 3 METHODOLOGY 37

3.1 Introduction 37

3.2 Research Flowchart 38

3.3 Synthesis of Ni Nanowires by Template-Assisted Electrochemical Deposition Method 39

3.3.1 Introduction 39

3.3.2 Electrolyte Preparation 39

3.3.3 Electrochemical Cell Setup 42

3.3.4 Electrochemical Deposition Mechanism 45

3.3.5 Etching Process 46

3.4 Physical Characterization 47

3.4.1 Introduction 47

3.4.2 X-Ray Diffraction (XRD) 48

3.4.3 Field Emission Scanning Electron Microscope (FESEM) 48

3.5 Molecular Dynamic Simulation 49

3.5.1 Introduction 49

3.5.2 How a MD simulation runs 50

3.5.3 Limitation of the MD simulation 51

3.6 Summary 53

CHAPTER 4 RESULTS AND DISCUSSION 55

4.1 Introduction 55

4.2 Synthesis of Ni Nanowires 55

4.3 Energy Dispersive X-Ray (EDX) Analysis 57

4.4 Field Emission Scanning Electron Microscope (FESEM) 57

4.4.1 Morphology of Ni Nanowires synthesized at different parameters 57

4.4.2 Influence of boric acid concentration and deposition temperature on morphology of Ni NW 63

4.4.3 Growth length of the Ni nanowires at different synthesis condition 65

4.4.4 Influence of Boric Acid Concentration and Deposition Bath Temperature on Growth Length 67

4.5 X-ray Diffraction (XRD) Analysis 68

4.5.1 XRD spectrum of Ni nanowires synthesized using boric acid concentration of 5 g/L and deposition bath temperature of 40 °C, 80 °C, and 120 °C 68

4.5.2 XRD spectrum of Ni nanowires synthesized using boric acid concentration of 37.5 g/L and deposition temperature of 40 °C, 80 °C, and 120 °C 70

4.5.3 XRD spectrum of Ni nanowires synthesized using boric acid concentration of 60 g/L and deposition temperature of 40, 80,and 120°C 72

4.5.4 Influence of Boric Acid Concentration and Deposition Temperature on Crystal Orientation 74

4.5.5 Crystal Size Calculation 75

4.5.6 Influence of Boric Acid Concentration and Deposition Temperature on Crystal Size 76

4.6 Mechanical Behavior of Ni Nanowires by MD Simulation 77

4.6.1 Modeling of Ni Nanowires 77

4.6.2 VMD snapshots 79

4.6.3 Stress-strain plot 80

4.6.4 Tensile Properties of Ni nanowires 83

4.7 Summary 85

CHAPTER 5 CONCLUSION 86

5.1 Introduction 86

5.2 Synthesis of 1-D Ni Nanowires 86

5.3 Influence of boric acid concentration and deposition temperature on physical properties of nickel nanowires 86

5.4 Mechanical Behavior of Ni Nanowires by Molecular Dynamic 88

5.5 Recommendations for future works 88

REFERENCES 90

LIST OF TABLES

Table 2.1	Summary of various synthesis techniques for metallic nanowires	18
Table 2.2	Summary of Molecular Dynamic Parameters and Properties Obtained for MNWs using MD	33
Table 2.3	MNWs Unique Properties and its Applications	35
Table 3.1	Different concentration of acids used as electrolytes.	40
Table 3.2	Synthesis parameter for electrochemical deposition	45
Table 4.1	EDX elemental composition of synthesized Ni nanowires	57
Table 4.2	Measured length of the grown Ni nanowire at different synthesis condition	65
Table 4.3	2-theta and spacing between atoms for Ni nanowires synthesized using boric acid concentration of 5 g/L and deposition bath temperature of 40 °C, 80 °C, and 120 °C.	69
Table 4.4	2-theta and spacing between atoms for Ni nanowires synthesized using boric acid concentration of 37.5 g/L and deposition bath temperature of 40 °C, 80 °C, and 120 °C	71
Table 4.5	2-theta and spacing between atoms for Ni nanowires synthesized using stabilizer concentration of 60 g/L and deposition bath temperature of 40 °C, 80 °C, and 120 °C	73
Table 4.6	Example of crystal size calculation for stabilizer concentration of 5 g/L and heating temperature of 40 °C	76
Table 4.7	Crystal size of all synthesized Ni nanowires	76
Table 4.8	Summary of Nickel Nanowire Model Dimension	78
Table 4.9	Simulated Mechanical Properties of Nickel Nanowires	84

LIST OF FIGURES

Figure 2.1 Nanomaterials with different 1D nano-shapes and size: (a) nanorods, (b) nanowires, and (c) nanobelts. 9

Figure 2.2 Schematic illustration of six different strategies accomplishing 1D growth; a) dictation by the anisotropic crystallographic structure of a solid; b) confinement by a liquid droplet as in the vapor-liquid-solid process; c) through the use of a template; d) kinetic control provided by a capping reagent; e) self-assembly of 0D nanostructures; f) size reduction of 1D microstructure 10

Figure 2.3 Schematic illustration of experimental apparatus and the template used for electrodeposition of nanowires. 12

Figure 3.1 Flowchart of the Research 38

Figure 3.2 Procedure for electrolyte preparation 41

Figure 3.3 Schematic of typical two electrode electrochemical deposition setup 42

Figure 3.4 (a) Components used for cathode preparation, and (b) the prepared cathode electrode (AAO template attached to copper tape) 43

Figure 3.5 Electrochemical cell setup for electrochemical deposition 43

Figure 3.6 Anode and cathode for electrochemical cell setup 44

Figure 3.7 Etching process of AAO template 47

Figure 3.8 Bruker D8 AdvanceX-ray Diffraction (XRD) 48

Figure 3.9 FESEM in Central Lab, Universiti Malaysia Pahang 49

Figure 4.1 FESEM images of synthesized Ni nanowires (a) Ni nanowires with diameter of 200 nm -310 nm, (b) Bundle of Ni nanowires 56

Figure 4.2 EDX spectrum of synthesized Ni NW 57

Figure 4.3 FESEM images of grown Ni nanowires using boric acid concentration of 5 g/L and deposition temperature of (a) 40 °C, (b) 80 °C, and (c) 120 °C 59

Figure 4.4 FESEM images of grown Ni nanowires using boric acid concentration of 37.5 g/L and deposition temperature of (a) 40 °C, (b) 80 °C, and (c) 120 °C 61

Figure 4.5 FESEM images of grown Ni nanowires using boric acid concentration of 60 g/L and deposition temperature of (a) 40 °C, (b) 80 °C, and (c) 120 °C 62

Figure 4.6 Compilation of FESEM images of synthesized Ni nanowires at different boric acid concentration with different deposition temperature 64

Figure 4.7 Average measurement growth length of Ni nanowires synthesized at a boric acid concentration of 60 g/L and deposition temperature 120 °C. 66

Figure 4.8 Ni nanowire length for different synthesis condition 67

Figure 4.9 X-ray diffraction spectrum of Ni nanowires synthesized using boric acid concentration of 5 g/L and deposition bath temperature of 40 °C, 80 °C, and 120 °C 68

Figure 4.10 Superimposed X-ray diffraction spectrum of Ni nanowires synthesized using boric acid concentration of 5 g/L and deposition bath temperature of 40 °C, 80 °C, and 120 °C 69

Figure 4.11 X-ray diffraction spectrum of Ni nanowires synthesized using boric acid concentration of 37.5 g/L and deposition bath temperature of 40 °C, 80 °C, and 120 °C 70

Figure 4.12 X-ray diffraction spectrum of Ni nanowires synthesized using boric acid concentration of 37.5 g/L and deposition bath temperature of 40 °C, 80 °C, and 120 °C 71

Figure 4.13 X-ray diffraction spectrum of Ni nanowires synthesized using boric acid concentration of 60 g/L and deposition bath temperature of 40 °C, 80 °C, and 120 °C 72

Figure 4.14 X-ray diffraction spectrum of Ni nanowires synthesized using boric acid concentration of 60 g/L and deposition bath temperature of 40 °C, 80 °C, and 120 °C 73

Figure 4.15 XRD spectrum of Ni nanowires synthesized at different boric acid concentration with deposition bath temperature 75

Figure 4.16 Crystal size of Ni nanowires synthesized at different boric acid concentration and deposition bath temperature 77

Figure 4.17 Simulation Cell of Nickel Nanowire 78

Figure 4.18 Failure under tensile deformation process of Ni nanowire 79

Figure 4.19 Stress-strain curve from all the Ni nanowires model tested using MD simulation 82

Figure 4.20 Stress-strain curve of modeled Ni nanowire 85

LIST OF SYMBOLS

λ	Wavelength of incident X-ray
d	Space between atomic planes in the crystalline phase
D	Diameter of crystallites
K	Crystallites shape factors
β	Full width at half maximum (radians)
σ_y	Yield strength
E	Young Modulus
σ	Stress
ε	Strain

LIST OF ABBREVIATIONS

Ni	Nickel
NW	Nanowire
MNW	Metallic Nanowire
MD	Molecular Dynamic
LAMMPS	Large-scale Atomic or Molecular Massively Parallel Simulator
VMD	Visual Molecular Dynamic
1D	One Dimensional
AAO	Anodic Alumina Oxide
FESEM	Field Emission Scanning Electron Microscope
EDX	Energy Dispersive X-ray Detector
XRD	X-ray Diffraction
FWHM	Full width at half maximum
EAM	Embedded-atom-method
fcc	Face cubic centre

SYNTHESIS, CHARACTERIZATION AND MODELLING OF NICKEL NANOWIRES SYNTHESIZED VIA TEMPLATE-ASSISTED ELECTRODEPOSITION

NURHANIS SOFIAH BT ABD GHAFAR

Thesis submitted in fulfillment of the requirements
for the award of the degree of
Master of Science

Faculty of Mechanical Engineering

UNIVERSITI MALAYSIA PAHANG

AUGUST 2017

ABSTRAK

Struktur bahan dengan saiz nano telah menarik perhatian ramai kerana keunikan sifat mekanikal, elektronik, optik, elektrik dan sifat magnetnya yang telah membuka pelbagai idea untuk mengaplikasikan struktur bahan ini. Wayar nano logam adalah salah satu struktur nano yang mempunyai skala panjang dalam lingkungan 1-1000 nanometer, berbentuk pepejal dalam satu dimensi. Wayar nano logam seperti nikel dijangkakan memainkan peranan yang penting di masa akan datang. Pelbagai proses sintesis dan kaedah pencirian telah dijalankan untuk menghasilkan struktur ini, tetapi kerana sifat struktur ini yang mempamerkan sifat-sifat yang berbeza pada keadaan sistesis yang berbeza, pengetahuan yang menyeluruh mengenai struktur ini masih pada peringkat awal. Selain itu, kerana saiz struktur ini yang sangat kecil, teknik pencirian mekanikal yang diaplikasikan kepada struktur bahan bersaiz makro tidak dapat digunakan untuk mengkaji sifat-sifat mekanikal struktur bahan bersaiz nano. Oleh itu, kaedah pemodelan dan simulasi akan menjadi kaedah alternatif untuk menganggarkan mekanisme dan sifat-sifat mekanikal struktur bahan bersaiz nano. Oleh itu, objektif kajian ini adalah untuk mensintesis wayar nano nikel melalui teknik pemendapan elektrokimia dengan bantuan templat dan untuk memahami pengaruh suhu pemendapan dan kepekatan asid borik kepada sifat-sifat fizikal wayar nano nikel. Dalam kajian ini, kepekatan asid boric diubah daripada 5 g / L, 37.5 g / L dan 60 g / L dengan suhu pemendapan 40 °C, 80 °C, dan 120 °C. Morfologi, analisis unsur dan sifat-sifat kristalografi dianalisis menggunakan FESEM, EDX, dan XRD. Huraian sifat-sifat fizikal wayar nano nikel diperoleh dengan mengambil kira kesan kepekatan borik asid dan suhu pemendapan kepada komposisi unsur, morfologi permukaan, panjang pertumbuhan, orientasi kristal dan saiz kristal wayar nano nikel yang disintesis dibincangkan. Sifat-sifat mekanik wayar nano nikel adalah dianggarkan melalui simulasi Molecular Dynamic (MD). Kajian ini telah mendapati wayar nano nikel dengan ketulenan yang tinggi (97.97% berdasarkan analisis EDX) berjaya dihasilkan melalui kaedah pemendapan elektokimia dengan bantuan template. Analisis kualitatif daripada imej FESEM menunjukkan bahawa semua tekstur permukaan wayar nano nikel didapati kasar dan tidak stabil apabila peningkatan suhu pemendapan ditingkatkan. Analisis XRD menunjukkan bahawa semua wayar nano nikel yang dihasilkan adalah polikristal dan spektrum XRD yang diperolehi tidak menunjukkan apa-apa perubahan dalam orientasi kristal apabila keadaan sintesis yang berbeza telah diaplikasikan. Walau bagaimanapun, peningkatan dalam saiz kristal telah dikesan apabila suhu pemendapan meningkat, dan ia juga menunjukkan bahawa purata peningkatan saiz kristal dalam jumlah kecil apabila kepekatan asid boric dikurangkan. Dari simulasi MD, elastic modulus untuk wayar nano nikel yang dimodel dianggarkan antara 140.02-142.5 GPa, kekuatan tegangan adalah dalam anggaran 16.465-16.732 GPa dan kekuatan keterikan dihasilkan adalah antara 0.1181-0.1209. Penyelidikan ini mampu menyumbang kepada pemahaman yang lebih mendalam terhadap pengaruh parameter ketika sintesis dijalankan terhadap sifat-sifat fizikal nanowires logam, serta dapat memberi idea yang lebih baik untuk merekabentuk eksperimen untuk bahan-bahan nanostructure lain di masa akan datang.

ABSTRACT

Nanometer-sized structures have attracted lots of interest due to its unique mechanical, electronic, optical, electrical, chemical and magnetic properties; opening up a broad view of the application. Metallic nanowires classified as a nano-sized material with the characteristic length scale in the range of 1-1000 nanometers. As one of the most important one-dimensional (1D) nanostructures, metallic nanowire such as Nickel (Ni) expected to play a vital part in the future. Many synthesis and characterization method have been developed to produce this structures, but due to the nature of this structures which exhibits different behavior at different condition (environmental and synthesis), the comprehensive knowledge of these structures still in its early stages. Apart from that, due to the size of these structures, the well-established macro-scale mechanical characterization technique could not be used to determine the mechanical properties of these structures. As such, the modeling and simulation methods would be the alternate methods to provide further insights into various deformation mechanisms and mechanical properties. Therefore, the objectives of this research are to synthesize Ni nanowires via template-assisted electrochemical deposition technique; and to understand the influence of deposition bath temperature and stabilizer concentration on the physical properties. In this study, the stabilizer concentration was varied from 5 g/L, 37.5 g/L and 60 g/L with the deposition bath temperature of 40 °C, 80 °C, and 120 °C. The morphology, elemental analysis and crystallographic properties were analyzed using FESEM, EDX, and XRD. The elaboration of the physical properties of obtained Ni nanowires by taking into account the effect of stabilizer concentration and deposition bath temperature on the elemental composition, surface morphology, growth length, crystal orientation and crystal size of the synthesized Ni nanowires discussed. The mechanical properties of Ni nanowires are estimated through molecular dynamic (MD) simulation. Key research insight from the present investigation concludes that the template-assisted electrochemical deposition approach successfully synthesized high purity Ni nanowires (97.97% based on EDX analysis). Qualitative analysis from FESEM images showed that all the surface texture of Ni nanowires found to be rough and flaky with rough surface texture when the deposition temperature increase. XRD analysis suggests that all the grown Ni nanowire is polycrystalline in nature and the obtained XRD spectrum does not show any change in the crystal orientation when different synthesis condition was applied. However, increase in crystal size was noticed when deposition temperature increased, and it is also noted that the average of crystal size increase in small amount when the stabilizer concentration reduced. From MD simulation, the estimated elastic modulus for Ni nanowires is between 140.02 to 142.5 GPa, the yielding stress between 16.465 to 16.732 GPa and the yielding strain between 0.1181 to 0.1209. The present research contributes to the understanding the influence of processing parameter towards the physical properties of metallic nanowires, as well as designing experimental procedure for future extension to other nanomaterials.

REFERENCES

Abbasi, N. M., Yu, H., Wang, L., Zain ul, A., Amer, W. A., Akram, M., Khalid, H., Chen, Y., Saleem, M., Sun, R. & Shan, J. 2015. Preparation of silver nanowires and their application in conducting polymer nanocomposites. *Materials Chemistry and Physics,* 166**,** 1-15.

Adeela, N., Maaz, K., Khan, U., Karim, S., Ahmad, M., Iqbal, M., Riaz, S., Han, X. & Maqbool, M. 2015. Fabrication and temperature dependent magnetic properties of nickel nanowires embedded in alumina templates. *Ceramics International,* 41**,** 12081-12086.

Agrawal, R., Peng, B., Gdoutos, E. E. & Espinosa, H. D. 2008. Elasticity size effects in ZnO nanowires− a combined experimental-computational approach. *Nano Letters,* 8**,** 3668-3674.

Ahmad, I., Dee, C. F., Husnain, G., Rafique, H. M., Long, Y. & Naseem, S. 2012. Use of high-intensity electron beam to form nanohole, induce bending and fabricate nanocontact on a ZnO nanowire. *Micro & Nano Letters,* 7**,** 122-124.

Al-Salman, R., Sommer, H., Brezesinski, T. & Janek, J. 2015. Template-Free Electrochemical Synthesis of High Aspect Ratio Sn Nanowires in Ionic Liquids: A General Route to Large-Area Metal and Semimetal Nanowire Arrays? *Chemistry of Materials,* 27**,** 3830-3837.

Alducin, D., Borja, R., Ortega, E., Velazquez-Salazar, J. J., Covarrubias, M., Santoyo, F. M., Bazán-Díaz, L., Sanchez, J. E., Torres, N., Ponce, A. & José-Yacamán, M. 2016. In situ transmission electron microscopy mechanical deformation and fracture of a silver nanowire. *Scripta Materialia,* 113**,** 63-67.

Anderson, J. A., Lorenz, C. D. & Travesset, A. 2008. General purpose molecular dynamics simulations fully implemented on graphics processing units. *Journal of Computational Physics,* 227**,** 5342-5359.

Araneo, R., Rinaldi, A., Notargiacomo, A., Bini, F., Pea, M., Celozzi, S., Marinozzi, F. & Lovat, G. 2014. Design Concepts, Fabrication and Advanced Characterization Methods of Innovative Piezoelectric Sensors Based on ZnO Nanowires. *Sensors,* 14**,** 23539.

Arif, M., Heo, K., Lee, B. Y., Lee, J., Seo, D. H., Seo, S., Jian, J. K. & Hong, S. 2011. Metallic nanowire-graphene hybrid nanostructures for highly flexible field emission devices. *Nanotechnology,* 22.

Bard, A. J. 1980. LR Faulkner Electrochemical Methods. Wiley, New York.

Bechelany, M., Amin, A., Brioude, A., Cornu, D. & Miele, P. 2012. ZnO nanotubes by template-assisted sol–gel route. *Journal of Nanoparticle Research,* 14**,** 980.

Bera, D., Kuiry, S. C. & Seal, S. 2004. Synthesis of nanostructured materials using template-assisted electrodeposition. *JOM,* 56**,** 49-53.

Biswas, A., Bayer, I. S., Biris, A. S., Wang, T., Dervishi, E. & Faupel, F. 2012. Advances in top–down and bottom–up surface nanofabrication: Techniques, applications & future prospects. *Advances in Colloid and Interface Science,* 170**,** 2-27.

Bograchev, D. A., Volgin, V. M. & Davydov, A. D. 2013a. Simple model of mass transfer in template synthesis of metal ordered nanowire arrays. *Electrochimica Acta,* 96**,** 1-7.

Bograchev, D. A., Volgin, V. M. & Davydov, A. D. 2013b. Simulation of inhomogeneous pores filling in template electrodeposition of ordered metal nanowire arrays. *Electrochimica Acta,* 112**,** 279-286.

Boukai, A. I., Bunimovich, Y., Tahir-Kheli, J., Yu, J.-K., Goddard Iii, W. A. & Heath, J. R. 2008. Silicon nanowires as efficient thermoelectric materials. *Nature,* 451**,** 168-171.

Branício, P. S. & Rino, J.-P. 2000. Large deformation and amorphization of Ni nanowires under uniaxial strain: a molecular dynamics study. *Physical Review B,* 62**,** 16950.

Brumlik, C. J., Menon, V. P. & Martin, C. R. 1994. Template synthesis of metal microtubule ensembles utilizing chemical, electrochemical, and vacuum deposition techniques. *Journal of Materials Research,* 9**,** 1174-1183.

Cai, H., Wang, W., Liu, P., Wang, G., Liu, A., He, Z., Cheng, Z., Zhang, S. & Xia, M. 2015. Enhanced synthesis of Sn nanowires with aid of Se atom via physical vapor transport. *Journal of Crystal Growth,* 420**,** 42-46.

Cann, M., Large, M. J., Henley, S. J., Milne, D., Sato, T., Chan, H., Jurewicz, I. & Dalton, A. B. 2016. High performance transparent multi-touch sensors based on silver nanowires. *Materials Today Communications,* 7**,** 42-50.

Cao, G. 2004a. *Nanostructures & Nanomaterials: Synthesis, Properties & Application,* Imperial College Press.

Cao, G. 2004b. *Nanostructures and nanomaterials: synthesis, properties and applications,* World Scientific.

Carmo, M., Sekol, R. C., Ding, S. Y., Kumar, G., Schroers, J. & Taylor, A. D. 2011. Bulk Metallic Glass Nanowire Architecture for Electrochemical Applications. *Acs Nano,* 5**,** 2979-2983.

Carreño-Fuentes, L., Ascencio, J. A., Medina, A., Aguila, S., Palomares, L. A. & Ramírez, O. T. 2013. Strategies for specifically directing metal functionalization of protein nanotubes: constructing protein coated silver nanowires. *Nanotechnology,* 24**,** 235602.

Chakravorty, D., Basu, S., Pal, B., Mukherjee, P., Ghosh, B., Chatterjee, K., Bose, A., Bhattacharya, S. & Banerjee, A. 2008. Synthesis of nanocomposites using glasses and mica as templates. *Bulletin of Materials Science,* 31**,** 263-276.

Chang, Y.-C., Lin, P.-S., Liu, F.-K., Guo, J.-Y. & Chen, C.-M. 2016. One-step and single source synthesis of Cu-doped ZnO nanowires on flexible brass foil for highly efficient field emission and photocatalytic applications. *Journal of Alloys and Compounds,* 688, Part B**,** 242-251.

Chen, Y., Wang, X., Xie, S., Liu, J., Cheng, H., Zheng, X., Liu, F. & Yang, J. 2012. Temperature Effect on the Microstructures and Optical Properties of ZnO Nanowires. *Journal of Nanomaterials,* 2012**,** 5.

Choi, H. & Park, S.-H. 2004. Seedless growth of free-standing copper nanowires by chemical vapor deposition. *Journal of the American Chemical Society,* 126**,** 6248-6249.

Choi, J. S., Sauer, G., Goring, P., Nielsch, K., Wehrspohn, R. B. & Gosele, U. 2003. Monodisperse metal nanowire arrays on Si by integration of template synthesis with silicon technology. *Journal of Materials Chemistry,* 13**,** 1100-1103.

Colburn, M., Johnson, S. C., Stewart, M. D., Damle, S., Bailey, T. C., Choi, B., Wedlake, M., Michaelson, T. B., Sreenivasan, S. & Ekerdt, J. G. Step and flash imprint lithography: a new approach to high-resolution patterning. Microlithography'99, 1999. International Society for Optics and Photonics, 379-389.

Cortés, A., Riveros, G., Palma, J. L., Denardin, J. C., Marotti, R. E., Dalchiele, E. A. & Gómez, H. 2009. Single-crystal growth of nickel nanowires: influence of deposition conditions on structural and magnetic properties. *Journal of nanoscience and nanotechnology,* 9**,** 1992-2000.

Courtier, P., Freydier, J.-F. G. & Rabier, M. 1993. 8. WJ Randel and JC Gille, ibid. 48, 2336 (1991). 9. M. Yanai and T. Maruyama, J. Meteorol. Soc. Jpn. *Science,* 261**,** 3.

Dai, S. & Park, H. S. 2013. Surface effects on the piezoelectricity of ZnO nanowires. *Journal of the Mechanics and Physics of Solids,* 61**,** 385-397.

Dayeh, S. A., Yu, E. T. & Wang, D. 2007. III− V nanowire growth mechanism: V/III ratio and temperature effects. *Nano letters,* 7**,** 2486-2490.

de AA Soler-Illia, G. J., Crepaldi, E. L., Grosso, D. & Sanchez, C. 2003. Block copolymer-templated mesoporous oxides. *Current Opinion in Colloid & Interface Science,* 8**,** 109-126.

Decker, C., Solanki, R., Freeouf, J., Carruthers, J. & Evans, D. 2004. Directed growth of nickel silicide nanowires. *Applied physics letters,* 84**,** 1389-1391.

Dou, R. & Derby, B. 2008. The strength of gold nanowire forests. *Scripta Materialia,* 59**,** 151-154.

Duanmu, Y. Q. & Huang, Q. 2015. Analysis and optimization of the edge effect for III-V nanowire synthesis via selective area metal-organic chemical vapor deposition. *Iie Transactions,* 47**,** 1424-1431.

Dupont, V. & Sansoz, F. 2009. Molecular dynamics study of crystal plasticity during nanoindentation in Ni nanowires. *Journal of Materials Research,* 24**,** 948-956.

Ertan, A., Tewari, S. N. & Talu, O. 2008. Electrodeposition of nickel nanowires and nanotubes using various templates. *Journal of Experimental Nanoscience,* 3**,** 287-295.

Espinosa, H. D., Bernal, R. A. & Minary-Jolandan, M. 2012. A Review of Mechanical and Electromechanical Properties of Piezoelectric Nanowires. *Advanced Materials,* 24**,** 4656-4675.

French, W. R., Iacovella, C. R. & Cummings, P. T. 2011. The influence of molecular adsorption on elongating gold nanowires. *The Journal of Physical Chemistry C,* 115**,** 18422-18433.

Gall, K., Diao, J. & Dunn, M. L. 2004. The strength of gold nanowires. *Nano Letters,* 4**,** 2431-2436.

Gambhire, A. B., Lande, M. K., Kalokhe, S. B., Shirsat, M. D., Patil, K. R., Gholap, R. S. & Arbad, B. R. 2008. Synthesis and characterization of high surface area CeO2-doped SnO2 nanomaterial. *Materials Chemistry and Physics,* 112**,** 719-722.

Gan, Q. Q., Hu, H. F., Xu, H. N., Liu, K., Jiang, S. H. & Cartwright, A. N. 2011. Wavelength-Independent Optical Polarizer Based on Metallic Nanowire Arrays. *Ieee Photonics Journal,* 3**,** 1083-1092.

García, M., Batalla, P. & Escarpa, A. 2014. Metallic and polymeric nanowires for electrochemical sensing and biosensing. *TrAC Trends in Analytical Chemistry,* 57**,** 6-22.

Gdoutos, E. E., Agrawal, R. & Espinosa, H. D. 2010. Comparison of the Ewald and Wolf methods for modeling electrostatic interactions in nanowires. *International Journal for Numerical Methods in Engineering,* 84**,** 1541-1551.

Ghahremaninezhad, A. & Dolati, A. 2009. A study on electrochemical growth behavior of the Co–Ni alloy nanowires in anodic aluminum oxide template. *Journal of Alloys and Compounds,* 480**,** 275-278.

Gianola, D. & Eberl, C. 2009. Micro-and nanoscale tensile testing of materials. *JOM,* 61**,** 24-35.

Gonzalez-Garcia, L., Maurer, J. H. M., Reiser, B., Kanelidis, I. & Kraus, T. 2016. Ultrathin Gold Nanowires for Transparent Electronics: Breaking Barriers. *Procedia Engineering,* 141**,** 152-156.

Gopal, R., Singh, M. K., Agarwal, A., Singh, S. C. & Swarnkar, R. K. 2009. Synthesis of Nickel Nanomaterial by Pulsed Laser Ablation in Liquid Medium and its Characterization. *Transport and Optical Properties of Nanomaterials,* 1147**,** 199-204.

Greer, J. R. & Nix, W. D. 2006. Nanoscale gold pillars strengthened through dislocation starvation. *Physical Review B,* 73**,** 245410.

Guha, P., Chakrabarti, S. & Chaudhuri, S. 2004. Synthesis of beta-Ga2O3 nanowire from elemental Ga metal and its photoluminescence study. *Physica E-Low-Dimensional Systems & Nanostructures,* 23**,** 81-85.

Guo, F., Cheng, K., Ye, K., Wang, G. & Cao, D. 2016. Preparation of nickel-cobalt nanowire arrays anode electro-catalyst and its application in direct urea/hydrogen peroxide fuel cell. *Electrochimica Acta,* 199**,** 290-296.

Guo, Y. Y., Wang, M., Mao, X. B., Jiang, Y. X., Wang, C. & Yang, Y. L. 2010. Growth Mechanism for Controlled Synthesis of Metal Nanotube and Nanowire Arrays Using Anodic Aluminum Oxide Templates. *Acta Physico-Chimica Sinica,* 26**,** 2037-2043.

Haberkorn, N., Condó, A. M., Sirena, M., Soldera, F. & Lovey, F. C. 2014. Single crystalline β phase Cu–Zn nanowires: Synthesis and martensitic transformation. *Materials Letters,* 124**,** 256-260.

Hamidinezhad, H. 2016. Thickness effect of catalyst layer on silicon nanowires morphology and features. *Applied Surface Science,* 364**,** 484-489.

Hanson, J., Rodriguez, B., Nemanich, R. & Gruverman, A. 2006. Fabrication of metallic nanowires on a ferroelectric template via photochemical reaction. *Nanotechnology,* 17**,** 4946.

Haque, M. A. & Saif, M. T. A. 2002. In-situ tensile testing of nano-scale specimens in SEM and TEM. *Experimental Mechanics,* 42**,** 123-128.

Hasan, M., Jamal, M. & Razeeb, K. M. 2012. Coaxial NiO/Ni nanowire arrays for high performance pseudocapacitor applications. *Electrochimica Acta,* 60**,** 193-200.

Hayashi, T., Muramatsu, H., Kim, Y. A., Kajitani, H., Imai, S., Kawakami, H., Kobayashi, M., Matoba, T., Endo, M. & Dresselhaus, M. S. 2006. TEM image simulation study of small carbon nanotubes and carbon nanowire. *Carbon,* 44**,** 1130-1136.

He, W. & Ye, C. 2015. Flexible Transparent Conductive Films on the Basis of Ag Nanowires: Design and Applications: A Review. *Journal of Materials Science & Technology,* 31**,** 581-588.

Hertzberg, R. W. 1989. Deformation and fracture mechanics of engineering materials.

Hochbaum, A. I., Chen, R., Delgado, R. D., Liang, W., Garnett, E. C., Najarian, M., Majumdar, A. & Yang, P. 2008. Enhanced thermoelectric performance of rough silicon nanowires. *Nature,* 451**,** 163-167.

Hou, Y. X., Xu, W., Hu, J. G. & Xiao, Y. M. 2015. Quantized Acoustic-Phonon Modes in Metallic Nanowire Structures. *Rare Metal Materials and Engineering,* 44**,** 3019-3022.

Hsu, P. C., Liu, X. G., Liu, C., Xie, X., Lee, H. R., Welch, A. J., Zhao, T. & Cui, Y. 2015. Personal Thermal Management by Metallic Nanowire-Coated Textile. *Nano Letters,* 15**,** 365-371.

Hsu, S. Y., Lee, M. C., Lee, K. L. & Wei, P. K. 2008. Extraction enhancement in organic light emitting devices by using metallic nanowire arrays. *Applied Physics Letters,* 92.

Huang, D. & Qiao, P. 2010. Mechanical behavior and size sensitivity of nanocrystalline nickel wires using molecular dynamics simulation. *Journal of Aerospace Engineering,* 24**,** 147-153.

Huang, D., Zhang, Q. & Qiao, P. 2011. Molecular dynamics evaluation of strain rate and size effects on mechanical properties of FCC nickel nanowires. *Computational Materials Science,* 50**,** 903-910.

Huczko, A. 2000. Template-based synthesis of nanomaterials. *Applied Physics A,* 70**,** 365-376.

Ikeda, K. & Kawaguchi, H. 2013. Metallic nanowire lasers. *Journal of the Optical Society of America B-Optical Physics,* 30**,** 1981-1986.

Irshad, M., Ahmad, F., Mohamed, N. & Abdullah, M. 2014. Preparation and structural characterization of template assisted electrodeposited copper nanowires. *Int. J. Electrochem. Sci,* 9**,** 2548-2555.

Jang, I., Kang, T., Cho, W., Kang, Y. S., Oh, S.-G. & Im, S. S. 2015. Preparation of silver nanowires coated with TiO2 using chemical binder and their applications as photoanodes in dye sensitized solar cell. *Journal of Physics and Chemistry of Solids,* 86**,** 122-130.

Jung, Y. S., Lee, J. H., Lee, J. Y. & Ross, C. A. 2010. Fabrication of Diverse Metallic Nanowire Arrays Based on Block Copolymer Self-Assembly. *Nano Letters,* 10**,** 3722-3726.

Kamalakar, M. V. 2011. Synthesis, characterization and investigation of electrical transport in metal nanowires and nanotubes. *arXiv preprint arXiv:1110.5260*.

Kang, M., Lee, H., Kang, T. & Kim, B. 2015. Synthesis, Properties, and Biological Application of Perfect Crystal Gold Nanowires: A Review. *Journal of Materials Science & Technology,* 31**,** 573-580.

Kaur, N., Comini, E., Poli, N., Zappa, D. & Sberveglieri, G. 2015. Nickel Oxide Nanowires Growth by VLS Technique for Gas Sensing Application. *Procedia Engineering,* 120**,** 760-763.

Kelsall, R., Hamley, I. W. & Geoghegan, M. 2005a. *Nanoscale science and technology,* John Wiley & Sons.

Kelsall, R. W., Hamley, I. W., Geoghegan, M. & Wiley, J. 2005b. *Nanoscale science and technology,* Wiley Online Library.

Khan, A. & Kordesch, M. E. 2006. Large-scale fabrication of metallic Zn nanowires by thermal evaporation. *Physica E: Low-dimensional Systems and Nanostructures,* 33**,** 88-91.

Kline, T. R., Tian, M., Wang, J., Sen, A., Chan, M. W. & Mallouk, T. E. 2006. Template-grown metal nanowires. *Inorganic chemistry,* 45**,** 7555-7565.

Koo, S., Kumar, M. S., Shin, J., Kim, D. & Park, N. 2009. Extraordinary Magnetic Field Enhancement with Metallic Nanowire: Role of Surface Impedance in Babinet's Principle for Sub-Skin-Depth Regime. *Physical Review Letters,* 103.

Kottmann, J. P., Martin, O. J. F., Smith, D. R. & Schultz, S. 2001. Plasmon resonances of silver nanowires with a nonregular cross section. *Physical Review B,* 64**,** 235402.

Kurban, M. & Erkoç, Ş. 2016. Mechanical properties of CdZnTe nanowires under uniaxial stretching and compression: A molecular dynamics simulation study. *Computational Materials Science,* 122**,** 295-300.

Lamrani, S., Guittoum, A., Schäfer, R., Hemmous, M., Neu, V., Pofahl, S., Hadjersi, T. & Benbrahim, N. 2015. Morphology, structure and magnetic study of permalloy films electroplated on silicon nanowires. *Journal of Magnetism and Magnetic Materials,* 396**,** 263-267.

Langley, D. P., Lagrange, M., Giusti, G., Jimenez, C., Brechet, Y., Nguyen, N. D. & Bellet, D. 2014. Metallic nanowire networks: effects of thermal annealing on electrical resistance. *Nanoscale,* 6**,** 13535-13543.

Lee, D., Park, H., Ryu, H., Jeon, S. & Hong, S. 2011. Microstructure and mechanical properties of SiC-nanowire-augmented tungsten composites. *Journal of Alloys and Compounds,* 509**,** 9060-9064.

Lee, J., Lee, P., Lee, H., Lee, D., Lee, S. S. & Ko, S. H. 2012. Very long Ag nanowire synthesis and its application in a highly transparent, conductive and flexible metal electrode touch panel. *Nanoscale,* 4**,** 6408-6414.

Lee, S., Im, J., Yoo, Y., Bitzek, E., Kiener, D., Richter, G., Kim, B. & Oh, S. H. 2014. Reversible cyclic deformation mechanism of gold nanowires by twinning–detwinning transition evidenced from in situ TEM. *Nature communications,* 5.

Li, X. D., Meng, G. W., Qin, S. Y., Xu, Q. L., Chu, Z. Q., Zhu, X. G., Kong, M. G. & Li, A. P. 2012. Nanochannel-Directed Growth of Multi-Segment Nanowire Heterojunctions of Metallic Au1-xGex and Semiconducting Ge. *Acs Nano,* 6**,** 831-836.

Li, X. D., Meng, G. W., Xu, Q. L., Kong, M. G., Zhu, X. G., Chu, Z. Q. & Li, A. P. 2011. Controlled Synthesis of Germanium Nanowires and Nanotubes with Variable Morphologies and Sizes. *Nano Letters,* 11**,** 1704-1709.

Li, Z., Leung, C., Gao, F. & Gu, Z. 2015. Effects of nanowire length and surface roughness on the electrochemical sensor properties of Nafion-free, vertically aligned Pt nanowire array electrodes. *Sensors,* 15**,** 22473-22489.

Liang, H., Upmanyu, M. & Huang, H. 2005. Size-dependent elasticity of nanowires: nonlinear effects. *Physical Review B,* 71**,** 241403.

Lieber, C. M. 1998. One-dimensional nanostructures: chemistry, physics & applications. *Solid state communications,* 107**,** 607-616.

Lin, H. Y., Chen, H. A. & Lin, H. N. 2008. Fabrication of a single metal nanowire connected with dissimilar metal electrodes and its application to chemical sensing. *Analytical Chemistry,* 80**,** 1937-1941.

Lin, J.-Y., Hsueh, Y.-L., Huang, J.-J. & Wu, J.-R. 2015. Effect of silver nitrate concentration of silver nanowires synthesized using a polyol method and their application as transparent conductive films. *Thin Solid Films,* 584**,** 243-247.

Liu, C., Liu, H. T. & Zhong, Y. 2014a. Impact of surface plasmon polaritons and other waves on the radiation of a dipole emitter close to a metallic nanowire antenna. *Optics Express,* 22**,** 25539-25549.

Liu, X., Shao, Y., Li, J. F., Chen, N. & Yao, K. F. 2014b. Large-area and uniform amorphous metallic nanowire arrays prepared by die nanoimprinting. *Journal of Alloys and Compounds,* 605**,** 7-11.

Lu, Y., Peng, C., Ganesan, Y., Huang, J. Y. & Lou, J. 2011. Quantitative in situ TEM tensile testing of an individual nickel nanowire. *Nanotechnology,* 22.

Maisch, P., Tam, K. C., Lucera, L., Egelhaaf, H.-J., Scheiber, H., Maier, E. & Brabec, C. J. 2016. Inkjet printed silver nanowire percolation networks as electrodes for highly efficient semitransparent organic solar cells. *Organic Electronics,* 38**,** 139-143.

Mao, Y., Wang, C. & Yang, H. 2015. Rapid and uniform synthesis of silver nanowires via rice-shaped silver nucleant. *Materials Letters,* 142**,** 102-105.

Martin, C. R. 1996. Membrane-based synthesis of nanomaterials. *Chemistry of Materials,* 8**,** 1739-1746.

Masuda, T., Asoh, H., Haraguchi, S. & Ono, S. 2015. Fabrication and Characterization of Single Phase α-Alumina Membranes with Tunable Pore Diameters. *Materials,* 8**,** 1350.

Mijatovic, D., Eijkel, J. C. T. & van den Berg, A. 2005. Technologies for nanofluidic systems: top-down vs. bottom-up-a review. *Lab on a Chip,* 5**,** 492-500.

Mohan, R. & Liang, Y. 2010. *Tensile and Flexural Deformation of Nickel Nanowires via Molecular Dynamics Simulations,* INTECH Open Access Publisher.

Mohanty, U. S. 2011. Electrodeposition: a versatile and inexpensive tool for the synthesis of nanoparticles, nanorods, nanowires, and nanoclusters of metals. *Journal of Applied Electrochemistry,* 41**,** 257-270.

Mu, C. & He, J. H. 2010. Synthesis of Single Crystal Metal Sulfide Nanowires and Nanowire Arrays by Chemical Precipitation in Templates. *Journal of Nanoscience and Nanotechnology,* 10**,** 8191-8198.

Narayanan, T. N., Shaijumon, M. M., Ci, L., Ajayan, P. M. & Anantharaman, M. R. 2008. On the growth mechanism of nickel and cobalt nanowires and comparison of their magnetic properties. *Nano Research,* 1**,** 465-473.

Nath, S. D. & Kim, S.-G. 2012. On the elastic, elastic-plastic properties of Au nanowires in the range of diameter 1-200 nm. *Journal of Applied Physics,* 112**,** 123522.

Pantano, M. F., Espinosa, H. D. & Pagnotta, L. 2012. Mechanical characterization of materials at small length scales. *Journal of Mechanical Science and Technology,* 26**,** 545-561.

Patolsky, F., Weizmann, Y. & Willner, I. 2004. Actin-based metallic nanowires as bio-nanotransporters. *Nature materials,* 3**,** 692-695.

Pearson, D. & Tonucci, R. 1995. Nanochannel glass replica membranes. *Science,* 270**,** 68.

Phillips, F. R., Fang, D., Zheng, H. X. & Lagoudas, D. C. 2011. Phase transformation in free-standing SMA nanowires. *Acta Materialia,* 59**,** 1871-1880.

Prina-Mello, A., Diao, Z. & Coey, J. M. D. 2006. Internalization of ferromagnetic nanowires by different living cells. *Journal of nanobiotechnology,* 4**,** 9.

Qin, Q., Xu, F., Cao, Y., Ro, P. I. & Zhu, Y. 2012. Measuring true Young's modulus of a cantilevered nanowire: effect of clamping on resonance frequency. *Small,* 8**,** 2571-2576.

Ren, R., Faber, M. S., Dziedzic, R., Wen, Z. H., Jin, S., Mao, S. & Chen, J. H. 2015. Metallic CoS2 nanowire electrodes for high cycling performance supercapacitors. *Nanotechnology,* 26.

Sainath, G. & Choudhary, B. 2015. Molecular dynamics simulation of twin boundary effect on deformation of Cu nanopillars. *Physics Letters A,* 379**,** 1902-1905.

Sainath, G., Choudhary, B. K. & Jayakumar, T. 2015. Molecular dynamics simulation studies on the size dependent tensile deformation and fracture behaviour of body centred cubic iron nanowires. *Computational Materials Science,* 104**,** 76-83.

Samykano, M., Mohan, R. & Aravamudhan, S. 2014. Morphology and Crystallographic Characterization of Nickel Nanowires—Influence of Magnetic Field and Current Density During Synthesis. *Journal of Nanotechnology in Engineering and Medicine,* 5**,** 021005.

Sekol, R. C., Carmo, M., Kumar, G., Gittleson, F., Doubek, G., Sun, K., Schroers, J. & Taylor, A. D. 2013. Pd–Ni–Cu–P metallic glass nanowires for methanol and ethanol oxidation in alkaline media. *International Journal of Hydrogen Energy,* 38**,** 11248-11255.

Setoodeh, A., Attariani, H. & Khosrownejad, M. 2008. Nickel nanowires under uniaxial loads: A molecular dynamics simulation study. *Computational Materials Science,* 44**,** 378-384.

Sharma, G., Pishko, M. V. & Grimes, C. A. 2007. Fabrication of metallic nanowire arrays by electrodeposition into nanoporous alumina membranes: effect of barrier layer. *Journal of Materials Science,* 42**,** 4738-4744.

Sharma, M. & Kuanr, B. K. 2015. Electrodeposition of Ferromagnetic Nanostructures. *Electroplating of Nanostructures.* Rijeka: InTech.

Shin-Pon, J., Jenn-Sen, L. & Wen-Jay, L. 2004. A molecular dynamics study of the tensile behaviour of ultrathin gold nanowires. *Nanotechnology,* 15**,** 1221.

Shui, J. & Li, J. C. 2009. Platinum nanowires produced by electrospinning. *Nano letters,* 9**,** 1307-1314.

Şişman, İ. 2011. Template-assisted electrochemical synthesis of semiconductor nanowires. *Nanowires–Implementations and Applications.* InTech.

Šupicová, M., Rozik, R., Trnkova, L., Oriňáková, R. & Galova, M. 2006. Influence of boric acid on the electrochemical deposition of Ni. *Journal of Solid State Electrochemistry,* 10**,** 61-68.

Suriani, A. B., Alfarisa, S., Mohamed, A., Kamari, A., Hashim, N., Isa, I. M., Mamat, M. H., Malek, M. F. & Ahmad, M. K. 2015. Amorphous Al–Cu alloy nanowires decorated with carbon spheres synthesised from waste engine oil. *Journal of Alloys and Compounds,* 642**,** 111-116.

Sutrakar, V. K., Mahapatra, D. R. & Pillai, A. C. R. 2012. Temperature-pressure-induced solid-solid < 100 > to < 110 > reorientation in FCC metallic nanowire: a molecular dynamic study. *Journal of Physics-Condensed Matter,* 24.

Takeshi, O. 2012. Magnetoresistance of Nanowires Electrodeposited into Anodized Aluminum Oxide Nanochannels.

Tan, E. P. S. & Lim, C. T. 2006. Mechanical characterization of nanofibers – A review. *Composites Science and Technology,* 66**,** 1102-1111.

Tang, S., Vongehr, S., Wan, N. & Meng, X. 2013. Rapid synthesis of pentagonal silver nanowires with diameter-dependent tensile yield strength. *Materials Chemistry and Physics,* 142**,** 17-26.

Thanka Rajan, S., Subramanian, B., Nanda Kumar, A. K., Jayachandran, M. & Ramachandra Rao, M. S. 2014. Fabrication of nanowires of Al-doped ZnO using nanoparticle assisted pulsed laser deposition (NAPLD) for device applications. *Journal of Alloys and Compounds,* 584**,** 611-616.

Toimil-Molares, M. E. 2012. Characterization and properties of micro- and nanowires of controlled size, composition, and geometry fabricated by electrodeposition and ion-track technology. *Beilstein Journal of Nanotechnology,* 3**,** 860-883.

Tsuru, Y., Nomura, M. & Foulkes, F. 2002. Effects of boric acid on hydrogen evolution and internal stress in films deposited from a nickel sulfamate bath. *Journal of Applied Electrochemistry,* 32**,** 629-634.

Vicenzo, A. & Cavallotti, P. 2008. Structure and electrokinetic study of nickel electrodeposition. *Russian Journal of Electrochemistry,* 44**,** 716-727.

Vlassov, S., Polyakov, B., Dorogin, L. M., Antsov, M., Mets, M., Umalas, M., Saar, R., Lõhmus, R. & Kink, I. 2014. Elasticity and yield strength of pentagonal silver nanowires: In situ bending tests. *Materials Chemistry and Physics,* 143**,** 1026-1031.

Wang, B., Shi, D., Jia, J., Wang, G., Chen, X. & Zhao, J. 2005a. Elastic and plastic deformations of nickel nanowires under uniaxial compression. *Physica E: Low-dimensional Systems and Nanostructures,* 30**,** 45-50.

Wang, D. H., Zhou, W. L., McCaughy, B. F., Hampsey, J. E., Ji, X. L., Jiang, Y. B., Xu, H. F., Tang, J. K., Schmehl, R. H., O'Connor, C., Brinker, C. J. & Lu, Y. F. 2003. Electrodeposition of metallic nanowire thin films using mesoporous silica templates. *Advanced Materials,* 15**,** 130-+.

Wang, J.-G., Tian, M.-L., Kumar, N. & Mallouk, T. E. 2005b. Controllable template synthesis of superconducting Zn nanowires with different microstructures by electrochemical deposition. *Nano letters,* 5**,** 1247-1253.

Wang, J., Chen, X., Wang, G., Wang, B., Lu, W. & Zhao, J. 2002. Melting behavior in ultrathin metallic nanowires. *Physical Review B,* 66**,** 085408.

Wang, L., Lu, Y., Kong, D., Xiao, L., Sha, X., Sun, J., Zhang, Z. & Han, X. 2015. Dynamic and atomic-scale understanding of the twin thickness effect on dislocation nucleation and propagation activities by in situ bending of Ni nanowires. *Acta Materialia,* 90**,** 194-203.

Wang, L., Peng, C. & Gong, J. 2009. Molecular dynamics study of the mechanics for Ni single-wall nanowires. *European Journal of Mechanics-A/Solids,* 28**,** 877-881.

Wang, W.-d., Yi, C.-l. & Fan, K.-q. 2013a. Molecular dynamics study on temperature and strain rate dependences of mechanical tensile properties of ultrathin nickel nanowires. *Transactions of Nonferrous Metals Society of China,* 23**,** 3353-3361.

Wang, Y., Fan, D., Wu, D., Zhang, Y., Ma, H., Du, B. & Wei, Q. 2016. Simple synthesis of silver nanoparticles functionalized cuprous oxide nanowires nanocomposites and its

application in electrochemical immunosensor. *Sensors and Actuators B: Chemical,* 236**,** 241-248.

Wang, Z.-L., Guo, R., Ding, L.-X., Tong, Y.-X. & Li, G.-R. 2013b. Controllable Template-Assisted Electrodeposition of Single- and Multi-Walled Nanotube Arrays for Electrochemical Energy Storage. *Scientific Reports,* 3**,** 1204.

Wang, Z. Y., Shi, L. Y., Wu, F. Q., Yuan, S. A., Zhao, Y. & Zhang, M. H. 2011. The sol-gel template synthesis of porous TiO2 for a high performance humidity sensor. *Nanotechnology,* 22.

Weber, F., Schestakow, I., Roters, F. & Raabe, D. 2008a. Texture evolution during bending of a single crystal copper nanowire studied by EBSD and crystal plasticity finite element simulations. *Advanced Engineering Materials,* 10**,** 737-741.

Weber, J., Singhal, R., Zekri, S. & Kumar, A. 2008b. One-dimensional nanostructures: fabrication, characterisation and applications. *International Materials Reviews,* 53**,** 235-255.

Weir, E., Lawlor, A., Whelan, A. & Regan, F. 2008. The use of nanoparticles in anti-microbial materials and their characterization. *Analyst,* 133**,** 835-845.

Wen, X., Xie, Y., Choi, C. L., Wan, K. C., Li, X.-Y. & Yang, S. 2005. Copper-based nanowire materials: templated syntheses, characterizations, and applications. *Langmuir,* 21**,** 4729-4737.

Wen, Y.-H., Wang, Q., Liew, K. M. & Zhu, Z.-Z. 2010. Compressive mechanical behavior of Au nanowires. *Physics Letters A,* 374**,** 2949-2952.

Wen, Y.-H., Zhu, Z.-Z. & Zhu, R.-Z. 2008. Molecular dynamics study of the mechanical behavior of nickel nanowire: Strain rate effects. *Computational Materials Science,* 41**,** 553-560.

Wen, Y.-H., Zhu, Z.-Z., Zhu, R. & Shao, G.-F. 2004. Size effects on the melting of nickel nanowires: a molecular dynamics study. *Physica E: Low-dimensional Systems and Nanostructures,* 25**,** 47-54.

Wu, B., Heidelberg, A. & Boland, J. J. 2005. Mechanical properties of ultrahigh-strength gold nanowires. *Nat Mater,* 4**,** 525-529.

Wu, H. A., Wang, X. X., Liang, H. Y. & Liu, G. Y. 2002. Progress in mechanical behavior of metal nanowire. *Acta Metallurgica Sinica,* 38**,** 903-907.

Xia, S., Liu, L., Kong, Y. & Wang, M. 2016. Uniaxial strain effects on the optoelectronic properties of GaN nanowires. *Superlattices and Microstructures,* 97**,** 327-334.

Xia, Y., Yang, P., Sun, Y., Wu, Y., Mayers, B., Gates, B., Yin, Y., Kim, F. & Yan, H. 2003a. One-Dimensional Nanostructures: Synthesis, Characterization, and Applications. *Advanced Materials,* 15**,** 353-389.

Xia, Y., Yang, P., Sun, Y., Wu, Y., Mayers, B., Gates, B., Yin, Y., Kim, F. & Yan, H. 2003b. One-dimensional nanostructures: synthesis, characterization, and applications. *Advanced materials,* 15**,** 353-389.

Xie, P., Xiong, Q., Fang, Y., Qing, Q. & Lieber, C. M. 2012. Local electrical potential detection of DNA by nanowire-nanopore sensors. *Nature nanotechnology,* 7**,** 119-125.

Yang, F. & Li, J. C.-M. 2008. *Micro and nano mechanical testing of materials and devices,* Springer.

Yao, Y. & Chen, S. 2016. Surface effect in the bending of nanowires. *Mechanics of Materials,* 100**,** 12-21.

Yue, Y., Liu, P., Zhang, Z., Han, X. & Ma, E. 2011. Approaching the theoretical elastic strain limit in copper nanowires. *Nano letters,* 11**,** 3151-3155.

Yuksel, R., Coskun, S., Kalay, Y. E. & Unalan, H. E. 2016. Flexible, silver nanowire network nickel hydroxide core-shell electrodes for supercapacitors. *Journal of Power Sources,* 328**,** 167-173.

Yum, K., Wang, Z., Suryavanshi, A. P. & Yu, M.-F. 2004. Experimental measurement and model analysis of damping effect in nanoscale mechanical beam resonators in air. *Journal of Applied Physics,* 96**,** 3933-3938.

Zhan, H., Gu, Y., Yan, C. & Yarlagadda, P. 2014a. Bending properties of Ag nanowires with pre-existing surface defects. *Computational Materials Science,* 81**,** 45-51.

Zhan, H., Gu, Y., Yan, C. & Yarlagadda, P. K. 2014b. Tensile properties of Si nanowires with faulted stacking layers. *Science of Advanced Materials,* 6**,** 1489-1492.

Zhang, D., Breguet, J.-M., Clavel, R., Philippe, L., Utke, I. & Michler, J. 2009. In situ tensile testing of individual Co nanowires inside a scanning electron microscope. *Nanotechnology,* 20**,** 365706.

Zhang, H., Gu, X., Zhang, X., Ye, X. & Gong, X. 2004. Structures and properties of Ni nanowires. *Physics Letters A,* 331**,** 332-336.

Zhang, Q., Li, Q.-K. & Li, M. 2015. Internal stress and its effect on mechanical strength of metallic glass nanowires. *Acta Materialia,* 91**,** 174-182.

Zhang, Y., Ru, C., Liu, X., Zhong, Y., Sun, X., Hoyle, D., Cotton, I. & Sun, Y. A MEMS tensile testing device for mechanical characterization of individual nanowires. Sensors, 2010 IEEE, 1-4 Nov. 2010 2010. 2581-2584.

Zhang, Y. & Zhao, Y. P. 2011. Adhesive Contact of Nanowire in Three-Point Bending Test. *Journal of Adhesion Science and Technology,* 25**,** 1107-1129.

Zheng, M., Zhang, L., Li, G. & Shen, W. 2002. Fabrication and optical properties of large-scale uniform zinc oxide nanowire arrays by one-step electrochemical deposition technique. *Chemical Physics Letters,* 363**,** 123-128.

Zhu, L. L., Guo, X. & Lu, J. 2014. Surface Stress Effects on the Yield Strength in Nanotwinned Polycrystal Face-Centered-Cubic Metallic Nanowires. *Journal of Applied Mechanics-Transactions of the Asme,* 81**,** 6.

Zhu, Y., Moldovan, N. & Espinosa, H. D. 2005. A microelectromechanical load sensor for in situ electron and x-ray microscopy tensile testing of nanostructures. *Applied physics letters,* 86**,** 013506.

Zhu, Y., Qin, Q., Xu, F., Fan, F., Ding, Y., Zhang, T., Wiley, B. J. & Wang, Z. L. 2012. Size effects on elasticity, yielding, and fracture of silver nanowires: In situ experiments. *Physical review B,* 85**,** 045443.