SYNTHESIS AND PHYSICAL PROPERTY CHARACTERIZATION OF NICKEL NANOWIRES

SANTHI A/P ULAKANATHAN

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.

____

(Supervisor's Signature)

Full Name : TS. DR. NGUI WAI KENG

Position : SENIOR LECTURER

Date : 15/11/2021

____

(Co-supervisor's Signature)

Full Name : IR. TS. DR. MAHENDRAN SAMYKANO

Position : ASSOCIATE PROFESSOR

Date : 15/11/2021

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 : SANTHI A/P ULAKANATHAN

ID Number : MSM17004

Date : 15/11/2021

SYNTHESIS AND PHYSICAL PROPERTY CHARACTERIZATION OF NICKEL NANOWIRES

SANTHI A/P ULAKANATHAN

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

College of Engineering
UNIVERSITI MALAYSIA PAHANG

NOVEMBER 2021

ACKNOWLEDGEMENTS

All praises are to GOD Almighty for the wisdom he bestowed upon me, strength, and countless love for completing my research successfully.

Foremost, I dedicate this accomplishment to my late father, Mr. Ulakanathan, who served as an inspiration to pursue this undertaking and for always believing in me. I would like to extend my deepest gratitude towards my family for giving unfailing support and endless encouragement during the years of study.

My heartfelt thanks to my direct supervisor, Ts. Dr. Ngui Wai Keng, for his undivided attention, guidance, and supervision throughout this study, helped bring this research into success. Also, special thanks to my co-supervisor Assoc. Prof. Ir. Ts. Dr. Mahendran Samykano for imparting his knowledge in this project.

My thanks and appreciation also go to people who have willingly helped me out with their abilities. Completing this dissertation couldn’t have been possible without the support and contributions of the kind of people around me. Their contributions had been invaluable, for which I am incredibly grateful.

ABSTRAK

Satu dimensi wayar nano nikel merupakan struktur nano logam yang dipercayai menyumbang dengan ketara untuk kemajuan bidang bahan saintifik berikutan ciri-ciri kimia, mekanikal and magnetik yang unik. Maka, adalah penting untuk memastikan kajian diteruskan supaya kesemua sifat unik wayar nano nikel dapat dignunakan dengan optimum untuk menghasilkan product berteknologi tinggi. Oleh itu, objektif kajian ini adalah seperti berikut; untuk menjana satu dimensi wayar nano nikel melalui teknik pemendapan kimia menggunakan templat aluminium oksida pada pelbagai suhu pemendapan larutan elekrokimia dan kepekatan asid borik; mengkaji pengaruh pelbagai suhu pemendapan dan asid boric terhadap sifat fizikal wayar nano nikel yang dihasilkan dan untuk membina persamaan matematik menggunakan kaedah RSM (Response Surface Methodology) untuk mengaitkan sifat fizik wayar nano nikel terhadap keadaan sintesis yang berbeza. Dalam kajian ini, kepekatan asid borik diubah daripada 6, 40, dan 70 g/l manakala suhu pemprosesan diubah pada 30, 70 dan 110 °C. Sifat fizikal wayar nano nikel yang dijana dikaji menggunakan pelbagai teknik dan peralatan dan kedua-dua analisis kualitatif dan kuantitatif dibincang dengan terperinci. Kajian menggunakan teknik FESEM (Field Emission Scanning Electron Microscopy) merumuskan bahawa tekstur permukaan wayar nano nikel semakin kasar dengan penigkatan suhu pemendapan dan kepekatan asid boric. Imej FESEM juga menunjukkan bahawa wayar nano nikel memanjang dengan penigkatan suhu tetapi memendek dengan penigkatan kepekatan asid borik. Analisis unsur asas menggunakan EDX (Energy Dispersive X-ray Detector) pula membuktikan penghasilan wayar nano nikel yang bertulin tinggi dengan ketulinan atom nikel sebanyak 97.97 %. Hasil kajian XRD (X-ray Diffraction) memaparkan ciri polikristal untuk wayar nano nikel yang dijana dan orientasi kristal tidak berubah pada keadaan sintesis yang berlainan. Tetapi, saiz kristal mengecil dengan peningkatan kepekatan asid borik dan membesar dengan peratusan yang sedikit dengan peningkatan suhu pemendapan. Persamaan matematik dibentuk dengan kaedah RSM untuk mengaitkan panjang wayar nano dan saiz kristal terhadap proses parameter yang digunakan dalam kajian ini. Analisis menunjukkan bahawa suhu mempengaruhi pemanjangan wayar nano nikel dengan berkesan pada 76.82%. Manakala, saiz kristal dipengaruhi oleh kepekatan asid boric pada 39.49% dan suhu pemendapan pada 53.44%. Ralat nilai data eksperimen berbanding ramalan nilai sebenar untuk panjang wayar ialah 1.0 % dan untuk saiz kristal adalah 0.55 %. Persamaan matematik yang dibentuk ini membolehkan ramalan parameter pemprosesan yang sleanjutnya pada keadaan sintesis yang tertentu, tanpa keperluan untuk mengulangi eksperimen di mana ia menyumbang mengurangkan kos dan menjimatkan masa.

ABSTRACT

1D (one-dimensional) Ni (Nickel) NW (nanowire) is a metallic nanostructure that is anticipated to contribute substantially to material scientific advancement due to its unique chemical, mechanical, and magnetic properties. Hence, it is essential to ensure continuity of researches to utilize and optimize the exclusive properties of Ni NWs to develop high technology products. Therefore, the objectives of this research are as follows: to synthesize 1D Ni NWs using AAO (anodic aluminium oxide) template-assisted electrodeposition technique at various electrolyte bath temperatures and boric acid concentrations; to investigate the influence of electrolyte bath temperatures and boric acid concentrations towards physical properties of Ni NWs synthesized and to develop a mathematical equation using RSM (Response Surface Methodology) to correlate physical properties of Ni NWs towards synthesis condition. In this research, boric acid concentration was varied at 6, 40, and 70 g/L while the processing temperature was varied at 30, 70, and 110 °C. Physical properties of Ni NWs synthesized were analyzed using different characterization tools and both qualitative and quantitative findings were discussed in detail. Investigation using FESEM (Field Emission Scanning Electron Microscopy) showed the surface morphology became rougher with increasing electrolyte bath temperature and boric acid concentration. FESEM images also revealed that there is a growth in Ni NW length when the temperature increases but the NWs became shorter with high boric acid concentration. The elemental composition analysis using EDX (Energy Dispersive X-ray Detector) proved successful fabrication of high purity Ni NWs with 97.97 % Ni atom. XRD (X-ray Diffraction) finding showed the Ni NWs produced are in polycrystalline structure and the crystal orientation remains unchanged with different processing conditions. However, the crystal size became smaller with increasing boric acid concentration and grows bigger in a small percentage with higher deposition temperature. The mathematical equation was developed using RSM to corelate Ni NW growth length and crystal size towards the processing parameters employed in this research. The analysis showed that the temperature influences Ni NW growth length significantly, at 76.82 %. Meanwhile, the crystal size was influenced by boric acid concentration at 39.49% and electrodeposition bath temperature at 53.44 %. The error of experimental data versus predicted data for NWs growth length is 1.0 %, and for crystal size is 0.55 %. The established mathematical equation enables prediction of future values for specified processing conditions, thus eliminate the need to repeat the experiments and offers cost and time savings benefits.

TABLE OF CONTENT

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.

Abd Ghafar, N. S., Ulakanathan, S., Samykano, M., Kadirgama, K., Mohammed, H. A. & Ngui, W. K. 2020. Template Synthesis of Ni Nanowires: Characterization and Modelling. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences,* 77**,** 76-90.

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.

Ahghari, M. R., Soltaninejad, V. & Maleki, A. 2020. Synthesis of nickel nanoparticles by a green and convenient method as a magnetic mirror with antibacterial activities. *Scientific reports,* 10**,** 1-10.

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.

Alali, K. T., Lu, Z., Zhang, H., Liu, J., Liu, Q., Li, R., Aljebawi, K. & Wang, J. 2017. P–p heterojunction CuO/CuCo 2 O 4 nanotubes synthesized via electrospinning technology for detecting n-propanol gas at room temperature. *Inorganic Chemistry Frontiers,* 4**,** 1219-1230.

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.

Argueta-Figueroa, L., Morales-Luckie, R. A., Scougall-Vilchis, R. J. & Olea-Mejía, O. F. 2014. Synthesis, characterization and antibacterial activity of copper, nickel and bimetallic Cu–Ni nanoparticles for potential use in dental materials. *Progress in Natural Science: Materials International,* 24**,** 321-328.

Anirudh Sharma , Yuechen Zhu , ShengShee Thor , Fang Zhou , Bethanie Stadler , and Allison Hubel 2013. Magnetic Barcode Nanowires for Osteosarcoma Cell Control, Detection and Separation

AZoNetwork 2000. Empyrean Multi-Purpose Research X-Ray Diffractometer XRD.

Barakat, N. A., Khil, M. S., Sheikh, F. A. & Kim, H. Y. 2008. Synthesis and optical properties of two cobalt oxides (CoO and Co3O4) nanofibers produced by electrospinning process. *The Journal of Physical Chemistry C,* 112**,** 12225-12233.

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

Baskaran, S. 2010. Structure and Regulation of Yeast Glycogen Synthase.

Bayca, S. U., Altinok, H. & Akcay, A. 2019. Synthesis of nickel nanothorn particles by the hydrothermal method. *Journal of Dispersion Science and Technology***,** 1-11.

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.

Box, G. E. & Wilson, K. B. 1951. On the experimental attainment of optimum conditions. *Journal of the royal statistical society: Series b (Methodological),* 13**,** 1-38.

Brady, J. B., Newton, R. M. & Boardman, S. J. 1995. New uses for powder X-Ray diffraction experiments in the undergraduate curriculum. *Journal of Geological Education,* 43**,** 466-470.

Bragg, W. H. & Bragg, W. L. 1913. The structure of the diamond. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character,* 89**,** 277-291.

Campos, C., do Nascimento-Junior, A., de Miranda, M. H., Guerra, Y., Viana, B. C., Peña-Garcia, R. & Padrón-Hernández, E. 2020. The temperature dependence of coercivity for Ni nanowires: Possible effect of NiO antiferromagnetic clusters. *Journal of Magnetism and Magnetic Materials,* 508**,** 166889.

Cao, G. 2004. *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.

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.

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.

Cherns, D. 1974. Direct resolution of surface atomic steps by transmission electron microscopy. *Philosophical Magazine,* 30**,** 549-556.

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.

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.

Cullity, B. D. 1956. *Elements of X-ray Diffraction*, Addison-Wesley Publishing.

Davalos, C., Lopez, J., Ruiz, H., Méndez, A., Antano-Lopez, R. & Trejo, G. 2013. Study of the role of boric acid during the electrochemical deposition of Ni in a sulfamate bath. *Int J Electrochem Sci,* 8**,** 9785.

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.

Deng, H., Hu, X., Li, H. A., Luo, B. & Wang, W. 2016. Improved pore-structure characterization in shale formations with FESEM technique. *Journal of Natural Gas Science and Engineering,* 35**,** 309-319.

El-Khatib, K., Hameed, R. A., Amin, R. & Fetohi, A. E. 2019. Core-shell structured Pt-transition metals nanoparticles supported on activated carbon for direct methanol fuel cells. *Microchemical Journal,* 145**,** 566-577.

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

Fa, D., Yu, B. & Miao, Y. 2019. Synthesis of ultra-long nanowires of nickel phosphate by a template-free hydrothermal method for electrocatalytic oxidation of glucose. *Colloids and Surfaces A: Physicochemical and Engineering Aspects,* 564**,** 31-38.

Faivre, D. & Godec, T. U. 2015. From bacteria to mollusks: the principles underlying the biomineralization of iron oxide materials. *Angewandte Chemie International Edition,* 54**,** 4728-4747.

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.

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

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.

Graham, L. M. 2014. *The effect of boric acid on the growth mechanism of electrodeposited metal nanostructures.*

Guiliani, J., Cadena, J. & Monton, C. 2018. Template-assisted electrodeposition of Ni and Ni/Au nanowires on planar and curved substrates. *Nanotechnology,* 29**,** 075301.

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.

Gupta, R., Chauhan, R., Chakarvarti, S. & Kumar, R. 2019. Effect of SHI on properties of template synthesized Cu nanowires. *Ionics,* 25**,** 341-352.

Hao, Q., Huang, H., Fan, X., Hou, X., Yin, Y., Li, W., Si, L., Nan, H., Wang, H. & Mei, Y. 2017. Facile design of ultra-thin anodic aluminum oxide membranes for the fabrication of plasmonic nanoarrays. *Nanotechnology,* 28**,** 105301.

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.

Haque, M. A. & Saif, M. T. A. 2003. A review of MEMS-based microscale and nanoscale tensile and bending testing. *Experimental Mechanics,* 43**,** 248-255.

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., Liang, Z., Ji, K., Sun, Q., Zhai, T. & Xu, X. 2018. Hierarchical Ni-Co-S@ Ni-WO core–shell nanosheet arrays on nickel foam for high-performance asymmetric supercapacitors. *Nano Research,* 11**,** 1415-1425.

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, 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.

Hu, S., Zeng, S., Li, X., Jiang, J., Yang, W., Chen, Y., Li, M. & Zheng, J. 2020. Flexible and high performance of n-type thermoelectric PVDF composite film induced by nickel nanowires. *Materials & Design,* 188**,** 108496.

Huang, X., Zhang, Z., Kong, X.-Y., Sun, Y., Zhu, C., Liu, P., Pang, J., Jiang, L. & Wen, L. 2019. Engineered PES/SPES nanochannel membrane for salinity gradient power generation. *Nano Energy,* 59**,** 354-362.

Hung, C. M., Phuong, H. V., Van Duy, N., Hoa, N. D. & Van Hieu, N. 2018. Comparative effects of synthesis parameters on the NO2 gas-sensing performance of on-chip grown ZnO and Zn2SnO4 nanowire sensors. *Journal of Alloys and Compounds,* 765**,** 1237-1242.

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.

Jiang, K., Shao, Q., Zhao, D., Bu, L., Guo, J. & Huang, X. 2017. Phase and composition tuning of 1D platinum-nickel nanostructures for highly efficient electrocatalysis. *Advanced Functional Materials,* 27**,** 1700830.

Jung, I., Choi, J. & Tak, Y. 2010a. Nickel oxalate nanostructures for supercapacitors. *Journal of Materials Chemistry,* 20**,** 6164-6169.

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

Kalkabay, G., Kozlovskiy, A., Zdorovets, M., Borgekov, D., Kaniukov, E. & Shumskaya, A. 2019a. Influence of temperature and electrodeposition potential on structure and magnetic properties of nickel nanotubes. *Journal of Magnetism and Magnetic Materials,* 489**,** 165436.

Kalkabay, G., Shlimas, D., Kozlovskiy, A., Zdorovets, M., Tikhonov, A., Shumskaya, A. & Kaniukov, E. Y. 2019b. Peculiarities of template assisted electrodeposition onedimensional nickel nanostructures from chloride electrolyte. *Advanced Physical Research,* 1**,** 5-13.

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

Kamarulzaman, N. & Jaafar, M. 2012. Synthesis and Stoichiometric Analysis of a Li-Ion Battery Cathode Material.

Kang, S., Su, P., Park, Y., Saito, Y. & Prinz, F. 2006. Thin-film solid oxide fuel cells on porous nickel substrates with multistage nanohole array. *Journal of the Electrochemical Society,* 153**,** A554.

Kashid, S. B., Raut, R. W. & Malghe, Y. S. 2016. Microwave assisted synthesis of nickel nanostructures by hydrazine reduction route: Effect of solvent and capping agent on morphology and magnetic properties. *Materials Chemistry and Physics,* 170**,** 24-31.

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.

Khan, M., Rafique, M. Y., Razaq, A., Mir, A., Karim, S., Anwar, S. & Sultana, I. 2020. Fabrication of Au/Ni/NiO heterostructure nanowires by electrochemical deposition and their temperature dependent magnetic properties. *Journal of Solid State Chemistry,* 284**,** 121186.

Kong, Y.-Y., Somarowthu, A. & Ding, N. 2015. Effects of spectral degradation on attentional modulation of cortical auditory responses to continuous speech. *Journal of the Association for Research in Otolaryngology,* 16**,** 783-796.

Kozlovskiy, A., Dukenbayev, K., Ivanov, I., Kozin, S., Aleksandrenko, V., Kurakhmedov, A., Sambaev, E., Kenzhina, I., Tosi, D. & Loginov, V. 2018. Investigation of the influence of irradiation with Fe+ 7 ions on structural properties of AlN ceramics. *Materials Research Express,* 5**,** 065502.

Kozlovskiy, A. & Zdorovets, M. 2020. The study of the structural characteristics and catalytic activity of Co/CoCo2O4 nanowires. *Composites Part B: Engineering,* 191**,** 107968.

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.

Li, L., Liu, X., Liu, C., Wan, H., Zhang, J., Liang, P., Wang, H. & Wang, H. 2018. Ultra-long life nickel nanowires@ nickel-cobalt hydroxide nanoarrays composite pseudocapacitive electrode: Construction and activation mechanism. *Electrochimica Acta,* 259**,** 303-312.

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, 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.

Ling, L., Xiao, M., Han, D., Ren, S., Wang, S. & Meng, Y. 2019. Porous composite membrane of PVDF/Sulfonic silica with high ion selectivity for vanadium redox flow battery. *Journal of Membrane Science,* 585**,** 230-237.

Logutenko, O. A., Titkov, A. I., Vorob'Yov, A. M., Yukhin, Y. M. & Lyakhov, N. Z. 2016. Characterization and growth mechanism of nickel nanowires resulting from reduction of nickel formate in polyol medium. *Journal of Nanomaterials,* 2016.

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.

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.

Melzer, M., Karnaushenko, D., Lin, G., Baunack, S., Makarov, D. & Schmidt, O. G. 2015. Direct transfer of magnetic sensor devices to elastomeric supports for stretchable electronics. *Advanced Materials,* 27**,** 1333-1338.

Meng, X. & Deng, D. 2019. Bio-inspired synthesis of 3-D network of NiO-Ni nanowires on carbonized eggshell membrane for lithium-ion batteries. *Chemical Engineering Science,* 194**,** 134-141.

Milano, G., Cultrera, A., Bejtka, K., De Leo, N., Callegaro, L., Ricciardi, C. & Boarino, L. 2020. Mapping Time-Dependent Conductivity of Metallic Nanowire Networks by Electrical Resistance Tomography toward Transparent Conductive Materials. *ACS Applied Nano Materials*.

Mohamed, N. M., Irshad, M. I., Abdullah, M. Z. & Saheed, M. S. M. 2016. Novel growth of carbon nanotubes on nickel nanowires. *Diamond and Related Materials,* 65**,** 59-64.

Mohammadi, M., Fardindoost, S. & Almasi-Kashi, M. 2020. Room temperature selective sensing of aligned Ni nanowires using impedance spectroscopy. *Materials Research Express,* 7**,** 025044.

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.

Nie, M., Sun, H., Cai, H., Xue, Z., Yang, C., Li, Q., Qin, L. & Wu, M. 2020. Study on electrocatalytic property of ZnO and Ag/ZnO. *Materials Letters,* 271**,** 127785.

Nunes, S. P. 2016. Block copolymer membranes for aqueous solution applications. *Macromolecules,* 49**,** 2905-2916.

Obodo, R. M., Shinde, N. M., Chime, U. K., Ezugwu, S., Nwanya, A. C., Ahmad, I., Maaza, M., Ejikeme, P. M. & Ezema, F. I. 2020. Recent advances in metal oxide/hydroxide on three-dimensional nickel foam substrate for high performance pseudocapacitive electrodes. *Current Opinion in Electrochemistry,* 21**,** 242-249.

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.

Park, K. & Lee, J.-S. 2016. Controlled synthesis of Ni/CuO x/Ni nanowires by electrochemical deposition with self-compliance bipolar resistive switching. *Scientific reports,* 6**,** 1-6.

Patel, A. & Acharya, N. 2018. Metal coated and nanofiller doped polycarbonate membrane for hydrogen transport. *International Journal of Hydrogen Energy,* 43**,** 21675-21682.

Pateras, A., Harder, R., Manna, S., Kiefer, B., Sandberg, R. L., Trugman, S., Kim, J. W., de la Venta, J., Fullerton, E. E. & Shpyrko, O. G. 2019. Room temperature giant magnetostriction in single-crystal nickel nanowires. *NPG Asia Materials,* 11**,** 1-7.

Patil, S., Kim, J. & Lee, D. 2017. Self-assembled Ni3S2//CoNi2S4 nanoarrays for ultra high-performance supercapacitor. *Chemical Engineering Journal,* 322**,** 498-509.

Pratama, S. N., Kurniawan, Y., Muhammady, S., Takase, K. & Darma, Y. 2018. Structural and magnetic properties of nickel nanowires grown in porous anodic aluminium oxide template by electrochemical deposition technique. *Materials Research Express,* 5**,** 034008.

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

Revathy, R., Varma, M. R. & Surendran, K. P. 2019. Effect of morphology and ageing on the magnetic properties of nickel nanowires. *Materials Research Bulletin,* 120**,** 110576.

Samanifar, S., Kashi, M. A., Ramazani, A. & Alikhani, M. 2015. Reversal modes in FeCoNi nanowire arrays: Correlation between magnetostatic interactions and nanowires length. *Journal of Magnetism and Magnetic Materials,* 378**,** 73-83.

Samykano, M. 2015. *Physical and Mechanical Characterization of Electrodeposited Nickel Nanowires–Influence of Current Density and External Magnetic Field*, North Carolina Agricultural and Technical State University.

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.

Samykano, M., Mohan, R. & Aravamudhan, S. 2015a. Effect of current density and magnetic field on the growth and morphology of nickel nanowires. *MEMS and Nanotechnology, Volume 8.* Springer International Publishing.

Samykano, M., Mohan, R. & Aravamudhan, S. 2015b. Structure and Morphology of Electrodeposited Nickel Nanowires at an Electrode Distance of 20mm. *Structure,* 1**,** 23704.

Santhi, U., Ngui, W., Mahendran, S., Kadirgama, K., Bm, S. & Kumar, M. 2019. *Cobalt nanowires: Advancing into future nanomaterial*.

Saraji, S. & Piri, M. 2015. The representative sample size in shale oil rocks and nano-scale characterization of transport properties. *International Journal of Coal Geology,* 146**,** 42-54.

Schütz, M. B., Xiao, L., Lehnen, T., Fischer, T. & Mathur, S. 2018. Microwave-assisted synthesis of nanocrystalline binary and ternary metal oxides. *International Materials Reviews,* 63**,** 341-374.

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.

Semnani, D. 2017. 7 - Geometrical characterization of electrospun nanofibers. *In:* AFSHARI, M. (ed.) *Electrospun Nanofibers.* Woodhead Publishing.

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.

Shubham Sharma 1,2 , Swarna Jaiswal 2 , Brendan Duffy 2 and Amit K. Jaiswal 1,*

Şişman, İ. 2011. Nanostructured Materials for Food Applications: Spectroscopy, Microscopy and Physical Properties

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

Sofiah, A., Kananathan, J., Samykano, M., Ulakanathan, S., Lah, N., Harun, W., Sudhakar, K., Kadirgama, K., Ngui, W. & Siregar, J. Electrochemical deposited nickel nanowires: influence of deposition bath temperature on the morphology and physical properties. IOP Conference Series: Materials Science and Engineering, 2017. IOP Publishing, 012032.

Sofiah, A., Samykano, M., Kadirgama, K., Mohan, R. & Lah, N. 2018. Metallic nanowires: Mechanical properties–Theory and experiment. *Applied Materials Today,* 11**,** 320-337.

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.

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

Tishkevich, D., Vorobjova, A., Shimanovich, D., Vinnik, D., Zubar, T., Kozlovskiy, A., Zdorovets, M., Yakimchuk, D., Trukhanov, S. & Trukhanov, A. 2019a. Formation and corrosion properties of Ni-based composite material in the anodic alumina porous matrix. *Journal of Alloys and Compounds,* 804**,** 139-146.

Tishkevich, D., Vorobjova, A. & Vinnik, D. A. Template assisted Ni nanowires fabrication. Materials Science Forum, 2019b. Trans Tech Publ, 235-241.

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.

Ussano, E. 2016. *Electrochemistry of Molecular Systems for New Nanostructured Materials and Bioelectronic Devices.* alma.

Vakil, P. N., Hardy, D. A. & Strouse, G. F. 2018. Synthesis of highly uniform nickel multipods with tunable aspect ratio by microwave power control. *ACS nano,* 12**,** 6784-6793.

Velázquez-Galván, Y. & Encinas, A. 2020. Analytical magnetostatic model for 2D arrays of interacting magnetic nanowires and nanotubes. *Physical Chemistry Chemical Physics,* 22**,** 13320-13328.

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

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

Wang, J., Zhang, S., Shi, Z., Jiu, J., Wu, C., Sugahara, T., Nagao, S., Suganuma, K. & He, P. 2018a. Nanoridge patterns on polymeric film by a photodegradation copying method for metallic nanowire networks. *RSC advances,* 8**,** 40740-40747.

Wang, L., Bai, X., Zhao, T. & Lin, Y. 2020. Facile synthesis of N, S-codoped honeycomb-like C/Ni3S2 composites for broadband microwave absorption with low filler mass loading. *Journal of Colloid and Interface Science,* 580**,** 126-134.

Wang, L., Zhu, W., Lu, W., Qin, X. & Xu, X. 2018b. Surface plasmon aided high sensitive non-enzymatic glucose sensor using Au/NiAu multilayered nanowire arrays. *Biosensors and Bioelectronics,* 111**,** 41-46.

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

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

Wong-Leung, J., Yang, I., Li, Z., Karuturi, S. K., Fu, L., Tan, H. H. & Jagadish, C. 2020. Engineering III–V Semiconductor Nanowires for Device Applications. *Advanced Materials,* 32**,** 1904359.

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

Yang, J., Cho, M. & Lee, Y. 2016. Synthesis of hierarchical Ni (OH) 2 hollow nanorod via chemical bath deposition and its glucose sensing performance. *Sensors and Actuators B: Chemical,* 222**,** 674-681.

Yang, Z. Y., Zhao, M., Dai, N. L., Yang, G., Long, H., Li, Y. H. & Lu, P. X. 2008. Broadband polarizers using dual-layer metallic nanowire grids. *Ieee Photonics Technology Letters,* 20**,** 697-699.

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, X., Jiang, X., Xiong, F., Wang, C. & Yang, S. 2017. Controlled synthesis and magnetic properties of Ni nanotubes and nanowires. *Materials Research Bulletin,* 95**,** 248-252.

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, Y. & Espinosa, H. D. 2005. An electromechanical material testing system for in situ electron microscopy and applications. *Proceedings of the National Academy of Sciences of the United States of America,* 102**,** 14503-14508.