American Journal of Engineering and Applied Sciences

Original Research Paper

# Hydrothermal Synthesis of $CuWO_4$-Reduced Graphene Oxide Hybrids and Supercapacitor Application

**Koyal Suman Samantaray, Surjit Sahoo and Chandra Sekhar Rout**

*School of Basic Sciences, Indian Institute of Technology Bhubaneswar, Bhubaneswar-751013, India*

*Article history*
Received: 15-07-2016
Revised: 08-08-2016
Accepted: 09-08-2016

Corresponding Author:
Chandra Sekhar Rout
School of Basic Sciences,
Indian Institute of Technology Bhubaneswar, Bhubaneswar-751013, India
Email: csrout@iitbbs.ac.in, csrout@gmail.com

**Abstract:** This study reports a facile hydrothermal synthesis of Copper tungsten oxide ($CuWO_4$) and $CuWO_4$-reduced graphene oxide hybrid nanoparticles and its application as an electrode for supercapacitor application. The morphology and composition has been characterized using X-Ray Diffraction (XRD), Field Emission Scanning Electron Microscopy (FESEM) and EDAX. The supercapacitive behavior has been studied from cyclic voltammetry and galvanostatic charge-discharge tests. The $CuWO_4$-reduced graphene oxide hybrid nanoparticles show highest specific capacitance of 35.71 F/g at a current density of 0.25 A/g with excellent cycling stability.

**Keywords:** Nanoparticle, $CuWO_4$-Reduced Graphene Oxide, Supercapacitor

## Introduction

The rising consumption of energy and the rapid depletion of global energy resources have made researchers (Dresselhaus and Thomas, 2001; Eisenberg and Nocera, 2005) to develop alternate energy sources. The need for clean and sustainable energy sources has always attracted the scientific community to develop (Liu *et al*., 2010a; Pushparaj *et al*., 2007; Rakhi *et al*., 2012) highly efficient energy storing devices. In the past decade the rapid growth in human population, advancement of hybrid electronic devices and exhaustion of energy sources have given many highly performing (Yang *et al*., 2011; Aricol *et al*., 2005) energy storage devices. Among various energy storage systems, supercapacitor also known as ultracapacitor or electrochemical capacitor has acquired the electronics market due to its fast charge-discharge rate, long cycle life, high power density and high reliability. Compared to battery and fuel cells the supercapacitor (Gao, 2005) has successfully fulfilled the need for (Khaligh and Li, 2010) energy backup systems, consumer portable devices and electrical hybrid automobiles. To design high performing supercapacitor (Yan *et al*., 2014) many criteria are taken into consideration such as high specific capacitance, large rate capability, high cycle stability, toxicity and the cost of the material.

Supercapacitors are categorized into two classes (Halper and Ellenbogen, 2006; Cultura II and Salameh, 2015) based on their energy storing mechanisms (i) Electrochemical Double Layer Capacitors (EDLCs) (ii) pseudocapacitors. EDLC (Yoon *et al*., 2004) stores charge physically through electrostatic mechanism or non faradic process, while pseudocapacitor (Conway *et al*., 1997) stores charge chemically through redox reactions known as faradic process. For high performing EDLC (Kim *et al*., 2006) specific surface area, electrical conductivity, pore size and distribution are taken into consideration. For EDLCs, capacitance values are directly proportional to electrode surface area. Hence, increase of surface area (Lota *et al*., 2008) is of primary importance for obtaining increased content of the energy stored. For pseudocapacitors (Lu and Zhou, 2011; Nithya *et al*., 2013; Wu *et al*., 2011) increase of active material usage in a redox reaction is of primary importance for increasing pseudo-capacitance values. So, activated carbon, CNTs, mesoporous carbon or generally porous carbon materials are used as EDLC while transition metal oxides, conducting polymers are used as pseudocapacitors.

Metaloxides (Wang *et al*., 2015; Yuan *et al*., 2014) are highly used to develop high performing supercapacitor. $RuO_2$ shows specific capacitance of 1585 F/g (Ponrouch *et al*., 2013) but due to its toxicity and high cost synthesis, the investigation for novel, low cost, environment friendly material is still going on. Nanostructuring (Chen *et al*., 2013; Wua *et al*., 2015; Yu *et al*., 2015) the materials is a reasonable method to improve the supercapacitance of the material. Among many nanomaterials $CuWO_4$ (Kumar and Karuppuchamy, 2014; Kumar *et al*., 2015) is a promising material for supercapacitor. It is also used for

water splitting (Tang *et al*., 2016; Gaillard *et al*., 2013) and photocatalyst (Yourey, 2014). The preparation of $CuWO_4$ plays vital role in determining the supercapacitance. Hydrothermal synthesis (Yang *et al*., 2013) of metal oxides is a promising method for large scale and low-cost production with high-quality crystals. Recently many works have been reported on graphene based metal oxides (Liu *et al*., 2010b; Wang *et al*., 2015; Dong *et al*., 2012; Huang *et al*., 2012) to enhance the performance of supercapacitor because graphene shows (Geim, 2009) large surface area, high electrical conductivity (Neto *et al*., 2009), thermal conductivity (Balandin, 2011), profuse interlayer structure and excellent mechanical stability.

In this study we have reported the facile hydrothermal synthesis of $CuWO_4$ and $CuWO_4$-reduced graphene oxide hybrid nanostructures. The morphology and composition have been characterized using XRD, SEM and EDAX. The electrochemical measurements have been performed to study specific capacitance of the prepared materials.

## Experimental Section

### *Chemicals Used*

Copper (II) Sulphate anhydrous [$CuO_4S$, Alfa Aesar (India)], Urea [$CH_4N_2O$, SRL (India)], Sodium tungstate dihydrate [$Na_2WO_4.2H_2O$, Lobal Chemie (India)], Graphene Oxide [Reinste] were used to synthesize Copper Tungsten Oxide [$CuWO_4$] nanopaticles and $CuWO_4$-reduced graphene oxide hybrid nanostructures. For electrochemical measurements 3M aqueous solution of potassium Hydroxide [KOH, 85%, Alfa Aesar (UK)] was used. All the chemicals were used as received without further variation.

### *Preparation of $CuWO_4$ and $CuWO_4$-Reduced Graphene Oxide Hybrid Nanostructure*

The synthesis of $CuWO_4$ and $CuWO_4$-reduced graphene oxide hybrid nanostructures followed facile hydrothermal method. A mixture of 0.392 g $CuO_4S$, 0.79 g $Na_2WO_4.2N_2O$ and 1.92 g urea was mixed in 40 mL of de-ionised water and stirred for 1 h at room temperature at 900 rpm. Then the solution was transferred to a 50 mL Teflon lined stainless steel autoclave and heated for 12 h at 200°C in hot air oven. After the synthesis, the precipitate was collected and rinsed several times with ethanol. Then the collected sample was dried at 70°C for and annealed at 450°C for 12 h.

For the synthesis of $CuWO_4$-reduced graphene oxide hybrid nanostructures the same procedure has been followed as mentioned above but with addition graphene oxide to obtain different concentration of $CuWO_4$-reduced graphene oxide hybrid nanostructures.

### *Material Characterization*

The elemental composition and morphology of the prepared sample was investigated by Energy dispersive X-ray spectroscopy (EDAX) and Field Emission Scanning Electron Microscopy [(FESEM) (MERLIN Compact with GEMINI I electron column, Zeiss Pvt. Ltd., Germany)]. The powder X-ray diffraction spectra were measured by (Bruker D8 advanced diffractometer) method with Cu Kα radiation, λ = 0.154184 nm. The electrochemical performance was recorded by a three electrode electrochemical test using a Potentiostat (PG-16125, Techno science instrument, Bangalore, India).

### *Preparation of Electrode and Electrochemical Measurement*

The working electrode for electrochemical measurement was prepared by mixing the obtained sample with ethanol and then coating it on nickel foam. The prepared sample and ethanol was sonicated for almost 20 min to make homogeneous mixture and then coated on the rectangular nickel foam strip for two times to get uniform coating. Then the coated nickel foam was dried at room temperature in a vacuum container for almost 24 h followed by pressing. The mass of the Ni foam was recorded before the coating and after the coating to know the amount of material deposited on it. The electrochemical performance of the $CuWO_4$ and $CuWO_4$-reduced graphene oxide hybrid nanostructures was observed by a three electrode electrochemical test using a Potentiostat (PG-16125, Techno science instrument, Bangalore, India) in 3M aqueous KOH solution. The Cyclic voltammetry and Charge-discharge tests were carried out at room temperature within a potential range between -0.1 to 0.4 V Vs. Ag/AgCl electrode. The coated nickel strip was used as the working electrode and Pt coil as counter electrode in this three electrode test. Specific capacitance (Cs) of a material is obtained from the cyclic voltammetry curve at different scan rates using the Equation 1:

$$C_s = \frac{\int_{V_i}^{V_f} I(V)dV}{m.s.[V_f - V_i]} \quad (1)$$

where, the numerator gives the total area under the *CV* curve, $[V_f\text{-}V_i]$ is called the potential window ($V_f$ = Final potential value and $V_i$ = Initial potential value], '*m*' is mass loaded on the Working electrode and '*s*' is the scan rate.

The specific capacitance can also be obtained from the charge-discharge curve using Equation 2:

$$C_m = \frac{\mathrm{I}}{m.\frac{dV}{dt}} \quad (2)$$

where, '*I*' is the discharge current, '*m*' is the mass of sample loaded on the working electrode and '*dV*/*dt*' is the slope of the discharge curve.

## Results and Discussion

### *Composition and Morphology Study*

Figure 2(a) and (b) shows the FESEM picture of $CuWO_4$-reduced graphene oxide hybrid nanostructures. From the image it can be clearly observed that the prepared sample consists of nanoparticles of avg. diameter 20-30 nm. The uniform growth of the 80 mg $CuWO_4$-reduced graphene oxide hybrid nanostructures nanoparticle was examined from the Fig. 2(c) shows the EDAX spectrum and elemental composition data which demonstrates the presence of Cu, W, O and C that confirms the proper formation of CuWO4-reduced graphene oxide hybrid nanopartcles. For further understanding of chemical composition of the prepared sample the elemental mapping is studied which is shown in Fig. 3.

### *X-Ray Diffraction*

Figure 1 shows the X-ray diffraction peaks of the $CuWO_4$-reduced graphene oxide hybrid nanostructures and $CuWO_4$. The peak matches completely with the characteristic peaks of $CuWO_4$ (Jcpds No 88-0269). In addition to the characteristic peaks of $CuWO_4$, the peaks of graphene can be observed from the figure. The peak at $2\theta = 25.95°$ can be interpreted as the merged peak of $CuWO_4$ [(110)] and graphene [(111)]. The characteristic peaks of graphene shows two peaks at $2\theta = 26.5°$ (111) and 54.6° (222). Here, in figure two peaks were observed due to the presence of graphene one at $2\theta = 25.95°$ and the other at 55°. The combined presence of both $CuWO_4$ and graphene confirms the formation of pure $CuWO_4$-reduced graphene oxide hybrid nanostructures.

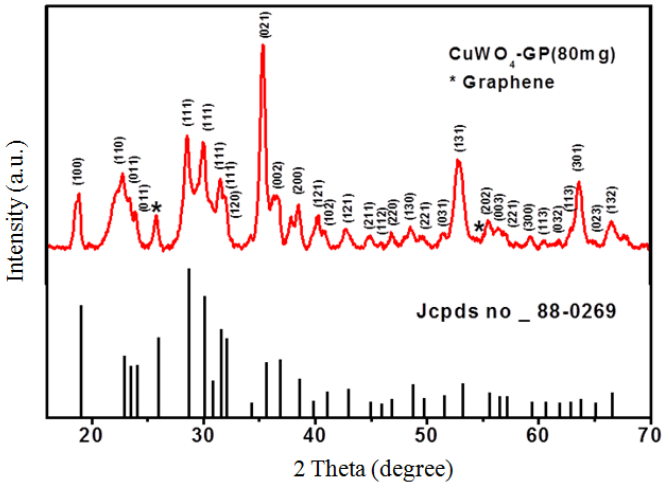


Fig. 1. X-ray diffraction of $CuWO_4$-reduced graphene oxide hybrid nanostructures and comparison with JCPDS file No-88-0269

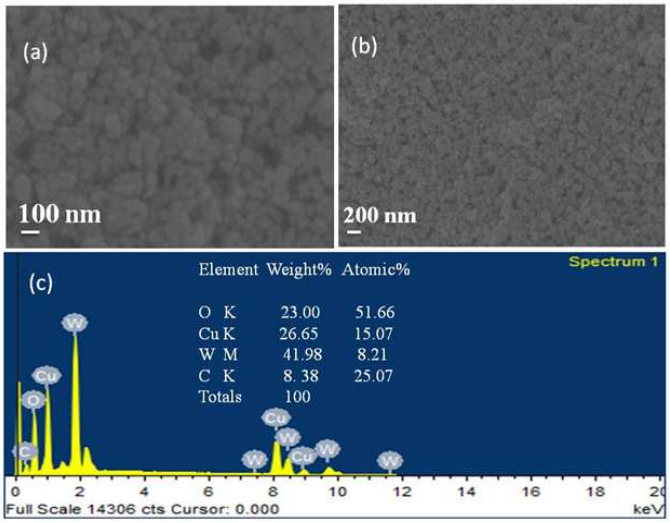


Fig. 2. (a) High magnification (b) Low magnification FESEM images (c) EDS spectra showing composition of constituent elements Cu, W, O, C

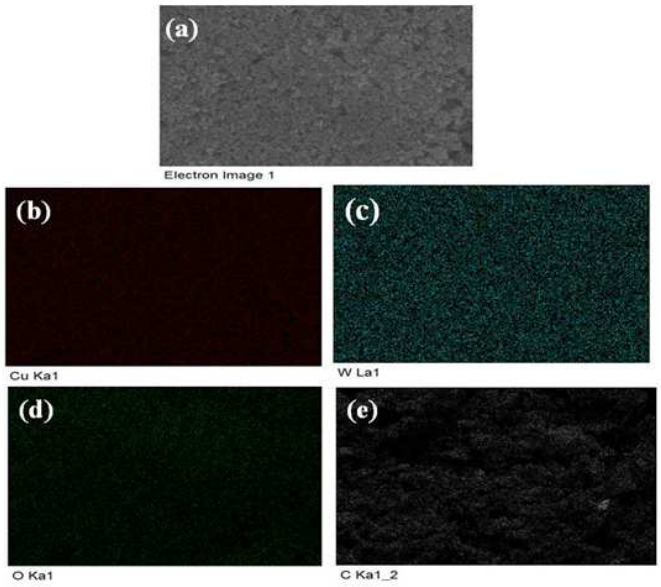


Fig. 3. Elemental mapping of $CuWO_4$-reduced graphene oxide hybrid nanostructures (a) electronic image over which mapping has been performed (b) presence of Cu (c) presence of W (d) presence of O (e) and presence of C is confirmed from the mapping data

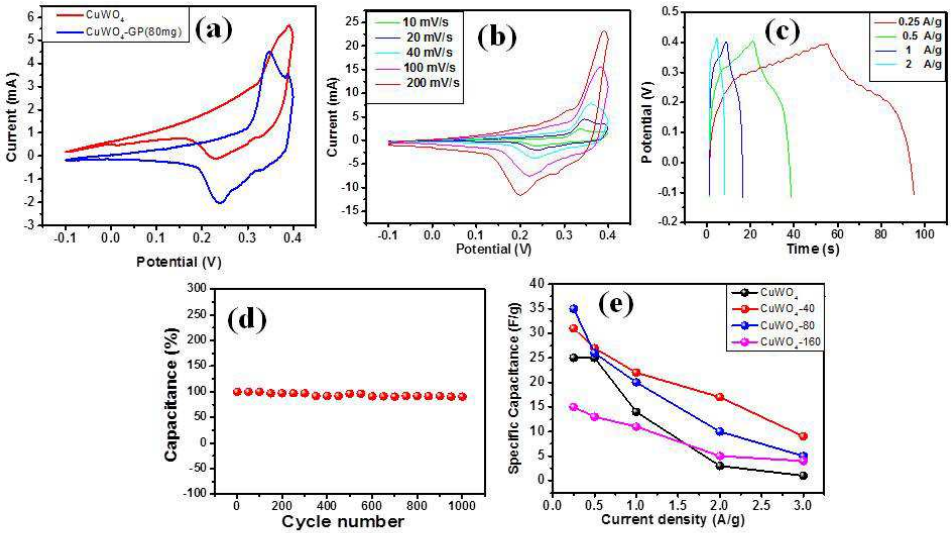


Fig. 4. Electrochemical study of $CuWO_4$-reduced graphene oxide hybrid nanostructures (a) CV curves comparing $CuWO_4$ and 80 mg $CuWO_4$-reduced graphene oxide hybrid nanostructures (b) CV curves of 80 mg CuWO4-reduced graphene oxide hybrid nanostructures $CuWO_4$ at different scan rates(c) CD curves of 80 mg $CuWO_4$-reduced graphene oxide hybrid nanostructures at different current densities (d) Cycle Number vs. percentage of capacity retention of the 80 mg $CuWO_4$-reduced graphene oxide hybrid nanostructures $CuWO_4$ showing good stability over 1000 cycles (e) Current Density vs. specific capacitance curves of different synthesized materials

## *Electrochemical Measurement*

The electrochemical measurements were carried out to study the supercapacitive behavior of the synthesized materials. The measurements followed three electrode cyclic voltammetry and charge discharge test in 3M aqueous KOH solution. The experiments were performed keeping the potential window in the range of -0.1 to 0.4 volt. Figure 4(a) shows the cyclic voltammetry measurement of $CuWO_4$ and 80 mg $CuWO_4$-reduced graphene oxide hybrid nanostructures. From this figure it was calculated that $CuWO_4$ shows specific capacitance (Cs) of 11.8 F/g while 80 mg $CuWO_4$-reduced graphene oxide hybrid nanostructures shows specific capacitance (Cs) of 16.6 F/g at 2 mv/s scan rate. The cyclic voltammetry curves of 80 mg $CuWO_4$-reduced graphene

oxide hybrid nanostructures at different scan rates can be examined from the Fig. 4(b). It can be observed that the decrease of specific capacitance and shifting of the reduction peak towards left takes place with increase in scan rate. The maximum obtained specific capacitance of the 80 mg $CuWO_4$-reduced graphene oxide hybrid nanostructures was found to be 16.6 F/g at 2 mv/s. The galvanostatic charge discharge test was conducted to have better understanding of the supercapacitive performance of the material. Figure 4(c) shows the charge-discharge curves of the 80 mg $CuWO_4$-reduced graphene oxide hybrid nanostructures at different current densities of 0.25, 0.5, 1 and 2 A/g. The maximum value of specific capacitance from charge discharge curves was found to be 35.71 F/g at current density of 0.25 A/g. Here the specific capacitance decreases with increase in current density which can be clearly observed from the figure. From the Fig. 4(d) the cycle stability of the 80 mg $CuWO_4$-reduced graphene oxide hybrid nanostructures $CuWO_4$ can be clearly observed. The long Cycle stability is the most important criteria for a material to perform as supercapacitor. Here, from the figure it can be inferred that the $CuWO_4$-reduced graphene oxide hybrid nanostructures material shows good cycle stability over 1000 cycles. The galvanostatic charge discharge test for cycle stability was performed at 10 A/g. The material has maintained the initially obtained specific capacitance value even at 1000 cycles. This ensures the material to be a promising candidate for supercapacitor application. Figure 4(e) shows a comparison curve of different synthesized materials on the basis of their specific capacitance value. The different synthesized materials are $CuWO_4$, 40 mg $CuWO_4$-reduced graphene oxide hybrid nanostructures, 80mg $CuWO_4$-reduced graphene oxide hybrid nanostructures and 160 mg $CuWO_4$-reduced graphene oxide hybrid nanostructures. From the charge discharge curve it was calculated that the synthesized material shows specific capacitance of 25, 31.2, 35.7 and 15.6 at 0.25 A/g respectively. Hence, the 80 mg $CuWO_4$-reduced graphene oxide hybrid nanostructures shows highest specific capacitance of 35.7 F/g with excellent cycle stability and can be utilized as a promising electrode for supercapacitor application in future.

## Conclusion

Here we report the successful synthesis of $CuWO_4$ and $CuWO_4$-reduced graphene oxide hybrid nanostructures by hydrothermal route. The XRD, FESEM, EDAX illustrates the morphology and structure of the prepared sample in detail. The supercapacitive behavior has been studied using cyclic voltammetry and galvanostatic charge discharge tests. Among all prepared samples the $CuWO_4$-reduced graphene oxide hybrid nanostructures shows maximum specific capacitance of 35.71 at 0.25 A/g with excellent cycle stability. Considering all the obtained data, the $CuWO_4$-reduced graphene oxide (with 80 mg GO) hybrid nanostructures can be utilized as an electrode for supercapacitor application.

## Funding Information

Dr. C.S. Rout would like to thank DST (Government of India) for the Ramanujan fellowship. This work was supported by the DST-SERB Fast-track Young scientist (Grant No. SB/FTP/PS-065/2013), Ramanujan Fellowship research grants (Grant No. SR/S2/RJN-21/2012) and UGC-UKIERI thematic awards (Grant No. UGC-2013-14/005).

## Author's Contributions

All the authors contributed equally.

## Ethics

The authors declare no competing financial interest. This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

## References

Aricol, A.S., P. Bruce, B. Scrosati, J.M. Tarascon and W. van Schalkwijk, 2005. Nanostructured materials for advanced energy conversion and storage devices. Nature Mater., 4: 366-377. DOI: 10.1038/nmat1368

Balandin, A.A., 2011. Thermal properties of graphene and nanostructured carbon materials. Nature Mater., 10: 569-581. DOI: 10.1038/NMAT3064

Chen, H., L. Hu, Y. Yan, R. Che and M. Chen *et al*., 2013. One-step fabrication of ultrathin porous nickel hydroxide-manganese dioxide hybrid nanosheets for supercapacitor electrodes with excellent capacitive performance. Adv. Energy Mater., 3: 1636-1646. DOI: 10.1002/aenm.201300580

Conway, B.E., V. Birss and J. Wojtowicz, 1997. The role and utilization of pseudocapacitance for energy storage by supercapacitors. J. Power Sources, 66: 1-14. DOI: 10.1016/S0378-7753(96)02474-3

Cultura II, A.B. and Z.M. Salameh, 2015. Modeling, evaluation and simulation of a supercapacitor module for energy storage application. Proceedings of the International Conference on Computer Information Systems and Industrial Applications, (ISIA '15). DOI: 10.2991/cisia-15.2015.235

Dong, X.C., H. Xu, X.W. Wang, Y.X. Huang and M.B. Chan-Park *et al*., 2012. 3D graphene–cobalt oxide electrode for high-performance supercapacitor and enzymeless glucose detection. ACS NANO, 6: 3206-3213. DOI: 10.1021/nn300097q

Dresselhaus, M.S. and I.L. Thomas, 2001. Overview Alternative energy technologies. Nature, 414: 332-337. DOI: 10.1038/35104599

Eisenberg, R. and D.G. Nocera, 2005. Preface: Overview of the forum on solar and renewable energy. Inorg. Chem., 44: 6799-6801. DOI: 10.1021/ic058006i

Gaillard, N., Y. Chang, A. DeAngelis S. Higgins and A. Braun, 2013. A nanocomposite photoelectrode made of 2.2 eV band gap copper tungstate ($CuWO_4$) and multi-wall carbon nanotubes for solar-assisted water splitting. Int. J. Hydrogen Energy, 38: 3166-3176. DOI: 10.1016/j.ijhydene.2012.12.104

Gao, W., 2005. Performance comparison of a fuel cell-battery hybrid powertrain and a fuel cell-ultracapacitor hybrid powertrain. IEEE Trans. Vehicular Technol., 54: 846-855. DOI: 10.1109/TVT.2005.847229

Geim, A.K., 2009. Graphene: Status and prospects. Science, 324: 1530-1534. DOI: 10.1126/science.1158877

Halper, M.S. and J.C. Ellenbogen, 2006. Supercapacitors: A brief overview. MITRE Nanosystems Group.

Huang, Y., J. Liang and Y. Chen, 2012. An overview of the applications of graphene-based materials in supercapacitors. Small, 8: 1805-1834. DOI: 10.1002/Smll.201102635

Khaligh, A. and Z. Li, 2010. Battery, ultracapacitor, fuel cell and Hybrid energy storage systems for electric, hybrid electric, fuel cell and plug-in hybrid electric vehicles: State of the art. IEEE Trans. Vehicular Technol., 59: 2806-2814. DOI: 10.1109/TVT.2010.2047877

Kim, J.H., K.W. Nam, S.B. Ma and K.B. Kim, 2006. Fabrication and electrochemical properties of carbon nanotube film electrodes. Carbon, 44: 1963-1968. DOI: 10.1016/j.carbon.2006.02.002

Kumar, R.D. and S. Karuppuchamy, 2014. Microwave-assisted synthesis of copper tungstate nanopowder for supercapacitor applications. Ceram. Int., 40: 12397-12402. DOI: 10.1016/j.ceramint.2014.04.090

Kumar, R.D., Y. Andou, M. Sathish, S. Karuppuchamy, 2015. Synthesis of nanostructured Cu-$WO_3$ and $CuWO_4$ for supercapacitor applications. J. Mater. Sci.: Mater. Electron, 27: 2926-2932. DOI: 10.1007/s10854-015-4111-z

Liu, C., F. Li, L.P. Ma and H.M. Cheng, 2010a. Advanced materials for energy storage. Adv. Mater., 22: E28-E62. DOI: 10.1002/adma.200903328

Liu, C., Z. Yu, D. Neff, A. Zhamu and B.Z. Jang, 2010b. Graphene-based supercapacitor with an ultrahigh energy density. Nano. Lett., 10: 4863-4868. DOI: 10.1021/nl102661q

Lota, G., T.A. Centeno, E. Frackowiak and F. Stoeckli, 2008. Improvement of the structural and chemical properties of a commercial activated carbon for its application in electrochemical capacitors. Electrochimica Acta, 53: 2210-2216. DOI: 10.1016/j.electacta.2007.09.028

Lu, Q. and Y. Zhou, 2011. Synthesis of mesoporous polythiophene/$MnO_2$ nanocomposite and its enhanced pseudocapacitive properties. J. Power Sources, 196: 4088-4094. DOI: 10.1016/j.jpowsour.2010.12.059

Neto, A.H.C., F. Guinea, N.M.R. Peres, K.S. Novoselov and A.K. Geim, 2009. The electronic properties of graphene. Rev. Mod. Phys., 81: 109-109. DOI: 10.1103/RevModPhys.81.109

Nithya, V.D., R.K. Selvan, D. Kalpana, L. Vasylechko and C. Sanjeeviraja, 2013. Synthesis of $Bi_2WO_6$ nanoparticles and its electrochemical properties in different electrolytes for pseudocapacitor electrodes. Electrochimica Acta, 109: 720-731. DOI: 10.1016/j.electacta.2013.07.138

Ponrouch, A., S. Garbarino, E. Bertin and D. Guay, 2013. Ultra high capacitance values of Pt@$RuO_2$ core–shell nanotubular electrodes for microsupercapacitor applications. J. Power Sources, 221: 228-231. DOI: 10.1016/j.jpowsour.2012.08.033

Pushparaj, V.L., M.M. Shaijumon, A. Kumar, S. Murugesan and R. Vajtai *et al*., 2007. Flexible energy storage devices based on nanocomposite paper. PNAS, 104: 13574-13577. DOI: 10.1073/pnas.0706508104

Rakhi, R.B., W. Chen, D. Cha and H.N. Alshareef, 2012. Nanostructured ternary electrodes for energy-storage applications. Adv. Energy Mater., 2: 381-389. DOI: 10.1002/aenm.201100609

Tang, Y., N. Rong, F. Liu, M. Chu and Y. Zhang *et al*., 2016. Enhancement of the photoelectrochemical performance of $CuWO_4$ films for water splitting by hydrogen treatment. Applied Surface Sci., 361: 133-140. DOI: 10.1016/j.apsusc.2015.11.129

Wang, Y., J. Guo, T. Wang, J. Shao and D. Wang *et al*., 2015. Mesoporous transition metal oxides for supercapacitors. Nanomaterials, 5: 1667-1689. DOI: 10.3390/nano5041667

Wu, J.B., Y. Lin, X.H. Xia, J.Y. Xu and Q.Y. Shia, 2011. Pseudocapacitive properties of electrodeposited porous nanowall $Co_3O_4$ film. Electrochimica Acta, 56: 7163-7170. DOI: 10.1016/j.electacta.2011.05.067

Wua, Z., X. Pub and X. Jia, 2015. High energy density asymmetric supercapacitors from mesoporous $NiCo_2S_4$ nanosheets. Electrochimica Acta, 174: 238-245. DOI: 10.1016/j.electacta.2015.06.011

Yan, J., Q. Wang, T. Wei and Z. Fan, 2014. Recent advances in design and fabrication of electrochemical supercapacitors with high energy densities. Adv. Energy Mater. DOI: 10.1002/aenm.201300816

Yang, Q., Z. Lu, J. Liu, Z. Chang and L. Luo, 2013. Metal oxide and hydroxide nanoarrays: Hydrothermal synthesis and applications as supercapacitors and nanocatalysts. Progress Natural Sci.: Mater. Int., 23: 351-366. DOI: 10.1016/j.pnsc.2013.06.015

Yang, Z., J. Zhang, M.C.W. Kintner-Meyer, X. Lu and D. Choi *et al*., 2011. Electrochemical energy storage for green grid. Chem. Rev., 111: 3577-3613. DOI: 10.1021/cr100290v

Yoon, B.J., S.H. Jeong, K.H. Lee, H.S. Kim and C.G. Park *et al*., 2004. Electrical properties of electrical double layer capacitors with integrated carbon nanotube electrodes. Chem. Phys. Lett., 388: 170-174. DOI: 10.1016/j.cplett.2004.02.071

Yourey, J.E., 2014. Photoelectrochemical and photocatalytic water oxidation using metal oxides. PhD Thesis, University of Michigan.

Yu, Z., L. Tetard, L. Zhai and J. Thomas, 2015. Supercapacitor electrode materials: Nanostructures from 0 to 3 dimensions. Energy Environ. Sci., 8: 702-730. DOI: 10.1039/c4ee03229b

Yuan, C., H.B. Wu, Y. Xie and X.W. (David) Lou, 2014. Mixed transition-metal oxides: Design, synthesis and energy-related applications. Angew. Chem. Int. Ed., 53: 1488-1504. DOI: 10.1002/anie.201303971