

LIST ABBREVIATIONS AND SYMBOLS USED

AFM	atomic force microscopy
Al ₂ O ₃	Aluminium oxide
Ag ⁻¹	Ampere per gram
Ag	Silver
Au	Gold
AgCl	Silver chloride
4-AP	4-aminophenol
CH ₄	methane
cm ⁻¹	per centimetre
cm ³ g ⁻¹	cubic centimetre per gram
cm ² V ⁻¹ s ⁻¹	centimetre square per volt per second
C ₀	initial concentration
C _e	equilibrium concentrations
CHCl ₃	chloroform
CMG	chemically modified graphene
CNTs	carbon nanotubes
CO	carbonmonooxide
CO ₂	carbondioxide
Co	cobalt
Co ₃ O ₄	Cobalt oxide
Cu	copper
CuCl	cuprous chloride
CuO	copper oxide
Cu ₂ O	cuprous oxide
CV	cyclic voltammeter
CVD	chemical vapor deposition
C _s	specific capacitance
DI	deionised water
DLS	dynamic light scattering
DETA	diethylenetriamine
DMFCs	direct methanol fuel cells
EIS	electrochemical impedance spectroscopy

ECSA	electrochemically active surface area
EDLC	electrical double layer capacitance
eV	electron volt
Fg ⁻¹	Faraday per gram
Fe	Iron
Fe ₂ O ₃	Iron oxide
FTIR	Fourier transform infrared
g	gram
GCE	glassy carbon electrode
GCD	galvanostatic charge-discharge
Ge	Germanium
GO	graphene oxide
GPa	Gigapascal
GS	graphene sponge
h	hours
H ₂	Hydrogen gas
HER	hydrogen evolution reaction
H ₂ O ₂	Hydrogen peroxide
HNO ₃	Nitric acid
H ₂ SO ₄	Sulfuric acid
HCl	Hydrochloric acid
Hz	Hertz
<i>I</i>	net current
Ir	Iridium
<i>I_D/I_G</i>	ratio of intensities of D and G bands in Raman spectrum
K	Kelvin
<i>k</i>	rate constant
K _L	Langmuir constants
K _F	Freundlich constants
kJ mol ⁻¹	kilojoules per mole
KBr	Potassium bromide
KMnO ₄	Potassium permanganate
KOH	Potassium hydroxide
m	metre
<i>m</i>	mass

M	molar
mA	miliampere
mA/cm ²	miliampere per centimeter square
mg	milligram
m ² g ⁻¹	square metre per gram
min	minutes
mL	milliliter
mmol	millimolar
MnO	Manganese oxide
MoO ₃	Molybdenum trioxide
MO	methyl orange
MV	methyl violet
mV	millivolt
mV s ⁻¹	millivolt per second
MWCNT	multiwalled carbonnano tube
Na	Sodium
N ₂	Nitrogen
NaBH ₄	Sodium borohydride
nm	nanometer
4-NP	4-nitrophenol
NaNO ₃	Sodium nitrate
NaOH	Sodium hydroxide
Ni	Nickel
NiO	Nickel oxide
Ni(OH) ₂	Nickel hydroxide
ORR	oxygen reduction reaction
Pd	Paladium
Pt	Platinum
PDDA	poly (diallyldimethylammonium chloride)
PECVD	plasma enhanced chemical vapor deposition
PPy	polypyrrole
PPD	<i>p</i> -phenylenediamine
PVP	polyvinylpyrrolidone
q _e	adsorption capacity
q _m	maximum adsorption capacity

rGO	reduced graphene oxide
Rh	Rhodium
Ru	Ruthenium
RuO ₂	Ruthenium oxide
R _{CT}	interfacial charge-transfer resistance
R _S	series resistance
R _W	Warburg impedance
s	seconds
Sn	Tin
SnO ₂	Tin oxide
S cm ⁻¹	Siemens per centimetre
SEM	scanning electron microscope
SG	sulfonated graphene
SWNT	singlewalled carbonnano tube
T	absolute temperature
TEM	transmission electron microscope
TiCl ₃	Titanium trichloride
TiO ₂	Titanium dioxide
UV	ultraviolet
UV-vis	ultraviolet-visible
V	voltage
v	volume
V _{max}	maximum voltage
wt%	weight percentage
X	degradation factor
XRD	X-ray diffraction
XPS	X-ray photoelectron spectroscopy
Z'	impedance (real)
Z''	impedance (imaginary)
ZnO	Zinc oxide
ZrO ₂	Zirconium oxide
ZrOCl ₂	Zirconium oxychloride
°C	degree Celsius
θ	elevation angle
λ_{max}	maximum absorption wavelength

LIST OF FIGURES

Chapter 1: General introduction

- Fig.1.1** Graphene, the basic building material for other allotropes of carbon, 0D fullerene, 1D carbon nanotube and 3D graphite 1.2
- Fig.1.2** Illustration on the preparation of GO and rGO 1.5
- Fig.1.3** (i) Single layer graphene, first observed by Geim (ii) XRD of (a) pristine graphite, (b) GO, (c) chemically reduced GO and (d) electrochemically reduced GO and (iii) Raman spectra for graphite and graphene 1.6
- Fig.1.4** (a) Schematic Lerf-Klinowski model of GO (b) TEM image of GO and (c) XPS of graphene and GO 1.7
- Fig.1.5** (a) π - π or C-H $\cdots\pi$ interactions of graphene (b) both π - π and hydrogen bonds with GO 1.9
- Fig.1.6** Suggested reaction pathway for the oxidation of acrolein to acrylic acid at the graphitic carbon surface 1.15
- Fig.1.7** Oxidation of benzyl alcohol and *cis*-stilbene and hydration of 1-ethynylbenzene catalyzed by GO 1.16
- Fig.1.8** Suzuki-Miyaura reactions of aryl bromides with Pd/GO 1.16
- Fig.1.9** (a) Schematic of the chemical structures of the composite (b) CV of ORR on exfoliated graphene, GO, and composite (c) Electrochemical activity for (Fe-P)_n MOF, GO and the composite 1.19
- Fig.1.10** CV curve of Pt/Ni(OH)₂/rGO in 1 M KOH. (b) CV curves of Pt/Ni(OH)₂/rGO, Pt/rGO hybrid and standard 20 wt% Pt/C in 1 M methanol/1 M KOH. (c) Short-term durability measurement of the materials 1.20
- Fig.1.11** Illustration of the three-step electron transfer process involved in making graphene a 2D conducting support 1.21
- Figure 1.12** (a) Diffuse reflectance absorption spectra of P25-graphene, (b) structure of P25-graphene and possible process of photo-degradation; comparison of photocatalytic activity under (c) UV light and (d) visible light 1.22
- Fig. 1.13** The proposed charge transfer mechanism during the photo degradation of dye in the presence of Ce or Fe doped graphene-TiO₂ nanocomposite 1.23

Fig.1.14 (a) and (b) A GS in rhodamine B solution (a) at the beginning and (b) for 180 min (c) and (d) The same GS adsorbed with rhodamine B in ethanol for (c) 2 min and (d) 10 min 1.23

Chapter 2: Section A-Synthesis of copper oxide/reduced graphene oxide nanocomposite and its enhanced catalytic activity towards reduction of 4-nitrophenol

Fig.2.1.1 FTIR spectrum of (a) GO, (b) CuCl and (c) CuO-rGO nanocomposite 2.5

Fig.2.1.2 XRD patterns of (a) GO, (b) CuCl and (c) CuO-rGO nanocomposite 2.6

Fig. 2.1.3 SEM images of (a) CuCl and (b) CuO-rGO nanocomposite 2.7

Fig. 2.1.4 EDX spectrum of CuO-rGO nanocomposite 2.7

Fig. 2.1.5 UV-vis absorption spectra of the reduction of 4-NP by NaBH₄ in the presence of (a) CuO_{0.01}-rGO (b) CuO_{0.05}-rGO (c) CuO_{0.1}-rGO. 2.8

Fig. 2.1.6 Plots of ln(C/C₀) of 4-NP versus reaction time in the presence of (a) CuO_{0.01}-rGO (b) CuO_{0.05}-rGO (c) CuO_{0.1}-rGO. 2.9

Fig. 2.1.7 (a) Plots of ln(C/C₀) of 4-NP versus reaction time for successive 5 cycles (b) Value of *k* for each cycle with CuO-rGO_{0.05} nanocomposite as catalyst 2.10

Chapter 2: Section B-Copper oxide/reduced graphene oxide as an electrocatalyst for methanol electro-oxidation

Fig.2.2.1 FTIR spectrum of (a) GO, (b) CuO, (c) CuO-rGO and (d) CuO-rGO_{calcined} nanocomposites 2.20

Fig.2.2.2 XRD spectrum of (a) GO, (b) CuO, (c) CuO-rGO and (d) CuO-rGO_{calcined} nanocomposites 2.21

Fig.2.2.3 Raman spectra of (a) GO, (b) CuO-rGO and (c) CuO-rGO_{calcined} nanocomposites 2.23

Fig.2.2.4 SEM images of (a) GO, (b) CuO, (c) CuO-rGO and (d) CuO-rGO_{calcined} nanocomposite 2.24

Fig.2.2.5 EDX spectrum of CuO-rGO_{calcined} nanocomposites 2.24

Fig. 2.2.6 Particle size distribution of CuO-rGO_{calcined} nanocomposite 2.25

Fig.2.2.7 CVs of the (a) CuO-rGO, (b) CuO and (c) CuO-rGO_{calcined} in 1.0 M methanol solution containing 0.1 M NaOH. Scan rate: 50 mV s⁻¹. 2.26

Fig.2.2.8 Chronoamperograms of (a) CuO and (b) CuO-rGO_{cal} for methanol oxidation in methanol solution (1.0 M) containing 0.1 M NaOH at a fixed potential of 0.4 V. 2.27

Fig. 2.2.9 CVs of the CuO-rGO_{cal} in 1.0 M methanol solution containing 0.1 M NaOH at scan rate: 50 mV s⁻¹ for 100 cycles. 2.28

Chapter 3: Multifunctional ternary nanocomposites of Ni/polypyrrole/reduced graphene oxide as supercapacitor and electrocatalyst in methanol oxidation

Fig.3.1 FTIR spectra of (a) GO (b) rGO (c) PPy (d) PPy/rGO (e) Ni/PPy/rGO 3.6

Fig.3.2 XRD pattern of (a) GO (b) rGO (c) PPy/rGO and (d) Ni/PPy/rGO 3.7

Fig.3.3 Raman spectra of (a) GO (b) PPy (c) PPy/rGO and (d) Ni/PPy/rGO 3.8

Fig.3.4 SEM images of (a) GO (b) PPy (c) PPy/rGO and (d) Ni/PPy/rGO nanocomposites 3.9

Fig. 3.5 EDX analysis of Ni/PPy/rGO nanocomposites 3.9

Fig. 3.6 (a) TEM and (b) XPS analysis of Ni/PPy/rGO nanocomposites 3.10

Fig. 3.7 Particle size distribution of Ni/PPy/rGO nanocomposites 3.10

Fig.3.8 Cyclic voltammograms of (a) Ni/PPy/rGO (b) PPy/rGO (c) rGO and (d) Ni/rGO 3.12

Fig.3.9 (a) CVs recorded at different scan rate and (b) CVs for continuous 200 cycles for Ni/PPy/rGO 3.13

Fig. 3.10 (a) Charge/discharge curves of Ni/PPy/rGO at different current densities (b) Specific capacitances of Ni/PPy/rGO at different current densities and (c) Cyclic stability of Ni/PPy/rGO upto 200 charge/discharge cycles 3.14

Fig.3.11 Charge/discharge curves of (a) Ni/PPy/rGO, (b) PPy/rGO and (c) rGO 3.15

Fig.3.12 Nyquist impedance plots of (a) Ni/PPy/rGO and (b) PPy/rGO 3.16

Fig.3.13 CVs of the different composites (a) Ni/PPy/rGO, (b) Ni/rGO and (c) PPy/rGO in 1KOH + 1M methanol at 25°C and at the scan rate of 50 mVs⁻¹ scan rate 3.17

Fig.3.11 Chronoamperograms of (a) Ni/PPy/rGO (b) Ni/rGO and (c) PPy/rGO in 1M KOH + 1M methanol at operational potential of 0.035V 3.18

Chapter 4: Photocatalytic degradation of dye over zirconium oxide supported on sulfonated graphene under visible light

- Fig.4.1** FTIR spectrum of (a) GO, (b) SG, (c) $m\text{-ZrO}_2/\text{rGO}_{1200^\circ\text{C}}$, and (d) $m\text{-ZrO}_2/\text{SG}_{1200^\circ\text{C}}$ 4.5
- Fig.4.2** XRD pattern of (a) SG, (b) $m\text{-ZrO}_2/\text{rGO}_{600^\circ\text{C}}$, (c) $m\text{-ZrO}_2/\text{rGO}_{1000^\circ\text{C}}$, (d) $m\text{-ZrO}_2/\text{rGO}_{1200^\circ\text{C}}$ and (e) $m\text{-ZrO}_2/\text{SG}_{1200^\circ\text{C}}$ 4.6
- Fig.4.3** Raman spectra of (a) rGO, (b) SG, (c) $m\text{-ZrO}_2/\text{rGO}_{1200^\circ\text{C}}$ and (d) $m\text{-ZrO}_2/\text{SG}_{1200^\circ\text{C}}$ 4.7
- Fig.4.4** SEM image of (a) rGO, (b) ZrO_2 (c) $m\text{-ZrO}_2/\text{rGO}_{1200^\circ\text{C}}$ and (d) $m\text{-ZrO}_2/\text{rGO}_{1200^\circ\text{C}}$ 4.8
- Fig.4.5** (a) EDX analysis of $m\text{-ZrO}_2/\text{rGO}_{1200^\circ\text{C}}$ (b) EDX analysis $m\text{-ZrO}_2/\text{SG}_{1200^\circ\text{C}}$ 4.9
- Fig.4.6** (a) UV-vis spectrum of the dye after treatment in visible light (a) in absence of catalyst, (b) in presence of SG 4.10
- Fig.4.7** Degradation factor vs time plots of (a) (a) in absence of catalyst, (b) in presence of SG 4.10
- Fig.4.8** (a) UV spectrum of photocatalytic degradation of MV by (a) $m\text{-ZrO}_2/\text{rGO}_{600^\circ\text{C}}$, (b) $m\text{-ZrO}_2/\text{rGO}_{1000^\circ\text{C}}$, (c) $m\text{-ZrO}_2/\text{rGO}_{1200^\circ\text{C}}$ and (d) $m\text{-ZrO}_2/\text{SG}_{1200^\circ\text{C}}$ 4.11
- Fig.4.9** Degradation factor vs time (minutes) plots for (a) $m\text{-ZrO}_2/\text{rGO}_{600^\circ\text{C}}$, (b) $m\text{-ZrO}_2/\text{rGO}_{1000^\circ\text{C}}$, (c) $m\text{-ZrO}_2/\text{rGO}_{1200^\circ\text{C}}$ and (d) $m\text{-ZrO}_2/\text{SG}_{1200^\circ\text{C}}$ 4.12
- Fig.4.10** Column graph showing change in concentration of MV solution versus number cycles. 4.13

Chapter 5: Selective dye adsorption by pH modulation on amine functionalized reduced graphene oxide-carbon nanotube hybrid

- Fig.5.1** FTIR spectrum of (a) GO, (b) MWCNT, (c) GO-CNT (d) rGO-CNT-PPD (e) rGO-PPD and (f) CNT-PPD 5.6
- Fig.5.2** XRD patterns of (a) GO, (b) CNT, (c) GO-CNT and (d) rGO-CNT-PPD 5.7
- Fig.5.3** SEM images of (a) GO-CNT and (b) rGO-CNT-PPD hybrid 5.7
- Fig.5.4** TEM images of (a) GO-CNT and (b) rGO-CNT-PPD hybrid. Inset in (a) is the TEM image of GO-CNT hybrid at higher resolution. 5.8
- Fig.5.5** Effect of contact time on adsorption capacity at pH 7.0 and pH 3.0 onto rGO-CNT-PPD hybrid 5.9

Fig.5.6 Effect of pH on adsorption of MV-MO mixture on rGO-CNT-PPD hybrid at 464 nm and 582 nm and (b) uv-visible spectra of MO+MV solution before adsorption (red), after adsorption at pH 7.0 (yellow) and at pH 3.0 (violet). 5.12

Fig.5.7 Removal efficiency of MV at pH 7.0 on rGO-CNT-PPD hybrid in different cycles. 5.14

LIST OF SCHEMES

Chapter 1: General introduction

- Scheme 1.1** Procedure to design TiO₂-graphene nanosheet 1.11
- Scheme 1.2** Illustration of the one-step electro deposition of ZrO₂-graphene nanocomposite and its application for the extraction and electrochemical detection of MP 1.12
- Scheme 1.3** Schematic illustration of the preparation of GN-ZnSe nanocomposites 1.14
- Scheme 1.4** Schematic A plausible mechanism for the reduction of 4-nitrophenol catalyzed by the Pd/graphene catalyst in the presence of NaBH₄ 1.17

Chapter 5: Selective dye adsorption by pH modulation on amine functionalized reduced graphene oxide-carbon nanotube hybrid

- Scheme 5.1** Effect of pH on adsorption of MV and MO 5.13

LIST OF TABLES

Chapter 1: General introduction

Table 1.1 Physical properties of graphitic carbon materials	1.3
Table 1.2 Comparison of preparation methods for metal-graphene nanocomposites, accompanied by the corresponding metal precursors and particle size	1.10
Table 1.3 Comparison of preparation methods for graphene-metal oxide nanocomposites, accompanied by the corresponding metal precursors and particle size	1.13
Table 1.4 Comparison of the methanol oxidation reaction performances with graphene-based noble-metal nanocomposites as electrocatalysts	1.20

Chapter 2: Section A- Synthesis of copper oxide/reduced graphene oxide nanocomposite and its enhanced catalytic activity towards reduction of 4-nitrophenol

Table 2.1.1 Catalytic rate constants of reduction of 4-NP in the presence of CuO _x -rGO nanocomposites and the R ² values for the ln(C/C ₀) vs t plots	2.9
Table 2.1.2 Comparison of values of rate constant for 4-NP reduction to 4-AP catalyzed by various catalysts	2.11

Chapter 4: Photocatalytic degradation of dye over zirconium oxide supported on sulfonated graphene under visible light

Table 4.1 Raman Shift of D & G-band of the mentioned materials and their intensity ratio	4.7
Table 4.2 Degradation time of MV and % degradation for the subsequent photocatalysts	4.12

Chapter 5: Selective dye adsorption by pH modulation on amine functionalized reduced graphene oxide-carbon nanotube hybrid

Table 5.1 Kinetic Parameters for the adsorption of MV at pH 7.0 and MO at pH 3.0 onto rGO-CNT-PPD hybrid	5.10
Table 5.2 Isotherm Parameters for the adsorption of MV and MO by rGO-CNT-PPD hybrid at pH 7.0 and 3.0 respectively	5.11

Table 5.3 Comparison of adsorption capacities of MV and MO onto various adsorbents

5.15