# (7DEC7J;H?7BI ?D 87JJ;H?;I

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)L;H 30 0;7HI E< :;L;BEFC;DJ, B?J>?KC-?ED 87JJ;H?;I (&#BI) >7L; 8;;D M;BB 7FFB?;: ?D IC7HJ ;B;9JHED?9I, ;B;9

# 2 CHAPTER 7



3

<;9JI) 97D FH;L;DJ &?\* <HEC >EFF?D= J>HEK=> J>; 9HOIJ7B IJHK9JKH; 596. #D 7::?J?ED, J>; :?<<KI?ED E< &?\* 7BED= J>; (001) :?H;9J?ED ?I I?=D?<?97DJBO :;B7O;: JE 8BE9A &? :?<<K-I?ED, H;IKBJ?D= ?D 7 B7H=; ;B;9JHE9>;C?97B FEB7H?P7J?ED 7D: MEHI; H7J; F;H<EHC7D9;. .>;H;<EH; M>;D J>; &? ;\*) 4 ?I :;9H;7I;: JE 7 9H?J?97B L7BK;, J>; DKC8;H E< JH7FF;: &? ?EDI 97D 8; I?=D?<?97DJBO H;:K9;:.</pre>

#### 7.1.3 Inhibit electrode cracking and powdering

.>; ?DJ;H97B7J?ED-JOF; C7J;H?7BI IK9> 7I =H7F>?J; >7L; IC7BB LEBKC; 9>7D=;I (<10%) I?D9; J>; B7JJ?9; 9>7H79J;H?IJ?9 ?I DEJ 9>7D=;: :KH?D= J>; B?J>?KC ?EDI ?DJ;H97-B7J?ED. .>; 7BBEO-JOF; C7J;H?7BI =;D;H7BBO EMD 7 I?=D?<?97DJBO B7H=;H &? ?EDI IJEH7=; 97F79?JO J>7D J>; =H7F>?J; 7DE:;. AI J>; JOF?97B 7BBEO 7DE:;, I?B?9ED >7I 7 97F79?JO E< 3579 CA>/= <EH &? ?EDI IJEH7=;; >EM;L;H, -? IK<<;HI 7 B7H=; LEBKC; 9>7D=; E< 420% :KH?D= (:;)B?J>?7J?ED 97KI?D= J>; H7F?: 97F79?JO BEII E< &#BI. .>; C;9>7D?97B JJH;II H;IKBJ?D= <HEC LEBKC;JH?9 9>7D=; ?I J>; L?J7B <79JEH B?C?J?D= J>; 7FFB?97J?ED E< 7BBEO-JOF; 7DE:; C7J;H?7B E< !; 7D: -D 80 260% 7D: \* 80 300% ?D J>; LEBKC;JH?9 9>7D=;I ( ?=.7.1A) 5106. .>; C;9>7D?97B JJH;II ?D:K9;: 80 J>;I; I?=D?<?97DJ LEBKC; 9>7D=;I H;IKBJI ?D C;9>7D?97B <7?BKH;I, IK9> 7I C7J;H?7B <H79JKH;, FKBL;H?P7J?ED, 7D: I;F7H7J?ED <HEC J>; 9KHH;DJ 9EB8;9JEHI, I?=D?<?97DJBO I>EHJ;D?D= J>; 9098; B?<;.

(7DEC7J;H?7BI 97D 7BB;L?7J; LEBKC; ;NF7DI?ED 7D: H;I?IJ J>; C;9>7D?97B <7?BKH; E< J>; ;B;9JHE:;...>; 9H?J?97B <H79JKH; I?P; E< ;B;9JHE:; C7J;H?7BI :;F;D:I ED J>; C7-



#### FIGURE 7.1

(A) CH79A?D=7D: <hr/>
<h

J:H?78'I B?J>?7J?ED C:9>7D?IC. F>0I?978 FHEF:HJ?:I. 7D: LE8KC:JH?9 9>7D=: H7J?E. .>: C;9>7D?IC E< IJH; II =; D; H7J?ED, F7HJ?9B; C;9>7D?97B <7?BKH;, 7D: J>; H; 7IED78B; I?P; E< -? F7HJ?9B; I M;H; IOIJ; C7J?97BBO IJK:?; : 80 . E ' . A F7HJ?9B; IC7BB;H J>7D 150 DC 97D 799ECCE:7J; J>; IJH7?D 97KI;: 80 B?J>?7J?ED JE 7LE?: F7HJ?9B; 9H79A?D= EH FKBL;H-?P7J?ED 5116.

) D;-:?C;DI?ED78 I?8?9ED D7DEC7J;H?78I (-? D7DEM?H;I, -? D7DEJK8;I) >7L; 8;JJ;H IJHK9JKH7B IJ78?B?JO :K; JE J>;?H =EE: C;9>7D?97B FHEF;HJ?:I 512,136. -?D9; J>; H;79-J?ED E99KHI 7J J>; ?DJ;H<79; 8;JM;;D J>; ;B;9JHE:; 7D: ;B;9JHEBOJ;, ED;-:?C;DI?ED7B D7DEC7J;H?7BI 97D ?D9H;7I; J>; ;B;9JHE9>;C?97B H;79J?ED I?J;I :K; JE J>; B7H=;H IF;-9?<?9 IKH<79; 7H;7. #D J;HCI E< C7II JH7DIFEHJ, J>; 7N?78 ED;-:?C;DI?ED7B D7DEC7J;H?-7BI <79?B?J7J; J>; JH7DI<;H E< ?EDI JE ;D>7D9; J>; H;79J?ED A?D;J?9I. KHJ>;HCEH;, D7D-EJK8; I 7H; CEH; ;<<?9?; DJ ?D 7BB; L?7J?D= LEBKC; JH?9 IJH; II J>7D D7DEM?H; I EM?D= JE J>; >EBBEM IF79; E< J>; ?DD; H JK8;.

#### 7.1.4 Generation of stable solid electrolyte interfaces

-?D9; J>; :B;9JHE9>;C?97B MEHA?D= LEBJ7=; E< J>; 7DE:; ?I BEM;H J>7D J>; LEBJ7=; J>7J J>; EH=7D?9 97H8ED7J; IEBL; DJ ?D 9EC CED EH=7D?9 ;B; 9JHEBOJ; I ?I H; :K9; : (78EKJ **1.0** 0 LI &?\*/&?), J>; ;B;9JHEBOJ; KD: ;H=E;I 7 H; :K9J?ED H;79J?ED :KH?D= J>; 9>7H=?D= JE FHE:K9; 7 IEB?: ;B;9JHEBOJ; ?DJ;HB7O;H (-E#) ?I ED J>; IKH<79; E< 7DE:: C7J;H?7BI ( ?=. 7.1B 7D: C) 5146. ABJ>EK=> - E# ?I 7 &?+ 9ED: K9JEH H; B7J?L; JE ;B; 9JHED?9 ?DIK-B7J?ED, J>; =HEMJ> E< - E# 9EDIKC; I; B; 9JHEBOJ; I 7D: >?D: ;HI J>; C?=H7J?ED E< ?EDI 7D: ;B:9JHEDI. .>;H:<EH; 7 IJ78B; -E# B70;H ?I >?=>B0; NF;9J; :<EH J>; H7J; 97F78?B?JO 7D: IJ78?B?JO E< J>; 7DE: ;. / D<EHJKD7J;BO, IJ78B; - E# <?BCI 7H; DEJ ;7IO JE E8J7?D ?D >?=>-97F79?JO B?J>?KC 7D: I?B?9ED 7DE:; I.

.>; ;NJH; C; BO BEM H; : K9J?ED FEJ; DJ?7B E< C; J7BB?9 B?J>?KC B; 7 : I JE J>; ?D; L?J78B; H;79J?ED 8;JM;;D ?JI; K 7D: J>; ;B;9JHEBOJ;, 7D: J>; >;J;HE=;D;EKI - E# ?I ;7I?BO 8HE-A;D :KH?D= J>; 9>7H=;-:?I9>7H=; 909B;I 5156. .>; IJ78B; -E# <?BC ?I D;9;II7HO <EH ?CFHEL?D= J>; ;B;9JHE9>; C?97B H;L;HI?8?B?JO 7D: IJ78?B?JO E< J>; B?J>?KC C;J7B 7DE:;. .>; 9KHH;DJ H;I;7H9> C7?DBO <E9KI;I ED ;B;9JHEBOJ; EFJ?C?P7J?ED 7D: 7HJ?<?9?7B D7DE - E# 9EDIJHK9J?ED. CECF7H;: M?J> ;B;9JHEB0J; EFJ?C?P7J?ED, 7HJ?<?9?7B D7DE - E# 9ED-IJHK9J?ED 97D CEH; ;<???;DJBO ?CFHEL; J>; BED=-909B; F;H<EHC7D9; E<B?J>?KC 7DE:;. AD - E# <?BC M?J> 7 IF;9?<?9 9ECFEI?J?ED 97D 8; <EHC; : J>HEK=> J>; H;79J?ED 8;JM;;D C; J7BB?9 B?J>?KC 7D: 7D ?D?J?7JEH. #J M7I < EKD: J>7J H; 79J?L; =7I; I 97D F7II?L7J; J>; D;=7J?L: ;B;9JHE:: JE 7 9;HJ7?D :NJ;DJ. H:ED 97D 7BIE H:79J M?J>=H7F>;D; 9ECFEI-?J; 7D: C;J7B B?J>?KC 7DE:; JE <EHC 7D ;<<;9J?L; &? ?DJ;H<79; 1 ?J> J>; 9EDJ?DKEKI ;NFBEH7J?ED E< J>; 9ECFEI?J?ED7B IJHK9JKH; E< - E#, 7 B?J>?EF>?B?9/B?J>?F>E8?9 =H7:?-;DJ ?DJ;H<79; B70;H (4D)/C (.-C (.) 97D 8;JJ;H H;7B?P; J>; B?J>?KC :;FEI?J?ED KD:;H J>: FHEJ:9J?L: B70:H, J>:H:80 ;DIKH?D= J>: KBJH7-BED= 909B?D= E< B?J>?KC C:J7B 7DE::I 5166.

ADEJ>;H ;N7CFB; E< 7D KDIJ78B; -E# ?I J>; I?B?9ED 7DE:;, M>?9> HKFJKH;I 7D: H;IJHK9JKH;I :K; JE H;F;7J;: LEBKC; 9>7D=;I. .>; :?I7:L7DJ7=;I E< KDIJ78B; -E# C7?DB0 97KI; J>; BEM 97F79?JO 7D: FEM;H H; :K9J?ED E< &#BI. .>;H:<EH; 1 K ;J 7B. 5176 :: I?=D:: 7D - E# 7HEKD: I?8?9ED D7DEJK8: I 8:97KI: J>: >EBBEM IF79: E< D7D-

4

5

EJK8;I 97D FHEL?:; J>; D;9;II7HO LE?:I JE 799ECCE:7J; J>; LEBKC; ;NF7DI?ED. ,;-9;DJBO, JE ?D>?8?J J>; LEBKC;JH?9 ;NF7DI?ED E< -? B?J>?7J?ED, J>; JEK=> .?)<sub>2</sub>, -?C, -?)<sub>N</sub>, 7D: .?)<sub>N</sub> M;H; KI;: 7I I>;BBI JE FHEJ;9J IJHK9JKH7B -? :KH?D= 909B;I 518–216.

# 7.2 Nanomaterials in Li–S batteries

&?J>?KC-IKB<KH (&?--) 87JJ;HO M7I ?DL;IJ?=7J;: I?D9; J>; 1960I. -?D9; J>; 9ECC;H-9?7B?P7J?ED E< &#BI, DE 8H;7AJ>HEK=>I >7L; 8;;D C7:; ?D IEBL?D= J>; <7J7B FHE8B;CI <79?D= &?-- 87JJ;H?;I <EH C7DO 0;7HI. -?D9; 2009, ?J >7I =EJ CEH; 9ED9;HDI 7I 7D;N-9;BB;DJ 97D:?:7J; <EH J>; D;NJ =;D;H7J?ED E< >?=>-;<<?9?;D90 ;B;9JH?97B;D;H=O IJEH7=; J;9>DEBE=?;I 7<J;H J>; H;LEBKJ?ED7HO J;9>DEBE=O E< &?-- 87JJ;HO M?J> ?CFHEL;: F;H-<EHC7D9; 5226. BO C7J9>?D= J>; IKB</br>VECTOP; 5226. BO C7J9>?D= J>; IKBKH 97J>E:; 7D: B?J>?KC 7DE:; (J>;EH;J?97B 97F79-?JO E< 1675 CA>/= 7D: 3840 CA>/=, H;IF;9J?L;B0), J>; &?-- 87JJ;HO 7<<EH:I 7 >?=> J>;EH;J?97B;D;H=O :;DI?JO 7D: LEBJ7=; FB7J<EHC. .>;H;<EH; J>; 87JJ;HO 97D E8J7?D 7 :?I9>7H=; 97F79?JO E< 2-3 J?C;I B7H=;H J>7D J>; 9ECC;H9?7B &#B 7D: C;;J 7 :H?L?D= H7D=; E< EL;H 500 AC <EH;B;9JH?9 L;>?9B;I (?=. 7.2A) 5236. 'EH;EL;H, J>; BEM 9EIJ E< 79J?L; C7J;H?7BI FHEL?:;I &?-- 87JJ;H?;I M?J>;9EDEC?9 7D: ;DL?HEDC;DJ7B 7:L7D-J7=;I, C7A?D= J>;C ;NJH;C;BO 7JJH79J?L; <EH J>; ;D;H=O IJEH7=; <?;B:I 5246.</td>



#### FIGURE 7.2

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(A) -9>;C; E< &?-- 87JJ;HO 5236. CEFOH?=>J 2014, ;;FHE:K9;: M?J>F;HC?II?ED E< AC;H?97D C>;C?97B -E9?;JO. (B) .>; 9ECF;D:?KC E< FEBOIKB<?:; 9ECFEI?J?ED 7D: ;LEBKJ?ED ?D &?-- 87J-J;HO 5246. CEFOH?=>J 2018, ;;FHE:K9;: M?J>F;HC?II?ED E< 1 ?B;O-OC". (C) -KCC7HO E< :;=H7-:7J?ED C;9>7D?ICI 5256. CEFOH?=>J 2015, ;;FHE:K9;: M?J>F;HC?II?ED E< ,EO7B -E9?;JO E< C>;C?IJHO. (D) -9>;C7J?9 E< J>; LEBKC;JH?9 ;NF7DI?ED 7D: FEBOIKB<?:; :?IIEBKJ?ED FHE9;II 5266.

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80% <EH IKB<br/><KH :K; JE J>; :;DI?JO :?<<;H;D9; 8;JM;;D -<br/>8 7D: &?<- (2.03 7D: 1.66 =/ 9C<sup>3</sup>) 97D <br/>B;7: JE <H7=C;DJ7J?ED 7D: IJHK9JKH7B 9H79A?D= 7J J>; ;B;9JHE:; B;L;B ( ?=. 7.2D) 5266.

.>;H;<EH; D7DEI97B; ;D=?D;;H?D=>7I 8;;D M?:;B0 ?DL;IJ?=7J;: <EH >?=>-F;H<EH-C7D9; &?-- IOIJ;CI JE IEBL; FHE8B;CI E< J>; &?-- 87JJ;HO C;DJ?ED;: 78EL;.

# 7.2.1 Nanomaterials in the sulfur composite cathode

. E IEBL; J>; FHE8B; CI E< ?DIKB7J?D= IKB</br>

(;9J E< FEBOIKB<?:;I, 97H8ED/IKB</H 9ECFEI?J; 97J>E:;I>7L; 8;;D:;L;BEF;:. D?<<;H;DJ IJHK9JKH;: 97H8ED79;EKI D7DEC7J;H?7BI, <EH;N7CFB;, =H7F>;D; 5286, 97H8ED D7D-EJK8;I 5296, C;IEFEHEKI 97H8EDI 5226, 7D: >EBBEM 97H8ED D7DEIF>;H;I 5306, M?J> 7

>?=>;B;9JH?9 9ED:K9J?L?JO 7D: FEHEKI IJHK9JKH;, 97D I;HL; 7I;N9;BB;DJ 97J>E:; >EIJ.

-;L;H7B IJK:?;I >7L; 8;;D H;FEHJ;: J>7J =H7F>;D; EN?:; (!)) ?I 7 IK?J78B; >EIJ <EH IKB<KH 799ECCE:7J?ED...>; FH;I;D9; E<;FENO 7D: >O:HENOB =HEKFI ?D !) FHECEJ;I J>; ?CCE8?B?P7J?ED E< IKB<KH, J>KI FH;L;DJ?D= ?JI :?IIEBKJ?ED...;9;DJBO, =H7F>;D;/IKB-<KH 9ECFEI?J;I 7I 97J>E:;I >7L; 8;;D IODJ>;I?P;: 7D: J;IJ;: ?D &?-- 87JJ;H?;I...>;O ;N>?8?J 8;JJ;H 97F79?JO, CEKBEC8?9 ;<<?9?;D90, 7D: 909B?D= IJ78?B?JO F;H</p>

.>; =H7F>;D;/IKB<KH 9ECFEI?J;I >7L; <7IJ;H ?ED :?<<KI?ED 7D: >?=>;H ;B;9JH?97B 9ED:K9J?L?JO J>7D J>; FKH; IKB<KH 97J>E:;. +?K 7D: 9EMEHA;HI H;FEHJ;: 7 D7DE9EC-FEI?J; 97J>E:; J>7J IKB<KH ?I MH7FF;: ?DI?:; J>; >;J;HE7JEC-:EF;: =H7F>;D; >EIJ ((!)..>; 2-H7O IF;9JHE19EF?9 7D7BOI?I 7D: D .97B9KB7J?ED ?CFBO J>; (<KD9J?ED7B =HEKFI ?D J>; (!>EIJ 97D <EHC IJHED= 9>;C?97B 8ED:I M?J> FEBOIKB<?:;I..>;H<EH; M?J> 7 60 MJ.% IKB<KH BE7:?D=, J>; 97J>E:; 9EKB: FHEL?:; EKJIJ7D:?D= F;H<EHC7D9; 7D: 7D KBJH7BEM 97F79?JO :;970 H7J;5316.

.>; KD?GK; >EBBEM D7DEIJHK9JKH;I E< C ( . I C7A; ?J ;7IO JE FHEL?:; <7IJ J>H;;-:?-C;DI?ED7B;B;9JHED F7J>M7OI 7D: I;HL; 7I 7 8K<<;H PED; <EH J>; IKB<KH >EIJ : KH?D=J>; :?I9>7H=; /9>7H=; LEBKC; ;NF7DI?ED. A>D;J 7B. IODJ>;I?P;: 7 M;BB-:?IF;HI;: ' 1 - C ( ./IKB<KH 97J>E:; 80 FH;9?F?J7J?ED C;J>E:, 7D: IKB<KH M7I ?D<?BJH7J;: ?DJE J>; >EB-BEM 9>7DD;B E< ' 1 C ( .I 5296. .>; 9ECFEI?J; D7DEC7J;H?7B;N>?8?J;: 7 >?=> IKB<KH 9EDJ;JJ E< 80 MJ.% M?J> 1300 CA>/= IF;9?<?9 97F79?JO. "EM;L;H, 7 H7J>;H H7F?: :;-9H;7I; ?D 97F79?JO M7I E8J7?D;: EL;H 30 909B;I, M?J> 854 CA>/= E8I;HL;:..>;I; H;IKBJI ?D:?97J;: 7 H7J>;H B?C?J;: ;<<

A&J>EK=> J>;H; >7I &;;D ;NJ;DI?L; H;I;7H9> ED 97H8ED C7J;H?7BI 7I IK&<KH >EIJI, J>; IODJ>;I?I 9EIJI IJ?& >?D:;HJ>; M?:;IFH;7: KI; E<=H7F>;D; 7D: C ( . I ?D J>; 97J>-E:;. #DIJ;7:, BEM-9EIJ &?EC7II-:;H?L;: FEHEKI 97H8ED C7J;H?7BI M?J> CE:;H7J; ;B;9-JHED?9 9ED:K9J?L?JO 7H; CEH; FH79J?97B 7I >EIJ C7J;H?7BI &? 7D: 9EMEHA;HI <?HIJ ;D-97FIK&7J;: IK&<KH ?D EH:;H;: C;IEFEHEKI 97H8ED 80 7 C;BJ?D=-:?<KI?ED C;J>E: 5226. .>; 9ECFEI?J;I 9EKB: FHEL?:; ;DEK=> IF79; JE H;B?;L; J>; LEBKC; ;NF7DI?ED E< IKB-<KH :KH?D= 9>7H=?D=/:?I9>7H=?D=, M>?9> E8J7?D;: 7 >?=> :?I9>7H=; 97F79?JO E< EL;H 1300 CA>/=. B7I;: ED J>?I H;I;7H9>, 7 I;H?;I E< FEHEKI 97H8ED/IK&<KH D7DE9ECFEI-?J;I >7L; &;;D IJK:?;: JE 8EEIJ J>; F;H<EHC7D9; E< &?-- 87JJ;H?;I 531–336.

(7DEIJHK9JKH;: JH7DI?J?ED C;J7B 9ECFEKD:I (IK9> 7I .?)<sub>2</sub>, CE<sub>3</sub>)<sub>4</sub>, CE<sub>-2</sub>, 7D: '2-;D;)>7L; 7BIE 8;;D KI;: 7I FEJ;DJ?7B 97J>E:; >EIJ C7J;H?7BI. .H7DI?J?ED C;J7B 9EC-FEKD:I <79?B?J7J; FEB7H FEBOIKB<?:; 7:IEHFJ?ED, H;IKBJ?D= ?D J>; 87JJ;HO'I >?=> IJ78?B?J0 5346. 'EH;EL;H, JH7DI?J?ED C;J7B 9ECFEKD:I 97D ?CFHEL; 97J>E:; 9ED:K9J?L?J0 7D: ;D>7D9; FEBOIKB<?:;I' H;:EN A?D;J?97BB0.

.H7DI?J?ED C;J7B EN?:;I (. ')I) 7H; KDIK?J78B; JE 8; :?H;9JBO KI;: 7I 7 IKB<KH >EIJ IJHK9JKH; :K; JE J>;?H FEEH FEHEI?JO 7D: IBK==?I> ;B;9JHED 7D: ?ED JH7DIFEHJ. .>;H;<EH; L7HO?D= . ') CEHF>EBE=?;I 7H; =;D;H7BBO KI;: 7I 9ECFEI?J;: 97J>E:;I

M?J> EJ>;H >?=>B0 9ED:K9J?L; D7DEC7J;H?7BI (IK9> 7I 97H8ED C7J;H?7BI, '2;D;, '),7D: 9ED:K9J?L; FEBOC;H) JE ?D9H:7I; 97J>E:; KJ?B?P7J?ED.

ACED= . ' ) I, .?) 2 M7I J>; ;7HB?;IJ IJK:?;: 97J>E:; >EIJ C7J;H?7B :K; JE ?JI 9EDJHEBB78B; D7DEIJHK9JKH; 7D: IJHED= FEB7H?JO. .E ?D>?8?J J>; I>KJJB; ;<<;9J E< FEBO-IKB<?:;, 7 I;H?;I E< :?<<;H;DJ IJHK9JKH;I E< .?) 2 >7L; 8;;D ;NFBEH;: 7I 97J>E:; >EIJ C7J;H?7BI, IK9> 7I I>;BBI, D7DEJK8;I, 7D: D7DEM?H;I, EH J>HEK=> J>;?H 9EC8?D7J?ED M?J> J7?BEH;: 97H8ED IJHK9JKH;I. CK? ;J 7B. IODJ>;I?P;: FEB7H .?) 2 OEBA I>;BB D7DEI-JHK9JKH; 7I 97J>E:; >EIJ C7J;H?7B ( ?=. 7.3A) 5266. .>; ;N9;BB;DJ 97F79?JO 8;D;<?JI <HEC IK<<?9?;DJ ?DJ;HD7B IF79; JE C?J?=7J; J>; LEBKC; ;NF7DI?ED E< J>; 79J?L; C7J;-H?7B :KH?D= 909B?D=. ' EH;EL;H, FEB7H .? ) =HEKFI 7D: >O:HENOB =HEKFI 7H; H;=7H:;:



#### FIGURE 7.3

(A) -9>; C7J?9 ?BBKIJH7J?ED E< --.?) 2 D7DEIJHK9JKH; I 5266. CEFOH?=>J 2013, ;; FHE:K9;: M?J> F; HC?II?ED E< (7JKH; \*K8B?I>?D= ! HEKF. (B) -9>; C7J?9 ?BBKIJH7J?ED E< J>; ?<<; H; D9; ?D 97H8ED/ IKB<KH 97J>E:; 7D: CE-2-?D9EHFEH7J;: 97H8ED/IKB<KH 97J>E:; :KH?D=9>7H=?D=5366. CEFOH?=>J 2016, ,; FHE:K9;: M?J> F; HC?II?ED E< AC; H?97D C>; C?97B -E9?; JO. (C) -JH7J;=?; I JE 7::H; II IEC; ?IIK; I E< &?-- 87JJ; H?; I 80 KJ?B?P?D=97J?ED-I; B; 9J?L; I; F7H7JEHI H; =KB7J?D= ?ED?9 JH7DIFEHJ 5376.

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JE 8?D: M?J> FEBOIKB<?:;I ?D C?D?C?P?D= FEBOIKB<?:; :?IIEBKJ?ED. .>; 87JJ;HO;N>?8?JI 7 >?=> 97F79?JO E< 1000 CA>/= 7D: 7 BEM <7:; H7J; E< 0.033% EL;H 1000 909B;I. "EM;L;H, IBK==?I> ;B;9JHED JH7DI<;H 7D: FEEH ;B;9JH?97B 9ED:K9J?L?JO 97KI;: 7 <7IJ 97F79?JO BEII 7J 7 >?=> H7J;. .>;H;<EH; 7 >;J;HEIJHK9JKH; E< .?) 2 (>?=> 78IEHFJ?L?JO) 7D: .?( (>?=>;B;9JH?97B 9ED:K9J?L?JO) M7I IODJ>;I?P;: 80 4>EK 7D: 9EMEHA;HI 5356.

.>;>;J;HEIJHK9JKH; ;N;HJ;: 7 IOD;H=?IJ?9 ;<<;9J, 7BBEM?D= H7F?: :?<<KI?ED E< FEBO-IKB<?:; JE J>; 9ED:K9J?L; 97H8ED IKH<79; M>?B; ?CFHEL?D= J>; :;FEI?J?ED E< &?<sub>2</sub>-..>; KD?GK; >;J;HEIJHK9JKH; 79>?;L;I 7D ?D?J?7B :?I9>7H=; 97F79?JO E< **927** CA>/= 7D: 7D KBJH7BEM IJ78B; 97F79?JO H;J;DJ?ED E< **73%** :KH?D= J>; **2000** 909B;I.

.H7DI?J?ED C;J7B IKK<?:;I (. ' -I) 79J 7I 7 97J>E:; >EIJ 7::?J?L;, M?J> C;J7B ?EDI IKK<KH ?EDI, FHEL?:?D= 7 >?=> L7B;D9; ;B;9JHED :;DI?JO JE J>; C;J7B 7JECI, M>?9> 9H;-7J;I 8?D:?D= I?J;I <EH ;NJH?DI?9 IEH8;DJI FEBOIKK<?:;I. EH ;N7CFB;, .?-2 5386, CE-2 5366, 7D: CE<sub>9-8</sub> 5396 M;H; 7::;: ?DJE &?<sub>2-6</sub> IEBKJ?ED JE I?CKB7J; J>; 7:IEHFJ?ED E< &?-- 87JJ;HO ?DJ;HC;:? 9

$$\begin{split} &\text{8EJ> I?:: I E< I; F7H7JEH. E 9EDIJHK9J 7D ?ED-I; B; 9J?L; I; F7H7JEH 87I;: ED J>; FEH; \\ &\text{I?P; }; <<: 9J, J>; I; F7H7JEH CE: ?<?97J?ED C7J; H?7BI 7H; H; GK?H;: JE ;N>?8?J IK8C?-9HE/D7DEFEHEKI JJHK9JKH; I, M>?9> ?D9BK:; JME-:?C; DI?ED7B (2D) D7DEC7J; H?7BI 7D: C; J7B-EH=7D?9 <H7C; MEHAI (') I). 17D=; J 7B. <?HIJ FHEFEI;: 7 2D .?_3C_2.N-<KD9-J?ED7B?P;: I; F7H7JEH <EH 7D9>EH?D= FEBOIKB<?:; I 5406. .>; &?-- 87JJ; H0 M?J> .?_3C_2.N-<KD9J?ED7B?P;: I; F7H7JEH I>EM;: 7 :?I9>7H=; 97F79?J0 E< 550 CA>/= :K; JE J>; 87B7D9; E< J>; 88E9A?D= E< FEBOIKB<?:; I 7D: ?CFHEL; C; DJ ?D ;B; 9JHED 9ED: K9J?L-?J0. #J ;N>?8?J;: 7 IJ78B; 909B?D= F; H<EHC7D9; 7D: >?=> H; J; DJ?ED 7J 0.5 C EL; H 500 909B; I. \end{split}$$

## 7.3 Nanomaterials in metal-air batteries

.>; C;J7B-7?H 87JJ;HO 97D H;7B?P; J>; ;D;H=O 9EDL;HI?ED 8;JM;;D J>; 9>;C?97B ;D-;H=O 7D: J>; ;B;9JH?9?JO 80 H;:EN H;79J?ED EF;H7J?D= ED J>; ;B;9JHE:;I. .>; F;H<EH-C7D9; E< 71I;C8B;: 87JJ;HO ?DLEBL?D= H7J; 78?B?JO, ;D;H=O 9EDL;HI?ED ;<<?9?;D9O, 7D: 909B?D= IJ78?B?JO 5416, ?I ?DJ;DI;BO 9EHH;B7J;: M?J> J>; 7?H ;B;9JHE:; H;79J?ED E< M>;H; J>; ;B;9JHE97J7B0J?9 ENO=;D H;:K9J?ED H;79J?ED (), ,) 7D: ENO=;D ;LEBKJ?ED H;79J?ED (), ,) 7D: ENO=;D ;LEBKJ?ED H;79J?ED (), ,) 7D: ENO=;D ;LEBKJ?ED H;79J?ED ()E,) 5426. #J ?DLEBL;I J>; ENO=;D H;:EN H;79J?EDI E99KHH?D= ?D 9ECFB;N JH?FB;-F>7I; ?DJ;H<79;I (=7I;EKI ENO=;D/B?GK?: ;B;9JHEB0J;/IEB?: 97J7B0IJ) 5436. CED-IJHK9J?D= J>; 7:L7D9;: 7?H ;B;9JHE:;I H;GK?H;I J>; 97J7B0IJI JE =;J J>; 7FFB?978B; A?D;J?9 H;79J?ED. (7DEC7J;H?7BI EH D7DEIJHK9JKH;I FB7O L?J7B ;<<;9JI ?D :;L;BEF?D= >?=>-F;H<EHC7D9; 97J7B0IJI.

.>; ),, 7IIE9?7J;: M?J> 7?H-97J>E:; H;79J?EDI I>EKB: 8; :;I9H?8;: 7I J>; <EB-BEM?D= IJ;FI 544-466:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- [4e \text{ pathway}], \qquad (7.1)$$

$$O_2 + H_2O + 2e^- \rightarrow HO_2^- + OH^-$$
 [2e pathway], (7.2)

.>; ), , 9EKB: FHE9;;: J>HEK=> 7 <EKH-;B;9JHED (4;) HEKJ; (7.1) EH 7 JME-;B;9JHED (2;) HEKJ; (7.2). .>HEK=> J>; 4; F7J>M70, J>; ), , EMDI J>; >?=>;IJ-;D;H=O 9EDL;H-I?ED ;<<?9?;D90. "EM;L;H, J>; 2; F7J>M70 97D FHE:K9; J>; F;HEN?:; J>7J 97KI;I J>; ;B;9JHE:; JE 9EHHE:; JE :=H7:; 87JJ;HO F;H

.>; ) E , F7J>M7OI 7H; CEH; 9ECFB;N. .>; ;B;C;DJ7HO IJ;FI ?DLEBL; J>; 7:IEHF-J?ED E< ) " 7D: ) IF;9?;I ED 79J?L; I?J;I (\*) 7D: 7I J>; H;79J?EDI E< (7.3) 7D: (7.4) 5476:

$$OH^- + * \rightarrow OH^* + e^-, \tag{7.3}$$

$$OH^* + OH^- \to O * + H_2O + e^-,$$
 (7.4)

.>; A?D;J?9I E< ENO=; D H; 79J?EDI ?I ?DJH?DI?97BBO IBK==?I>, M>?9> ?I J>; C7@EH E8-IJ79B; JE :;L;BEF?D= C;J7B-7?H 87JJ;H?;I. .>; D7DEC7J;H?7BI ?D ;NFBEH?D= J>; 8?<KD9-J?ED7B 97J7BOIJI JEM7H: ),, 7D: )E, 7H; E<=H;7J I?=D?<?97D9; 7D: >7L; 8;9EC; J>; C7?D 7FFHE79>;I JE ?CFHEL; J>; F;H<EHC7D9; E< C;J7B-7?H 87JJ;H?;I.

#### 7.3.1 Noble metals and alloys catalysts

\*B7J?DKC-=HEKF C;J7BI (\* ! ' I) >7L; 8;;D M?:;B0 H;I;7H9>;: 7I J>; CEIJ 79J?L; 97J-7B0IJI <EH J>; ),,, M?J> H;C7HA78B; ;B;9JHE9>;C?97B F;H<EHC7D9; 7D: >?=> IJ78?B-?JO. \*J D7DEF7HJ?9B;I, 7JEC?9 9BKIJ;HI, 7D: I?D=B; 7JECI KD?<EHCB0 :?IJH?8KJ;: ED J>; IKFFEHJI M?J> 7 >?=> IKH<79; 7H;7 >7L; 8;;D KI;: 7I 7:L7D9;: ),, ;B;9JHE97J7B0IJI. \*J 97J7B0IJI EMD ;N9;BB;DJ 97J7B0J?9 79J?L?JO 7D: IJ78?B?JO. "EM;L;H, >?=> 9EIJ 7D: I97H9?J0 I;H?EKIB0 B?C?J J>; 7FFB?97J?EDI E< \*J 97J7B0IJI. .>;H;<EH; ;NJ;DI?L; ;<<EHJI 7H; F70?D= JE ;B?C?D7J; J>; >?=> 9EIJI 80 <?D:?D= J>; 7BJ;HD7J?L;I IK9> 7I \*J 7BBE0I, DEDDE88; C;J7BI, EH C;J7B-<H;; 97J7B0IJI.

\*J-87I;: 7BBEOI 9EC8?D= \*J C;J7B M?J> 7DEJ>;H C;J7B 7H; 9ECF7H78BO 79J?L; <EH ), 7D: ) E, M?J> FKH; \*J. #D &?-) 2 9;BBI, J>; 7?H ;B;9JHE:; M?J> \*JAK/C 97J7BOIJ ;N>?8?J;: J>; :?I9>7H=; 7D: 9>7H=; LEBJ7=; 9BEI; JE AK/C 7D: \*J/C 5486 8;97KI; AK 7D: \*J 7JECI 7HEKD: J>; IKH<79; E< 97J7BOIJI 97D ;D>7D9; J>; ), 7D: ) E, A?D;J-?9I.

#### 7.3.2 Transition metal compounds catalysts

. H7DI?J?ED C;J7B 9ECFEKD:I, ?D9bK:?D= EN?:;I, IKB<?:;I, F>EIF>?:;I, 7D: D?JH?:;I, >7L; 8;;D; NFBEH;: 7I ), ,/)E, 97J7B0IJI (?=. 7.4) 5496. .>; ?DJ;DI?L; IJK:?;I >7L; FHEDEKD9;: J>7J HE9A-I7BJ-JOF; CEDEN?:;I IK9> 7I CE ) 7D: (?) 9EKB: I?=D?<-?97DJB0 ?CFHEL; ), ,/)E, 97J7B0J?9 79J?L?J?;I 7D: F;H<EHC 9ECF7H78B0 JE J>; DE8B; C;J7B 97J7B0IJI 5506. .>; H;FH;I;DJ7J?L; IF?D;B IJHK9JKH; E< CE<sub>3</sub>)<sub>4</sub> 7D: (?CE<sub>2</sub>)<sub>4</sub> >7L; 8;;D M;BB :; CEDIJH7J;: JE I?CKBJ7D;EKIBO 97J7BOP; J>; ), , 7D: )E, :K; JE J>;?H >?=>B0 ;B;9JHE97J7B0J?9 79J?L?J?;I.

. '-I >7L; 8;;D FHEC?I?D= 7I J>;?H =EE: 79J?L?JO JEM7H: ) E, /), , 7D: I?CFB; FH;F7H7J?ED 7FFHE79>;I. 1 >;D ?J ?I ?D J>; EN?:7J?ED FHE9;II, J>; C;J7B EN?:;/>O:HEN-?:; IF;9?;I 97D 8; FHE:K9;: ED J>; IKH<79; E<. '- JE 9EDJH?8KJ; JE J>; ;B;9JHE97J-7BOJ?9 79J?L?JO E< ) E, /), , 5516. .>; H;9;DJ H;IKBJI IK==;IJ;: J>7J ?DJHE:K9?D= J>; JH7DI?J?ED C;J7B F>EIF>?:; (. '\*) ?DJE J>; . '- 97D 9>;C?97BBO IJH;D=J>;D J>; 8ED:-?D= JE ?CFHEL; J>; :KH78?B?JO E< J>; 97J7BOIJI. .>; ?CFHEL;: F;H<EHC7D9; 9EKB: 7H?I; <HEC J>; 3F EH8?J7B BED; F7?H;B;9JHEDI 7D: <H;; 3: EH8?J7BI E< C;J7B F>EIF>EHKI 5526. 'EIJ JH7DI?J?ED C;J7B 9ECFEKD:I, ?D9BK:?D= .') I, >O:HE(ENO)EN?:;I, 7D: IKB<?:;I, 7H; ;?J>;H ?DIKB7JEHI EH I;C?9ED:K9JEHI; ?DJH?DI?97BBO, 7I 7 9EDI;GK;D9;, 9EDI?:;H78B; ;<<EHJI >7L; 8;;D :;LEJ;: JE IEBL?D= J>; ?DJ;H<79?7B;D;H=O 87HH?;HI :K; JE J>; FEEH ;B;9JHED 9ED:K9J?L?JO 7D: J>; ?D9H;7I;: EL;HFEJ;DJ?7B, M>?9> >7CF;HI ;D;H=O 9ED-L;HI?ED ;<<?P9?;D9O. .>; 9HK9?7B 9>7BB;D=;I ?D 8EEIJ?D= ;B;9JHE97J7BOI?I F;H<EHC7D9; 7H; jE 799;B;H7J; ;B;9JHED JH7DIFEHJ.

#D =;D;H7B, EM?D= JE J>; C;J7BB?9;B;9JHED JH7DIFEHJ 8;>7L?EH E< JH7DI?J?ED C;J7B D?JH?:;I (. ' (I), ?J 97D 799;B;H7J; J>; 9>7H=; JH7DI<;H 8;JM;;D J>; 97J7B0IJI 7D: J>; IKFFEHJI. #D 7::?J?ED, . ' (I 7H; ?DJ;HIJ?J?7B 9ECFEKD:I EH 7BBEOI M?J> 7 <79;-9;D-J;H;: 9K8?9 7HH7D=;C;DJ E< C;J7B 7JECI. .>; ?DJHE:K9J?ED E< D?JH?:; 7JECI ?DJE J>; F7H;DJ C;J7BI 97D H;IKBJ ?DJE J>; ;NF7D:?D= E< B7JJ?9; F7H7C;J;H. -?D9; J>; =EE:



#### FIGURE 7.4

-9>; C7J?9 E< ?DJ;DI;BO H;I;7H9>;: JH7DI?J?ED C;J7B EN?:; 97J7BOIJI <EH ENO=;D H;:K9J?ED H;79-J?ED EH ENO=;D ;LEBKJ?ED H;79J?ED 5496.

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## 7.3.3 Metal-free carbon-based catalysts

C7H8ED C7J;H?7BI >7L; ;N9;BB;DJ <B;N?8?B?JO, >?=> I>7F; 9ED<EHC78?B?JO, 7D: ;B;9JH?-97B 9ED:K9J?L?JO 7H; 9EDI?:;H; 9ECC;H9?7BBO 7L7?B78B; IK8IJH7J; <EH J>; =7I :?<<K-I?ED B7O;HI E< C;J7B-7?H 87JJ;H?;I. CECF7H; M?J> 9EDL;DJ?ED7B FEM:;HO 9EKDJ;H-F7HJI, J>; I;B<-IKFFEHJ; 97H8ED IJHK9JKH; >7I C7DO ?DJH?DI?9 7:L7DJ7=;I. .>; >O-:HEF>?B?9 97H8ED IKFFEHJI 97D =HEM J>; 97J7BOIJI :?H;9JBO JE 7LE?: J>; 7::?J?ED E<

7D0 7D9?BB7H0 7::?J?L;, M>?9>;N>?8?J;:>?=> 97J7B0I?I F;H<EHC7D9; <EH J>; ), 7D: ) E . . . >; IK8IJH7J; C7J;H?7BI 97D H?L;J 7D: :?IF;HI; 97J7BOIJI, J>KI FHEL?:?D= BEM ?D-J;H<79?7B 9EDJ79J H;I?IJ7D9; 7D: >?=> 799;II?8?B?JO E< CKBJ?F>7I; 79J?L; I?J;I. #D J>?I H;=7H:, &?K'I =HEKF 5556 FH;F7H;: 7 =H7F>;D; 9EDJ7?D?D= H?9> ;:=:I 7D: J>; ENO-=;D7J;: IF;9?;I ED 97H8ED 9BEJ> IK8IJH7J; ( ?=. 7.5A). .>; E8J7?D;: 97J7BOIJ L?7 2D-I?JK AH FB7IC7 JH;7JC;DJ 97D 8; KI;: 7I 8?<KD9J?ED7B ) E,/), ;B;9JHE:; '7 ; J 7B. H; FEHJ; : 7  $\triangleleft$ ; N?8B; I; B<-IKFFEHJ; : =-C<sub>3</sub> ( $_{4}$  97J7BOIJI M?J> F>EIF>EHKI : EF?D=, M>?9> 97D H;L;HI?8BO 97J7BOP; ),, 7D: ) E, 5566. -?C?87HBO, C;J7B-<H;; 97J7BOIJ E< J>; \*-: EF;: =-C<sub>3</sub>(4 =HEM?D= ED 97H8ED <?8;H F7F;H (\*C(-C \*) M?J> 7 B7H=; 7H;7 (10 W 15 9C ?D I?P;) 7D: >?=> <8;N?8?B?JO ( ?=. 7.5B), M7I <78H?97J;:, M>;H; \*-:EF;:  $=-C_3(_4:?H;9JBO=H;M ED J>; C * JE FHE:K9; 7 < BEM;H-B?A; FEHEKI < H7C;MEHAI (?=.)$ 7.5C). DK78 : EF?D= E< ;B;C;DJ7H0 (7D: \*;D78B;: J>; C7II 7D: 9>7H=; JH7DI<;H, J>; 3D C \* <H7C; MEHA M?J> 7 <BEM; H-B?A; D7DEIJHK9JKH; ;D87H=;: J>; 79J?L; IKH<79; 7H-;7I. .>;H;<EH; J>; \*C (-C \* JEM7H: 8EJ> ) , ,/)E , ;N>?8?J;: J>; IKF;H?EH 79J?L?JO, IJ78282JO, 7D: H;L;HI28282JO EL;H 2JI FEM: ;HO 9EKDJ;HF7HJ. .>; 2DJ;=H7J;: ;B;9JHE: ;I 7H; ;7I?;H JE H;7B?P; 799;II?8?B?JO E< 79J?L; I?J;I 7D: JE :;9H;7I; 9EDJ79J H;I?IJ7D9; M?J>EKJ 7::?J?ED7B DED9ED:K9J?L; 8?D:;H. .>;I; 7:L7DJ7=;I <7LEH 8EELJ?D= F;H<EH-C7D9; E< 4D-7?H 87JJ;H?;I.

.>; :;<;9JI ?D 97H8ED C7J;H?7BI 9EKB: 8H?D= J>; ;B;9JHEBOJ?9 79J?L?JO <EH ), ,/ ) E ,, J>; ;B;9JHED?9 90HK%=KH7J?ED CE:KB7J?ED 80 JKD?D= J>; :;<;9JI ?D 97H8ED 97D EFJ?C?P; J>; 7:IEHFJ?ED ;D;H=O E< ?DJ;HC;:?7J;I :KH?D= ), ,/)E,. 4>7D= 7D: 9EMEHA;HI FH;F7H;: J>; JEFEBE=?97B :;<;9JI-;DH?9>;: =H7F>;D;I KI?D= J>; IJ?9AO H?9; 7D: C;B7C?D; 7I 97H8ED FH;9KHIEHI 7D: '=) 7I J;CFB7J;I. .>; ;NF;H?C;DJ7B IJK:O 7D: )J>;EH;J?97B I?CKB7J?EDI 9EDI?IJ;DJBO <EKD: J>7J J>; 7:079;DJ :;<;9JI E< F;DJ7=ED 7D: >;FJ7=ED (C5+C7) 9EDJH?8KJ; JE J>; FHEC?D;DJ ), , 7D: )E, 79J?L?JO H7J>;H J>7D (-:EF?D= I?J;I 5576 ( ?=. 7.6A,B). B;I?:;I J>; :;<;9JI <EHC;: 7HEKD: 97H8ED C7J;H?7BI,>;J;HE7JECI :EF?D= ?I 7 I?=D?<?97DJ HEKJ; JE ;D78B; J>; 97J7B0J?9 79J?L



#### FIGURE 7.6

(A) -9>;C7J?9 ?BBKIJH7J?ED E<=H7F>;D; D7DEH?88ED M?J>:?<<:H;DJ (-:EF;: IF;9?;I EH JEFEBE=?-97B :;<:9JI. (B) 0EB97DE FBEJI E< ) , , 7D: ) E , EL;HFEJ;DJ?7B 9ED9;HD?D=7:IEHFJ?ED ;D;H=0 E< ) "\* 5576. CEFOH?=>J 2016, , ;FHE:K9;: M?J> F;HC?II?ED E< \$E>D 1 ?B;O 7D: -EDI. (C) . E ' ?C-7=;I E< (-:EF;: FEHEKI 97H8ED 5596.

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$$\begin{split} J>; 9>7H=; :?IJH?8KJ?ED E<7: %79;DJ 97H8ED 7JECI. (?JHE=;D 7JEC ?I J>; ;NJ;DI?L;BO IJK:?;:>;J;HE7JEC :EF7DJ. EH ;N7CF8;, J>; EFJ?C?P;: (-:EF;: C (.I;B;9JHE97J-7BOIJ M7I KI;: 7I 7?H-97J>E:; IKFFB0 J>; ;N9;BB;DJ FEM;H :;DI?J0 E< J>; 4D-7?H 87J-J;H0 5586. .>; >?;H7H9>?97B0 FEHEKI (-:EF;: 97H8ED 97D 8; FHE:K9;: 80 FEBOC;H?P?D= E-F>;D0B;D;:?7C?D; ED I?B?97 J; CFB7J; 7D: J>; IK8I;GK;DJ 97H8ED?P7J?ED FHE9;II 7D: ("3;J9>?D= FHE9;II;I (?=. 7.6C). 5596. AI 7 H;IKBJ, ?J;N>?8?J;: 7D;N9;BB;DJ), , 79J?L?J0 9ECF7H78B; M?J>*J/C. .>; C;J7B-<H;; 97H8ED 97J7B0IJ M7I E8J7?D;: 80 7II;C8B?D= J>; (-:EF;: =H7F>;D; M?J> J>; H;J7?D;: FEHEI?J0 7D: 7FFB?;: JE &?-) 2 87JJ;H?;I 5606. .>; H;IKBJI :; CEDIJH7J;: J>; IKF;H?EH ;B;9JHE97J7B0J?9 F;H<EHC7D9;I 9ECF7H;: M?J> J>; I?C?B7H 17CFB;I 9EDJ7?D?D= J>; .') I EH J>; FH;9?EKI C;J7BI. \end{split}$$

## 7.4 Nanomaterials in all-solid-state batteries

DEF?D= ?DEH=7D?9 D7DEF7HJ?98;I ?DJE FEBOC;H ;B;9JHEBOJ; IOIJ;CI ?I 7D 7FFHE79> M?:;BO KI;: JE EFJ?C?P; F;H<EHC7D9; E< IEB?: ;B;9JHEBOJ;I. .>; H;7IEDI E< J>; ;N-9;BB;DJ F;H<EHC7D9; E< FEBOC;H IEB?: ;B;9JHEBOJ;I M?J> ?DEH=7D?9 <?BB;HI 7H;: (1) ?D-EH=7D?9 <?BB;HI 97D :;9H;7I; J>; 9HOIJ7BB?D?JO E< FEBOC;HI JE ?D9H;7I; J>; 7CEHF>EKI F>7I; H;=?ED, M>?9> ?I 8;D;<?J;: <EH &?+ C?=H7J?ED; (2) J>;0 ?D9H;7I; <7IJ ?ED JH7DI<;H 9>7DD;BI D;7H J>; <?BB;H F7HJ?9B;I; (3) J>;0 97D 7BIE ?CFHEL; J>; C;9>7D?978 FHEF;H-J?;I E< FEBOC;H ;B;9JHEBOJ;I. #DEH=7D?9 <?BB;HI 97D 8; =;D;H7BB0 :?L?:;: ?DJE ?D;HJ C7-J;H?7BI, ?ED?9 9ED:K9JEH <?BB;HI, 7D: ;B;9JHED?9 9ED:K9JEH <?BB;HI, 7CED= M>?9> ?D;HJ <?BB;HI 7D: ?ED?9 9ED:K9JEH <?BB;HI 7H; J>; CEIJ IJK:?;:.

# 7.4.1 Nano-inert materials in composite electrolytes

.>; ?D;HJ <?BB;H C7?DBO FHECEJ;I J>; B?J>?KC I7BJI :?IIE9?7J;: 7D: BEM;HI J>; 9HOI-J7BB?D?JO E< J>; FEBOC;H;B;9JHEBOJ;I J>HEK=> &;M?I 79?: 7D: 7BA7B? 79J?EDI JE ?CFHEL; J>;7BFD????PJ?EDI????JO, M>?B; ?J 97D 7BIE ?D9H;7I; J>; J>;HC7B IJ78?B?JO 7D: J>; C;-9>7D?97B F;H<EHC7D9; E< ;B;9JHEBOJ;. '7DO JOF;I E< ?D;HJ C7J;H?7BI ?D9BK:?D= -?) 2 5616, AB<sub>2</sub> ) 3 5626, .? ) 2 5636, 4H ) 2 5646, ;J9., >7L; 8;;D M?:;BO KI;: JE 9EDIJHK9J J>; 9ECFEI?J; IEB?: ;B;9JHEBOJ;I E< ?DEH=7D?9-EH=7D?9 <EH IEB?:-IJ7J; B?J>?KC C;J7B 87J-J;H?;I, 7I I>EMD ?D ?=. 7.7A. .>; ?D;HJ

?D



#### FIGURE 7.7

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A0J?L;-<?BB;H <?BB;: ;B;9JHEBOJ; >7I CEH; 9ECFB;N 7D: IF;9?7B ?ED?9 9ED:K9J?L; 8;->7L?EH. ?HIJ, 79J?L;-<?BB;H ?JI;B< 97D JH7DIFEHJ &?+. -;9ED:, J>; JME-F>7I; ?DJ;H<79; <EHC;: 80 J>; 79J?L; <?BB;H 7D: J>; FEBOC;H >7I 7 IF79; <EHC;: 80 J>; :;<;9J H;79-J?ED E< &?+ C?=H7J?ED JE J>; 9H0IJ7B IKH<79;. .>; 9EDJ?DKEKI IF79; 9>7H=; H;=?ED ?I 7BIE J>; JH7DIFEHJ F7J> E< &?+ 7I I>EMD ?D ?=. 7.7B. .>;H;<EH; 79J?L; <?BB;HI 97D I?=D?<?97DJBO ?CFHEL; J>; ?ED?9 9ED:K9J?L?JO E< IEB?: ;B;9JHEBOJ;I CEH; J>7D ?D;HJ <?BB;HI.

## 7.4.3 Nanometer electronic conductor in composite electrolytes

EB;9JHED?9 9ED:K9J?L?JO ?I =;D;H7BBO C?D?C?P;: 7I 7D ;B;9JHEBOJ; I?D9; CEIJ 7JJ;DJ?ED >7I 8;;D <E9KI;: ED ?CFHEL?D= IEB?: ;B;9JHEBOJ; ?ED JH7DI<;H H7J;...>;H;<EH; J>; 7F-FB?97J?ED E< ;B;9JHED?9 9ED:K9JEHI ?D IEB?: ;B;9JHEBOJ;I ?I 9EDI?: ;H78BO H7H;. #D I;L-;H7B H;9;DJ 0;7HI, ?J M7I :?I9EL;H;: J>7J ?D-I?JK CE:?<?97J?ED E< J>; ;B;9JHE:;-;B;9-JHEBOJ; ?DJ;H<79; M?J> ;B;9JHED 9ED:K9JEHI JE ;DIKH; ;B;9JHED >ECE=;D;?JO 7J J>; ;B;9-JHE:;-;B;9-JHE:]; ?D];H<79; 9EKB: 79>?;L; =EE: ?DJ;H<79?7B 9EDJ79J 7D: BED=-B7IJ?D= 87JJ;H0 909B;I.

4>;D= ;J 78. 5686 :;I?=D;: J>; ?D-I?JK =HEMJ> E< D7DE-I?P;: "<BEM;H"-B?A; 9ED: :K9J?L; FEB0J>?EF>;D; F7HJ?9B;I 7J J>; ;B;9JHE:;-;B;9JHEB0J; ?DJ;H<79;, ?DJ;HJM?D;: M?J> \*E) JE <EHC 7 C?N;: ?ED-;B;9JHED JH7DI<;H ?DJ;H<79; B70;H (?=. 7.7D). CE?D9?-:;DJ7BB0, 7I 7D ;B;9JHED?9 D7DE<?BB;H, J>; !) I M;H; 7::;: ?DJE - EB?: \*EBOC;H EB;9-JHEB0J;I (-\*EI) 7J :?<<;H;DJ H7J?EI. 1>;D J>; !) 9EDJ;DJ ?I 1.0 MJ.%, J>; ?ED?9 9ED-:K9J?L?JO E< J>; 9ECFEI?J; ;B;9JHEB0J; ?I H7?I;: JE 4.0 W 10<sup>-4</sup> -/9C (?=. 7.7E).

# 7.5 Summary and outlook

1 ?J> J>; C7HA;J D;;:I <EH BED=-H7D=; ;B;9JH?9 7KJECE8?B;I 7D: B7H=;-I97B; ;D;H=O IJEH7=; IJ7J?EDI, >?=>-;D;H=O-:;DI?JO 87JJ;H?;I >7L; 8;;D 7JJH79J;: CEH; 7JJ;DJ?ED. (7DEC7J;H?7BI 7D: D7DEJ;9>DEBE=?;I >7L; I?=D?<?97DJBO 7<<;9J;: J>; :;L;BEFC;DJ E< ;B;9JHE:; C7J;H?7BI <EH 9EDL;DJ?ED7B &#BI 7D: D;M 87JJ;HO IOIJ;CI M?J> FEJ;DJ?7B 7FFB?97J?EDI (&?-- 87JJ;H?;I, C;J7B-7?H 87JJ;H?;I, 7D: 7BB-IEB?:-IJ7J; 87JJ;H?;I).

&#BI <79; C7DO 9>7BB;D=;I, IK9> 7I I?:; H;79J?EDI, IBEM A?D;J?9 H7J;I, IJHK9JKH7B :7C7=;, 7D: KDIJ78B; IKH<79; -EB?: EB;9JHEBOJ; #DJ;HF>7I; (-E#), M>?9> M?BB 7<<;9J J>; 78?B?JO E<;B;9JHE:; C7J;H?7BI <HEC ;B;9JHED?9 9ED:K9J?L?JO, 7D: &?<sup>+</sup> :?<KI?L?JO JE E8J7?D J>; EFJ?C7B ;B;9JHE9>;C?97B F;H<EHC7D9;. &?-- 87JJ;H?;I ;D9EKDJ;H;: J>; FEBOIKB<?:; I>KJJB; ;<<:9J, BEM 9ED:K9J?L?JO, 7D: B7H=; LEBKC;JH?9 ;NF7DI?ED. .>; DEL;B C7J;H?7B/79J?L; C7J;H?7B >EB:?D= IKB<KH, D7DEJ;9>DEBE=O ED J>; ;B;9JHE:;, :;-I?=D E< CKBJ?<KD9J?ED7B I;F7H7JEHI, 7D: J>; <KD:7C;DJ7B H;79J?ED C;9>7D?IC >7L; 8;;D M?:;BO 9ED9;HD;:. .>; FH;9?EKI 97J7BOIJI M?J> >?=>-9EIJ 7D: I97H9?JO <EH C;J7B-7?H 87JJ;H?;I >7L; I;H?EKIBO B?C?J;: J>;?H 7FFB?97J?EDI. D;I?=D?D= 7D: :;L;B-EF?D= DEDDE88; C;J7B 97J7BOIJI M?J> >?=> 79J?L?JO 80 D7DEJ;9>DEBE=?;I >7L; 8;;D :;CEDIJH7J;: 7I ;<<;9J?L; C;7DI JE 8EEIJ J>; ) , /)E, E< C;J7B-7?H 87JJ;H?;I. -EB?: ;B;9JHEBOJ;I 7H; 9H?J?97B ?D J>; :;L;BEFC;DJ E< 7BB IEB?: 87JJ;H?;I. E;D>7D9; J>; ?ED 9ED:K9J?L?JO 7D: JE ?CFHEL; J>; C;9>7D?97B IJ78?B7J0 E< IEB?: ;B;9JHEBOJ;I 97D ?CFHEL; J>; 9>7H=;-:?I9>7H=;, H7J;, 7D: IJ78?B7J0 F;H<EHC7D9; E< 7BB-IEB?:-IJ7J; 87JJ;H?;I.

";H;, M; 8H?; do EL;HL?;M;: 7D: :?I9KII;: D7DEC7J;H?7BI' 7:L7DJ7=;I ?D IEBL?D= J>; 78EL; FHE8B;CI. ';7DM>?B;, J>; 9>7BB;D=;I IK9> 7I J>; >?=>-9EIJ 7D: 9ECFB;N CKBJ?IJ;F FHE9;II?D= 80 KJ?B?P?D= D7DEC7J;H?7BI ?D 87JJ;H?;I >7L; JE 8; 9EDI?:;H;:. ENFBEH?D= DEL;B D7DEC7J;H?7BI, :;I?=D?D= H7J?ED7B D7DEIJHK9JKH;, 7D: =;JJ?D= =EE: 9ECF7J?8?B?JO M?J>;B;9JHE:; C7J;H?7BI MEKB: 8; J>; FEII?8B; HEKJ;I JE 7FFB0 D7DE-C7J;H?7BI ?D 87JJ;H?;I I>EHJBO.

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