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

7

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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;9JH;B;9

8ED 9E7J?D= ?I JOF?97BBO ;;FEI?J;; KI?D= J>; EH=7D?9 7D: FEBOC;H 7I FH;9KHIEHI 80
J>;HC7B L7FEH ;;FEI?J?ED (. 0D) 7D: >?=>-J;CF;H7JKH; 7DD;7B?D= ?D 7D ?D;HJ 7JCEI-
F>;H;. CEDIJHK9J?D= 7 C;J7B EH C;J7B EN?.; 9E7J?D=

UNCORRECTED PROOF

<;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;:.

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>; B7J?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 IJH;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 IJH;II ?D:K9;: 80 J>;I; I?D?<?97DJ LEBKC; 9>7D=:;I H;IKBJ ?D C; 9>7D?97B <7?BKH;I, IK9> 7I C7J;H?7B <H79JKH; , FKB L;H?P7J?ED, 7D: I;F7H7J?ED <HEC J>; 9KHH;DJ 9EBB;9JEHI, I?D?<?97DJBO I>EHJ;D?D= J>; 909B; 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-

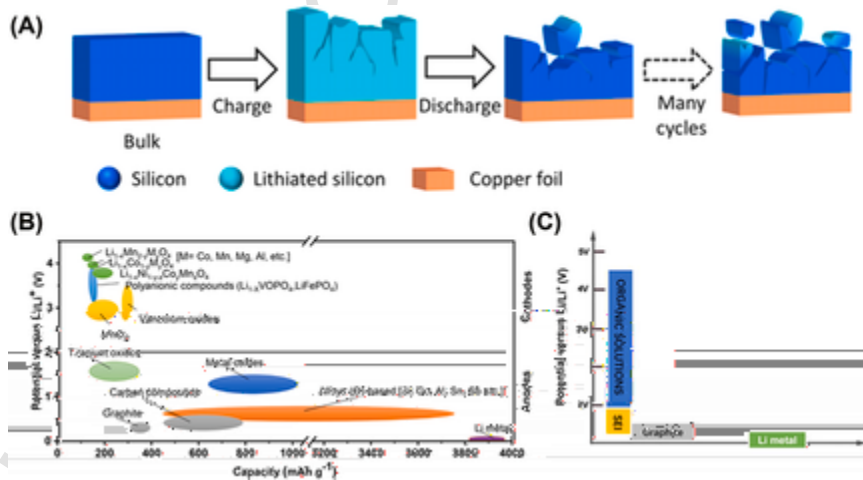


FIGURE 7.1

(A) CH79A?D= 7D: <H79JKH; E< 7BBEO-JOF; 79J?L; F7HJ?9B; I EL;H B?J>?7J?ED/: ;B?J>?7J?ED 909B?D= 5106. CEFOH?=>J 2017, , ;FHE:K9;: M?J> F;HC?II?ED E< AC;H?97D C>;C?97B -E9?;JO. (B) 0EBJ7=; L;H-IKI 97F79?JO <EH 97I>E: ?9 7D: 7DE: ?9 C7J;H?7BI. (C) .>; LEBJ7=; M?D:EMI <EH ;B;9JHEBOJ; IJ78?B-?JO 7D: J>; <EHC;: -E#.

J;H?7B' I B?J>?7J?ED C;9>7D?IC, F>OI?97B FHEF;HJ?;I, 7D: LEBKC;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?ED7B I?B?9ED D7DEC7J;H?7BI (-? D7DEM?H;I, -? D7DEJK8;I) >7L; 8;J;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?7B ED;-: ?C;DI?ED7B D7DEC7J;H?7BI <79?B?7J; 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 9ECCED 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;HB70;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;B?J?L; JE ;B;9JHE9? ?DIK-B7J?ED, J>; =HEM> 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 =>?BO ;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 E8J?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;B< 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?D?BO <E9KI;I ED ;B;9JHEBOJ; EFJ?C?P7J?ED 7D: 7HJ?<9?7B D7DE -E# 9EDIJHK9J?ED. CECF7H;: M?J> ;B;9JHEBOJ; EFJ?C?P7J?ED, 7HJ?<9?7B D7DE -E# 9ED-IJHK9J?ED 97D CEH; ;<<?9?;DJBO ?CFHEL; J>; BED=-909B; F;H<EH C7D9; 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;J;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?D?BO 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?B?9ED D7DEJK8;I 8;97KI; J>; >EBBEM IF79; E< D7D-

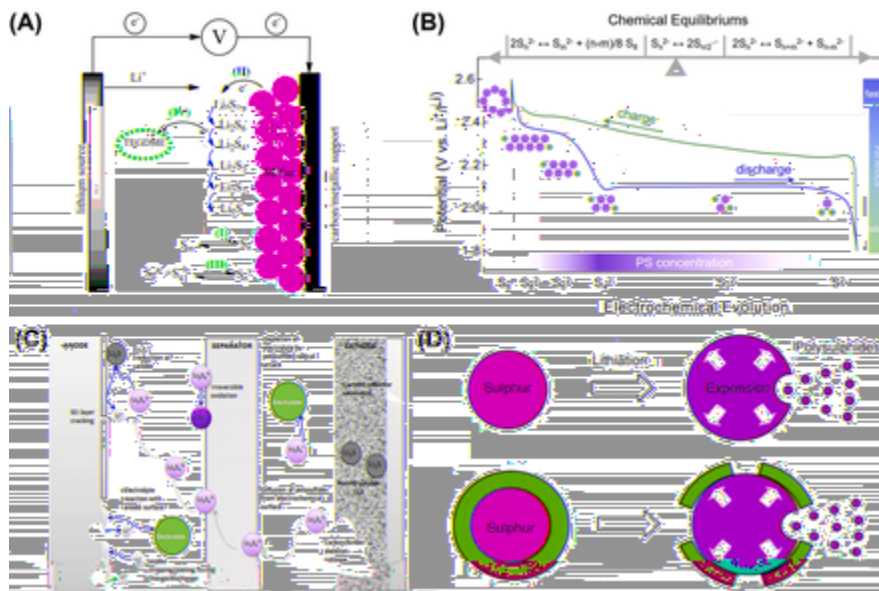


FIGURE 7.2

(A) -9>; C; E< &?-- 87J;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?I?ED 7D: ;LEBKJ?ED ?D &?-- 87J-J;HO 5246. CEFOH?=>J 2018, , ;FHE;K9;: M?J> F;HC?II?ED E< 1 ?B;0-0C ". (C) -KCC7HO E< ;:=H7-: 7I?ED C;9>7D?ICI 5256. CEFOH?=>J 2015, , ;FHE;K9;: M?J> F;HC?II?ED E< ,E07B -E9?;JO E< C>;C?IJHO. (D) -9>;C7J?9 E< J>;LEBK;JH?9 ;NF7DI?ED 7D: FEBOIKB<?:; ;?IIEBKJ?ED FHE9;II 5266.

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80% <EH IKB<KH :K; JE J>; ;DI?JO :?<<H;D9; 8;JM;D -8 7D: &?2- (2.03 7D: 1.66 =/ 9C³) 97D 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?; ;BO ?DL;IJ?=7J;: <EH >?=>-F;H<EH-C7D9; &?-- IOIJ;CI JE IEHL; FHE8B;CI E< J>; &?-- 87J;HO C;DJ?ED;: 78EL;.

7.2.1 Nanomaterials in the sulfur composite cathode

.E IEHL; J>; FHE8B;CI E< ?DIK87J?D= IKB<KH, LEBK; ;NF7DI?ED, 7D: J>; I>KJJB; ;<-<;9J E< FEBOIKB<?:;I, 97H8ED/IKB<KH 9ECFEI?I; 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:K9?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: >0:HENOB =HEKFI ?D !) FHECEJ;I
J>; ?CCE8?P7J?ED E< IKB<KH, J>KI FH;L;DJ?D= ?JI :?IEBKJ?ED. , ;9;DJB0, =H7F>;D;/IKB-
<KH 9ECFEI?J;I 7I 97J>E:;I >7L; 8;;D IODJ>;I?P:; 7D: J;IJ:; ?D &?-- 87JJ;H?;I. .>;0
;N>?8?J 8;J;H 97F79?JO, CEKBEC8?9 ;<<?9;D90, 7D: 909B?D= IJ78?B?JO F;H<EHC7D9;.

.>; =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-H70 IF;9JHEI9EF?9 7D7B0I?I 7D: D . 97B9KB7J?ED ?CFB0 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 ;7I0 JE FHEL?:; <7IJ J>H;;-: ?-
C;DI?ED7B ;B;9JHED F7J>M70I 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<?B?H7J;: ?DJE J>; >EB-
BEM 9>7DD;B E< ' 1 C (. I 5296. .>; 9ECFEI?J; D7DEC7J;H?7B ;N>?8?J;: 7 >?=> IKB<KH
9EDJ;DJ 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 E8J?D;: EL;H 30 909B;I, M?J> 854 CA>/= E8I;HL;: . .>;I;
H;IKBJI ?D: ?97J;: 7 H7J>;H B?C?J;: ;<<9J E< FKH; C (. I <EH FEBOIKB<?:; JH7FF?D=.

ABJ>EK=> J>;H; >7I 8;;D ;NJ;DI?L; H;I;7H9> ED 97H8ED C7J;H?7BI 7I IKB<KH >EIJ,
J>; IODJ>;I?I 9EIJ IJ?BB >?D:;H J>; M?;:IFH;7: KI; E<=H7F>;D; 7D: C (. I ?D J>; 97J>-
E:; . #DIJ;7: ;BEM-9EIJ 8?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-
97FIK87J;: IKB<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> E8J?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/IKB<KH D7DE9ECFEI-
?J;I >7L; 8;;D IJK?:;: JE 8EEIJ J>; F;H<EHC7D9; E< &?-- 87JJ;H?;I 531-336.

(7DEIJHK9JKH;: JH7DI?J?ED C;J7B 9ECFEKD:I (IK9> 7I .?)₂, CE₃)₄, CE₋₂, 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?JO
5346. ' EH;EL;H, JH7DI?J?ED C;J7B 9ECFEKD:I 97D ?CFHEL; 97J>E:; 9ED:K9J?L?JO 7D:
>D>7D9; FEBOIKB<?:;I' H;: EN A?D;J?97BBO.

.H7DI?J?ED C;J7B EN?:;I (. ') I) 7H; KDIK?J78B; JE 8; : ?H;9B0 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 >?=80 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:HENO8 =HEKFI 7H; H;=7H::;

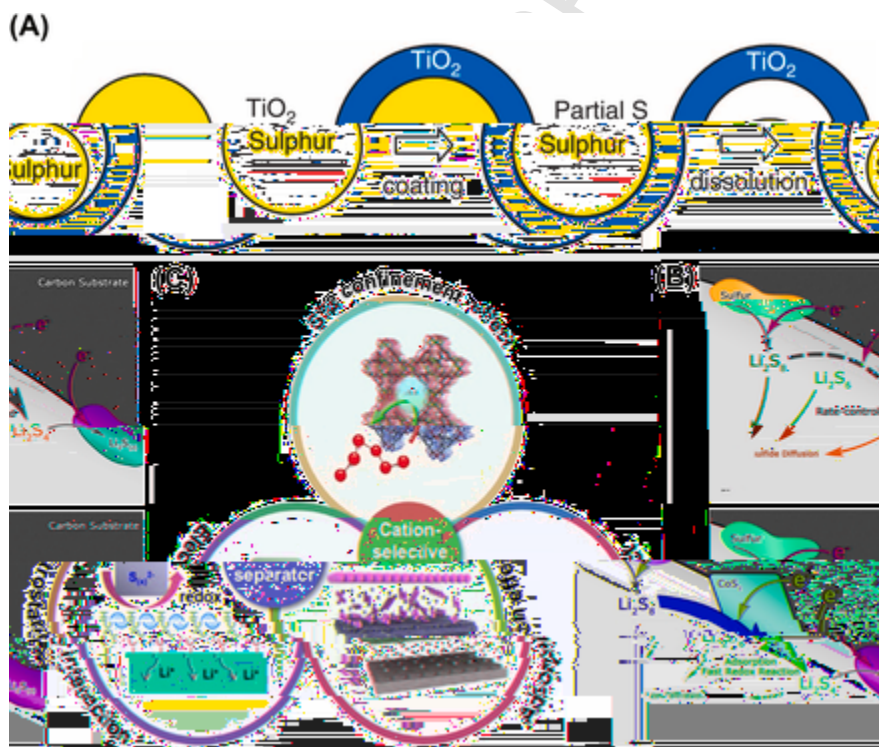


FIGURE 7.3

(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< &?-- 87J;H?;I 80 KJ?B?P?D= 97J?ED-I;B;9J?L; I;F7H7JEH H;=K87?D= ?ED?9 JH7DIFEHJ 5376.

JE 8?D: M?J> FEBOIKB<?: ;I ?D C?D?C?P?D= FEBOIKB<?: ; : ?IEBKJ?ED. .>; 87JJ;HO ;N>?8?JI
 7 >?=> 97F79?JO E< 1000 CA>/= 7D: 7 BEM <?: ; 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< &?_2-. .>;
 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 IKB<?: ;I (. ' -I) 79J 7I 7 97J>E; ; >EIJ 7: :?J?L; M?J> C;J7B ?EDI
 IKB<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 FEBOIKB<?: ;I. EH ;N7CFB; , .?-2 5386, CE-2
 5366, 7D: CE₉₋₈ 5396 M;H; 7: : ; : ?DJE &?_2-6 IEBKJ?ED JE I?CKB7J; J>; 7: IEHFJ?ED E<
 &?-- 87JJ;HO ?DJ;HC;: ?

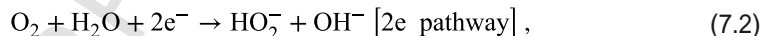
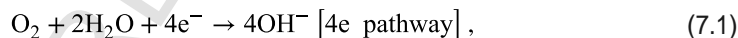
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8EJ> I?; I E< I;F7H7JEH. .E 9EDIJHK9J 7D ?ED-I;B;9J?L; I;F7H7JEH 87I;: ED J>; FEH; I?P; ;<<;9J, J>; I;F7H7JEH CE:??97J?ED C7J;H?7BI 7H; H;GK?H;: JE ;N>?8J IK8C?-9HE/D7DEFHEHEKI IJHK9JKH;I, M>?9> ?D9BK.; JME-: ?C;DI?ED7B (2D) D7DEC7J;H?7BI 7D: C;J7B-EH=7D?9 <H7C;MEHAI (') I). 1 7D= ;J 7B. <?HIJ FHEFEI;: 7 2D .?3C2.N<KD9- J?ED7B?P;: I;F7H7JEH <EH 7D9>EH?D= FEBOIKB<?;:I 5406. .>; &?-- 87J;HO M?J> .?3C2.N<KD9J?ED7B?P;: I;F7H7JEH I>EM;: 7 :?I9>7H=; 97F79?JO E< 550 CA>/= :K; JE J>; 87B7D9; E< J>; 8BE9A?D= E< FEBOIKB<?;:I 7D: ?CFHEL;C;DJ ?D ;B;9JHED 9ED:K9J?L-?JO. #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.

7.3 Nanomaterials in metal–air batteries

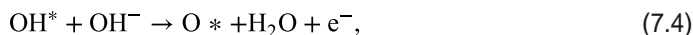
.>; C;J7B-7?H 87J;HO 97D H;7B?P; J>; ;D;H=0 9EDL;HI?ED 8;JM;:D J>; 9>; C?97B ;D-;H=0 7D: J>; ;B;9JH?9?JO 80 H;:EN H;79J?ED EF;H7J?D= ED J>; ;B;9JHE;:I. .>; F;H<EH- C7D9; E< 7II;C8B;: 87J;HO ?DLEBL?D= H7J; 78?B?JO, ;D;H=0 9EDL;HI?ED ;<<9?;D90, 7D: 909B?D= IJ78B?JO 5416, ?I ?DJ;DI;BO 9EHH;B7J;: M?J> J>; 7?H ;B;9JHE;: H;79J?ED E< M>;H; J>; ;B;9JHE97J7BOJ?9 ENO=;D H;:K9J?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;9JHEBOJ;/IEB?: 97J7BOIJ 5436. CED-IJHK9J?D= J>; 7:L7D9;: 7?H ;B;9JHE;:I H;GK?H;I J>; 97J7BOIJ JE =;J J>; 7FFB?978B; A?D;J?9 H;79J?ED. (7DEC7J;H?7BI EH D7DEIJHK9JKH;I FB70 L?J7B ;<<;9JI ?D ;:L;BEF?D= >?=>-F;H<EHC7D9; 97J7BOIJ.

.>;) , , 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:



.>;) , , 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=0 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 9EHH;: JE ;:;=H7;: 87J;HO F;H<EHC7D9;.

.>;) E , F7J>M70I 7H; CEH; 9ECFB;N. .>; ;B;C;DJ7HO II;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:



.>; 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 87J;H?;I. .>; D7DEC7J;H?7BI ?D ;NFBEH?D= J>; 8?<KD9-J?ED7B 97J7BOIJ JEM7H:) , , 7D:) E , 7H; E< =H;7J I?D?<97D9; 7D: >?L; 8;9EC; J>; C7?D 7FFHE79>;I JE ?CFHEL; J>; F;H<EHC7D9; E< C;J7B-7?H 87J;H?;I.

7.3.1 Noble metals and alloys catalysts

B7J?DKC-==HEKF C;J7BI (! ' I) >7L; 8;;D M?.;BO H;I;7H9>;: 7I J>; CEIJ 79J?L; 97J-7BOIJI <EH J>;) , , M?J> H;C7HA78B; ;B;9JHE9>;C?97B F;H-EHC7D9; 7D: >?=> IJ78?B-?JO. *J D7DEF7HJ?9B;I, 7JEC?9 9BKI;HI, 7D: I?D=B; 7JECI KD?<EHCBO :?IJH?8KJ;: ED J>; IKFFEHI M?J> 7 >?=> IKH<79; 7H;7 >7L; 8;;D KI;: 7I 7:L7D9;:) , , ;B;9JHE97J7BOIJI. *J 97J7BOIJI EMD ;N9;BB;DJ 97J7BOJ?9 79J?L?JO 7D: IJ78?B?JO. "EM;L;H; >?=> 9EIJ 7D: I97H9?JO I;H?EKIBO B?C?J J>; 7FFB?97J?EDI E< *J 97J7BOIJI. .>;H;<EH; ;NJ;DI?L; ;<<EHJI 7H; F70?D= JE ;B?C?D7J; J>; >?=> 9EIJ 80 <?D: ?D= J>; 7BJ;HD7J?L;I IK9> 7I *J 7BBEOI, DEDDE8B; C;J7BI, EH C;J7B-<H; ; 97J7BOIJI.

*J-87I;: 7BBEOI 9EC8?D= *J C;J7B M?J> 7DEJ>;H C;J7B 7H; 9ECF7H7880 79J?L; <EH) , , 7D:) E , M?J> FKH; *J. #D &?-) 2 9;BBI, J>; 7?H ;B;9JHE;: M?J> *JAK/C 97J7BOIJ ;N>?8J;: 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 , 97J7BOIJI (?= 7.4) 5496. .>; ?DJ;DI?L; IJK: ?;I >7L; FHEDEKD9;: J>7J HE9A-I7BJ-JOF; CEDEN?.;I IK9> 7I CE) 7D: (?) 9EKB: I?D?<-?97D?BO ?CFHEL;) , , /) E , 97J7BOJ?9 79J?L?J?;I 7D: F;H<EHC 9ECF7H7880 JE J>; DE8B; C;J7B 97J7BOIJI 5506. .>; H;FH;I;DJ7J?L; IF?D;B IJHK9JKH; E< CE₃) 4 7D: (?CE₂) 4 >7L; 8;;D M;BB :; CEDIJH7J;: JE I?CKBJ7D;EKIBO 97J7BOP; J>;) , , 7D:) E , :K; JE J>;?H >?=>BO ;B;9JHE97J7BOJ?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;F7H7?J?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 ;<<?9?;D90. .>; 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>; 97J7BOIJI 7D: J>; IKFFEHI. #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>; ;NFB7D: ?D= E< B7J?9; F7H7C;J;H. -?D9; J>; =EE:

7D0 7D9?BB7HO 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; 97J7B0IJI, 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; : 97J7B0IJ L7
 ?D-I?JK AH FB7IC7 JH;7JC;DJ 97D 8; KI; : 7I 8?<KD9?ED7B) E , /) , , ;B;9JHE:; . ' 7
 ;J 7B. H;FEHJ; : 7 <B;N?8B; I;B<IKFFEJ; : =-C₃ (4 97J7B0IJI M?J> F>EIF>EHKI :EF?D=
 M>?9> 97D H;L;HI?8B0 97J7BOP;) , , 7D:) E , 5566. -?C?B7HBO, C;J7B-<H; : 97J7B0IJ E<
 J>; *-:EF; : =-C₃ (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: >?=> <B;N?8?B?JO (?= . 7.5B), M7I <78H?97J; : , M>;H; *-:EF; :
 =-C₃ (4 :?H;9B0 =H;M ED J>; C * JE FHE:K9; 7 <BEM;H-B?A; FEHEKI <H7C;MEHAI (?=
 7.5C). DK7B :EF?D= E< ;B;C;DJ7HO (7D: * ;D78B; : J>; C7II 7D: 9>7H=; JH7DI<;H, J>;
 3D C * <H7C;MEHA M?J> 7 <BEM;H-B?A; D7DEIJHK9JKH; ;D?7H=; : J>; 79J?L; IKH<7Dp?H&19D:
 ;7I. .>;H;<EH; J>; *C (-C * JEM7H: 8EJ>) , , /) E , ;N>?8?J; : J>; IKF;H?EH 79J?L?JO,
 IJ78?B?JO, 7D: H;L;HI?8?B?JO EL;H ?JI FEM: ;HO 9EKDJ;HF7HJ. .>; ?DJ;=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 8EEIJ?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 9ED<?<KH7J?ED CE:KB7J?ED 80 JKD?D= J>; : ;<;9JI ?D 97H8ED 97D
 EFJ?C?P; J>; 7:IEHFJ?ED ;D;H=0 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:0
 7D: J>;EH;J?97B I?CKB7J?EDI 9EDI?IJ;DJBO <EKD: J>7J J>; 7: ?79;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?JO

IJ9 ë

J>52 R6&V&1?

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7BP

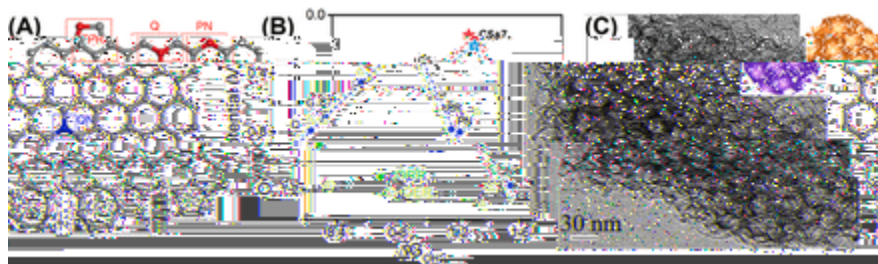


FIGURE 7.6

(A) Schematic diagram of a battery structure showing layers and components. (B) Energy-dispersive X-ray (EDX) spectrum showing peaks for various elements, with a peak at 5576 eV labeled 'C547'. (C) High-resolution transmission electron microscopy (HRTEM) image showing atomic lattice fringes with a 30 nm scale bar.

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J>; 9>7H=; :?IJH?8KJ?ED E< 7:079;DJ 97H8ED 7JECI. (?JHE=;D 7JEC ?I J>; ;NJ;DI?L;BO IJK:?: ;>;J;HE7JEC :EF7DJ. EH ;N7CFB; ; J>; EFJ?C?P;: (-:EF;: C (. I ;b;9JHE97J-7B0IJ M7I KI;: 7I 7?H-97J>E;: IKFFB0 J>; ;N9;BB;DJ FEM;H :;DI?JO E< J>; 4D-7?H 87J-J;HO 5586. .>; >?;H7H9>?97BBO FEHEKI (-:EF;: 97H8ED 97D 8; FHE:K9;: 80 FEBOC;H?P-?D= E-F>;DOB;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?JO 9ECF7H78B; M?J> *J/C. .>; C;J7B-<H; ; 97H8ED 97J7B0IJ M7I E8J7?D;: 80 7II;C88?D= J>; (-:EF;: =H7F>;D; M?J> J>; H;J7?D;: FEHEI?JO 7D: 7FFB?;: JE &?-) 2 87J;H?;I 5606. .>; H;IKBJI :;CEDIJH7J;: J>; IKF;H?EH ;B;9JHE97J7B0J?9 F;H<EHC7D9;I 9ECF7H;: M?J> J>; I?C?B7H I7CFB;I 9EDJ7?D?D= J>; . ') I EH J>; FH;9?EKI C;J7BI.

7.4 Nanomaterials in all-solid-state batteries

DEF?D= ?DEH=7D?9 D7DEF7HJ?9B;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>;O ?D9H;7I; <7IJ ?ED JH7DI<;H 9>7DD;BI D;7H J>; <?BB;H F7HJ?9B;I; (3) J>;O 97D 7BIE ?CFHEL; J>; C;9>7D?97B FHEF;H-J?; I E< FEBOC;H ;B;9JHEBOJ;I. #DEH=7D?9 <?BB;HI 97D 8; =;D;H7BBO :?L?;: ?DJE ?D;HJ C7-J;H?7BI, ?ED?9 9ED:K9JEH <?BB;HI, 7D: ;B;9JHE?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?D8O 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>;=H?9 9ED:K9J?L?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= -?)
 5616, A₂)₃ 5626, .?)₂ 5636, 4H)₂ 5646, ;J9., >7L; 8;;D M?:;BO KI;; JE 9EDIJHK9J J>;
 9ECFEL; IEB?: ;B;9JHEBOJ;I E< ?DEH=7D?9-EHJ?9 <EH IEB?:-IJ7J; B?J>?KC C;J7B 87J-
 J;H?;I, 7I I>EMD ?D ?=. 7.7A. .>; ?D;HJ 4

<BHO
 <Dy(F 3a—J7BJI
 ?JO=J7#?T@
 87J

:?17B

UNCORRECTED PROOF

J>E?B?9)ÔÉô;CÉô•

IC?7B-
 ???? ?A?6?C?4?6?0:7Bv p

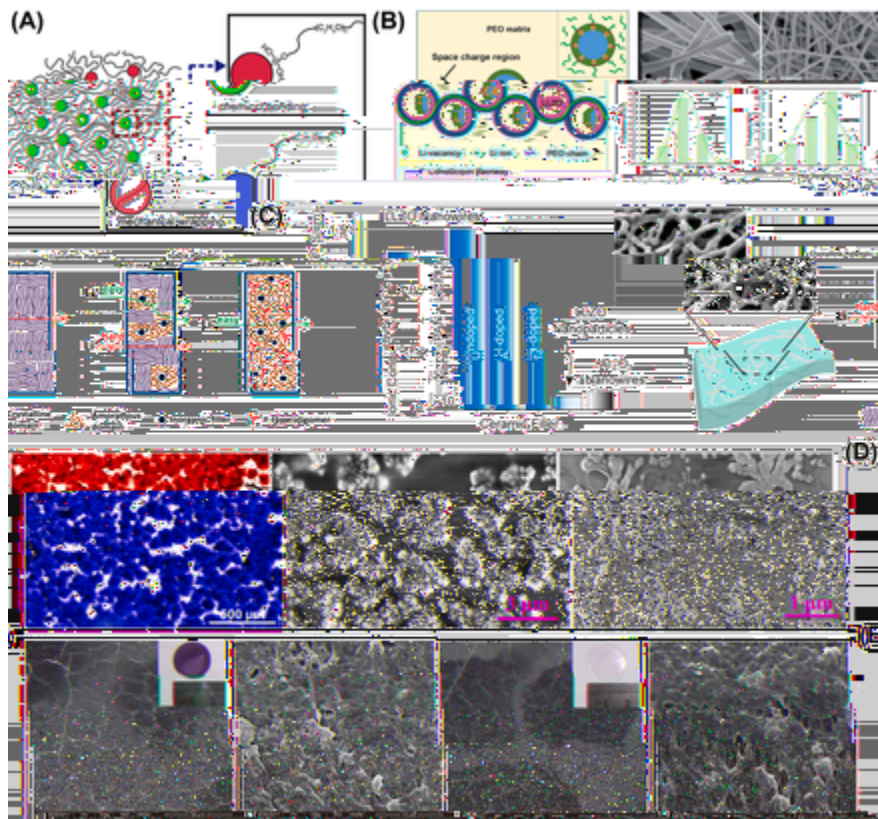


FIGURE 7.7

(A) Schematic of a porous network with a red sphere and a blue arrow. (B) Schematic of a porous network with a red sphere and a blue arrow, and a bar chart showing "Space charge region" and "PED matrix". (C) SEM images of a porous structure with a red and blue color scale. (D, E) SEM images of a porous structure with a red and blue color scale.

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A9J?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>; 9HOIJ7B 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.

4>7D= ;J 7B. :EF;: :?<<H;DJ FHEFEHJ?EDI E< &?0.33&70.57.?) 3 (&&.) ?D J>; *E) ;B;9JHEBOJ; JE ?D9H;7I; ?JI F>OI?97B FHEF;HJ?;I 7D: ?ED?9 9ED:K9J?L?JO 7D: M?J>-IJ7D: LEBJ7=; IJ78?B?JO M?D:EM. DEF?D= 7D 7FFHEFH?7J; FHEFEHJ?ED E< D7DE-9;H7C?9 <?BB;HI M?J> ?ED?9 9ED:K9J?L?JO ?D *E) 97D ?CFHEL; J>; F;H<EHC7D9; E< *E)-87I;: IEB?; ;B;9JHEBOJ; C;C8H7D; , C7A?D= ?J CEH; IJ78B; 7D: JH7DIFEHJ?D= CEH; B?J>?KC ?EDI 9ECF7H;: M?J> J>; IEB?; FEBOC;H ;B;9JHEBOJ; M?J>EKJ &&.) , J>; =EE: :?I-F;HI?ED E< &&.) F7HJ?9B;I ?D J>; *E) C7JH?N 97D =;D;H7J; &?-?ED JH7DI<;H 9>7D-D;BI D;7H J>; F7HJ?9B;I JE ;D>7D9; J>; &?-?ED JH7DIFEHJ 566,676. -?C?B7BO, M>;D 20 MJ.% &?6.75&734H1.75 .70.25) 12 (&&4.) M7I ?DJHE:K9; ? ?DJE *A (-87I;: IEB?; ;B;9-JHEBOJ; , J>; E8J7?D;: ;B;9JHEBOJ; ;N>?8?J;: J>; >?=>;H ?ED?9 9ED:K9J?L?JO, J>; M?J>-IJ7D: LEBJ7=; IJ78?B?JO M?D:EM H;79>;: 4.9 0, IK==;IJ?D= J>7J J>; :EF?D= E< &&4.) 97D ?D9H;7I; J>; &?+ C?>H7J?ED DKC8;H 7D: 909B?D= IJ78?B?JO E< J>; IEB?; ;B;9JHEBOJ; . &&4.) ?I 7BIE >;B?<KB ?D ?CFHEL?D= J>; ?DJ;H79J?ED 8;JM; ;D J>; *A (C7JH?N 7D: B?J>?KC ?EDI JE ?D9H;7I; J>; 7CEKDJ E< :?IEBL;: B?J>?KC ?EDI 5726, 7I I>EMD ?D ?=. 7.7C.

7.4.3 Nanometer electronic conductor in composite electrolytes

EB;9JHED?9 9ED:K9J?L?JO ?I=;D;H7BO C?D?C?P;: 7I 7D ;B;9JHEBOJ; I?D9; CEIJ 7J;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?;:H7880 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;9JHEBOJ; ?DJ;H?79; 9EKB: 79>?;L; =EE: ?DJ;H?79?7B 9EDI79J 7D: BED=-B7IJ?D= 87J;HO 909B;I.

4>;D= ;J 7B. 5686 ;:I?>D;: J>; ?D-I?JK =HEMJ> E< D7DE-I?P;: " <BEM;H" -B?A; 9ED-:K9J?L; FEBOJ>?EF>;D; F7HJ?9B;I 7J J>; ;B;9JHE:;-;B;9JHEBOJ; ?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?>;:DJ7BO, 7I 7D ;B;9JHED?9 D7DE<?BB;H, J>; !) I M;H; 7:;: ?DJE -EB?; *EBOC;H EB;9-JHEBOJ;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;9JHEBOJ; ?I H7?I;: JE 4.0 W 10⁻⁴ -/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=0 IJH7=; IJ7J?EDI, >?=>-;D;H=0-;:DI?JO 87J;H?;I >7L; 8; ;D 7JH79J;: CEH; 7J;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 87J;HO IOIJ;CI M?J> FEJ;DJ?7B 7FFB?97J?EDI (&?-- 87J;H?;I, C;J7B-7?H 87J;H?;I, 7D: 7BB-IEB?;:-IJ7J; 87J;H?;I).

&#BI <79; C7D0 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: &?+ :?<<KI?L?JO JE

E8J?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=0 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= DEDDE8B; 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?B?JO E< IEB?: ;B;9JHEBOJ;I, J>; 7F- FB?97J?ED E< ?D;HJ 7D: 79J?L; D7DEC7J;H?7BI ?D J>; IEB?: ;B;9JHEBOJ;I 97D ?CFHEL; J>; 9>7H=;-: ?I9>7H=;; H7J;; 7D: IJ78?B?JO F;H<EHC7D9; E< 7BB-IEB?: -IJ7J; 87JJ;H?;I.

" ;H;; M; 8H?;<BO 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;;.. ENFBEB?D= DEL;B D7DEC7J;H?7BI, ;: I?D?D= H7J?ED7B D7DEIJHK9JKH;; 7D: =;JJ?D= =EE: 9ECF7J8?B?JO M?J>; ;B;9JHE:;; C7J;H?7BI MEKB; 8; J>; FEII?8B; HEKJ;I JE 7FFB?O D7DE- C7J;H?7BI ?D 87JJ;H?;I I>EHJBO.

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;B;9JHEBOJ;I M?J> 7BB-<BKEH?D7J;: IEHL;DJI C7J9>?D= H;9>7H=;78B; >?=>-LEBJ7=; &?-C.;J7B
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9ED<EH C7B 97H8ED 9E7J?D= ED -? D7DEF7HJ?9B;I <EH ;D>7D9;; B?J>?KC IJH7=;; AC- AFFB.
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9ECFEI?J; 7I 7D 7DE:; C7J;H?7B <EH B?J>?KC-?ED 87J;H?;I, AC- AFFB. ' 7J;H. #DJ;H<79; 9
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EH=7D?9 CEDJCEH?BBED?J; C;C8H7D; ;N>?8?J?D= :;DI; IJHK9JKH; <EH B?J>?KC ?ED 87J;HO,
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C;C8H7D; CE:??;: M?J> ?IE907D7J;-=H7<J;: .?3+ :EF;: .?)₂ D7DEM?H;I <EH B?J>?KC
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C7J;H?7B I;B;9?ED, :;I?D, 7D: 7FFB?97J?ED

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