

6XOSKXU GRSLQJ RI QLFNHO IHUULWH QDQR ZDWHU R[LGDWLRQ

+DIXQ/ LX %aQ' RQJ

&ROOHJH RI &KHPLV(QUL D QIGW&HHP&M&B&B&U&R I +HDY\ 2 L O Q B U R G F H M H U L Q L W & R W 3 H W U
&KLQD 4LQJGDR &KLQD

\$EVWUDQFQXVWULDO ZDTXHLU HHO KE JVKLOR ODH F W K M U H H D Q Q V G E H P S U H L Q J R (\ J H Q H Y
UHDFWLRQ 2(5 F D W D O \ V W V W X F E X D V C E D F U J H Q R S H G H D Q L Q M \ D W O R Z R Y H U S
DYDLODEOH 2(5 F D W D O \ V W V V W L O O Z H H P H S L R U W D D J W D F L Q H F K D D G G O F R Q Y H Q W
WR JURZ YHUWLF B B G L I Q R Q R E H F N D O O W F U R Q W H Q F D D F R V K H L) H 2 ,) D V O
FXUUHQW GHQVLTWKH2Y5H B W W D D O V W D O U D Q V F D D Q R I V K H U H M U J H H O H F W U R F
DUHD DQG WKH VSDFLQJ EHWZHHQ E D E R W U R D \ W H D D F E H O V R Z V R R W K H I E
LQWURGXFWRQ RI 6 HQKDQFHG W B W H D G D R G S R S W Q P D Q H G G W K N R F G D R M L S
LQWHUPHGLDWHV \$ V D U H V X O W G F W M H Y 2 W ,) Z L M K E D L W R W X S S R W R I Q W L D O
P9 WR DFKLHYH D Q G H V S H P S W L P I H O R E D Q V G W D S E O D L W U L Q D O N D O L Q H P H
WKH V \ Q W K H V L V V M W D W F D Q G E H Y D S P R E S H Q G U M D R V L W K L R Q P H W D O R [L G H V Z L
VXSSRUWHG HDUWKV D I R X Q G G Q D Q Q D H E M H D Q H F D Q H B F D W H O D W H G U H D F W L R Q V

.H\ZRUGM FNHO IHUULWH D Q R O V K I X H W G R S L Q J : D W H U R [L G D W L

, QWURGXFWRQ

VXSSRUWHG QDQRDUUD\V FDQ RIIHU

VXUIDFH DUHD DQG WKH VSDFLQJ E
2(\JHQ HYROXWLRQ UHDFWLRQ 2(5 O Q R Z W R H N H H F W R L D H P L O H F W K H R O \ W H
H I I L F L H Q F \ R I Z D W H U H O H F W U R O D R I U H F Y X H U W L R Q L W W X V O R E Z Z W I K Q R I W W R H Q
SURFHVV DQG WKH GHYHORSPHQWX B V W U D M L H Q W O H O Z H F W R U R F D V S D Q \ F W D
LV UHJDUGHG DV DQ H I I H F W L Y H F X Z D A H Q W R R Y O H F F R R H U W D Q G W K H D F W
ERWWOHQHFN > @ &XUUHQWO\ V G K I O D P I L Q H D W E R K R W W S R I W D F W R L Y H K I P D K W H
H I I L F L H Q F \ H O H F W U R O \ W L F Z D W H U Q V S M D H G V W V W R F K M H R R U W W H U Q R E O Z H
PHWDOV DQG WUDQVLWLRQ PHWDQ Q F R I P S R I X Q Q V V X O H F U L R Q V F R U S R D O W H
2(5 F D W D O \ V W V 5 X F K I W D F V , D Z H F D W W D H Q E X O D W J U R Z Q) R Q L D K G U R W K H
FRQVLGHUHG DV WKH EHVW P D W H H D F W L R Q R U S V 2 (5 F D W H D O W D W Q G L Q J H
+RZHYHU WKH\ DUH H [S H Q V L Y H V H R O U F I H W L V Q U H P R U N D F H O H F D Q D Q R W L F D
DYDLODEOH IRUG X D W U H D O F D O S S O L Z D W M I U R R [L G D W L R Q L Q D O N D O L Q H P H G
7KHUHIRUH LW LV L P S R U W D Q W W Y B W K H S O R F U H D S S R I Q D F K L S U R S X O H G D Q
DFWLYLW\ QRQ SUHFLRXV PHWDOH F D M O C H G W D W D R J H O P S U B O H D S S R D F K I
H I I L F L H Q F \ > @ P H W D O R [L G H V I R U Y D U L R X V D S S
, Q U H F H Q W \ H D U V W U D Q V L W L R Q P X S H D F R S D G H W R U 2 V P H W X D O K D L U E D W V
VSLQHO SHURYVNLWH DQG K \ G U R [L G H K D Y H H P H U J H G D V
SURPLVLQJ 2(5 F D W D O \ V W V G X H W R W K H L U U L F K L O W U L Q V L F U H G R I
SDLUV DEXQGDQW UHVHUYHV DQG (O R Z F R V W > @ + R Z H Y H U
702V K D Y H L Q K H U H Q W O R Z H O H F W U L F D O F R Q G X F V
OLPLWHG DFWLYH VLWHV WKDW VWLQO Q H I I G D W R E H H S G G U M L R H G W R I X U
ERRVW WKH F D W D O \ W L F D F W L Y L W & K A P U F B O V P H Y K R G V P X F K D V I P H L G
LQWHU VXUIDFH GHVLJQ > @ F R X S Q L F K D Z H Y K I F R P E R Q R K D W H M L D Q V Q J
> @ D Q G G R S L Q J Z L W K K H W H U R D W L R M O > @ K O R Y H G H H Q + Z V K H Q W R X U H D
LPSURYH WKH 2(5 H O B F W U R F D D Q D R I 6 7 0 2 V G G S R W D V L X P K I G U R [L G H
\$ P R Q J W K H V H P H W K R G V K H W H U R D W L R K D F R S L Q J R P V 6 E R R S K S U P H G
W R E H W K H P H W K R G W R S R I R Y H V W K H J
H O H F W U R F D W D O \ W L F S H U I R U P D Q F H R I 7 0 2 V , Q D G G L W L R Q V H O I

6KDQJKDL &KLQD 'HLRQLJHG ', ZDWHUX QDWVX DHOGLQ VPOVVLRQ
H[SHULPHQVV

3UHSDUDWLRQ, RI 7KH HLXVROXWLRQ ZC
E\ GLVVROYLQJ PPRORR 1L&ORI

0 &+16 DTXHRXV VROXWLRQ WKHQ
PLQ WR IRUP D KRPRJHQHRXV VROX

WUDQVIHUHG LQWR D P/ 7HIO
DXWRFODYH ZLWK D SLHFH RI ,)

PDLQWDLQHG DW f & IRU K LC
DXWRFODYH FRRHG VORZO\ WR UR\

ZDV WDNHQ RXW DQG ZDVKHG ZLWK
WKRURJKO\ IROORZHG E\ YDFXP GU\LQJ

3UHSDUDWLRQ) R)RIL)FRPSDOL)RQ 1L)H
ZDV DOVR SUHSDUHG E\ KIGURWKHUPDO

1L)H ,) ZDV V\QWKHVLJHG XVLQJ
6 1L)H,) H\FHSW IRU WKH UGXURJHQ

WKH K\GURWKHUPDO WUHDWPHQW DV WKH
DQG D KLJK FRQRXUFRSLRQ WJLFKH VW

3K\VLFDQ &KDUDFWHULJDWLRQ 1L)H ,)
7KH FUIVWDOOLQH VWUXFWXUHV RI WKH

E\ SRZGHU ; UD\ GLIUDFWLRQ ; 5 E\ X
GLIUDFWRPHWHU ZLWK &X .. UDGLWLRQ

7KH VWUXFWXUHV DQG PRUSKRORJLV
VFDQQLQJ HOHFWURORPKELRVFRSHQG

UHVROXWLRQ WUDQVLEWLRQFRSHQHFV
* N9 7KH FRUUHVSRRGLQJ 1L)H ,) 36

VSHFWURVFRS\ ('6 PDSSLQJ DQD
UHSUHVHQWDWLYH DUHDV ; UD\ SRWR

;36 ZHUH FDUUHG FRORQWHP
WHPSHUDWXUH QR DGGLWLRQDO SH

(OHFWURFKHPLFDO PHDVXUHPHQW E
2(5 WHVWV ZHUH FRQGXFWHG 60 DP

FRQILJXUDWLRQ ZLWK DQ HOHFWURV
*DPU\ 5HIHUFHQW DQWWRPHW HPSHU

7KH REWDLQHG VDPSOH SODWLQXP)
0 .2+ HOHFWURGHWKHUZRIGNDQJ

FRXQWHU HOHFWURGH DQG UHIHURQ
\$OO RI WKH HOHFWURGHV DHPWV FRQ

LQ 0 .2+ VROXWLRQ IRU 2(5 7KH
ZHUH FRQYHUWHG WR WKH SRWHQWL

K\GURJHQ HOHFWURGH 5+(DFREU
HTXDWRQ +J +J2 i S+ 1L)H QH

VZHHS YROWDPPHWU\ /69 PHDVXUH
ZLWK D VFDQ UDWRVWVZMUKHVS

ZHUH REWDLQHG IURP WKH FRUROR
DFFRUGLQJ WR WKH EDORR HZKDWL

LV WKH RYHUSRWKHQWXDOHQVWGHQ

7DIHO VORSH 7KH HOHFWURFKHPL

FDWDO\VV LV HVWLPDWHG IURP HQ

FDSDFLWDQFH &GO ZKLFK LV FR

GRXEOH OD\HU FKDUJLQJ IURP WKH

LQ QRQ)DUDGLF SRWHQWLDO UDF

WKHQ ILW WR OLQHDU UHJUHVS

(OHFWURFKHPLFDO WLPVFRSDFH &

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RI FDWDO\VVV ZDV REWDLQHG

FKURQRSRWHQWLRPHWU\ FXUYH

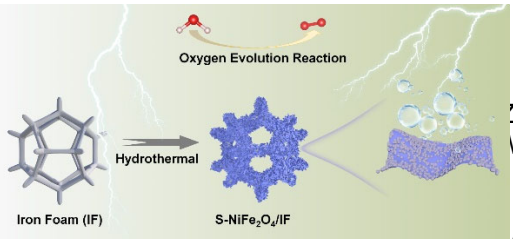


Figure 1: S-NiFe₂O₄/IF

ZDV WDNHQ RXW DQG ZDVKHG ZLWK
WKRURJKO\ IROORZHG E\ YDFXP GU\LQJ

3UHSDUDWLRQ) R)RIL)FRPSDOL)RQ 1L)H
ZDV DOVR SUHSDUHG E\ KIGURWKHUPDO

1L)H ,) ZDV V\QWKHVLJHG XVLQJ
6 1L)H,) H\FHSW IRU WKH UGXURJHQ

WKH K\GURWKHUPDO WUHDWPHQW DV WKH
DQG D KLJK FRQRXUFRSLRQ WJLFKH VW

3K\VLFDQ &KDUDFWHULJDWLRQ 1L)H ,)
7KH FUIVWDOOLQH VWUXFWXUHV RI WKH

E\ SRZGHU ; UD\ GLIUDFWLRQ ; 5 E\ X
GLIUDFWRPHWHU ZLWK &X .. UDGLWLRQ

7KH VWUXFWXUHV DQG PRUSKRORJLV
VFDQQLQJ HOHFWURORPKELRVFRSHQG

UHVROXWLRQ WUDQVLEWLRQFRSHQHFV
* N9 7KH FRUUHVSRRGLQJ 1L)H ,) 36

VSHFWURVFRS\ ('6 PDSSLQJ DQD
UHSUHVHQWDWLYH DUHDV ; UD\ SRWR

;36 ZHUH FDUUHG FRORQWHP
WHPSHUDWXUH QR DGGLWLRQDO SH

(OHFWURFKHPLFDO PHDVXUHPHQW E
2(5 WHVWV ZHUH FRQGXFWHG 60 DP

FRQILJXUDWLRQ ZLWK DQ HOHFWURV
*DPU\ 5HIHUFHQW DQWWRPHW HPSHU

7KH REWDLQHG VDPSOH SODWLQXP)
0 .2+ HOHFWURGHWKHUZRIGNDQJ

FRXQWHU HOHFWURGH DQG UHIHURQ
\$OO RI WKH HOHFWURGHV DHPWV FRQ

LQ 0 .2+ VROXWLRQ IRU 2(5 7KH
ZHUH FRQYHUWHG WR WKH SRWHQWL

K\GURJHQ HOHFWURGH 5+(DFREU
HTXDWRQ +J +J2 i S+ 1L)H QH

VZHHS YROWDPPHWU\ /69 PHDVXUH
ZLWK D VFDQ UDWRVWVZMUKHVS

ZHUH REWDLQHG IURP WKH FRUROR
DFFRUGLQJ WR WKH EDORR HZKDWL

LV WKH RYHUSRWKHQWXDOHQVWGHQ

7DIHO VORSH 7KH HOHFWURFKHPL

FDWDO\VV LV HVWLPDWHG IURP HQ

FDSDFLWDQFH &GO ZKLFK LV FR

GRXEOH OD\HU FKDUJLQJ IURP WKH

LQ QRQ)DUDGLF SRWHQWLDO UDF

WKHQ ILW WR OLQHDU UHJUHVS

(OHFWURFKHPLFDO WLPVFRSDFH &

LQ WKH IUHTXHQFWRURP +) 7KH

RI FDWDO\VVV ZDV REWDLQHG

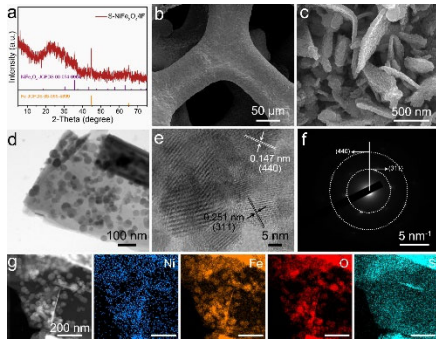


Figure 2: D ; 5' SDWWH2Q, RI 6 1L 0 LPDJH RI 6
,) F 6(0 LPDJH2R,) 6 GL 7(0 LPDJH RI 6
1L) 8 ,) H +57(0 LPDJH 2 R) 6 11 6) \$ ('
LPDJH RI 2 ; 1L) H +\$\$') 67(0 ('6 PDSSLQJ RI
6 1L) 2H,)

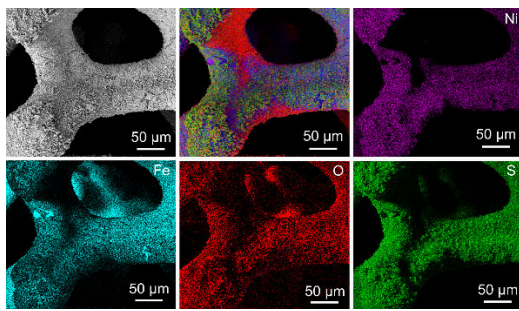


Figure 3: 7 KH 6(0 SSSLQJ 6 1L,) H

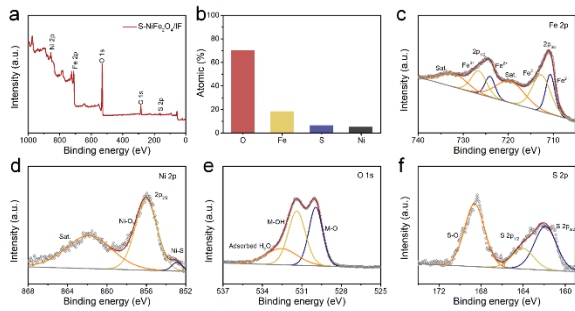


Figure 4: D ; 36 VXUYH2 R,) 6 EL 7KH FRQWHQW RI
2)H 6 DQG 1L HOHPHQWV 2 ; 36 LQSHFF RWDQ RI
)H S UHJLRQ G HL 2S WUHLRQ DQG E RYHUSRWHQW DQG XQGH
UHJLRQ

ORFDWHG DW DQG H9KZDV EH
RWKHU SHDNV DW DQG H9
VDWHOOLWH SHDN)RWWKHLU)FRUH WK
RI WKH 1LSHFWUXP FDQ EH GHFRQYR
SHDNV ZKHUH WKH ERQGLQJ HGHUJL
H9 DWWULEXWHG WR WKH FKDUU
VSHFLHV DQG VKDNH XS VDWHOOL
UHVSHFWLYHO\ \$ V VKRZQ LQ)LJXUH
IXUWKHU ILWWHG ZLWK IRXU GRXEOH
H9 0 2+ DW H9 DQG DWGVRUEH
UHVSHFWLYHO\ \$ FOHDU FKHPLVUE
VKRZLQJ WKH H[FHOHQW DGVRUSW
FDWDO\ VW IRU R\JHQ FRQWDLQLQJ L
VKRZV 6 S KLJK UHVROXWLRKWSHFV
SHDNV DW WKH ELQGLQJ HGHUJL RI
6 1L) 2HLV RZLQJ WRDQGH6 S VSHFWLYH
7KH RWKHU SHDNV RI 6 S DW WKH
a H9 DUH UHFRJQL]HG DV WKH R
2 \$OO WKH DERYH UHVXOWV GHPR
LQWURGXFWRQ RI 6 DW RWDQRIQ
VXUIDFH RI WKH ,)

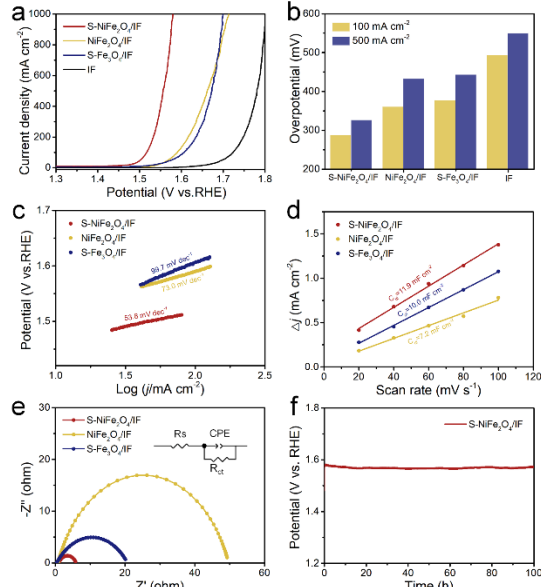


Figure 5: 215 HOHFWURFKHPLFDO S VSHFWLYH
RWKHU FRQWUDWZ VDPSORWDL]DWLRQ
E RYHUSRWHQW DQG XQGH
G WKH GRFXOWDQV DQG UHV
HOHFWURFKHPLFDO DV 6 XLVW SORW I
& KURDDPSHUPHWL) FXIURH RIK 6 1L) H
7R GHWHUPLQH WKH DVVDFWFK HDQ
VWUXFWXUH DQ ; UD\ SKRWRHOHFWRQ VSHFWURVFRS\ ; 36
VXUYH\ ZDV UHFRUGHG 7KH UHVXOWV RYHUORQWL]HG
VSHFWUD IURP WKH)H S 1L S 2DW DQG WIRU 2 RYH ZDV UHFRQGXVHG R
UHJLRQV DUH FROOHFWHG LQ HOHFWRURGH \$FRWWRQV QGHU WONDOLQ
VSHFWUD RI 6 1L) H 6 2 HOHPHQWV DKH SURJHGH OHFWURGH UHTXLUH
LQ 6 1L) H)LJXUH D DJUHLQJR ZHU SRWKORWLDQ WR UHDFK P \$
PDSSLQJ UHVXOWV 7KH FRQWHQW RI 2 HGH 6 DQG 1L RWKHU DV
SUHSDUH 6) 6 HWHUPLQH E\ ; 36 UHODWHG WR HOHFWURFKHPLFDO NLQ
ZHUH DQG UHVSHFWLYHO\ ZDHO SORW WKH IDVWHU WH
WKH)H S KLJK UHVROXWLRQ ; 36 VSHFWUXP RI 6 1L) H DQG 26 ZHUH
)LJXUH F WZR VSLQ RUELW GRXEOHV VDW ELQGLQJ HGHUJL) GH
FD DQG H9 FDQ EH DWVSHFWLYHO\ WLGGLDWHLQJ S WKH ID
DQG)H UHVSHFWLYHO\ 2QH GRXEOHV RI HOHFWRURGH: H) LXXUWKH HYDO
DQG H9 ZDV EHODQGHQ WKH RQ
WKH (& \$ RI DV SUHSDUH FDWDO\ V

LQWULQVLF VXUIDFH DUHD DFWLYLW\ ZKLFK LKSHORSRUWLRQDVO DCR WIK
 &G 6 1L2H) SRVVHWD XH RI' PGRFFW HQJLQHHULQJ WR SURPRV
 ZKLFK LV ODUJHU 2WKDQ WRDWRGU 1UHFDFWLRQ \$GYDQFHG)XQFWLRQD
 6)H P) FP)LJXUH G 7KLV VKRZV WKDW WKH
 VXOILGDWLRQ SURFHVV FDQ LQFUHDVH WKH (&\$ /XDOXH DGR HW
 VXOILGDWLRQ SURFHVV LKSHORSRUWLRQDVO DCR WIKHQHULQJ HQJLQHHULQJ
 QXPEHU RI H[SRVHG DFWLYH VLWV SURGXFWLRQ DFRPWRQDOLQH
 RYHUSRWHQWLDO RI 9 +J +J2 ZDWHUWKH DSSOLHG SWR DQFHG)X
 SUREH WKH HOHFWRUGH NLQHWFV XQGHU WKH 2(5 SURFHVV \$V
 VKRZQ LQ)LJXUH H WKH 1\TXLWV SORW LQ WKH KLJK HW D
 IUHTXHQF\ UDGJH SUHVHQW VWDQGDUGV YHPFLUFOHV &ZKHQ HW D
 GLDPHWHUV DUHGHKWHUFLUHQH GEMU RYHURVWUXUH ILOP VWLWFKH
 5w 7KRI56 1L)H LV DERXW ZKLFK YX
 PXFK VPDOOHU WKDQ WKRVH RIQL) HOHFWRUGH IRU RYHUDOO ZDWHU
 6)H ~)LJXUH H VXJJHVW EDWHULHV \$GYDQFHG ODWHULDO
 FKDUJH WUDQVIHU ZDWHUWKH 6215)H / X % OF(OKHQQ) HW DO
 HOHFWRFKHPLFDO VWDELWLW\ LV DQRWKHU ULWLFDO DFRPWRQDOLQH
 HYDOXDWLQJ FDWVWV)SHUIRWR RYHURVWUXUH ILOP VWLWFKH
 ORQJ WHUP 2(5 SURFHVV VWDELWLW\ EDWHULHV LQ DUULHG ZDWHU IRU SOL
 K DW D ILHG FXUUHQW GHQXW RYHURVWUXUH LQ HW DO 6LHQFH YRO
 I DQG WKHUH ZDV QR HYLGHQW RYHURVWUXUH LQ HW DO 6LHQFH YRO
 FRQFOXVLRQ2 WKH DWHU KDV H[FOHQRW < =KHQJ HW DO 6H
 VWDELWLW\ LQ 0.2+ DEXQGDQW QDQRDUUD\ DV HIIL
 HOHFWRFDWDO\VV IRU HQHUJ\ U
 &DWDO\VLV YRO i

&RQFOXVLRQ

7 0D 6 'DL 6 4LDR 6HOI
 ,Q FRQFOXVLRQLD DFRPWRQDOLQH HOHFWRFDWDO\VV IRU DGYDQF
 DQG VXFHVVIXOO\ GHPRQVWUDWHG SURFHVVHG ODWHULDOV 7RGD\
 1L)H) YLD KIGURWKHUPDO PHWKRQ %HQHFWLWLRQJ IURP HW DO 5DV
 WKH UDWLRQDOO\ GHVLJQH ' KLK RYHURVWUXUH LQ HW DO 6LHQFH YRO
 RSWLPLJHG FRPSRVLWLRQ ZLWK JRRGHUHQHFWLWLRQDOLQH HOHFWR
 WKH DV V\QWKZV\ KDV 6GHLRQVWUDWHG RYHURVWUXUH LQ HW DO 6LHQFH YRO
 RYHUSRWHQWLDO RI DFRPWRQDOLQH DSHOP ±
 VORSH RI DQRQJ WHUP VWDELWLW\ RYHURVWUXUH / /L HW DO 6XOSK
 K LQ DONDOLQH 2(5 SURFHVV 7KH RYHURVWUXUH LQ HW DO 6LHQFH YRO
 FDWDO\VV PDWHULDOV LQ SURSHU VWLWLRQ RYHURVWUXUH LQ HW DO 6LHQFH YRO
 SURGXFWLRQ HQDEOH LWV SRWHQW ZLWK DSSOLHVWLRQDOLQH HOHFWR
 ZDWHU VSOLWLRQJ (QJLQHHULQJ -RXUQDO YRO
 - &KL ; =HQJ ; 6KDQJ (PEHGGLO
 FR GRSHG FDUERQ QDQRVKHOOV
 SKRVSKRUL]DWLRQ DQG SIURO\VLV

\$FNQRZOHGJHPHQWV

7KLV ZRUN LV ILQDQLDOO\ VXSSRUWHG E\ RYHURVWUXUH LQ HW DO 6LHQFH YRO
 6FLHQFH)RXQGDWLRQ RI &KLQD DQG

5HIHUUHQFHV

- < 6XQ - :X < ;LH HW DO '\QDPLFV RI ERWK DFWLYH SKDVH DQG FDWDO\VLV SDWKZD\ IRU VSLQHO ZDWHU R[LGWLRQ FDWDO\VV \$GYDQFHG)XQFWLRQDOLQH ODWHULDOV YRO
- & .RX - =KRX + :DQJ HW DO %RURQ SUHWUHDWPHQW SURPRWHV SKRVSKRUL]DWLRQ RI)H1L FDWDO\VV IRU R[\JHQ HYROXWLRQ \$SSOLHG &DWDO\VLV % (QYLURQPHQWDO YRO
- < <DQ . +XDQJ - /LQ HW DO &KDUJH UHGLVWULEXWLRQ LQ)H22+ QDQRDUUD\ E\ HFRORJLFDQ R[\JHQ UHGXFWRQ GHSRVLWLRQ IRU ERRVWLQJ HOHFWRFDWDO\WLF ZDWHU R[LGWLRQ \$SSOLHG &DWDO\VLV % (QYLURQPHQWDO YRO