



!"#\$%&'(\$)\*!+,!-\$((+.'\$!/!"#\$%&'(\$)\*!+,!)0&!1&()&'#!234!&

!

50&!"- /"12!6\$#738&!9'+8'3:;! ;&4+')!

<\$(\$)+!2+=.:>\$3?!@.=\*BA!AC!DEFG

!

"#\$%&%#'( )\*!+,-'&!.##/\$!01#\*2#!

!

!

034(\*5&6-\*78#2(!

H%&'%\$&!

!F!(Y4\*(6#X6->3'(!%(>&?#1\$%!%((4(6?\*'#&'3%!(-'1(!!\$&5(\*6&,'!-!;&66-3\*&!0-3'1!@:\*&=
G%3=#&B&\$Z#?1?-\*#2![;0@G9\#\$%!'1(!I\$&5(\*6&,'!-!:'1(J(6(\*\$!'#4(!:-!\*6344-\*&\$?
2,!\*(6(#\*=1!5&6&'!-'!I\$&5(\*6&,'!-;&66-3\*&C!>32X&#SF!:((>!(Y\*(2(>,!1-\$-3\*(%!#\$%
#44\*(=&#&5(!-'!1#5(!X((\$!6(>=('(%!:-!\*'1&6!#A#\*%S#D#\*6!A&>>X(!#\$!&24-\*#'\$!&24('36
2(!-'!=\$&\$3(!2,!\*(6(#\*=1!&\$!W\*(\$!8#\$-'(=1\$->-?;!#\$%!'#\$=(!)\*#2(\$!S!

D1(!4\*&2#\*,!43\*4-6(!:'1&6!'\*&4!A#6!'!-A-\*Z!A&'1!-3\$\*\*(\$!=->>#X-\*#-\*C!9\*+5!(6!H#''&
])&\*('-\*C!W\*(\$!8#\$-'(=1\$->-?;!('\$\* \C!'-2#&\$#&\$%6\*(\$?'1(\$!long-term!=->>#X-\*#&E
\*(6(#\*=1!X('A((\$!)0DE;&\$'(Z Nanotechnology Innovation Centre (NIC)!)(4#\*2(\$!-!:

<&-'(=1\$->-?;C!IJ"!#\$%!'F\$6'&'3'(!-!W\*(\$!8#\$-'(=1\$->-?;!#\$%!'#\$=(!8#\$-'(=1\$->-?,
9>#:'-2!])(4#\*2(\$!-!:#%&->-?;C!;\S! !9\*-'!H#''&!#\$%!'1&6!('#2!#!3\$&5(\*6&,'!-!;&66-3\*&!

4(\*-\*2%!&\$-5#&5(!#\$%!'4&-\$((\*&\$?)\*(6(#\*=1!-\$!'1(!?\*((\$!6,\$'1(6&6!-!?!?->%!\$\$-4#\*!
D1(!2#&\$!-X/(='&5(!-'!1&6!\*(6(#\*=1!5&6&'!A#6!'!?'!)\*#&\$&\$?!&\$?!\*(\$!6,\$'1(6&6!-!#\$-\$-

@!=->>#X-\*#&5(!\*(6(#\*=1!?\*#'\$!4\*-4-6#>[;NIJ"!#6!63X2&'(%!'!-!)(4#\*2(\$!-!0=&(\$=(!
#\$%!'D(=1\$->-?;)S'&\$?!'1&6!\*(6(#\*=1!5&6&'C!(Y4(\*&2(\$#-A#6!Z&6=366(%!A&-'!H#''&7!

\*(6(#\*=1!('#2C!A1&=1!A&>>1(>4!36!'!\*(1&4!>#\$\$&\$?!:-\*(Y(=3'&\$?!'1(!4\*-'(=>S&\$?!2,!
6#,'!-!:-3\*A((Z6!&\$!LKM]C!F!5&6&'(%!9\*-'(-2&=6!'>?;!=\*(!>#X6C!4#\*#&=&4#&2#!

=->>#X-\*#&5(!A-\*Z61-4!#\$%!'(\$%(%!#!6=&(\$&.&=12('&\$@9%&&-\$#>>C!2,!5&6&'!8
4\*(6(\$#&-\$6!#\$%!'%&6=366&-\$6!\*(>#(%!'!-'1(\*!6=&(\$&.&=143638!69#\*%!1#6!4\*-5&%
2(!23=1!\$((%(%!2-'&5#&-\$!#\$%!'=#\*((!%!(5(>-42(\$!'1\*-3?1!4\*-5&%&\$?Z!-44-\*3&&'&(6!

A&'1!(Y4(\*6!&\$!'14#\*#>>)(6(#\*=1!:&(>75!#6!(Y\*(2(>,%(>&?1'(%61-A=#6(!-3!\*'(6(#\*=1!
4\*-4-6#>!-'!63=1!#\$!(\$?#?&\$?!?\*'-34!-!4(-4>(S!F!#>6!=-\$\$=(%!A&'1!-'1(\*'(6(#\*=1'6!

6#2(!:&(>%C!&=1!A&>>!-N(C! :3'3'(!=->>#X-\*#&-\$! -44-\*3\$&'&(6&\$?! #! 4#\*! -! ;!!
=-223\$&,'!1#6!X((\$!-\$!-'!1(!X(6!(Y4(\*&(\$=(6!-!2!>&:(S!F!#5(!?#&\$(%!#!>&:(!(\$1#=\$
(Y4(\*&(\$=(!1#!A&>>:-\*(5\*!(\$&=1!2,!4(\*6-\$#>!#\$%!'#=#%(2&=!%!(5(>!42(\$!S





S&8:&#)T?!5&())\$#8!+,!PQ/B.O9(!+#!%3'\$+.(!0.:3#!K3#K&!K&==!=\$#&(R!!  
V3\*! 2#&\$! #&2! &\$! '1&6! 6(?2(\$! A#6(5#>3#'( &\$! 5&'\*≠, '-Y&=&!,! -:! U<N@3896! -\$! 5#\*&  
=#\$=(!=>!)>&\$ (6S  
-&)0+N+=+8\*!  
2&==!=\$#&(13#N!K.=).'&!K+#N\$)\$+#!  
D1(!=>6![9"QC!9@8"QC!;F@!9@"@NM!A(\*(!=3>'3\*(%!#\$\$%!2#&\$#&64%&\$!2(%&#  
6344>(2(\$'(!A&'1!MKg!:(#>!X-5&\$(!6(\*32!#\$\$%!#\$\$&X&-'&=6![Lg!4(\$&=&>&\$h6'\*(4'-2,;  
2>iM\!S! D1(! =(>6! A(\*(! 2#&\$#&\$(%! &\$! #! 2-\$->#,( \*! =3>'3\*(!)"#B\$%)(\*! #! 132&%&:8  
#'2-641(\*(! -:! Pg! "V \_L!S! D1(! =(>6! A(\*(! 6X>'3\*(%! X,! '\*,46&\$&T#&-\$! [KSKLPg! '\*,46  
KSKKLPg! G)D@\$\$%! 2#&\$#&\$(%! &\$! #! 3>'3\*(! >#X-\*#'-,\*! #! '1(! W\*((!\$ 8#-\$!(=1\$->-?!,!  
"(\$'(\*C!;!S!"(>>!)\$32X(\*!#\$\$%!5&#X&>&!,!A(\*(!2-\$&'-(%!X,!6#\$\$#\*%!'\*,4#X>3(!%,(!Y:  
4\*-(%3\*(6\$!  
!  
2&==!)&3):&#)!3#N!K\*)+)+W\$(\$)\*!Z-55!3((3\*[ ^!!  
U<N@3896! A(\*(! (5#>3#'(%! ≠, '-Y&=&!,! #?#&\$S!QC! 9@8!@\$\$%! ;F@! 9@N@S!>6! A(\*(!  
6((%(%!&\$!

;&(.=)!

)&::(\*(\$!=#\$=(\*!=(>>!>&\$'Q!9\*-6'#(!=#\$=(\*C!9@8"Q!#\$\$%;F@!9@[96\$M(#&=#\$=(\*!  
=>>!>&\$'6(!36(%!'-(5#>3#('!1(!#\$&=#\$=(\*#=#&5&,'-!U<N@3896bC!b!#\$\$%!]L!1-3\*\$  
;DD!=(>>!4\*->&:(\*#&-\$!(66#,!1#6!X((\$!36(%!:-\*'1(!5#>3#&-\$!-!:=,'-Y&=&,'S!  
\_\*-2!1(!%#'#C&!'&6!\*(5(#>(%!'1#!U<N@3896!\$-!61-A!#\$,!4\*-:-3\$%!2-\*41->-?&=#>!=1#&  
&\$F@N9@"@NM!=(>>!>&\$'6C!(5(\$!#\*6!L(#'2(\$S! 8- !=,'-Y&=&,'!A#6!-X6(\*5(%!&\$!;N  
9@"@NM!=(>>!!#&\$'6! -! ;F@N9@"@NM!=(>>6! A(\*! 6'&>>! 5&#X>! #! 1&?1(6! =-\$  
J1(\*#6C!#X-3!PKg!-!9@8"Q!=(>>6!A(5&#X>#!( \*!b!1\*6S!D1&6!5&#X&>&,'!\*(2#&\$(%!=  
(5(\$!#:'!#\$!(Y'(\$%(%!4(\*&-%L! 1-3\*6!-!:'\*#2(\$! -!U<N@3896&?!M!#\$\$%L1&6!(!&\$!9"  
=>>6C! ?\*-A'1! &\$1&X&&-\$! A#6! &\$! bPg!=(>>6! #:('! ]L! 1-3\*6! -! '!(#2(\$!@!! 6&?\$&:&:  
%=(#6(!&\$!=(>>!5&#X&>&,'-!9@8"Q!#\$\$%!9"Q!=(>>6!#6!=-24#\*(%!'!=-\$\*->!=(>>6!A#6

!

!

!

!

\#%&()\$83)\$+#!+&M&!'&8.=3)\$+#!  
V\$=(! '1(! =,'-Y&=&,'! -! U<N@3896#6! (6#X>&61(%C! '1(! \$(Y! 6'(4! A#6! '-! (Y4>-\*(!  
2=(1#\$\$&62! X(1&\$%! U<N@3896! &\$%3=(%! =,'-Y&=&,'! 36&\$4\*(6&-\$! #\$\$#>,6&6\$6!  
4\*(5&-36>!,61-A\$!-!X(!&\$5->5(%!&\$!2#?&:(\*&\$! =,'-Y&=&,'!A#66(>=(%!'!-!'1&6!6'3%,S!

!

@6! #! :&\*6! 6'(4! -:! ?(\$! (Y4\*(66&-\$! #\$\$>,6&6C! 4\*&2(\*6! 1#5(! X((\$! %(6&?\$(\$! '-! &\$5(!  
(Y4\*(66&-\$! >(5(>6! -:!!\$&\$(!?(\$!&\$!\* (64-\$6(!'-'\* (#'2(\$! -5#\*&-36! =#\$=(\*)

\*(6(#\*=1!A-\*ZS!

-"! <&)'\$#3!\* P&3=)0! 2&#)&'C! 4\*-5&%(6! 6N#(N'1N#\*! :#=#>&'&X(6!=\$%3='&\$?! \*(6(#\*=  
\*(>(5#\$!'!-\$#&2#>!#\$\$%! 132#\$\$! 1(#>'1! =-\$( \*\$S! H#''&! ?#5(! 2(! #\$\$! -44-\*'3\$&'!-'! 5&6&  
c('\*&\$#\*! 1(#>'1! =(('\$! #\$\$%&6=366DE;&\$'(Z! 8F"! \*(6(#\*=1! 4\*-/('6! A&'1! \*(6(#\*=1(\*6! &  
c('\*&\$#\*! U(#>'1!('\$(\*C! A1&=1! A-3>%! X(!e3&'(!1(>4:3>!: -\*! :3'3\*! \*(6(#\*=1)X-\*#&-\$6S!!  
F!#''(\$%(!#A-\*Z61-4!#\$\$&2#>!1#\$\$%>#\$\$%#2! :&\*6!(5(\*!(Y4(\*&(\$=(!A&'1#\$\$&2#>!1#\$\$%>  
&\$!#\$(Y4(\*&2(\$#>!6('N34S!!

D1\*-3?19\*-'!H#''&76!(::-\*'6C?F!#! =1#\$\$=(!-'!5&6&'!5#\*&-36!-'1(\*!>#X6!-2&=6!=-\*(!:#=#>&'  
;->(=3>#\*!'!'->-'!'-\*(!\_#=#>&#!#!'1(! !;! =#2436S! F! A#6! :-\*'3#\$(!-'! %&6=366! 2,! \*(6(#  
4\*-/('6! A&'1! 9\*-'! <#\*#&\$! 9S! ;--\$([ @66=-&#'(!)&\*('=-f! C! 9\*-'(-2&=6!('\$(\*\! #\$\$%! ?-'! -!>(#\*\$  
#X-3! '1(&\*! &\$'(\*6'&\$?! =3\*\*(\$! \*(6(#\*=1! A-\*ZS! =-3>%! %&6=366! 4\*-4-6(%! -X/('=&5(6!  
\*(6(#\*=1!>#X!#\$\$%!/-&\$!?'#\$\$!4\*-4-6#>S!F!=-3>%!#>6-!?'(!&\$:-\*2#&-\$!#X-3!'\*(#2(\$'C!6'-\*  
61&44&\$?!4\*-'(%3\*(6!-'!6#24>(6! [&:!'(e3&\*(%!\!-'!4\*-'(-2&=#\$#>,6&6S!F!#>6-!=-3>%!  
#\$\$%!?'!&\$:-\*2#&-\$!#X-3!'1(!5#\*&-36!&\$6'\*32(\$'6C!>#X-\*#-'!12%>-?-'!('=S!

F!X(>&(5(!'1#''1&6!2(('&\$?!A&'1!&6'3&'(!&\$6'\*32(\$#>!#\$\$! =\*3=&#>!- \*! :3'3\*(!=->>#X-\*#&5(!/  
@!2(('&\$?!A&'1! 9\*-'! @>(Y#\$\$(\*!+3\*Z(5@-66=-&#'(!)&\*('=-\*C!;->(=3>#\*!'!'->-'!'-\*(!\_#=#>  
4\*-5&%(%)2(!A&'1!&\$5#>3#X>(!&\$:-\*2#&-\$!#X-3!'1&6!:#6=#&\$#&\$?!\*(6(#\*=1S!

F!=-3>%!#>6-!&#&\$\*(='(#&-\$#>!#=#&5&'!=( '\$'A&'1!A#6!#\$(Y=&&\$?!(Y4(\*&(\$=( \$! ;! 5&6&  
A#6!\*(#>>!,#\$((\$>&?1'(\$2(\$!-'!X-'1!X-%,!#\$\$%!2&\$%S!

S...3'\* !

;;! :&\*6! (Y4(\*&(\$=(! A&'1! ;! NIJ"! >&\$Z#?(! 4\*-\*#2! A&>>! 1#5(! ?\*(#! &24#='2; \$!#\*('!  
%(5(>-42(\$'S! @! !;! =#2436C! 2,! (Y4(\*&(\$=(! #6! #! \*(6(#\*=1(\*! (Y'(\$%6! :#\*! X(-,%!  
)4#\*2(\$! -! :! #%&->-?;! X(=#36(! -!'1(!6'-\$?! =>>#X-\*#&-\$6!'1#! (Y&6!'!2-\$?!'1(!=>>(?  
#=-\*66!=#2436S!A#6!e3&'(!&\$'(\*6'&\$?!-'!%-15#\*&-36!>#X!'\*#&\$&\$?#S!!2#\$(#64(='6!'1#!  
=#\$!X(!&\$=-\*4-\*#'(%)&\$!-3\*!\*(6(#\*=1!>#X6!#6!A(>>S!V3\*!?'-34!#\$\$%!9\*-'!H#''&76!?'-34!;  
&\$!4#\*#>>(>!:&(>%6!6-'1&6!5&6&'!1#6!X((\$!#!6-3\*=(!-! :36(:3>!:((%X#=#ZC!5#>3#X>(!\*(  
&\$6&?1'6!&\$!-'!%&:\*( '\$!2('1-%>-?&=#>!#44\*-'!#(H&S!-'!43X>&61!-\$!\*(6(#\*=1!4#4(\*!#\$\$%  
=-\$:((\$=(! 4\*(6(\$#&-\$! :\*-2! '1&6! =>>#X-\*#&5(! \*(6(#\*=1! A-\*Z! ?(\$\*#'(%) :\*-2! ;INIJ"!  
4#\*'\$(\*61&4S!!0@G9!A&>>!63\*(>!,=-\$'\*&X3'(!&\$!=#4#=#&'!X3&>%&\$?!-! :3'3\*(!,-3\$?!\*(  
X-'1!3\$&5(\*6&&(6S!D#1'(\$\*61&46!>&Z(!!;0@G9!A&>>!1(>4!X-'1!&\$6'&'3&-\$6!-'!#=1&(5!  
-! :4\*(4#\*&\$?!'1(&\*!6'3%(\$'6!-'!X(!\*(#>!q?>-X#>!=#&'&T(\$6rS!



@4#\*! :\*-2! \*(6(#\*=1! A-\*ZC! '1&6! 3\$&e3(! 5&6&! #>6-! ?#5(! 2(! # \$! -44-\*'3\$&'! '!' (Y4>-\*(! ;  
=-3\$'\*,! # \$%! '-! X(! % #TT>(! X,! \$(A! =3>'3\*(! # \$%! =36'-26S! F! A&61! I;0@G9! 4\*-'\*#2  
=-\$'&\$3(%! :-\*(5(\*\$

BK7#+l=&N8&:&#) (!!

F! A-3>%! >&Z(! '!' (Y'(\$%! Ø&\$=(\*(! ?\*#'&'3%(! # \$%! #44\*(=&#&-\$! '!' '1(!

F\$(\*\$#&-\$#>!.(>#&-\$6!V::&=(#!"IJ"![:6!)(X\*#B#26-\$C!;\*!B(->,\$!+#=Z6-\$C!;6!U&>%#!J.  
#\$\$!;6!.361\$&!0#>&(\S!

F!A-3>%!#>6-!#Z(!'1&6!-44-\*3\$&,'!-'1#Z!9\*-'!;#\*!&\$!V\$#9&2&6\*',!)(4#\*2(\$'C!IJ\C !  
A1-!#>6-!5&6&'(!;A1&>(!F!A#6!'1(\*S!U&6!4\*(6(\$=(!&\$!e3&'(!1(>4:3>:-\*!2(!?'&\$?!  
#=e3#&\$'(!A&'1!'1(\$A!4>#=(S!

F!A#\$!'!-(Y4\*(66!2,!%((4(6!'?\*'#!'3%(!'!9\*-'!;(\*5&\$!;(,\* !-'! ?&5(!2(!'1&6!A-\$%(\*:3>  
-44-\*3\$&,'S!F!#2!&\$=\*(%&X>,:-'\*3\$#('!-'1#5&2#6!2,!;(\$-'\*S! F!'\*3>,#44\*(=&#('!#\$%!5#  
(5(\*,'1&\$?!F!#5(!>(#\*\$!'!:\*-2!1&2C!A1&=1!A&>>!:-(5(\*!X(!#!2#/-\*!=-\$\*&X3'&-\$!X(1&!  
63==(66!#\$%!#=1&(5(2(\$'6S!F!X(>&(5(!'1#!F!A&>>X(!#X>(!-'!>(#%!'!-A#\*%6!#!63==(66:  
1&6&\$=(\*(!6344-\*!#\$%!2(\$-'\*61&4B!1#5(!'1(!3'2-6!'\*(64(=!:-\*!1&2SU(!1#6X((\$C!#\$%  
=-\$&\$3%!'!-X(!#\$!(Y=(>>(\$!'!->(!2-%(>!'!-1&6P%(\$'6S!

!  
!  
!