CONSEQUENCES OF THE CONDITIONS FOR SUPERLINEAR INTRINSIC PHOTOCONDUCTIVITY

by F. N. HOOGÉ

Abstract

The conditions for superlinear intrinsic photoconductivity — derived in a previous paper — are used for a discussion of the relation between \( n \) and \( U \) in and around the extremely superlinear situation. An aspect of this problem is the width of the intensity range over which superlinearity can be observed. The conditions for the transition rates lead to conditions for capture cross-sections, which make it possible to show that a three-level model, where both \( A \) and \( C \) are donors and \( B \) an acceptor, is most suitable for the realization of extreme superlinearity.

Introduction

In a previous publication \(^1\) the conditions for superlinear intrinsic photoconductivity were derived, i.e. the conditions under which \( \frac{d \ln n}{d \ln U} > 1 \) when \( n \gg p \); \( n \) and \( p \) are the concentrations of the free electrons and free holes and \( U \) is the number of electrons raised from the valence band into the conduction band by the action of the light.

In this paper these conditions will be used for a more detailed treatment of the superlinear situation, the width of the \( U \)-range over which superlinearity can be observed and the relationship between \( n \) and \( U \) in and around the superlinear situation. A discussion will be given of conditions for capture cross-sections of the levels, following from the already deduced conditions for transition rates. The results will enable us to choose that combination of acceptor and donor levels which will probably be the most suitable one for the practical realization of extreme superlinearity.

We shall use the same model and symbols as in the first paper, see fig. 1. There are two levels \( A \) and \( B \). The level over which the main part of the recombination takes place will be the \( A \)-level; \( f^{A}_{n} \) is the fraction of \( A \)-levels occupied by electrons; \( f^{A}_{p} = 1 - f^{A}_{n} \); \( n^{A}_{1} \) and \( p^{A}_{1} \) are the electrons and hole concen-

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Fig. 1. Transitions of electrons considered in the model. The relative positions of \( A \) and \( B \) are arbitrary.
trations in thermal equilibrium with A-levels that are just half occupied. The kinetic constants $C^A_n$, $C^A_p$ and $C^B_n$, $C^B_p$ are proportional to the concentrations of A and B, respectively.

The following equations describe the kinetics of the model and charge neutrality.

\begin{align*}
C^A_n nf^{A_p} &= C^A_n nA_1 f^{A_n} + U_A, \\
C^A_p pf^{A_n} &= C^A_p pA_1 f^{A_p} + U_A, \\
C^B_n nf^{B_p} &= C^B_n nB_1 f^{B_n} + U_B, \\
C^B_p pf^{B_n} &= C^B_p pB_1 f^{B_p} + U_B, \\
U &\simeq U_A \gg U_B
\end{align*}

and

\begin{align*}
n + f^{A_n} A + f^{B_n} B &= p + K,
\end{align*}

where $K$ is a constant depending on the donor or acceptor character of the level.

Further we shall use the notation $A^0 = Af^{A_n}$, $A^+ = Af^{A_p}$, $B^0 = Bf^{B_n}$ and $B^+ = Bf^{B_p}$. In the first publication it was shown that $d \ln n/d \ln U > (n \gg p)$ if the conditions of table I are fulfilled.

**TABLE I**

<table>
<thead>
<tr>
<th>Conditions for superlinearity in $n$ ($n \gg p$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_A \gg U_B$</td>
</tr>
<tr>
<td>$np \gg n_0 p_0$</td>
</tr>
<tr>
<td>$C^A_n n \gg C^A_p (p + pA_1) + C^A_n nA_1$</td>
</tr>
<tr>
<td>$C^B_p f^{B_n} p \simeq C^B_p f^{B_p} pB_1 \gg C^B_n f^{B_n} n \simeq U_B \gg C^B_n f^{B_n} nB_1$</td>
</tr>
<tr>
<td>$B^0 B^+/B = \text{const.} \gg n + A^+$</td>
</tr>
<tr>
<td>(\rightarrow U_s = C^A_p pB_1 B^+/B^0)</td>
</tr>
<tr>
<td>(A^+ \simeq B^0 \gg n)</td>
</tr>
</tbody>
</table>

There are two types of superlinearity:

(a) Quadratic superlinearity, where $n \propto U^2$.

(b) Extreme superlinearity, where in first approximation $n$ jumps from a value $n_{\text{min}}$ to a value $n_{\text{max}}$ at a fixed value of $U = U_s = C^A_p pB_1 B^+/B^0$. In the extremely superlinear situation both $B^+$ and $B^0$ are virtually constant.
2. Extreme superlinearity in two-level models

In the last section of our previous paper it was shown that in two-level models extreme superlinearity can occur if $A$ is an acceptor and $B$ is a donor. In the extremely superlinear situation the charge-neutrality equation therefore reduces to

$$A^0 \simeq B^+.$$  \hspace{1cm} (15)

The concentration of $B$ must be greater than that of $A$. For the sake of simplicity we shall take here $B \gg A$. Then because of $B^+ \simeq A^0 \simeq A \ll B \simeq B^0$ the term $B^0 B^+/B$ can simply be replaced by $B^+$.

Now $n$ can be calculated as a function of $U$ in and around the extremely superlinear situation. In the first column of table II the equations (1) to (6) are given. If all conditions of table I hold, the terms between square brackets can be neglected. One then finds $U_s = C_{A;p} B_1 A/B$.

A limit of the extremely superlinear case is reached if one of the conditions of table I breaks down. In the neighbourhood of this limit all other conditions still hold, and the only consequence of the breakdown of a condition is that in the corresponding equation (given in the first column in table II) the term between square brackets can no longer be neglected. Using this procedure we have calculated $n$ as a function of $U$ for all possible limits. The results are given in the 4th and 5th columns of table II and they are depicted in fig. 2. The third column indicates whether the condition determines a lower or an upper limit for $n$, and hence also for $U$.

In situations directly before the superlinear situation, the approximate relations between $n$ and $U$ can be found from the relations for the lower limits by neglecting $U$ with respect to $U_s$. Neglecting $U_s$ with respect to $U$ in the relations for the upper limits, we find the approximate relations between $n$ and $U$ in situations following the superlinear one, see fig. 2. Under the conditions for extreme superlinearity formula (21) of the previous publication reads

$$\frac{d \ln n}{d \ln U} = \left( \frac{n}{A} + \frac{A^+}{A} + \frac{C_{B;B_1} n}{C_{B;p} B_1} \right)^{-1}. \hspace{1cm} (16)$$

The three terms between the brackets correspond to three limits for superlinearity (cases 3, 1 and 4 in fig. 2). In the superlinear situation each of them is smaller than about 1, but they vary superlinearly with $U$. The first one which reaches the value about 1 sets a limit to the superlinearity. Besides these three limits there are two others which make $d \ln n/d \ln U = d \ln n/d \ln p$ (cases 2 and 5 in fig. 2).

From fig. 2 it is clear that extreme superlinearity can be observed only over a $U$-range which is smaller than one decade. This width of the $U$-range is due to terms that give only small contributions to $d \ln n/d \ln U$ as long as $U$ is not too far from $U_s$.  

## TABLE II

Extreme superlinearity for two-level models with $B \gg A$

<table>
<thead>
<tr>
<th>approximated equations</th>
<th>limit given by</th>
<th>relation between $n$ and $U$ cases in fig. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_A^A f_A^A p_n = C_A^A f_A^A n A_1 + U_A$</td>
<td>$C_A^A f_A^A p A_1 \rightarrow U^*$</td>
<td>$U \ll C_A^A f_A^A n A_1$</td>
</tr>
<tr>
<td>$C_A^A p f_A^A n p = [C_A^A p f_A^A n A_1] + U_A$</td>
<td>$L$</td>
<td>$n A_1 p A_1 C_A^A \frac{1}{U S - U}$</td>
</tr>
<tr>
<td>${ C_B^B p B_1 + [C_B^B n] } f_B^B p = C_B^B p f_B^B n$</td>
<td>$U$</td>
<td>$C_B^B p A_1 \frac{U}{C_B^B n}$ $U S - U$</td>
</tr>
<tr>
<td>$U = U_A + [U_B] = C_A^A f_A^A n + [C_B^B f_B^B n]$</td>
<td>$U_B \rightarrow U_A$</td>
<td>$B^* = A^0 + [n]$</td>
</tr>
<tr>
<td>$B^* = A^0 + [n]$</td>
<td>$n \rightarrow A$</td>
<td>$U\ll C_A^A f_A^A n A_1$</td>
</tr>
<tr>
<td>$A = A^0 + [A^+]$</td>
<td>$A^+ \rightarrow A$</td>
<td>$U \gg C_A^A f_A^A n A_1$</td>
</tr>
<tr>
<td>$B = B^0$</td>
<td>$L$</td>
<td>$n A_1 \frac{U + \sqrt{U U S}}{U S - U}$ $1$ $U (U S + \sqrt{U U S})$ $U S - U$</td>
</tr>
</tbody>
</table>

*) This condition corresponds to $n p \rightarrow n_0 p_0$ for $U \ll C_A^A f_A^A n A_1$ and to $C_A^A n \rightarrow C_A^A p A_1$ for $U \gg C_A^A f_A^A n A_1$.

**) $C_B^B p p_1 \rightarrow C_B^B p B_1$ does not set a limit to the superlinear situation because this $p$-value cannot be reached when $C_B^B n < C_B^B n B_1$ and $n p > n_0 p_0$.
There is another effect which, in experimental observations, may broaden the superlinear $U$-range by an extra factor 2. This effect is due to inhomogeneous illumination at different depths of the sample, because of the light absorption. For an illustration of this effect we shall consider the special case where in first approximation $n \propto U$, before and behind the superlinear situation, see fig. 3. Let $d$ be the thickness of the crystal and $U_0$ the light intensity just below the surface. The intensity at a depth $x$ is then given by

$$U(x) = U_0 \exp(-\alpha x),$$

(17)

where $\alpha$ is the adsorption coefficient.

According to our assumption about the relations between $n$ and $U$ before and behind the superlinear situation we have,
if \( U_z < U_s \), \( n(x) = AU(x); \) \( (18) \)
if \( U_z > U_s \), \( n(x) = BU(x). \) \( (19) \)

The value of \( x \), where \( U(x) = U_s \), will be called \( x_s \), thus
\[ U_s = U_0 \exp (-ax_s). \] \( (20) \)

For small intensities, i.e. when \( U_0 < U_s \),
\[
\bar{n} \propto \int_0^d AU_0 \exp (-ax) \, dx = AU_0 \left\{ -1 \exp (-ad) \right\}. \] \( (21) \)

Thus for infinitely thick samples \( (d \rightarrow \infty) \) the average value of \( n \) will be
\[ \bar{n} \propto AU_0, \] \( (22) \)
when for higher intensities \( U_0 > U_s > U_d \) (\( U_d \) is the intensity at \( x = d \))
\[
\bar{n} \propto \int_{x_s}^d BU_0 \exp (-ax) \, dx + \int_{x_s}^d AU_0 \exp (-ax) \, dx =
BU_0 (1 - U_s/U_0) + AU_0 \left\{ U_s/U_0 - \exp (-ad) \right\}. \] \( (23) \)

For thick samples one finds
\[ \bar{n} \propto B (U_0 - U_s) + AU_S. \] \( (24) \)

For high intensities, when \( U_d > U_s \), one finds, following the same reasoning,
\[ \bar{n} = BU_0. \] \( (25) \)

In the plot of \( \bar{n} \) versus \( U_0 \) there are three regions where \( \bar{n} \) is proportional to
\( AU_0 \) \( (22) \), to \( B (U_0 - U_s) + AU_S \) \( (24) \) and to \( BU_0 \) \( (25) \), successively. This
results in a broadening by at most a factor 2 if \( B \gg A \) and \( ad \gg 1 \), see fig. 3.

The two broadening effects — nearly negligible terms over a wider \( U \)-range
around \( U = U_s \) and inhomogeneous illumination — make it possible to ob-
serve extreme superlinearity over a \( U \)-range of about one decade.

**3. Quadratic superlinearity in two-level models**

For the quadratic superlinear situation one can determine the limits of this
situation by the same procedure as was used for the extremely superlinear
situation. It does not seem worth while, however, to give a detailed analysis
of this case because it is obvious that at the borders of the quadratic region
the slope will vary smoothly from quadratic to the constant slope of the neigh-
bouring region. For that reason too the broadening due to inhomogeneous
illuminations will be of less importance. Indeed the whole problem of the
broadening will be less interesting, because the \(U\)-range is already extended.

In sec. 6 an example will be given of a quadratically superlinear situation
with its neighbouring situations, see figs 5a and 6a.

4. Conditions for capture cross-sections

Thus far only mathematical conditions have been considered. It may now
be asked whether it is possible to fulfill these mathematical conditions in known
semiconductors, with given impurity concentrations, and positions of the levels, at
attainable illumination levels and temperatures. To answer this question in all
its details is difficult, because there is such a wide range of values for the cross-
sections \(C_{n}/A\) etc. However, there are some trends in the correlation of these
cross-sections with the effective charge of the centres. This makes it plausible
to consider some of the superlinear situations as unrealistic, although they are
possible from the purely mathematical point of view. Therefore we shall first
consider the physical “arguments” which will be used for deciding whether
or not a superlinear situation is realistic. After showing that a two-level model
generally does not lead to realistic superlinear situations, we shall consider
models with three levels. In this way we avoid treating too many cases, most
of which seem to be unrealistic.

We introduce here cross-section per centre, defined by

\[
C_{A_{n}} = \frac{C_{A_{n}}}{A}
\]  

(26)

and we shall add to these cross-sections \((-\), (0), or \((+\), denoting the effective
charge of the centre before the transition, characterized by this cross-section,
see fig. 4.

For the cross-sections there exists the general trend

\[
c_{n}(0) < c_{n}(+)
\]

(27)

and

\[
c_{p}(0) < c_{p}(-).
\]

(28)

This is certainly not more than a trend, to which there are exceptions. We shall
use (27) and (28) only for selecting the most probable possibility for the realiza-
tion of extreme superlinearity. Strictly speaking, by using (27) and (28) one

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Fig. 4. Nomenclature for the cross-sections.
cannot exclude with absolute certainty the situations that will be excluded by us in the following treatment.

For this discussion the most important condition for superlinearity is the combination of (1), (5) and (9):

\[ C_{A+n} f_{A+} n \geq U_A \gg U_B \simeq C_{B+n} f_{B+} n. \]  
(29)

This inequality for the first and fourth term reads in terms of cross sections

\[ c_{A+n} A^+ \gg c_{B+n} B^+. \]  
(30)

For the extremely superlinear case with

\[ B^+ \gg B^0 B^+/B \gg n + A^+, \]  
(10)

eq (30) leads to

\[ c_{A+n} \gg c_{B+n}. \]  
(31)

For extreme superlinearity in two-level models \( A \) must be an acceptor and \( B \) a donor. We then have the condition

\[ c_{A+n}(0) \gg c_{B+n}(+), \]  
(32)

which is in contradiction with the general trend (27). From this we conclude that extreme superlinearity is not likely to be observed in crystals containing only two types of centres.

For the quadratic case where \( A \) is a donor and \( B \) an acceptor and with \( A^+ = B^0 \) and \( B = B^+ \), the condition (29) leads to

\[ c_{A+n}(+) B^0 \gg c_{B+n}(0) B. \]  
(33)

This is a condition that can easily be fulfilled, so the experimental observation of quadratic superlinearity will well be possible on crystals containing two types of centres.

At this point we wish to make a short note about mobility variations with light intensity. When \( n \propto U^2 \), then

\[ A^+(+)=B^0(-) \propto U^{-1}. \]  
(34)

With increasing \( U \), the number of charged centres decreases; therefore, impurity scattering is dominant,

\[ \frac{d \ln \mu}{d \ln U} > 1. \]  
(35)

If the superlinearity of Mn-doped Ge \(^2\) and perhaps also the superlinearity of CdSe \(^3\) can be interpreted as being quadratic, than there is experimental evidence for our conclusion, that in the quadratic situation \( \frac{d \ln \mu}{d \ln U} > 1 \) \(^4,5\).

If one observes superlinearity over a range of \( U \)-values wider than one decade, the relation between \( n \) and \( U \) must be quadratic, according to our model.
Deviations from the precise value of 2 for \( d \ln \sigma / d \ln U \) may be due to three effects:
(a) variation of \( \mu \), causing \( d \ln \sigma / d \ln U \) to increase;
(b) almost negligible terms near the limits;
(c) inhomogeneous illumination of the sample.
Both (b) and (c) cause some decrease in \( d \ln \sigma / d \ln U \), but certainly not much.

5. Extreme superlinearity in models with three levels

We have seen that, for physical reasons, extreme superlinearity is unlikely to be realized in two-level models. This leads us to the investigation of models with three levels. For the sake of simplicity we shall study models in which the only difference from the two-level models is the introduction of an extra constant term \( C \) in the charge-neutrality condition. In the equation for the recombination processes nothing will be changed, so that a condition for our model is

\[
U_C \ll U_A. \tag{36}
\]

There is no condition for \( U_C/U_B \).

When \( C \) is an empty donor (\( C = C^+(-) \)) only transitions between \( C \) and the conduction band may occur in considerable amount, because (36) requires

\[
C^n p(0)f^n p \ll U \tag{37}
\]

and

\[
C^n n(0)f^n n \ll U. \tag{38}
\]

Now we can systematically investigate the 8 combinations obtained by taking either acceptors or donors for \( A, B \) and \( C \). Then we can see which combination of donors and acceptors will be most suitable for extreme superlinearity.

Because of the condition (31), \( c^{4n} \gg c^{2n} \), models with \( A \) as an acceptor and \( B \) as a donor are unlikely. Extreme superlinearity is possible in models where \( A \) and \( B \) have the same character. When both \( A \) and \( B \) are acceptors, the charge-neutrality equation must be

\[
n + C^0 = p + A^+ + B^+ \tag{39}
\]

in order to have a possibility for the fulfilment of (10). When this charge-neutrality equation reduces to

\[
C^0 = B^+ \gg n + A^+ \tag{40}
\]

and all other conditions are fulfilled, extreme superlinearity will be found at

\[
U_S = \frac{C^0 p B^1 C}{B - C}. \tag{41}
\]
When both \( A \) and \( B \) are donors, the charge-neutrality equation must read
\[
 n + A^0 + B^0 = p + C^+.
\] (42)

Now there are two possibilities:
(a) In the approximation
\[
 B^0 = C^+ \gg A = A^0 \gg A^+ + n
\] (43)
superlinearity will be found at
\[
 U_S = \frac{C A p B_1 (B - C)}{C}.
\] (44)
(b) In the approximation
\[
 A^0 \simeq A \simeq C^+ \gg B^0 \simeq (C - A) \gg A^+ + n
\] (45)
superlinearity will be found at
\[
 U_S = \frac{C A p B_1 (B - C + A)}{C - A}.
\] (46)

Although extreme superlinearity is possible when \( A \) and \( B \) are both donors or both acceptors, the models most likely to lead to extreme superlinearity are those in which \( A \) is a donor and \( B \) an acceptor. This statement is based on the condition (31)
\[
 c^A n \gg c^B n.
\]

Depending on the character of \( C \) there are now two charge-neutrality conditions possible:
\[
 n + B^0 = p + A^+ + C^+
\] (47)
and
\[
 n + B^0 + C^0 = p + A^+.
\] (48)

Condition (47) is the charge-neutrality condition when \( C \) is a donor, whereas (48) holds when \( C \) is an acceptor. The latter is not in agreement with the condition for superlinearity \( B^0 \gg B^0 B^+/B \gg n + A^+ \) (10). Therefore there remains only one possibility to be considered as specially suitable for extreme superlinearity, i.e. (47) with \( B \) being an acceptor and \( A \) and \( C \) being donors. Because of \( B^0 \gg n + A^+ \) (10), eq. (47) reduces to
\[
 B^0 = C^+.
\] (49)
in the extremely superlinear situation.

This case is closely related to the two-level model with \( B^0 = A^+ \) leading to quadratic superlinearity. By gradually introducing \( C \)-levels it is possible to let
an extremely superlinear situation develop on the quadratic situation, see figs 5a, b and c.

![Diagram](image)

Fig. 5. Log $n$ versus log $U$ and $1/T$ for a special model. The influence of a third level is shown in $a$, $b$ and $c$.

$a$: $C = 0$,  
$b$: $C < A$,  
$c$: $C > A$.

6. Analysis of an example of the case $n + B^0 = p + A^+ + C^+$

An example of the case where $A$ and $C$ are both donors and $B$ is an acceptor will be analyzed here to a first approximation. The exact variation of $n$ with $U$ near the border of two situations will not be considered. No attention will therefore be paid here to the width of the $U$-range of the extremely superlinear situation, because this aspect of the problem is the same as in two-level models.
In order to avoid too many complications, especially in the temperature dependence, some extra assumptions will be made. Consequently our model does not represent all possibilities for limits of superlinearity and neighbouring situations. Our only intention is to show here how to apply the general conditions to a special given case. The extra conditions assumed for all situations of this example are

\[ B \gg A, \]  
\[ U_A \gg U_B, \]  
\[ C_A n f_A p n \gg C_A p f_A p A \]  
and
\[ n^{A_1} \text{ is virtually temperature-independent.} \]

The last condition means that the \( A \)-level lies close to the conduction band; the consequence is that the only temperature-dependent term in the results is \( p^{B_1} \) (in figs 6a, b and c, \( p^{B_1} \) is represented by \( p_1 \) in order to save space for exponents).

In the superlinear situation all conditions of table I hold. Now we shall investigate what happens when in a neighbouring situation one of the conditions has broken down, while the other conditions still hold. In one of the equations for the kinetics a term which was negligible in the superlinear situation will now become the most important one in the adjoining region, and we shall treat this term in this adjoining region as the only term to be considered, neglecting the term which was dominant in the superlinear region. By systematically treating all conditions in this way we obtain \( n_{\text{max}} \) and \( n_{\text{min}} \) of the superlinear situation, and a sketchy outline of the variation of \( n \) with \( U \) in the other situations.

By doing so, Klasens' method of approximation \(^6\) is used, therefore his and our results for \( n(U) \) are of the same form.

The equations used in this analysis are given in the first column of table III. In the extremely superlinear situation the terms between square brackets can be neglected, leading to

\[ U_S = C_A p B_1 (B - C)/C. \]  

If one of the conditions (2nd column) breaks down, then in the corresponding equation in the first column the term between brackets becomes the more important one, and the other term is now to be neglected.

The other equations are to be used in the same approximation as in the superlinear situation. By such a procedure approximations for \( n \) are found in the form

\[ n = a (p^{B_1})^\beta U^{\gamma_1}. \]  

The intersection of two situations can be found as a solution of the equation

\[ a_1(p^{B_1})^{\beta_1} U^{\gamma_1} = a_2(p^{B_1})^{\beta_2} U^{\gamma_2}. \]
TABLE III

Limits of the superlinear situation when \( n + B^0 = A^+ + C^+ \)

<table>
<thead>
<tr>
<th>approximated equations</th>
<th>limits for superlinearity</th>
<th>representation of the limits in fig. 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_n A_n f A_n p = U + [C_n A_n f A_n n A_1] )</td>
<td>( U \rightarrow C_n A_n f A_n n A_1(\text{quadr.)}) )</td>
<td>dots</td>
</tr>
<tr>
<td>( C_p f A_n p = U )</td>
<td>( A^+ \rightarrow A )</td>
<td>crosses</td>
</tr>
<tr>
<td>( C_n f B_n p = C_n f B_n p B_1 + [C_n f B_n p n] )</td>
<td>( C_n n \rightarrow C_n p B_1 )</td>
<td>broken line</td>
</tr>
<tr>
<td>( l = A^0 + [A^+] )</td>
<td>( 1 A^+ \rightarrow C(\text{extr.quadr.)}) )</td>
<td>full line</td>
</tr>
<tr>
<td>( B^0 = [A^+] + C^+ )</td>
<td>( 2 n \rightarrow C )</td>
<td>full line</td>
</tr>
</tbody>
</table>

These intersecting lines are straight lines in plots of \( \ln p B_1 \) or \( 1/T \) versus \( \ln U \), see fig. 5. In the figures 5 and 6 we have given the results for three cases with \( a) \): \( C = 0 \), \( b) \): \( C \) is somewhat smaller than \( A \), and \( c) \): \( C \) is somewhat greater.

![Fig. 6a](see legend next page).
Fig. 6. Variation of $n$, $A^+$ and $B^0$ with $U$ and $1/T$. In each region $n$, $A^+$ and $B^0$ are given in this order; $p_1$ stands for $pU_1$.
For $n$, figs 6 $a$, $b$ and $c$ are projections of figs 5$a$, $b$ and $c$ on the plane through the log $U$ and $1/T$-axis.

$a$: $C = 0$,   
$b$: $C < A$,   
$c$: $C > A$. 
than $A$. For the case $C = 0$ only quadratic superlinearity is present. When $C < A$ also extreme superlinearity exists, immediately following the quadratic superlinear situation. When $C > A$ extreme superlinearity is the only type of superlinearity present.

For $0 < C < A$ the transition from quadratic to extreme superlinearity is found at the intensity where the charge-neutrality equation goes over from the approximation $B^0 = A^+$ into the approximation $B^0 = C^+$. This is illustrated in fig. 7, where we have plotted $n$, $A^+$ and $B^0$ in and around the superlinear region of fig. 6b.

Fig. 7. Detail of fig. 6b is given in the top of the figure ($1/T$ vertical, $\log U$ horizontal axis). Cross-sections for constant $T$ at I and II are shown in the middle and bottom part of the figure, with concentrations plotted vertically as functions of $\log U$.

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