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Negative Conductance in SCLC Diodes with Traps
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In honour of Prof. Dr. F. Stöckmann’s 60th birthday

The small-signal admittance of SCLC diodes with traps is analysed in the high frequency range where transit time effects occur. Numerical results and also analytical expressions of an approximated theory are given for the frequency dependence of capacitance and conductance. It is shown that those diodes do exhibit a negative differential conductance. Finally, this prediction is confirmed for the first time using n-type Si diodes with Au traps.

1. Introduction

In recent years the influence of transit time effects on the small-signal properties of semiconductor diodes has been analysed in order to examine whether negative differential conductances (n.d.c) are feasible or not. Also SCLC diodes have been proposed [1 to 3], the characteristics of which are mainly determined by the sign of the injected carriers and the space charge situation. For example, in case of majority carrier injection into SCLC diodes no n.d.c. due to transit time effects can be observed as has been shown and discussed in a recent publication [1]. It has been demonstrated, however, that in order to get n.d.c. in SCLC diodes one has to reduce the velocity-modulated current density. Nevertheless, this may be realized using a fixed space charge; two ways are possible: On one hand the steady state free carrier concentration may be reduced using Schottky contacts and minority carrier injection (BARIT diode [3]) or using a SCLC diode with traps and majority carrier injection as has already been indicated in a previous paper [2].

In this paper the small-signal admittance of a SCLC diode with traps is analysed: The differential equation for the ac electric field yields both numerical and approximated analytical results for the capacitance and the conductance of the diode. The frequency dependence of these parameters is investigated in a region where transit time effects occur. The theoretical predictions are then compared with experimental results performed on Si diodes with Au traps.

2. SCLC Diode with Traps

Majority carrier injection into a n-type semiconductor diode with two ohmic contacts gives rise to a spatially dependent free carrier concentration \( n(x) \) and electric field \( E(x) \), if the transit time \( T \) of the injected carriers is small compared to their dielectric relaxation time, i.e. \( n(x) \gg n_0 \) (\( n_0 \) concentration of thermally generated carriers) holds.

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In this case the current is purely space-charge-limited (SCLC diode). A general theory of those diodes has been given in [1]. Furthermore, the calculation of the current-voltage characteristic and the admittance of a SCLC diode with traps is mainly simplified due to the fact, that the stationary space charge \( n(x) = n_0 \) and thus the steady state electric field \( E_0(x) \) are not influenced by the traps: The charge carriers are distributed between the majority band and the trap level according to Fermi-Dirac statistics. Thus only the spatially independent fraction [2]

\[
\theta = \tau_c / (\tau_c + \tau_e) = n(x) / (n(x) + n_T(x))
\]

(\( \tau_c \) and \( \tau_e \) are the capture and emission time constant of the trap level, respectively) of the carriers contributes to the diode current. \( n_T(x) \) denotes the density of trapped electrons.

Now from the usual Poisson and current equation [1] one immediately obtains the stationary equation (subscript 0) and the small-signal approximation (subscript 1) for the current density \( J \) of the diode with traps

\[
\frac{J_0}{\varepsilon} = \theta \mu E_0(x) E'_0(x) + \theta \omega_D E_0(x),
\]

\[
\frac{J_1}{\varepsilon} = \mu E_0(x) E'_1(x) + \theta \mu E_1(x) E'_0(x) + (j \omega + \theta \omega_D) E_1(x),
\]

where \( \mu \) is the mobility, \( E_1 \) the ac electric field, \( \varepsilon \) the permittivity, and \( \omega_D \) the common dielectric relaxation frequency. The prime denotes partial derivation with respect to \( x \). Equations (2), (3) are only valid in a frequency region \( \omega \gg \tau_c^{-1}, \tau_e^{-1} \), where the trap occupation is stationary with respect to the signal frequency. As can be seen from (2) and (3) the steady state current density as well as the velocity modulated term of \( J_1 \) is reduced by the factor \( \theta \): This fact gives rise to the possibility of a negative differential conductance, n.d.c., in SCLC diodes with traps, provided that \( \theta \ll 1 \).

In the following (2) and (3) should be solved in order to evaluate the n.d.c. values for a SCLC diode with traps. Since the influence of the thermally generated carriers on the characteristics of SCLC diodes has already been discussed in a preceding paper [1] \( \omega_D \) is set to zero for the following theoretical treatment. Then (2) yields the well-known relation

\[
E_0(x) = \left( 2J_0/\varepsilon \mu \theta \right) x^{1/2},
\]

i.e. the square root law for the spatial dependence of the steady electric field. The transit time \( T \) is given by

\[
T = 4L^2/3U_0,
\]

where \( L \) denotes the diode length and \( U_0 \) the de bias.

The solution of (3) results in the small-signal admittance \( Y \) of the diode and a variation of \( \theta \) yields two limiting cases: a) \( \theta = 1 \), describing the SCLC diode without traps, the solution of which is given in [1]; b) \( \theta \to 0 \), that is the case of a nearly compensated semiconductor, then an integration of (3) may easily be performed.

Assuming now \( \theta \ll 1 \) (this condition is easily realized using sufficiently deep traps, since \( \tau_e \) increases exponentially with increasing energy distance of the trap level from the conduction band edge), the solution of (3) is easily found to be

\[
E_1(x) = \frac{J_1}{j \omega e} \left( 1 - \exp \left( -j \omega T(x/L)^{1/2} \right) \right).
\]

From (6) the small-signal admittance of a strongly compensated SCLC diode is ob-
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Fig. 1. Small-signal admittance of SCLC diode with traps as a function of the transit angle; parameter is $\theta$: (1) $\theta = 1$; (2) 0.5; (3) 0.1; (4) 0.01; (5) 0.001. Dashed curves are numerical results calculated from (3). The full lines correspond to the analysis of (8) and (9). a) Capacitance $C$ normalized to the geometrical value $C_0$ and b) conductance $G$ normalized to $G_0^*$ obtained which yields

$$Y(\omega) = \frac{G_0 q^3}{6} \left( \sin \varphi - q \cos \varphi + j(1 + q^2/2 - \cos \varphi - q \sin \varphi) \right),$$

(7)

where $G_0 = 3 e/2 L T$ denotes the differential conductance of the trap free diode and $q = \omega T$ the transit angle. Finally, separation of (7) into imaginary and real parts gives the following expressions for the capacitance $C(\omega)$ normalized to the geometrical capacitance $C_0$ and the conductance $G(\omega)$ normalized to $G_0^*$,

$$C(\omega) = \frac{G_0 q^2}{2} \frac{1 + q^2/2 - q \sin \varphi - \cos \varphi}{(q \sin \varphi + \cos \varphi - 1 - q^2/2)^2 + (q \cos \varphi - \sin \varphi)^2},$$

(8)

and

$$G(\omega) = \frac{G_0 q^3}{6} \frac{\sin \varphi - q \cos \varphi}{(q \sin \varphi + \cos \varphi - 1 - q^2/2)^2 + (q \cos \varphi - \sin \varphi)^2}.$$  

(9)

Equations (8), (9) are valid in case of $\theta \to 0$.

In the general case, $0 < \theta < 1$, (3) can only be solved by numerical methods, the results are discussed in the following section.

3. Discussion

Fig. 1 shows the frequency dependence of the normalized capacitance and conductance calculated by a numerical integration of (3). $C_0$ is again the geometrical capacitance and $G_0^*$ is obtained by an extrapolation $\omega \to 0$ in the general case. In order to make a comparison with the approximated analysis the results of (8) and (9) are also shown: As can be seen these analytical expressions give quite good results if $\theta$ is less than 0.01, the maximum error is about 10%. On the other hand the calculated admittance in the case of $\theta = 1$ is that of the trap free diode [1].

The transit time effects are obvious; $C$ and $G$ exhibit periodic variations with frequency. In the lower frequency range $C = 0.75 C_0$ ($\theta = 1$) and $C = 0.56 C_0$ ($\theta \to 0$), the first maximum in $C$ is larger than $C_0$ in case of the diode with traps, cf. Fig. 1a.
The most important feature, however, is shown in Fig. 1b: the SCLC diode with traps exhibits a negative conductance at a frequency value of the reciprocal transit time. This n.d.c. reaches a maximum in case of a highly compensated material ($\theta < 0.001$). An increasing density of thermally generated carriers reduces this n.d.c. value. In case of $\theta \approx 0.5$ no n.d.c. occurs. The maximum value of n.d.c. is calculated from (9):

$$G_{\text{max}} = -4G_0/3.$$  

The electrical characteristics of the SCLC diode with traps are analogous to those of the BARITT diode: In both type of diodes free carriers are injected into a region with fixed space charge; minority carriers into a region with the charge of ionized impurity centres (BARITT diode) or majority carriers into a region with charged traps (SCLC diode). The reduction of the lossy velocity-modulated ac current density leads to the possibility of n.d.c. due to transit time effects.

4. Experimental Results

The diodes were made from Cu compensated n-Si with a specific resistance of 100 k$\Omega$ cm and $L = 360$ $\mu$m. The ohmic contacts were made by alloying AuSb on both sides [2]. The experimental set-up is that of [1]. The results of capacitance and conductance measurements as a function of frequency are shown in Fig. 2a and b, respectively.

The transit time effects are obvious: $C$ and $G$ exhibit minima and maxima which shift to higher frequencies if the bias is enhanced. Apparently this is due to a decreasing transit time with increasing bias in agreement with (5). The most important result, however, which should be noted is that $G$ is negative in some frequency regions as has been predicted by the theory.

A comparison of the experimental results with those of the theory in Fig. 1 shows that $\theta$ should be about 0.3. From the $J_0$, $U_0$-characteristics and the doping concentration $N_D = 2.6 \times 10^{14}$ cm$^{-3}$ of the silicon substrate before the Au diffusion process one concludes $\theta \approx 10^{-3}$. This disagreement, however, may be traced back to the fact that on one hand the thermally generated carriers may not be neglected and on the other hand the Au trap level is not suitable as to observe a well defined SCLC behaviour with those diodes [4]. Therefore, in this particular case of our samples, a more accurate theory could use an $E_0(x)$ which may directly be integrated from (2) rather than take an $E_0(x)$ from the approximation in (4).

Fig. 2. Experimental results of admittance of SCLC diodes with traps as a function of signal frequency; parameter is the dc bias $U_0$: (1) $U = 11.8$ $V$ (△), (2) 17.3 (○), (3) 28.5 (∇), (4) 31.5 V (□). a) Capacitance $C$ normalized to the geometrical value $C_0 = 6.5$ pF and b) conductance $G$ normalized to $G_0 = G_0 (1$ MHz).
5. Conclusion

Transit time effects in the small-signal admittance of SCLC diodes with traps have been discussed. Both theoretical and experimental results have shown that the conductance can become negative at frequencies in the vicinity of the reciprocal transit time. This n.d.c. may lead to interesting technical applications of those diodes which are easily produced. An optimization may be realized using a proper semiconductor and suitable traps for compensation. Finally, it is worthwhile to notice that the influence of traps on the small-signal admittance of BARITT devices has also been studied, an increase of the negative conductance due to the traps has been predicted [5].

References


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