Minority and Majority Carrier Mobilities Determined by Microwave Measurements

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Within the high-frequency and microwave range the small-signal admittance of semiconductor diodes is determined by transit time effects, i.e. conductance and capacitance exhibit periodical variations with frequency. From measurements of maxima and minima the transit time is obtained. In case of ohmic contacts majority carrier injection occurs and space charge limited currents (SCLC) are observed. From experimental values of the transit time the majority carrier mobility is derived. In case of Schottky contacts on the same material minority carriers are injected under punchthrough conditions (MSM-BARRETT diode). Then from experimental values of the transit time the minority carrier mobility is determined. Finally bias variation yields the velocity-field characteristics of both minority and majority carrier mobilities of the same material. For 12 kΩ cm n-type silicon low-field values $\mu_p = 390 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $\mu_n = 1360 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ are obtained.

Im Hochfrequenz- und Mikrowellenbereich wird die Kleinsignal-Admittanz von Halbleiter-Dioden durch Lauzeiteffekte bestimmt, der Leitwert und die Kapazität zeigen periodische Schwankungen in Abhängigkeit von der Frequenz. Daher kann aus Messungen der Maxima und Minima die Lauzeit experimentell bestimmt werden. Im Fall ohmscher Kontakte findet Majoritätsträger-Injektion statt, und raumladungsgebegrenzte Ströme werden beobachtet. Aus den experimentellen Werten für die Lauzeit wird die Majoritätsträger-Beweglichkeit bestimmt. Im Fall von Schottky-Kontakten auf demselben Material werden unter „punchthrough“-Bedingungen Minoritätsträger injiziert. Dann wird aus der Lauzeit die Minoritätsträger-Beweglichkeit berechnet. Darüber hinaus liefert die Änderung der Diodenvorspannung die Feldstärkeabhängigkeit der Beweglichkeit von Minoritätsträger und Majoritätsträger. Für kleine Feldstärken werden für 12 kΩ cm-n-Silizium folgende Werte erhalten: $\mu_p = 390 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, $\mu_n = 1360 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$.

1. Introduction

The small-signal admittance of semiconductor diodes exhibit transit time effects if the test frequency is comparable to or larger than the reciprocal value of the transit time. This influence, however, may only be observed if the drifting space charge does not diverge due to dielectric relaxation within the transit time. Therefore, the product of transit time and characteristic frequency for dielectric relaxation should be small as compared with one.

In recent years the influence of transit time effects on the small-signal admittance of semiconductor diodes has often been investigated in order to realize negative differential conductances for microwave oscillator applications, e.g. [1 to 4]. It has been demonstrated that a large variety of diodes are feasible depending on contact preparation, sign of injected space charge, and distribution of fixed space charge [4]. General formulae for the small signal admittance have been derived showing periodical variations with the test frequency. The periodicity is given by the reciprocal value of the transit time and therefore by the mobility of the charge carriers. Hence from small-signal admittance measurements the mobility may be obtained.

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In this paper experimental results of the transit time effects in semiconductor diodes are presented, carried out by sensitive microwave measuring techniques which have been described in a previous paper [4]. Sele diodes with majority carrier injection and MSM punch-through diodes with minority carrier injection prepared on the same material (12 kΩ cm n-Si) are used. Experimental values of majority and minority carrier mobilities are given which agree very well with those of literature [5, 6].

2. Sele Diode

Without loss of generality a diode on n-type semiconducting substrate with thickness \( L \), doping concentration \( N_D \), and free charge carrier density \( \mu_n = N_D \) is assumed in the following. Ohmic contacts with area \( A \) are prepared on both sides of the material. The dc current density–voltage \( (J_0 - U_0) \) characteristic of this diode exhibits ohmic behaviour in the low bias regime and is purely space-charge-limited if the sele current density \( J_{sel} \) given by the well-known Mott–Gurney equation

\[
J_{sel} = \frac{9}{8} \varepsilon \mu_n U_0^2 \frac{L^2}{L}
\]

(1)

exceeds the ohmic current density \( J_0 = \sigma U_0/L \), where \( \varepsilon, \mu_n, \) and \( \sigma \) denote permittivity, electron mobility, and conductivity, respectively. The transit time is given by

\[
T = \begin{cases} \frac{L^2}{\mu_n U_0} & \text{ohmic condition, } \theta_D \gg 1, \\ 4 \frac{L^2}{\mu_n U_0} & \text{selc behaviour, } \theta_D \ll 1, \\ 3 \frac{L^2}{\mu_n U_0} & \end{cases}
\]

(2)

supposing that \( \mu_n \) is independent of the electric field throughout the diode. Thus, the diode shows ohmic behaviour if \( \theta_D \gg 1 \) and selc if \( \theta_D \ll 1 \) is valid where \( \theta_D = \omega_D T \) denotes the transit angle and \( \omega_D \) the characteristic frequency of dielectric relaxation. One, therefore, concludes that selc behaviour is observed in a practical voltage range \( U_n > \sigma L^2/\mu_n \) using a low-doped semiconductor and small thickness.

In [4] a general expression for the small-signal admittance of real sele diodes is given: the frequency dependence of conductance \( G \) and capacitance \( C \) taking into account the influence of free carriers \( \mu_p \), i.e. the finite conductivity of the substrate. From these results it can be seen that the transit time effects predicted by sele theory are evident if \( \theta_D \approx 1 \). The best indications are clear minima of \( G \) at transit angles \( \theta = 2.15\pi; 4.20\pi; 6.21\pi \ldots \) where \( \theta = \omega T \) includes the angular frequency \( \omega = 2\pi/ \) and the mobility \( \mu_n \), equation (2). In [4] one may find an approximate expression for the transit time \( T \), equation (2), if \( \theta_D \approx 1 \) is valid.

3. BARITT Diode

Using Schottky contacts instead of ohmic metallization an MSM-BARITT diode results [2]. Under punch-through conditions the \( J_0 - U_0 \) characteristic is determined by minority carrier injection. Now two cases must be distinguished: If the density of the injected holes is much larger than the fixed space charge due to ionized donors, the diode \( J_0 - U_0 \) characteristic is space-charge-limited and the equations of Section 2 hold. In this case, however, the hole mobility \( \mu_p \) must be introduced into the above equations instead of \( \mu_n \). If on the other hand the drifting hole concentration is small compared with the fixed lattice charge density the usual behaviour of the BARITT diode is expected. Now the electric field within the semiconductor bulk varies linearly between cathode and anode of the device yielding \( T = L^2/(\mu_n U_0) \), if constant mobility and small initial velocity at the anode is assumed. In this case, however, it should be noted that admittance and transit time are influenced by the blocking contact.
Hence no simple equations for the transit angle $\theta$ of minima and maxima in $G$ and $C$ may be derived as above. For theoretical analysis of the general admittance the diode is divided into characteristic regions [7], a procedure which should also be used if the electric field becomes too large so that the mobility becomes field dependent. This is the most difficult case where the relation between $T$ and $\theta$ ($G = \text{min}$) may be evaluated only numerically.

4. Experimental Results

For experimental investigations diodes with the following data have been prepared on n-type silicon with $\sigma^{-1} = 12$ k$\Omega$ cm. Solo diode: $L = 210 \mu$m, $A = 0.080$ cm$^2$, the ohmic contacts were alloyed Au/Sb. BARITT diode: $L = 150 \mu$m, $A = 0.071$ cm$^2$, the Schottky contacts were formed by evaporated Au. Similar results were obtained with Al, Pd, and Pt Schottky contacts. The diode quality has first been established by dc characteristics which correspond to theoretical predictions [8, 9]. In case of the BARITT diode Fig. 1 shows that punch-through takes place at about $U_0 \approx 5$ V, therefore at higher voltages the minority carrier injection is dominant and it can be seen that for $U_0 > 15$ V the slope becomes 2. This shows that the current becomes space-charge-limited, equation (1).

From geometrical and electrical data of the diodes the transit time effects are expected in the vicinity of about 50 MHz. For this frequency range sensitive microwave measuring techniques have been developed which are fully described in a previous paper [4]: The small-signal admittance has been measured using 50 $\Omega$ coaxial systems. Two methods have been employed: detection of phase and magnitude of reflected and transmitted waves when the diode is placed against the shortened end of the 7 mm APC system or between the inner conductors of the 7 mm APC transmission unit, respectively. Errors in measurement of $Y$ are well below 5% in the desired frequency range.

The measured frequency dependences of conductance for example of scc and BARITT diodes are shown in Fig. 2 and 3 [4]. On the ordinates the differential conductances $\sigma_0 = dJ_0/dU_0$ of the stationary $J_0-U_0$ curves are also given. These curves clearly exhibit transit time effects which agree very well with theoretical calculations if the contact influence is taken into account. They lead to Fig. 4 and 5 where experimental results for mobility evaluation are presented: a plot of $J_0/\theta$ versus $U_0$ where $J_0$ is the transit frequency ($G = \text{min}$). From the slope $m$ of these curves the mobility is given by

$$\mu = \frac{2\pi F L^2 m}{(3)}$$

so that from measurements the following values for the low-field mobilities are achieved:

$$\mu_n = 1360 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \pm 1\%,$$

$$\mu_p = 390 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \pm 2\%.$$
Fig. 2. $G-f$ characteristic of a n-Inp seIc diode; 
$\circ G = \frac{dJ_0}{dU_0}$

Fig. 3. $G-f$ characteristic of a MSM-BARITT diode; 
$\circ G = \frac{dJ_0}{dU_0}$

The plots of Fig. 4 and 5 exhibit decreasing slopes with increasing bias, i.e. increasing electric field strength. In a first order approximation one obtains for example

$\mu_n (E_0 = 2.0 \text{ kV/cm}) = 1140 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$,

$\mu_p (E_0 = 2.0 \text{ kV/cm}) = 205 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$.

These results are also in excellent agreement with the dc characteristics where the seIc current at high voltage levels deviates from the square law since the mobility decreases when the electric field is enhanced.

5. Summary and Conclusions

In this paper sensitive microwave techniques have been used to determine the small-signal admittance of both seIc and BARITT diodes. In this way transit time effects of the drifting majority and minority carriers in the same material, here $12 \Omega \text{ cm}$ n-Si, could be established. The results of dc as well as ac measurements agree well with
theory. The mobilities derived from measurements are in accordance with those of literature.

It is demonstrated that the small-signal measurements are excellent methods to determine the mobility of both kinds of charge carriers, which is a very important parameter in solid state physics. There are only very few influences which may invalidate the results. Therefore, the experimental investigations are of relatively high accuracy.

References


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