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Drift mobility in n- and p-conducting a-Si:H

By M. HOHEISEL
Siemens AG, Zentrale Forschung und Entwicklung,
Otto-Hahn-Ring 6, D-8000 München 83, F.R. Germany

and W. FUHS
Fachbereich Physik der Universität Marburg,
Renthof 5, D-3350 Marburg, F.R. Germany

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ABSTRACT

The drift mobility of a series of undoped and doped a-Si:H films has been determined from their steady-state photoconductivity and response time. The drift mobilities at 300 K were 0·1 $cm^2 V^{-1} s^{-1}$ and $5 \times 10^{-4} cm^2 V^{-1} s^{-1}$ for electrons and holes, respectively. The activation energies were 0·13 and 0·27 eV. There is no influence of doping up to a doping level of 1000 ppm of either PH_3 or B_2H_6. The temperature dependence of the response time reflects changes in the dominant recombination path. At low temperatures tunnelling processes prevail, but with increasing temperature direct capture of free carriers by dangling bonds becomes predominant.

§ 1. INTRODUCTION

Investigations of drift mobility have led to important findings about transport and trapping in hydrogenated amorphous silicon. Since the fundamental time-of-flight measurements were first made (Le Comber and Spear 1970), numerous experiments have been carried out in this field (Le Comber, Madan and Spear 1972, Moore 1977, Allan 1978, Fuhs, Milleville and Stuke 1978, Tiedje, Abeles, Morel, Moustakas and Wronski 1980, Crandall 1981, Silver, Giles, Snow, Shaw, Cannella and Adler 1982, Spear and Steemers 1984). All authors found an activated temperature dependence of the drift mobility, with activation energies for electron transport in the range 0·12–0·20 eV and for hole transport of about 0·4 eV. This led to the conclusion that the band tails contain occupied trapping states centred about 0·15 eV below the conduction band and about 0·4 eV above the valence band.

A crucial condition for time-of-flight measurements is that the samples have to be highly resistive, so this method can be applied only to undoped or very lightly doped samples. In earlier time-of-flight investigations by Street, Zesch and Thompson (1983), results could be obtained only for doping levels up to 2 ppm PH_3 and 100 ppm B_2H_6. In this range no effect was found on the carrier mobility. Measurements on compensated samples have been carried out by Marshall, Street and Thompson (1984). These compensated specimens behaved quite differently: the activation energies were considerably larger and the drift mobility was field dependent. It remained an open question as to what kind of changes occurred in the band tail region to cause this behaviour. It would therefore be desirable to have drift mobility data also for singly doped films at higher doping levels.

In this report we apply an alternative method for studying the drift mobility: from measurements of the steady-state photoconductivity and the response time, the drift mobility of the majority carriers can be obtained, even for doped samples. This method was first applied by Moustakas and Weiser (1975) for the investigation of amorphous arsenic telluride. Later, such studies were performed on amorphous germanium (Moustakas and Paul 1977) and hydrogenated amorphous silicon (Fuhs *et al.* 1978, Crandall 1980). It was found that the response-time method and time-of-flight experiments yield comparable results for hydrogenated amorphous silicon.

It is important to note the differences between these methods. In time-of-flight experiments the semiconductor is initially in thermal equilibrium—that is, the states in the upper half of the gap are nearly empty according to the Fermi distribution. In the time-of-flight experiment the probe charge is kept small so that no major perturbation of the equilibrium distribution occurs. However, the states in the gap of an illuminated sample are more or less occupied in the steady state. In the energy range between the mobility edge and the demarcation level, their occupation can be described by a quasi-Fermi distribution (Rose 1963), and so the non-zero occupation of the traps has to be taken into account.

§2. Experimental

We carried out measurements of the response time on a series of differently doped samples of hydrogenated amorphous silicon prepared by the glow-discharge technique. The samples were deposited to a thickness of about 1 μm onto quartz substrates held at 280°C. Besides undoped samples, we also used doped samples with doping levels up to 1000 ppm PH_3 or B_2H_6 in the gas phase. The Fermi-level positions with respect to E_c are given in the caption of fig. 2. Evaporated chromium gap-electrodes gave fairly good Ohmic contacts for field strengths from $0{\cdot}1$–2×10^4 V cm^{-1}.

The samples were illuminated with a flux density of about 10 mW cm^{-2} by a He–Ne laser (1·96 eV) for several seconds until the photocurrent had reached its steady-state value; the light was then switched off by a Pockels cell. The current was fed through a fast current–voltage converter, and the transient was recorded on a digital storage oscilloscope (Gould OS 4040). The time resolution for photocurrents of 10^{-8} A was better than 500 ns. Although the transients were non-exponential, the response time can be defined from the slope during the first few microseconds after the onset of the decay (fig. 1) by the equation

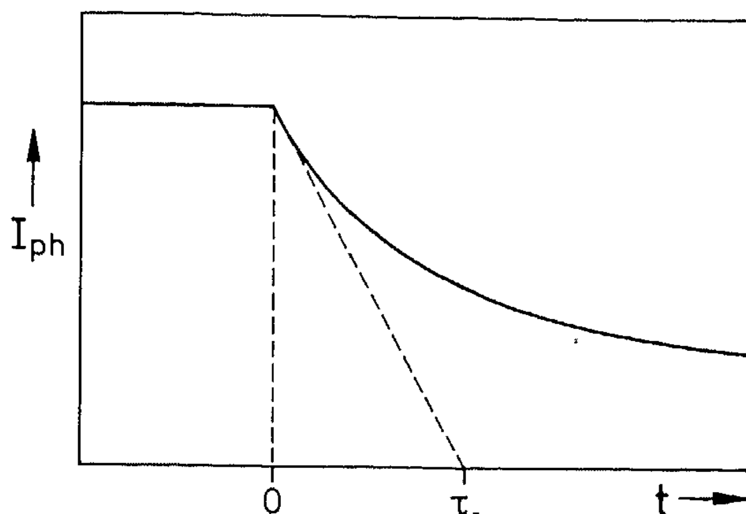
$$\frac{1}{\tau_r} = -\frac{1}{I_{ph}}\frac{dI_{ph}}{dt}\bigg|_{t=0} \qquad (1)$$

This quantity has been shown to be identical to the response time which determines the steady-state photoconductivity (Moustakas and Weiser 1975, Fuhs *et al.* 1978, Crandall 1980).

In order to determine the $\mu\tau$ product, absorption measurements were carried out on all samples investigated. The quantum efficiency η for free-carrier generation decreases from unity at room temperature to about 0·1 at 100 K (Jahn, Carius and Fuhs 1987). For simplicity this temperature dependence was neglected, and the quantum effciency was assumed to be unity. The photoconductivity is given by

$$\sigma_{ph} = eg\mu\tau_0 = eg\mu_d\tau_r, \qquad (2)$$

Fig. 1



The photocurrent I_{ph} after switching off illumination at $t=0$. The initial decay defines τ_r.

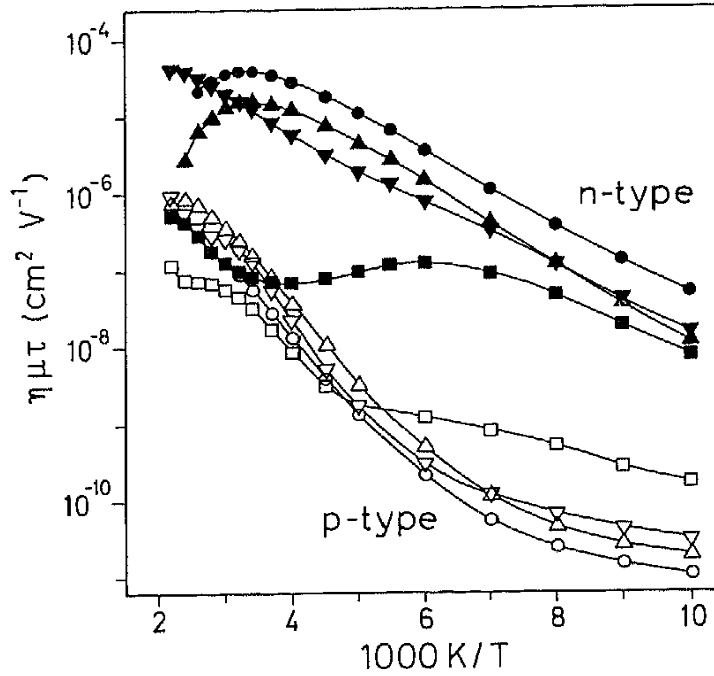
where g is the generation rate and τ_0 the free-carrier lifetime. The drift mobility μ_d can therefore be determined from the measured values of the $\mu\tau$ product and the response time τ_r.

§ 3. Results

The dependence of the $\mu\tau$ product on temperature for the different films is shown in fig. 2. All phosphorus-doped samples are highly photoconducting, $\mu\tau$ at room temperature being about 10^{-5} to $4\times10^{-5}\,cm^2\,V^{-1}$. Below about 300 K the curves exhibit an activated behaviour with activation energies of between 0·08 and 0·10 eV. The boron-doped films are less photoconducting, $\mu\tau$ at room temperature being about $10^{-7}\,cm^2\,V^{-1}$. At temperatures above 200 K the curves show an activation energy of about 0·2 eV; at lower temperatures the slope decreases and $\mu\tau$ approaches a minimum value of about $10^{-11}\,cm^2\,V^{-1}$. This behaviour can be explained by a change in the transport mechanism. On lowering the temperature, activated trap-controlled conduction becomes negligible, and the conduction is governed by the contribution of the excited carriers during their thermalization until they are localized in band tail states (Hoheisel, Carius and Fuhs 1984). This kind of transport is expected to be independent of temperature. The curve for the undoped sample is of particular interest; it shows a temperature range over which $\mu\tau$ decreases with increasing temperature, which arises from thermal quenching (as is discussed below).

The response times and their dependences on temperature are plotted in fig. 3. At the lowest temperatures the response times of the n-type samples are nearly independent of temperature (fig. 3 (*a*)). There follows an intermediate range in which all curves tend to decrease with temperature, and this decrease is particularly strong in the undoped film where the decrease already occurs at a low temperature. The reason for this behaviour is the thermal quenching of the photoconductivity, that is, a decrease in lifetime. These temperature dependences reflect the changes in the recombination process with temperature. In particular, the general behaviour can be described by competition between tunnelling transitions between band tail states and dangling bonds, and direct capture of free carriers by dangling bonds. At higher temperatures recombination with thermally occupied states determines the response time. The

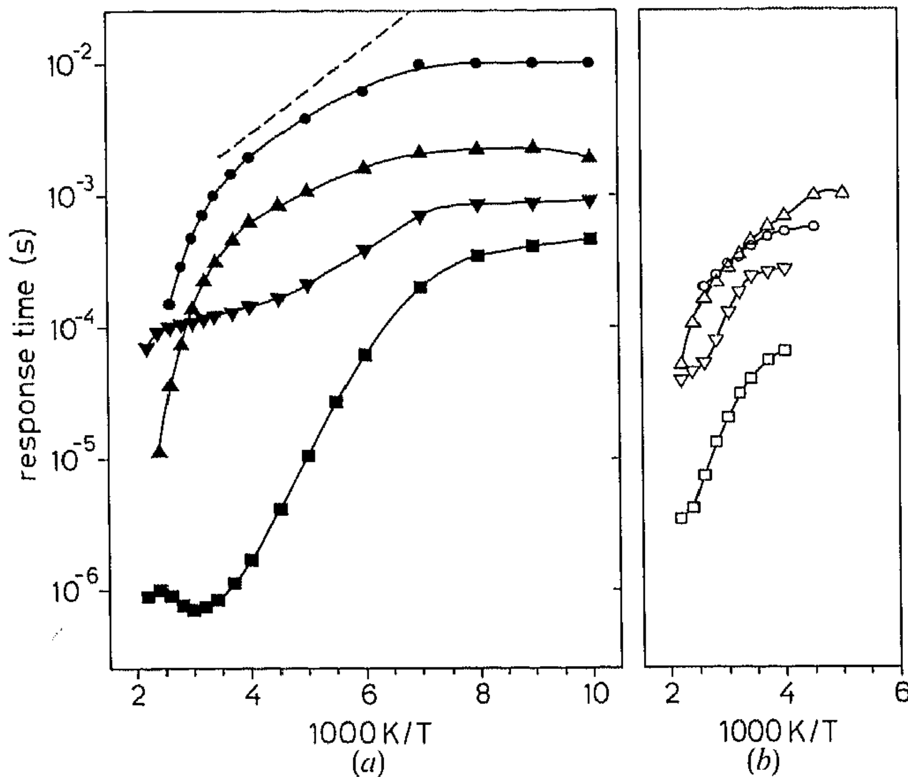
Fig. 2



The temperature dependence of the $\eta\mu\tau$ product for undoped and for phosphorus- and boron-doped samples.

	$(E_c - E_F)$ (eV)		$(E_c - E_F)$ (eV)
■ undoped	0·87	□ 30 ppm B_2H_6	0·93
▼ 33 ppm PH_3	0·59	▽ 100 ppm B_2H_6	1·01
● 100 ppm PH_3	0·31	△ 500 ppm B_2H_6	1·23
▲ 1000 ppm PH_3	0·34	○ 1000 ppm B_2H_6	1·30

Fig. 3



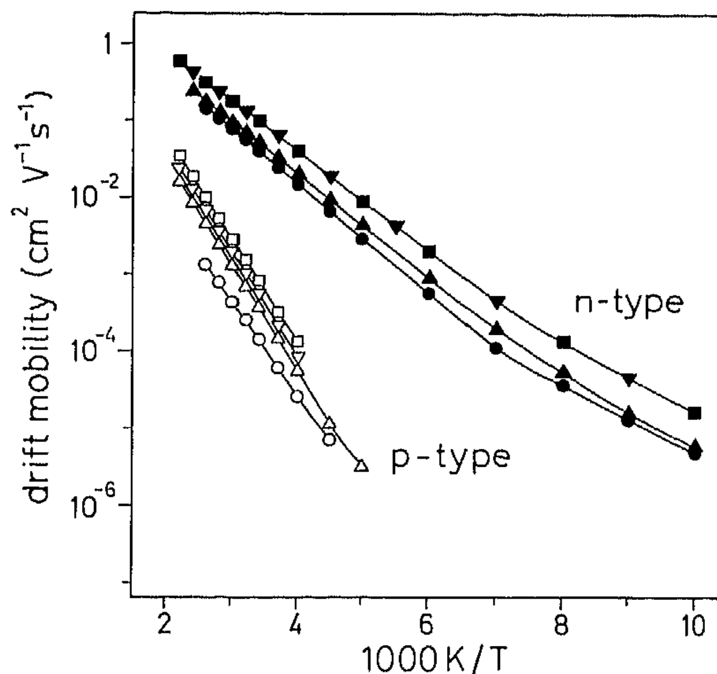
The temperature dependence of the response time for (*a*) undoped and phosphorus-doped samples, and (*b*) for boron-doped samples. The key is as for fig. 2.

$\mu\tau$ product for highly phosphorus-doped samples then shows a maximum, as observed also by Spear, Loveland and Al-Sharbaty (1974). According to fig. 3 this originates from a pronounced decrease in τ_r. It is interesting that this maximum is never found in boron-doped samples (fig. 2). A more detailed discussion of the temperature dependences is given below.

The p-type films show a very similar behaviour. However, the form of the transients did not allow a meaningful response time to be defined at low temperatures because the transients consist of a very rapid component and a much slower contribution from multiple trapping (Hoheisel *et al.* 1984). The drift mobility (fig. 4) of the majority carriers is obtained from the $\mu\tau$ product and the response time as given by eqn. (2). It came as a surprise that all the differences in the various temperature dependences of $\mu\tau$ and τ_r vanish, and the samples fall into two groups. All n-type samples, including the undoped one, which had a more complicated temperature dependence, show a rather similar dependence of the drift mobility, with values at room temperature of around $0{\cdot}1\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ and an activation energy of 0·13 eV. The p-type films have a room-temperature mobility of about $5\times10^{-4}\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ and an activation energy of 0·27 eV.

These results are comparable, considering the uncertainties, to those obtained by time-of-flight techniques on undoped films by other investigators. It is important to note that doping with up to 1000 ppm PH_3 or B_2H_6 in the gas phase does not influence the drift mobility. This contrasts with the behaviour of compensated samples in which, with increasing compensation level, the drift mobility decreases and the activation energy increases strongly (Marshall *et al.* 1984). These results show that the electronic structure in the band tail region is markedly different in singly doped and in compensated films. Marshall *et al.* (1984) concluded that compensation introduces new

Fig. 4



The temperature dependence of the drift mobility for undoped, phosphorus, and boron-doped samples. The two groups of curves show the characteristic values for n- and p-type conduction. The key is as for fig. 2.

states near both band edges which are not present in singly doped material. These states act as shallow traps and reduce the drift mobility; it is suggested that they originate from boron–phosphorus complexes.

§4. Discussion

Our drift mobility data show two different kinds of behaviour, which can clearly be related to n-type and p-type conduction. As the samples span a range of doping levels from undoped to 1000 ppm, their defect densities will be very different. The undoped sample had a dangling-bond concentration of about $10^{16}\,cm^{-3}$. This concentration will be strongly raised by doping, since dangling-bond states are created when the samples are doped (Street 1982). We thus conclude that trapping and release processes with dangling bonds do not influence the drift mobility measured under steady-state conditions.

Since the drift mobility is determined by the band tail states only, its activation energy is a measure of the average depth of the states which take part in this interaction. These energies are 0·13 eV for electrons and 0·27 eV for holes. The doping concentration has no detectable influence on the drift mobility, so it follows that the trapping states remain unaffected.

The temperature dependence of the response time reflects changes that occur in the recombination mechanism. At low temperatures the most important recombination step takes place by tunnelling transitions from localized conduction-band tail states to neutral dangling bonds. This transition is spin dependent and can be identified by a quenching of the photoconductivity when the specimen is brought into microwave resonance (Dersch, Schweitzer and Stuke 1983). In doped samples also this tunnelling transition is an important recombination step (Dersch 1983). In doped samples the magnetic-field-induced change of σ_{ph} decreases with increasing temperature, and this temperature dependence is very similar to that of the i.r. quenching of σ_{ph} (Fuhs 1985). This has been explained by means of a model in which the i.r. quenching arises from the excitation of electrons from negatively charged dangling bonds to the conduction band, and where the tunnelling transition from the band tails is the limiting step for recombination. The competitive process which decreases both the spin-dependent photoconductivity and the i.r. quenching is then attributed to the direct capture of free electrons into neutral dangling bonds (Fuhs 1985). This process short-circuits the tunnelling process when the temperature increases, and thus results in a decrease of the response time.

The dynamics of the equilibrium between trapping, retrapping and recombination can be explained by the following rate equations. For the concentration of free carriers,

$$\frac{dn}{dt}=g-\nu_0\frac{N_t}{N_c}n+\nu_0\exp[-(E_c-E_t)/kT]n_t-\frac{n}{\tau_0}, \tag{3}$$

where the second and third terms on the right-hand side describe trapping and retrapping, and the last term is the direct capture rate of free carriers.

For the concentration of trapped carriers which are in thermal equilibrium with the conducting states, the rate equation is

$$\frac{dn_t}{dt}=\nu_0\frac{N_t}{N_c}n-\nu_0\exp[-(E_c-E_t)/kT]n_t-\frac{n_t}{\tau_t}. \tag{4}$$

In this equation the last term describes the recombination from localized tail states by tunnelling to neutral dangling bonds; τ_t is the time constant for this process. On adding eqns. (3) and (4) we obtain

$$\frac{d(n+n_t)}{dt}=g-\frac{n}{\tau_0}-\frac{n_t}{\tau_t}, \tag{5}$$

which describes the time dependence of the total carrier population: the sum of free and trapped carriers.

After switching off the illumination we observe a transient as sketched in fig. 1. The slope of the decay at the onset is used to define the response time (eqn. (1)). This means that the total carrier population starts to decay with time constant τ_r, in accordance with the relation

$$\frac{d(n+n_t)}{dt}=-\frac{(n+n_t)}{\tau_r}. \tag{6}$$

By comparing eqns. (5) and (6) we obtain the response time as

$$\frac{1}{\tau_r}=\frac{1}{\tau_0}\frac{n}{n+n_t}+\frac{1}{\tau_t}\frac{n_t}{n+n_t}. \tag{7}$$

In general, when both recombination processes are operating, the expression for τ_r becomes rather complex. However, we can discuss two limiting cases:

(*a*) If the recombination takes place predominantly by capture of free carriers, then,

$$\tau_r=\tau_0\frac{n+n_t}{n}=\tau_0\frac{N_t}{N_c}\exp\left[(E_c-E_t)/kT\right], \quad n_t \gg n. \tag{8}$$

This temperature dependence is therefore given by a Boltzmann factor and leads to an increase of τ_r with decreasing temperature, as is found in all samples at temperatures which are not too low. Hence, direct capture processes determine the recombination rate near room temperature.

(*b*) If recombination by tunnelling transitions from localized tail states prevails then

$$\tau_r=\tau_t\frac{n+n_t}{n_t}=\tau_t, \quad n_t \gg n. \tag{9}$$

Since the tunnelling processes are only weakly temperature dependent, we expect from this expression a nearly constant response time. This kind of behaviour is observed at low temperatures for all n-type samples.

The behaviour in the various temperature ranges is summarized as follows.

(*a*) At low temperatures, recombination takes place by tunnelling transitions of trapped electrons from tail states to singly occupied dangling bonds. This step is spin-dependent and was identified by spin-dependent photoconductivity measurements (Dersch *et al.* 1983). The tunnelling processes are only slightly temperature-dependent. The response time is equal to the tunnelling time constant (eqn. (9)) and therefore nearly constant (fig. 3).

(*b*) At intermediate temperatures, capture of free carriers into dangling bonds occurs in addition to tunnelling. Since there is a gradual transition between the two processes, the response time is not given simply by eqn. (8), but there is an obvious decrease with temperature.

(*c*) At high temperatures the response time falls off rapidly with rising temperature. In the phosphorus-doped samples this also manifests itself in a decrease of the $\mu\tau$ product (fig. 2). It is remarkable that this does not occur in boron-doped films. This maximum of σ_{ph} has been observed by various authors (Spear *et al.* 1974, Fuhs *et al.* 1978) in phosphorus-doped films.

The undoped sample exhibits a more complicated temperature dependence. Figure 2 shows that the $\mu\tau$ product has a negative temperature coefficient in the medium-temperature range, although the drift mobility is equal to that of the n-doped samples (fig. 4). The response time shows a pronounced decrease with temperature which sets in at much lower temperatures than in the other samples (fig. 3). These features are known as thermal quenching (Vanier and Griffith 1982, Dersch and Schweitzer 1984, Carius, Fuhs and Weber 1987). The recombination rate in these undoped films is limited by the diffusion of trapped band tail holes towards the dangling bonds (Dersch 1983). In the temperature range where this diffusion becomes thermally enhanced, or when the trapped holes are excited to the conducting states, the recombination rate increases, resulting in a pronounced decrease of τ_r.

§ 5. Conclusions

The $\mu\tau$ product and the response time of hydrogenated amorphous silicon samples have been obtained from steady-state and transient photoconductivity measurements. From these data we determined the drift mobility of doped samples using a gap-cell geometry. We conclude from these results that, in undoped and doped samples, the drift mobility is determined by the interaction of free carriers with trapping states in the band tails which are not affected by doping. The drift mobility is activated rather uniformly over the temperature range investigated. The features of the temperature dependence of the photoconductivity originate from changes in the recombination mechanism. At low temperatures tunnelling processes are dominant, while with increasing temperature the direct capture of free electrons into dangling bonds becomes more and more competitive.

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