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ELECTRON TRANSPORT IN HYDROGENATED AMORPHOUS SILICON
SCHOTTKY BARRIERS AND DEEP LOCALIZED STATES KINETICS (a)

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Abstract: We present a method for analysing transport in Schottky diodes on hydrogenated amorphous silicon (aSiH). Experimental results show a correlation between the reduction of carrier collection velocity, the reduction of barrier height for reduced space-charge regions. In the same way, the kinetics of "midgap" localized states is slowed as bulk states located near the Pt-aSiH contact contribute to capacitance.

Introduction. - It is often assumed that transport in Schottky diodes on amorphous materials is limited by a diffusion process in the space-charge region. The mean reason put forward is an account for the low carrier mobility in these types of materials. Nevertheless, the thermionic theory has often been supposed to hold to measure the density of states (D.O.S.) in the gap of hydrogenated amorphous silicon (aSiH) by the C(V) technique [1], [2], [3]. In order to avoid the doubt about transport, several authors [4], [5], [6] carry out capacitance measurements at zero bias versus frequency and (or) temperature.

In this paper, we present a method of analysing results of current-voltage I(V), zero bias low frequency capacitance C(ω) characteristics versus temperature which must lead to a better understanding of the actual nature of extended state electron transport through Schottky barriers on aSiH. We put in evidence the influence of the extension of the space-charge region on the collection velocity of carriers at the metal-aSiH interface. An analogous treatment is used for the analysis of the kinetics of localized states around the Fermi level with experimentally determined parameters derived from C(ω) measurements.

The samples investigated were obtained by glow discharge decomposition of silane at three substrate temperatures : 350, 400 and 450°C. The back contact is a 0.1μm thick n-layer (PH3/SiH4=5%) deposited on a tantalum-alumina substrate. The Schottky contact is obtained by sputtering a 50Å-100Å thick Pt layer on top of the intrinsic (~1μm thick) aSiH. The diodes achieved on the 400°C material exhibit more than 2% power efficiency [5].

Electrical characterization. - Current-voltage I(V) characteristics are performed in the range of temperature [-90°C, +180°C] [5], [7]. They first behave exponentially (fig.2) for forward bias lower than the built-in potential Vse (fig.1) following the relation :

(a) Work supported by COMES
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* Samples achieved by B. BOURDON, CRCGE Marcoussi, France
where \( I_0 = I_{0e} \exp(-\frac{\phi_B}{kT}) \) (2) will give the barrier height \( \phi_B \) (Fig.1), \( \beta \) is the ideality factor of the diode.

At higher voltage, we obtain a linear dependence of current with voltage. The slope of the characteristics allows us to determine a mean value of the bulk conductance \( G_B \) of the material. Its activation energy will give the mean electron quasi-Fermi level distance \( (E_C-E_F) \) from the conduction band (Fig.1). Thus we have:

\[
G_B = \sigma_B \frac{S}{t} \quad \text{with} \quad \sigma_B = \sigma_0 \exp \left( -\frac{E_C-E_F}{kT} \right)
\]

where \( \sigma_B \) is the mean bulk conductivity, \( S \) is the surface of the Pt contact, \( t \) the thickness of the intrinsic aSiH layer, \( \sigma_0 \) is given by:

\[
\sigma_0 = q N_C \mu 
\]

\( N_C \) being the effective density of states at \( E_C \), \( \mu \) the electron mobility, \( q \) the electron charge.

In the same range of temperature we perform low-frequency \( C(\omega) \) measurements (1Hz, 10Hz) (see fig.3) for 1Hz capacitance. For temperatures higher than \( T_{resp} \) the capacitance starts to rise: the states around the Fermi level at the neutral bulk boundary-\( w \) (fig.1) begin to respond to the modulation.

In the same way, when the capacitance saturates at a temperature \( T_{sat} \) the bulk states around \( E_F \) near the Pt-aSiH interface contribute to capacitance (neglecting the response of surface states). The saturation value of low frequency capacitance (typically 1Hz fig.3) \( C_{sat} \) allows us to deduce the D.O.S. around the midgap in the case of a uniform distribution \( N \):

\[
N = \frac{C_{sat}}{q^2} \left( \text{Table I} \right).
\]

Thus, the equilibrium value of the space-charge width will be:

\[ w = L_D \log \left( \frac{C}{C_{sat}} \right) \left( \text{Table I} \right) \]

The electrical potential \( V(x) \) having an exponentialshape: \( V(x) = V_{so} \exp(-\frac{x}{L_D}) \).

\( L_D \) being the Debye length associated to the uniform D.O.S. around the midgap:

\[
L_D = \left( \frac{e N}{q^2} \right)^{1/2}
\]

**Table I - Results (electrical characterization)**

<table>
<thead>
<tr>
<th>( T ) (°C)</th>
<th>( E_g ) (eV)</th>
<th>( \phi_B ) (eV)</th>
<th>( E_C-E_F ) (eV)</th>
<th>( V_{so} ) (V)</th>
<th>( B )</th>
<th>( I_0 ) (Acm(^{-2}))</th>
<th>( \sigma_0 ) (( \Omega^{-1} )cm(^{-1}))</th>
<th>( N ) (cm(^{-3})eV(^{-1}))</th>
<th>( w ) (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>1.72</td>
<td>0.81</td>
<td>0.62</td>
<td>0.19</td>
<td>1.2</td>
<td>1.1 \times 10^2</td>
<td>1.3 \times 10^2</td>
<td>3.5 \times 10^6</td>
<td>0.28</td>
</tr>
<tr>
<td>400</td>
<td>1.79</td>
<td>1.02</td>
<td>0.66</td>
<td>0.36</td>
<td>1.54</td>
<td>9.3 \times 10^5</td>
<td>3 \times 10^2</td>
<td>1 \times 10^16</td>
<td>0.67</td>
</tr>
<tr>
<td>450</td>
<td>1.71</td>
<td>0.72</td>
<td>0.52</td>
<td>0.20</td>
<td>1.16</td>
<td>2.7 \times 10^4</td>
<td>1.9 \times 10^2</td>
<td>2.5 \times 10^{17}</td>
<td>0.115</td>
</tr>
</tbody>
</table>

Electron collection velocity. - In a general way, the dark free electron current \( I_s \rightarrow m \) from the semiconductor to the metal can be expressed by:

\[
I_s \rightarrow m = q N_C u_s \exp\left( -\frac{\phi_B}{kT} \right) \exp \left( \frac{qV}{kT} \right)
\]
where \( u_s \) is the mean collection velocity of carriers at the interface. If the current is diffusion limited then \( u_s \) is the drift velocity \( v_{ds} \) at the interface:

\[
u_s = \frac{VFS}{Vds} \quad \text{where } F_s \text{ is the field at the interface given by:}
\]

\[
F_s = \frac{VFS}{v_{ds}} \quad \text{(4) (Table II)}.
\]

- If the thermionic theory holds, then \( u_s \) is the metal collection velocity and will have the thermal velocity \( v_{th} \) as a maximum value \([8]\).

Thus, we will have according to relation (2):

\[
Q = \alpha N_{C} u_s. \quad \text{(5)}
\]

From relations (3) and (5) we deduce:

\[
u_s = \frac{Q}{\alpha N_{C} F_s}. \quad \text{(6)}
\]

The ratio \( u_s/v_{ds} \) can then be evaluated from experimentally derived parameters (Table II).

Dynamic behaviour of midgap states. - When the states located at \( W \) start contributing to capacitance their response time \( \tau_{resp} \) is given by S.R.H statistics:

\[
\tau_{resp} = \tau_{F} \exp \frac{E_F-E_F}{K_{T_{resp}}} \quad \text{where } \tau_{F} = \frac{1}{\sigma_F v_{th1}(E_F)K_{T_{resp}}}. \quad \text{(6)}
\]

When the capacitance saturates we expect all the states located at a distance \( q_{gb} \) from the conduction band to contribute plainly to capacitance [5] with a response time:

\[
\tau_{sat} = \tau_{gb} \exp \frac{q_{gb}}{K_{sat}} \quad \text{where } \tau_{gb} = \frac{1}{\sigma_{gb} v_{th2}(E_F)K_{T_{sat}}}. \quad \text{(7)}
\]

In (6) and (7): \( \sigma_F \) and \( \sigma_{gb} \) are the electronic capture cross sections of the states around the Fermi level respectively at \( W \) and at the interface, \( v_{th1} \) and \( v_{th2} \) are the thermal velocities at \( T_{resp} \) and \( T_{sat} \), \( N(E_F) \) is the density of states at \( E_F \).

We thus consider that the bulk states at the distance \( q_{gb} \) don't necessarily obey the same kinetics as the states at \( (E_F-E_F) \) even if the energy difference \( q_{VS0} \) is small as it is the case for 350°C and 450°C samples (Table I).

For a given working frequency \( \nu \) we must have a response temperature and a saturation temperature and:

\[
\nu \nu)^{-1} = \tau_{resp} = \tau_{sat} (\text{see fig.3 for } 1\text{Hz capacitance}).
\]

In practice, we observe a linear dependence of Log \( \nu \) as a function of \( (T_{resp})^{-1} \) (fig.4). In figure 4 the activation energy given experimentally is \( (E_F-E_F) \) that shows a posteriori that the bulk Fermi level determined from the linear part of \( I(V) \) characteristics is correct. From the pre-exponential factor of the curves in fig.4 we can determine \( \tau_{OF} \) (Table II).

### Table II - Experimentally determined d.c. transport and dynamic parameters

<table>
<thead>
<tr>
<th>( T ) (°C)</th>
<th>( t ) (\text{h})</th>
<th>( F_s ) (\text{V/cm})</th>
<th>( v_{ds} ) (\text{V/cm})</th>
<th>( \tau_{resp} ) (\text{s})</th>
<th>( \tau_{sat} ) (\text{s})</th>
<th>( \Delta T ) (°K)</th>
<th>( \tau_{OF} ) (\text{s})</th>
<th>( \tau_{q_{gb}} ) (\text{s})</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>0.9</td>
<td>1.5•10^{-4}</td>
<td>170</td>
<td>220</td>
<td>343</td>
<td>123</td>
<td>6.5•10^{-13}</td>
<td>1.2•10^{-11}</td>
</tr>
<tr>
<td>400</td>
<td>0.9</td>
<td>1.4•10^{-4}</td>
<td>7</td>
<td>273</td>
<td>433</td>
<td>160</td>
<td>7•10^{-13}</td>
<td>7•10^{-13}</td>
</tr>
<tr>
<td>450</td>
<td>1</td>
<td>3.6•10^{-4}</td>
<td>169</td>
<td>193</td>
<td>333</td>
<td>140</td>
<td>3•10^{-14}</td>
<td>1.5•10^{-11}</td>
</tr>
</tbody>
</table>

* For 1Hz capacitance

For a given material, if the response kinetics of the states around \( E_F \) were the same at \( W \) and at the interface then the quantity \( \Delta T = (T_{sat} - T_{resp}) \) should be proportional to \( v_{S0} \) according to S.R.H statistics. For small values of \( v_{S0} \), \( \Delta T \) is too large (Table II). For the same samples, the great difference between \( \tau_{OF} \) and \( \tau_{q_{gb}} \) shows that the kinetics is slowed as the bulk states at \( q_{gb} \) contribute to capacitance in materials with a thin space-charge region.

In the same way, the ratio \( u_s/v_{ds} \) gets smaller (Table II) and the barrier height \( q_{gb} \) decreases as \( W \) decreases.

Possible interpretation. - We are in right to imagine that the static and dynamic behaviour of the Schottky diode have the same origin. The possibility of carrier collection by intermediate trapping in localized band-tail states in the space-charge region must not be excluded. Thus, the ratio \( u_s/v_{ds} \) decreases as \( W \) decreases.
Classically, we would have expected the contrary if transport were diffusion limited. As a matter of fact, the effect is more pronounced as the band-bending at the Pt-aSiH contact is more important: (case of 350 and 450°C materials) : \( u_s \) is smaller than \( v_d \) by a factor of 10².

The dynamic behaviour follows the static behaviour. (Table II). The communication between deep states at interface and the conduction band is probably established via intermediate trapping of the electrons in band-tail states. Thus \( \tau_{\text{eff}} \) can be higher than \( \tau_0 \) by a factor of 10².

Conclusion. - We have presented a method of analysis of \( I(V) \), \( C(\omega) \) characteristics versus temperature that can lead to a better understanding of transport in Pt-aSiH Schottky diodes as well as the kinetics of deep localized gap states in aSiH. We have proposed a possible interpretation for the reduction of collection velocity of extended states electrons at the metal-aSiH Schottky contact. This phenomena is accompanied by an enhancement of thermal release time of the deep bulk states at the surface Fermi level and a reduction of the barrier height. That reflects also the indirect influence of the D.O.S. around the midgap on the extended states electron transport.

References


