AC LOSS IN AMORPHOUS GERMANIUM AT LOW TEMPERATURES
A. Long, W. Hogg, N. Balkan, R. Ferrier

To cite this version:

HAL Id: jpa-00220816
https://hal.archives-ouvertes.fr/jpa-00220816
Submitted on 1 Jan 1981

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
AC LOSS IN AMORPHOUS GERMANIUM AT LOW TEMPERATURES

Department of Natural Philosophy, University of Glasgow, Glasgow G12 8QQ, Scotland

Abstract.—The frequency, temperature and field dependences of the audio frequency AC loss in a series of sputtered hydrogenated amorphous germanium samples are investigated over the temperature range 1 - 10K. The results conflict with the predictions of the model in which electrons are assumed to tunnel between localised states uniformly distributed in space and in energy.

1. Introduction. The aim of this work was to extend our previous measurements of AC loss in amorphous germanium, performed at around liquid nitrogen temperature (1,2) to very much lower temperatures. At liquid nitrogen temperatures and above, the elementary theory of electron hopping processes suggests that typical hopping energies will be of magnitude a few kT, and hence are almost certain to involve multi-phonon processes, for which the matrix elements are not yet well known (3,4). However if measurements are made at liquid helium temperatures then the thermal energies involved are much smaller and single phonon processes should dominate (4). It is in this low temperature regime that DC variable range hopping is observed in impurity bands (5) and inversion layers (6). It was our intention to study the AC loss at liquid helium temperatures to see if the ideas of variable range hopping are more successful in explaining the new experimental data than they were in accounting for our previous observations (1,2).

2. Predictions of the theory for AC loss by tunnelling between localised states.

The theories of AC loss in amorphous germanium or silicon invariably assume a population of electron states uniformly distributed in energy and in space, between which electron transfer occurs by tunnelling. The calculations are usually performed in the pair approximation and assume a relaxation time for electron transfer between states separated in energy by $\Delta$ and in space by $R$ of the form

$$\tau \sim \tau_0 \exp(2aR) \exp(\Delta/kT)$$

(1)

For reasons of state occupation, the loss will be dominated by states close to the fermi level ($\Delta/kT < 1$). Moreover if each pair of states is assumed to respond as a Debye oscillator, then the maximum loss will occur for an angular frequency $\omega = \tau^{-1}$. Taking these results together implies an effective hopping length at an angular frequency $\omega$ of

$$R_{eff} \sim -(2\alpha)^{-1} \cdot \ln(\omega \tau_0)$$

(2)

Considering the contribution of each pair of states independently it is straightforward to deduce an AC conductivity

$$\sigma \sim \frac{2e^2}{(2\alpha)^5} \omega kT \left[-\ln(\omega \tau_0)\right]^4$$

(3)

where $g$ is the density states. This result, first derived by Austin and Mott (7), was confirmed using more detailed statistics by Pollak (8) and using a percolation approach by Butcher and Hayden (9). It predicts a loss which varies directly as the...
temperature, and has a frequency exponent $s$ (when the loss is expressed as $\omega^s$) given by

$$s = 1 - 4/\left[2 \ln(\omega \tau)\right]$$

which should be approximately independent of frequency for $\omega \tau << 1$ and independent of temperature. Recently a more refined calculation by Movaghar, Pohlmann and Sauer (10) has shown that $s$ may be a weak function of temperature.

3. Experimental Observations. For our investigation, we chose to work with amorphous germanium samples sputtered in argon and argon/hydrogen atmospheres which can be prepared in a more reproducible manner than evaporated samples. Our samples were of sandwich configuration and measured using a simple AC bridge. Some DC properties measured around liquid nitrogen temperatures are given in table 1. These, together with the higher temperature AC loss results are to be discussed in a forthcoming paper. The most interesting result for our purposes is that the DC conductivity of these samples at 77K varies by some 6 orders when hydrogen is incorporated, which is not fully explained by the changes in $\tau_{0}$, the temperature exponent in the Mott $\tau_{0}^{a}$ relationship (accurately obeyed by all the samples around 77K).

However when the AC loss in these samples at helium temperatures was measured, it was found to vary very little with hydrogen content (see table 1); all the conductivities measured at the same temperature (4.2K) and frequency were within a factor of 2 of one another. The frequency exponents $s$ (measured at 4.2K) were again similar from sample to sample having values in the range of 0.9. $s$ was observed to be only a weakly decreasing function of temperature, varying for sample B5 for example from 0.88 at 1.2K to 0.84 at 8K. These results are in accord with the equations of §2. On the other hand the temperature dependence of the conductance (G) at a fixed frequency (figure 1) does not agree with equation 3. G does not have a simple power law dependence on temperature, but becomes less temperature dependent as the temperature is lowered.

In addition to these standard observations, we have detected a new low temperature effect, an AC field effect. As the AC electric field $F$ across our sample is increased, the conductivity, initially independent of field, begins to increase (figure 2). The onset field at which changes begin increases with temperature, and at high fields the loss curves for different temperatures converge, with the loss becoming temperature independent. Similar field curves are observed over the full range of frequencies at which data was taken (figure 2). We were not able, to the accuracy of our data, to detect any frequency variation of the onset field.

It should be emphasised that the variation of conductance with field is an AC effect, and is not related to the DC conductance. Although these samples invariably have a field dependent DC leakage path in parallel with the AC loss, in the measurements described this leakage was never more than 10% of the AC conductance at low fields and could be subtracted from the data to leave the AC loss without introducing an error of greater than a few per cent. The accuracy of this conclusion is confirmed by the observation that a similar field effect is observed at all
An important clue as to the meaning of the field effect is provided when curves of \( G(F) \) at a constant low temperature and \( G(T) \) at low field are compared (figure 1). The similarity between these sets of data suggest that the energy changes associated with temperature \((kT)\) and with the applied field \((eF_{\text{eff}})\) act in the same way. For the sample illustrated, by comparing regions of constant conductance and writing \( eF_{\text{eff}} \approx kT \), we may estimate \( R_{\text{eff}} \) as \((0.8 \pm 0.1) \text{nm}\).

Unfortunately complete enough sets of temperature and field data are not available for all the samples. For these we estimate \( R_{\text{eff}} \) by determining the field at which the conductance had increased by 10\% over its low frequency value (measured at 4.2K and 3KHz) and using \( eF_{\text{eff}} \approx kT \). The \( R_{\text{eff}} \) values given by this technique are given in the table in brackets and serve as a good indication of the pronounced trend in our data, which is for \( R_{\text{eff}} \) to increase strongly as the hydrogen incorporated (measured by its concentration in the sputtering gas) increases.

4. Interpretaion in terms of tunnelling between localised states at the Fermi level. In applying the theory of section 2 to our data, we start from the feature most closely in agreement with theory, namely the temperature independent value of 0.9. Using equation 4, this suggests a \( t_0 \) value of around \( 10^{-22} \text{ s} \). This is similar to the values obtained from trying to fit AC data at higher temperatures \((9, 10)\), and is not easy to explain using realistic parameters, even in the framework of the Miller-Abrahams \((11)\) relaxation rates. A more important obstacle becomes apparent however when this result is applied to calculate \( R_{\text{eff}} \) using equation 2. Taking estimates of \( \alpha^{-1} \) of \( 1 \text{nm} \) from thickness dependent conductivity \((12)\) or \( 1.5 \text{nm} \) from DC field effect \((13)\) (both results assuming the validity of the Mott variable range hopping model), we get \( R_{\text{eff}} \) values of 20 and 30nm respectively, very much greater than the field effect values of Table 1. Alternatively, reversing the argument, accepting the \( R_{\text{eff}} \) values from the AC field effect, we obtain an \( \alpha^{-1} \) for the pure film of around \( 40 \text{ pm} \), which would correspond, using simple quantum mechanics to an energy gap value of \( 24 \text{ eV} \). Such a value is obviously unphysical. Moreover one would not expect from this model such a rapid variation of \( \alpha^{-1} \) with hydrogen content. (The optical gap changes by some 100\% over this range of hydrogenation \((14)\), but the change is in the opposite sense to that predicted by simple quantum mechanics from the \( \alpha^{-1} \) data).

The temperature dependence and field effect data cannot be explained either using the ideas of tunnelling in a uniform density of states. As we have already suggested, the low field loss should vary linearly with temperature. The observed temperature dependence would imply a narrow peak in the density of states at the Fermi level of width \( \sim kT \), which we consider physically unlikely. In the high field

![Fig. 2. The AC field dependence of the conductance at different frequencies and temperatures (Sample B2).](image)
limit, the AC loss is non-linear and difficult to calculate. However we do not believe that the observations are in accord with this model.

Our conclusion therefore is that, as with the high temperature data (1,2), tunnelling of electrons between states uniformly distributed in space and in energy cannot provide an explanation of the observations.

5. Conclusion. Given that the effective hopping distance for pure films is only of the order of \( \text{lnnm} \), we postulate that the AC loss we are measuring occurs in intimate pairs of states with only weak coupling between the pairs. In order to explain why these states respond at audio frequencies, while retaining a reasonable value for the intrinsic "attack frequency" \( T_0^{-1} \), the pairs must be coupled via a potential barrier of magnitude many times \( kT \). This model resembles the ideas which have been successful in explaining our nitrogen temperature data (1,2) and we hope to pursue this comparison in future work.

### Table 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>Area/Thickness</th>
<th>( \sigma_{DC}^{77K} ) /( 10^{-4} \text{ m} )</th>
<th>( T_0 ) /( K )</th>
<th>( \sigma_{AC}^{4.2K} ) /( 10^{-8} \text{ m} )</th>
<th>( S_{4.2K} ) /( K )</th>
<th>( S_{4.2K} ) /( \text{nm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>B5</td>
<td>Pure Ar</td>
<td>23.7</td>
<td>6.6 ( 10^{-4} )</td>
<td>9.2 ( 10^7 )</td>
<td>2.0 ( 10^{-8} )</td>
<td>0.88</td>
</tr>
<tr>
<td>NS12</td>
<td>5:1</td>
<td>10.8</td>
<td>9.7 ( 10^{-6} )</td>
<td>9.4 ( 10^7 )</td>
<td>4.4 ( 10^{-8} )</td>
<td>0.90</td>
</tr>
<tr>
<td>B2</td>
<td>3:1</td>
<td>10.5</td>
<td>1.35 ( 10^{-7} )</td>
<td>1.56 ( 10^8 )</td>
<td>3.6 ( 10^{-8} )</td>
<td>0.89</td>
</tr>
<tr>
<td>B1</td>
<td>2:1</td>
<td>4.2</td>
<td>3.1 ( 10^{-9} )</td>
<td>3.12 ( 10^8 )</td>
<td>2.9 ( 10^{-8} )</td>
<td>(6.9)</td>
</tr>
</tbody>
</table>

### References