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AC FIELD AND FREQUENCY DEPENDENCE OF a-Si:H CONDUCTIVITY AT 4.2 K

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Abstract. - The a.c. field and frequency dependences of complex conductivity of a-Si:H sandwiches are observed at 4.2 K. The results are consistent with spatial limitation of motion of carriers, in extended states, confined in potential wells.

Introduction. The frequency dependence of the a.c. conductivity of compensated crystalline, as well as amorphous and glassy semiconductors, has been the subject of a large amount of experimental and theoretical research. Since the paper of Pollak and Geballe (1), it has been found, in a large variety of materials, an a.c. conductivity $\sigma_{ac} \propto \omega^s$, with $s < 1$, although in few instances (2) a law $\sigma_{ac} \propto \omega^2$, followed by a saturation, not due to spurious series resistances, seems to have been observed. Models of hopping proposed in order to account for the data have been reviewed by Jonscher (3) and Pollak (4). Possible effects of the inhomogeneity of the samples were considered by Jonscher (5), Gilbert and Adkins (6), and the effect of contact barriers were taken into account by Fritzsche (7), and by Snell et al (8). In the case of amorphous silicon, we shall mention the work of Abkowitz et al (9), Snell et al (8), on glow discharge deposited material, and of G. Rieder (10) on non hydrogenated films obtained by evaporation and annealing. In this paper we report measurements, performed at 4.2 K, on the frequency dependence of the complex admittance of a-Si:H sandwiches, as a function of a.c. field amplitude.

Experimental results. The samples were a-Si:H films, with metallic electrodes, in sandwich configuration, coming from various origins, chiefly :

- samples A : undoped a-Si:H, grown at L.G.E.P., C.N.R.S. Paris, by d.c. Sputtering on a glass substrate partly coated with chromium-antimony. Evaporated platinum or platinum coated with aluminium was used as top electrode (rectifying contact) ;
- samples B : phosphorous doped a-Si:H elaborated at Thomson-CSF by C.V.D. on crystalline n⁺-Si, with or without annealing at 400° C in hydrogen plasma. Top contact was obtained by evaporating successively Ti and Al films (non rectifying contacts).

Admittance measurements were performed, using either a low frequency response analyser in the range $10^2 - 10^6$ Hz, or a capacitance bridge and a lock-in amplifier especially in the frequency range where the conductivity is field dependent.

Although it will be shown that the sample is probably an inhomogeneous medium constituted by domains of different electric properties, it is convenient, in order to compare the properties of samples of different origins, size and thickness, to consider the apparent permittivity ϵ_{ac} and conductivity σ_{ac} of an equivalent homogeneous medium which would provide the same sample admittance.

For all samples we find that, in the low frequency range, i.e. roughly up to about 10^4 Hz, σ_{ac} increases with frequency and with a.c. field amplitude. In the case of samples B (Fig. 1), this field dependence is linear, up to at least $7 \cdot 10^5$ V/m, and given by :

$$\sigma_{ac}(E) = (aE + K_0) f \quad (1)$$

where E is the average r.m.s. electric field across the sample, a and K_0 are

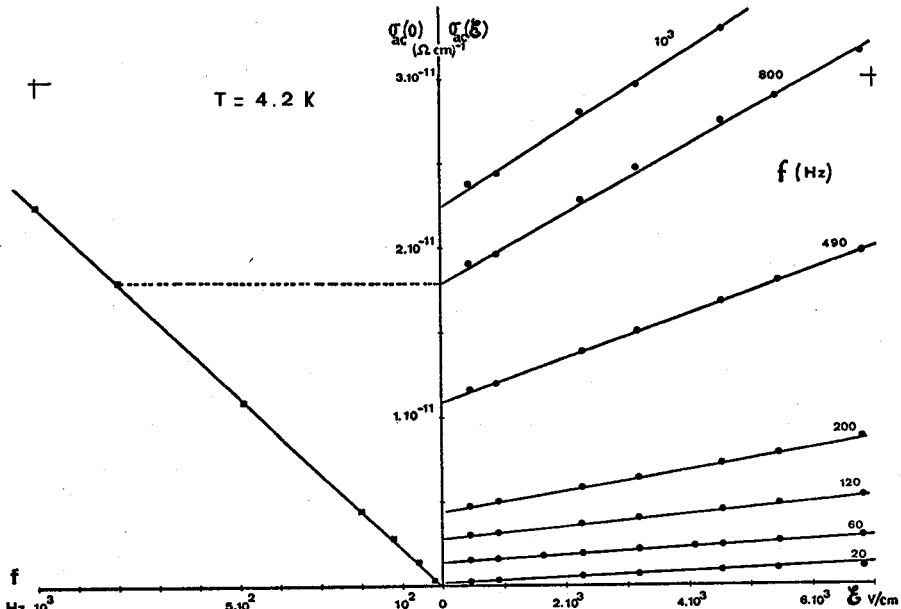


FIGURE 1. A.C. CONDUCTIVITY FIELD AND FREQUENCY DEPENDENCE OF α -Si₁₄H TYPE B SAMPLE

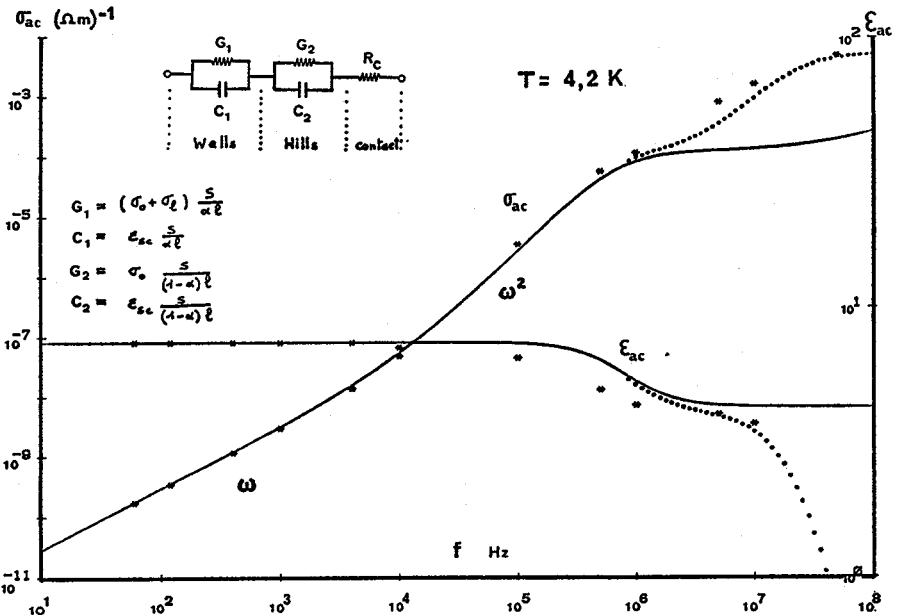


FIGURE 2. CONDUCTIVITY AND DIELECTRIC CONSTANT FREQUENCY DEPENDENCE : EXPERIMENTAL POINTS (x) FIT ACCORDING TO CIRCUIT ENCLOSED WITH $R_c = 0$ (—), AND WITH $R_c \neq 0$ (.....). NOTE THE ω - ω^2 TRANSITION

constants characteristic of the sample, f is the frequency. The values obtained for some samples are given in Table I. A d.c. field of similar or higher intensity, superimposed to the a.c. field, does not change noticeably the value nor the field dependence of σ_{ac} , showing that this effect is not due to a barrier lowering. A remarkable result is that the zero field conductivity $\sigma_{ac}(0)$ is proportional to frequency. In the same frequency range $\epsilon_{ac}(E)$ decreases slightly when ω/E increases and tends towards a limit ϵ_{lim} : in first approximation $(\epsilon_{ac} - \epsilon_{lim})^{-1}$ is a linear function of ω/E .

| SAMPLE TYPE | DOPING LEVEL (phosphorous) | TOP CONTACT | THICKNESS (μm) | TEMPERATURE T (K) | CHARACTERISTIC PARAMETERS | |
|-------------|-------------------------------|-------------|--------------------------|---------------------------|-------------------------------------|---------------------------------------|
| | | | | | a ($\mu V Hz$) ⁻¹ | k_0 ($\mu m Hz$) ⁻¹ |
| A | 0 | Pt | 1.25 | 4.2 | $1.6 \cdot 10^{-18}$ | $2 \cdot 10^{-12}$ |
| B | 10^{-3} | Ti Al | 0.22 | 4.2 | $2.4 \cdot 10^{-18}$ | $2.3 \cdot 10^{-12}$ |
| B | 10^{-3} | Ti Al | 0.22 | 4.2 | $5.1 \cdot 10^{-18}$ | $3.8 \cdot 10^{-12}$ |
| B | $3 \cdot 10^{-4}$ | Ti Al | 0.16 | 4.2 | $6.3 \cdot 10^{-18}$ | $5.4 \cdot 10^{-12}$ |
| B | 10^{-5} | Ti Al | 0.35 | 4.2 | $4.1 \cdot 10^{-19}$ | $0.9 \cdot 10^{-12}$ |

Table I

In the high frequency range σ_{ac} and ϵ_{ac} do not depend anymore on the field intensity: σ_{ac} varies as ω^2 and finally saturates while ϵ_{ac} remains constant. This effect may not be confounded with that of a spurious series contact resistance R_c , on the condition that R_c is sufficiently small, as shown on Fig. 2.

Interpretation. Fritzsche (7), Snell et al. (8), proposed an equivalent circuit consisting of two parallel RC circuits in series, the one representing the contact barrier, the other the bulk. We shall consider here that barriers separating potential wells may be located at the contact interfaces, and (or) in the bulk in presence of spatial fluctuations of potential (Pistoulet et al. (11)). In the simplest representation of this inhomogeneous medium, composed of stacked sheets, we consider potential hills of conductivity σ_o occupying a fraction $(1 - \alpha)$ of the total thickness, separated by potential wells of conductivity $\sigma_l + \sigma_l$ occupying the fraction α of the thickness ($0 < \alpha < 1$). The apparent conductivity and permittivity of this medium are then :

$$\sigma_{ac} = \sigma_o + \alpha \sigma_l \frac{\sigma_o (\sigma_o + \sigma_l (1 - \alpha)) + \omega^2 \epsilon_{sc}^2}{(\sigma_o + \sigma_l (1 - \alpha))^2 + \omega^2 \epsilon_{sc}^2} \quad (2)$$

$$\epsilon_{ac} = \epsilon_{sc} \left(1 + \frac{\alpha (1 - \alpha) \sigma_l^2}{(\sigma_o + \sigma_l (1 - \alpha))^2 + \omega^2 \epsilon_{sc}^2} \right) \quad (3)$$

1° In the high frequency range (except possibly at $f > 10^7$ Hz) $\sigma_o \ll \sigma_l$, and these expressions reduce, by putting $\tau = \epsilon_{sc} / [\sigma_o + \sigma_l (1 - \alpha)]$, to :

$$\sigma_{ac} \sim \sigma_l \alpha \frac{\omega^2 \tau^2}{1 + \omega^2 \tau^2} \quad (4) ; \quad \epsilon_{ac} \sim \epsilon_{sc} \left(1 + \frac{\alpha / (1 - \alpha)}{1 + \omega^2 \tau^2} \right) \quad (5)$$

The experimental data may be well fitted by these expressions (Fig. 2), where σ_l is assumed to be independent of frequency. Besides, at the highest frequencies it is necessary to consider the decreases of ϵ_{ac} and the saturation of σ_{ac} due to the spurious effect of the series contact resistance R_c .

2° In the low frequency range, $\omega \tau \ll 1$, and it is found from experiment that, at the limit of the L.F. and H.F. ranges, $\sigma_o \ll \sigma_l$ so that :

$$\sigma_{ac} \approx \frac{\sigma_o}{1 - \alpha} \left(1 + \frac{\alpha \epsilon_{sc}^2 \omega^2}{\sigma_l \sigma_o (1 - \alpha)} \right) \quad (6)$$

This equation may only be compatible with the experimental equation (1) if σ_o is proportional to ω , and σ_l is proportional to ω/E in the L.F. range. This behaviour of σ_l , which is constant in the H.F. range, may be understood if the conductivity is due to free carriers in extended states : at low frequency, the motion of these car-

riers is limited by the size of the wells, and so, the active current through the sample is no more sinusoidal. This has been confirmed by recording this very small current. When the ratio ω/E is such that the transit time in the wells is small compared to half a period of the field, the fundamental component of the current is proportional to ω , and independent of the field :

$$i_1 \sim \frac{4}{\pi} \cdot \frac{\alpha z_0 \sigma_l \omega}{\mu} \quad (7)$$

where z_0 is the thickness of the wells. Thus it appears that the apparent conductivity σ'_l of the wells, at the fundamental frequency, is proportional to ω/E . Replacing σ_l by σ'_l in (6), we get an expression having the same form as (1). Furthermore, the variation of ϵ_{ac} with ω/E , due to this limitation of the motion of the carriers in the wells, may also be explained by a Fourier series development.

Let us go back to the frequency proportionality of $\sigma'_o = (1 - \alpha) \sigma_{ac}(o)$. We may first attempt to ascribe this frequency dependence to a hopping conduction mechanism. However it is known that the hopping models, which have been developed till now, lead to laws $\sigma \propto \omega^s$ with $s < 1$; they are unable to explain values of s equal to unity (10,12).^{ac} In order to overcome this difficulty, we suggest another tentative explanation. The conductivity σ'_o may be due to electrons of the conduction band jumping over the barriers, and this leads to a Debye dispersion law; the values of the time constant involved in this law may be distributed over a large interval as a consequence of a continuous distribution of traps, and, as it is known, the result of the integration is then a conductivity proportional to ω .

Conclusion. Our data on the field and frequency dependence of the complex conductivity of a-Si:H sandwiches at 4.2 K may be explained by considering that electrons in extended states are located in potential wells. On the other hand, it appears unlikely that the observed low frequency zero field conductivity may be attributed to hopping, the hopping conduction being probably overcome by a conduction mechanism of the Debye type.

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