dc and ac photoconductivities in hydrogenated amorphous germanium

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The dc and ac photoconductivities $\sigma_p(0)$ and $\sigma_p(f)$ of hydrogenated amorphous germanium have been measured in the temperature range 18–300 K. The ratio $\sigma_p(f)/\sigma_p(0)$ for different intensities of illumination follows a universal function of frequency at temperatures below 50 K. The low-temperature photoconductivity is discussed in terms of dispersive diffusion of electrons in band tails.

Since temperature-independent dc photoconductivity below about 50 K was reported in hydrogenated amorphous silicon (*a*-Si:H),[1] there have been a number of reports presenting experimental data on low-temperature photoconductivity in *a*-Si:H.[2–7] Nearly the same features have also been found in nonhydrogenated amorphous Ge and Si and chalcogenide glasses.[7] Theoretical models[8] have been developed to explain this universal behavior of the low-temperature transport properties, suggesting that the transport is dominated by simultaneous diffusion and recombination of electron-hole pairs in band tails. The various measurements and models have been reviewed by Fritzsche.[9]

The measurement of ac photoconductivity (ac loss under steady illumination) could provide information about the dynamical diffusion property of photoexcited carriers.[5,6,9,10] Shklovskii, Fritzsche, and Baranovskii[10] have predicted that $\sigma_p(f)$ at lower temperatures is proportional to $f^s L^\gamma$ with $s \simeq 0.8$ and $\gamma \simeq 0.3$, where f is the frequency and L is the illumination intensity. The experimental ac photoconductivity data of *a*-Si:H (Refs. 5 and 6) have been compared with this theory,[10] and the agreement with the theory seems to be poor.[6,10] It is of interest to measure ac photoconductivity in other material systems, as this could provide more information on the dynamic responses of hopping carriers.

In the present study, the dc and ac photoconductivities $\sigma_p(0)$ and $\sigma_p(f)$ of hydrogenated amorphous germanium (*a*-Ge:H) are measured in the temperature range 18–300 K. It is found that $\sigma_p(f)$ is strongly related to $\sigma_p(0)$, and the relationship $\sigma_p(f) \propto f^2 L^\gamma$(const s and γ), predicted by Shklovskii, Fritzsche, and Baranovskii[10] does not hold. These behaviors will be discussed in terms of the continuous-time random-walk model.[11]

Photosensitive *a*-Ge:H films were prepared by decomposing 1.27% GeH_4 diluted with H_2 in an electron-cyclotron-resonance (ECR) plasma reactor. A microwave power density of 15 mW/cm^3, pressure of 5 m Torr, total gas flow rate of 40 sccm, and substrate temperature of 200 °C were maintained during deposition onto Corning 7059 glasses. Details of preparation are described elsewhere.[12,13] Coplanar gap-cell electrodes using NiCr contacts (gap spacing 25 μm, gap width 0.8 cm) were fabricated. A halogen lamp was used with an ir-cut water filter and neutral density (ND) filters to measure the intensity dependence of photoconductivity. The ac photoconductivity (500 Hz–300 kHz) was measured using a LCR meter [Hewlett-Packard (HP) 4284A].

Figure 1 shows the temperature dependences of the dc photoconductivity $\sigma_p(0)$ (solid circles) and the ac photoconductivity $\sigma_p(f=10\ \text{kHz})$ (crosses), which were measured under the illumination of 3.6 mW/cm^2, for an *a*-Ge:H film (0.07 μm in thickness). The dc conductivity σ_{dc} is shown by the solid line. Note that the Tauc gap E_0 of 1.15 eV was obtained from this film. Almost the same behaviors have also been observed for a thicker film (0.18 μm). Note also that a decrease in photoconductivity during illumination (the Staebler-Wronski effect) (Ref. 14) has not been observed even at higher intensities of illumination (45 mW/cm^2) for the present *a*-Ge:H. Here, $\sigma_p(0)$ becomes nearly constant below $T_c \simeq 50$ K. Similar behavior has also been found in *a*-Si:H ($T_c \simeq 50$ K) (Refs. 1,7, and 9) and amorphous chalcogenides ($T_c \simeq 100$ K).[7] The ac photoconductivity around 300 K is independent of frequency and is the same as the dc photoconductivity, although the low-temperature $\sigma_p(f)$ is larger than $\sigma_p(0)$. The electronic transport path above 200 K can be the extended states, since a straight line of $\ln\sigma_{dc}$ vs $\Delta E/T$ with $\Delta E = 0.54$ eV was obtained (not shown in the figure).

Figure 2 shows the frequency dependence of the ac photoconductivity $\sigma_p(f)$ for three different illumination intensities (1: 45 mW/cm^2; 2: 18 mW/cm^2; 3: 3.6 mW/cm^2) at 18 K. As the ac dark conductivity $\sigma_{dark}(f)$ which can originate from deep localized states is much smaller than $\sigma_p(f)$, subtraction $[\sigma_p(f)-\sigma_{dark}(f)]$ to isolate the "pure" ac photoconductivity is not necessary here. The value of $\sigma_p(f)$ approaches the dc photoconductivity $\sigma_p(0)$ at lower frequencies. If the dc and ac transports are the same hopping mechanism, the Scher-Lax continuous-time random-walk (CTRW) approximation[15] or the extended pair approximation[16] (EPA) might be the proper approach.[11,17,18] A simple form of the CTRW ac conductivity has been developed using a percolation argument:[11]

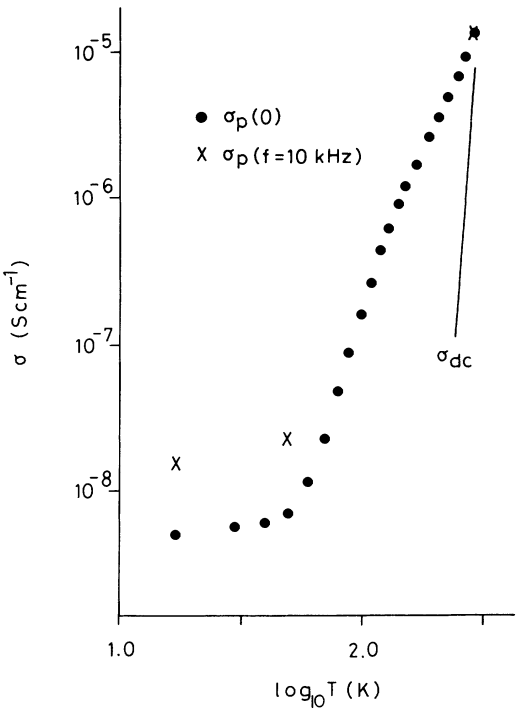

FIG. 1. Temperature dependence of conductivities in *a*-Ge:H. The dc photoconductivity is shown by solid circles and the ac photoconductivity at 10 kHz is shown by crosses. The dark dc conductivity is shown by the solid line.

$$\sigma(f)=\sigma_{\rm dc}\frac{if/f_c}{\ln(1+if/f_c)}\ , \tag{1}$$

where f is the frequency of applied field and f_c is the characteristic frequency. For the dc percolation network there is a critical longest hop with characteristic frequency f_c, and the dc conductivity is proportional to this frequency.[11,17] Above f_c only limited percolation clusters respond, and the conductivity will increase with frequency. It is expected therefore that f_c lies close to the onset frequency at which the conductivity becomes frequency dependent. The only free parameter to fit the experimental data is f_c in Eq. (1). The solid lines in Fig. 2 show the ac photoconductivities (real part) calculated using Eq. (1), where $\sigma_p(0)$ is the experimental value (see Fig. 4) and f_c is chosen to obtain the best fit. The location of f_c is shown by the arrow for each line. The f_c value increases with increasing illumination intensity. In a random distribution of localized states, hopping is a percolative process.[11,19] The f_c value for a higher density of hopping sites is expected to be larger than that for a lower density of sites, since the critical longest hop distance will decrease with increasing site density. For higher intensities of illumination, assuming electron transport, the quasi-Fermi-level (and hence transport path) moves toward the conduction band (CB). If the transport originates from hopping in band tails, as suggested by Shklovskii, Fritzsche, and Baranovskii,[8,10] photocarriers will pass through higher energies (and hence higher densities) of tail states in high illumination intensity, yielding an increase of the f_c value, as observed experimentally.

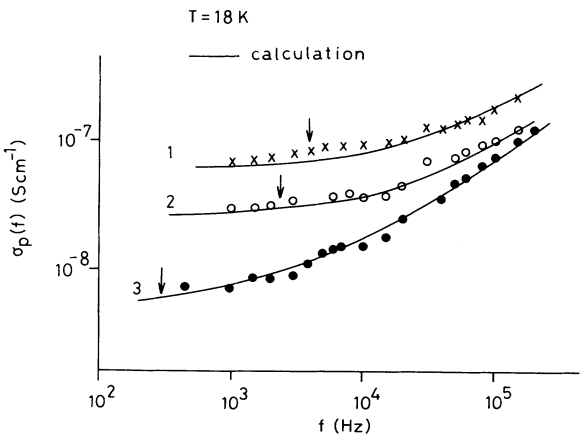

FIG. 2. Frequency-dependent ac photoconductivity measured at 18 K with different intensities of illumination for *a*-Ge:H. The crosses (1), open circles (2), and solid circles (3) refer to intensities of 45, 18, and 3.6 mW/cm^2, respectively. The arrow indicates the location of f_c. The solid lines represent results of calculations using Eq. (1).

If the present percolation argument is correct, the ac photoconductivity normalized to the equivalent dc photoconductivity for different intensities of illumination, $\sigma_p(f)/\sigma_p(0)$, should follow a universal function of the reduced frequency f/f_c (scaling law). In Fig. 3 the data of Fig. 2 are plotted in the form $\sigma_p(f)/\sigma_p(0)$ versus f/f_c. The solid line is the curve obtained from Eq. (1). The scaling is extremely good, suggesting that the dc and ac photoconductions are dominated by the same hopping mechanism. The same scaling behavior has also been reported in hydrogenated amorphous silicon (*a*-Si:H) using the extended pair approximation.[6] If the low-temperature photoconduction were due to photocarriers passing through the extended states, this type of scaling behavior would not be expected.[6]

In Fig. 4, the ac photoconductivity data (10 and 100 kHz) of Fig. 2 measured at 18 K are plotted in the form of $\sigma_p(f)$ versus illumination intensity L, together with the dc photoconductivity. The photoconductivity is approximately proportional to L^γ, with $\gamma=1.0$, 0.72, and

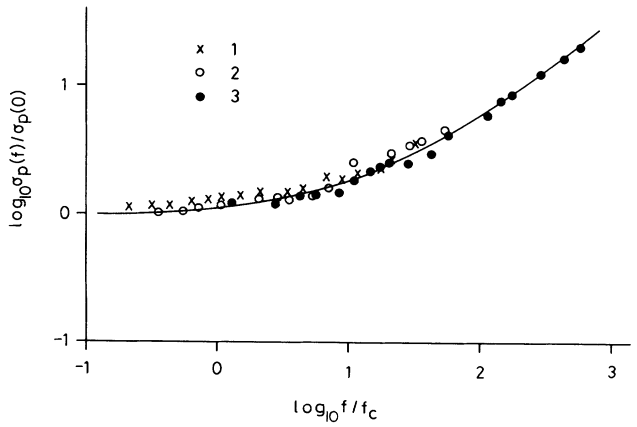

FIG. 3. Data of Fig. 2 in scaled form. The full curve is the prediction of the continuous-time random-walk approximation.

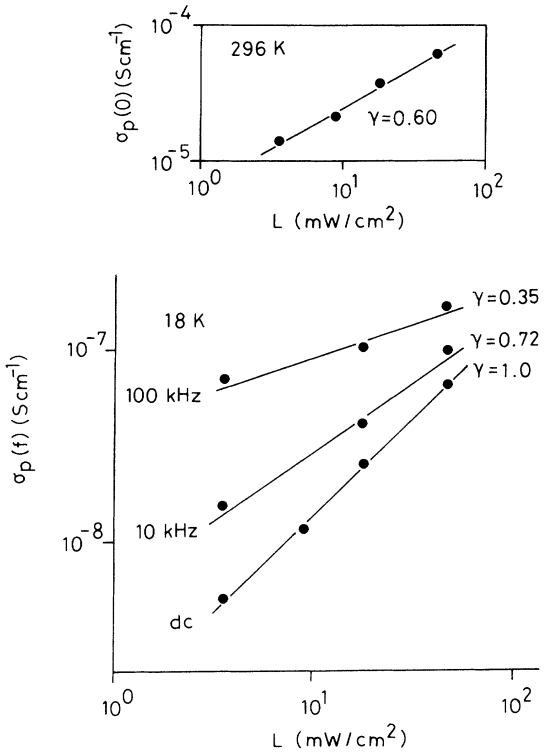

FIG. 4. Dependence of dc and ac photoconductivities on illumination intensity at 18 K. Inset: The intensity dependence of dc photoconductivity measured at 296 K.

0.35, for dc, 10 kHz, and 100 kHz, respectively. The inset shows the intensity dependence of the dc photoconductivity measured at 296 K, indicating $\sigma_p(0) \propto L^{0.60}$. The ac photoconductivity at this temperature is independent of frequency and is almost the same as the dc photoconductivity measured by means of an electrometer, suggesting that photoconduction occurs in the extended states as well as dark conduction (stated above). For transport in extended states, no frequency-dependent conductivity can be observed in the audio frequency range if macroscopic conductivity fluctuations[17] are not important. The exponent γ value in the relation of $\sigma_p(0) \propto L^{\gamma}$ drops from a value of 1.0 at 18 K to 0.60 at 296 K. Similar behavior has been observed in *a*-Si:H and amorphous chalcogenides.[7] The universal properties observed have been interpreted in terms of the hopping of photocarriers in band tails.[8–10]

Next, the intensity dependence of the ac photoconductivity will be considered. The exponent γ decreases with increasing frequency, which can be predicted from Eq. (1). Shklovskii, Fritzsche, and Baranovskii,[10] using the pair approximation[20] (PA) in which the condition $\sigma_p(f) \gg \sigma_p(0)$ is implicitly assumed, predict $\gamma \simeq 0.3$ for audio frequencies. In *a*-Si:H (Ref. 6) $\gamma \simeq 0.2$ has been observed, which is somewhat smaller than the value predicted by Shklovskii, Fritzsche, and Baranovskii.[10] The γ value should depend on the location of f_c and hence strongly depends on frequency in the CTRW model.[11] Then the value should not be universally constant. The PA approximation used in the model[10] may not be valid when $\sigma_p(f) \gtrsim \sigma_p(0)$ (present hopping case).

In summary, both the dc and ac photoconductivities have been measured in *a*-Ge:H to elucidate the universal behavior of low-temperature photoconductivity in amorphous semiconductors. Overall features observed in *a*-Ge:H are very similar to those reported in *a*-Si:H and *a*-chalcogenides. The scaling behavior $\sigma_p(f)/\sigma_p(0)$ for different intensities of illumination follows a universal function of f/f_c, suggesting that percolative hopping of photocarriers in band tails dominates photoconduction at low temperatures.

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