Thermal quenching of photoconductivity in doped *a*-Si:H films

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A thermal quenching of the photoconductivity accompanying the Staebler-Wronski effect has been observed in doped *a*-Si:H films. A model incorporating the broadening of levels of dangling bonds and an effect of the temperature on the optical charge exchange of levels is proposed in an attempt to explain the quenching

Much interest has recently been attracted to the recombination processes in hydrated amorphous silicon, *a*-Si:H, which determine the efficiency at which solar energy is converted into electrical energy. This research has apparently established solidly that the primary recombination centers are ruptured bonds with a positive correlation energy.[1,2] The corresponding energy diagram, with two discrete levels, is used in essentially all of the recombination models, but these models run into well-known difficulties in efforts to explain such features of the photoconductivity as the thermal quenching. A model which has been proposed[3] for describing the thermal quenching in undoped *a*-Si:H films starts with the assumption that the recombination rate is determined by the diffusion of holes among localized states in the tail of the valence band and their subsequent trapping by negatively charged dangling bonds (D^- centers). This model explains the reasons for the suppression of the thermal quenching of the interband photoconductivity in undoped films accompanying the Staebler-Wronski effect, i.e., after a prolonged preliminary illumination of the film, which increases the concentration of dangling bonds. Correspondingly, the thermal quenching of the photoconductivity is ordinarily regarded as evidence of a low concentration of dangling bonds in the material.

In the present letter we report the first observation of a thermal quenching of the photoconductivity in doped *a*-Si:H films, synthesized by the standard technique involving the decomposition of a gaseous mixture of silane and phosphine in the rf glow discharge. Figure 1 shows the temperature dependence of the dark conductivity and of the photoconductivity of one of the films, before and after a preliminary illumination

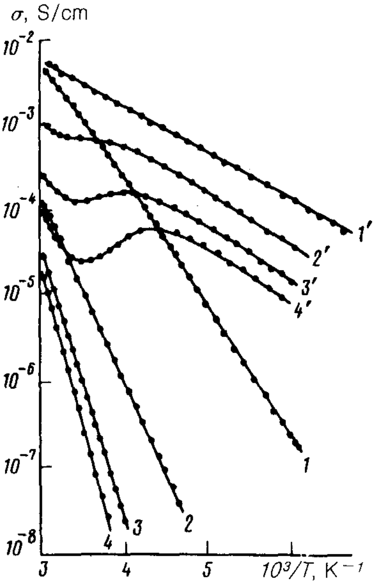

FIG. 1. Temperature dependence of the dark conductivity (1–4) and of the photoconductivity (1'–4') of a phosphorus-doped *a*-Si:H film. 1,1'—no preliminary illumination; 2,2'—after a preliminary illumination for 1.5 min; 3,3'—the same, for 15 min; 4,4'—the same, for 30 min.

of varying duration. We see that the illumination causes the activation energy for the dark conductivity to increase; i.e., the Fermi level shifts downward. At activation energies above about 0.65 eV, a thermal quenching of the photoconductivity arises, and it persists even in the face of a prolonged illumination. The shift of the Fermi level accompanying the Staebler-Wronski effect is a consequence of a compensation for impurity states with increasing concentration of dangling bonds. Since the concentration of dangling bonds in the undoped *a*-Si:H films is high, and it increases after a preliminary illumination, the model of Ref. 3 is not successful in describing the thermal quenching under these conditions.

The model proposed below for explaining the thermal quenching of the photoconductivity in samples with a high concentration of dangling bonds takes into account the broadening of the levels of dangling bonds which unavoidably occurs in such samples and which may lead to a significant overlap of these levels. This model also incorporates the difference in the trapping coefficients for electrons c_n^0, c_n^+ and for holes c_p^0, c_p^- by neutral and charged dangling bonds (D^0, D^+, and D^- centers). By virtue of the overlap of the broadened alternative levels, I and II, which correspond to a single and double filling of a dangling bond (Fig. 2), the equilibrium concentrations of the charged dangling bonds are generally rather large even at low temperatures: The states of level I, with energies ε above the equilibrium Fermi level μ, correspond to D^+ centers, while the states of level II with $\epsilon < \mu$ correspond to D^- centers. According to the data of Refs. 4 and 5, at room temperature we would have $c_n^+ \approx 5c_n^0$, $c_p^- \approx 3c_p^0$, $c_n^0 \approx c_p^-$, so that we would have a ratio $c_n^0 c_p^0/(c_n^+ c_p^-) = 1/15$, and this ratio would become even smaller with decreasing temperature. Under the conditions corresponding to measurements of the steady-state interband photoconductivity, because of the small value of this ratio, there will be a charge exchange of levels: The concentrations of the charged dangling bonds will fall off, and the fast recombination channel involv-

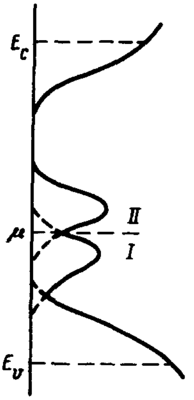

FIG. 2. Diagram of the state density in a-Si:H.

ing the trapping of electrons by D^+ centers becomes ineffective. A temperature increase leads to a liberation of holes from the D^0 centers with energies $\epsilon < \mu_p(T)$, where $\mu_p(T)$ is the Fermi quasilevel for holes. At a low excitation level, the liberated holes go to D^0 centers with $\epsilon > \mu_p(T)$. The formation of D^+ centers causes an increase in the rate of recombination transitions, a decrease in the concentration of electrons in the conduction band, and the appearance of a thermal quenching of the photoconductivity.

These features of the charge exchange of levels in the model of Fig. 2 were studied quantitatively on the basis of a system of levels describing transitions between delocalized states of bands, tail states, and dangling-bond levels. The necessary condition for quenching can be written $Q > 0$, where $Q = -d \ln n_t / d\mu_p$, and n_t is the concentration of electrons in the tail of the conduction band. The calculations show that for the ratio of trapping cross sections given above the function $Q(\mu_p)$ is positive for all μ_p only if the overlap of levels is large, and the ratio of the concentration of charged donors to the concentration of dangling bonds is low. The reason is that when the level overlap is small, the concentration of D^+ centers remains essentially constant with increasing temperature, since level I is below μ_p and cannot trap holes. On the other hand, the condition for thermal quenching is violated if the Fermi level is high, so that the equilibrium concentration of D^+ centers is low, and there is essentially no charge exchange. The conditions under which a thermal quenching of the photoconductivity is possible is this model correspond to the conditions (described above) for the observation of thermal quenching in doped a-Si:H films. In n-type films, the formation of dangling bonds after a preliminary illumination leads to a decrease in the ratio of the concentration of charged donors to the concentration of dangling bonds.[6]

The model proposed in this letter, which incorporates the effect of an overlap of dangling-bond levels on recombination processes, describes not only the thermal quenching but also several other features of the photoconductivity, e.g., the minimum in the photoconductivity as the position of the equilibrium Fermi level is changed by doping or ion implantation.

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