Electron drift mobility measurements on annealed and light-soaked hydrogenated amorphous silicon

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We measured the effects of light soaking on the electron drift mobility for three specimens of hydrogenated amorphous silicon (a-Si:H) from different laboratories. The temperature range 130-300 K was studied. The measurements in all cases reveal two temporal regimes: an early time regime associated with bandtail transport, and a later-time regime associated with deep trapping of the electrons. We found no evidence for effects of light soaking on the bandtail regime within a reproducibility error of 20%. Deep trapping was significantly affected by light soaking, in agreement with extensive prior measurements.

For many years it has been known that light soaking modifies the drift of photocarriers in hydrogenated amorphous silicon (a-Si:H). Staebler and Wronski first observed the effect in dark and photoconductivity measurements, which were substantially and reversibly affected by the prior illumination history of an annealed specimen. Later work on drift mobilities in annealed and light-soaked material clearly showed that light soaking also accelerates “deep trapping” of photogenerated electrons and holes in proportion to the increase in the deep-level density. It has been presumed that light soaking does not affect the fundamental transport mechanism, which is usually accepted to involve bandtail states. However, the experimental limits on the magnitude of bandtail effects established by the early work are relatively crude, and there are some preliminary reports suggesting that such an effect may exist.

Since the performance of a-Si:H solar cells is determined by the light-soaked state, a clear understanding of this issue is crucial for operating solar cells. A convincing demonstration of an effect of light soaking on bandtail transport would also significantly change theoretical views of the mechanisms limiting mobilities in a-Si:H. We have performed studies of the electron drift mobility using photocarrier “time-of-flight” techniques for optimized, undoped a-Si:H specimens from three different laboratories. We studied these effects between 130 and 300 K. A preliminary account of parts of this work and the description of instrumentation were given elsewhere. We find very little effect of light soaking on the drift mobility (cf. appendix of Ref. 9).

We measured a family of transient photocurrent responses for varying bias voltages at four different temperatures. Two light-soaking states were examined: the annealed state (obtained by heating the specimen at 180 °C for 90 min) and a light-soaked state (obtained by 2 h of illumination using a 250 W tungsten halogen illuminator (type ENH) at 30 cm from the specimen); the intensity of illumination was about 250 mW/cm². There was no significant attenuation of this intensity by the SnO₂ electrode.

In Fig. 1, we present logarithmic plots of the normalized transient photocurrent: \( \frac{i(t)}{(d^2/Q_0 V)} \), where \( V \) is the reverse bias voltage applied to the diode 18 μs before the laser pulse. \( d \) is the thickness of the undoped layer of the diode. \( Q_0 \) is the total charge of mobile electrons in the diode (assuming quantum efficiency \( \eta \) is independent of temperature). The procedure used to determine \( Q_0 \) will be discussed shortly, note that the normalized photocurrent has the dimensions of mobility. The rather slow rise of \( i(t) \) (about 30 ns) for this specimen is due to diode series resistance effects remaining after our scribing procedure. The particular transients presented in Fig. 1 were measured with bias voltages chosen so that neither internal field effects nor the effects of electron transit across the specimen are apparent. We have shown in previous work that hole photocurrents are negligible in a-Si:H under the conditions of Fig. 1 despite the use of weakly absorbed illumination.

Figure 1 is thus a highly condensed representation of the measurements; however, for brevity we shall not present complete families of transient photocurrents measured.
FIG. 1. Mobility-normalized transient photocurrents for a 10-μm-thick a-Si:H p-i-n diode prepared at Chronar, Inc. Two specimen states are illustrated: AN—annealed, LS—light soaked. See Table I for details.

The families exhibited the well-understood effects of photocarrier transit for larger voltages, and we integrated these higher voltage transients at 300 K to obtain \( Q_c \). The measurements illustrated are typical of an "ohmic" regime for the transient photocurrents. At voltages significantly lower than those used for Fig. 1, the transient photocurrent is nearly independent of voltage due to internal fields in the p-i-n diode structure.

With these precautions, the curves in Fig. 1 may be interpreted as measurements of an electron "transient drift mobility" \( \mu(t) = v(t)/E \), where \( v(t) \) is the speed of the mean position \( x(t) \) of the photocarrier distribution. We have checked in several specimens that \( \mu(t) \) can be used to predict transit times observed at higher voltages; see Ref. 9.

We first discuss the annealed state data. At 300 K, the initial electron mobility is just below 1 cm²/V s, as usual for electrons in a-Si:H near room temperature. The steep decline in \( \tau(t) \) after about 300 ns is the signature of deep trapping. We estimated the deep-trapping mobility-lifetime product \( \mu \tau_{el} \) at 300 K using the standard "Hecht" procedure of graphing the charge collected up to 10 μs as a function of voltage. For the annealed state, charge collection due to internal fields was about 0.3 \( Q_0 \); we used the slope of the \( Q \) versus \( V \) relation near \( V=0 \) to estimate \( \mu \tau_{el} \).

For the light-soaked state, deep trapping occurred much earlier; the initial mobilities were probably comparable at 300 K, but these data are inconclusive because of the slow rise time. The value of \( \mu \tau_{el} \) for the light-soaked state is reported in Table I; note that light soaking reduced this value by nearly tenfold.

In Fig. 2, we present similar measurements (using 610 nm laser wavelength) for a 4.8-μm diode prepared at Syracuse University (SU). This specimen was light soaked through a top electrode which attenuated the illumination approximately tenfold. The specimen was illuminated for 72 h with a filter which cut off wavelengths shorter than 665 nm. We measured a threefold drop in the value of \( \mu \tau_{el} \) (cf. Table I). The effects of light soaking are clearly shown in the accelerated onset of deep trapping at 300 K.

In Fig. 1, we see that the low-temperature transients for the two light-soaking states tend to converge at the earlier times, and diverge significantly at the longest times in the transient. These measurements may be interpreted as follows. Below 300 K, the electron mobility in a-Si:H declines with time as a power-law (with the exponent between 0 and -1) because of bandtail trapping effects (i.e., multiple trapping). This "dispersion" effect occurs earlier than deep trapping and is apparently unrelated to it. At later times, deep trapping accelerates the decay of the transients; as expected the light-soaked state shows deep-trapping effects earlier than the annealed state. We can therefore constrain the effect of light soaking on the bandtail transport by examining the earliest times in the transients; at 190 K the difference between the light-soaked and annealed states is about 20% at 10⁻⁷ s. This difference is comparable to the absolute reproducibility of the measurements.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Illumination time (h)</th>
<th>( \mu \tau_{el} ) (cm²/V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pd/nip/SnO₂/gl</td>
<td>0</td>
<td>2.9 × 10⁻⁷</td>
</tr>
<tr>
<td>10 μm (Chronar)</td>
<td>2</td>
<td>2.8 × 10⁻⁸</td>
</tr>
<tr>
<td>Al/i/Cr/gl</td>
<td>0</td>
<td>2.1 × 10⁻⁷</td>
</tr>
<tr>
<td>4.8 μm (SU)</td>
<td>72</td>
<td>6.3 × 10⁻⁸</td>
</tr>
<tr>
<td>Pd/pin/Cr/gl</td>
<td>0</td>
<td>4 × 10⁻⁸</td>
</tr>
<tr>
<td>2.65 μm (ECD)</td>
<td>20</td>
<td>1.8 × 10⁻⁸</td>
</tr>
</tbody>
</table>

*Light soaked through semitransparent upper electrode.*
In Fig. 3, we present the measurements (using 610 nm laser wavelength) for a 2.65 μm diode prepared at Energy Conversion Devices, Inc. (ECD). This specimen was clearly different than either the Chronar or Syracuse specimens. In the annealed state the electron deep-trapping mobility lifetime product $\mu \tau_{e,l}$ was significantly smaller; however, the hole deep-trapping mobility lifetime product $\mu \tau_{h,l}$ was essentially equal to the electron $\mu \tau_{e,r}$. For most undoped specimens previously reported $\mu \tau_{e,l} = 10 \mu \tau_{h,l}$ (cf. Fig. 7 of Ref. 9). The absolute magnitude of the electron drift mobility at lower temperatures is comparable to that of the Chronar specimen down to 130 K. Light soaking was performed prior to deposition of the top electrode to prevent attenuation of the illumination; nonetheless $\mu \tau_{e,l}$ declined relatively little under light soaking for this specimen.

As for the Chronar specimen, the rise time of the transient photocurrent tends to obscure the initial bandtail region at 300 K for the light-soaked state. For this specimen, we analyzed the short-time region fairly carefully. We found that the light-soaked transient was interpretable as a simple exponential; the extrapolated initial mobility was 1.0 cm²/V·s. This value is the same as directly measured for the annealed state. The 190 K data suggest a small difference in bandtail mobility, but this effect is not apparent at 160 and 130 K. We therefore conclude that the effects of light soaking are again no larger than 20% for the drift mobility of this specimen.

Some data for the Syracuse and ECD specimens are previously published. For the ECD specimen, we previously reported a factor 2 difference between the light-soaked diode and an annealed diode below 200 K. The light-soaked diode was prepared by first light soaking and then depositing the top Pd electrode; the annealed one was a “sister” diode at a different location on the substrate. We did not find comparably large effects when the same diode was used for both states, and it thus seems probable that differences between the diodes were interpreted as evidence for a light-soaking effect.

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