to note that these displacements are proportional to electric field. They are based on laser-pulse "time-of-flight" measurements [41].

First consider the electron behavior. For the earlier times (10^{-10} to 10^{-7} s), the displacement is simply proportional to the time, so we can just write the displacement as $L(t) = \mu_{\mathrm{e}} Ft$. The parameter μ_{e} is an electron mobility; it is about 1 cm^2/Vs, which is much lower than the mobility for electrons in crystal silicon (about 1000 cm^2/Vs near room temperature). For longer times the electron displacement saturates at a value $L_{e,t} = 3 \times 10^{-3}$ cm. This effect is due to the capture of electrons by defects, which is called deep trapping.[8]

Let us briefly consider how these electron parameters affect the functioning of an amorphous silicon cell under short-circuit conditions. The main concern is the possible buildup of electric charge in the cell under solar illumination. If this "space charge density" is too large, then the electric field across the cell will "collapse." A collapsed field reduces the range over which the cell collects carriers, and reduces the cell's efficiency.

We start by determining the travel time of an electron under short-circuit conditions. If the absorber (undoped) layer has a thickness $d = 500$ nm and a built-in potential $V_{\mathrm{BI}} = 1.5$ V across it (as for Figure 12.14), then the electric field $E \approx V_{\mathrm{BI}}/d$ in the dark is about 3×10^4 V/cm. Note that Figure 12.15 was prepared using this value for E. An electron that is photogenerated near the middle of the absorber layer needs to travel about 250 nm to reach the n-layer (moving right across Figure 12.14). Inspection of Figure 12.15 shows that an electron's typical travel time t_{T} across the absorber layer will be about 1 ns.

We can use this travel time of 1 ns to roughly estimate how much the total charge of electrons builds up under solar illumination. We write $\zeta = jt_{\mathrm{T}}/2$, where ζ is the total electron space charge in the absorber layer (per unit area of the cell); the factor of 2 implies that the current is carried equally by electrons and holes. For short-circuit conditions with $J_{\mathrm{SC}} = 10$ mA/cm^2, we obtain $\zeta = 5 \times 10^{-12}$ C/cm^2. To find out whether the built-in electric field is affected by this space charge density, we compare it to the built-in charge density σ_{BI} near the doped layers; σ_{BI} is the charge that actually creates the built-in electric field. Using the standard expression for the charge densities in a parallel plate capacitor, we estimate $\zeta_{\mathrm{BI}} = \varepsilon\varepsilon_0 V_{\mathrm{BI}}/d$ (ε is the dielectric constant and ε_0 is the "permittivity of the vacuum;" their product is about 10^{-10} C/Vm for silicon). We obtain $\zeta_{\mathrm{BI}} \approx 3 \times 10^{-8}$ C/cm^2. Since ζ_{BI} is about 6000 times larger than the drifting space charge σ of electrons, we conclude that the drifting electrons do not significantly modify the built-in electric field.

We now turn to holes. Two aspects deserve particular attention. First, Figure 12.15 shows that the drift of holes is *much* slower (orders of magnitude slower) than that of electrons. Second, and this also differs significantly from the properties of electrons, the displacement of holes is *not* proportional to time. Instead, the displacement $L(t)$ for holes rises as a peculiar power law with time:

$$L(t) = K(\mu_{\mathrm{h}}/\nu)(\nu t)^{\alpha} E \tag{12.2}$$

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[8] Quantitative study of deep trapping involves normalizing of measured values for the drift length $L_{\mathrm{e},t}$ by the electric field E, which yields the "deep-trapping mobility-lifetime product" $\mu\tau_{\mathrm{e},t} = L_{\mathrm{e},t}/E$. $L_{\mathrm{e},t}$ varies inversely with the density of defects in undoped a-Si:H [23, 48].