solar cell acts somewhat like an ordinary electrical battery, which also maintains different Fermi levels at its two terminals.

We now define the electron and hole quasi-Fermi energies E_{Fe} and E_{Fh} [131, 132]. For the electron quasi-Fermi energy E_{Fe}, we write

$$n \equiv N_{\mathrm{C}} \exp\left(-(E_{\mathrm{C}} - E_{\mathrm{Fe}})/k_{\mathrm{B}}T\right) \tag{12.3}$$

where n is the density of mobile electrons in the conduction band (i.e. in the shaded region of the conduction band in Figure 12.9). N_{C} is the effective density (1/cm^3) of these conduction band states. A similar expression accounts for the density of holes p in terms of a distinct quasi-Fermi energy for holes E_{Fh} and for the effective density N_{V} of valence band states.

Interestingly, in Figure 12.14 the hole quasi-Fermi level is nearly constant across the cell, showing sizable variation only where it catches up to E_{Fe} in the n-layer. Similarly, the electron quasi-Fermi level is constant except near the p-layer. This constancy means that the quasi-Fermi levels in the middle of the cell largely determine V_{OC}. The panel also shows that, in the middle of the cell, the bandedge potentials are essentially constant and the electric field is very weak. As mentioned earlier, in such field-free regions the electron and hole photocarrier densities are equal and are determined by the condition that the recombination and photogeneration rates are matched. For cells that have attained the intrinsic limit, it is these fundamental processes that determine V_{OC}.

We now turn to the measured dependence of V_{OC} upon the illumination intensity. Some recent measurements are presented in Figure 12.18(b) [130]. The intensity was varied by using "neutral density" filters that attenuate all photon energies to the same extent. The short-circuit current density J_{SC} has been used as a "surrogate" for intensity based on their proportionality. Consider first the uppermost set of measurements ("as-deposited, best p/i interface"). The logarithmic dependence of V_{OC} upon incident photon flux F is typical of photodiodes [124, 133]. For this sample, the slope of this dependence is determined by the defects; a second line in Figure 12.18 ("light-soaked, best p/i") indicates how the dependence changed following an extended period of light soaking. Interestingly, the difference in the two V_{OC} versus $\ln(J_{\mathrm{SC}})$ lines is fairly small (about 0.02 V) under full solar illumination (about 10 mA/cm^2), where the effect of defects upon electron and hole motions is relatively unimportant. This fact partly explains why the dependence of V_{OC} upon band gap can be simple despite the wide variations in defect density for varying materials.

Our previous discussion concerns open-circuit voltages in the intrinsic limit. As might be expected, it is easy to fabricate a-Si:H solar cells with inferior open-circuit voltages. In Figure 12.18, we have also shown the V_{OC} versus $\ln(J_{\mathrm{SC}})$ relation [130] for a cell with a (intentionally) defective p/i interface (open squares). This cell was based on the same intrinsic material as the as-deposited cell with the best p/i interface (solid circles); the slope of the V_{OC} versus $\ln(J_{\mathrm{SC}})$ relation is now noticeably reduced by the interface effect.

What aspect of nonideal p/i interfaces leads to a reduction in V_{OC}? The physical mechanism through which a poor p/i interface diminishes V_{OC} is the flow of photogenerated holes from the intrinsic layer (where they are generated) to the p/i interface (where