For weakly absorbed illumination (5000/cm – corresponding to a photon energy of 1.8 eV in Figure 12.2), power saturation occurs when the intrinsic layer is about 300-nm thick. This collection length [128] originates in the region where field collapse had occurred in Figure 12.16. The collapsed electric field is strongest near the p-layer and weaker near the n-layer. It may not be evident, but recombination of electrons and holes occurs predominantly in the weak field regions. This effect can be roughly understood from the following argument. In regions with a field near zero, drift processes driven by electric fields do not determine the densities of photogenerated electrons and holes. Since the electrons and holes are being generated at the same rate, their densities are equal, and they build up under illumination until their rate R of recombination with each other matches the rate G of photogeneration, $G = R$. It is worth noting that these conditions also apply to photoconductivity measurements that are made on isolated films of a particular material.

The asymmetry in the drift of electrons and holes explains why amorphous silicon–based *pin* solar cells are more efficient when illuminated through their p-layers. In Figure 12.17 we have also shown (as open symbols) calculations for the power produced by cells that are illuminated through their n-layers. Consider first the results with weakly absorbed light (5000/cm). In this case, the photogeneration of carriers is essentially uniform throughout the cells for all the thicknesses shown, and the cells do not "know" which side has been illuminated. Correspondingly, the power generation is essentially the same for illumination through the p-layer and through the n-layer.

Now consider more strongly absorbed light entering through the n-layer (50 000/cm). When the cells are thinner than the absorption length (about 200 nm in this case), the photogeneration is essentially uniform. There is again no difference in the power generated for illumination through the n- and p-layers. However, for thicker cells, there is a pronounced drop in the power from the cell for illumination through the n-layer compared to illumination through the p-layer. The power falls because the holes, on average, must drift noticeably further to reach the p-layer than when they are generated by illumination through the p-layer. The electric charge of the slowly drifting holes builds up and "collapses" the electric field, leading to recombination and loss of power.

12.4.4 The Open-circuit Voltage

In Figure 12.18 we present a summary of the open-circuit voltages (V_{OC}) for a-Si:H-based solar cells from United Solar Systems Corp. as a function of the band gap of the intrinsic absorber layer [129].[9] The measurements were done under standard solar illumination conditions. This graph is quite important for understanding the efficiencies of a-Si:H solar cells. For each photon absorbed, the solar cell delivers an energy $E = (FF)eV_{OC}$. The relation $V_{OC} = (E_G/e) - 0.80$ shows that most cells deliver a voltage that is 0.80 V below the band gap. We can now roughly estimate the power delivered by a cell. For a 500-nm-thick cell and a 1.75-eV band gap, Figure 12.2 shows that a typical photon absorbed by the cell under solar illumination actually carries nearly $h\nu \approx 2.5$ eV of energy. Since fill factors are necessarily less than 1, the energy actually delivered by the cell can be no

---

[9] We have assumed familiarity with the standard solar cell terminology of short-circuit current density J_{SC}, open-circuit voltage V_{OC}, and fill factor FF. See Chapter 3 for definitions of these terms.