they recombine with electrons) [124]. The flow means that the hole quasi-Fermi level has a gradient [132] near the p/i interface that reduces V_{OC} below its intrinsic limit. You can just barely notice this gradient effect in Figure 12.14.

The reason this hole current flows is to balance an exactly equal current of electrons. The electrons are being thermionically emitted from the intrinsic layer and over the electrostatic barrier at the p/i interface. You can envision this thermionic process using the bottom panel of Figure 12.14, which shows a barrier of $W = 0.6$ eV for electron emission from the quasi-Fermi level E_{Fe} in the intrinsic material into the p-layer.

The best open-circuit voltages in substrate solar cells are achieved using a boron-doped silicon film [134]. This material is generally referred to as microcrystalline, although extensive characterization of the type presented in Figure 12.13 suggests this p-layer may also be dominated by an amorphous phase. The best open-circuit voltages in superstrate solar cells have been achieved using boron-doped amorphous silicon–carbon alloys (a-SiC:H:B). An indication of the subtlety required to achieve high open-circuit voltages is that cells using a-SiC:H:B p-layers also include a thin ($<$10 nm) "buffer layer" of undoped a-SiC:H between the p-layer and the intrinsic layer of the cell [135–137]. The precise mechanism by which these buffer layers improve V_{OC} is not conclusively established. We would speculate that the buffer layer impedes electron emission into the p-layer, in accordance with the "thermionic emission" model for the p/i interface effects just described.

12.4.5 Optical Design of a-Si:H Solar Cells

In this section we briefly review the use of *back reflectors* and *substrate texturing,* which are optical design principles that are used to improve the power output of amorphous silicon–based solar cells. The interested reader will find a more comprehensive treatment in the recent monograph of Schropp and Zeman [123] and Chapter 8.

Incorporating a back reflector increases the power output of solar cells. In Figure 12.19, an ideal back reflector doubles the power output for weakly absorbed light (5000/cm in the figure); we are neglecting optical interference and "rereflection" of light by the top of the cell, so the light passes through the cell twice, once on its way down to the reflector, and again on its way back out the top. The back reflector has no effect on power output for strongly absorbed light (50 000/cm in the figure), since that light never "sees" the back reflector. The effects of the back reflector are fairly complex when the thickness, absorption length of the illumination, and collection length for the holes are all comparable, which is what occurs for thicknesses in the range of 100 to 300 nm with 50 000/cm illumination.

For weakly absorbed light, a back reflector for the simple planar structures just described increases power collection about twofold. Much larger improvements may be envisaged. The fundamental idea is "light trapping." An optical beam propagating inside a dielectric structure may be trapped by total internal reflection at the interface with air, which has a lower index of refraction than the dielectric. The principle is the same as that underlying the operation of optical fibers: an optical beam that enters the fiber at one end can travel kilometers without leaving the fiber. For solar cells, the light-trapping idea