through the bottom of the funnel. Water, representing the incident sunlight, is poured into the top of the funnel. Water flowing out of the funnel through the stopcock represents the current delivered by the solar cell. Since the funnel is full of holes, some of the water leaks out instead of flowing through the stopcock. This leakage represents the recombination of minority carriers in the solar cell. The different-shaped holes represent different sources of recombination. For instance, square holes might represent recombination in the base region, round holes might be recombination in the space-charge region, triangular holes might be surface recombination at the back contact, and so on. The rate at which water pours in is proportional to the light intensity. At steady state, the water will find a height such that the flow of water in, I_{gen}, is equal to the flow through the stopcock (I) plus the water that leaks through the holes (I_{recomb}). This height represents the solar cell voltage (V).

When the stopcock is fully open, the water flows out through the stopcock at its maximum rate (I_{SC}), although some water will leak out through the holes so that $I_{SC} < I_{gen}$. This is analogous to the collection efficiency, η_C, of a solar cell – the objective being to minimize the amount of leakage (recombination) so that η_C is as close to unity as possible. Smaller holes means less recombination and $I_{SC} \rightarrow I_{gen}$.

As the stopcock is slowly closed, the level of liquid in the funnel rises – just as the solar cell voltage increases as the current decreases. When the stopcock is completely closed, the height of the water is representative of the open-circuit voltage (V_{OC}). At open circuit all the minority carriers must recombine just as all the water must leak out of the funnel in this analogy. If the holes are all big, the height of the water will be low. This is equivalent to short minority-carrier lifetimes and large surface recombination velocities that result in a low V_{OC}. By reducing the size of the holes (i.e. increasing the minority-carrier lifetimes and reducing the surface recombination velocities), the height of the water in the funnel (i.e. V_{OC}) is increased. Reducing the size of only the square holes (by increasing the minority-carrier lifetime in the base) will not increase the height of the water as much as might be expected since the round holes (recombination in the depletion region) are still large. All leaks (recombination sources) must be plugged (recombination rates minimized) before the height of the water (V_{OC}) increases substantially.

3.5 ADDITIONAL TOPICS

3.5.1 Efficiency and Band gap

Since only photons with $h\nu > E_G$ can create electron – hole pairs and contribute to the output of the solar cell, it is obvious that the band gap determines how well the solar cell is coupled to the solar spectrum. A simple analysis can be performed to predict the maximum solar cell efficiency. More complete analyses of the theoretical limits of solar cells are given elsewhere [17–19] and are also discussed in Chapter 4 of this handbook. Assuming the maximum energy that can be extracted from an absorbed photon is E_G, the maximum efficiency can be expressed as

$$\eta_{max}(E_G) = \frac{\frac{1}{q}E_G I_{inc}}{P_{in}} = \frac{E_G}{(P_{in}/A)} \int_{\lambda<\lambda_G} f(\lambda)\,d\lambda. \tag{3.145}$$