frequently turning the lamp on and off. At least one module manufacturer uses an array of tungsten-halogen bulbs for production testing of modules in their multi-megawatt plant. They operate the bulbs at a low "simmer" voltage between $I-V$ measurements to greatly increase the lifetime of the bulbs. They use "matched" reference cells to minimize their sensitivity to spectral errors. The spectral irradiance of filament lamps is characterized by a black-body spectrum of 3200 to 3450 K. These lamps are deficient in the blue region of the solar spectrum because the AM0 spectrum can be approximated as a 5900 K black body.

16.4 SPECTRAL RESPONSIVITY MEASUREMENTS

The spectral responsivity ($S(\lambda)$) or quantum efficiency ($QE(\lambda)$) is essential for understanding current generation, recombination, and diffusion mechanisms in photovoltaic devices. PV cell and module calibrations often require a spectral correction factor that uses the spectral responsivity (i.e. equations 16.16–16.22). The spectral responsivity is measured in units of current produced per unit power and can be converted to quantum yield, or electron–hole pairs produced per incident photon through the equation:

$$QE(\lambda) = \frac{qS(\lambda)}{\lambda hc} \tag{16.33}$$

The factor hc/q equals 0.80655 for the wavelength in units of μm and the spectral responsivity in units of A/W. The quantum yield, in units of electron per photon, is often multiplied by 100, giving the quantum efficiency.

Typically, the spectral responsivity is measured at short-circuit current because it is easy to define and usually is the same as the photocurrent except for cells exhibiting voltage-dependent current collection like a-Si devices. PV devices normally operate near their maximum-power point. The spectral responsivity is assumed to be the same at the maximum-power and short-circuit points. Voltage-dependent spectral responsivities have been reported for a-Si [144], CdTe [145], and Cu(Ga,In)(S,Se) [146] material systems. (See Chapters 12, 13, and 14 for further discussion of voltage dependent collection in these types of devices).

The PV community has designed a variety of spectral response measurement systems, including ones based on interference filters, grating monochrometers, and interferometers [74, 77, 80, 81, 147–154]. For a single-junction solar cell, $S(\lambda)$ is determined by illuminating the cell with periodic (i.e. "chopped") monochromatic light and continuous broadband bias light of much greater intensity. The AC photocurrent from the device due to periodic monochromatic light is converted to an AC voltage and measured with a lock-in amplifier. An AC voltmeter may be used instead of a lock-in amplifier if the AC signal is large compared to the AC noise. The measured photocurrent is often in the μA to mA range with a broadband DC bias light near the device's intended operating point, for example, 1 sun.

For a two-terminal multijunction device, measuring the spectral responsivity of the individual junctions requires that the junction to be measured is the one which actually determines the photocurrent through the device (e.g. is the current-limiting junction).