for a-Si:H solar cells made with several different textures and back reflectors. The quantum efficiency is defined as the ratio, at a specific photon energy, of the photocurrent density j (A/cm^2) to the incident photon flux f:

$$QE = j/ef \tag{12.4}$$

Consider first the lowest of the curves (smooth substrate, no back reflector shown with black diamonds). In this sample, photons incident on the p-layer are either absorbed in the cell or pass through the cell and leave it through the glass substrate. The rise of QE as the photon energy increases up to about 2.5 eV is due to the increase in absorption. A -1 V bias was applied, and the resulting electric field prevented the loss of photocarriers to recombination. Near 2.5 eV the QE is nearly one: essentially all incident photons are absorbed and nearly all the photocarriers generated are subsequently collected. The result is sensible. Inspection of Figure 12.2 shows that the absorption coefficient is about 10^5/cm at this energy, so that photons are absorbed within about 100 nm of the top surface of the a-Si:H. Since this length is much smaller than the sample thickness, essentially all photons are absorbed. Some photons are lost because of reflection from the glass and TCO interfaces, which accounts for most of the remaining losses.

For photon energies greater than 2.5 eV, the absorption coefficient continues to increase, so photons are absorbed within a few tens of nanometer at the top of the p-layer. A significant fraction of these photons is absorbed in the p-layer or the TCO; these photons do not contribute to the photocurrent, and so the QE declines for higher photon energies.

Now consider the data for the cell with an untextured substrate (0% haze) and a smooth Ag back reflector (open triangles). For photon energies that are weakly absorbed (below 2.5 eV), the QE increases about twofold because of the back reflector; for strongly absorbed photons, there is little effect of the back reflector. These effects were just explained for the computer modeling of Figure 12.19(a). Interestingly, the use of a textured back reflector further improves the QE. The textured reflector increases the typical angle between the paths of reflected photons and the axis normal to the substrate; this effect increases the typical path length of the reflected photon in the a-Si:H as well as the chance of reflection when a reflected photon arrives back at the top of the cell. The uppermost two curves, with the highest QEs, correspond to cells with textured substrates. For lower photon energies, the textured substrates further improve the QE, although certainly not to the maximum extent $4n^2$ calculated by Yablonovitch. Note also that substrate texturing also leads to a modest improvement of the QE in the blue spectral region (beyond 2.5 eV) due to a reduction in the front-surface reflectance of the cell.

Roughly, the effect of back reflectors and texturing for lower photon energies shown in Figure 12.19 is to reduce the energy threshold for collection of an incident photon by about 0.2 eV. Using Figure 12.2 one can estimate that this reduction in threshold increases the incident solar power absorbed by a 0.5-μm cell from 420 to 520 W/m^2. This estimate is broadly consistent with measurements showing an increase in short-circuit photocurrent under solar illumination of about 25% when textured substrates are used [140–142].

The implementations of texturing and back reflectors, as well as of a front "anti-reflection" coating to reduce the reflection, vary dramatically between superstrate and