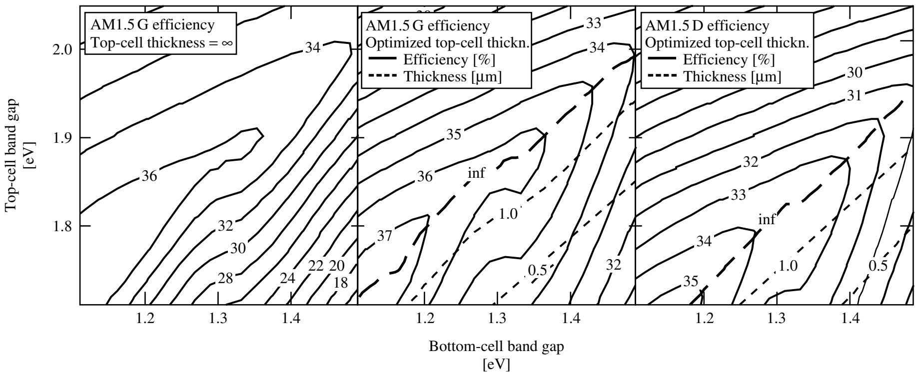
that the band gap is allowed to vary. The absorption coefficient is shifted rigidly with the band gap so that it correctly goes to zero as the photon energy decreases below the band gap energy. Likewise, for the top subcell, the model uses the material properties of GaInP, again allowing the band gap to vary. The diffusion lengths at 300 K for the GaAs cell are $L_b = 17$ µm and $L_e = 0.8$ µm; for the GaInP cell, $L_b = 3.7$ µm and $L_e = 0.6$ µm. For simplicity, and to give results representing the maximum possible performance, all surface recombination is taken as zero. The emitters for both subcells have thickness $x_e = 0.1$ µm and ionized dopant concentration $N_e = 2 \times 10^{18}/\text{cm}^3$, and the bases for both subcells have $N_b = 10^{17}/\text{cm}^3$. These values are comparable to those used in actual GaInP/GaAs multijunction cells, which provide an optimal combination of high quantum efficiency, low dark current, and low series resistance. Using this model, Figure 9.6(a) plots contours of cell efficiency for a two-junction series-connected cell with infinitely thick subcells, calculated for the one-sun standard AM1.5 global spectrum. Similar contours are shown for a variety of spectra and concentrations by Nell and Barnett [20] and by Wanlass *et al.* [18]. At the optimal band gap combination of $\{E_{gt} = 1.75 \text{ eV}, E_{gb} = 1.13 \text{ eV}\}$ an efficiency of almost 38% is predicted, well in excess of the 29% efficiency that the model would predict for the best single-junction device.

Even at a bandgap combination of $\{E_{gt} = 1.95 \text{ eV}, E_{gb} = 1.42 \text{ eV}\}$, though well away from the optimal bandgap combination, the efficiency is still much higher than the best single-junction efficiency. This band gap pair was chosen for consideration because the bottom-subcell band gap is the band gap of GaAs, while the top-subcell band gap is only slightly higher than the 1.85 eV band gap obtained under typical growth conditions for GaInP. But as E_{gt} decreases from 1.95 eV to the GaInP band gap of 1.85 eV (with E_{gb} held at the GaAs band gap of 1.42 eV) the efficiency falls very rapidly, from 35 to 30%. This drop-off is due to the dependence of the top- and bottom-subcell photocurrents



(a) (b) (c)

Figure 9.6 Contour plots of efficiency versus subcell band gaps for a series-connected two-terminal two-junction tandem cell. Adapted from Kurtz S, Faine P and Olson J, *J. Appl. Phys.* **68**, 1890 (1980) [7]. Panel (a) is calculated for the AM1.5 global spectrum, with an infinitely thick top subcell. Panel (b) is calculated for the same spectrum, but for the top subcell thickness that optimizes the tandem-cell efficiency at each combination of top- and bottom-cell band gap; the dashed contours show this optimal thickness. In the region of the graph above the thickness = ∞ contour, the tandem current is limited by the top cell. Panel (c) shows efficiencies and optimal top-cell thicknesses calculated as in (b) but for the AM1.5 direct spectrum