cell that is slightly top-subcell limited at 300 K. The top-subcell $J_{SC}$ increases faster with temperature than does the bottom-subcell $J_{SC}$, leading to a crossover from top- to bottom-subcell limited as the temperature is raised above 350 K. The tandem $\mathrm{d}J_{SC}/\mathrm{d}T$ likewise crosses over from $\mathrm{d}J_{SCt}/\mathrm{d}T$ to $\mathrm{d}J_{SCb}/\mathrm{d}T$.

#### *9.5.10.3 Fill factor*

Because the tandem-cell fill factor is determined more by the current-limiting subcell than by the other subcell(s), the current-matching crossover has similar implications for dFF/d$T$ as for $\mathrm{d}J_{SC}/\mathrm{d}T$. For the cell of Figure 9.11, the crossover from top- to bottom-subcell limited causes dFF/dT to change, as shown in Panel (c).

#### *9.5.10.4 Efficiency*

Because the efficiency is proportional to $V_{OC} \times J_{SC} \times$ FF, and $\mathrm{d}J_{SC}/\mathrm{d}T$ and dFF/d$T$ change in opposite directions as the temperature goes through the current-matched temperature, dEff/d$T$ is a relatively smooth function of temperature.

## 9.6 MATERIALS ISSUES RELATED TO GaInP/GaAs/Ge SOLAR CELLS

### 9.6.1 Overview

In the previous section, we discussed the basic elements of a monolithic, multijunction solar cell, such as that shown in Figure 9.1, including subcell band gaps and thicknesses, metallization, and AR coating effects. We also assumed unity collection efficiency for all photogenerated carriers, implying that component semiconductor materials, interfaces, and junctions are virtually perfect. In practice, however, numerous intrinsic and extrinsic factors tend to limit the quality and performance of multijunction solar cells. In this section, we review various aspects of real materials and devices, including issues associated with their growth.

### 9.6.2 MOCVD

The GaInP/GaAs/Ge dual- and triple-junction solar cells are produced commercially in relatively large volumes by several companies in the United States. These cells are fabricated in large MOCVD reactors made by Emcore Corporation in the United States and Aixtron in Germany. Although these devices can be grown by other techniques such as molecular beam epitaxy (MBE) [33], the predominant growth technique is MOCVD and is, therefore, the focus of this section. A description of the basic MOCVD reactors used at NREL can be found elsewhere [34]. Briefly, most of the results presented here are from layers and devices grown by MOCVD using trimethylgallium (TMG), trimethylindium (TMI), arsine, and phosphine in a Pd-purified $H_2$ carrier gas. The dopants sources included $H_2Se$, $Si_2H_6$, diethylzinc (DEZ), and $CCl_4$.