for III-V devices. Although a detailed discussion of linearity is outside the scope of this chapter, it is worth mentioning because different degrees of nonlinearity for different subcells in the device could lead to a crossover between top-cell-limited and bottom-cell-limited performance as a function of concentration.

## 9.5.10 Temperature Dependence

To predict device performance at realistic operating temperatures, and to be able to interpret measured device characteristics at these temperatures, it is useful to analyze the temperature coefficients of these devices using the basic cell equations (9.1–9.16) [31]. We shall see that the current-matching constraint for series-connected multijunction cells leads to effects in the temperature coefficients that are not seen for single-junction devices.

### *9.5.10.1* $V_{OC}$

Because the series-connected multijunction $V_{OC}$ is simply the sum of the subcell $V_{OC}$s, the temperature coefficient $\mathrm{d}V_{OC}/\mathrm{d}T$ of the multijunction $V_{OC}$ is likewise the sum of the $\mathrm{d}V_{OC}/\mathrm{d}T$ values for the subcells. Taking the GaInP/GaAs tandem cell as an example, both the GaInP and GaAs subcells have $\mathrm{d}V_{OC}/\mathrm{d}T \approx -2$ mV/°C. The tandem therefore has $\mathrm{d}V_{OC}/\mathrm{d}T \approx -4$ mV/°C [31]. Table 9.2 compares these temperature coefficients for several types of cells. The GaInP/GaAs/Ge three-junction cell is seen to have a more negative $1/V_{OC}\,\mathrm{d}V_{OC}/\mathrm{d}T$ value than the GaInP/GaAs two-junction cell, due to the contribution of the low band gap Ge junction. However, going to high concentrations reduced the magnitude of $1/V_{OC}\,\mathrm{d}V_{OC}/\mathrm{d}T$, due to the increase in $V_{OC}$ with concentration.

### *9.5.10.2* $J_{SC}$

Although the $V_{OC}$ temperature coefficients for the subcells of a series-connected multijunction cell are independent and additive, the multijunction $J_{SC}$ temperature coefficient

**Table 9.2** $V_{OC}$ temperature coefficients at 300 K for multijunction cells and their single-junction component subcells, assuming junction ideality factors $n = 1$. One-sun illumination is assumed except as noted. Values are guidelines for comparison with actual cells, but precise agreement should not be expected, especially for junctions whose ideality factor deviates significantly from $n = 1$. For comparison, data are also shown for a passivated emitter rear locally diffused (PERL) Si cell, which has a significantly lower temperature coefficient than that of standard Si cells [32]

| Cell | $V_{OC}$ [mV] | $\mathrm{d}V_{OC}/\mathrm{d}T$ [mV/K] | $1/V_{OC}\,\mathrm{d}V_{OC}/\mathrm{d}T$ [%/K] |
|---|---|---|---|
| Ge | 200 | −1.8 | −0.90 |
| GaAs | 1050 | −2.0 | −0.19 |
| GaInP | 1350 | −2.2 | −0.16 |
| GaInP/GaAs | 2400 | −4.2 | −0.17 |
| GaInP/GaAs/Ge | 2600 | −6.0 | −0.23 |
| GaInP/GaAs/Ge (500 suns) | 3080 | −6.0 | −0.19 |
| PERL Si | 711 | −1.7 | −0.24 |