of what J_{SCt} would be for an infinite-thickness top subcell. The ability of such a thin cell to absorb such a high fraction of the incident light is due to the large absorption coefficient of this direct gap material.

By comparison with the thinned top-subcell case, for an infinitely thick top subcell the multijunction J_{SC} would be determined by the bottom subcell at a current $J_{SCb} = 13.4$ mA/cm^2. This improvement in J_{SC} on thinning the top cell results in a corresponding improvement in the cell efficiency, from 30% to approximately $15.8/13.4 * 30\% \approx 35\%$. This estimate is only approximate because, as will be discussed below, top-cell thinning affects the fill factor and V_{OC}, as well as J_{SC}. However, these are second-order effects, and the approximation of scaling efficiency with J_{SC} alone is quite good. We can see this in Figure 9.6(b), which shows contours of cell efficiency vs. top- and bottom-subcell band gap, for optimal top-subcell thickness. The figure confirms that the cell efficiency at $\{E_{gt} = 1.85$ eV $E_{gb} = 1.42$ eV$\}$ is about 35%. The figure also shows contours of the optimal top-subcell thickness. The optimal thickness decreases with increasing E_{gb} or decreasing E_{gt}, as required, to maintain current matching. The thick dashed line is the contour of infinite top-subcell thickness; above this contour, the tandem-cell current is always limited by the top subcell, whereas below this contour, thinning the top subcell improves the tandem-cell efficiency. Comparing the optimized efficiencies to the infinite-thickness efficiencies of Figure 9.6(a), we see that the top-subcell thinning greatly reduces the sensitivity of the tandem efficiency on subcell band gap, in effect widening the range of band gaps that can be selected.

9.5.6 Current-matching Effect on Fill Factor and V_{OC}

The fill factor (FF) of the tandem cell depends on the top- and bottom-subcell photocurrents. Figure 9.7(c) shows the fill factor as a function of top-cell thickness, and thus effectively as a function of J_{SCt}/J_{SCb}, for the device of Figure 9.7(b). The fill factor is a minimum at the current-matched condition, an effect that holds in general for reasonably ideal (nonleaky) subcells. This effect slightly undermines the efficiency gains that accrue from the increase in J_{SC} at the current-matched condition; however, the decrease in fill factor at current matching is roughly half the increase in J_{SC}. This dependence of fill factor on the ratio of the subcell currents is important, because it implies that correctly measuring the fill factor of an actual device requires correctly light-biasing the subcells. This subject is discussed further in the chapter on measurements (see Chapter 16).

As equations (9.13–9.15) show, V_{OC} also depends on cell thickness. Figure 9.8 shows how finite base thickness x_b and base surface recombination velocity S_b affect the V_{OC} of a GaInP cell. These curves were calculated using equations (9.13–9.15), assuming a bulk recombination velocity $D_b/L_b = 2.8 \times 10^4$ cm/s, a typical value for a GaInP cell. The figure shows that for a cell with a well-passivated base, that is, S_b small enough that $S_b \ll D_b/L_b$, thinning the cell results in a meaningful increase in V_{OC}. On the other hand, for a cell whose base is so poorly passivated that $S_b > D_b/L_b$, thinning the cell lowers V_{OC}. For the GaInP/GaAs tandem structure, with the thin top subcell required for current matching, the passivation of the base of the top subcell is thus an important consideration for the overall device efficiency. The passivation of GaInP surfaces will be discussed later in this chapter.