As a deep donor, oxygen is a bigger problem in *p*-type AlGaInP. Other researchers found that strained, Ga-rich $Ga_xIn_{1-x}P$ was superior to either disordered lattice-matched GaInP or AlGaAs [89]. Recently, however, the best commercial tandem solar cells use AlGaInP [90] or AlInP [91] BSFs. The growth of high-quality Zn-doped AlInGaP and the techniques for assessing the quality thereof have been published by several others [81, 83, 92].

9.6.3.5 Characteristics of state-of-the-art GaInP cells

Because the band gap of GaInP can change so dramatically with growth conditions, it is not meaningful to talk of "state-of-the-art" GaInP cells using only efficiency as the measure of quality. As the band gap increases, V_{OC} should increase, but J_{SC} and efficiency should decrease. (Note, however, that the efficiency of a current-matched GaInP/GaAs tandem cell should increase slightly with increasing GaInP band gap as discussed in Section 9.5.4 above.) Also, in any optimized multijunction solar cell the thickness of the GaInP cell is likely to be optically thin, that is, it will absorb fewer photons and hence *may* be lower in efficiency than an optically thick cell. So thickness and band gap are two important parameters that must be considered when comparing single-junction efficiencies. In general, relative measures of quality, for example, V_{OC}/E_g, are more useful.

9.6.4 GaAs Cells

9.6.4.1 Quality of GaAs on Ge(100) substrates

Despite the close lattice matching between GaAs and Ge substrates, the quality of GaAs grown on Ge can be quite variable. (See Section 9.6.5.3 for a discussion on the heteroepitaxy of GaAs on Ge.) The primary criterion for good-quality heteroepitaxial GaAs is, of course, the efficiency of overlying GaAs and GaInP solar cells. Generally, a good indicator of quality is a specular episurface with little or no haze (often caused by antiphase domains or APDs) and few extended defect features such as pits, hillocks, or slip lines. For a specular, epitaxial GaAs layer, one should observe a faint "crosshatch" pattern. This "crosshatch" is a replica or shadow of the misfit dislocation array located in the GaAs/Ge interface plane. Sometimes, the absence of this "crosshatch" pattern is an indicator that the misfit is being relaxed by threading dislocations. The density of these threading dislocations can become high enough to affect the minority-carrier transport properties of the GaAs and GaInP solar cells, and should, therefore, be avoided.

The morphology of $Ga_xIn_{1-x}P$ grown on GaAs is an even more sensitive indicator of the quality of the original GaAs surface. Morphologically faint defects in or on the GaAs will be "decorated" by the growth of $Ga_xIn_{1-x}P$. This is probably caused by differences in the attachment of Ga and In to the different surface orientations offered by the defect.

GaAs grown on Ge can be "lattice matched" to the Ge substrate by the addition of about 1% indium. This eliminates the "crosshatch" in good heteroepitaxy, but does not appear to make the task of heteroepitaxy any easier. Under the best conditions, a $Ga_{0.99}In_{0.01}As$ solar cell will be slightly better than a GaAs cell on Ge [93].