presumably because of the adverse effect of Al (and the associated oxygen contamination) on minority-carrier properties [122].

The Ge junction collects about twice as much photocurrent as the other two junctions in the GaInP/GaAs/Ge cell. The three-junction cell efficiency will increase, theoretically, if the GaAs band gap is lowered, the Ge band gap is increased, or a fourth junction is added between the GaAs and Ge junctions.

The most common approach is to add indium to the GaAs layer and perhaps to the GaInP layer. A small amount of indium improves the lattice matching to Ge and improves the efficiency of the cell even without the use of any buffer layer [124]. Addition of larger quantities of indium (e.g. 12%) is being widely investigated in the hope of increasing the efficiency by $\sim$2% absolute [125]. Higher efficiencies require the growth of a buffer layer that successfully relieves the strain without allowing threading (and other) dislocations to propagate into the active layers of the solar cell. Results are promising, but the efficiencies, so far, have been similar to those for lattice-matched cells [125–128]. Researchers at Varian studied a two-step approach allowing the mismatched layers to be grown on the back of the wafer, whereas the "sunny-side" layers were grown lattice matched [129, 130]. The effects of lattice mismatch on the manufacturability and lifetime of solar cells are not known.

Considerable effort has also been invested toward the addition of a fourth, 1-eV junction (to be added between the GaAs and Ge junctions). Such a four-junction structure has a theoretical efficiency of >50% [99], translating to a practical efficiency of 40% if appropriate materials could be identified. Unfortunately, identifying an appropriate (high quality and lattice matched to GaAs) 1-eV material has proven difficult. The most promising candidate for this junction is currently the alloy GaInAsN. Other materials have been investigated, but do not show as much promise. $ZnGeAs_2$ is somewhat difficult to grow (especially at low pressures) and can cause cross contamination (e.g. Zn contamination of subsequent growth) [131]. $Ga_{0.5}Tl_{0.5}P$ was reported to be lattice matched to GaAs with a band gap of about 0.9 eV [132], but a number of laboratories have been unable to duplicate the original report [133, 134]. The band gap of BGaInAs lattice matched to GaAs has been pushed down to 1.35 eV, but so far, not to 1.0 eV [135]. BGaInAs also exhibits inferior material quality [136], resulting in devices with decreased photovoltages and currents.

$Ga_{1-x}In_xAs_{1-y}N_y$ can be grown lattice matched ($x = 3y$) to GaAs with a band gap of about 1 eV [137], but the minority-carrier diffusion length is small [138–140]. GaAsN is unusual because the band gap decreases from 1.4 eV to about 1 eV with the addition of about 3% nitrogen. The alloy scattering is expected to be larger than in a conventional alloy, partially explaining the reduced majority-carrier mobility. However, the more serious problem is the low minority-carrier lifetimes, which have not yet been adequately explained. C and H contamination of MOCVD-grown GaInAsN is reported to be higher than that for MBE-grown GaInAsN [141], but the MBE material has not been evaluated for solar cells.

9.8.2 Mechanical Stacks

A high-efficiency result may also be obtained by a mechanical stack, relaxing the need to consider lattice matching. The most probable candidates for this are GaInP/GaAs stacked