

epilayers and the high temperatures involved in heteroepitaxial process, diffusion of both Group III and Group V atoms into the Ge substrate is unavoidable. The challenge is to control the process so as to obtain a Ge subcell with good photovoltaic properties and simultaneously form a defect-free heteroepitaxial layer of GaAs with the appropriate conductivity type and level. A detailed description of the optimum process is beyond the scope of the review, but a few critical factors that have to be considered are listed below:

- Diffusion coefficients are thermally activated. So, in general, dopants and junctions are less mobile and more stable at lower growth temperatures.
- As noted by Tobin *et al.* [103], the diffusion coefficient of As in Ge at 700°C is higher than that of Ga, but the solid solubility of Ga is larger than that of As.
- For three-junction GaInP/GaAs/Ge devices with a reasonably good-quality Ge subcell, the only Ge device parameter that is of consequence is the V_{OC} , because the J_{SC} of the Ge subcell is potentially much greater than that of the GaInP (or GaAs) subcell.
- The highest V_{OC} of a Ge solar cell reported to date is 0.239 [100]. This V_{OC} is a sensitive function of process conditions and is most sensitive to the quality of the III-V/Ge interface and its fabrication [100].
- AsH₃ etches Ge. The etch rate increases with temperature and AsH₃ partial pressure. Heavily etched, singular and vicinal Ge(100) surfaces are microscopically rough [104]. Hence, prolonged AsH₃ exposures should be avoided.
- The etch rate for PH₃ is much lower, and there appears to be much less roughening of the surface from PH₃ exposure [104]. The diffusion coefficient of P at 600°C is about two orders of magnitude lower than that of As [37]. Hence, PH₃ may be a better Group V, *n*-type dopant than AsH₃.

9.6.5.3 III-V heteroepitaxy

Although there are a number of “recipes” for the growth of GaAs on Ge(100) with specular morphologies or low antiphase domain (APD) or low stacking-fault densities, many present contradictory results. For example, Pelosi *et al.* [105] found that the GaAs surface morphology is best for very low V/III ratio (on the order of 1), using a moderate growth rate ($R_g \sim 3.5 \mu\text{m/h}$) and a low growth temperature ($T_g = 600^\circ\text{C}$). On the other hand, Li *et al.* [106] found that the lowest APD density occurs for high V/III, low R_g , and high T_g . Chen *et al.* [107] showed that “good” morphology could only be obtained for growth temperatures in the range of 600°C to 630°C.

The cause for this striking difference is not known with certainty. It may be due to differences in reactor design or purity. It may be related to the quality of the Ge substrates. Other researches [104] would suggest that it is related to the prenucleation conditions or the state of the Ge surface immediately prior to the GaAs nucleation step.

A lot has been published about the structure of Ge(100), but most of it is with regard to surfaces prepared in ultrahigh-vacuum (UHV) or MBE environments. It has been shown, however, that under most conditions, AsH₃-treated surfaces in an MOCVD reactor are quite different as explained below [104, 108, 109]. Arsenic on a Ge(100) terrace forms rows of dimers, similar to As on GaAs(100) [108, 109]. This reduces the (1×1) symmetry of the unreconstructed Ge surface to a surface that now has a (2×1)