for example, on the density of steps and kinks, that is, the substrate misorientation. This model is a much better fit than the *ad hoc* form $n \propto P_{Se}^{x} P_{V}^{y}$ most often published in the literature.

For electron concentrations greater than about $2 \times 10^{18}/cm^3$, the band gap energy of GaInP increases, the ordering decreases, and the morphology of the growth surface becomes very smooth [63]. At sufficiently high fluxes of Se, the surface again begins to roughen. At the same time, the electron concentration begins to decrease [60] and Se precipitates are observed in Transmission Electron Microscopy (TEM) [1]. Selenium has been linked to DX-like centers in $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ with Al concentrations greater than about $x = 0.4$ [66].

Silicon

Silicon is another widely used dopant in III-V materials and devices and the most popular source is Si_2H_6. The first report of using Si_2H_6 to dope GaInP was by Hotta and coworkers [67]. They found that for $T_g < 640°C$, n decreased with decreasing T_g presumably due to a decrease in Si_2H_6 pyrolysis rate. For $T_g > 640°C$, n saturates at about $n = 5 \times 10^{18}/cm^3$ with Si_2H_6, presumably due to the formation of nonionized complexes, such as $(Si_{III}{}^{+} - Si_{V}{}^{-})$ or $(Si_{III}{}^{+} - V_{III}{}^{-})$. The results [67] for Si-doped GaAs were quantitatively similar. Scheffer and coworkers [68] saw no evidence of saturation for electron concentrations up to $8 \times 10^{18}/cm^3$ using Si_2H_6, whereas Minagawa and coworkers [69] found that the electron concentration saturated at about $1 \times 10^{19}/cm^3$, essentially independent of substrate orientation and growth temperature.

It has been shown that Si delta doping (where the doping is confined to a single layer or series of layers) in GaInP increases the maximum electron concentration and increases the electron mobility relative to that of uniformly doped layers [70, 71]. The conclusion from these studies is that Si delta doping yields fewer Si shallow acceptor defects. Silicon apparently does not introduce any deep states in GaInP, but does so in $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ for $x > 0.3$ [72]. As with Se, Si concentrations above some critical level tend to disorder $Ga_xIn_{1-x}P$, causing the band gap to increase. However, the details can be quite varied. Gomyo and coworkers [62] reported that a lower concentration of Si than that for Se was required to disorder GaInP. However, Minagawa and coworkers [69] found that Si concentrations closer to $1 \times 10^{19}/cm^3$, depending on T_g, were required to dissolve the ordering in $Ga_xIn_{1-x}P$.

9.6.3.3.2 p-type dopants

Zinc

The most common *p*-type dopant in GaInP is Zn. The typical sources are dimethylzinc (DMZ) and diethylzinc (DEZ). The Zn doping characteristics have been studied by a number of investigators [35, 60, 61, 73]. The incorporation efficiency is typically sublinear with the input flow, and increases with lower growth temperature and higher growth rate R_g. A model that accounts for some of these effects has been proposed by Kurtz *et al.* [73].

High Zn concentrations cause several problems in GaInP. Carrier concentrations in the neighborhood of $1 \times 10^{18}/cm^3$ destroy the ordering in $Ga_xIn_{1-x}P$ and increase the