



## Practical doping principles

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with killer defects, or prevent  $E_F$  from moving.” An example is the use of H during Mg doping<sup>12</sup> of GaN: without H, excessive  $p$ -type Mg doping will lead to the spontaneous formation of  $V_N$  once the Fermi energy moves sufficiently towards the VBM. But since H acts as a donor, it prevents the movement of  $E_F$  towards the VBM, thus defeats the formation of the  $V_N$  killer defect. Subsequently, H is annealed out. This rule suggests, for example, that  $p$ -type doping of oxides can be facilitated by creating internal oxygen precipitates that eliminate oxygen vacancies, e.g., using NO or NO<sub>2</sub> sources<sup>3,5</sup> for nitrogen-doping of ZnO, or using Li<sub>2</sub>O sources for Li doping of MgO (Ref. 23).

(ii) *Doping rules pertaining to chemical potential effects.*

In general, the second term of Eq. (1) shows how  $\Delta H$  for formation of anionic or cationic dopants can be regulated via control of the chemical potentials during growth [Fig. 1(b)]. This figure illustrates the fact that the enthalpy of forming