INTRINSIC CARRIER CONCENTRATION AND THE FUNDAMENTAL HIGH-TEMPERATURE OPERATING LIMIT OF WIDE-BANDGAP SEMICONDUCTORS

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Abstract. The replacement of silicon by wide-bandgap (WBG) semiconductors such as 4H-SiC and GaN is the central trend in modern power and high-temperature electronics. Their advantage is governed by the equilibrium statistics of charge carriers: a doped device operates correctly only while the thermally generated intrinsic population n_i remains far below the net doping. Using the classical nondegenerate carrier statistics, we compute $n_i(T)$ and the intrinsic-onset temperature T_i on a common footing for Ge, Si, GaAs, 4H-SiC, and GaN with a temperature-dependent gap. At 300 K, n_i spans about 23 orders of magnitude across the set, and T_i (defined at a 10^{16} cm^{-3} doping level) rises almost linearly with the band gap, reaching about 1550–1590 K for SiC and GaN versus 659 K for Si. The band gap is thus identified as the single dominant lever setting the fundamental high-temperature ceiling of a semiconductor device.

Keywords: wide-bandgap semiconductors; intrinsic carrier concentration; equilibrium statistics; high-temperature electronics; silicon carbide; gallium nitride.

1. Introduction

Wide-bandgap (WBG) semiconductors have become the defining material platform of contemporary power conversion, electric-vehicle drivetrains, fast chargers, photovoltaic inverters, and high-frequency RF systems. Silicon carbide (4H-SiC) and gallium nitride (GaN) devices now routinely outperform silicon in efficiency, switching speed, and operating temperature, and they are the focus of intense industrial and academic activity. The physical origin of these advantages is, however, classical: it is rooted in the equilibrium statistics of electrons and holes treated in standard semiconductor theory [1].

A doped semiconductor device functions as intended only while its majority-carrier population is controlled by ionized dopants rather than by carriers generated thermally across the gap. As temperature rises, the intrinsic concentration n_i grows exponentially; once it becomes comparable to the net doping, p–n junctions lose rectification, leakage currents diverge, and the device ceases to operate. The temperature at which this happens — here called the intrinsic-onset temperature T_i — therefore represents the fundamental, material-imposed ceiling on device operation. This study revisits the equilibrium statistics summarised by Kireev (Ch. III) [1] to quantify n_i(T) and T_i on a common, transparent footing for five representative semiconductors, and to make explicit the quantitative link between the band gap and the high-temperature limit that underpins the WBG revolution.

2. Theoretical model

For a nondegenerate semiconductor in thermal equilibrium, the concentrations of free electrons and holes are obtained from the Fermi–Dirac distribution in the Boltzmann limit, in which the band populations are governed by the effective densities of states of the conduction and valence bands [1, 2]:

$$N_c = 2\left(\frac{2\pi m_n^* k_B T}{h^2}\right)^{3/2}, \qquad N_v = 2\left(\frac{2\pi m_p^* k_B T}{h^2}\right)^{3/2} \tag{1}$$

where m_n^* and m_p^* are the density-of-states effective masses, k_B is the Boltzmann constant, h is Planck's constant and T the absolute temperature. With the Fermi level several k_BT inside the gap, the carrier concentrations reduce to

$$n = N_c \exp\left[-\frac{E_c - E_F}{k_B T}\right], \qquad p = N_v \exp\left[-\frac{E_F - E_v}{k_B T}\right] \tag{2}$$

Multiplying the two expressions eliminates the Fermi level and yields the law of mass action, which holds for both intrinsic and doped material:

$$np = n_i^2 = N_c N_v \exp\left[-\frac{E_g}{k_B T}\right] \tag{3}$$

so that the intrinsic carrier concentration takes the closed form

$$n_i = \sqrt{N_c N_v}\exp\left[-\frac{E_g}{2k_B T}\right] = 2\left(\frac{2\pi k_B T}{h^2}\right)^{3/2}(m_n^* m_p^*)^{3/4}\exp\left[-\frac{E_g}{2k_B T}\right] \tag{4}$$

The position of the intrinsic Fermi level, which fixes the reference for doping, follows as

$$E_i = \frac{E_c + E_v}{2} + \frac{3}{4}k_B T \ln\left(\frac{m_p^*}{m_n^*}\right) \tag{5}$$

Equation (4) shows that n_i is controlled overwhelmingly by the exponential factor $\exp(-E_g/2k_BT)$. Because the gap itself contracts with temperature, we use the empirical Varshni relation [3]

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta} \tag{6}$$

with material constants α and β. Finally, the intrinsic-onset temperature is defined by the condition that the intrinsic population reaches the net doping level N_{dop}:

$$n_i(T_i) = N_{\mathrm{dop}} \tag{7}$$

All curves below are evaluated directly from Eqs. (4)–(7); no empirical fitting is applied. The material parameters (band-gap and Varshni constants, density-of-states effective masses) are taken from standard compilations [2, 4, 5] and listed in Table 1, with $N_{dop} = 10^{16}$ cm^{-3} chosen as a representative net doping for a device active region.

3. Results

Table 1 collects the input parameters together with the computed room-temperature intrinsic concentration and the intrinsic-onset temperature for each material. The computed 300 K values agree closely with accepted figures, for example 8.1×10^9 cm^{-3} for Si and 2.1×10^6 cm^{-3} for GaAs, confirming the internal consistency of the model.

Material	E_g (eV)	m_n^*/m_0	m_p^*/m_0	n_i (cm^{-3})	T_i (K)
Ge	0.66	0.56	0.29	1.7×10^{13}	478
Si	1.12	1.08	0.81	8.1×10^{9}	659
GaAs	1.42	0.067	0.47	2.1×10^{6}	928
4H-SiC	3.25	0.77	1.20	1.2×10^{-8}	1552
GaN	3.43	0.20	1.40	1.4×10^{-10}	1586

Table 1. Material parameters and computed equilibrium quantities. Intrinsic-onset temperature T_i is defined by $n_i(T_i) = 10^{16}$ cm^{-3}.

Figure 1 presents n_i as a function of inverse temperature (an Arrhenius plot). The straight-line behaviour confirms the dominant exponential dependence, while the slope, proportional to E_g, increases markedly from Ge to GaN. At 300 K the intrinsic concentration spans roughly twenty-three orders of magnitude across the set.

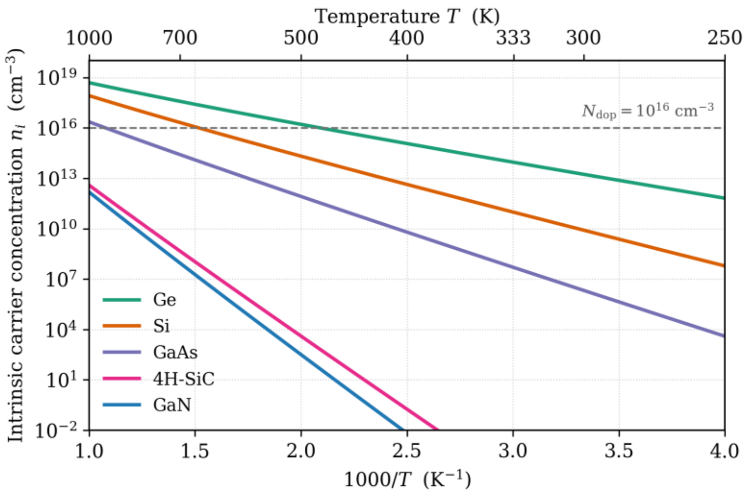

Fig. 1. Intrinsic carrier concentration n_i versus 1000/T for five semiconductors. The dashed line marks the assumed doping level 10^{16} cm^{-3}; its intersection with each curve gives T_i.

Figure 2 plots the resulting intrinsic-onset temperature against the room-temperature band gap. The relationship is nearly linear: T_i rises from 478 K for Ge and 659 K for Si to 928 K for GaAs and to roughly 1550–1590 K for 4H-SiC and GaN.

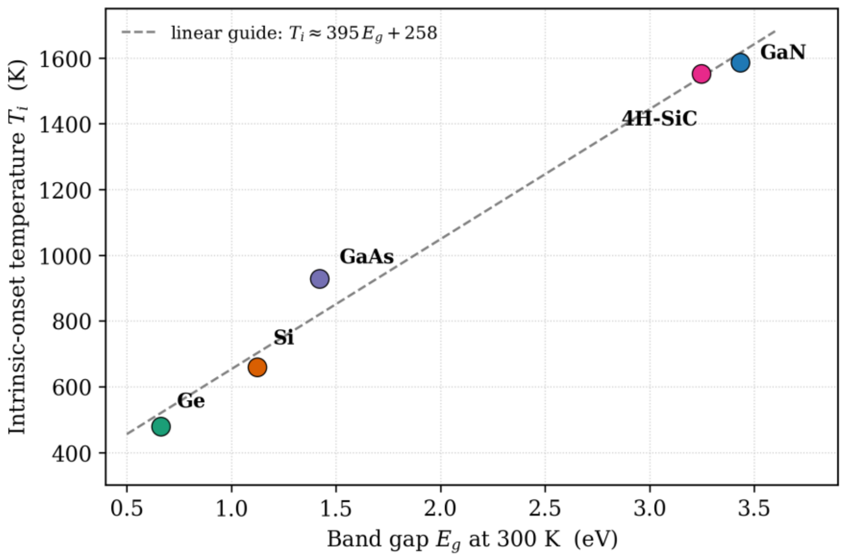

Fig. 2. Intrinsic-onset temperature T_i as a function of the 300 K band gap. The dashed line is a linear guide to the eye.

4. Discussion

The results give a compact physical explanation of the WBG advantage. Since n_i is dominated by $\exp(-E_g/2k_BT)$, a larger gap exponentially suppresses thermal carrier generation, so the doping-controlled regime extends to far higher temperatures; the near-linear $T_i(E_g)$ relation of Fig. 2 makes the band gap the single most important design lever, outweighing the weak influence of the effective masses. It must be stressed that T_i is a fundamental material limit, not the usable junction temperature: real devices are constrained well below it by packaging, contacts, gate-dielectric reliability and leakage. In practice silicon is limited to roughly 150–200 °C, whereas the large margin predicted for SiC and GaN is precisely what enables demonstrated operation at 300–600 °C [4, 5]. Parameter uncertainties shift the computed T_i by at most a few tens of kelvin and do not alter the ordering of the materials.

5. Conclusion

Starting from the classical equilibrium statistics of charge carriers, we computed the intrinsic carrier concentration and the intrinsic-onset temperature for Ge, Si, GaAs, 4H-SiC and GaN on a common footing. The intrinsic concentration spans about twenty-three orders of magnitude at room temperature, and the onset temperature scales almost linearly with the band gap, exceeding 1500 K for the wide-bandgap materials against 659 K for silicon. These results give a transparent baseline for the high-temperature capability of WBG semiconductors and identify the band gap, through the exponential factor of the law of mass action, as the dominant parameter behind their growing role in power electronics.

References

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