

Wide and Narrow Bandgap Semiconductors for Power Electronics: A New Valuation

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An advantage for some wide bandgap materials that is often overlooked is that the thermal coefficient of expansion (CTE) is better matched to the ceramics in use for electronic-packaging technology. The optimal choice for unipolar devices is GaN and the associated material system of GaN/AlGaIn. The future optimal choice for bipolar devices at all power levels is C (diamond). New expressions, $\mathcal{E}_c = 1.73 \times 10^5 (E_G)^{2.5}$ for direct-gap and $\mathcal{E}_c = 2.38 \times 10^5 (E_G)^2$ for indirect-gap semiconductors, relating the critical-electric field for breakdown in abrupt junctions to the material bandgap energy, and associated new expressions for specific on-resistance in power semiconductor devices is shown to further support the use of wide bandgap materials. Some low-voltage, power-electronics applications are shown to benefit by the use of Ge, C, and GaSb.*

Key words: Power electronics, wide bandgap, narrow bandgap, specific on-resistance, gallium nitride, diamond, critical-electric field

INTRODUCTION

Power-semiconductor devices made from materials with bandgap energies larger than in Si have been touted for many decades. The potential advantages of these wide bandgap devices include higher achievable junction temperatures and thinner drift regions (because of the associated higher critical-electric field values) that can result in much lower on-resistance than is possible in Si.¹⁻³ There are, however, several disadvantages associated with the use of devices fabricated from wide bandgap materials. Among these is that the ratio of the electron-to-hole mobility values range much higher than in Si, and typically, the hole mobility is quite low, so that the use of wide bandgap semiconductors for bipolar devices is not desirable.

An advantage to the use of some wide bandgap materials that is often overlooked, however, is that the coefficient of thermal expansion (CTE) is better suited to the ceramics used today in packaging technology. In addition, the maturity and expense of material processing plays a role in the optimal choice of the semiconductor system best suited for power-semiconductor devices. It will be shown that

the near-term optimal choice for unipolar devices is GaN. It will also be shown that the future optimal choice for unipolar and bipolar devices is C (diamond). In addition, a recently developed expression relating the critical-electric field for breakdown in abrupt junctions to the material bandgap energy is discussed along with newly derived expressions for specific on-resistance in power-semiconductor devices.⁴ A short discussion of the use of various materials in low-voltage, power-electronics applications is given and extended to include possible integrated-circuit design using complementary metal-oxide semiconductor (CMOS) or n metal-oxide semiconductor (NMOS) topologies.

OPTIMAL SEMICONDUCTOR MATERIALS FOR HIGH-VOLTAGE DEVICES

Thermomechanical Properties

Various semiconductor-material parameters are listed in Table I. The references for the material parameters in the table are denoted with capital letter superscripts and are listed separately in the reference section at the end of the paper. Table II lists some of the physical parameters of typical power-electronic

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*See list of symbols in Appendix.

Table I. Parameters of Various Semiconductors at 300 K

Semiconductor Material	Bandgap (eV) Direct (D) Indirect (I)	Intrinsic Carrier Concentration n_i (cm^{-3})	Electron Mobility μ_e ($\text{cm}^2/\text{V} \cdot \text{s}$)	Hole Mobility μ_h ($\text{cm}^2/\text{V} \cdot \text{s}$)	Electron Effective Mass (m_n/m_o)	Hole Effective Mass (m_p/m_o)
InSb	0.17, ^[6] D	2×10^{16} ^[6]	77,000 ^[6]	850 ^[6]	0.014 ^[6]	m_h/m_l ^[6]
InAs	0.354, ^[6] D	1×10^{15} ^[6]	44,000 ^[6]	500 ^[6]	0.023 ^[6]	0.43/0.015 m_h/m_l ^[6]
InN	0.7–0.8, ^[16,17] D	—	1,000 ^[16]	—	0.11 ^[15]	0.41/0.026 m_h/m_l ^[15]
GaSb	0.726, ^[6] D	1.5×10^{12} ^[6]	3,000 ^[6]	1,000 ^[6]	0.041 ^[6]	1.63/0.27 m_h/m_l ^[6]
InP	1.344, ^[6] D	1.3×10^7 ^[6]	5,400 ^[6]	200 ^[6]	0.08 ^[6]	0.4/0.05 m_h/m_l ^[6]
GaAs	1.424, ^[6] D	2.1×10^6 ^[6]	8,500 ^[6]	400 ^[6]	0.063 ^[6]	0.6/0.089 m_h/m_l ^[6]
GaN (Wurzite)	3.39, ^[15] D	1.9×10^{-10} ^[14]	$\leq 1,000$ ^[15]	≤ 200 ^[15]	0.2 ^[15]	0.51/0.082 m_h/m_l ^[15]
(Zinc Blende)	3.2, ^[15] D	—	$\leq 1,000$ ^[15]	≤ 350 ^[15]	0.13 ^[15]	1.4/0.8 1.3/0.2
BN (H)	5.8, ^[5] D	—	—	—	—	—
AlN	6.2, ^[15] D	10^{-31} ^[14]	300 ^[5,15] –1,100 ^[14]	14 ^[5,15]	0.4 ^[15] –0.48 ^[5]	m_h/m_l ^[15] k_z : 3.53/3.53 k_x : 10.42/0.24
Ge	0.661, ^[6] I	2×10^{13} ^[6]	3,900 ^[6]	1,900 ^[6]	m_h/m_t ^[6]	m_h/m_l ^[6]
Si	1.12, ^[6] I	10^{10} ^[6]	1,400 ^[6]	450 ^[6]	1.6/0.08 m_h/m_t ^[6]	0.33/0.043 m_h/m_l ^[6]
AlSb	1.615, ^[5] I	—	200 ^[5]	400 ^[5]	0.98/0.19 m_h/m_t ^[5]	0.49/0.16 m_h/m_l ^[5]
BAAs	1.8–1.9, ^[5] I	—	—	—	1.8/0.259	0.336/0.123
AlAs	2.153, ^[5] I	—	290 ^[5]	180 ^[8]	0.15 ^[5]	m_h/m_l ^[5]
BP	2.2, ^[5] I	—	100 ^[5]	20–40 ^[5]	0.67 ^[5]	1.02/0.11
GaP	2.26, ^[6] I	2 ^[6]	250 ^[6] –350 ^[14]	150 ^[6]	m_h/m_t ^[6]	0.042 ^[5] m_h/m_l ^[6]
AlP	2.42, ^[5,7] I	—	60 ^[5]	450 ^[5]	1.12/0.22 m_h/m_t ^[5]	0.79/0.14 m_h/m_l ^[5]
SiC (3C, β)	2.36, ^[5,11,15] I	1.2 ^[11]	≤ 800 ^[15]	≤ 320 ^[15]	3.67/0.212 m_h/m_t ^[5,15]	1.37/0.145 0.6 ^[15]
SiC (6H, α)	3.0, ^[15] I	10^{-6} ^[11]	330 ^[8] –400 ^[11] ≤ 400 ^[15]	75 ^[11] ≤ 90 ^[15]	m_h/m_t ^[15]	1.0 ^[15]
SiC (4H, α)	3.23, ^[15] I	8.2×10^{-9} ^[14]	700 ^[8] –980 ^[14] ≤ 900 ^[15]	≤ 120 ^[15]	m_h/m_t ^[15]	1.0 ^[15]
C (diamond)	5.46–5.6, ^[6] I	10^{-27} ^[6]	1,900 ^[14] –2,200 ^[6]	1,800 ^[6]	0.29/0.42 m_h/m_t ^[6]	m_h/m_l ^[6] 2.12/0.7
BN (C)	6.4, ^[5] I	—	0.2 ^[5]	0.2 ^[5]	—	—

package substrates, metals, and solder materials. From Tables I and II, it can be shown that the materials with a value of thermal conductivity close to or exceeding Si (above 100 W/m · K) and with CTE values of 4–8 ppm/K (to closely match typical substrate materials) are as displayed in Fig. 1a and b. The resulting short list of semiconductors that have both a relatively high value of thermal conductivity and a close CTE match to package substrate materials becomes GaN, AlN, GaP, SiC (6H), and SiC (4H). Diamond and the cubic polytype of BN are included in the discussion because it can be argued that the extremely high,

thermal-conductivity values of these materials make the CTE match less of an issue. In fact, it could be reasoned that diamond devices on an insulating (intrinsic or polycrystalline) diamond substrate would cause no CTE mismatch and provide low thermal resistance and high electrical isolation.

Electrical Properties

It has been shown that the traditionally used relationship¹⁸ between the critical-electric field (breakdown field) and energy bandgap of a semiconductor is not accurate.⁴ The traditionally used expression is

Critical or Breakdown Field E_c (V/cm)	Thermal Conductivity σ_T (W/m·K)	CTE (ppm/K)
1,000 ^[6]	18 ^[6]	5.37 ^[6]
40,000 ^[6]	27 ^[6]	4.52 ^[6]
—	450 ^[15]	2.9–3.8 ^[15]
50,000 ^[6]	32 ^[6]	7.75 ^[6]
500,000 ^[6]	68 ^[6]	4.6 ^[6]
400,000 ^[6,9]	55 ^[6]	5.73 ^[6]
{3 ^[10] –3.3 ^[14] × 10 ⁶ , 3.5 × 10 ⁶ ^[12] , 5 × 10 ⁶ ^[15] }	130 ^[15]	3.2–5.6 ^[15]
—	200 ^[5]	10.2 ^[5]
11.7 × 10 ⁶ ^[14]	285 ^[15]	4.2–5.3 ^[15]
100,000 ^[6]	58 ^[6]	5.9 ^[6]
300,000 ^[6]	130 ^[6]	2.6 ^[6]
—	59 ^[5]	3.7 ^[5]
—	—	—
—	84 ^[5]	5.2 ^[5]
—	360 ^[5]	3.65 ^[5]
1,000,000 ^[6]	110 ^[6]	4.65 ^[6]
—	130 ^[5]	—
1.0 ^[15] –1.3 ^[12] × 10 ⁶ at $v_{sat} =$ 2.5 × 10 ⁷ cm/s ^[13]	360 ^[15]	3.8 ^[15]
2,400,000 ^[9] 3–5 × 10 ⁶ ^[15]	490 ^[15]	4.3–4.7 ^[15]
2.0 ^[14] –3.2 ^[12] × 10 ⁶ 3–5 × 10 ⁶ ^[15]	370 ^[15]	5.12 ^[8,15]
5.6 ^[14] –5.7 × 10 ⁶ ^[6,9] (7,000,000 ^H @ $v_{sat} = 3 \times 10^7$ cm/s)	600–2,000 ^[6]	0.8 ^[6]
—	1,300 ^[5]	1.8 ^[5]

given by Eq. 1:^{18,19}

$$\mathcal{E}_c = 1.02 \times 10^7 \sqrt{\frac{q}{\epsilon}} N_B^{1/8} E_G^{3/4} \quad (1)$$

where q is the electron charge, ϵ is the permittivity of the semiconductor material, N_B is the impurity-doping concentration on the low-doped side of the junction, and E_G is the bandgap energy. It should be noted that, in high-voltage power semiconductors, the impurity concentration on the low-doped side of the junction is typically as low as possible to allow for optimized voltage breakdown in the device (for

Si in the range of 10^{13} – 10^{14} cm⁻³), resulting in a dependence of the critical field on the bandgap energy to the power of 0.75 and relatively independent of the exact value of N_B . The expression in Eq. 1 has been used extensively in the literature to derive empirical dependencies between bandgap and critical field or breakdown voltage and to further derive forms of on-resistance, R_{ON} , or specific on-resistance, R_{ONsp} , as figures of merit for power-device performance.^{1–3,19}

Recently, expressions for the critical-electric field in terms of the bandgap energy were derived for direct- and indirect-bandgap semiconductors.⁴ These are shown by Eqs. 2 and 3 below for direct and indirect materials, respectively. Comparison of Eq. 2 to 1 indicates a greater advantage to wide bandgap materials than was previously derived from the limited data set used previously.¹⁸ There is no dependence on background doping included because power-electronic devices are always low-doped for increased voltage capability.

$$\mathcal{E}_c = 1.73 \times 10^5 (E_G)^{2.5} \quad (2)$$

$$\mathcal{E}_c = 2.38 \times 10^5 (E_G)^2 \quad (3)$$

Figure 2a and b shows a comparison of Eqs. 1–3 as well as the data from Table I, assuming a nominal base-doping density of 10^{14} cm⁻³. Equation 1 works well for Si and GaAs and somewhat less well for Ge. This is to be expected because Eq. 1 was derived by optimizing the relationship using only Si, Ge, GaAs, and GaP. Note that Eq. 1 greatly overestimates the critical field for small bandgap values and underestimates the critical field for wide bandgap materials as compared to the reported values.

A new expression using Eqs. 2 and 3 was derived for the specific on-resistance, R_{ONsp} , associated with an abrupt pn junction.⁴ The on-resistance value refers to the structure of a majority carrier device, specifically for electrons because of the larger value of mobility, and only accounting for the drift-region drop (e.g., ignoring other contributions to the device forward-voltage drop during conduction). Specifically for this work, the appropriate expressions for direct- and indirect-bandgap semiconductors are given by Eqs. 4 and 5, respectively.

$$R_{ONsp} = \frac{8.725 \times 10^{-3} V_B^2 E_G^{-7.5}}{\mu_e \epsilon_r} \quad (4)$$

$$R_{ONsp} = \frac{3.351 \times 10^{-3} V_B^2 E_G^{-6}}{\mu_e \epsilon_r} \quad (5)$$

The new results in Eqs. 4 and 5 are, as compared to previous results, given by¹⁹

$$R_{ONsp} = \frac{1.716 \times 10^{-6} \epsilon_r^{0.5} V_B^{2.5} E_G^{-3}}{\mu_e} \quad (6)$$

The equations for R_{ONsp} are compared in Fig. 3 for Si, SiC (4H), and GaN. Note that Eq. 6 overestimates the on-resistance for both SiC and GaN primarily because the basis for the derivation of Eq. 6

Table II. Package Material Parameters at 300 K

Material	CTE (ppm/K)	Mass Density (g/cm ³)	Thermal Conductivity (W/m · K)
AlN substrate	4.5	3.3	200
AlSiC substrate (high volume of SiC)	7	3	200
Al ₂ O ₃ (alumina) substrate	6.5	3.9	30
Metal Matrix Composites (W/Cu, 85/15)	6.5	16.6	170
Beryllia (BeO) substrate	6.1	2.9	280
Copper (Cu) baseplate, pole pieces, direct bond copper (DBC) metal	17	8.9	400
Tungsten (W)	4.6	19.3	188
Molybdenum (Mo)	4.9	10.2	140
Aluminum (Al)	23	2.7	235
Lead (Pb)	29	11.3	35
95/5 solder (Pb/Sn high temperature)	29	11.2	35
50/50 solder (Pb/Sn)	29	9.3	46
40/60 solder (Pb/Sn near-eutectic)	25	—	50
Tin (Sn)	23	7.3	66
Thermal grease	—	—	0.75

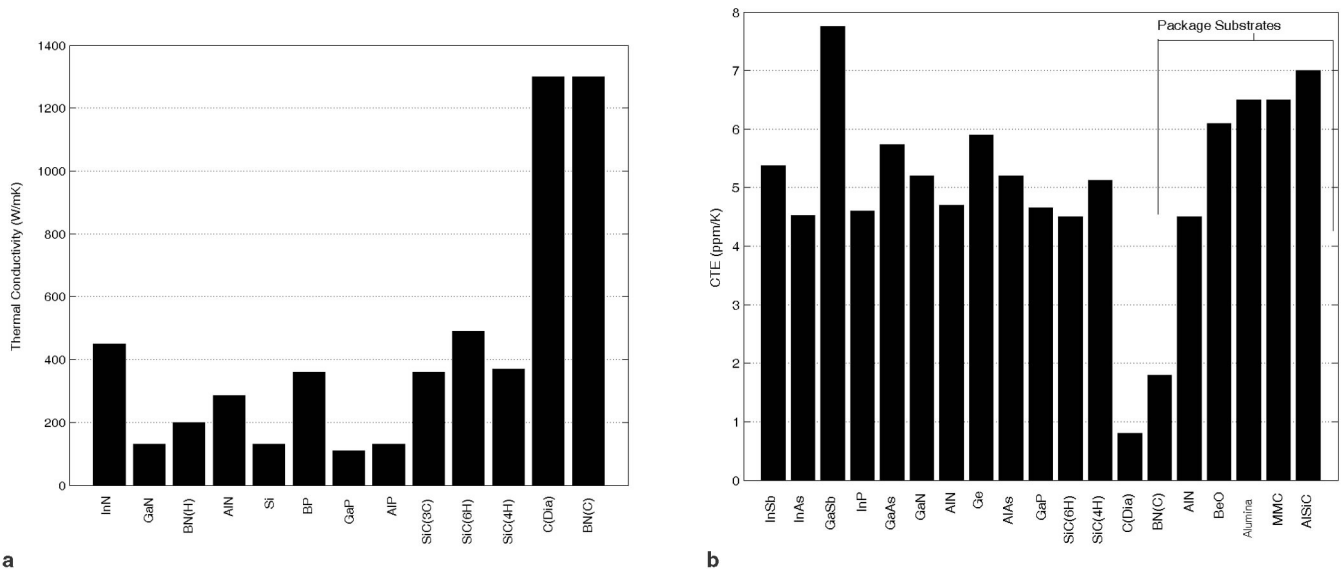


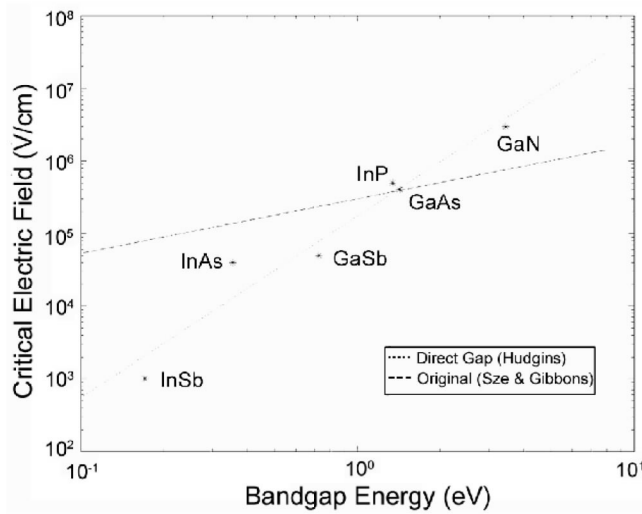
Fig. 1. (a) The semiconductors with a thermal-conductivity value above 100 W/m · K. (b) Semiconductors with a CTE value between 4–8 ppm/K that closely match package substrates. The C and BN (cubic) are included because of high thermal conductivity. Typical package substrates are indicated.

depends upon Eq. 1. Equation 1 was created based on data that was closely fitted to Si. The close overlay of curves in Fig. 3 for Si indicates the expected similar results.

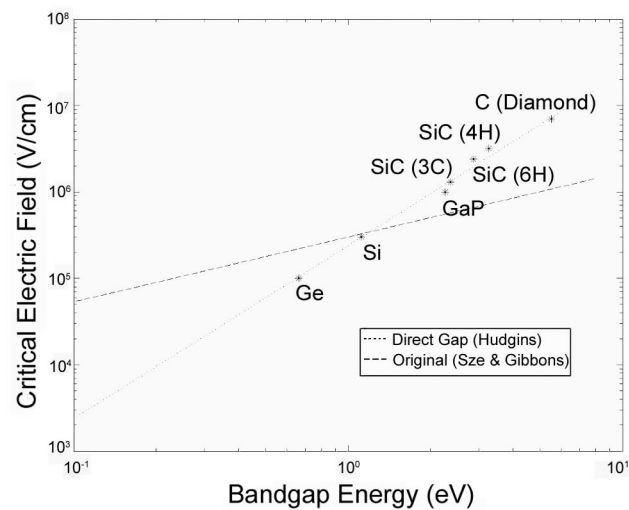
A scatter plot of the electron mobility in terms of bandgap energy for the semiconductors in Table I is shown in Fig. 4. Semiconductors with electron mobilities above 700 cm²/V-s and with a bandgap energy above 1 eV are InP, GaAs, GaN, AlN, Si, SiC (3C), SiC (4H), and C. Table III compares the results from the thermomechanical evaluation and the electrical evaluation of semiconductors for high-voltage, unipolar (majority carrier) power devices. The results are SiC (4H) polytype, the GaN/AlN system (including the ternary AlGaIn), and diamond (C).

Device Considerations

The best semiconductor material for the future is C (diamond). It has the highest thermal conductivity, bandgap, and electron mobility of any of the materials from Table III. However, there are two aspects of C (diamond) that make it less than ideal. First, the material and device fabrication technology is much less mature and developed than for SiC and GaN. Second, the CTE for C (diamond) is very low. Comparing the value of 0.8 ppm/K to typical package material CTEs (listed in Table II), there is a clear thermomechanical mismatch, though this may be offset by the extremely high thermal conductivity and the future possibility of integrating



a



b

Fig. 2. (a) The comparison of Eqs. 1 and 2 relating bandgap energy and critical-electric field for direct-gap semiconductors and associated reported data. (b) Comparison of Eqs. 1 and 3 relating bandgap energy and critical-electric field for indirect-gap semiconductors and associated reported data.

diamond substrates directly with diamond-based semiconductor devices to eliminate the CTE mismatch. The GaN and SiC are by comparison to C (diamond) very well suited to typical package materials and, in fact, provide a better thermomechanical match than Si.

The SiC is beginning to be used in commercial power devices, particularly diodes. However, GaN and related III-V devices are also being used in radio-frequency and electro-optic applications. Various polytypes of SiC have electron mobilities similar to, but generally less than, GaN. The hole mobilities are very similar in value to GaN, as well as the CTE values. Silicon carbide has a larger thermal conductivity, but this is more than offset by the larger bandgap (and associated theoretical-maximum junction temperature of operation) in GaN. Based on new and more precise on-resistance calculations (Fig. 3), an

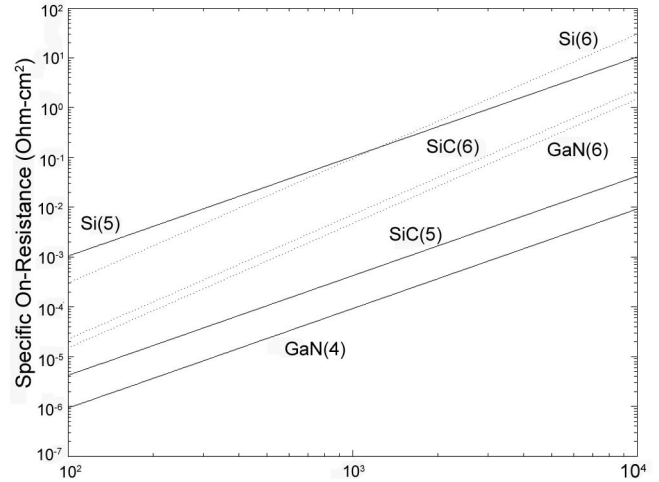


Fig. 3. The comparison between Eqs. 4 (solid line), 5 (solid lines), and 6 (dashed lines) for specific on-resistances, R_{ONsp} , as a function of breakdown voltage for Si, SiC (4H), and GaN.

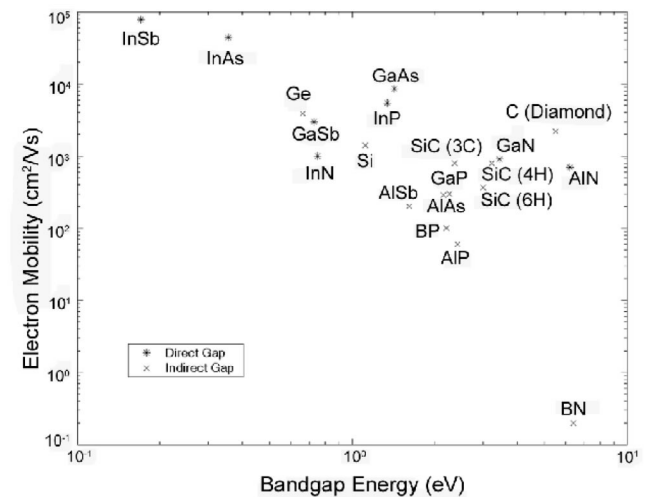


Fig. 4. The electron mobility in terms of bandgap energy for the semiconductors of Table I.

Table III. Semiconductors with Good Thermal, Electrical, or Mechanical Parameters

Thermomechanical Best	Electrical Best
GaN	InP
AlN	GaAs
GaP	GaN
SiC (6H)	AlN
SiC (4H)	Si
C (diamond)	SiC (3C)
BN (C)	SiC (4H)
—	C (diamond)

even greater advantage can be had by increasing the bandgap energy than previously thought, thus favoring GaN/AlN over SiC further.

Unique materials properties of GaN-based semiconductors have stimulated a great deal of interest in research and development in materials growth and opto-electronic and electronic devices using this

semiconductor system. The major advantages of nitride-based devices that make them extremely promising for high-power, high-temperature applications are high electron mobility and saturation velocity, high sheet-carrier concentration at heterojunction interfaces, high breakdown field, and low thermal impedance when grown over SiC substrates. The chemical inertness of nitrides is a key property to provide high reliability.

The major problems with the nitride-based devices are related to the material quality. Because there is no bulk GaN crystals available to date, the epitaxial films are grown over sapphire or SiC substrates. In both cases, because of significant lattice mismatching, the films contain a high concentration of defects, which affects the breakdown voltage, the carrier mobility, device reliability, and other important characteristics. Typical values for the room-temperature electron mobility in the doped-GaN films do not exceed $300 \text{ cm}^2/\text{V}\cdot\text{s}$, though $900 \text{ cm}^2/\text{V}\cdot\text{s}$ has been reported (Table I). The breakthrough in the GaN-based transistor development, though, is associated with the demonstration of a high-density, two-dimensional (2-D) electron gas at the AlGaIn/GaN interface.²⁰ Because of the extremely large bandgap offsets at the interface, the 2-D gas density in the AlGaIn/GaN heterostructures can be as high as $2 \times 10^{13} \text{ cm}^{-2}$, which is about 10 times higher compared to AlGaAs/GaAs structures. It was also shown that, in the 2-D gas, the screening of the defect and impurity scattering allows for much higher mobility, up to $1,500\text{--}2,000 \text{ cm}^2/\text{V}\cdot\text{s}$. Since the first demonstrations in 1991 and 1992, several groups had reported high-power operation of AlGaIn/GaN heterostructure field-effect transistors at microwave frequencies,^{21–23} including a 100-W output power, single-chip amplifier developed by Cree, Inc. (Durham, NC) and 100-GHz cutoff frequency devices.²⁴ Recently, several MOS-type structures have been reported using heterojunctions (GaIn/AlGaIn) with the capability to withstand breakdown at up to 500 V and conduct current densities of up to $1.5 \text{ kA}/\text{cm}$.^{24,25–27}

OPTIMAL SEMICONDUCTOR MATERIALS FOR LOW-VOLTAGE DEVICES

Many power-semiconductor devices are used in low-voltage applications, from 42-V automotive systems to power supplies operating digital-processor integrated circuits (ICs) at and below 1.3 V. These applications can push the physical limits of devices fabricated using Si. All applications requiring devices other than n-channel metal-oxide semiconductor field-effect transistors (includes synchronous rectifiers) will have at least one pn-junction drop. For low-voltage IC power, this becomes a significant limiting factor in using silicon. Figure 5 shows the built-in junction potential for several semiconductors. The materials with voltage drops less than Si are GaSb, Ge, InN, InAs, and InSb. The use of Ge or GaSb provides a good alternative, as each of them

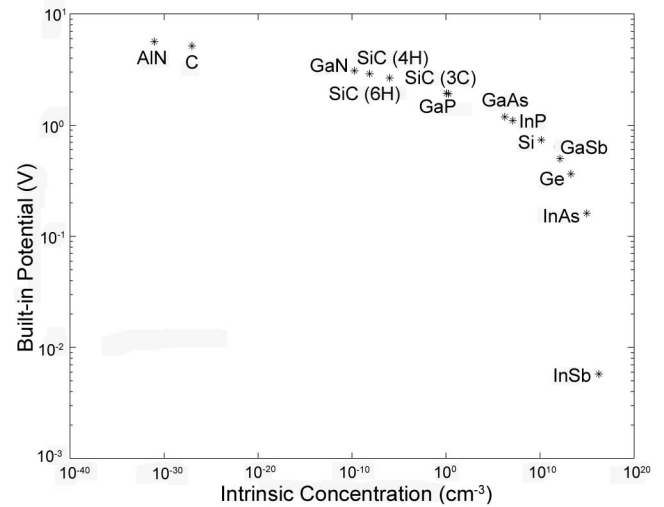


Fig. 5. The built-in potential of a step pn-junction for various semiconductors.

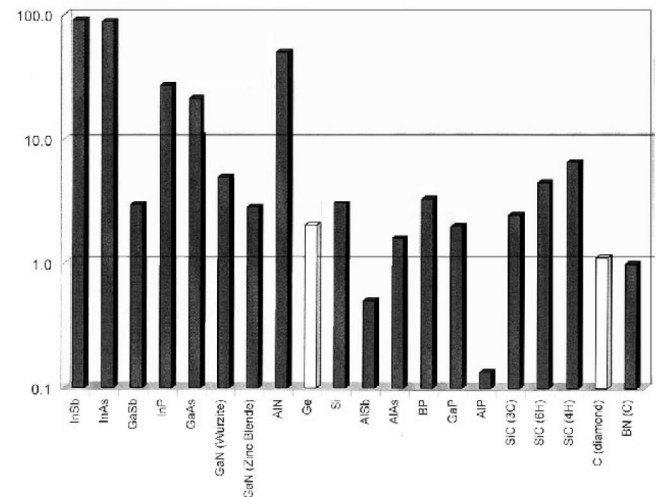


Fig. 6. The graph of the electron-to-hole mobility ratios for the semiconductors of Table I. The Ge and C are indicated in white because their mobility ratios are less than 2.5 and their electric mobilities exceed $1,000 \text{ cm}^2/\text{V}\cdot\text{s}$.

has electron and hole mobilities larger than Si. Low-voltage bipolar devices, such as insulated-gate bipolar transistors and diodes, can be contemplated in these materials.

A graph of the electron-to-hole mobility ratios for the semiconductors of Table I is given in Fig. 6. Very few semiconductors have a ratio below three and also have an electron mobility above $1,000 \text{ cm}^2/\text{V}\cdot\text{s}$. As can be seen from the plot in Fig. 6, only Ge and diamond meet these conditions. The near-unity ratio of diamond makes it ideal for CMOS circuit designs, particularly in operating environments of elevated temperatures. Where low-voltage applications have junction voltage drops as a critical limiting factor, Ge is again the material of choice. If NMOS circuit design is used, then an ultrahigh mobility material, such as InAs, could be useful, though the small

bandgap energy would require operation in well-controlled temperature environments.

CONCLUSIONS

The GaN, SiC (4H), and C (diamond) are the best semiconductor material systems in which to create future power-electronic devices. Specifically, it has been shown that the traditionally used relationship between energy bandgap and critical-electric field is incorrect and underestimates the gains to be had by using wide bandgap semiconductors for high-voltage devices. A comparison of the revised equations for R_{ONsp} was given. In light of the maturity of the fabrication technology and thermomechanical-material properties, GaN appears to be the best choice, overall, for the next decade of development. The GaN/AlN system (AlGaIn ternary) has a good CTE match to package materials, the second highest bandgap (compared to diamond), and can be used to create heterojunction devices that give effective electron-mobility values above $2,000 \text{ cm}^2/\text{V} \cdot \text{s}$.

For low-voltage applications, where junction voltage drops are critical or CMOS circuits are to be used, it has been argued that Ge is overall the best material. The GaSb is also worthy of consideration, though this material system suffers from the lack of material growth and processing infrastructure that is in place for Ge. Finally, it has been shown that high-voltage unipolar and bipolar power-electronic devices, low-voltage CMOS, and possibly high-voltage CMOS ICs can gain greatly in performance by being fabricated using C (diamond). The near match and high values of carrier mobilities as well as the large bandgap and high thermal conductivity make diamond the ideal material for electronic devices of all power levels and types.

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APPENDIX

List of Symbols

CTE	Coefficient of thermal expansion (ppm/K or $\mu\text{m}/\text{m} \cdot \text{K}$)
E_G	Bandgap energy (eV)
$\mathcal{E}(x)$	Electric field as a function of position (V/cm)
\mathcal{E}_c	Critical-electric field (V/cm)
ϵ	Permittivity (F/cm)
ϵ	Relative permittivity
m_o	Electron rest mass (kg)
m_n	Electron density-of-states effective mass (kg)
m_l	Longitudinal electron density-of-states effective mass (in m_o)

m_t	Transverse electron density-of-states effective mass (in m_o)
m_p	Hole density-of-states effective mass (kg)
m_h	Heavy valence-band hole density-of-states effective mass (in m_o)
m_l	Light valence-band hole density-of-states effective mass (in m_o)
μ_e	Electron conduction mobility ($\text{cm}^2/\text{V} \cdot \text{s}$)
μ_h	Hole-conduction mobility ($\text{cm}^2/\text{V} \cdot \text{s}$)
N_B	Impurity-density concentration (cm^{-3})
n_i	Intrinsic-carrier concentration (cm^{-3})
R_{ONsp}	Specific on-resistance ($\Omega \cdot \text{cm}^2$)
σ_T	Thermal conductivity ($\text{W}/\text{m} \cdot \text{K}$)
V_B	Breakdown voltage (V)