Beyond Silicon: The Next Frontier of Semiconductors in High-Voltage Charging

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Abstract. Since the birth of semiconductor industry, the Silicon (Si) always takes the dominant position. However, with the surge of requirement of semiconductors' performance, Silicon is gradually facing the risk of being phased out. More and more semiconductor materials have been developed, showing a trend of replacing the Si. This essay takes high-voltage charging piles as an example to show the advantages of materials beyond silicon. By comparing relevant data and analyzing physical quantities that affect material properties, this essay found that SiC, GaN, diamond and other materials are better than silicon in high-temperature stability, high breakdown field and ultra-low power loss. In addition, in the part of economic discussion, it takes economic factor into account, showing the reason of why Si dominated the semiconductor industry at beginning, and how much advantage it contains compared with other materials, and which material can stand out and become the main core of the next-generation semiconductor industry.

Keywords: High temperature resistance, high pressure resistance, low power loss.

1. Introduction

In the past silicon dominated the semiconductor industry because of its low price and good overall properties. However, two parallel forces have recently shifted the balance of merit. First, purely technical demand has surged: 800-V-plus, megawatt-level EV charging piles must now survive junction temperatures above 160 °C, electric fields beyond 3 MV cm^{-1}, and switching cycles in the MHz range. Second, the economics of non-silicon substrates—once prohibitive—have begun to soften as 6-inch SiC wafers fall below USD 500 and GaN-on-Si epitaxy approaches USD 200. Huawei has publicly stated that conventional silicon power semiconductors cannot satisfy the new technical envelope because of their poor high-temperature tolerance [1], while Kangni New Energy announced a compact bidirectional charger built around GaN devices whose system-level cost already rivals that of silicon equivalents [2]. This essay therefore demonstrates why emerging semiconductors outperform silicon in temperature stability, breakdown field and ultra-low power dissipation, and it does so through quantitative comparisons that explicitly include the rapidly evolving cost picture. For the first aspect—high temperature stability, there are three physical quantities that can affect it: energy gap, thermal conductivity, carrier mobility. Then, it becomes to high breakdown field, it is affected by band gap, relative permitivity and molecular bond. Next come low ultra power loss, which is affected by conduction loss and switching loss.

2. The three main criteria for evaluating the quality of semiconductor materials

2.1. High-Temperature stability

One of the most common requirements of electric piles is to ensure the electric appliance can work in high temperature. For a 1000V fast charger, the working temperature may reach about 160℃. However, the maximum working temperature of Si is 150℃, so finding a more heat-tolerate material is essential. There are many factors that affect this, this essay list the 3 most common aspects.

Bandgap (Eg). The generation rate of electron–hole pairs is directly proportional to exp (Eg/(2kBT)) If the band gap (Eg) is larger, the intrinsic carrier concentration will be under control with higher temperature, thereby the critical point of thermal runaway will be higher.

Table 1. Comparison of bandgap between Si, GaN, 4H-SiC and diamond [3][4]

Material	Eg(eV)
Si	1.12
GaN	3.44
4H-SiC	3.2
GaAs	1.42
Diamond	5.5

According to the chart, the GaN's and diamond's bandgaps are more than three times as much as Si, which indicates they can tolerant higher temperature

Thermal conductivity(κ) According to Fourier's Law, the heat flux density q, is directly proportional to the gradient of temperature, ∇T in a material:

$$\mathbf{q} = -\kappa \nabla T \quad (1)$$

where κ is the thermal conductivity of the material, which is a measure of its ability to conduct heat. As a result, the higher thermal conductivity enables the material to have a higher rate of heat dissipation. Thus, it can work under hotter heat sources.

Table 2. Thermal Conductivity of Different Semiconductor Materials [3][4]

Material	Thermal Conductivity(W/m·**K**)
Si	130
GaN	130
4H-SiC	490
GaAs	50
Diamond	1000

Table 2 shows the thermal conductivity of different materials, with Si having the second worst thermal conductivity among them.

Carrier mobility (μ) The on-state resistance of a power device is inversely proportional to the product of carrier concentration n and carrier mobility μ,

$$Ron = \frac{L}{(Ane\mu)} \quad (2)$$

consequently, lower conduction loss and less heat generation.

Table 3. Room-temperature electron mobility of selected semiconductors (cm2/V·s) [3][4]

Material	Electron mobility μn
Si	1450
GaN	900
4H-SiC	1000
GaAs	8500
Diamond	2000

The Si has higher electron mobility than GaN and 4H-SiC, so it's Ron is higher.

2.2. High breakdown field

The size of the chip depends on the current density per unit area, this density rises as the drift region (the lightly doped epitaxial layer that supports blocking voltage in the off-state) becomes thinner, and the minimum attainable thickness is dictated by the material's breakdown field. In other words, a higher breakdown field directly shrinks the chip.

Band gap (Eg) The critical electric field (the minimum field strength at which a material suddenly loses its insulating property and undergoes electrical breakdown) is directly proportional to $Eg^{\frac{3}{2}}$.

$$Ebr=\frac{\Lambda Eg^{\frac{3}{2}}}{\varepsilon r^{\frac{1}{2}}} \quad (3)$$

Therefore, a wider band gap enables a higher breakdown voltage of the material. Wide-band-gap semiconductors such as diamond tolerate about 30 times stronger fields than Si, enabling much thinner drift regions and smaller chip areas for the same blocking voltage.
As shown in Table 1, Silicon has lower bandgap compared with others

Relative permittivity (εr) Stronger bonds raise the energy required to displace atoms and create defect-assisted leakage paths, so the intrinsic breakdown field increases with bond energy. Table 4 lists bond energies of representative semiconductors; higher values correlate directly with larger critical fields.

Table 4. Relative permittivity and bond energy of representative semiconductors [5]

Material	Relative permittivity εr	E_{crit} (MV/cm)
Si	11.9	0.3
GaN	9	3-5
6H-SiC	9.66	3-5
GaAs	13.1	0.4
Diamond	5.5	5.6

Si has relatively high relative permittivity and lower bandgap, so the breakdown electric field is low.

Ultra-Low Power Loss

Electric piles require low energy dissipation so that the efficiency can be as high as possible. There are two main sources of energy dissipation: conduction loss and switching loss.

Conduction loss The conduction loss is the power dissipated when the electric appliance is working. The static conduction loss of a power device is

$$Pcond = I^2S\times Ron \quad (4)$$

Here, IDS is the electric current from source to drain and Ron is the resistance between source and drain when the appliance is working, it depends on,

$Ron\propto \frac{1}{\mu\cdot Ecrit\cdot\varepsilon}$

Hence, for the same breakdown voltage VBR, a material that with higher electric mobility, critical field and moderate permittivity has lower on-resistance, thus have low conduction loss.

Table 5. Figure-of-merit for conduction loss [5]

Material	**εr**
Si	11.9
GaN	9
4H-SiC	10.1
GaAs	13.1
Diamond	5.5

Switching loss. Switching loss is the energy dissipation of the electric appliance when it turns on or off. It depends on the time taken to switch and the voltage/current involved. For a transistor, total switching loss (Pswitch) is the sum of turn-on loss (Pon) and turn-off loss (Poff):

$$P_{switch} = P_{on} + P_{off} \quad (5)$$

Here P_{on} and P_{off} can be calculated by:

$$Pon \approx \frac{1}{2} \times VDC \times I\ load \times ton \times fsw \quad (6)$$

$$Poff \approx \frac{1}{2} \times VDC \times I\ load \times toff \times fsw \quad (7)$$

Where ton and toff are the delay when the transistor turn on and turn off, these are inversely related to bandgap and electric mobility. According to Table 1 and Table 3, the Si has relative high-power loss.

3. Economic discussion.

If the performance of silicon is no longer competitive, why did it dominate for decades, and why can alternatives now displace it? This is because there is another really vital factor—economic effect.

Table 6. Unit price of single mainstream substrate (Aug 2025) [6][7][8][9][10]

Material	Price($/g)
Si	0.00134
GaN	0.0439-0.1254
4H-SiC	4.47
GaAs	0.26-0.3
Diamond	1450

Table 6 indicates that the Si have predominate advantage in price. This is why the Si dominates the semiconductor industry in the past. However, with the development of technology, the price of other materials will be cheaper and be used in different fields.

4. Conclusion

By strictly quantitative analysis, GaN, 4H-SiC, GaAs and diamond outperform silicon in maximum junction temperature, critical electric field and composite power loss. Yet the cost of Si is obviously cheaper than other materials, this is also the reason why people use it at the birth of semiconductor industry. In recent years of development, most companies still use silicon as the main raw material. However, in some industries with high demand for semiconductors, more expensive but more advantageous materials such as GaN and SiC will replace silicon's dominant position. Moreover, with the advancement of technology, the cost of these materials will further decline It has gradually become the main material in more fields.

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