Prospects for the development of power electronics by application of technologies for production of power semiconductor switches based on silicon carbide

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Abstract: *The article presents an analysis of the technical characteristics of promising technologies of power transistors based on silicon (Si) and silicon carbide (SiC). A comparative analysis of the energy characteristics of power diodes, MOSFETs and IGBT transistors of various classes based on these technologies is presented. An analysis of current-voltage characteristics and values of static and dynamic power losses in power switches is also given.*

KEYWORDS*: POWER ELECTRONICS, SILICON CARBIDE, GALLIUM NITRIDE, TECHNOLOGIES, TRANSISTOR*

1. Introduction

In recent decades, the most common power transistors that are used in power conversion technology are MOSFETs, IGBT transistors, as well as IGCT and GTO tyritors [1, 2]. Each of these types of semiconductor switches is optimally used for its niche of switching frequency, voltage class and load current [3, 4].

Recently, high-voltage power electronics has shown increased interest in power silicon-carbide MOSFETs (metal-oxide-semiconductor field effect transistor) and IGBT (insulated-gate bipolar transistor) transistors [5, 6].

Silicon is still the main semiconductor material for modern electronics, however, in a number of areas it is starting to lose ground. If we talk about the segment of power electronics, the most promising materials here are gallium nitride (GaN) and silicon carbide (SiC) [7, 8].

The main markets driving the development of new materials for power electronics are electric vehicles, power generation, household electrical appliances and electronics. In addition, chargers for mobile phones and laptops are produced, in which the use of new transistors (albeit from gallium nitride, not silicon carbide) made it possible to make them 1.5...2 times more compact than conventional ones at the same power. It is expected that the total capacity of the markets for complex semiconductors in the coming years will amount to several billion dollars a year.

2. Features of technology based on silicon carbide

Silicon carbide is a semiconductor material consisting of silicon and carbon in equal proportions and having the formula SiC. The strengths of SiC, which are important in terms of semiconductor technology, are due to the wide band gap. This is a high electric field, in which the material breaks through, and has a high thermal conductivity [9]. This means that, as a rule, wide-gap semiconductors are capable of operating at higher voltages and temperatures than narrow-gap semiconductors.

Gallium arsenide, which has a wider band gap than silicon, has a smaller temperature range: its crystal lattice begins to collapse from overheating before it turns into a conductor. There are even wider-gap semiconductors than SiC, for example, gallium oxide Ga_2O_3, boron nitride BN or aluminum nitride AlN, but they have not yet reached the stage of applicability in mass electronics. But diamond has almost reached it, which has a forbidden zone of 5.4 eV and a huge thermal conductivity up to 26 W / (cm·K) versus 4.9 W / (cm·K) for silicon carbide and 3.9 W / (cm·K) for copper.

So far, diamond substrates are massively used only for heat dissipation, but soon synthetic diamond will become sufficiently cheap and of high quality to make the devices themselves on it. Of course, "soon" in this case is a loose concept. Cree, one of the pioneers of SiC semiconductor products, was founded in 1987. The first commercially available silicon carbide diodes appeared in 2006, the first transistors – in 2011, and widespread use began just a couple of years ago, when not only the technologies were developed, but also the prices dropped sufficiently.

The same story is with the gallium nitride developing in parallel – from the first commercial samples to mobile phone chargers it has been a long way for 20 years. But the first breakthroughs in materials for power electronics were inevitably followed by a wave of various scientific studies, and their results are already leaving the walls of laboratories to factories.

The use of SiC instead of silicon in a power diode gives: first, it copes better with overheating due to its higher thermal conductivity; secondly, with the same breakdown voltage, it can make a significantly lower forward resistance (and hence, increase the efficiency) or, with comparable resistance, a much smaller area [10, 11].

A smaller area will give less parasitic capacitance, which means faster switching, less losses in its process and the ability to work at high frequency with good efficiency.

Thus, SiC has many advantages besides price, but with the growth of production volumes, the cost of diodes and transistors based on silicon carbide is already approaching silicon counterparts. This makes it possible to fully reveal the advantages of the new material in mass products due to the fact that the better characteristics of more expensive devices based on SiC allow saving on other parts of the project [12, 13].

In Fig. 1 shows a comparison of different types of power switches in terms of power and frequency, it shows what power and at what frequency can be switched by different semiconductor devices. The Y-axis is marked up to GW, which means that not only electric locomotives, but also power plants can switch with semiconductor devices.

In addition, new materials can significantly increase the switching frequency, which is very important for increasing the efficiency and reducing the size of devices [14].

For power MOSFETs, silicon carbide is useful in the same way as for diodes – better material parameters allow to make the low-doped layer much thinner and, accordingly, radically reduce the on-state resistance of the transistor.

Moreover, it works even on the simplest structures. And their presence on silicon allows us to assume that although the gain in specific resistance can already be hundreds of times, there is room for carbide to grow even further.

Gallium nitride, due to its high electron mobility, excellent drift velocity and high thermal conductivity, is actively used to create low-voltage power transistors (usually up to 200 V).

Silicon carbide also outperforms conventional silicon in a number of ways.

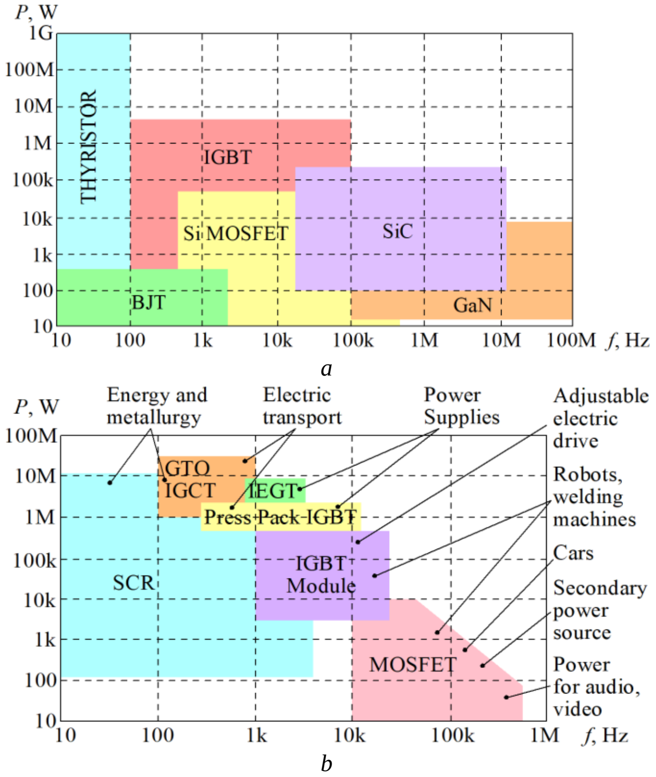


Fig. 1. *Comparison of power switches by power and frequency: a – power switches of different types; b – scope of application*

We are talking about high breakdown voltage, high drift velocity, excellent thermal conductivity, and a significant band gap. All this makes silicon carbide an ideal material for the production of high voltage power transistors.

Currently, various types of transistors are common in power electronics. The low voltage niche has long been occupied by silicon MOSFET switches. Now they are gradually being replaced by gallium nitride transistors. Silicon MOSFETs are also mainly used in the high-speed system segment.

Unfortunately, the effective operating voltage of silicon switches does not exceed 650 V, so IGBTs are preferred for high voltage applications with low switching frequencies. However, IGBTs also have drawbacks, in particular, low performance – their operating frequency is only 100...150 kHz. For this reason, silicon carbide transistors have proven to be very popular in the high-speed high-voltage applications segment.

Table 1 shows a comparative analysis of the characteristics of power transistors based on SiC and Si.

Table 1

Comparative analysis of the characteristics of power transistors based on SiC and Si

Parameter	Comparison of SiC and Si	Advantages
Breakdown voltage	SiC is ≈ 10 times higher than Si	The ability to make a higher breakdown voltage in the transistor
Electron saturation drift velocity	SiC is ≈ 2 times higher than Si	Higher performance
Band gap	SiC is ≈ 3 times higher than Si	Higher switching stability
Thermal conductivity	SiC has a higher thermal conductivity	Higher operating temperature
Recovery energy of the reverse diode	SiC has less energy	Less power loss

Graphically, a comparative analysis of two transistors is shown in Fig. 2.

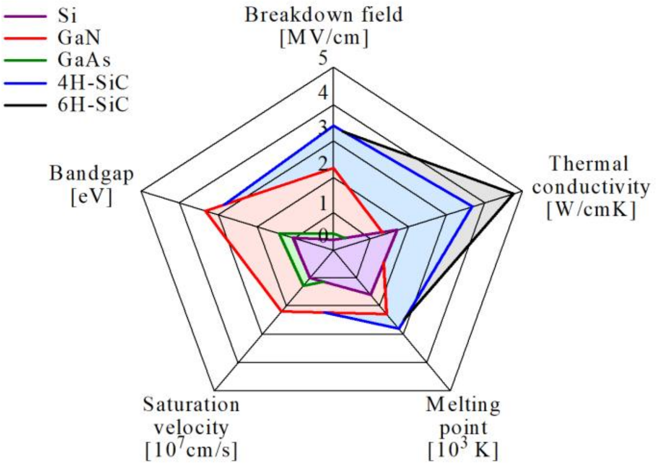


Fig. 2. *Basic physical properties of some popular semiconductors*

In Fig. 2 introduced the following notation:

– bandgap is a forbidden zone;

– breakdown field – breakdown electric field. The higher it is, the easier it is to make a high-voltage device based on the material;

– saturation velocity – the limiting velocity of charge carriers in the material (three orders of magnitude less than the speed of light);

– thermal conductivity – thermal conductivity. It is very important for power applications, since the excess heat in them is very large, even at very high efficiency, and this excess must be removed from the active region of the device;

– melting point – the melting point that limits the working range of the material.

Due to the unique characteristics of silicon carbide, it is possible to create power SiC MOSFETs that combine the advantages of IGBT and silicon MOSFETs. From silicon MOSFETs, silicon carbide transistors have inherited high speed, low losses, and ease of control. In addition, they, like IGBTs, are capable of operating at high voltages up to 1200 V and higher.

As seen from Fig. 2, there are areas in which different types of power transistors can be applied. Moreover, the choice between them is based on comparing their effectiveness. Studies show that SiC MOSFETs significantly outperform IGBTs in terms of efficiency.

They are distinguished by both low conductivity losses, which are determined by the ultra-low resistance of the conducting channel, and by minimal dynamic losses, which are a consequence of low switching losses.

There are two main types of silicon carbide transistors:

– hybrid SiC transistors – these are MOSFETs and IGBT transistors, in which only the reverse diode is built using silicon carbide technology;

– full SiC transistors are only MOSFET transistors in which both the transistor and the reverse diode are built using silicon carbide technology.

The expected relative values of static and dynamic losses of power switches of various types (IGBT and Si diode, IGBT and SiC diode; SiC MOSFET and SiC diode) are shown in Fig. 3.

Cree's SiC MOSFETs have a resistance of 10 mΩ and offer better light load efficiency at low frequencies than silicon IGBTs. As a result, according to the calculations, the power loss in the inverter will be 67 % lower than that of analogs on silicon switches. Reducing the level of losses will reduce the size of the cooling system, which will significantly reduce the size and weight of the inverter, as well as reduce cooling costs.

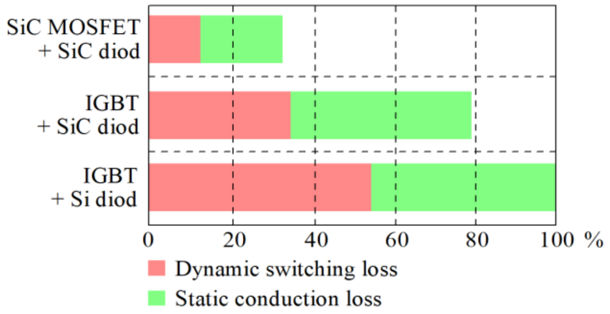


Fig. 3. *Expected loss reduction from hybrid and full SiC transistors versus silicon transistors*

Comparison of the parameters of silicon and silicon carbide MOSFET transistors is shown in Fig. 4.

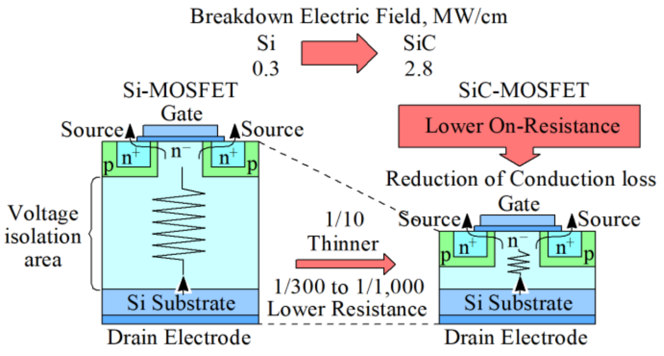


Fig. 4. *Comparison of parameters of silicon and silicon carbide MOSFET transistors*

Silicon carbide MOSFET transistors should be opened with a sufficiently high voltage, about 18...20 V, while silicon analogs can be easily operated at voltages of 10...12 V. This is due to the fact that the resistance of the lightly doped layer in carbide transistors is very small, and against its background, other resistances begin to play a more noticeable role, including the resistance of the transistor channel, which strongly depends on the gate voltage. And then the channel resistance has a negative temperature coefficient, and the resistance of the lightly doped layer is positive [15].

If open the transistor with a low voltage, then the contribution of the channel resistance is large, and those cells that, due to the spread of parameters, pass a little more current, will heat up more and their resistance will decrease, because of which they will begin to conduct even more current, which means they will warm up even stronger and so on until the transistor burns out.

If the total resistance is dominated by a component with a positive temperature coefficient, then the current through different cells of the transistor will self-balance. This characteristic of carbide does not show up in silicon MOSFETs because the resistance of the lightly doped layer is much higher than the channel resistance at any gate voltage.

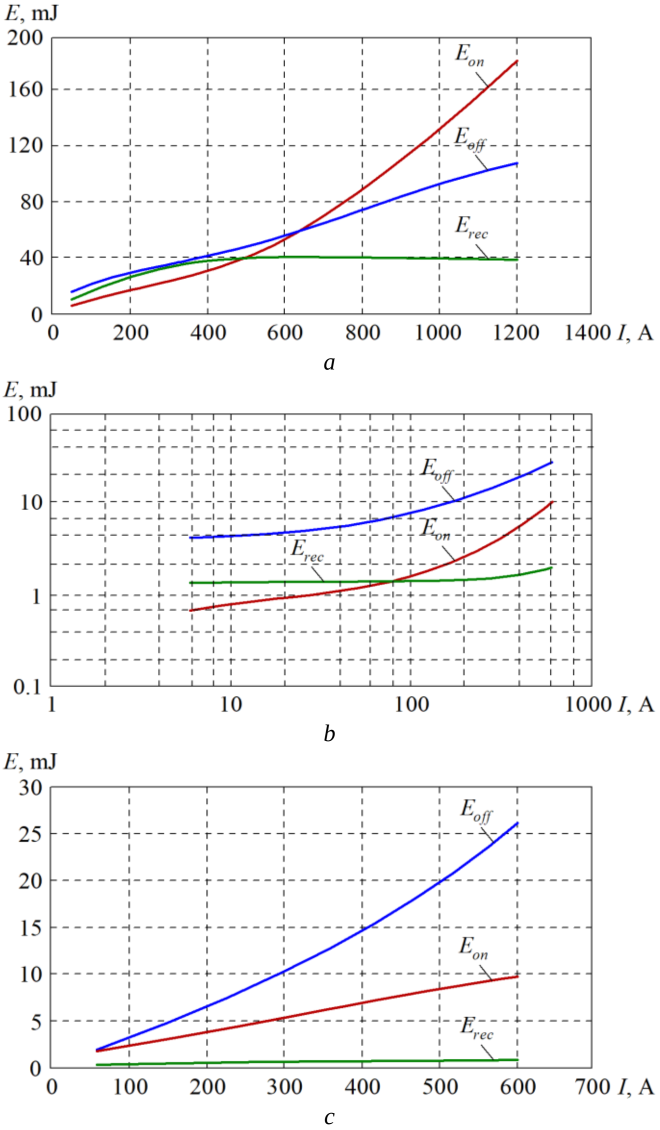
3. Comparative analysis of transistors with different manufacturer technologies

Mitsubishi Electric transistors were selected for comparative analysis:

– silicon IGBT type CM600DX-24T1;
– hybrid SiC IGBT type CMH600DU-24NFH;
– full SiC MOSFET type FMF600DX2-24A.

In Fig. 5 shows the dependence of the switching energy of the transistor on the load current.

Table 2 shows the parameters of power transistors based on SiC and Si.



a

b

c

Fig. 5. *Dependences of the switching energy of the transistor on the load current:*
a – silicon Si IGBT type CM600DX-24T1; b – hybrid SiC IGBT type CMH600DU-24NFH; c – full SiC MOSFET type FMF600DX2-24A

Table 2

Parameters of power transistors based on SiC and Si

Parameter	Transistor type		
	Silicic Si CM600DX-24T1	Hybrid SiC CMH600DU-24NFH	Full SiC FMF600DX2-24A
Voltage drop at 400 A	1.5 V	4 V	0,8 V
Voltage drop at 600 A, 125 °C	2.15 V	5 V	2,02 V
E_{on} at 400 A	30 mJ	11 mJ	7 mJ
E_{off} at 400 A	40 mJ	6 mJ	14 mJ
E_{rec} at 300 A	30 mJ	1,5 mJ	0,8 mJ
E_{on} at 600 A, 600 V, 125 °C	53 mJ	10 mJ	9,7 mJ
E_{off} at 600 A	56 mJ	26 mJ	26,2 mJ
E_{rec} at 600 A	40 mJ	1,9 mJ	0,8 mJ
Turn-on time, μs	600	400	60
Turn-off time, μs	800	700	60

4. Industrial applications of silicon carbide transistors

The practical application of power transistors based on silicon carbide is already used in electric vehicles [16, 17]. It is worth noting that the Tesla Model S inverter was assembled from discrete silicon IGBTs, and SiC transistors have already appeared in Model 3, and not discrete, as in Model S, but in the form of ready-made modules.

Another example of an EV with SiC transistors is the Venturi in Formula E. The first generation, rated for 200 kW at 600 V operating voltage, was all-silicon: IGBTs and discrete diodes.

The second generation used silicon carbide diodes, which saved 13 % mass and 19 % volume, and also reduced energy losses during conversion by 30 %. The third generation, already completely silicon carbide, turned out to be 40 % lighter than the original, 43 % more compact and four times less power loss.

5. Results and discussion

The following conclusions can be drawn from the analysis:

– switching energy of transistors based on silicon carbide in comparison with traditional silicon transistors is 3...4 times less;

– turn-off energy is 3...6 times less;

– the recovery energy of the reverse diode is 20...40 times less;

– static power losses (voltage drop across the transistor in the on state) is 2 times less;

– a decrease in the switching time of transistors leads to a decrease in dynamic losses, which in turn leads to a significant increase in the maximum possible switching frequency of power switches, a decrease in losses and an increase in efficiency;

– significantly smaller mass-dimensional indicators of SiC transistors, which is quite a significant plus for electric vehicles, aviation, etc.

Further trends in the development of silicon carbide-based transistors is to increase the voltage classes of this switch technology.

The ability to operate in extreme temperatures is useful in the oil industry, jet engine control circuits, and space.

6. Conclusion

The article presents an analysis of the technical characteristics of existing and promising technologies for the production of power semiconductor switches.

The characteristics of power diodes, MOSFETs and IGBT transistors of various classes based on silicon and silicon carbide are given. Comparative analysis of current-voltage characteristics and values of static and dynamic losses in power switches is presented.

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