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The Possibilities of Using the Nature of Semiconductors in Practical Life

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Abstract. *The transformation of the global automotive market with the increase in the production of electric vehicles in recent years has created an incredible demand for the development of electronic components based on SiC and GaN semiconductors with a wide band gap in the world, without which it is impossible to imagine the electronics of modern and future hybrid and electric vehicles, communication systems, mobile devices and space technology. This demand has led to a sharp increase in investment in the development and development of new technologies for SiC and GaN wafers of larger diameters in order to reduce the cost of manufacturing electronic products and continue to displace classic silicon components. Every year, semiconductor devices based on SiC and GaN are penetrating deeper into our lives. The past 2021 allowed them to make an impressive breakthrough and lay the foundation for growth in their consumption in the next five years and beyond. The main driver of this growth is the automotive market, or more precisely, hybrid and electric cars.*

Keywords: *electric vehicle, components, battery, power, semiconductors*

Introduction

Semiconductors are materials that can conduct electricity, but to a limited extent. Their unique feature is that their electrical conductivity can be controlled and modified by introducing appropriate dopants or by changing external conditions, such as temperature, pressure, or an electric field. Under normal conditions, semiconductors act as insulators, but under certain circumstances, they can conduct electricity, making them indispensable in the production of electronic components.

Natural semiconductors, such as pure silicon, do not have sufficient electrical properties for use in modern electronic devices. To increase their ability to conduct electricity, doping is used, which involves introducing small amounts of other chemical elements into the semiconductor structure. Depending on the type of dopant, two main types of doped semiconductors can be distinguished:
An n-type semiconductor is formed by doping a semiconductor with elements with a large number of electrons, such as phosphorus or arsenic. The introduction of these impurities creates an excess of electrons that can move freely within the material, increasing its conductivity. A p-type semiconductor is formed by doping a semiconductor with elements with a smaller number of electrons, such as boron or aluminum. These impurities form so-called electron holes, which act as positive charge carriers and also help improve the material's conductivity.

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The most common semiconductor materials are silicon (Si) and germanium (Ge), although many other compounds with semiconducting properties exist, such as gallium arsenide (GaAs) and indium phosphide (InP). These materials are used to manufacture semiconductor components such as diodes, transistors, and integrated circuits, which form the basis of modern technology. The share of hybrid and electric vehicle sales in the country reached 94.9%. Norway is actively building charging and service infrastructure, and numerous tax breaks for citizens buying electric vehicles are stimulating the transition away from internal combustion engine vehicles. Next-generation electric vehicles require power devices that can improve the efficiency of the vehicle (with a subsequent increase in the driving range) and the speed of battery charging. Figure 1 shows the key nodes of the vehicle where SiC and GaN electronic components can be used. SiC inverters have proven to be a key solution to meet these requirements. In addition to converting the input DC to AC, the inverter regulates the level of power supplied to the motor in accordance with driving needs (Challenges and Future Perspectives).

Methods

The progress of silicon carbide technology, in terms of increasing diameter, production volume, improving quality and decreasing cost of SiC, has reached the point where mass production of 150 mm wafers is based on the use of silicon carbide blanks, as shown in Fig. 1. The progress of silicon carbide technology, in terms of increasing diameter, production volume, improving quality and decreasing cost of SiC, has reached the point where mass production of 150mm wafers is based on the use of silicon carbide blanks, as shown in Fig. 1.

Figure 1. Production of 150 mm thick silicon carbide plate

Findings and Discussion

The role of the inverter is increasing as the electric vehicle industry gradually transitions from 400 to 800 V. The efficiency of transferring battery power to the motor in a traditional inverter is 97–98%, while the efficiency of a SiC inverter reaches 99%. Note that an increase in efficiency of one or two decimal places provides very significant benefits to the entire vehicle (Compound Semiconductor Quarterly Market Monitor, 2021).

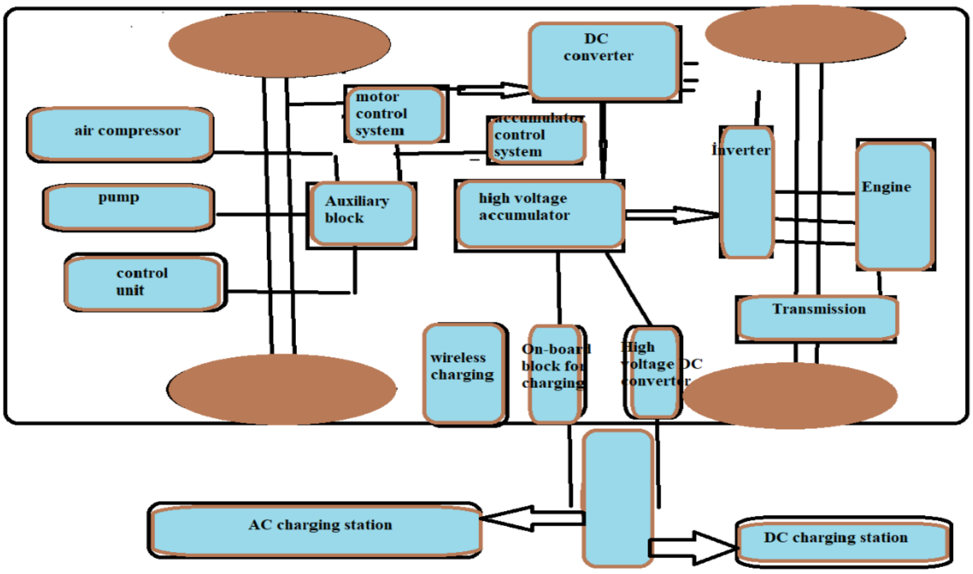

Figure 2. Key nodes for the application of SiC and GaN-based electronic components in an electric vehicle

SiC inverters are ideal for these applications because they can withstand high voltages and temperatures, allowing all other components to be smaller. With 800 V batteries, the required current is reduced and smaller cables can be used, reducing costs, vehicle weight, and electrical system assembly time. This not only improves the range of EVs, but also their efficiency. Charging times for 800 V batteries can be reduced to one-fifth of the time required for 400 V batteries by using powerful SiC DC/DC converters. The former's high efficiency allows the amount of energy delivered to the batteries to be maximized during charging with negligible power losses (SiC and GaN: A Tale of Two Semiconductors, 2021).

The global growth of the BEV market, which meets modern standards for efficiency and CO2 emissions, requires the use of new semiconductor technologies in the drive inverter. The supply voltage of the BEV inverter is in the range of 400–900 V, depending on the drive power, battery type and the presence of a step-up converter. Since the drive inverter controls the motor, its operating frequency is usually less than 20 kHz. The advantage of using higher frequencies here is only to move away from the audible range of audio noise. Therefore, the main losses of the inverter are conduction losses, especially at low BEV loads (SiC and GaN: A tale of two semiconductors, 2021).

Typically, the choice in such cases is a silicon IGBT, but its inherent saturation threshold voltage (due to its "bipolar" structure) at low loads cannot be reduced, even when a large number of IGBTs are connected in parallel. Silicon carbide has an electric field strength 10 times higher (~3 MV/cm) than Si, so the unipolar SiC MOSFET structure is well suited for the implementation of 650, 900 and 1200 V power transistors due to the following main features:
SiC MOSFETs do not have a saturation voltage, unlike Si IGBTs; when paralleling SiC MOSFET chips, the on-resistance can be reduced to ≤ 1–2 mOhm;
SiC MOSFETs can conduct in the third quadrant (unlike Si IGBTs) by using a body diode during the dead time (Tdt is very short for SiC structures) and then turning on the SiC MOSFET channel in the third quadrant, which gives the same low losses in the reverse conduction state as in the forward conduction state. The combination of using a body diode during the dead time and synchronous rectification eliminates the need for an external antiparallel diode, which reduces the size and cost with minimal impact on efficiency at frequencies up to 50 kHz; using SiC MOSFETs can reduce inverter losses in a typical BEV EPA drive cycle by up to ~78%. The basic technology for developing

low-resistance SiC MOSFET power modules can be scaled from 650-900 V to 1200 V by simply modifying the epitaxial drift zone (blocking layer) and edge regions.

The topology remains the same for all devices in the specified voltage range, ensuring easy integration into power modules (GaN Systems listed on 2021 Deloitte Technology Fast 500*)*. Figure 3 illustrates the traditional method of connecting conductors using ultrasonic welding to the top contact surface using the third generation of SiC MOSFET crystals as an example. This technology can be used in 650, 900 or 1200 V modules with a slight change in the chip topology. 900 V crystals with low channel resistance (10 mOhm for the CPM3-0900-0010A) are already available. They were used in the development of a version of the 900 V modules, the static and dynamic losses of which have already been tested.

Conclusion

The rapid growth of the global automobile market with the gradual predominance of the production of hybrid and electric vehicles guarantees accelerated development and further reduction in the cost of semiconductor devices based on SiC and GaN. Assessing the good market prospects of SiC and GaN products, large foreign companies continue to increase investments in their production, as well as in the acquisition of companies developing these products and materials, including for the start of production of new areas of electronic components that were previously absent in these companies (GaN Systems' power transistor prices drop below $1, 2021*)*.

Figure 3. Chips Wolfspeed SiC MOSFET

The development of electronic components based on GaN is evolving from the creation of simpler power discrete components (transistors, diodes, etc.) and control microcircuits (drivers, controllers) to more complex integrated solutions with high energy efficiency, including for use in harsh space conditions. Increasing the diameter of SiC wafers to 200 mm, which will happen in 2022 despite technical difficulties, is the main means that will reduce the cost and price of production of silicon carbide ECs.

The first epitaxial GaN wafers on a silicon substrate with a diameter of 300 mm with high homogeneity and low defects, presented on the market in 2021, will further reduce the cost of production and prices of electronic GaN components. Evolution and progress in the industrial development of the technology of vertical GaN-on-GaN and GaN-on-Si structures for active components with low cost in the future will create competition not only for silicon IGBTs, but also for SiC transistors, diodes in the high-voltage range up to 10 kV.

Recently, much attention has been paid to the sintering technology of SiC chips, which allows eliminating the use of welded conductors during assembly. One of the main advantages is an increase in the so-called intermittent service life (IOL), since fatigue processes in welded conductor joints or crystal connections often cause failures. Other potential advantages include better (two-way) cooling, better heat distribution and higher short-circuit resistance (Quantum physics; Semiconductor; HyperPhysics; YOLE Intelligence).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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