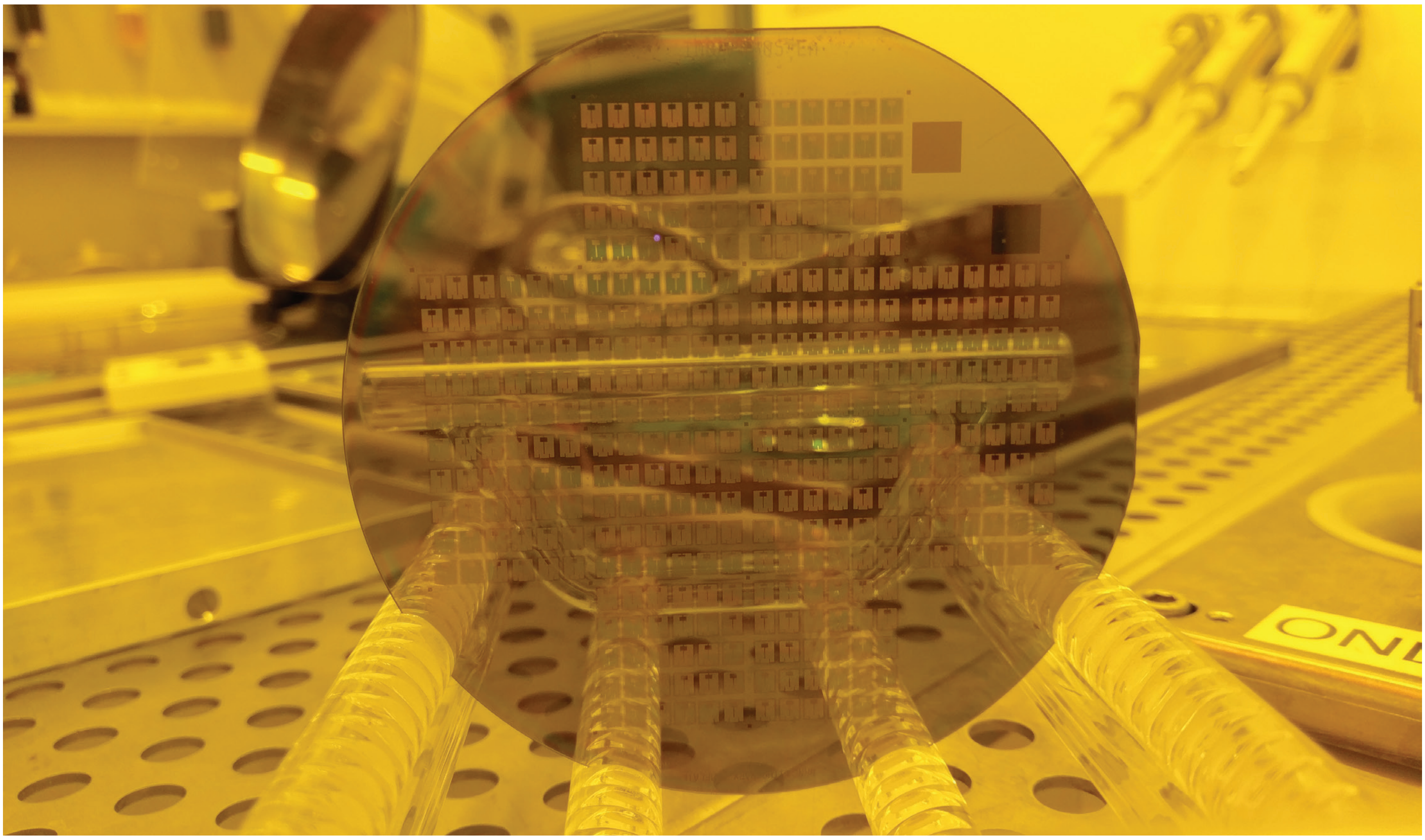
# HUGE ENERGY-SAVINGS BY WBG SEMICONDUCTORS

Power electronics are now found in mobile phone chargers as well as in the SBB locomotive or inverters of solar energy systems. These electronic components are usually based on the semiconductor material silicon. For some time now, researchers have been working on replacing silicon with so-called WBG semiconductors, the components of which have lower switching losses and thus enable devices manufactured with WBG semiconductors to be more energy-efficient. Ulrike Grossner, Professor at the Advanced Power Semiconductor Laboratory at the Swiss Federal Institute of Technology (ETH) in Zurich, explains in an interview the potential of WBG technology for an efficient energy supply.



Silicon carbide wafer for a project from Ulrike Grossner's ETH laboratory. MOSFET transistors (Metal oxide semiconductor field-effect transistors) are currently the most promising silicon carbide-based switches. Photo: Y. Ju/Copyright ETH Zurich

Interview referring to the results of a research project in the field of electricity, technologies which was financially supported by the Swiss Federal Office of Energy. The report has been published in the technical magazine Bulletin SEV/VSE (issue December 2019).

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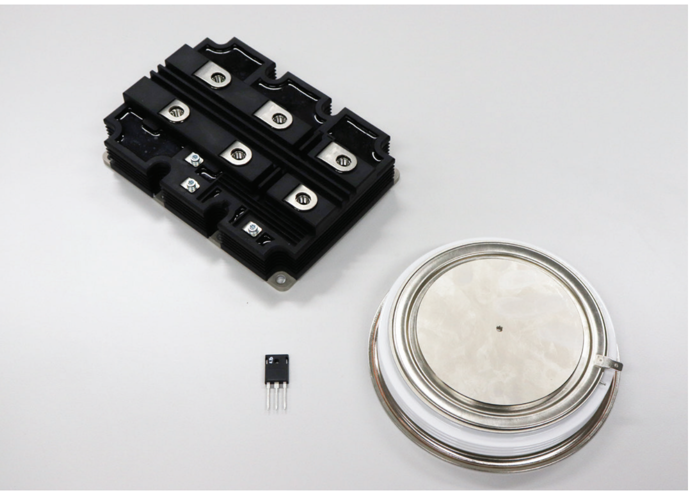
**Swiss Federal Office of Energy SFOE**

**Prof. Grossner, when components for the supply and control of electrical appliances are built with semiconductor materials, one speaks of power electronics. What role do power electronic components play in energy efficiency?**
U. Grossner: Power electronics enable efficient conversion of electrical current for the desired application. If conventional electrical technology, such as a transformer, is replaced by power electronics, this allows very efficient controllability, especially with motors. This brings a gain in energy efficiency for the overall system. Thanks to power electronics, for example, chargers for laptops and mobile phones have become not only more economical, but also more compact.

ETH Professor Ulrike Grossner.
Photo: ETHZ

**To what extent have power electronics already replaced traditional electrical technology?**
Power electronics are already widespread in private households, as the above examples make clear. What works on a small scale with a vacuum cleaner is now also standard in the SBB locomotive. Power electronics have gradually found their way into the locomotive's drive system: Thyristors, a powerful semiconductor element based on a silicon wafer, were first used to control these systems quickly and precisely. Meanwhile, instead of individual, large components, small chips arranged in modules are used. This also saves a lot of space. This has made it possible to build rail cars in which passengers can be accommodated in addition to the drive section, as in our modern double-deck trains.



Three examples of power electronics. Top: 6.5 kV 300 amp module containing multiple silicon semiconductor elements. It is an ABB traction module. Bottom left: MOSFET transistor based on silicon carbide with 1200 V, as used, for example, to control a vacuum cleaner gearbox (manufacturer: Wolfspeed). Bottom right: Thyristor from ABB production. It is a (rather slow) silicon-based power electronic switch, which is characterized by a very high current carrying capacity. Photo: B. Vogel

Power electronics have made many innovations in sustainable power supply possible in the first place: The electricity production of photovoltaic or wind power plants fluctuates, depending on the actual radiation and wind conditions. Only inverters based on semiconductors have made it possible to efficiently bring this electricity efficiently to the voltage level required for feeding them into the grid.

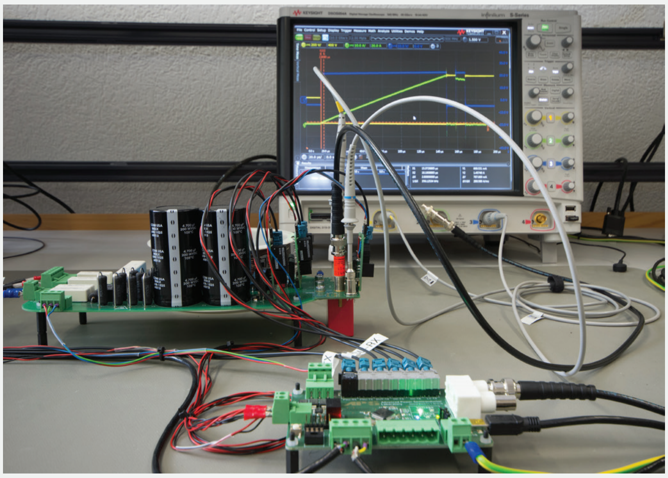
**Wide-bandgap semiconductors (WBG semiconductors for short) are a new generation of semiconductors that can be used to manufacture power electronics components even more efficiently. Observers speak of an energy efficiency "revolution." Has this revolution already arrived in Switzerland?**
It is true that it is possible to further increase the efficiency of power electronic components by replacing the commonly used silicon in electronic components with WBG semiconductors. Parallel to this rather future-oriented step of using WBG semiconductors, it should not be neglected to consistently implement an obvious first step: We should use power electronics based on existing silicon-based power electronics in all applications where this is possible today. With this approach, we can already tap a large, untapped potential for energy efficiency today.

**At ETH Zurich, you are researching wide-bandgap semiconductors such as silicon carbide. What is the energy-saving potential of these materials?**
The savings potential of WBG semiconductors is enormous! Let us take the mobile phone as an example: a study by the

## WHAT ARE WBG SEMICONDUCTORS?

Materials such as copper are always electrically conductive, whereas ceramics never are. Semiconductors are a middle thing between conductors and non-conductors (insulators): They conduct electrical current only when energy is supplied from outside (e.g. solar cells when supplied with sunlight). Semiconductors can be subdivided according to how much energy is required to make them conductive. With silicon - the most common semiconductor - this energy is comparatively low at 1.12 electron volts, whereas with silicon carbide it is relatively high at 3.27 electron volts.

When energy is supplied to a semiconductor from outside, this energy ensures that electrons are released from the atomic compound so that they can now move freely outside the atoms and (under the influence of an electric field) form an electric current. Physicists describe this process as the change of the electron from the valence band (electron bound to the atom) to the conduction band (free electron). The gap between the valence band and the conduction band is different for each semiconductor material, so it takes different amounts of energy to overcome the bandgap. For silicon, this bandgap is relatively small with the 1.12 electron volts mentioned above (small enough, by the way, that the energy of a light particle is sufficient to excite a current in silicon solar cells). Silicon carbide in its most common form has a large band gap of 3.27 electron volts. All semiconductors with a bandgap greater than 3 electron volts belong to the class of wide-bandgap semiconductors (WBG semiconductors for short).



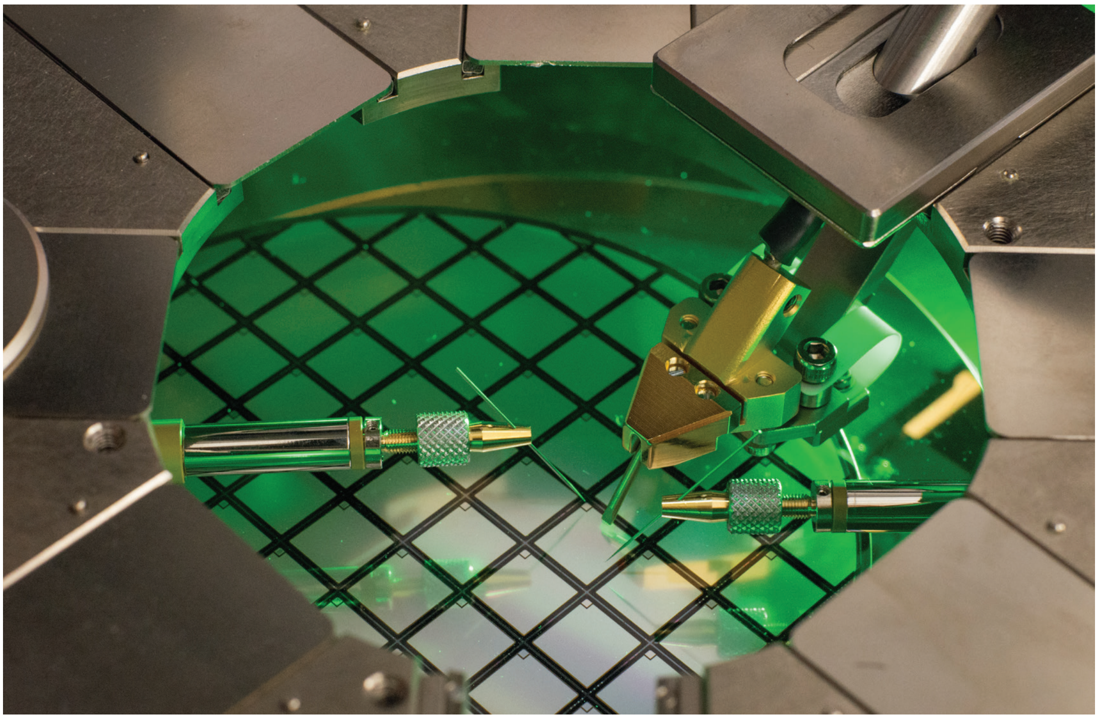
In the ETH laboratory of Prof. Ulrike Grossner, this test stand determines electrical losses in switching behavior. Photo: T. Ziemann/ Copyright ETH Zurich

WBG semiconductors are unsuitable for the construction of solar cells due to the large band spacing and the light spectrum prevailing on earth. On the other hand, they permit the manufacture of electronic components that perform switching operations with very low electrical losses (especially at high voltages and frequencies). The most important WBG semiconductors are silicon carbide (SiC) and gallium nitride (GaN). Ulrike Grossner's research group at ETH Zurich is investigating how silicon carbide and other WBG semiconductors can be processed into suitable components; her colleagues Prof. Johann W. Kolar and Prof. Jürgen Biela are working on their use and optimized control, e.g. for inverters for highly specialized applications. Japan is very active in silicon carbide research. ETH Zurich maintains a lively exchange with Japanese researchers. BV

US Department of Energy in 2015 puts the energy loss of mobile phones at 37%, with a considerable proportion being accounted for by silicon-based power electronics in chargers. For a single telephone, this amounts to only 4.2 kWh per year, but for all mobile phones worldwide 23.5 TWh. According to the study, losses could be reduced by around 5.5 TWh through the use of WBG semiconductors. This is almost one tenth of what Switzerland consumes in one year. WBG semiconductors could also increase the yield of commercial solar energy systems.

**Really?**

Yes, because the inverter used has a decisive influence on what proportion of the solar energy reaches the grid. Inverters based on silicon carbide work with an efficiency of up to 99% and thus around 50% more efficiently than the silicon inverters commonly used thus far. Unfortunately, silicon carbide inverters are often not used in large solar farms today, although they are available on the market, because they are more expensive than silicon inverters. In order for this to change, solar energy systems should not only be assessed on



A so-called 'wafer tester' in Ulrike Grossner's ETH laboratory. The functional characteristics of building components can be tested even before final separation and further processing into modules. Photo: T. Ziemann/ Copyright ETH Zurich

the basis of short-term construction costs, but also on the basis of total cost of ownership. This calculation is positively influenced by the additional yields thanks to the silicon carbide inverters.

**In a study commissioned by the Swiss Federal Office of Energy (see note at the end of the interview), you investigated the potential of WBG semiconductors. Where do you see additional fields of application?**

Today, silicon carbide is used in electronic components of solar inverters and charging stations for electric vehicles as well as in the power supply of telecommunications applications, but is also contained in power factor correction filters and in special components for electricity distribution and uninterrupted power supply. For the WBG semiconductor gallium nitride there are first applications for transistors in the automotive industry (e.g. air conditioning, radio). It would make sense to use it wherever relatively low power is required, for example in chargers for mobile phones or laptops. Other applications for WBG semiconductors include power electronic components for data centers, industrial motors, traction systems for railways and for hybrid and electric cars. A study carried out in 2017 came to the conclusion that WBG semiconductors could save up to 99 TWh of electricity in these areas— more than one and a half times the annual electricity consumption of Switzerland.

A silicon carbide wafer is about 25 times more expensive than a silicon wafer of the same size, but the silicon components are also larger than those made of silicon carbide for the same performance. Many manufacturers are reluctant to use WBG semiconductors because of the higher costs. This applies, for example, to the drive trains of electric vehicles - the automotive industry is extremely cost-sensitive. WBG semiconductors could also be used in chargers for laptops and mobile phones—but who is prepared today to spend money on a charger at all? This could perhaps be changed if such chargers had an energy label like electrical household appliances and if environmentally conscious consumers could make a conscious decision in favor of them. It would also be conceivable to use silicon carbide power electronics in the transformer stations of the power grid. At the turn of the millennium, ABB had the vision of converting all high-voltage converters to silicon carbide. For technical and cost reasons, however, other applications were and still are rather promising.

**In addition to silicon carbide and gallium nitride, there are other WBG semiconductors such as diamond or gallium oxide. What is their significance?**

Gallium oxide has been the subject of research for about five years. It has good potential, but the basics and properties are not yet sufficiently known. I am skeptical about diamond,

## SWITZERLAND IS COMMITTED TO PECTA

PECTA (short for: Power Electronic Conversion Technology Annex) is a new international group of experts under the umbrella of the International Energy Agency (IEA). The IEA maintains around 40 Technology Collaboration Programs (TCP), including the program 'Energy Efficient End-Use Equipment', TCP 4E for short. Since spring 2019, this program has included the PECTA working group, in which experts from all over the world work together under the auspices of three countries: Switzerland, Austria and Sweden.

The expert panel wants to evaluate the efficiency potential of the use and integration of wide-bandgap (WBG) semiconductors in power electronics applications. PECTA sees itself as "a basis and independent information and knowledge platform for political decision-makers and various other interest groups on the subject of WBG."

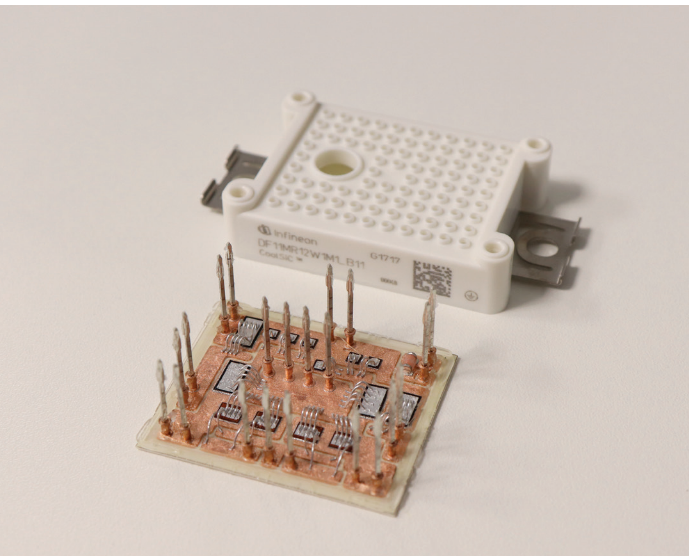
In a first step, the working group has set itself four tasks: First, the efficiency potential of various application areas for WBG semiconductors is to be examined. Secondly, a "Roadmap for Power Device" - a roadmap for the implementation of efficient electronic devices - is to be drawn up. The third goal is to embed semiconductor technologies into international standardization procedures. Finally, the committee is involved in international knowledge transfer and networking. This provides political decision-makers with a broad basis for targeted, regulatory and/or political measures to support the market entry of WBG technology.

A 'scoping study' will lay the foundation for the expert panel's further work by next spring. The work will then be carried out between 2020 and 2024 in exchange with research institutions and industry - including manufacturers of semiconductor materials and devices, but also system manufacturers. BV

↗ For more information on PECTA, see https://pecta.iea-4e.org/ or https://nachhaltigwirtschaften.at/de/iea/technologieprogramme/4e/iea-4e-tcp-pecta.php

because the advantages over silicon carbide are rather small; I doubt whether the development effort would be worthwhile here.

**Silicon carbide has been researched since the 1980s, gallium nitride since the turn of the century. What does it take to break these WBG semiconductors into the market?**
I think that the current climate debate or higher electricity prices could give the impetus to increase the use of the very efficient but more expensive WBG semiconductors. Toyota had first considered equipping the fourth generation of the 'Prius' electric powertrain with silicon carbide, but was reluctant to do so for cost reasons and doubts about reliability. Pressure from public debate about the energy revolution could be decisive in deciding in favor of WBG products in such cases in the future. This also applies to the procurement of buses or trains with the corresponding traction systems.



MOSFET module from Infineon based on silicon carbide. Among other things, ETH scientists are investigating packaging, i.e. the question of how WBG semiconductor elements can be correctly integrated into a chip environment. Photo: B. Vogel

Technically speaking, power electronic components based on WBG semiconductors are already quite mature. One remaining task is to integrate these chips into the system of the respective device, i.e. the so-called packaging. We also have to prepare the users - i.e. the system manufacturers - to handle these components properly. In addition, there is still a lack of essential reliability data, which is normally only available from a large number of products on the market.

Under the umbrella of the International Energy Agency (IEA), the PECTA working group is currently working on the topic of WBG power electronics at an international level. The working group, which was initiated by Switzerland and in which Switzerland plays a key role, aims to provide political decision-makers with the know-how and foundation they need to take political measures - where appropriate - to support the market entry of WBG power electronics.

- Prof. Ulrike Grossner's **report** on the potential of WBG technologies ("New power electronic materials and devices and its impact on the energy efficiency") can be found at:
  https://www.aramis.admin.ch/Texte/?ProjectID=40173

- Roland Brüniger (roland.brueniger[at]brueniger.swiss), Head of the SFOE Electricity Technologies Research Program, can provide **information** on this topic.

- Further **articles** on research, pilot, demonstration and flagship projects in the field of electricity technologies can be found at www.bfe.admin.ch/ec-strom

Interview: Dr. Benedikt Vogel, on behalf of the Swiss Federal Office of Energy (SFOE)
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