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Energy Conversion

Demanding challenges for Power Semiconductor Industry

New environmental policies focus specifically on the global development of regenerative energies, in particular wind and solar-based power generation and the improvement of energy efficiency. Both aims have a considerable impact on power electronics, the original purpose of which is the efficient control and conversion of electrical energy.

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As a result, power semiconductor components have to meet new demands in terms of efficiency, service life and compactness. Manufacturers are striving to meet these very demands by developing new assembly and connection technology, offering higher current densities and reliable chip temperatures, as well as using new semiconductor materials.

Over the next 2 decades, the global primary energy demand is expected to grow by an average of around 2% per year. By 2030 this would mean a 50% increase in demand. At present, one third of the primary energy is used in power generation alone.
In 2004, the average global consumption of electric energy was around 12 billion KWh (Source: CPES 2004). And around 40% of this total is used for driving – in most cases - non-controlled electric motors.

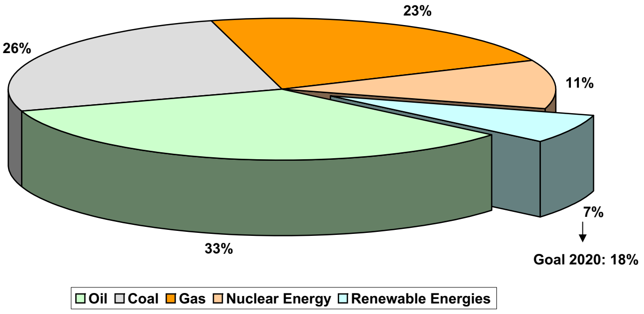
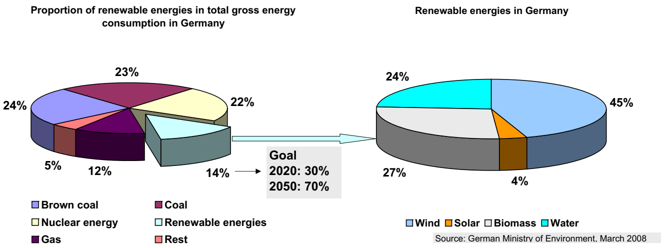


Figure 1: Proportion of renewable energies in primary energy consumption in Germany

Rethinking the climate policy

Today, the majority of the primary energy demand is covered by burning fossil fuels such as oil, gas and coal, contributing substantially to the global greenhouse effect. In recent years, increased awareness of the adverse effects of global warming has led to the introduction of targets for reduced greenhouse gas emissions. One cornerstone of this new climate policy is the global development and expansion of regenerative energies and the increase of energy efficiency.

Europe is a forerunner in modern energy and climate policy, and Germany a prime example of the use of new energy technologies. In view of the climate protection aim to reduce CO2 emissions by 14% by 2020 (as compared with emissions levels in 2005), the proportion of renewable energies in the primary energy consumption must be increased to 18% by 2020 (as compared to 6% in 2005). For the gross electricity consumption in Germany this means that the regenerative energy share is to be more than doubled by 2020 as seen in the figure 2. Looking further ahead, as much as 70% is planned for 2050.
Today, wind power is the largest segment in the regenerative energy market. In Germany, wind energy enjoys a 45% share, followed by biomass, hydropower and photovoltaics. (Source: Germany Ministry of Environment, March 2008)



Source: German Ministry of Environment, March 2008

Figure 2: Proportion of renewable energies in total gross energy consumption in Germany

Reducing electricity costs

Parallel to the implementation of political requirements and financial incentives offered by net metering programs, the cost of regenerative power generation is falling steadily.

Take, for example, the area of photovoltaics, which is still regarded as the most expensive alternative to conventional power generation. In September 2008, the price of a crystalline solar module was around €3.5/Watt; today, by contrast, a comparable module costs 35% less. This is owing to excess capacities, strong competition, in particular from Chinese manufacturers, the transition to mass production and, last but not least, a relaxation on the raw silicon market. By the end of 2010, prices as low as €1/Watt are possible. Given these cost factors, the price for one kWh of electricity produced using solar power will move into the price ranges for electricity produced by conventional means (Source: Spiegel Online, March 2009; Photon).

Profitable to the power semiconductor industry

The power semiconductor industry will profit from the forthcoming growth in the renewable energies market in two respects.
Firstly, power semiconductors are needed for energy conversion itself – for instance in inverters in wind power plants. Secondly, semiconductors are the core element of variable-speed drives, which are indispensable in wind, solar and biogas installations. Such control drives are used, for example, in solar trackers to adjust the solar panel to the path of the moving sun or in wind turbines for optimum blade pitch adjustment. In biogas plants, control drives are responsible for the precise feed and mixing of the biomass material.

Owing to their technical superiority as well as for reasons of user-friendliness, modules are used predominantly as electronic switches in regenerative power generation applications. A module is a component that comprises a silicon chip, an insulated ceramic substrate and a module case with the necessary power connections. These modules come in different versions as regards assembly and connection technology, as well as in respect to the integration stage, for example including integrated driver, current sensor and heat sink.

Figure 3 Cross-section of different power modules; Left: Standard IGBT half bridge module; Right: Intelligent power module (IPM) comprising semiconductor chips, insulation, driver with protective sensors, current sensors and heat sink

In 2008, power semiconductor modules for renewable energy applications had a mere 7.5% share of the modules market. That said, this market boasts the fastest growth rate, with an average of 25% growth per year. By 2012 this market is expected to generate US$ 380 million in sales (Source: IMS quarterly update, Feb 2009).

In wind power and solar power plants, supply reliability is top priority as this is what guarantees economic operation. Next in line are a high efficiency rate and compactness of the system. For manufacturers of power semiconductors, this means a particularly difficult challenge: how to meet these in some respects conflicting requirements. Furthermore, as inverter power increases, parallel module connection and heat management will become increasingly important. Let us take, for example, a wind turbine with an output of 3MW: here, around 45kW of thermal losses occur in the power semiconductor alone – a value that is comparable with the requirement for the heating system of 3 private homes.

New challenges for manufacturers

1. Solder connections
   In a conventional soldered power module with base plate, the solder connections often constitute the mechanical weak point of the module. Due to the materials' different coefficients of thermal expansion, high temperature fluctuations and excessive load cycling during operation will result in material fatigue of the solder layers. This is seen in the increased thermal resistance, which in turn leads to higher temperatures. This feedback mechanism will ultimately lead to component failure.
   In connections which are soldered to a PCB, cold solder joints are an additional reliability issue.

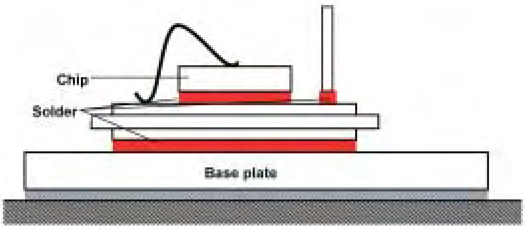


Figure 4: Cross-section of a module showing soldered connections

2. Base plate
   Base plates for modules with large dimensions and, consequently, high power output, can only be optimised with some difficulty and/or at considerable cost in view of best thermal and mechanical performance. The single-sided soldering for substrate connection results in a bimetal effect, causing non-homogenous warping. Consequently, a good thermal connection to the heat sink is not provided. Instead of optimum thermal connection with total material closure, thermal paste with poorer heat conducting properties has to be used to fill the gap between base plate and heat sink. The result: deterioration in the system's thermal resistance.

3. Internal module layout
   For modules of 200A and above, several semiconductor chips have to be connected to the DCB ceramic in parallel in order to achieve modules with increased current ratings. Owing to mechanical restrictions in the design of conventional modules with base plate, however, it is not possible to design fully symmetric DCB's. As a result, differences in switching properties and in current levels at the different chip positions occur. The module specifications therefore have to be based on the weakest chip. Internal circuitry with bond wires or connectors can worsen the internal module resistance and stray inductance.

4. Chip temperatures
   Improvements in semiconductor technology allow for finer silicon structures. In recent years this has led to smaller chip sizes, hand in hand with increased current densities. For example, a 150A/1200V IGBT has shrunk in size by more than 35% over the past few years. At the same time, the maximum permissible chip temperatures have increased to today's standard 175°C. This means that more compact modules are possible. One shortcoming of this trend, however, is the higher temperature gradient within a

module, which results in solder fatigue, a common cause of failure, as described in Section 1. In other words, overall module reliability is reduced.

Innovative technologies provide solutions

The problems described above are all interdependent factors. It therefore makes sense to search for an integral solution rather than looking at the problems as isolated matters.

A solution to the problem with the base plate and solder connections can be found in SKiiP technology, where the base plate and thus large fatigue-prone solder connection to the substrate was removed entirely, and a patent-protected pressure contact system used instead. In the pressure contact system, the substrate is pressed onto the heat sink by way of mechanical pressure. As the ceramic substrate is relatively flexible and the pressure applied by way of mechanical "fingers" located at several points, very close contact between the ceramic substrate and the heat sink is guaranteed. As a result, the thermal paste layer can be reduced to a minimum of just 20-30 um. By way of comparison, the thermal paste layer in modules with base plate is 100um.

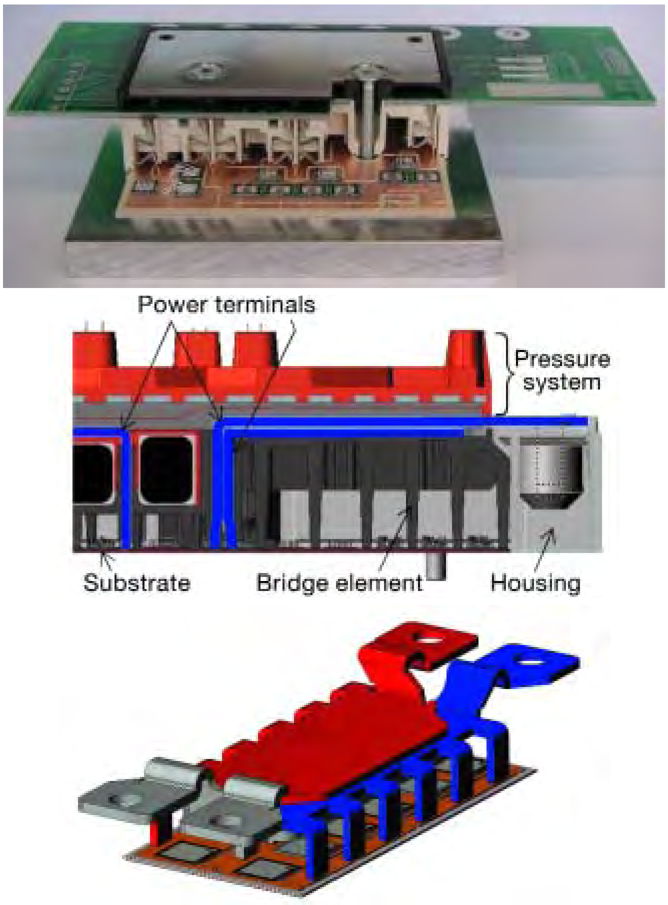


Figure 5: Comparison of different pressure contact systems. a) MiniSKiiP pressure contacts, b) SKiiP bridge element and c) SKiM with pressure contact rails. Pressure contact technology replaces fatigue-prone solder connections.

This pressure contact system can be adapted to the given conditions, irrespective of the module geometry. In MiniSKiiP modules, the pressure contacts are located on the plastic module case itself. In SKiiP and SKiM modules, pressure is applied by way of suitable pressure elements. The main terminals are also connected to the ceramic substrate using the same pressure contact system. Spring contacts are used instead of soldered gate terminals, as well as for load connections of up to 20A. Spring contacts have proven to be particularly suitable in cases where excessive vibrations occur.

The latest technological achievement is the use of silver sintering alloys rather than solders for chip connection. Table 1 shows a comparison of the chief parameters for solder and sinter connections. What is striking here is the far higher melting point of the sinter connection, meaning that the connection will age at a much lower rate at a given temperature swing. Thus, material fatigue and, consequently, failure will occur at a much later stage of lifetime. Using the approaches described here, the thermal cycling capability in power modules can be increased by a factor of five. As a result, higher chip operating temperatures are possible at no compromise to module reliability.

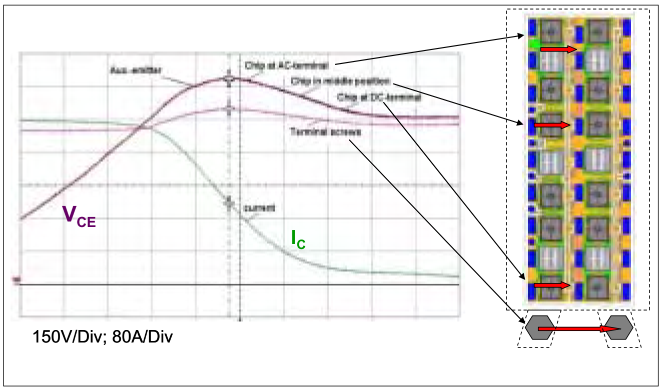


Figure 6: Layout of the ceramic substrate showing chip positions. The internal railing that doubles as a mechanical contact system is shown on the right-hand side.

A final point warranting consideration is the internal mechanical design in the new SKiM modules. Figure 5 shows the layout of the ceramic substrate with the chip positions. Note the highly symmetric layout. On the right, the internal power busbars, which double as a mechanical pressure contact system, can be seen. The laminar busbars and current draw directly across each chip result in a very low stray inductance of less than 20nH between the DC+ und DC terminals. As for IGBT turn-off, no difference can be found between the chips at the different positions.

Renewable energy sector

Despite the current economic situation, the renewable energy sector will play an important role in boosting a country's industrial production and employment rates in the future. The power semiconductor industry, it seems, has already taken on the challenges ahead. The technological demands posed by hybrid and electric vehicles, as well as new materials such as SiC and GaN will pave the way for new developments.

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Property		SnAg (3) solder layer	Ag sinter layer
Liquidus	°C	221	961
Thermal conductivity	W/mK	70	250
Electric conductivity	MS/m	8	41
Density	µm	~90	~20
CTE	ppm/K	28	19
Tensile strength	Mpa	30	55

Table 1: Comparison of the main parameters for solder and sinter connections. Note the far higher melting point in sinter connections