INCREASING LIFESPANS OF HIGH-POWER ELECTRICAL SYSTEMS

Using a combination of experimental testing and multiphysics simulation, researchers at ABB Semiconductors have redesigned the insulated-gate bipolar transistor modules (IGBT modules) used in high-power electrical components to increase device lifetime.

By **DEXTER JOHNSON**

THE HIGH-POWER electrical systems found in locomotives must be able to withstand the enormous amounts of stress brought on by the high currents and voltages surging through them. At the heart of these electrical systems are insulated-gate bipolar transistors (IGBTs), electronic switches that are used because of their high efficiency and fast switching to deliver power to locomotive systems. As a train travels from one station to the next, IGBT power modules are exposed to repeated electrical, thermal, and mechanical fatigue, which can degrade the module and cause failure.

"Typically, traction motors for driving locomotives are designed so the devices can withstand the harsh load profile for 30 years," explained Samuel Hartmann, principal R&D engineer at ABB Semiconductors in Lenzburg, Switzerland. If the IGBT modules wear out during the lifetime of the traction motor, they must be replaced. In order to meet the requirements of the traction motor's long lifetime and boost the reliability of these systems, Hartmann and his colleagues are leveraging computer simulation to better understand how the power cycling performance of IGBT modules can be increased.

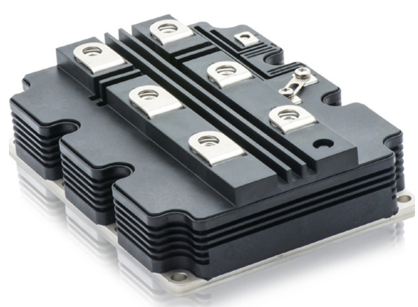

FIGURE 1: ABB HiPak power module with rated blocking voltage of 6500 V and nominal current of 750 A.

"Our team is looking into ways to improve the performance of ABB's HiPak power modules," said Hartmann (see Figure 1). "The modules are composed of many paralleled IGBT chips, which, in their 'on' state, can conduct high levels of current, and in their 'off' state can resist very high voltages." The modules are also used for applications such as industrial drives and renewable energy.

"During use in a locomotive, IGBT power modules are exposed to high temperatures, and as a result, the joints between different components can degrade due to thermo-mechanical stress," described Hartmann. "After the weakest bond fails and the wire pulls away from the emitter, electrical contact is lost and the remaining wire bonds interconnecting the semiconductor device and its packag-

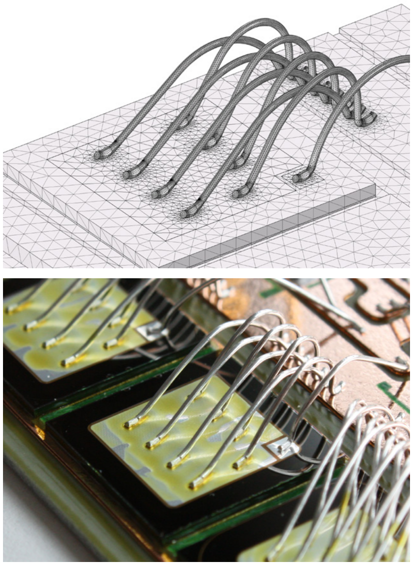

FIGURE 2: Top: The meshed COMSOL® software model of the reference wire bond layout. Bottom: Photo of the reference emitter.

ing must conduct higher currents. This eventually results in a cascading failure as the thermo-mechanical stress in the remaining bonds increases. If we can strengthen the weakest joint, then we can increase the overall lifetime of the device." By increasing the HiPak power module's usable lifetime, ABB can reduce the number of modules needed to reach the 30-year lifetime typically required of these

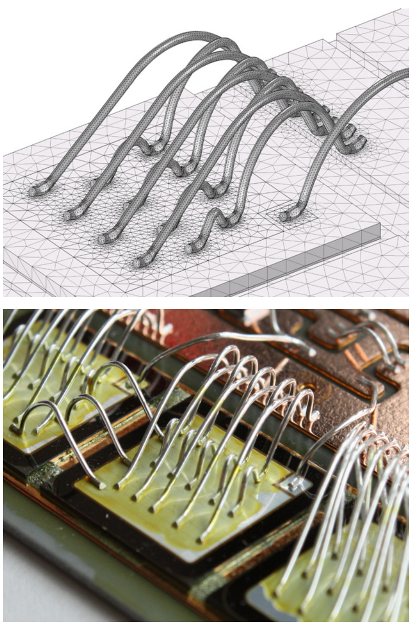

FIGURE 3: Top: The mesh of the stitch-bonded wire bond layout. Bottom: Photo of the stitch-bonded layout now used in some of the HiPak power modules.

motors, thereby saving resources and reducing the time needed for repairs.

» SIMULATIONS BRING CLARITY TO EXPERIMENTAL RESULTS

ABB'S HIPAK POWER modules typically consist of a baseplate, circuit boards, IGBT and diode chips, wire bonds, and conductor leads. In order to increase the lifetime of the power module, Hartmann explored a few different ways to increase the durability of the wire bond connections from the circuit board to the emitter bond pad.

"We explored two different methods for improving the design," described Hartmann. "In one case, we looked at different ways the wires were connected to the emitter to see if stitched bonding techniques could prevent component degradation and extend device lifetime." The meshed models and photos of the device for the commonly used reference wire bond layout and the stitch-bonded layout are shown in Figure 2 and Figure 3, respectively.

"For the second case, we used new joining techniques to bond a stress buffer between the emitter's silicon chip and the aluminum wire bonds," Hartmann continued. "The coefficient of thermal expansion (CTE) of the stress buffer is between the CTE of silicon and aluminum, and thus results in reduced

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thermal and mechanical loading."

The ABB team leveraged multiphysics simulation to gain a better understanding of the underlying mechanisms at play in the deterioration of the IGBT chips, such as the electro-thermal and thermo-mechanical response of different designs when exposed to repeated power cycling tests. "The higher the power cycling capability, the more durable and reliable the design," explained Hartmann.

"Experimentally, we have assessed several variants of these wire bond connections and used multiphysics simulation to understand why one variant is better than the other." Hartmann believes that ABB's use of the COMSOL Multiphysics® simulation software was key to the success of their design.

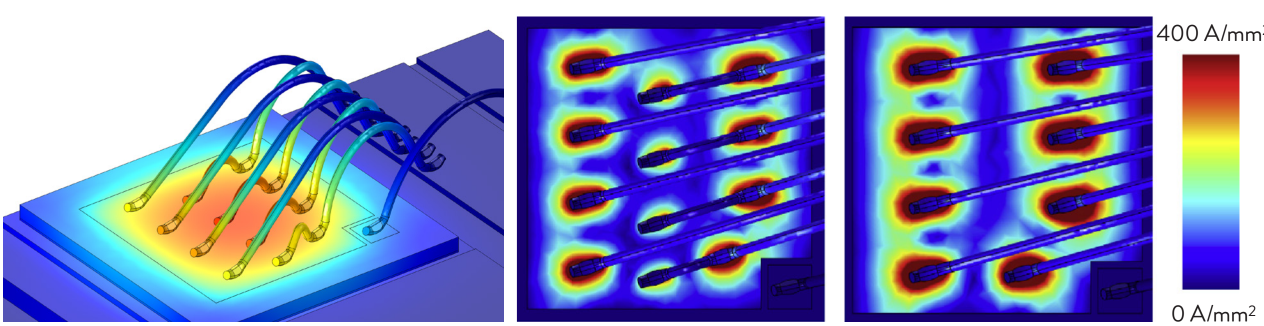

FIGURE 4: Left: COMSOL results showing the temperature distribution obtained for the stitch-bond layout. Right: Current density in the stitch-bonded and reference layout showing the reduction in current around the wire's feet for the new design.

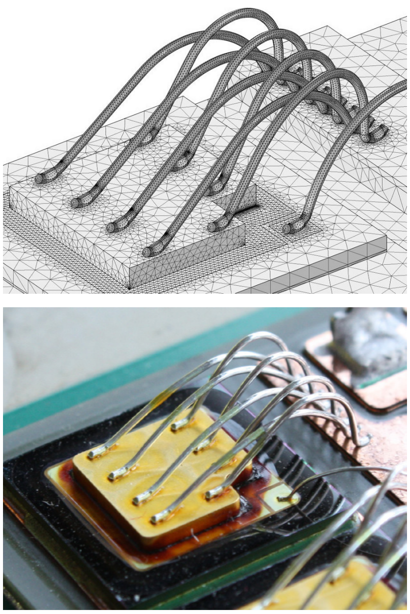

FIGURE 5: Top: The mesh of the reinforced emitter contact. Bottom: Photo of the reinforced emitter contact.

» *EXPLORING DIFFERENT IGBT MODULE DESIGNS WITH SIMULATION*

IN A FIRST EXPERIMENT, the ABB team tested two different bonding techniques: the reference wire bond layout (see Figure 2), and the stitch-bonded layout, where the wire is bonded to the surface of the chip more than once (see Figure 3).

Using simulation and experimental testing, Hartmann compared three different stitch-bonded layouts to the reference layout. "As expected, we found that, with more wire bonds on a single chip, the current density within the wires, especially at their feet, was also reduced," described Hartmann. "And thanks to simulation, we gained an unexpected insight: the stitch-bonded layout did not reduce temperature gradients or mechanical stress: the improved performances are due to the current density reduction resulting from a lower current density in the chip's metallization around the bond feet."

The additional bonds provide more locations for current to pass through the wires, therefore decreasing the amount of current dissipated by each wire (see Figure 4). "The new bond layout resulted in an IGBT design that has a power cycling capability that is four times higher than the reference layout. This new design is now being used in some of our HiPak power modules."

For a second experiment, Hartmann and his colleagues compared wires bonded directly on the chips with wires bonded to a metal plate attached to the chip that serves as reinforcement for the emitter (see Figure 5).

Using simulation, Hartmann found that for the reinforced emitter contact, the current density, the temperature variation, and the mechanical stress experienced by the wires at the bond interface was much lower than in the reference module (see Figure 6). This resulted in wire bonds that were

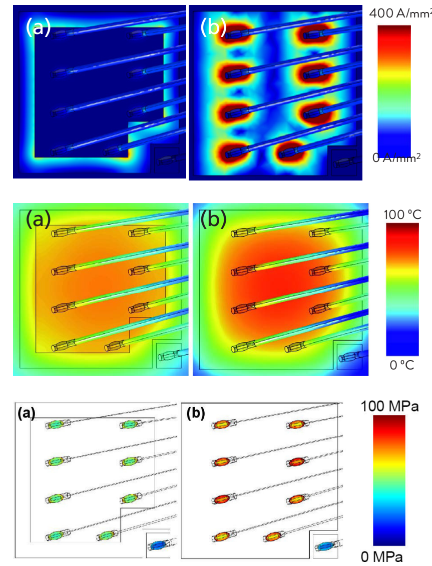

FIGURE 6: From top to bottom: Results from ABB's COMSOL model showing the simulated current density, temperature variation, and von Mises stresses at the bond-to-chip interface for the (a) reinforced and (b) reference emitter contacts on the front metallization and wire bonds.

Emre Oezkol (left) and Samuel Hartmann (right), holding the circuit board and the HiPak power module, respectively.

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less likely to detach from the emitter.

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» *INCREASED LIFETIME FOR IGBT POWER MODULES*

THE RESULT OF THE WIRE bond simulations and the new joining techniques has resulted in the lengthening of the lifetimes of ABB’s power modules by a factor of 4 for the stitch-bonded layout and a factor of 10 for the reinforced emitter contact. This improved lifetime translates into higher power output per device, which in turn leads to lowering costs for ABB’s power module customers.

“If the power cycling capability is increased, as in the case of the improved wire bond layout now available in our new modules,” explained Hartmann, “then a lower number of power modules are needed to reach the 30-year lifetime of a traction motor, which is the standard in the traction industry. This directly reduces the cost of a locomotive and enhances the competitiveness of our power modules.” ◎

JOULE HEATING AND THERMAL EXPANSION

BY HENRIK SÖNNERLIND

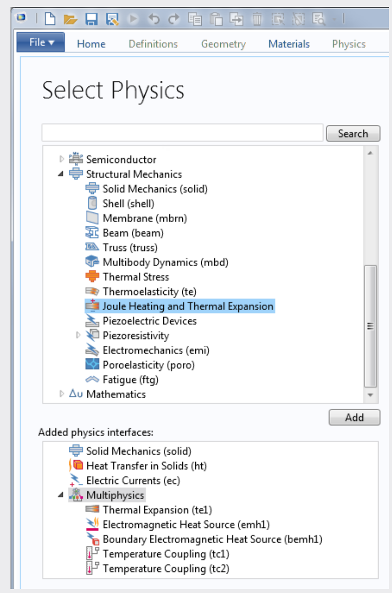
AN ELECTRIC CURRENT WILL generate heat through resistive losses, an effect called Joule heating. Since the resistivity usually has a strong dependence on the temperature, the heat transfer problem and the electrical problem must be solved simultaneously in order to accurately find the temperature and current distribution.

As an effect of the heating, thermal expansion will induce deformations. Large strains and stresses may then occur for several reasons. Deformations in materials with different coefficients of thermal expansion will not be compatible with each other; and there may also be large temperature gradients within a single material.

There are also certain cases where heat distribution is affected by structural deformations. For example, when objects come into contact with each other or large deformations cause changes in the electrical or thermal boundary conditions, a dramatic shape change occurs. If the heating cycle is repeated, the corresponding stress and strain cycles will be repeated as well. This may ultimately lead to a fatigue failure of the material.

In COMSOL Multiphysics® software, you can directly combine all these effects by selecting *Joule Heating and Thermal Expansion* in the list of available *Structural Mechanics* physics interfaces.

When doing so, the three contributing physics interfaces (*Solid Mechanics, Heat Transfer in Solids*, and *Electric Currents*) are added to the application, along with the necessary multiphysics couplings added through the *Multiphysics* node.



You can then choose settings for how to solve for the three physics interfaces. One approach would be to solve for the electric currents and temperatures together in a time-dependent study, and then solve the structural mechanics problem as stationary. Since the highest stresses could appear at any time during the thermal cycle, it is necessary to check stress values at several time steps.

For a qualitative comparison, it is sufficient to look at the computed stresses, but adding a *Fatigue* interface would make it possible to also make lifetime predictions.