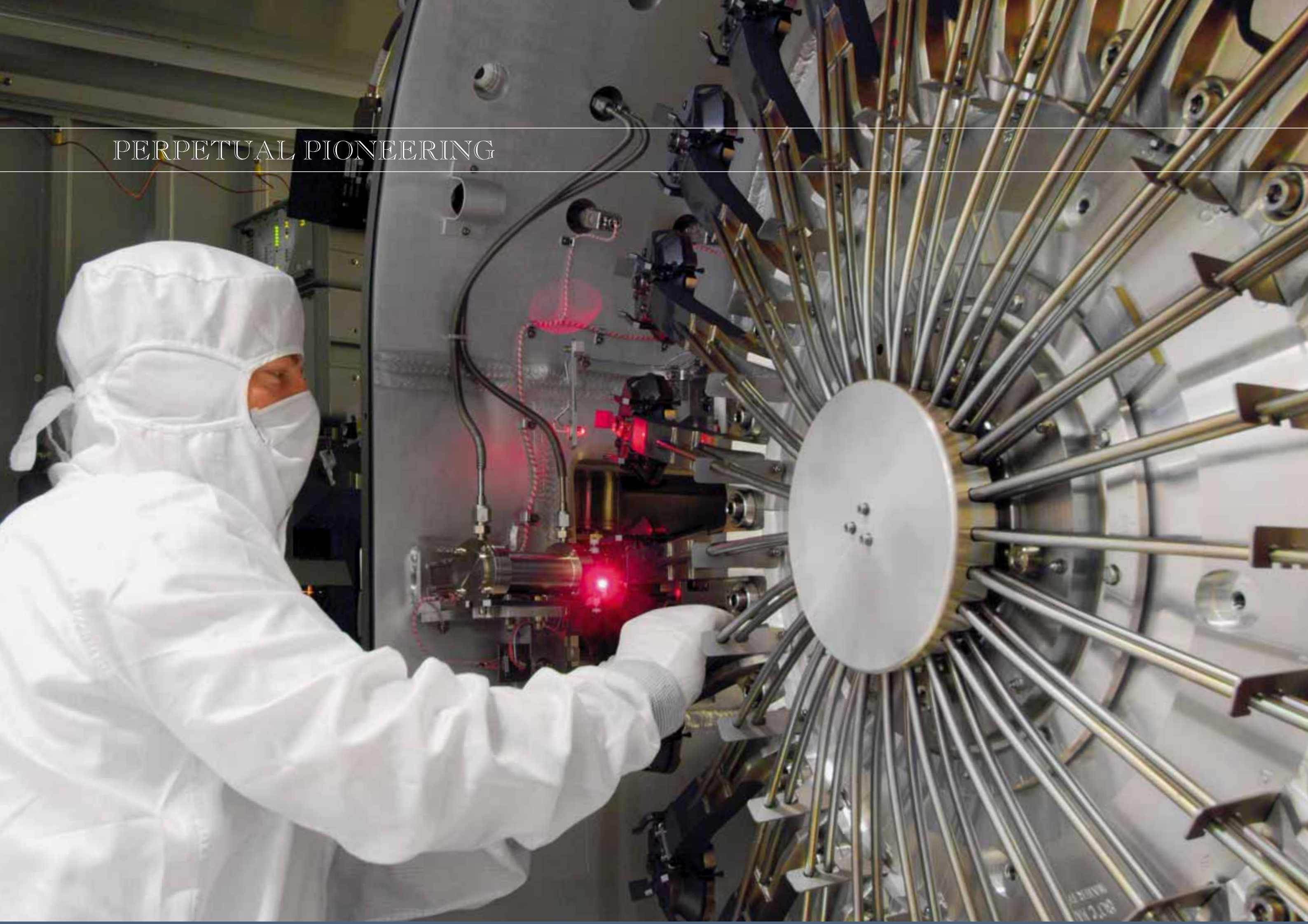


The winning chips

History of power semiconductors at ABB

Hansruedi Zeller

Imagine an electronic device with 100 billion switches that must simultaneously switch electrical current on or off in little more than a microsecond, and must repeat this action several hundred times every second. Taking into account that sophisticated redundancy is required to ensure that the device will operate correctly, even if some of the 100 billion elements do not switch off properly, is it believable that such a device can be made to work? Assuming that it exists, where would it be expected? Likely answers are supercomputers, military equipment, or big science installations such as CERN.

Surprisingly almost nobody associates this level of leading-edge semiconductor device technology with electrical power transmission. In fact, the example described refers to an HVDC converter station equipped with ABB's high voltage IGBT modules.

When the history of power semiconductors began, nobody even in their wildest dreams could ever have imagined that such complexity, sophistication and fine tuned functionality could ever be reached. Also nobody could have predicted that on its way from the power plant to the end customer, electrical current would one day flow through silicon junctions.

The history of power semiconductor devices in ABB's parent companies, BBC and ASEA, began a few years after the development of the transistor. At the time, rectifiers and switches were assembled from switching devices based on mercury vapor. These were bulky, costly and exhibited high power losses. There was an obvious demand for better solutions. Although the gap between the solid state technology of 1950 and the mature state-of-the-art of the mercury vapor devices was frustratingly high, development of power semiconductor devices was started around 1955 in both ASEA (Ludvika, Sweden) and BBC (Ennetbaden, Switzerland). Soon it was realized that germanium (Ge), which dominated the transistor technology of the early 1950s, was not the appropriate choice. The maximum operating temperature of a germanium diode at blocking voltages of a few hundred volts turned out to be limited to about 80 °C, which is insufficient for industrial applications. The physical properties of silicon are much more favorable. Much higher blocking voltages at reasonable operating temperatures seemed feasible. Nevertheless, the first commercial semiconductor device manufactured by BBC was a 100 A, 100 V germanium diode, introduced in 1956 for electrolysis applications. It was used in two commercial rectifier stations supplied by BBC.

At that time, silicon technology was very immature. A structured industrial added-value chain did not yet exist. As a result, processing started with raw silicon, followed by single crystal growth, sawing this into wafers and the subsequent device processing. For the silicon production, crystal growth presented a major challenge.

In 1961 both ASEA and BBC introduced Si diodes in the 100–200 A and 600 V range. The BBC diode DS 200 with 200 A, 600 V rating was used in electrolysis plants for aluminum production. Examples are a rectifier block 34.5 kA, 350 V commissioned in 1962 and a larger block with 108 kA and a variable secondary voltage (85–485 V) commissioned in 1963. Because BBC and ASEA concentrated on silicon technology, they rapidly became leaders in high-voltage devices.

Around 1958 semiconductor device development was also started by BBC in Mannheim (Germany), and considerable effort was invested in this venture. Soon, BBC Germany offered a large range of products.

Switches switch from mercury to silicon

The era of high power switches was initiated when BBC presented a 100 A, 1,200 V thyristor at the Hannover fair of 1961. At the same time ASEA conceived the first thyristor controlled converter for an industrial drive and announced a 130 A, 800 V thyristor in 1962. In the years to come, ASEA and BBC pioneered power semiconductor technology on an equal level Factbox 1.

The development of power semiconductors was started around 1955 in both ASEA and BBC.

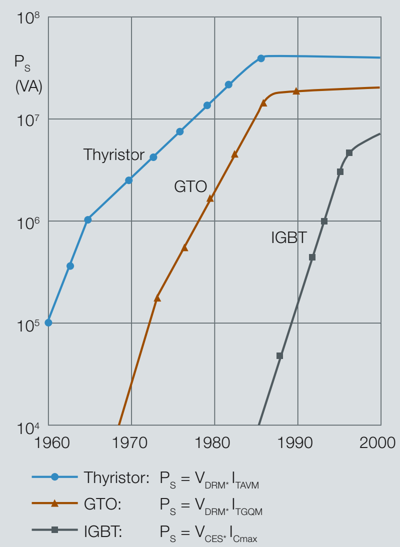
After the acquisition by BBC of Sécheron, a Geneva based company with a product range almost identical to the one of BBC (including power semiconductor devices), BBC planned to build a factory in Gland, on land owned by Sécheron. After a political struggle, the plan was abandoned and instead a well-equipped and modern factory was set up by BBC at Lampertheim (Germany) at the end of the 1960s.

In the years 1960 to 1970 the range of power semiconductor devices and their applications expanded rapidly. Mercury vapor devices quickly became obsolete. The power electronics divisions required ever-increasing voltage and current ratings. Switching speed and switching losses became a dominating issue in motor converters. The increasingly complex converter circuits required thyristors with an integrated anti-parallel diode (so-called reverse conducting thyristors) and protective elements such as diodes with controlled breakdown properties (so-called avalanche diodes). BBC became a leader in protective semiconductor devices. ASEA on the other hand pioneered line-commutated thyristors for power transmission applications. Although not considered feasible a few years previously, ASEA in-

Factbox 1 Thyristor

A thyristor is a switch that can be turned on by a current pulse to its gate. It cannot be turned off arbitrarily, but will turn off at the next zero crossing of the current. It may be compared to a toilet flush, which can be triggered at will, but where the water flow only stops when the water container is empty. The thyristor thus can be used only in applications where an alternating current waveform already exists.

Historical development of the switching power of the three major power semiconductors



Source: Jaecklin, A., "Advanced Power Bipolar Devices." Proc. 1988 Bipolar/BiCMOS Circuits and Technology, Minneapolis, MN, Sept. 1998.

The silicon wafers and housings of a 1.5 inch and a 5 inch thyristor for 5.5 kv (1983)

stalled the world's first semiconductor-based high voltage DC (HVDC) transmission line to the isle of Gotland. It had a length of 96 km, a voltage of +/– 150 kV and a power rating of 30 MW. This turned out to be the first step towards ASEA's worldwide leadership in HVDC technology.

ASEA installed the world's first semiconductor-based high-voltage DC transmission line to the isle of Gotland.

BBC's major technical contribution to power semiconductors in that period was "free-floating silicon" technology in which the silicon wafer is pressure contacted to a molybdenum disk for electrical contact. Other technologies such as soldering or alloying worked well for small wafers, but could not deliver sufficient robustness with respect to thermal cycling for large size devices. Pressure contacting, however, is not as trivial as it sounds. It requires very careful mechanical engineering. Competitors were also quick to realize that pressure contacting is mandatory for large-area devices. The strong patent position allowed BBC to enter cooperation- and license agreements with competitors.

All major electrotechnical companies had come to the conclusion that power semiconductor devices are strategic for their business and had thus set up in-house device development and manufacturing activities. Production was mostly intended for internal use and (at least for BBC) selling to outside customers was considered almost unethical. As a consequence, semiconductor manufacturing was mostly a project business. When ASEA or BBC was bidding for a large project, these companies needed semiconductors with project-specific improvements in functionality. If the bid was successful, the required device was developed and produced in the required quantity. At least for the leading-edge devices, no steady production volume existed and no attempts were made to achieve such a volume. The BBC activity at Lampertheim formed an exception; the unit had a fairly stable business in the area of medium-energy devices, which it offered on the open market. The relations between process stability, yield, reliability and stable production volume were not understood at that time.

At the end of the 1960s, BBC had a short interest in silicon carbide (SiC), a material whose properties are greatly superior to Si for high power devices. The project was stopped, when it became clear that a quality improvement of many orders of magnitude would be required for SiC single crystals. SiC crystal quality dramatically improved after 1990 when it was used in large quantities as substrate for light emitting diodes.

Thus ABB revisited SiC high voltage device development in the 1990s. Still, the requirements for very high voltage bipolar devices could not be met and the program was abandoned.

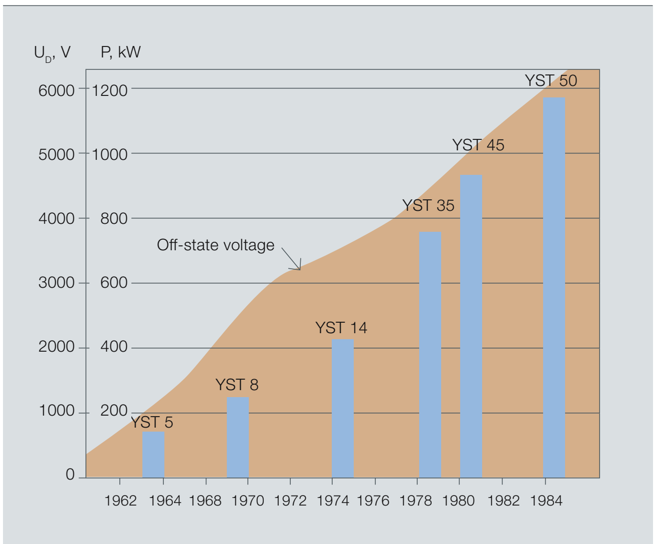
BBC's major contributions in the 1970s were the introduction (as the first company in Europe) of neutron "doped" Si, the pioneering of numerical modeling of power semiconductors and direct copper bonding for power modules.

In 1970, BBC decided to concentrate production at Lampertheim, Germany. The Ennetbaden, Switzerland activities were transferred to Birr and focused on development and pilot production. Birr, however, continued to produce devices on a modest level.

Lampertheim lacked some of the processes required for devices intended for heavy thermal cycling. Most of the internal demand for fast thyristors for motor converters was covered by production in Germany. Birr was engaged in the development of thyristors for

An early ASEA thyristor-based HVDC converter

Development of HVDC thyristor blocking voltage and power handling at ASEA (ASEA Journal 1983, Nr. 2, page 9)



high voltage DC transmission (HVDC) applications. In 1968 BBC entered the HVDC world in a consortium with AEG and Siemens. The partnership resulted in two major contracts: Cabora Bassa, Mozambique (1,920 MW, cable length 1,450 km, operational 1977) and Nelson River, Canada (cable length 940 km, 900 MW operational 1978 and 2,000 MW operational 1985). The semiconductor volume was split equally among the partners. The BBC part of the devices was first produced in Birr and later in a modern new factory established in Lenzburg (Switzerland) in 1979.

Stud-mounted thyristors (1966)

BBC Corporate Research started a power semiconductor research and development activity in 1970. Its major contributions in the 1970s were the introduction (as the first company in Europe) of neutron "doped" Si, the pioneering of numerical modeling of power semiconductors and direct copper bonding for power modules. In neutron "doping" a single Si crystal is exposed to a flux of slow neutrons. These cause some Si nuclei to transform into phosphorus, which is a dopant. This results in a very homogeneous dopant concentration. Direct copper bonding uses the fact that copper oxide forms a low melting point eutectic with copper and allows the bonding of copper electrodes directly onto ceramic substrates. Direct copper bonding became a significant competitive advantage for the BBC Lampertheim power module activities.

Today ABB is the only supplier in the world that can guarantee long-term survival of a failed module in series connection.

ASEA made impressive progress in thyristors for its HVDC business. Between 1960 and 1980 the maximum blocking voltage and the maximum power handling per device increased approximately linearly in time from virtually zero before 1960 to 6,000 V and 600 kW, respectively in 1980.

ASEA made a brief excursion into light-triggered thyristors, but concluded that light triggering offered no advantage compared to electrical triggering.

The power electronics divisions of ASEA and BBC were very reluctant to introduce gate turn-off thyristor (GTO) technology in their motor converters. They kept using increasingly sophisticated fast thyristors. As a result, GTO device manufacturing was lagging behind the Japanese competition. In 1985 BBC entered a technology transfer agreement with Toshiba to accelerate the introduction of GTOs. As a latecomer, ABB became world leader in GTO manufacturing in the 1990s and has kept this position Factbox 2.

ABB consolidates its resources

After the merger of ASEA and BBC in 1987, it became clear that the ever-increasing technology and business challenges could not be met by three separate production locations. It was thus decided to sell the Lampertheim activity to IXYS, a US company. In 1991 the Västerås activities were closed and semiconductor production within ABB was concentrated at Lenzburg, Switzerland. The newly formed company, ABB Semiconductors rapidly and successfully expanded its activities into the open market. Management with solid business and technology expertise was brought in. Andy Nilarp, who started his professional carrier at ASEA and later became a top rank executive at International Rectifier Company (El Segundo CA, USA), proved to be a charismatic and enthusiastic CEO. He pioneered the culture change from a fluctuating project business to a fine-tuned, high-volume production line with modern methods of process control.

As early as 1995, ABB Semiconductors became a finalist in the European Quality Award and in 1996 earned the "Supplier of the Year Award" from General Electric Company, USA.

The focus on high-voltage thyristors and GTOs led to some curious situations. For instance, when a last call for orders for a number of fast thyristors was sent to customers, a huge order came in for a device that had

Factbox 2 Gate turn-off thyristor (GTO)

The GTO is a switch similar to the thyristor. In contrast to the thyristor, a GTO can be turned off at any arbitrary point in the current waveform. Due to an inherent filamentary instability of the current distribution during turn off, it requires a protection circuit (snubber).

Factbox Insulated-gate bipolar transistor (IGBT)

This is a bipolar transistor that obtains its gate current from a MOS channel. As long as extreme operating conditions are avoided, the device exhibits no instabilities and allows operation with no or minimum protective circuitry.

Factbox Integrated gate-commutated thyristor (IGCT)

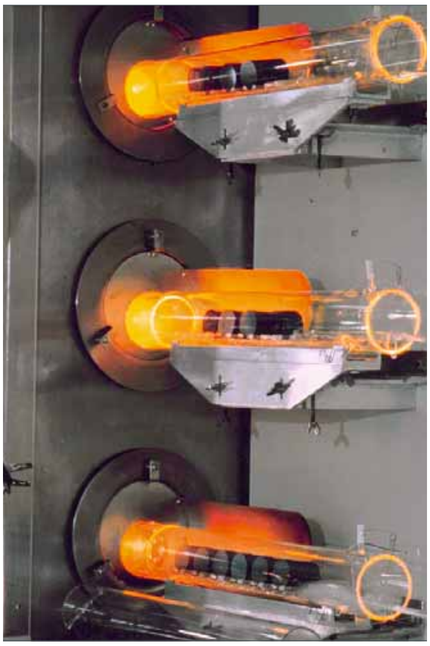
This is basically a GTO in which the filamentary current instability is avoided by commuting the anode current from the cathode to an external capacitor during turn-off. A snubber (protective) circuit is not mandatory.

never been ordered before and that had never got beyond the laboratory state. To meet the customer's demand, the obsolete device had to be developed with top priority.

Nanometers and megawatts

In the late 1980s it became clear that MOS-controlled power semiconductor devices could potentially reach power levels of interest to ABB. The prime advantage of a MOS-controlled device is that switching is controlled by a voltage signal, as opposed to a gate current as in bipolar switches such as thyristors and GTOs. BBC Corporate Research established a micro-laboratory with cleanroom and state of the art processing capabilities in 1988. ASEA entered a co-operation with IXYS to gain access to MOS processing capability.

Thyristor manufacturing



To ensure safe switching, a network of protective devices, so-called snubbers, is used. The IGBT is not a switch, but a transistor and hence does not exhibit instabilities during switching if operated within design margins.

However, it was not clear what a high voltage MOS-controlled device would look like. A large number of novel device concepts were discussed in technical literature. Two concepts were pursued by ABB: One consisted of a large area, high voltage thyristor with an integrated MOS structure to improve the turn-off properties (so called QCT, Q-Control Thyristor). The second was an MCT (MOS-Controlled Thyristor), which is a turn-off device similar to a GTO. For fundamental reasons, both device concepts turned out to be unrealistic. The QCT had performance and yield issues and the MCT was stopped by intrinsic turn-off instability problems.

In 1990, it was the generally accepted belief that the IGBT (insulated-gate bipolar transistor) would be restricted to blocking voltages below 1,500 V. The MCT under devleopment at ABB Corporate Research in Dättwil required a few IGBT cells to be turned on. It came as a big surprise when it was discovered that the 4.5 kV IGBT cells had favorable power losses. The MCT development was quickly cancelled and a program for high voltage IGBTs was initiated. Success came very fast. In 1992 the world's first sample of a 4.5 kV, 600 A IGBT module was presented.

It was clear that MOS-controlled devices such as IGBTs could not be produced in the Lenzburg facility. Neither the process equipment, nor the cleanroom was suited for the production of the delicate MOS structures. It was thus decided to enter a co-operation with International Rectifier Company, El Segundo (California) to use the latter company's production line. In 1994 the micro-laboratory at ABB Corporate Research Dättwil was closed, with key personnel being transferred to El Segundo.

External production of IGBTs was never considered to be the long term solution. In 1998 ABB opened a new factory at Lenzburg, Switzerland and the IGBT activities were shifted from the US back to Switzerland. This Lenzburg factory is the only factory in the world dedicated exclusively to IGBT manufacturing. Today ABB is the only supplier to offer the full product range of IGBTs and bipolar devices in the high voltage/high power range.

GTO and IGBT differ not only in the way switching is controlled. The GTO is a true switch and as such exhibits only two stable states, on and off. During turn-off it passes through a potentially destructive instability regime. To ensure safe switching, a network of protective devices, so called snubbers, is used. The IGBT is not a switch, but a transistor and does not exhibit instabilities during switching if operated inside design margins. Operation without a snubber circuit is possible. However, textbook wisdom says that a transistor (IGBT), in which charge carriers are injected only at one electrode has a higher on state voltage that a switch (GTO), in which charge carriers are injected from both sides. The development engineers of ABB Semiconductors did not accept the general belief and came up with high-voltage IGBTs with losses smaller than standard GTO losses.

Around 1995, ABB Power Systems started the development of HVDC Light® technology. This was intended for DC transmission in a power range up to 100 MW, but is now extended to higher power levels.

The on-state voltage of a high-voltage device is basically controlled by the concentration of electron-hole plasma in the device. In this respect a four-layer device such as the GTO has advantages compared to three layer devices (IGBT). In the GTO, plasma injection occurs both at the anode and at the cathode; in the IGBT it occurs only at the anode. The standard approach of industry for reducing IGBT losses was to introduce a trench structure at the cathode. This had proven successful for power MOSFETs. It did in fact also improve IGBT losses, but this was at the expense of device ruggedness and production complexity. ABB's approach was different. Careful engineering of the plasma distribution inside the IGBT, for instance by introducing obstacles to the outflow of holes at the cathode, led to planar devices with losses smaller than state-of-the-art trench devices. The same methods also allowed an extension of IGBT blocking voltages to 6.5 kV while retaining low on-state and switching losses. This was considered inconceivable a few years ago.

ABB is a leader in the manufacturing in IGBT and IGCT semiconductors.

The IGCT meets the IGBT challenge

The GTO developers at ABB accepted the IGBT challenge and came up with

two rather dramatic improvements. An anode with low injection efficiency combined with a novel doping profile was developed, which permitted substantially reductions in the device thickness and thus the losses.

To have the best of both worlds, a low-loss bipolar switch, but no turn-off instabilities, ABB introduced the IGCT. In the on- and off-state the IGCT behaves as a GTO with all its advantages. For a few microseconds during turn-off, the IGCT is transformed into a transistor by discharging a capacitor into its control gate. Potential current instabilities are thus avoided and snubberless switching becomes possible. All this happened at a time, when competitors had concluded that GTO development was no longer worthwhile and had shifted their engineers to other tasks.

Today IGBT and IGCT compete on an equal level for high voltage/high power applications. ABB is a leader in both areas.

Nanometers and megavolts

Around 1995, ABB Power Systems started the development of HVDC Light® technology. This was intended for DC transmission in a power range up to 100 MW, but is now extended to higher power levels. The converters are based on IGBT-module technology. ABB's semiconductor device engineers were faced with a very serious problem in the development of suitable IGBT modules. To illustrate this, an IGBT module rated at 2,000 A is considered, consisting of 50 IGBT chips in parallel. To reach blocking voltages exceeding 100 kV, a large number of modules are connected in series. Redundancy is provided by using more modules in series than required. However, this only works, if

ABB diodes from the 1980s

PERPETUAL PIONEERING

Semiconductor manufacturing

the failed module has a low resistivity such that it can carry the converter current.

If a chip fails, then potentially the full converter current of 2,000 A will be forced across the failed chip. Standard modules use wire bonded chips. In such modules the wires would vaporize instantaneously: An electric arc would form, leading to failure in the converter stack with potentially serious consequences for the stability of the power grid. In a module suitable for series connection, a chip has to have a "short circuit" failure mode such that it can carry the full converter current for the time period up to the next scheduled service. The standard pressure contact solution used for GTOs does not do the job. The chip heats up and highly brittle Si-Mo intermetallic compound are formed between chip and Mo contact plate. These prevent the formation of a stable short circuit current path. The solution was found by providing a contact plate consisting of a metal, which forms a low melting eutectic alloy with Si. This leads to a metallurgical contact with high current carrying capability. Today ABB is the only supplier in the world that can guarantee long-term survival of a failed module in series connection.

Innovation in high power semiconductor devices is still in full swing. The world's hunger for electricity has given new impetus even to the old fashioned HVDC thyristor technology. New DC transmission line projects ask for ever-increasing thyristor power handling capability and thus increased current and voltage ratings of the devices. The major competitor of ABB's high voltage IGBTs is in-house, consisting of ABB's GTO and IGCT range. ABB's customers thus have the unique opportunity to choose between two leading edge technologies for their power electronics applications.

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