
# Semiconductor generations

## ABB looks back on 60 years of progress in semiconductors

CHRISTOPH HOLTMANN, SVEN KLAKA, MUNAF RAHIMO ANDREAS MOGLESTUE – Many of the great transformational periods in human history were driven by technological breakthroughs, but had consequences reaching far beyond technology. Progress in maritime navigation in the 15th century opened up trade routes between continents. Refinement in mechanical engineering enabled industrialization in the 18th and 19th centuries. Recent decades have been marked by changes of similar dimensions, attributed to progress in computing and communications – and thus ultimately by progress in semiconductors. But semiconductors have at the same time also driven another revolution – one that is maybe less visible but equally significant: From the humble charging of mobile phones to the transmission of power over thousands of kilometers, power electronics has become a vital enabler of the modern lifestyle. ABB has over the past 60 years played a pivotal part in the development of power semiconductors and their applications.


ABB's predecessor companies, ASEA and BBC, both commenced semiconductor development in the early 1950s.

Just as there were large ships before Henry the Navigator and steam engines before James Watt, the basics of today's semiconductor applications predate the semiconductors they use. Early computers used relays, radios used tubes and power converters used mercury-arc valves[1] or mechanical switches. The basic circuit topologies at the heart of these examples were not too different to those still in use today. But because semiconductors led to more compact designs, greater reliability, lower losses, lower costs and greater ease of use, they opened the technology to new applications while developing it to levels of performance and sophistication orders of magnitude beyond what would otherwise have been possible.

**Title picture**
300 V / 800 A thyristors manufactured by BBC in the early 1970s

## Semiconductor basics

A semiconductor is called as such because it displays an intermediate level of conductivity between a conductor and a nonconductor. Its electrical behavior can furthermore be influenced by factors including the presence of impurities, electric fields, light and temperature. Many of these phenomena had already been recognized in the 19th century ➔ 1 but it was not until the early 1930s that a workable explanation emerged in the form of the band theory of conduction, drawing on insights from quantum physics.

In power electronics, semiconductor properties are used to create devices that can alternate between being "on," ie, conducting large electrical currents with as low an on-state voltage as feasible, and "off," ie, blocking as high a voltage as required with minimum leakage current. The transition phase between the two states should be kept as short as possible. The simultaneous presence of nonzero voltage and current leads to device-level losses, representing not only wasted energy but also threatening thermal damage of the device.

## The diode

The diode is the simplest of all power semiconductor devices. It simply conducts current in one direction and blocks it in the other. It is thus well suited for simple rectifier (AC to DC conversion) applications.

ABB's predecessor companies, ASEA and BBC, both commenced semiconductor development in the early 1950s. BBC's activities were based in Baden, Switzerland, and ASEA's in Ludvika, Sweden. BBC created its first semiconductor diode in 1954 ➔ 2. The first commercially available diode (100 V / 100 A), targeted at rectification for electrolysis followed in 1956. BBC's early diode designs used germanium, but because

**Footnote**
1 See also A. Moglestue, "From mercury arc to hybrid breaker: 100 years in power electronics," *ABB Review* 2/2013, pp. 70–78.

In rectifier applications, thyristors present the advantage over diodes that the phase angle can be controlled and hence the flow of power regulated.

1 Early milestones of semiconductor history

| | |
|---|---|
| 1787 | Antoine Lavoisier proposes the existence of the chemical element silicon |
| 1824 | Jöns Jacob Berzelius isolates pure silicon |
| 1833 | Michael Faraday observes a temperature dependency in the resistivity of silver sulfide, not conforming to that of a metal |
| 1839 | Alexandre-Edmond Becquerel observes the photovoltaic effect |
| 1874 | Karl Ferdinand Braun observes rectification in metal sulfides |
| 1886 | Clemens Winkler discovers the element germanium |
| 1897 | Joseph John Thomson discovers the electron |
| 1906 | Jagadish Chandra Bose, Greenleaf Whittier Pickard and others develop the “cat’s whisker detector,” a primitive semiconductor rectifier for radio receivers |
| 1907 | Henry Joseph Round invents the light-emitting diode |
| 1920s | First commercial diode-based rectifiers appear for low-power applications |
| 1926 | Julius Edgar Lilienfeld proposes the principle of the field-effect transistor |
| 1932 | Alan Herries Wilson explains energy bands |
| 1939 | Russell Ohl discovers the p-n junction |
| 1947 | William Shockley, John Bardeen, Walter Brattain and others produce the first transistor at Bell Labs |
| 1950 | William Shockley describes the principle of the thyristor (the first thyristor is produced by General Electric in 1956 and commercialized in 1958; BBC launches its first thyristor in 1960) |
| 1954 | BBC and ASEA independently commence development of power semiconductors |

2 BBC’s first semiconductor diode (germanium, 1954)


of the material’s thermal and blocking-voltage limitations, this was soon replaced by silicon.

## The thyristor

Moving beyond simple rectifier applications, a device was required that could be switched on at an arbitrary point in time. The design best suited to this was the thyristor – a device whose principle had been proposed by William Shockley in 1950. A thyristor has two main contacts rather like a diode (the anode and cathode) but also has an auxiliary contact (the gate). A current applied at the gate causes the thyristor to start conducting (if a positive voltage is present between anode and cathode). Once conduction has begun, the trigger current can be removed, with conduction not ceasing until the main current falls below a threshold value (usually at the zero-crossing of the current). A turn-off cannot be arbitrarily triggered unless auxiliary circuits are used to artificially force such a zero crossing.

Thyristors are thus well suited for inverter (DC to AC conversion) applications in which the receiving network is strong enough (eg, through support of local generation) to enable forced commutation of the inverter. They are also well suited for rectifiers where they present the advantage over diodes that the phase angle can be controlled and hence the flow of power is regulated. BBC produced its first thyristor in 1961 → 3.

## Successful traction applications

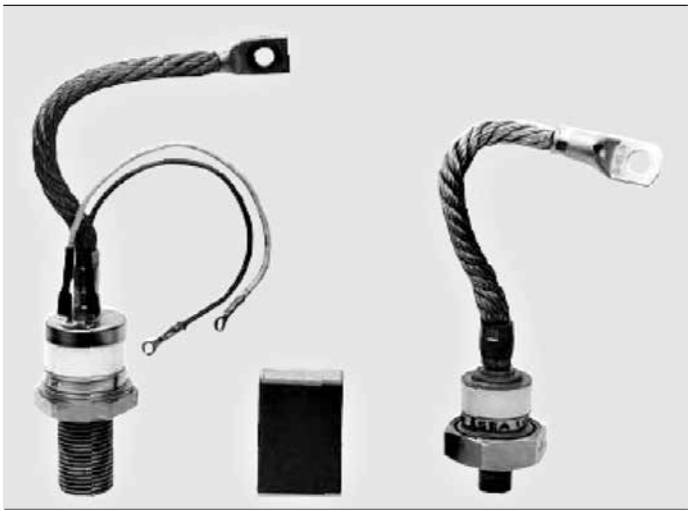
An early successful traction application for diodes was the type Re4/4 locomotive (4,980 kW) built for the BLS railway (Switzerland) from 1964 → 4. These locomotives, still featuring their original rectifier circuits, remain in use today.

Having no means to directly control a diode rectifier, traction was controlled by a tap changer on the transformer. Such was the rate of progress, however, that in 1967, ASEA began producing a locomotive controlled by thyristors. This was the 3,600 kW type Rc for SJ (Swedish Railways) → 5. Again, many of this type remain in use today.

## Improvements in semiconductors

From 1960 to 1980, blocking voltages and the power that could be handled per de-

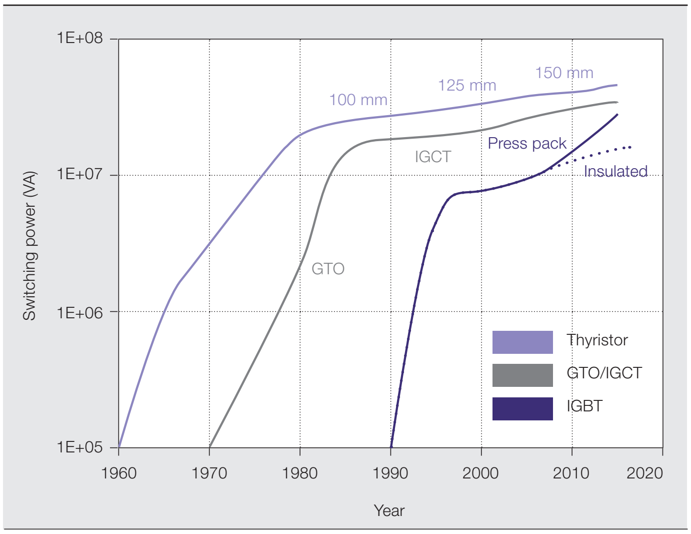
3 In 1961, BBC launched its first thyristor (1,200 V / 100 A). The diode range reached 650 V / 200 A.



4 The Re 4/4 locomotive (1964) of BLS (Switzerland) uses BBC diodes.

5 The Rc locomotive (1967) of SJ (Sweden) uses ASEA thyristors.

6 Evolution of switching power

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vice grew in a roughly linear fashion → 6–7. In 1976, BBC became the first European manufacturer to introduce neutron transmutation doping (as an alternative to doping with phosphorous atoms, neutrons would be irradiated into the silicon, converting some silicon atoms to phosphorous). This led to a very homogenous dopant concentration and permitted blocking voltages to advance to 4 kV.

In 1969, BBC acquired Sécheron and sought to consolidate this company's semiconductor activities with its own. Plans to build a joint manufacturing plant on Sécheron-owned land in Gland, Switzerland, fell through. However, a well-equipped and modern facility was opened at Lampertheim, Germany, in 1969. The following year the decision was made to concentrate all manufacturing activities there. Despite this, some of the Ennetbaden activities were transferred to Birr, Switzerland. Activities there were mostly focused on development and pilot production but small volumes of commercial manufacturing also occurred.

## HVDC

During the mercury-arc era, ASEA had maintained a position as undisputed leader in HVDC technology due to the high blocking voltages of its valves. Nevertheless, the company recognized that semiconductors were the way forward. The world's first commercial HVDC link, which dated to 1954, between the Swedish island of Gotland and the mainland was supplemented by an experimental semiconductor valve in 1967. The first commercial application of semiconductors for HVDC followed at the same location in 1970.[2]

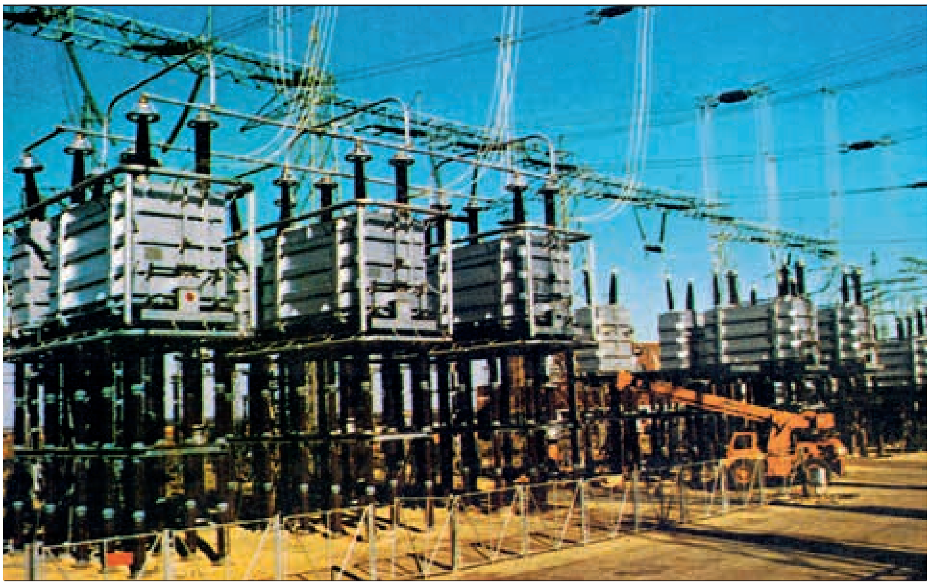
Footnote

2 See also A. Moglestue, "60 years of HVDC: ABB's road from pioneer to market leader," *ABB Review* 2/2014, pp 33–41.

**7 Milestones from ABB's 60 years in semiconductors**

| | |
|---|---|
| 1954 | Semiconductor development commences in Ludvika (ASEA) and Baden (BBC) |
| 1956 | BBC launches its first diode (100 V / 100 A) |
| 1961 | First BBC thyristor introduced (1,200 V / 100 A) |
| | Diodes reach 650 V / 200 A |
| 1969 | New plant opened in Lampertheim (BBC) |
| 1970 | Thyristors reach 3,000 V / 800 A |
| 1976 | Neutron transmutation doping introduced (BBC) |
| 1977 | New plant opened in Lenzburg (BBC) |
| 1980 | Thyristors reach 5 kV / 2 kA |
| 1988 | ASEA and BBC merge to form ABB |
| 1990 | Lampertheim plant is sold to IXYS |
| 1991 | ABB's semiconductor activities are concentrated in Lenzburg |
| 1992 | 4.5 kV / 600 A IGBT sample is presented |
| 1995 | First samples of 4.5 kV / 3 kA IGCT are presented |
| 1996 | GTO and diode offering reaches 4.5 kV / 4 kA |
| | 3.3 kV / 1.2 kA IGBT module for traction is introduced |
| | Bidirectional controlled thyristor (BCT) technology is introduced |
| 1997 | ABB launches a complete line of IGCTs from 500 kW to 9 MW |
| | 4.5 kV / 1.2 kA IGBT module for traction with integrated heat sink is introduced |
| | 2.5 kV / 700 A IGBT for HVDC Light® is introduced |
| 1998 | 5 inch IGBT wafer fab opens in Lenzburg |
| 2000 | 2.5 kV StakPak modules for HVDC light are introduced |
| 2001 | 1.2 kV – 1.7 kV thin wafer soft punch-through platform (SPT) IGBT is launched |
| 2003 | High-voltage SPT IGBT/diode platform is launched (with record-breaking safe operating area) |
| | 2.5kV – 3.3kV SPT-IGBT HiPak module platform is launched |
| 2005 | Lenzburg upgrades to 6 inch IGBT wafer fab |
| | 3.3kV-6.5kV SPT IGBT HV-HiPak module platform is launched |
| 2006 | 1.2 kV – 6.5 kV low loss SPT+ IGBT platform is launched |
| 2007 | High-power technology (HPT) IGCT platform is introduced |
| 2009 | 8.5 kV / 8 kA thyristor is introduced |
| | High-voltage BIGT technology is introduced |
| 2010 | Capacity extension is added at Lenzburg and Polovodice is acquired |
| | 4.5 kV StakPak modules for HVDC Light are introduced |
| | 10 kV IGCT technology is demonstrated |
| 2011 | BIGT is demonstrated for HVDC breaker |
| 2013 | Ground is broken for WBG lab in Baden-Dättwil Improved HiPak 2013 is introduced |
| | BGCT technology (IGCT with reverse-conduction diode on the same wafer) is introduced |
| 2014 | Enhanced-trench IGBT technology is introduced |
| | 60 years of semiconductors at ABB |

**8 The Cahora Bassa (Mozambique) HVDC project of 1970**



The disruptive innovation caused by the adoption of semiconductors for HVDC opened up the market to competition from other players. A consortium consisting of AEG, Siemens and BBC supplied the Cahora Bassa project in Mozambique in 1977 (1,920 MW, 1,450 km) → 8 and the Nelson River project in Canada in 1978 (900 MW, 940 km in 1985). Thyristor manufacturing for these projects was split equally among the three partners, with BBC's share being manufactured in Birr (Lampertheim was not set up for the processes required). This activity was transferred to a new plant in Lenzburg, Switzerland in 1979.

In response to the new competition, ASEA sought to consolidate its leadership by intensifying its thyristor development activities. In 1984, the company supplied the record-breaking Itaipu link in Brazil (780 km, 500 kV / 6,300 MW).

## The GTO

The major drawback of the thyristor is its need for auxiliary circuitry to support commutation when the receiving AC network is weak, or in a DC to DC conversion. This challenge was met by the gate turn-off thyristor (GTO). A GTO is similar to a thyristor, but can be turned off using a negative current at the gate. GTOs became especially popular in motor drive applications. Although GTOs were available from as early as 1960, both BBC and ASEA were late in entering this market. BBC introduced its first GTOs in 1980 (1,400 V). However, it was a technology transfer agreement with Toshiba in 1985 that finally permitted the company to catch up.

Despite this delayed start, ABB was in later years to become a world leader in GTO manufacturing, not least because many competitors had erroneously assumed the technology was heading for obsolescence (due to IGBT developments) and had prematurely ramped down their activities.

## The merger

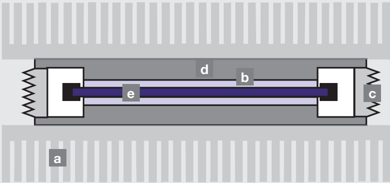
Following the merger of ASEA and BBC to form ABB in 1988, it was decided to concentrate all activities in Lenzburg. The Lampertheim facility was sold to IXYS in 1990 and that at Västerås was closed in 1991.

ABB's semiconductor manufacturing activities were vested in a subsidiary company, ABB Semiconductors Ltd. Previously, ABB had considered semiconductors a largely internal activity, with devices being developed and manufactured first and foremost to meet the requirements of other parts of the company. ABB Semiconductors broke with this paradigm and grew ABB's semiconductor market by actively selling semiconductors to external system manufacturers.

ABB Semiconductors' CEO, Anders Nilarp, soon earned himself a reputation as a charismatic manager, constantly seeking to motivate and empower employees. His continuous striving for higher quality

9 Cross-section of a pressure contact device

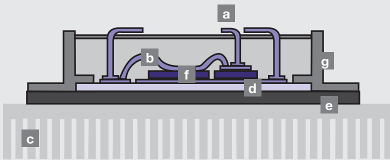
In pressure contact modules, the load current enters through one surface (d) and leaves through the opposing surface. Low electrical and thermal resitances of the contacts are assured through high mechanical pressure on those surfaces.




a Heat sink
b CTE compensation (Mo)
c Housing (ceramic)
d Copper
e Semiconductor

10 Cross-section of a HiPak IGBT module

In insulated housing modules, the semiconductor (f) is galvanically isolated from the heat sink (c). Electrical contacts within the module are provided by bonding wires.




a Power and control connections
b Bonding wire
c Heat sink
d Ceramic (usually AlN)
e Base plate (usually AlSiC)
f Semiconductor
g Housing

11 3.3 kV HiPak module launched in 2003

in both products and processes made ABB Semiconductors a finalist for the 1995 European Quality Award. In 1996 it was nominated "Supplier of the Year" by General Electric.

Nilarp also championed the semiconductor business within the ABB Group at a time that the Group saw its priorities elsewhere. His greatest achievement in this respect was gaining funds and approval for the new BiMOS (IGBT and diode) factory, which opened in Lenzburg in 1998.

## IGBT

An IGBT (insulated-gate bipolar transistor) is a switching device that can be controlled by applying a voltage rather than a current to the gate, hence greatly simplifying the design of gate drives. Another advantageous property lies in the IGBT's short-circuit capability. When the on-state voltage rises above a critical level, the device will intrinsically limit the current. An IGBT can thus survive exceptional operating conditions without requiring additional protective circuitry. All these factors allow for simpler converter designs.

> Following the merger of ASEA and BBC to form ABB in 1988, it was decided to concentrate all activities in Lenzburg.

A further advantage of IGBTs lies in their mechanical installation. GTOs and thyristors of higher ratings are pressure contact devices → 9, meaning the current flows "vertically" from one surface of the package to the other. To assure reliable electrical and thermal conductivity, devices are mounted in stacks at a specified pressure. Maintenance staff can thus not replace a failed device without dismantling an entire stack. In IGBT insulated modules, current flows through the module's external terminals, which are all arranged on the same side of the module → 10. The internal electrical contact to the devices is assured by bonded wires, whereas thermal conductivity is assured through the nonconducting base plate → 11. Both mechanical and electrical connections use bolts. Individual devices can thus be replaced with far greater ease. There are, however, applications that require press-pack modules (for example, redundancy requirements may rely on failed modules going into and remaining in short circuit). ABB's StakPak IGBT modules address these applications → 12.

As ABB's manufacturing facilities were initially not set up for the complexity of the IGBT manufacturing process, the company's early production relied on parts of the process being performed at external facilities. The 1998 completion

> A GTO is similar to a thyristor, but it can be turned off using a negative current at the gate.

12 2.5 kV StakPak Modules for HVDC light launched in 2000

13 IGCT modules for various power classes (1997)

of the BiMOS factory in Lenzburg finally enabled ABB to handle the entire IGBT production process in-house.

In the following years, with further technological improvements in terms of lower losses and higher robustness, IGBTs entered many markets previously dominated by GTOs, such as marine drives and railways, but also new applications such as converters for wind power, power-electronics-based transformers and the groundbreaking hybrid breaker for HVDC that ABB launched in 2013.[3]

### Thyristors and GTOs hold their own

Although one might be forgiven for assuming that the rapid advance of the IGBT would spell an equally rapid end to the GTO era, demand for these devices is still strong today. Indeed, development is ongoing.

In 1997, ABB launched a new GTO-based device: the IGCT (integrated gate-commutated thyristor). An IGCT is essentially a GTO with an integrated gate unit. The doping profile assures lower losses while an intense but brief current pulse assures a rapid turn-off ➔ 13.

The thyristor market too continues to thrive, as the device remains the unchallenged semiconductor of choice for high-power HVDC links. In 2009, ABB introduced a 150 mm, 8.5 kV thyristor for such projects.

An IGBT is a switching device that can be controlled by applying a voltage rather than a current to the gate, hence greatly simplifying the construction of gate drives.

Further strengthening its presence in the bipolar market, ABB acquired the Prague-based company, Polovodice, in 2010. Today, bipolar production occurs in both Prague and Lenzburg. In the same year, a further capacity enhancement was completed in Lenzburg for BiMOS and bipolar production. ABB thus has a strong position and manufacturing capability in both markets.

### Silicon carbide

Looking toward the future, ground was broken at the ABB Corporate Research Center in Baden-Dättwil, Switzerland, in 2013 for a research lab dedicated to wide-bandgap power-electronics material. SiC (silicon carbide) semiconductors, eg, offer lower losses than silicon and better tolerance to heat. ABB's predecessor companies had already researched SiC in the 1960s and 1990s, but understanding of the manufacturing techniques has since advanced to the point that such devices are genuinely becoming feasible.

### Ready for the future

The chain of the delivery of electrical power, spanning transmission, conversion and delivery, is embarking on an era of exciting changes. On the demand side this is being driven by the growth and integration of renewable energies and the greater emphasis on efficiency. But these demands would remain wishful thinking were it not for the progress at the semiconductor level that is making this revolution possible.

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**Footnote**

3 See also M. Callavik *et al*., "Breakthrough!: ABB's hybrid HVDC breaker, an innovation breakthrough enabling reliable HVDC grids." *ABB Review* 2/2013, pp. 7–13.

**Further reading**
H. Zeller, "The winning chips: History of power semiconductors at ABB." *ABB Review* 3/2008, pp. 72–78.