The Sixth Decade of the Thyristor

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***Abstract*—The invention of the Silicon Controlled Rectifier (SCR) in the late 1950s, today known as thyristor has led to the revolution in the control of electric power, i.e. in the field of power electronics. At present, about 70% of electric power is consumed by the process of power electronic equipments, and it is expected to grow up in the future. This paper is dedicated to the 50th anniversary of the thyristor. The first part of the paper is dealing with the history and the second with the evolution from SCR to IGCT and ETO and the main characteristics of several members of the thyristor family.**

***Index Terms*—Silicon Controlled Rectifier (SCR), thyristor, triac.**

I. Introduction

TODAY, it is inconceivable to think of living in a society without electricity. In today's modern society, almost everything runs on electrical power. The need for power processing is obvious.

Power Electronics, as an enabling technology is becoming more and more important and is the basis for many industrial processes, for the rational use of the energy, for new technologies in individual and mass transportation, areas that are rapidly growing requiring new concepts in order to fulfill cost, reliability and miniaturization. The impact of power electronics is perhaps equally striking in terms of our environment. Power electronics systems are expected to control up to 80 percent of all electricity used in USA by the year 2010 [1]. The fast development in power electronics was triggered by the invention of the thyristor, in 1957, or Silicon Controlled Rectifier (SCR) as called in that time.

The IEEE Dictionary defines SCR as "an alternative name for the reverse blocking triode thyristor". It is a four layer, three-terminal, solid-state device that controls current flow. It is made from single crystal, high-purity silicon (semiconductor) material. A *p*-type layer acts as an anode and an *n*-type layer acts as a cathode; the *p*-type layer closer to the cathode functions as a gate. It is a solid-state functional equivalent for the older gas-discharge or mercury-arc controlled rectifier known as thyratron.

In 1957 the three-terminal *p-n-p-n* device was introduced by GE as the Silicon controlled rectifier (SCR, later thyristor). This device became very soon the dominant control device in the power industry. The early history of this work (1954–1960), including the shorted-emitter and symmetrical switch (TRIAC), is described in the paper. The early work proved the need to employ, besides the basic vertical *p-n-p-n* layering, lateral *p-n* patterning and the use of the lateral geometry for three-terminal operation, shorted emitters, symmetrical switches (TRIACs), regenerative gate operation, and ultimately gate-turn-off switches.

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Once the SCR came onto the world stage, many people in various places played important roles in further developing it into the revolutionary device that it became. However, the name SCR was not the one chosen by GE for the device but rather some at GE chose the name "silicon controlled rectifier" or SCR. In July 1959, Westinghouse announced a solid-state controlled rectifier called "trinistor". By 1966, L. F. Stringer [2] and L. R. Tresino used the name thyristor. Some in Europe adopted the name thyristor more quickly than others elsewhere. This was partly due to IEC TC47 formed in 1960. It was several years before the name thyristor became universally accepted.

Early on, many people misjudged the role that the SCR would ultimately play. They considered it as being a tiny device capable of only a small power rating similar to the transistor. Power transistors were being developed at several places, but even a husky one was capable of controlling only 37 W compared with the 2-kW capacity of SCRs. The key missed by many people was the switching nature of SCRs, rather than the continuous-current mode of the transistor. The fast switching behavior of SCRs reduced the power loss that was dissipated into the rectifier device.

The prototype SCRs available in 1957 worked at 300 V and up to 7 A. The diameter of the junction was 3 mm, and the price was 60 USD each. The amount of control power required to trigger individual devices was about 15 mW.

Today we deal with whole family of thyristor based devices starting with classic SCR up to new complex devices with turn-off capabilities (IGCT [3] and ETO-Thyristors [4], [5]).

II. Brief Historical Evolution of Power Electronics

Officially, power electronics was born in 1901 by the invention of glass-bulb mercury-arc rectifier by Peter Cooper Hewitt of USA [6]. Then, it went through the eras of gas tube electronics in the 1930s and saturable core magnetic amplifiers in the 1940s. Hot cathode thyratron was introduced in 1926 and the ignitron rectifier in 1933. Power electronics applications began to spread and in 1930 the New York

Subway installs grid-controlled mercury-arc rectifier (3 MW) for DC drive. Then, in 1931 the German railways introduces mercury-arc cycloconverter for universal motor traction drive. In 1934 thyratron cycloconverter (synchronous motor 400 hp) was installed in Logan power station as a first variable frequency drive.

The present era of solid-state power electronics started with the introduction of thyristor or silicon controlled rectifier (SCR). Bell laboratories of USA published the historical paper on *p-n-p-n* triggering transistor in 1956 [7] of Moll (Fig. 1) et. al., and then, GE commercially introduced the thyristor in 1958. Since then, there has been a vast expansion of the technology with the research and development radiating in different directions as shown in the Fig. 2.

III. The Invention of the SCR

The invention of the bipolar transistor at BTL (1948) became a great stimulus for further investigation in semiconductor components in order to replace the bulky electronic tubes (vacuum, gas etc.) with much smaller and more efficient devices based on semiconductor technology.

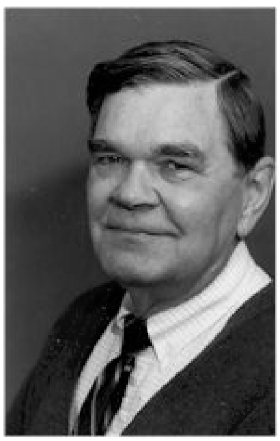


Fig. 1. John L. Moll.

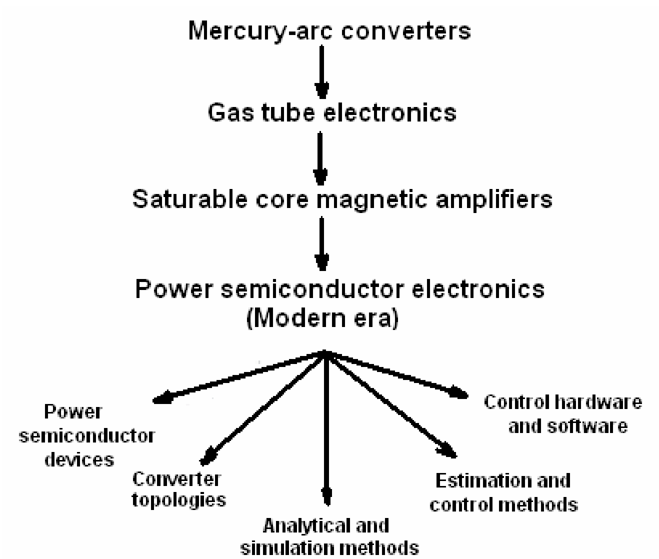


Fig. 2. Historical evolution of power electronics [8].

The Silicon Controlled Rectifier (SCR) or Thyristor was proposed by William Shockley in 1950. It was theoretically described in several papers by J. J. Ebers [9] and especially by J. L. Moll [7] and others at Bell Telephone Laboratories (BTL). In 1956 the SCR was developed by power engineers at General Electric (G.E.) led by Gordon Hall. The commercial version was developed in 1958 by G. E.'s Frank W. "Bill" Gutzwiller (Fig. 3).

The idea of the *p-n-p-n* switch was simulated by a circuit model, the Ebers' model [9], which is the center part of Fig. 3 between $A(+)$ at the bottom and $B(-)$ at the top. The idea of a *p-n-p-n* switch was that a *p-n-p* transistor (bottom) is driving an *n-p-n* (top) and, in turn, the *n-p-n* is driving the *p-n-p*. The collector of one, either one, drives the base of the other. This is guaranteed to yield instability. When the voltage from A to B reaches avalanche breakdown of the "*n-p*" diode (center of Fig. 4) and sufficient current flows in emitter shunt resistors R_1 and R_2 to bias on the emitters, the sum of α_{PNP} and α_{NPN} approaches unity, and to maintain current continuity switching occurs to low voltage. The two collectors switch from reverse to forward voltage, and to the "on" state of the A-B switch, which, of course, is still not a *p-n-p-n* switch in a single "slab" of *Si*. The question was: could such a switch be built, and would it, indeed, work?

In early autumn 1954, J. M. Goldey, from MIT, and Nick Holonyak Jr. (Fig. 5), from Bardeen's laboratory – Urbana, joined John Moll's BTL group with the specific task of constructing a Si *p–n–p–n* switch, that potentially could compete with a two terminal gas tube designed to be used, perhaps in large numbers, as a telephone crosspoint switch [10].

Not knowing, in the beginning (1954), the role of traps (defects) in governing the injection efficiency of Si *p-n* junctions, they followed pretty much Jim Ebers' two-transistor model for the proposed *p-n-p-n* switch [9]. For test reasons, multiple terminal structures with resistive paths were planned, including if necessary external resistors, to provide shunt leakage and variable bias at the *p-n-p-n* emitters, just as suggested in Fig. 4 by the five components stacked vertically from A to B (+ to -) within the diamond-shaped rectifier bridge. At avalanche breakdown of the center *n–p* collector

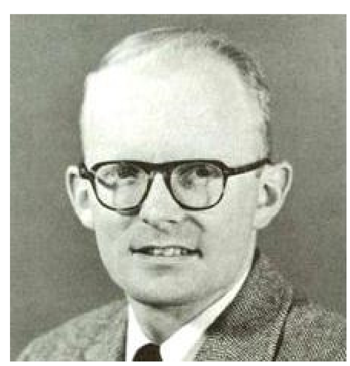


Fig. 3. Frank "Bill" Gutzwiller.

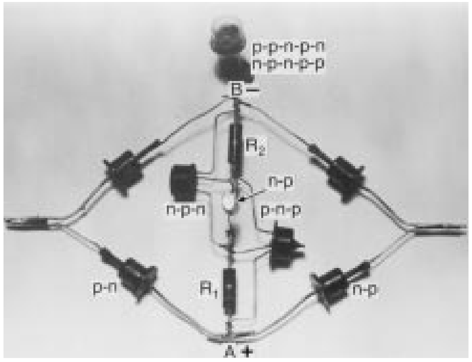


Fig. 4. Circuit model of a p-n-p-n switch made at GE [9].

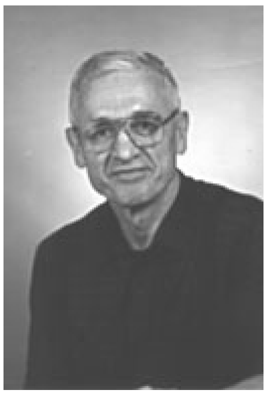


Fig. 5. Nick Holonyak Jr.

junction (in the circuit model the diode at the center of Fig. 4) a result shunt current provides emitter bias and forces the device to switch from high reverse bias (voltage) to low forward bias to maintain continuity of current, all a consequence of [9]. This is the key to the switch operation, the alpha sum approaching unity (and thus the need to switch).

Based on these ideas, they built relatively quickly (1954–1955) three and even four terminal Si *p-n-p-n* switches. At that time they were pleasantly surprised to find that the we didn't need shunt leakage or resistors around the emitter junctions (as in Fig. 4) are not needed because of the saturable traps inherent in the junctions [9]. Simultaneously (1954–55) their colleague from BTL, Mort Prince was observing and independently confirming the effect of defects (traps) on the injection behavior (*I-V* characteristics) of diffused junction Si rectifiers [11]. Because of the traps in the junction transition region, at lower current levels the diffused Si rectifiers, as well as the two emitters of the *p-n-p-n* switch, behaved essentially as *p-i-n* [12], and not *p–n* junctions. Not only a new device but also a new technology was introduced. In 1955 in BTL three forms of Si *p-n-p-n* switch were proposed (Fig. 6). The switch shown in Fig. 6b later (at GE in 1957) became the Silicon controlled rectifier.

The SCR became a huge success for General Electric. It was reported in the business press by Business Week in their December 28th edition headlined *New way to Change AC to DC*. Commercial SCR were on the market in early 1958 [14] and Bill Gutzwiller was responsible for their technical and promotional support.

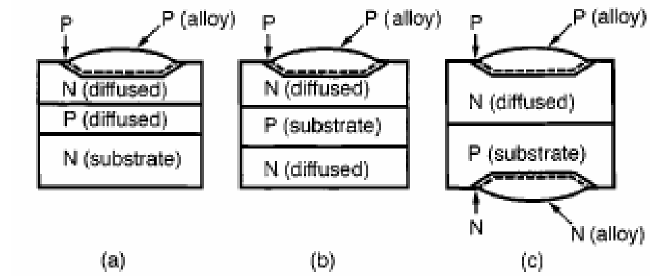


Fig. 6. Schematic cross sections [10] of three forms of Si p-n-p-n switches made at Bell Telephone Laboratories (BTL) in 1955. The switch shown in (b) became the Si controlled rectifier (SCR) at GE in 1957.

The demonstration of a SCR prototype from 1957 is shown in Fig. 7.

In the Spring of 1958, at a meeting in Syracuse, Holonyak and Aldrich were asked to develop a full wave controllable switch which could operate down to low forward voltages [15]. After the meeting Holonyak and Aldrich stayed on and devised a solution. Their prototype was made from a parent N-type wafer in a single diffusion step using gallium and phosphorus simultaneously Fig. 8.

Aldrich and Holonyak developed and described several bidirectional *p-n-p-n* devices having two, three, and more terminals. These devices utilized the "shorted emitter," an innovation of theirs which not only made single-chip bidirectional *p-n-p-n* devices possible, but also led to improvements in the characteristics of unidirectional devices (such as SCR's) [17].

The shorted-emitter did more than make possible the symmetrical (ac) switch. It made it possible to set, by design, a

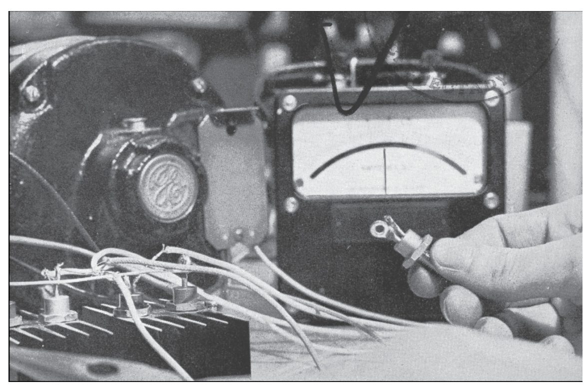


Fig. 7. Demonstration of prototype SCR in 1957 [13].

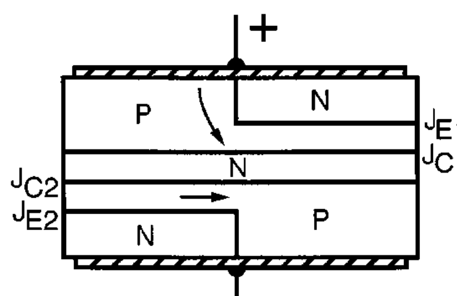


Fig. 8. Schematic cross section of a shorted-emitter symmetrical switch (DIAC) that in either polarity operates as a p-n-p-n switch [16].

certain current level before a *p-n-p-n* device switched, i.e. before the emitters became functional and thus $\alpha_{PNP} + \alpha_{NPN} \rightarrow 1$.

Adding to the structure a control electrode they obtained a controllable device called TRIAC (Triode alternating current switch). The first commercial Triacs were the *SC40* and *SC45*, rated 6 amperes and 10 amperes.

The thyristor era has begun.

IV. The Thyristor Evolution

From the invention of the thyristor up to present day's the power electronics has been continuing its growth centering on inverter and converters as its key system topologies. This has been accelerated by several evolutionary changes and breakthroughs achieved in the areas of power semiconductor device physics and process technology. The evolution of power electronics was directly related to the evolution of power electronics devices. The later can be categorized into four generations. The first generation spanning around 17 years, when thyristor-type devices dominated, is defined as the thyristor era. In the second generation, lasting about 10 years, self-controlled power devices (BJTs, power MOSFETs, and GTOs) appeared along with power ICs, microprocessors and ASIC chips. In the third generation, the most dominant power device, the IGBT, was introduced and became an important part in power electronics history. In addition, SITs, Intelligent power modules (IPMs), and powerful DSPs appeared. Finally, in the current or fourth generation, new devices, such as IGCTs, ETOs, cool MOSs and converters in integrated form as power electronic building block (PEBB) were introduced. The new materials are investigated and the technology is moving towards Silicon Carbide Devices.

The comparison of the characteristics of some power semiconductor devices with the year of their appearance is given in Table I.

Today the SCR family consists of:

- Thyristor (SCR);
- ASCR — Asymmetrical SCR;
- RCT — Reverse Conducting Thyristor;
- LASCR — Light Activated SCR (or LTT — Light triggered thyristor);
- DIAC & SIDAC — Both forms of trigger devices;
- BOD — Breakover Diode or Diode Thyristor (A gateless thyristor triggered by avalanche current);
- TRIAC — Triode for Alternating Current (A bidirectional switching device);
- BRT — Base Resistance Controlled Thyristor;
- SITh — Static Induction Thyristor (or FCTh — Field Controlled Thyristor) containing a gate structure that can shut down anode current flow;
- LASS — Light Activated Semiconducting Switch;
- GTO — Gate Turn-Off thyristor;
- MCT — MOS Controlled Thyristor (has two additional FET structures for on/off control);
- IGCT — Integrated Gate Commutated Thyristor;
- ETO — Emitter Turn-Off Thyristor.

The last four are thyristors with forced turn-off capabilities.

Until the appearance of the IGCT the main disadvantage of the thyristor was its incapability to be turned off by control signal. The GTO, invented in 1962, had high voltage drop in conducting state and needed very high turn-off gate current. As a result of intensive work, in 1996 and 1998 two new components, capable to turn off at any time, appeared. In 1983 the IGBT was introduced, but it suffers from limited voltage and current capabilities and high on-state voltage. The integrated gate turn-off thyristor (IGCT) appeared in 1996, and emitter turn-off thyristor (ETO), combining the best performance characteristics of IGBT and IGCT, appeared in 1998. Some of their characteristics are presented in Table I. Both components are using the unity-gain turn-off condition [18].

The key to achieve a hard-driven or unity-gain turn-off condition lies in the gate current commutation rate. A rate as high as 6 kA/μs is required for 4-kA turn-off [18]. The method to achieve this condition, used in IGCT, is to hold the gate loop inductance low enough (3 nH) so that a DC gate voltage less than the breakdown voltage of the gate–cathode junction (18 to 22 V) can generate a slew rate of 6 kA/μs. On the other hand the method used to achieve unity gain in the ETO thyristor is to insert an additional switch in series with the cathode of the GTO.

The key disadvantage of the IGCT approach (Fig. 9a) is the high cost associated with the low-inductance housing design

TABLE I

Comparison of Power Semiconductor Devices [19], [20], [21]

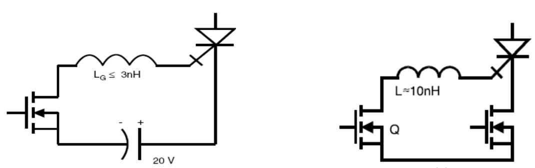
Device type	Year made available	Rated voltage	Rated current	Rated frequency	Rated power	Forward voltage
Thyristor (SCR)	1957	7 kV	3.5 kA	500 Hz	100's MW	1.5–2.5 V
Triac	1958	1 kV	100 A	500 Hz	100's kW	1.5–2 V
GTO	1962	4.5 kV	3 kA	2 kHz	10's MW	3–4 V
BJT (Darlington)	1960 s	1.2 kV	800 A	10 kHz	1 MW	1.5–3 V
MOSFET	1976	500V	50 A	1MHz	100 kW	3–4 V
IGBT	1983	1.2 kV	400 A	20 kHz	100's kW	3–4 V
SIT	1985	1.2 kV	300 A	100 kHz	10's kW	10–20 V
SITH	1988	1.5 kV	300 A	10 kHz	10's kW	2–4 V
MCT	1988	3 kV	2 kA	20–100 kHz	10's MW	1–2 V
IGCT	1996	6 kV	4 kA	1 kHz	100's MW	1.5–3 V
ETO	1998	6 kV	5 kA	2 kHz	100's MW	1–2.5 V

for the GTO and the low inductance and high current design for the gate driver.

Because of the use of hybrid approach based on conventional GTO, ETO devices (Fig. 9b) have clear advantages in terms of forward voltage drop, cost and gate drive power requirement over IGCTs. ETO devices also have two other advantages when compared with the IGCT. One is its feasibility of having a forward biased safe-operating area (FBSOA), and the other is its simplicity in overcurrent protection. Some comparative diagrams for the IGBT, IGCT and ETO's characteristics are given in Fig. 10.

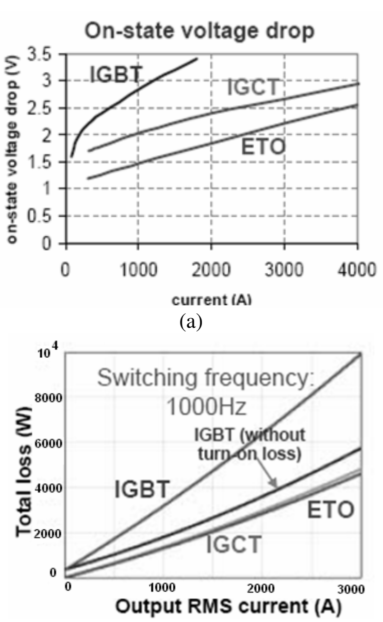
V. Comments and Conclusions

The power semiconductor devices discussed thus far are exclusively based on silicon material. Silicon has enjoyed a monopoly for a long period of time in both power and microelectronic devices, and this will remain so in the near future. However, new types of materials, such as gallium arsenide, silicon carbide, and diamond (in synthetic thin-film form), show tremendous promise for future generations of devices. SiC devices are particularly interesting for high-voltage, high-power applications because of their large band gap, high carrier mobility, and high electrical and thermal conductivities compared to silicon material. These properties permit devices with higher power capability, higher switching frequency, lower conduction drop, higher junction temperature. However, processing and fabrication of these materials are difficult and expensive. Most of the power devices based on SiC have been tried successfully in the laboratory. SiC-based power MOSFETS with *Tj* up to 350°C appear particularly interesting as replacements for medium-power silicon IGBTS in the future. Today, SiC-based high-voltage Schottky diodes (300–1700 V, 2–10 A) with close to a 1-V drop and negligible leakage and recovery currents are commercially available.



(a) (b)

Fig. 9. Circuit representation: (a) IGCT, (b) ETO [18].



(b)

Fig. 10. Comparisons of the device's (a) on-state voltage drop, (b) total losses in a PWM voltage source converter with sinusoid output [19].

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