Power Electronics
Thyristors GTOs and IGBTs - simplified
Sources

- M. D. Singh, Power Electronics, 2008
  - [http://books.google.pl/books?id=0_D6gfUHjecE](http://books.google.pl/books?id=0_D6gfUHjecE)

- J.S.Chitode, Power Electronics, 2008
  - [http://books.google.pl/books?id=VMC5AYf1YFwC](http://books.google.pl/books?id=VMC5AYf1YFwC)

- NPTEL Project (India)
  - [http://nptel.ac.in/downloads/108105066](http://nptel.ac.in/downloads/108105066)

Power transistors

- Bipolar junction transistors (BJT)
- Metal-oxide semiconductor field-effect transistors (MOSFET)
- Static Induction transistors (SIT)
- Insulated-gate bipolar transistors (IGBT)
Half-controlled device — Thyristor

- Another name: SCR—silicon controlled rectifier
- Thyristor Opened the power electronics era
  - 1956, invention, Bell Laboratories
  - 1957, development of the 1st product, GE
  - 1958, 1st commercialized product, GE
  - Thyristor replaced vacuum devices in almost every power processing area.
- Still in use in very high power situation. Thyristor still has the highest power-handling capability.

Appearance and symbol of thyristor
Structure and equivalent circuit of thyristor

• Structure

• Equivalent circuit

Physics of thyristor operation

- Equivalent circuit: A pnp transistor and an npn transistor interconnected together.
- Positive feedback
- Trigger
- Can not be turned off by control signal
- Half-controllable
Quantitative description of thyristor operation

\[ I_A = \frac{a_1 I_G + I_{CBO1} + I_{CBO2}}{1 - (a_1 + a_2)} \]  (2-5)

When \( I_G = 0 \), \( a_1 + a_2 \) is small.
When \( I_G > 0 \), \( a_1 + a_2 \) will approach 1, and \( I_A \) will be very large.

Other methods to trigger thyristor

- **UNDESIRED**
  - High voltage across anode and cathode—avalanche breakdown
  - High rising rate of anode voltage — \( dv/dt \) too high
  - High junction temperature

- **USEFUL**
  - Light activation
Light triggering

- In this method light particles (photons) are made to strike the reverse biased junction, which causes an increase in the number of electron hole pairs and triggering of the thyristor.
- For light-triggered SCRs, a slot (niche) is made in the inner P-layer.
- When it is irradiated, free charge carriers are generated just like when gate signal is applied b/w gate and cathode.
- Pulse light of appropriate wavelength is guided by optical fibers for irradiation.
- If the intensity of this light thrown on the recess exceeds a certain value, forward-biased SCR is turned on. Such a thyristor is known as light-activated SCR (LASCR).
- Light-triggered thyristors is mostly used in high-voltage direct current (HVDC) transmission systems.

Static characteristics of thyristor

- Blocking when reverse biased, no matter if there is gate current applied.
- Conducting only when forward biased and there is triggering current applied to the gate.
- Once triggered on, will be latched on conducting even when the gate current is no longer applied.
- Turning off: decreasing current to be near zero with the effect of external power circuit.
- Gate I-V characteristics.
Switching characteristics of thyristor

- **Turn-on transient**
  - Delay time $t_d$
  - Rise time $t_r$
  - Turn-on time $t_{gt}$

- **Turn-off transient**
  - Reverse recovery time $t_{rr}$
  - Forward recovery time $t_{gr}$
  - Turn-off time $t_q$

Specifications of thyristor

- Peak repetitive forward blocking voltage $U_{DRM}$
- Peak repetitive reverse blocking voltage $U_{RRM}$
- Peak on-state voltage $U_{TM}$
- Average on-state current $I_{T(AV)}$
- Holding current $I_H$
- Latching up current $I_L$
- Peak forward surge current $I_{TSM}$
- $du/dt$
- $di/dt$
The family of thyristors

- Fast switching thyristor — FST
- Triode AC switch — TRIAC (Bi-directional triode thyristor)
- Reverse-conducting thyristor — RCT
- Light-triggered (activated) thyristor — LTT

Typical fully-controlled devices

- Gate-turn-off thyristor — GTO
- Giant transistor (bipolar) — GTR
- Power metal-oxide-semiconductor field effect transistor — Power MOSFET
- Insulated-gate bipolar transistor — IGBT

Features
- IC fabrication technology, fully-controllable, high frequency

Applications
- Begin to be used in large amount in 1980s
- GTR is obsolete and GTO is also seldom used today.
- IGBT and power MOSFET are the two major power semiconductor devices nowadays.
Gate-turn-off thyristor—GTO

■ Major difference from conventional thyristor:
  The gate and cathode structures are highly integrated, with various types of geometric forms being used to layout the gates and cathodes.

Physics of GTO operation

■ The basic operation of GTO is the same as that of the conventional thyristor.

■ The principal differences lie in the modifications in the structure to achieve gate turn-off capability
  □ Large \( \alpha_2 \)
  □ \( \alpha_1 + \alpha_2 \) is just a little larger than the critical value 1.
  □ Short distance from gate to cathode makes it possible to drive current out of gate.
Characteristics of GTO

- Static characteristics
  - Identical to conventional thyristor in the forward direction
  - Rather low reverse breakdown voltage (20-30V)
- Switching characteristics

Specifications of GTO

- Most GTO specifications have the same meanings as those of conventional thyristor.
- Specifications different from thyristors’
  - Maximum controllable anode current $I_{ATO}$
  - Current turn-off gain $\beta_{off}$
  - Turn-on time $t_{on}$
  - Turn-off time $t_{off}$
Insulated-gate bipolar transistor — IGBT

Combination of MOSFET and GTR

**GTR:**
- low conduction losses (especially at larger blocking voltages),
- longer switching times, current-driven

**MOSFET:**
- faster switching speed, easy to drive (voltage-driven),
- larger conduction losses (especially for higher blocking voltages)

**Features**
- On-state losses are much smaller than those of a power MOSFET, and are comparable with those of a GTR
- Easy to drive — similar to power MOSFET
- Faster than GTR, but slower than power MOSFET

**Application**
- The device of choice in 500-4500V applications, at power levels of several kW to several MW

Structure and operation principle of IGBT

**Basic structure**

- Emitter
- Gate
- Collector

- Drift region
- Buffer layer
- Injecting layer

**Multiple cell structure**
- Basic structure similar to power MOSFET, except extra p region
- On-state: minority carriers are injected into drift region, leading to conductivity modulation
- Compared with power MOSFET: slower switching times, lower on-resistance useful at higher voltages (up to 4500V)
Equivalent circuit and circuit symbol of IGBT

Equivalent circuit

Circuit symbol

G
E
C
+
-
+-
+
-
ID RN
IC
VJ1
IDRon
Drift region resistance

Static characteristics of IGBT

Active region
Saturation region (On region)
Reverse blocking region
Cut-off (forward blocking) region
Switching characteristics of IGBT

- IGBT turn-on is similar to power MOSFET turn-on
- The major difference between IGBT turn-off and power MOSFET turn-off:
  - There is current tailing in the IGBT turn-off due to the stored charge in the drift region.

Parasitic thyristor and latch-up in IGBT

- Main current path pnp transistor and the parasitic npn transistor compose a parasitic thyristor inside IGBT.
- High emitter current tends to latch the parasitic thyristor on.
- Modern IGBTs are essentially latch-up proof
Specifications of IGBT

- Collector-emitter breakdown voltage $U_{CES}$
- Continuous collector current $I_C$
- Peak pulsed collector current $I_{CM}$
- Maximum power dissipation $P_{CM}$

- The IGBT has a rectangular SOA with similar shape to the power MOSFET.
- Usually fabricated with an anti-parallel fast diode

Examples of commercial IGBT

<table>
<thead>
<tr>
<th>Part number</th>
<th>Rated max voltage</th>
<th>Rated avg current</th>
<th>$V_f$ (typical)</th>
<th>$t_r$ (typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single-chip devices</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HGTG32N60E2</td>
<td>600V</td>
<td>32A</td>
<td>2.4V</td>
<td>0.62μs</td>
</tr>
<tr>
<td>HGTG30N120D2</td>
<td>1200V</td>
<td>30A</td>
<td>3.2A</td>
<td>0.58μs</td>
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<tr>
<td><strong>Multiple-chip power modules</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CM400HA-12E</td>
<td>600V</td>
<td>400A</td>
<td>2.7V</td>
<td>0.3μs</td>
</tr>
<tr>
<td>CM300HA-24E</td>
<td>1200V</td>
<td>300A</td>
<td>2.7V</td>
<td>0.3μs</td>
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</tbody>
</table>
OTHER NEW POWER ELECTRONIC DEVICES

Other new power electronic devices

- Static induction transistor — SIT
- Static induction thyristor — SITH
- MOS controlled thyristor — MCT
- Integrated gate-commutated thyristor — IGCT
- Power electronic devices based on wide band gap semiconductor material
Static induction transistor — SIT

- Another name: power junction field effect transistor — power JFET
- Features
  - Majority-carrier device
  - Fast switching, comparable to power MOSFET
  - Higher power-handling capability than power MOSFET
  - Higher conduction losses than power MOSFET
  - Normally-on device, not convenient (could be made normally-off but with even higher on-state losses)

Static induction thyristor—SITH

- other names
  - Field controlled thyristor—FCT
  - Field controlled diode
- Features
  - Minority-carrier device, a JFET structure with an additional injecting layer
  - Power-handling capability similar to GTO
  - Faster switching speeds than GTO
  - Normally-on device, not convenient (could be made normally-off but with even higher on-state losses)
MOS controlled thyristor—MCT

- Essentially a GTO with integrated MOS-driven gates controlling both turn-on and turn-off that potentially will significantly simplify the design of circuits using GTO.
- The difficulty is how to design a MCT that can be turned on and turned off equally well.
- Once believed as the most promising device, but still not commercialized in a large scale. The future remains uncertain.

Integrated gate-commutated thyristor — IGCT

- Introduced in 1997 by ABB
- Actually the close packaging of GTO and the gate drive circuit with multiple MOSFETs in parallel providing the gate currents
- Short name: GCT
- Conduction drop, gate driver loss, and switching speed are superior to GTO
- Competing with IGBT and other new devices to replace GTO
Power electronic devices based on wide band-gap semiconductor material

$E_4$ .................................................................

$E_3$ .................................................................

$E_2$ .................................................................

$E_1$ .................................................................

Band gap

Energy levels of an independent atom

Energy bands of an atom in a crystal structure

Properties of semiconductor materials with potential for power devices

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>GaAs</th>
<th>GaP</th>
<th>2H-GaN</th>
<th>AlN</th>
<th>3C-SiC</th>
<th>4H-SiC</th>
<th>6H-SiC</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band gap at 300K (eV)</td>
<td>1.12</td>
<td>1.43</td>
<td>2.26</td>
<td>3.44</td>
<td>6.28</td>
<td>2.36</td>
<td>3.26</td>
<td>3.1</td>
<td>5.45</td>
</tr>
<tr>
<td>Relative dielectric constant</td>
<td>11.8</td>
<td>12.8</td>
<td>11.1</td>
<td>9.5</td>
<td>8.5</td>
<td>9.6</td>
<td>10.3</td>
<td>10.3</td>
<td>5.5</td>
</tr>
<tr>
<td>Breakdown electric field (MV/cm)</td>
<td>0.3</td>
<td>0.4</td>
<td>1.3</td>
<td>3.3</td>
<td>12</td>
<td>1.2</td>
<td>2.0</td>
<td>2.4</td>
<td>10</td>
</tr>
<tr>
<td>Electron mobility at 300K (cm²/V·s)</td>
<td>1350</td>
<td>8500</td>
<td>350</td>
<td>900</td>
<td>300</td>
<td>900</td>
<td>720</td>
<td>370</td>
<td>2200</td>
</tr>
<tr>
<td>Maximum operating temperature (K)</td>
<td>300</td>
<td>460</td>
<td></td>
<td>873</td>
<td></td>
<td>1240</td>
<td>1100</td>
<td></td>
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</tr>
<tr>
<td>Melting temperature (°C)</td>
<td>1415</td>
<td>1238</td>
<td></td>
<td></td>
<td></td>
<td>Sublime &gt;&gt;1800</td>
<td>Sublime &gt;&gt;1800</td>
<td>Phase change</td>
<td></td>
</tr>
</tbody>
</table>
Physical Properties of Silicon Carbide

SiC overview

- Unipolar devices:
  - Existing – diodes,
  - Under development – JFET-based
- Bipolar devices
  - unavailable
- Being developed in LUT also
- Major issues:
  - defects (micropipes after etching)
  - High material cost
GaN and diamond

- GaN has much more potential than SiC to achieve higher switching frequency.
- Manufacturing of single crystal GaN material is still unsolved. But fabrication techniques of GaN devices based on substrates of other crystal material have major break enough in recent years.
- Commercialized GaN SBD (Shottky) has been available since 2007 and GaN MOSFET has been reported frequently by recent technical papers.
- Diamond is the material with the greatest potential for power devices.
- The state of diamond device technology is primitive compared to that of SiC and GaN. The method of fabricating single crystal wafer and the technique for doing selective diffusion of impurities and selective etching are still major obstacles.

Power integrated circuit and power module

Monolithic integration: power integrated circuit
- High voltage integrated circuit (HVIC)
  - (Lateral high-voltage devices fabricated with conventional logic-level devices)
- Smart power integrated circuit (Smart power IC, SPIC, Smart switch)
  - (Vertical power devices onto which additional components are added without changing the vertical power devices process sequence)

Packaging integration: power module
- Ordinary power module: just power devices packaged together
- Intelligent power module (IPM): power devices, drive circuit, protection circuit
- Integrated power electronics Module (IPEM): power devices, drive circuit, protection circuit, control circuit

For a high power equipment, more than one module may be needed, in which case the modules are also called Power electronics building blocks (PEBB)
Three major challenges to integration

- Electrical isolation of high-voltage components from low-voltage components
- Thermal management – power devices usually at higher temperatures than low-voltage devices
- Electro-magnetic interference (EMI) of power circuit to information circuit
Review of device classifications

- **Power electronic devices**
  - Current-driven (current-controlled) devices: thyristor, GTO, GTR
  - Voltage-driven (voltage-controlled) devices (Field-controlled devices): power MOSFET, IGBT, SIT, SITH, MCT, IGCT
  - Pulse-triggered devices: thyristor, GTO
  - Level-sensitive (Level-triggered) devices: GTR, power MOSFET, IGBT, SIT, SITH, MCT, IGCT
  - Uni-polar devices (Majority carrier devices): SBD, power MOSFET, SIT
  - Bipolar devices (Minority carrier devices): ordinary power diode, thyristor, GTO, GTR, IGCT, IGBT, SITH, MCT
  - Composite devices: IGBT, SITH, MCT

Comparison of the major types of devices

**Power-handling capability**

- MOSFETs
- IGBTs
- GTOs (being challenged by IGCTs, IGBTs etc.)
- Thyristors
Comparison of the major types of devices

Summary of major devices
- Power MOSFET (for power level less than 10KW)
- IGBT (for power level from several KW up to 10MW)
- Thyristor (for power level higher than 10MW)
- Devices based on wide band-gap materials are very promising
THE END
... and they lived happily ever after

Thank you for your attention
Dziękuję za uwagę
Gracias por su atención
Спасибо за ваше внимание