ELEC-E8421
Components of Power Electronics

Junction Field Effect Transistors (JFET)
High Electron Mobility Transistor (HEMT)
Vertical JFETs

- First vertical JFETs made of silicon in 80s were called Static Induction Transistors in Japan (SIT) and had vertical structure. Also enhancement mode (normally off) versions were made.
- In 2006 first vertical JFETs were manufactured of SiC.
- First vertical GaN JFETs were made in 2012 and are claimed to have avalanche capability.

Detailed cross-section view of surface gate Si JFET

Detailed cross-section view of buried gate Si JFET

Detailed cross-section view of vertical GaN JFET
GaN High Electron Mobility Transistor (HEMT)

- The electrons from AlGaN move to the GaN layer below and form there two dimensional electron gas (2DEG). Schottky junction of metal gate forms depletion region that can control continuity of the 2DEG and thus the resistance between source and drain.
- Both enhancement mode (normally off) and depletion mode (normally on) devices are available. Enhancement requires biasing the gate region by immobile negative charges (fluoride ions).
- Usually GaN is grown epitaxially on silicon wafer as this is the lowest cost alternative.
**GaN High Electron Mobility Transistor (HEMT)**

- GaN HEMTs are lateral devices, no body diode. However, even the enhancement mode (normally off) HEMTs channel will conduct with $U_{GS} = 0$ V when $U_{DS}$ is less than $-2$ V…$-3$ V.
- Lower gate voltage, 4…5 V is recommended for enhancement GaN HEMTs than for silicon MOSFETs that typically need 10…15 V gate voltage. GaN gate has leakage current $\approx 1$ mA.
GaN High Electron Mobility Transistor (HEMT)

- Very fast switching, up to 10 MHz range. Careful design is needed in order to minimize the stray inductances when high currents are switched off fast, for example in less than 10 ns.
- GaN HEMT's $R_{DS}$ increases slightly less with temperature than the silicon MOSFET's resistance.
- Could operate at higher temperatures than silicon components but at the moment cannot tolerate more than 150 °C.
- Poor avalanche tolerance. Thus, care has to be taken to avoid overvoltages.
- GaN HEMT reliability issues such as threshold voltage variation due to gate trapped charges seem to have been solved but long time reliability is still naturally unknown.
GaN High Electron Mobility Transistor (HEMT)

- First GaN depletion mode (normally on) HEMT on market by International Rectifier in 2009
- First GaN enhancement mode (= normally off) HEMTs were on market in 2010 by EPC.
- Today (2015) voltage ratings are up to 650 V and current ratings up to 100 A for enhancement mode HEMTs.
- Available as padded or ball grid array packages
- Lots of different acronyms used by manufacturers for their components (e-GaN FET, GIT, e-HEMT, HFET, etc) but the differences in their internal structure are largely unknown
Cascode connections

- Advantages: Speed of the fast low voltage component and high voltage rating of the main component
- Disadvantages: Additional conduction loss of low voltage component

- Emitter Switched Bipolar Transistor (ESBT)
  - T1 is npn transistor
  - T2 is low voltage MOSFET

- T1 is depletion mode JFET
- T2 is low voltage MOSFET

- Emitter Turn-Off (ETO) Thyristor (close relative of IGCT, requires high GTO gate current rating)
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Components of Power Electronics
Insulated Gate Bipolar Transistor (IGBT)
Insulated Gate Bipolar Transistor (IGBT)

- IGBT is MOSFET with n-layer added on the drain side – Note the parasitic thyristor!

Detailed cross-section view of IGBT
Non punch-through (NPT) type

Equivalent circuit of IGBT

IEC circuit symbol
IGBT

- Easy to control ( = MOSFET)
- Small voltage drop (2 … 3 V) at nominal current
- High switching frequency, 5 … 20 … 50 kHz depending of target application
- Good voltage rating (Up to 6,5 kV)
- Good current rating (Up to 3600 A)
- IGBT has no body diode (and its problems). Usually separate optimized diode chip, sometimes even SiC Schottky one, is added to the package
- Short circuit current is limited to 5 … 6 * I_N
- Short circuit withstand time \( t_p = 10 \mu s \) typically
- At the moment IGBT is the most common transistor for applications requiring more than 600 V rating
PT and NPT structures

• PT = Punch through
  – Higher doped n-type buffer layer as field stopper at the collector side p-n junction
  – Used especially when the IGBT is made using epitaxially grown silicon as it minimizes the thickness of the component
  – Common especially in low voltage (less than 600 V) IGBTs

• NPT = Non punch through
  – Long weakly doped n-layer, the depletion region does not extend to the collector p-n junction
  – Better short circuit behavior as the short circuit current is limited to lower values
  – Voltage drop increases with increasing temperature making parallel connection easy
Example of gate control circuit

- $R_{\text{off}}$ & C
  - Turn-off $\frac{di}{dt}$ and $\frac{du}{dt}$ limitation

- $R_{\text{on}}$
  - Turn-on $\frac{di}{dt}$ limitation

Reduction of IGBT switching losses through separate turn-on and turn-off optimization
Reverse blocking IGBT (RB-IGBT)

- Symmetrical blocking voltage characteristics
- Advantages
  - Smaller conduction losses than IGBT with series diode
  - Current can flow in one direction
  - Current can be blocked in both directions
  - Matrix converter can be made with 18 RB-IGBTs

Matrix converter
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Components of Power Electronics

Other transistors
Other semiconductor components

- **MESFET (Metal Semiconductor FET)**
  - JFET having Schottky junction instead of p-n junction
  - Used in radio frequency amplifiers (tens of GHz)

- **HBT (Heterojunction Bipolar Transistor)**
  - Different semiconductor materials are used for the emitter-base junction and the base-collector junction, thus creating a heterojunction.
  - Used in radio frequency amplifiers (tens of GHz)

- **MCT (MOS Controlled Thyristor)**
  - Much hype about MCTs at the end of 90s but high switching losses restricted its use in most applications. Today quite obsolete.
MCT

Detailed cross-section view of MC-thyristor (p-channel type)  Circuit symbol
MCT

• Switch ON
  – $U_{GK} < 0$
  – P-channel MOSFET conducts base current to the npn transistor
  – Thyristor turns on

• Switch OFF
  – $U_{GK} > 0$
  – P-channel MOSFET turns off and n-channel MOSFET turns on
  – n-gate of thyristor (base of pnp transistor) is shorted causing the pnp part to turn off
  – Npn transistor part turns off slowly
Bilateral MOSFET

- Can be made by connecting two MOSFETs together
- The gate and source are floating in respect of the potentials of drains 1 and 2
- Used as semiconductor relay
Smart power

• One smart semiconductor chip or module can contain
  – Power transistors and their gate drivers
  – Current, voltage and temperature measurements
  – Protection for over current, over voltage and over temperature
  – Control circuits (Digital/Analog)
  – Serial communication interface

• Used for well-defined specific purposes
  – Switched mode power supplies (SMPS)
  – Smart relays (for example automobile CAN-operated relays for lights and other devices)
  – Small motor drives (fans, hard disk drives, DVD players, toys, vacuum cleaners, etc.)
  – Gate drivers of IGBTs and MOSFETs
Voltage and current ratings of different transistors

a) Bipolar transistor
b) Darlington
c) MOSFET (Si)
d) IGBT
e) MOSFET (SiC)
f) GaN HEMT

[Year 2015]

Note: High voltage and high current darlington transistors are getting out of production.