SMART POWER

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VIJAYSAI PATNAIK
3rd Year, Electrical Engineering
IIT Delhi

Supervisor: Prof. H. Ryssel
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CHAPTER 1

INTRODUCTION TO POWER DEVICES

History of Power Devices
Power Semiconductor Devices

- Roots of power semiconductor technology extend before those for integrated circuits
- True revolution in power electronics: Thyristor
  - able to withstand very high reverse voltage and capable of carrying high current too
  - Introduced in 1957
- By 90s, ability to block 6500 V in off-state and conduct >2000 A in on-state
- Problem: once 'latched-on' in the conducting state, cannot be turned off by external control disadvantage in switching circuits
Bipolar Transistors

- Power bipolar junction transistors
  - Introduced in 1960s
  - Better switching performance & controllability
  - But less voltage and current ratings
- Rapid development in power handling capacities of discrete devices (BJT, thyristors) in the late 1970s
- Improvements of the Metal Oxide Semiconductor technology (initially developed to produce ICs)
- Process technology for bipolar power devices lagged behind → different process technologies for power devices and integrated circuits
MOS Power Devices

- Introduction of the power MOSFET in the late 1970s
- Advantages when compared with the bipolar transistor
  - high-input impedance (resulting in very low drive current and simpler gate drive circuits)
  - high switching speed (due to its unipolar conduction)
  - ease of paralleling (due to its positive thermal coefficient of resistance)

- Applications
  - Computer power supplies
  - Automotive electronics
Power MOSFET Basic Structure

- **Planar structure**
  - current and breakdown voltage ratings are both function of channel dimensions (respectively width and length of channel)

- **Vertical structure**
  - Voltage rating of transistor is function of doping and thickness of the N epitaxial layer
  - Current rating is function of channel width
  - Transistor sustains both high blocking voltage and high current within a compact piece of silicon
INTRODUCTION

N channel Power MOSFET
The on-state resistance of a power MOSFET is made up of several components as shown.

\[ R_{DS(on)} = R_{source} + R_{ch} + R_{A} + R_{J} + R_{D} + R_{sub} + R_{wcm1} \]

- \( R_{source} \): Source diffusion resistance
- \( R_{ch} \): Channel resistance
- \( R_{A} \): Accumulation resistance
- \( R_{J} \): "JFET" component-resistance of the region between the two body regions
- \( R_{D} \): Drift region resistance
- \( R_{sub} \): Substrate resistance
MOSFET problems: Higher $R_{DS(on)}$ (compared to BJT) in HV applications, low transconductance

Insulated-gate bipolar transistor (IGBT): new device incorporating features of both MOSFET and BJT

- Proposed in 1980s
- Better current density than MOSFET and better switching characteristics than BJT
- But turn off speed slower than MOSFET

- Suitable for medium-frequency applications (1-50 kHz)
- Examples: adjustable speed motor drives, appliance controls, and robotic/numerical controls
n-channel IGBT
Improvements in these new power devices, MOS and IGBT, linked to MOS technology and size reduction using the background of IC technology.

These devices produced in the same production facilities which were used for integrated circuits.

Introduction of MOS technology in power electronics paved way for power integration as the technology of power devices and integrated circuits has become compatible.
Power Integrated Circuits

- ICs combining high voltage and/or high current components monolithically with low voltage/low current control components
- Key feature: ability to handle high voltage, high current, or a combination of both
- In its simplest form
  - a PIC may consist of a level-shifting and drive circuit that translates logic-level input signals from a microprocessor to a voltage and current level sufficient to energize a load
  - Example: to operate electronic display where the load requires drive voltages above 100 V
At the other extreme:
- PIC may be required to perform load monitoring, diagnostic functions, self-protection, and information feedback to the microprocessor, in addition to handling large amounts of power to actuate the load.
- Example: An automotive multiplexed bus system with distributed power integrated circuits for control of lights, motors, air conditioning, and so forth.
- Applications: power converters, motor controllers, automotive switching, video amplifiers, bridge circuit drivers, display drivers, etc.
Monolithic Integration

- Monolithic integration of output power semiconductors with digital and analog circuitry includes power devices, signal processing, sensing and protection circuits on the same chip.

- Why monolithic solutions for power conversion and amplification?
  - Reduction of interfaces, and thus volume, weight and electromagnetic interferences.
  - Increasing efficiency, performance and reliability of the overall system.
SMART POWER TECHNOLOGY
Dawn of Smart Power

- Tremendous simplification in the control circuit due to Power MOSFET and the IGBT (having voltage-controlled characteristics)
- Development of Integrated Control Circuits
- Motivation to incorporate protective circuits on the control chips against over-voltage, over-current, and over-temperature conditions
- Also, need to interface with microprocessors led to the incorporation of logic circuits to provide encode/decode capability
- Dawn of smart power technology in the 1990s
Two kinds of PICs

- There are two types of PICs: Smart Power and HVICs

- High Voltage ICs
  - Deliver low output currents (up to 100mA) at supply voltages up to 1000V
  - Applications in automobiles, electrostatic and ink-jet printers, and plasma displays

- Smart Power – discussed next
What is Smart Power?

- Power integrated circuit which provides the interface between the digital control logic and the power load.

- Aimed to control the power of the system (up to a few hundreds of volts and a few amperes).

- Developed technologies for merging in the same chip:
  - power devices together with control, protection and sensing circuitries
  - microprocessor interfacing, fault diagnosis and process monitoring.
Functional Elements

SMART POWER TECHNOLOGY

POWER CONTROL
- POWER DEVICES
  - BIPOLAR POWER TRANSISTORS
  - POWER MOSFETs
  - INSULATED GATE BIPOLAR TRANSISTORS
  - MOS CONTROLLED THYRISTORS
- DRIVE CIRCUITS
  - 30 VOLT CMOS
  - HIGH VOLTAGE LEVEL SHIFT

SENSING & PROTECTION
- ANALOG CIRCUITS
  - HIGH SPEED BIPOLAR TRANSISTORS
  - OPERATIONAL AMPLIFIERS
- DETECTION CIRCUITS
  - OVER-VOLTAGE/UNDER-VOLTAGE
  - OVER-TEMPERATURE
  - OVER-CURRENT/NO-LOAD

INTERFACE
- LOGIC CIRCUITS
  - HIGH DENSITY CMOS
Power Control

1) Power Devices
   - required to handle high voltages or high currents, or both
   - low on-resistances
   - reduced switching times
   - without latch-up or current distribution problems
   - with a stable thermal behaviour
   - Furthermore, power devices should be able to be driven by a simple low power circuit

2) Drive Circuitry
   - provide sufficient drive signal to the power devices
   - capable of performing level shifting to high voltages

- Power device is generally a lateral (LDMOS) or vertical (VDMOS) MOS structure
Control & Processing Part

- This part contains microprocessor & DSP

- 1) Sensing & Diagnostic
  - over-current, over-voltage and over-temperature
  - no-load, short-circuit or under-voltage to provide sufficient biasing of the power devices

- 2) Control & self protection
  - Sensor technology together with local feedback for protection of the IC
  - response time is critical implemented using high performance analog circuits
Interface

- Using logic circuits (encode/decode operations)

- CMOS for logic circuits, since low power consumption and high density integration

- Requires integration of high-density CMOS circuits on the smart power chip

- Design challenges - Large voltage swings and high chip temperatures arises from self-heating
- Memories add flexibility to the system
- Few megabits used to store microprocessor software and data
Isolation in Power Devices

- In all ICs, the individual elements – transistors, resistances, capacitances, etc. must be mutually isolated.
- Isolation schemes for High Voltage ICs more complex than that for conventional VLSI with lower voltage.
- Power switch, control logic, high voltage and low voltage IC sections, and sensor circuits all operate off different voltage levels.
- Mainly three concepts are followed today, depending on the performance and cost desired.
The VDMOS transistor, the high voltage transistor, and the low voltage CMOS device are deposited on an epitaxial substrate.

- Allows very high current densities
- But due to the construction (common n$^+$ substrate) all switches on the same chip have to share the positive supply voltage
Various IC elements are accommodated in n doped wells, all of which may have different potentials.

More flexible but also more complex.

The benefits of CMOS for high integration and of bipolar for high precision analog functions can be combined with power.
Dielectric Isolation

Isolation is realized with SiO2; All Si islands are dielectrically isolated from each other and all islands can be connected to different potentials

- Low parasitic capacitance of components to substrate and to each other, low leakage currents
- Cost factor: High cost per mm² of chip area
Comparison of Isolation Technologies

- Simplest: Self Isolation
- Most effective: Dielectric isolation (high voltage)
- Cost: Dielectric > Junction > Self isolation

Due to the relatively high cost of dielectrically isolated Silicon wafers, most smart chips are being fabricated using Junction Isolation (standard applications)

- DI is used for specific applications requiring high level of isolation
In a high-voltage and smart power circuitry, a wide variety of power devices is needed to obtain proper device characteristics for different applications. This chapter investigates the structure and device characteristics of these different kinds of power devices.
Lateral HV Devices

- Lateral power semiconductor devices are smartly used for output devices in high-voltage and smart power ICs instead of vertical power devices.
- **Reason:** Compatibility with low-voltage IC circuitry.
- Output power semiconductors are used as switches, and the requirements for them include:
  - Low on-state voltage drop to minimize conduction loss.
  - High current density to reduce the chip size.
  - High input impedance for ease of drive.
  - Fast turn-off to minimize switching loss.
  - Finally, a large safe operating area (SOA).
For the fabrication of power MOSFET, a double diffusion process is used to diffuse phosphorus and boron sequentially from the same window opening (normally polysilicon gate).

The difference between the lateral junction depth of two diffusions determines the channel length.
Cross Section of LDMOSFET
LDMOSFET Characteristics

- Effective channel length (formed by lateral double diffusion) is defined by the difference in the lateral diffusions of the p body and the n⁺ source regions.

- LDMOSFET has three major serial resistance components - the metal resistance, the channel resistance, and the drift region resistance.

- For HV LDMOSFETs the dominant one is drift resistance.

- Trade-off between the breakdown voltage and the resistance of the drift region.
Advantage: The buried oxide helps to sustain a high electric field which results in a higher BV
Disadvantage: Self-heating effects during switching since buried oxide good thermal insulator
Cross section of the LIGBT
LIGBT Characteristics

- Major limitation of LDMOSFETs: relatively high specific on-resistance due to the majority carrier conduction mechanism

- In LIGBT, pnp bipolar transistor provides high current handling capability, and an n channel MOSFET gives high-impedance voltage control over bipolar base current

- Has a p+ anode instead of the n+ drain of LDMOSFETs
CHAPTER 4

RESURF

Reduced Surface Field Concept
Why RESURF?

- High-voltage devices usually require thick and low doped epitaxial layer
- Difficult to integrate with low-voltage circuitry
- On-state resistances of such devices is large because of the high-resistivity epitaxial layer
- In 1979, Appels and Vaes suggested the reduced surface field (RESURF) concept
- Gives a good trade-off between the breakdown voltage and the on-resistance of lateral devices
The RESURF principle utilizes a lightly doped substrate along with a thin epitaxial layer to block high-voltage.

RESURF structure:
- Lateral $p^+n$ diode (epitaxial) that defines the on-resistance characteristic of the device
- Vertical $pn$ diode which supports a space charge depletion region enabling high BV
Conventional and RESURF Diodes

(a) Conventional diode

(b) RESURF diode
RESURF Diode

- $N_{\text{epi}}$-p substrate depletion region interacts with depletion region of p-well and n-junction
- Depletion edge moves towards the n$^+$ region
- Strong reduction in the surface electric field
- Applied voltage is laterally almost equally distributed along the surface
- Peak electric field is forced to be in the bulk junction 
  → breakdown achieved when the horizontal junction breaks down
RESURF Diode

- A fully depleted area at the drift region during blocking state is achieved
- Makes it possible for lateral power devices to block a high-voltage even with a thin epitaxial layer
- To achieve a high BV in RESURF structures, it is required that the n-epi region is fully depleted before the lateral electric field reaches a critical value
Electric Field

Lateral RESURF structure at full depletion

Electric field comparison at the surface
Electric Field

- Second electric field peak formed due to the vertical junction of RESURF structure
- Electric field at the surface of the RESURF device (after full depletion) assumes a parabolic rather than a linear distribution (seen in conventional high-voltage devices)
- Reduces the electric field at the surface of the device during off-state
- Enables higher voltages to be applied
Summary

Evolution of Power Devices and ICs
Summary

- Need for Smart Power
- Requirements for a Smart Power system
- The choice of a power structure, the level of integration and the isolation technique are based on the type of application and, therefore, on the power range desired
- On-resistance vs. break down voltage trade off is considered
- Lateral High Voltage Devices for Smart Power applications were considered
- RESURF concept for integration of High voltage and Low voltage circuitry
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Thank You for your kind attention!