État de l’art et tendances des dispositifs semiconducteurs de puissance pour une gestion optimisée de l’énergie

---

State of the art and trends in power semiconductor devices for optimized power management

Frédéric MORANCHO
Assistant Professor — Université de Toulouse — LAAS-CNRS
• Introduction
• Unipolar power devices: MOSFETs
  – Conventional devices and their « silicon limits »
  – Novel concepts: Superjunction and floating islands
  – Limits of performance with these novel concepts
• Bipolar power devices: IGBTs
  – « Low losses » IGBT
  – Bidirectional IGBT
  – Integration of an IGBT transistor and a diode
  – Limits of performance of IGBTs
• Wide band-gap power semiconductor devices
  – Properties of wide band-gap semiconductors
  – Comparison of limits of performance
  – SiC, GaN, Diamond: future trends
• Conclusion
• **Introduction**

• **Unipolar power devices: MOSFETs**
  – Conventional devices and their « silicon limits »
  – Novel concepts: Superjunction and floating islands
  – Limits of performance with these novel concepts

• **Bipolar power devices: IGBTs**
  – « Low losses » IGBT
  – Bidirectional IGBT
  – Integration of an IGBT transistor and a diode
  – Limits of performance of IGBTs

• **Wide band-gap power semiconductor devices**
  – Properties of wide band-gap semiconductors
  – Comparison of limits of performance
  – SiC, GaN, Diamond: future trends

• **Conclusion**
• Despite many efforts to save energy, demand for electricity is expected to grow much faster than other energy sources over the next three decades.
• Today 40% of all energy consumption is in electrical energy, but this will grow to 60% by 2040.

![Graph showing power electrical consumption and population growth](image)

• Power electronics is the key technology to control the flow of electrical energy from the source to the load: it is responsible for the reliability and stability of the whole power supply infrastructure in the world from the sources, the energy transmission and distribution up to the huge variety of applications in industry, transportation systems and the home & office appliances.
• Semiconductors in power management are estimated to exceed 50 billion dollars by 2010.

High power (high voltage and/or high current), high frequency, high temperature and low losses power switches are needed for an optimized power management.
The power switch

OFF

Breakdown voltage \( (BV_{dss}) \)

ON

Specific ON-resistance \( (R_{ON-S}) \)

• Performances improvement:
  - \( BV_{dss} \): static OFF-state performance
  - \( R_{ON-S} \) (or \( V_{ON} \)): static ON-state performance
  - Operating frequency: switching losses
  - Operating temperature

• Functionalities increase:
  - Voltage bidirectionality
  - Current bidirectionality
Comparison of unipolar and bipolar power devices

Unipolar devices
(MOSFET, Schottky diode,...)

- low switching losses
- high frequency operation
- increasing on-resistance with breakdown voltage
- increasing conduction losses with breakdown voltage

Bipolar devices
(PN diode, bipolar transistor, IGBT,...)

- high switching losses
- low frequency operation
- on-resistance not depending on breakdown voltage
- low conduction losses
MOS gate devices are predominantly used in most of the application fields:
- LDMOSFETs in power ICs,
- MOSFETs for low voltage and medium voltage applications,
- IGBTs for high power applications

from *Silicon Limit Electrical Characteristics of Power Devices and ICs*, A. Nakagawa, Y. Kawaguchi, K. Nakamura, ISPS’08, Invited paper
• Introduction

• Unipolar power devices: MOSFETs
  – Conventional devices and their « silicon limits »
  – Novel concepts: Superjunction and floating islands
  – Limits of performance with these novel concepts

• Bipolar power devices: IGBTs
  – « Low losses » IGBT
  – Bidirectional IGBT
  – Integration of an IGBT transistor and a fast diode
  – Limits of performance of IGBTs

• Wide band-gap power semiconductor devices
  – Properties of wide band-gap semiconductors
  – Comparison of limits of performance
  – SiC, GaN, Diamond: future trends

• Conclusion
Unipolar power devices: MOSFETs

Conventional power MOSFETs

VDMOSFET

LDMOSFET

- **OFF-state**: the breakdown voltage ($BV_{dss}$) depends on $N_D$ and $H$

- **ON-state**: the specific on-resistance ($R_{on} \cdot S$) also depends on $N_D$ and $H$

“$R_{on} \cdot S / BV_{DSS}$” trade-off < “silicon limit”
Silicon limits of conventional unipolar devices

What is the “silicon limit”? 
Silicon limit = optimal specific on-resistance for a given breakdown voltage

\[ R_{ON} \cdot S = \frac{H}{q \cdot \mu_n \cdot N_D} \]  
(simple calculation with:  \[ R = \rho \cdot \frac{l}{S} \])

Vertical MOSFETs: \[ R_{ON} \cdot S (\Omega \cdot cm^2) = 8.9 \times 10^{-9} \times BV_{dss}^{2.4} \]

Lateral MOSFETs: \[ R_{ON} \cdot S (\Omega \cdot cm^2) = 1.66 \times 10^{-14} \times h^{-1} \times BV_{dss}^{3.56} \]

RESURF LDMOSFETs: \[ R_{ON} \cdot S (\Omega \cdot cm^2) = 1.02 \times 10^{-8} \times BV_{dss}^{2.33} \]
Novel concepts are mandatory

Superjunction

U-diode

FLI-diode
**The « Superjunction » concept**

**PRINCIPLE** : perfect charge balance between P and N-regions \((N_A \cdot W_P = N_D \cdot W_N)\)
(for example : \(N_A = N_D\) et \(W_N = W_P = W \ll H\))

- lateral depletion with: \(E_{y\text{MAX}} < E_C\)
- after lateral depletion: \(V_{ds} = E_z \cdot H\)

\[ BV_{dss} = E_C \cdot H \]

First application: the COOLMOS™ from Infineon
Vertical Superjunction MOSFETs

New limits for vertical power MOSFETs:

\[ R_{ON} \cdot S (\Omega \cdot cm^2) = 1.98 \times 10^{-1} \times W^{4/5} \times BV_{dss} \]

- Multiple epitaxies (Infineon, STMicroelectronics)
- Deep trench etching and filling with epitaxial layers (Fuji Electric)
- Deep trench etching, implantation / diffusion then filling with a dielectric (NXP, LAAS)
The Deep Trench Superjunction MOSFET

**Critical technological steps:**

- Deep Trench Reactive Ion Etching (DRIE)
- Boron diffusion through an oxide
- Trench filling with BCB (BenzoCycloButene)
- Chemical Mechanical Polishing (CMP) of the surface

<table>
<thead>
<tr>
<th></th>
<th>Conventional VDMOSFET</th>
<th>DT-SJMOSET</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{ON,S}$ (mΩ.cm$^2$)</td>
<td>507</td>
<td>51</td>
</tr>
</tbody>
</table>
The Deep Trench Superjunction MOSFET

1. DRIE with a quasi-perfect verticality of the trenches

2. Trench filling with BCB (BenzoCycloButene)

3. Central trenches and trench termination after CMP of the BCB at the surface
The “Floating Islands” concept

- **Breakdown voltage (BV_{dss}) improvement:**
  \[ N_{epi} \text{ (VDMOS)} = N_{epi} \text{ (FLYMOS)} \Rightarrow R_{ON} \text{ (VDMOS)} \approx R_{ON} \text{ (FLYMOS)} \]
  \[ BV_{dss} \text{ (VDMOS)} < BV_{dss} \text{ (FLYMOS)} \]

- **OR**

- **ON-resistance (R_{ON}) reduction:**
  \[ BV_{dss} \text{ VDMOS} = BV_{dss} \text{ FLYMOS} \Rightarrow N_{epi} \text{ (VDMOS)} < N_{epi} \text{ (FLYMOS)} \]
  \[ R_{ON} \text{ (VDMOS)} > R_{ON} \text{ (FLYMOS)} \]
New limits for vertical power MOSFETs:

\[ R_{ON} \cdot S (\Omega \cdot \text{cm}^2) = 1.78 \times 10^{-8} \times (BVDSS)^{2.4} \times (n + 1)^{-1.4} \]

(n = number of floating islands between drain and source)

First technological realization of FLYMOSFETs (\(BVDSS = 80\) V)

33% \(R_{ON} \cdot S\) improvement compared to a conventional 80 V VDMOSFET

200 V FLYMOSFETs with 2 levels of floating islands between drain and source (for the first time in the world)

Best performance (in terms of \(R_{ON} \cdot Q_{gd}\)) at \(BVDSS = 200\) V
Other « Floating Islands » devices

500 V Floating Islands MOSFET and its termination (University of Chengdu, China)

300 V Floating Islands Schottky diode and its termination (Toshiba)

80 V Floating Islands Trench MOSFET - FITMOS - (Toyota)
Limits of static performance with these new concepts on silicon

Conventional silicon limit:

$$R_{ON-S} = 8.9 \times 10^{-9} (BV_{dss})^{2.4} \text{ (}\Omega \cdot \text{cm}^2\text{)}$$

Superjunction devices:

$$R_{ON-S} = 1.98 \times 10^{-1} W^{5/4}(BV_{dss}) \text{ (}\Omega \cdot \text{cm}^2\text{)}$$

Floating Islands devices:

$$R_{ON-S} = 1.78 \times 10^{-8} (BV_{dss})^{-2.4}(n+1)^{-1.4} \text{ (}\Omega \cdot \text{cm}^2\text{)}$$

- superiority of Superjunction MOSFET at high voltage range (> 600 V)
- competition “FLYMOSFET/Superjunction MOSFET” at medium voltage range (200 to 600 V)
- superiority of FLYMOSFET at low voltage range (< 200 V)
Outline

• Introduction

• Unipolar power devices: MOSFETs
  – Conventional devices and their « silicon limits »
  – Novel concepts: Superjunction and floating islands
  – Limits of performance with these novel concepts

• Bipolar power devices: IGBTs
  – « Low losses » IGBT
  – Bidirectional IGBT
  – Integration of an IGBT transistor and a diode
  – Limits of performance of IGBTs

• Wide band-gap power semiconductor devices
  – Properties of wide band-gap semiconductors
  – Comparison of limits of performance
  – SiC, GaN, Diamond: future trends

• Conclusion
**Objective:** optimize the « conduction losses / switching losses » trade-off with a parallel association of 2 IGBTs:

- Fast IGBT: high $V_\text{ON}$ and low switching losses
- Slow IGBT: low $V_\text{ON}$ and high switching losses

**Diagram:**

- Driving cycle:
  - $V_g$ of the slow IGBT
  - $V_g$ of the fast IGBT

- Anode current repartition:
  - Fast IGBT
  - Slow IGBT
The « Low losses » IGBT

IGBT 1: Fast
IGBT 2: Slow
Configuration 1: slow IGBT // slow IGBT
Configuration 2: fast IGBT // fast IGBT
Configuration 3: slow IGBT // fast IGBT

Slow IGBT:
P⁺ Anode
(C_s = 3.10^{19} \text{ cm}^{-3}; X_j = 7 \text{ µm})

Fast IGBT:
Semi-transparent anode
(C_s = 10^{17} \text{ cm}^{-3}; X_j = 0.3 \text{ µm})
The bidirectional IGBT

ANR MOBIDIC

Monolithical integration

Use of wafer bonding technique or double face lithography
Integration of an IGBT and its freewheeling diode

The Reverse Conducting IGBT (RC-IGBT)

ON-state characteristics of the RC-IGBT

RC-IGBT reverse recovery current and gate control waveforms for charge extraction

from A High Current 3300V Module Employing Reverse Conducting IGBTs Setting a New Benchmark in Output Power Capability,
M. Rahimo et al, ABB Switzerland Ltd Semiconductors ISPSD’08, pp. 68-71.
High voltage (> 1 kV): IGBT is the best device. IGBT and SJMOSFET exhibit the same static performance but IGBT technology is cheaper.

Medium voltage (around 600 V): same performance for MOSFETs (FLYMOSFET, SJMOSFET) and IGBT. The choice will depend on the operating frequency.

Low voltage (< 400 Volts): MOSFETs (FLYMOSFET or SJMOSFET) are the best devices
• Introduction

• Unipolar power devices: MOSFETs
  – Conventional devices and their « silicon limits »
  – Novel concepts: Superjunction and floating islands
  – Limits of performance with these novel concepts

• Bipolar power devices: IGBTs
  – « Low losses » IGBT
  – Bidirectional IGBT
  – Integration of an IGBT transistor and a diode
  – Limits of performance of IGBTs

• Wide band-gap power semiconductor devices
  – Properties of wide band-gap semiconductors
  – Comparison of limits of performance
  – SiC, GaN, Diamond: future trends

• Conclusion
### Properties of wide band-gap semiconductors

#### Conventional Semiconductors vs. Wide Band-Gap Semiconductors

<table>
<thead>
<tr>
<th>Property</th>
<th>Si</th>
<th>GaAs</th>
<th>3C – SiC</th>
<th>6H – SiC</th>
<th>4H – SiC</th>
<th>GaN</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Band-gap</strong> $E_g$ (eV)</td>
<td>1.12</td>
<td>1.4</td>
<td>2.3</td>
<td>2.9</td>
<td>3.2</td>
<td>3.39</td>
<td>5.6</td>
</tr>
<tr>
<td><strong>Electron mobility</strong> $\mu_n$ (cm$^2$.V$^{-1}$.s$^{-1}$)</td>
<td>1 450</td>
<td>8 500</td>
<td>1000</td>
<td>415</td>
<td>950</td>
<td>1000</td>
<td>4000</td>
</tr>
<tr>
<td><strong>Hole mobility</strong> $\mu_p$ (cm$^2$.V$^{-1}$.s$^{-1}$)</td>
<td>450</td>
<td>400</td>
<td>45</td>
<td>90</td>
<td>115</td>
<td>35</td>
<td>3800</td>
</tr>
<tr>
<td><strong>Critical electric field</strong> $E_C$ (V.cm$^{-1}$)</td>
<td>$3 \times 10^5$</td>
<td>$4 \times 10^5$</td>
<td>$2 \times 10^6$</td>
<td>$2.5 \times 10^6$</td>
<td>$3 \times 10^6$</td>
<td>$5 \times 10^6$</td>
<td>$10^7$</td>
</tr>
<tr>
<td><strong>Intrinsic concentration</strong> $n_i$ (cm$^{-3}$)</td>
<td>$1.5 \times 10^{10}$</td>
<td>$2.1 \times 10^{10}$</td>
<td>$6.9$</td>
<td>$2.3 \times 10^{-6}$</td>
<td>$8.2 \times 10^{-6}$</td>
<td>$1.6 \times 10^{-10}$</td>
<td>$1.6 \times 10^{-27}$</td>
</tr>
<tr>
<td><strong>Saturation velocity</strong> $v_{sat}$ (cm.s$^{-1}$)</td>
<td>$10^7$</td>
<td>$2.10^7$</td>
<td>$2.5 \times 10^7$</td>
<td>$2.10^7$</td>
<td>$2 \times 10^7$</td>
<td>$2 \times 10^7$</td>
<td>$2 \times 10^7$</td>
</tr>
<tr>
<td><strong>Thermal conductivity</strong> $\lambda$ (W.cm$^{-1}$.K$^{-1}$)</td>
<td>1.3</td>
<td>0.54</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>1.3</td>
<td>20</td>
</tr>
<tr>
<td><strong>Maximal operation temperature</strong> $T_{max}$ (°C)</td>
<td>125</td>
<td>150</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>650</td>
<td>700</td>
</tr>
<tr>
<td><strong>Dielectric constant</strong></td>
<td>11.7</td>
<td>12.9</td>
<td>9.6</td>
<td>9.7</td>
<td>10</td>
<td>8.9</td>
<td>5.7</td>
</tr>
</tbody>
</table>

#### Wide Band-Gap Semiconductors

- High voltage, high temperature, high frequency, and low losses devices

![Diagram](image-url)
Compared to the conventional silicon limit, the improvement factor of the static performance is very important:

- $R_{\text{ON}} \cdot S$: 3 decades for SiC and 4 decades for GaN!
- $BV_{\text{dss}}$: more than 1 decade!

Compared to Superjunction devices limits:

Superjunction devices are theoretically performant at $BV_{\text{dss}} = 10 \text{ kV}$ but its technology would be too expensive (or impossible) in this voltage range.
SiC power diodes


Bipolar diode 4.5 kV, 150 A Brett A. Hull et al, ISPSD’06
SiC power transistors

JFET ($B_{\text{dss}} = 11 \text{kV}$, $R_{\text{ON}} \cdot S = 130 \text{ m\ensuremath{\Omega}\cdot\text{cm}^2}$)


MOSFET ($B_{\text{dss}} = 10 \text{kV}$, $R_{\text{ON}} \cdot S = 123 \text{ m\ensuremath{\Omega}\cdot\text{cm}^2}$)


Bipolar transistor 1200 V / 15 A (@$V_{\text{CE}}=2\text{V}$)

H.S. Lee et al, ICSCRM’07

N-type IGBT 13 kV / 4 A (@$V_{\text{F}}<5\text{ V}$)

M.K. Das et al, ICSCRM’07
GaN power devices

AlGaN/GaN HEMT \((B_{dss} = 1050 \text{ V}, R_{ON} \cdot S = 6 \text{ m}\Omega \cdot \text{cm}^2)\)
[Ueda et al, ISPSD’2005]

Schottky Diode \((B_{dss} = 1050 \text{ V}, R_{ON} \cdot S = 6 \text{ m}\Omega \cdot \text{cm}^2)\)
[Yoshida et al, ISPSD’2006]
GaN power MOSFETs

Lateral MOSFET (BV_{dss} = 940 V) [Huang et al, ISPSD’2006]

Trench Gate MOSFET [Otake et al. JJAP 2007]

RESURF LDMOSFET (BV_{dss} = 1570 V, R_{ON}·S = 30 mΩ·cm²) [Huang et al, ISPSD’2008]
### Trends in wide band-gap semiconductors

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>SiC</th>
<th>GaN</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
<td>+ + +</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td><strong>Substrate cost</strong></td>
<td>+ + +</td>
<td>+ (depends on the substrate)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td>+ + +</td>
<td>+</td>
<td>+ + (silicon compatible)</td>
<td>—</td>
</tr>
<tr>
<td><strong>Type of devices</strong></td>
<td>All</td>
<td>All (MOS gated devices only at very high voltage)</td>
<td>Essentially unipolar, lateral and normally-on devices</td>
<td>Unipolar (Schottky, JFET)</td>
</tr>
<tr>
<td><strong>Voltage range</strong></td>
<td>Low and medium voltage</td>
<td>Medium and high voltage</td>
<td>Medium voltage</td>
<td>Very high voltage</td>
</tr>
</tbody>
</table>

**SiC:** Schottky and JBS diodes are commercially available up to 1.2 kV. PiN diodes will be soon available. Regarding power switches, a normally-off switch is always expected.

**GaN** is already commercialised in photonics area. However, its application in power devices requires further work in material, processing and device design.

Can GaN power devices overtake or displace SiC power devices?

**Diamond:** material, processing and device design are at a very early stage.
Outline

• Introduction

• Unipolar power devices: MOSFETs
  – Conventional devices and their « silicon limits »
  – Novel concepts: Superjunction and floating islands
  – Limits of performance with these novel concepts

• Bipolar power devices: IGBTs
  – Low losses IGBT
  – Integration of an IGBT and a diode
  – Limits of performance of IGBTs

• Wide band-gap power semiconductor devices
  – Properties of wide band-gap semiconductors
  – Comparison of limits of performance
  – SiC, GaN, Diamond: future trends

• Conclusion
MOS gate devices (MOSFETs, IGBTs): new silicon architectures are available and performant up to 3.3 kV.

Schottky and JBS diodes: wide band-gap devices are displacing silicon devices even at breakdown voltages from 300 to 600 Volts.

Silicon still has a future in the « power devices » field, but rapid progress has been made in the development of wide band-gap power devices!
Integrated Power Switch Roadmap

System Integration (architecture)
- Integrated power switch
- Thermal management
- Galvanic insulation
- Control
- Protections
- Power Switch

2008 to 2010
- Switch (mono or bidi) + driver control, protections
- Si, SiC or GaN switch (mono and bidirectional switch)
- Flexible process:
  - Dry deep silicon etching
  - Trench MOS
  - Thin wafer techno
  - Wafer bonding
  - Vias
  - Backside lithography

2010 to 2012
- Galvanic insulation, Cooling Passive (L, C)
- IPS
- Technology integration
- Materials:
  - Magnetic
  - High K
  - Low K
  - Piezo
- 3D integration:
  - Planarisation process
  - Interconnect metallization
  - Stacking (3D integration)
  - Diamant, CNT
LAAS-CNRS: about 40 years of research in the « power devices » field

- First MOSFET (First power device)
- VMOSFET
- RESURF LDMOSFET
- VDMOSFET
- LDMOSFET
- MOS Thyristor
- Optical MOS Thyristor
- Dual Thyristor
- FLYMOSFET with 1 FI
- FLYMOSFET with 2 FI
- Bidirectional IGBT
- DT-SJMOSEF
- GaN LDMOSFET