Power semiconductor device: Past , Present, and the Future

Ichiro Omura
Kyushu Institute of Technology
Japan

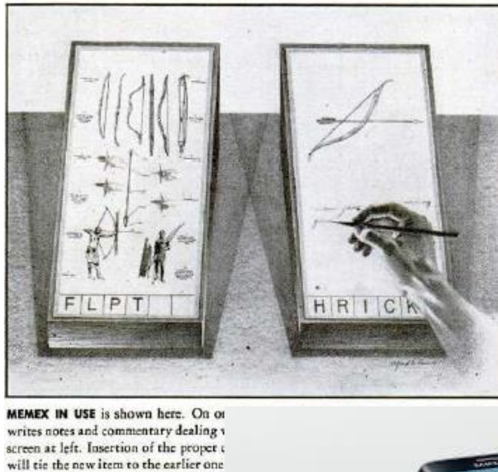
Plenary Talk Ⅱ [June 2 (Tue.) / 11:50~12:30]

Outline

H. Ohashi et al. “Role of Simulation Technology for the Progress in Power Devices and Their Applications,” IEEE T-ED, Vol. 60, issue 2, 2013.

- **Introduction:**
  - **Moore’s law**
  - **Power electronics trends and Negawatt cost**
- **Past and Present overview of power semiconductor**
  - **Dr. Newell prediction, 1973 talk in PESC**
  - **Types of discrete devices**
- **Present status explanation**
  - **Power MOSFET**
  - **IGBT**
  - **Lateral Device**
  - **Wafer technology (Silicon)**
  - **Simulation technology**
- **Future**

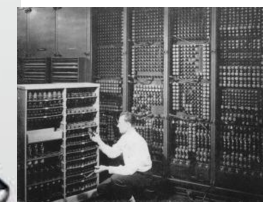
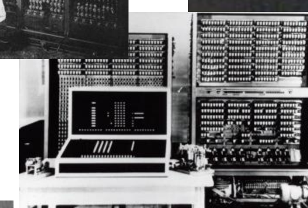
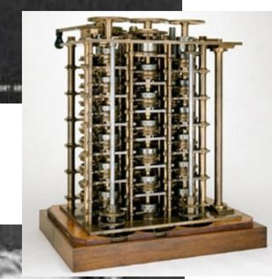
Vision, theory and producing for ICT world

“As we may think”
July 1945

Vannevar Bush
Steve Jobs



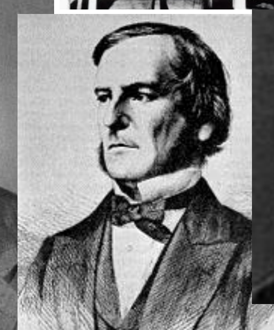
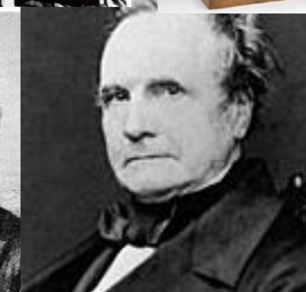




Claude Shannon







Ken Thompson
Dennis Ritchie

John Backus

Alan Turing

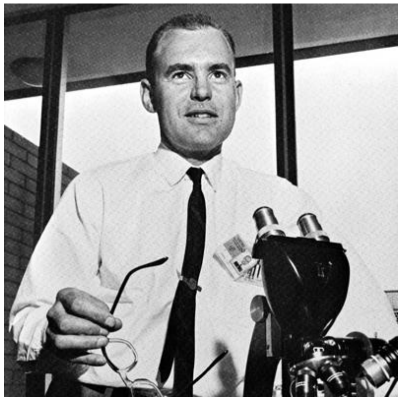
John von Neumann

George Boole

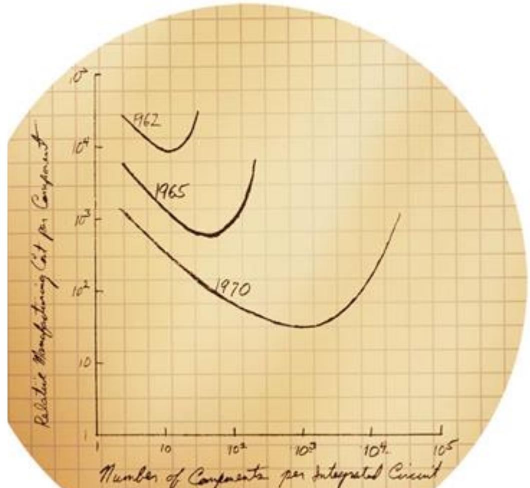
Charles Babbage

1965 - "Moore's Law"
Silicon Engine to drive ICT

Gordon E. Moore



Manufacturing cost per component



Number of components per integrated circuit

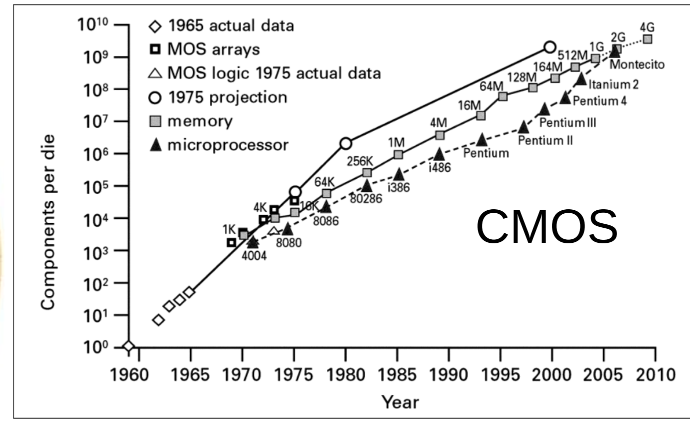
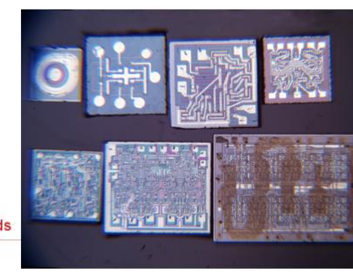
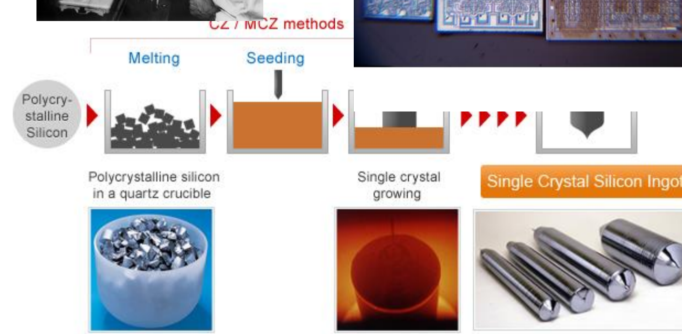


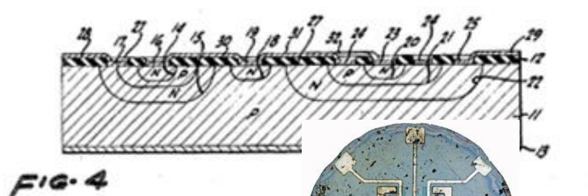
FIGURE 9. Integrated circuit complexity, actual data compared with 1975 projection. Source: Intel.

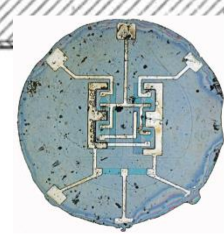




Robert Noyce

Integrated circuit patent in 1959



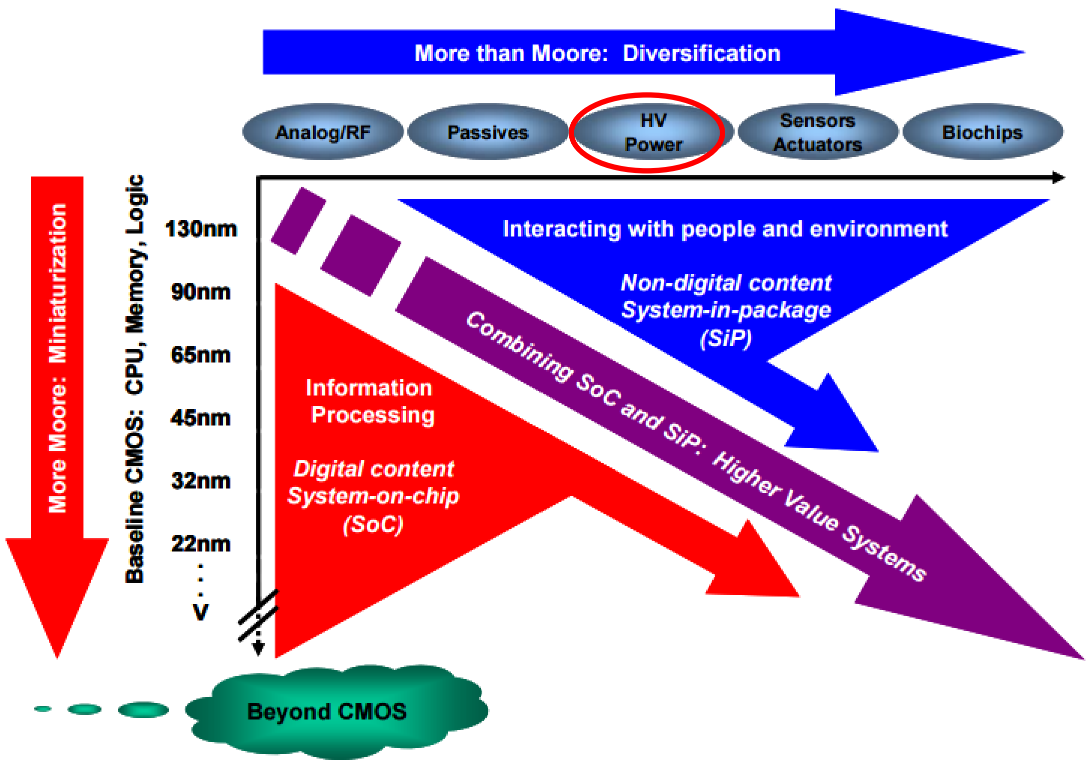


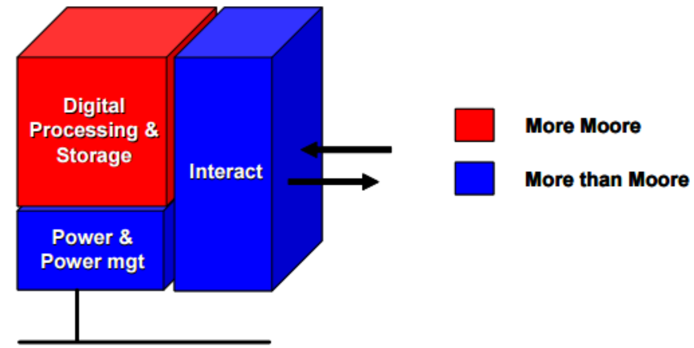
Toward digital cost free => ICT for everybody

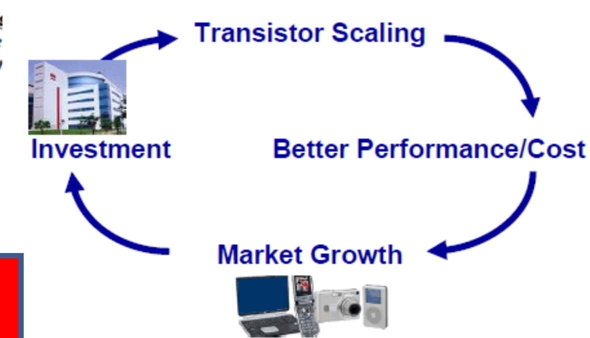
“More-than-Moore”(MtM) White Paper

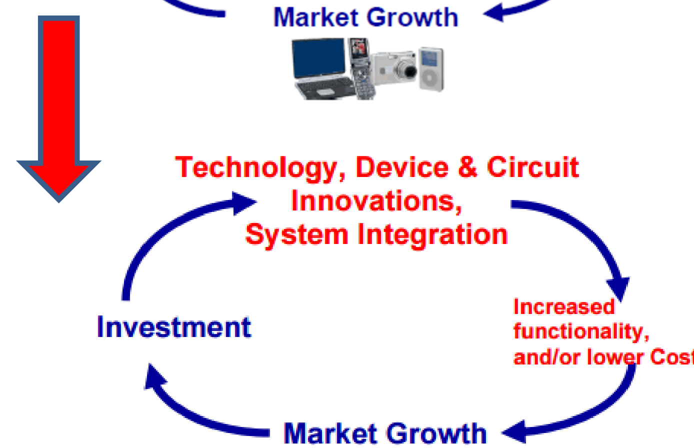
They are trying to change the game.

International Technology Roadmap for Semiconductors







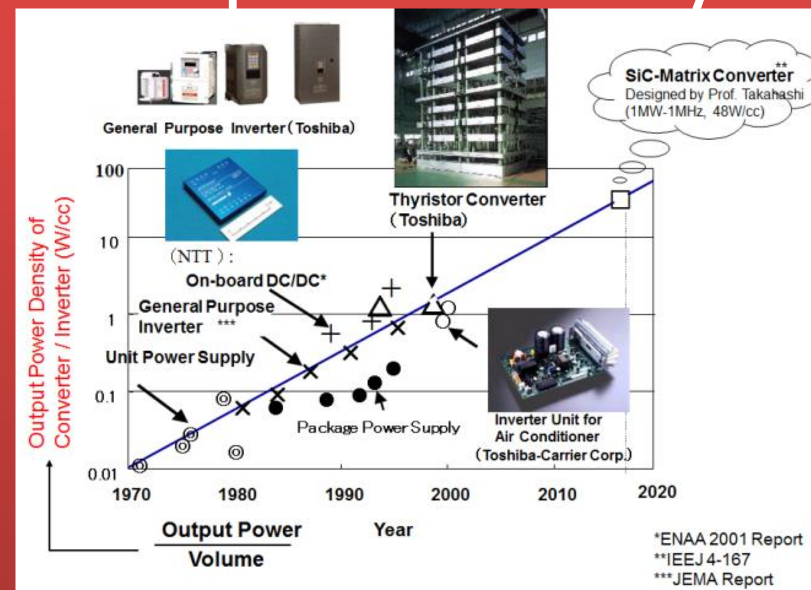


Is power electronics less than peripheral?

FOMs, Roadmaps, Trends for PE

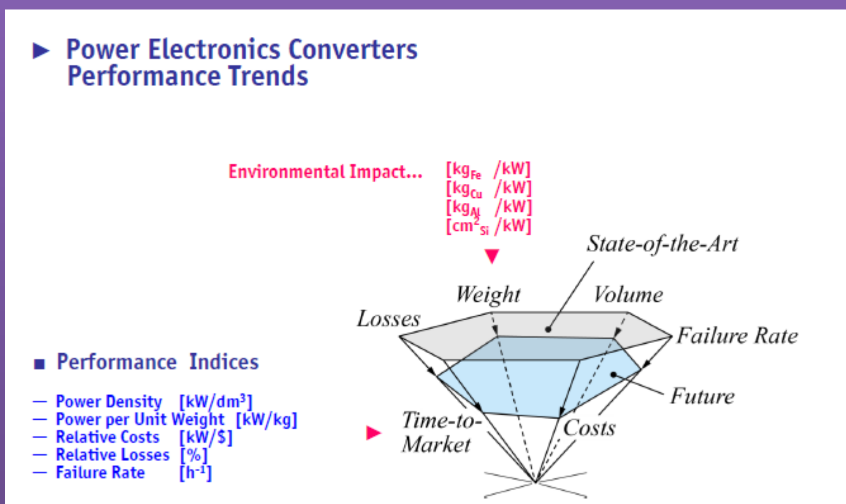
Efficiency

Output Power Density



H. Ohashi, Proc. of 4th Int. Conf. on Integrated Power Systems, June 2006, Naples (Italy), pp. 153-156.

Cost, Reliability, Loss etc. in addition to power density



Prof. Kolar, ETH Zurich

Negawatt Cost ?

“Negawatt cost”

Key factor for energy saving by Power Elec.

Efficiency Improvement × **Prevalence (Cost reduction)**

Negawatt cost definition
as index for wide use of PE technology

Negawatt cost =

$$\frac{\textit{Initial cost} + \textit{Total maintenance cost}}{\textit{Saved power} \times \textit{Total operating time}}$$

Power generation cost comparison with Negawatt co

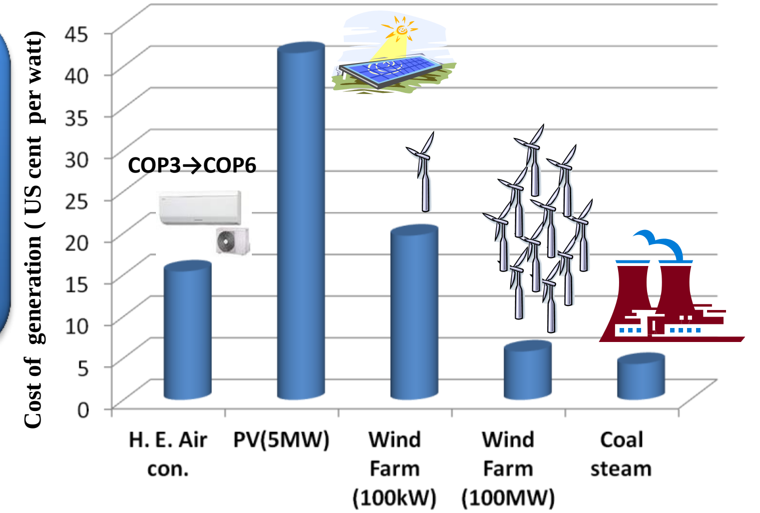
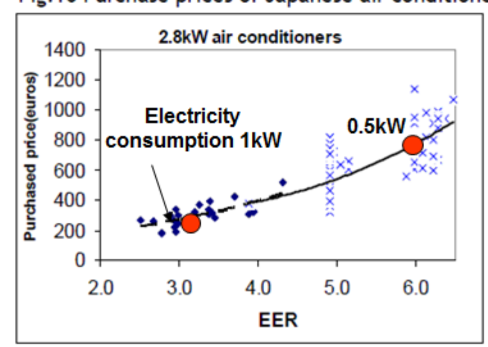
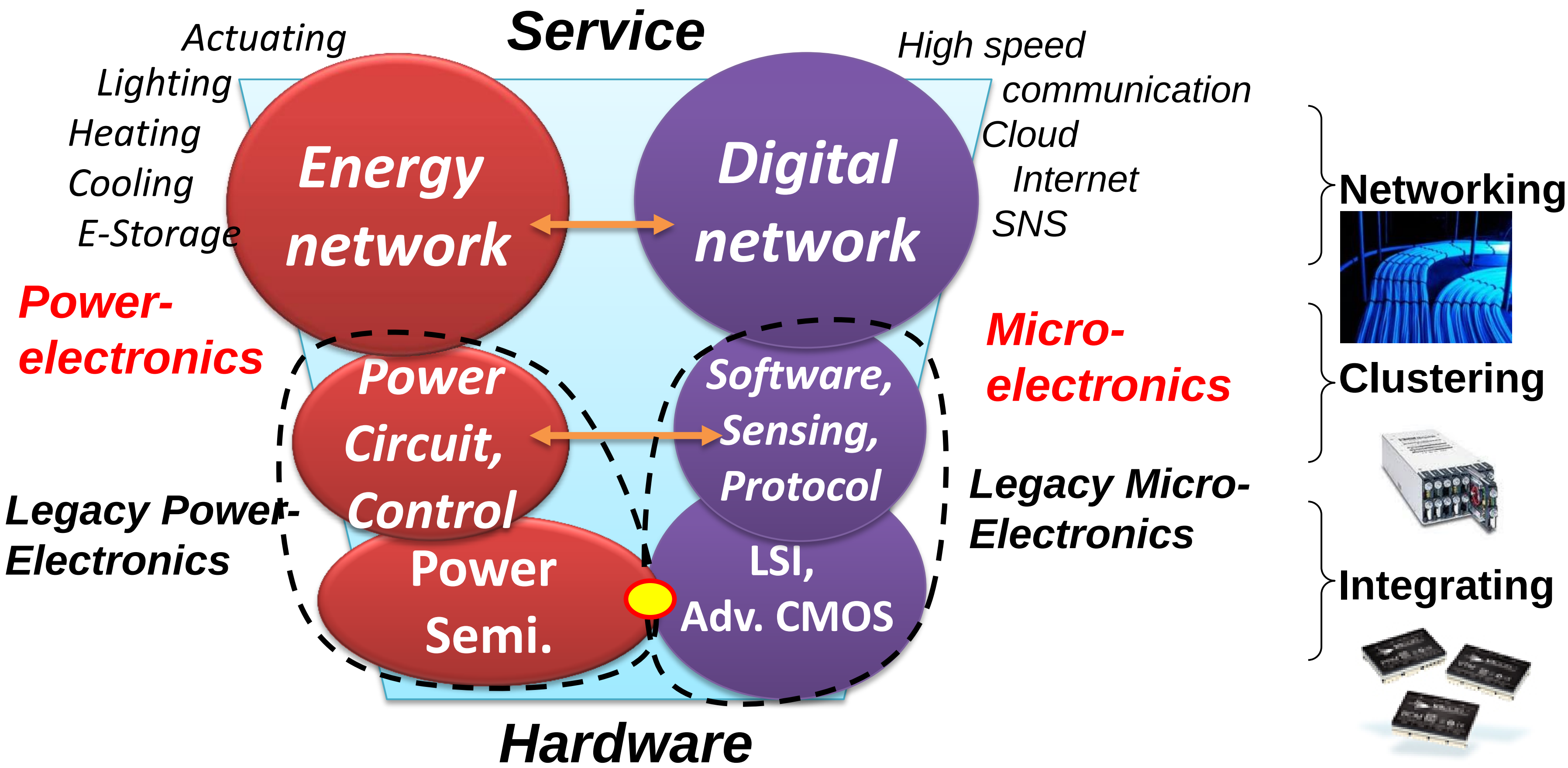


Fig.16 Purchase prices of Japanese air conditioner



Payback time of power electronics equipment sufficiently competes with another renewable energy

Power electronics and micro electronics



Negawatt cost will be discussed up to network level.

I. Omura, SIIQ report, Oct. 2012, in Japanese

Outline

- **Introduction:**
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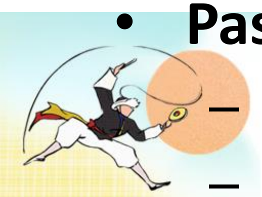
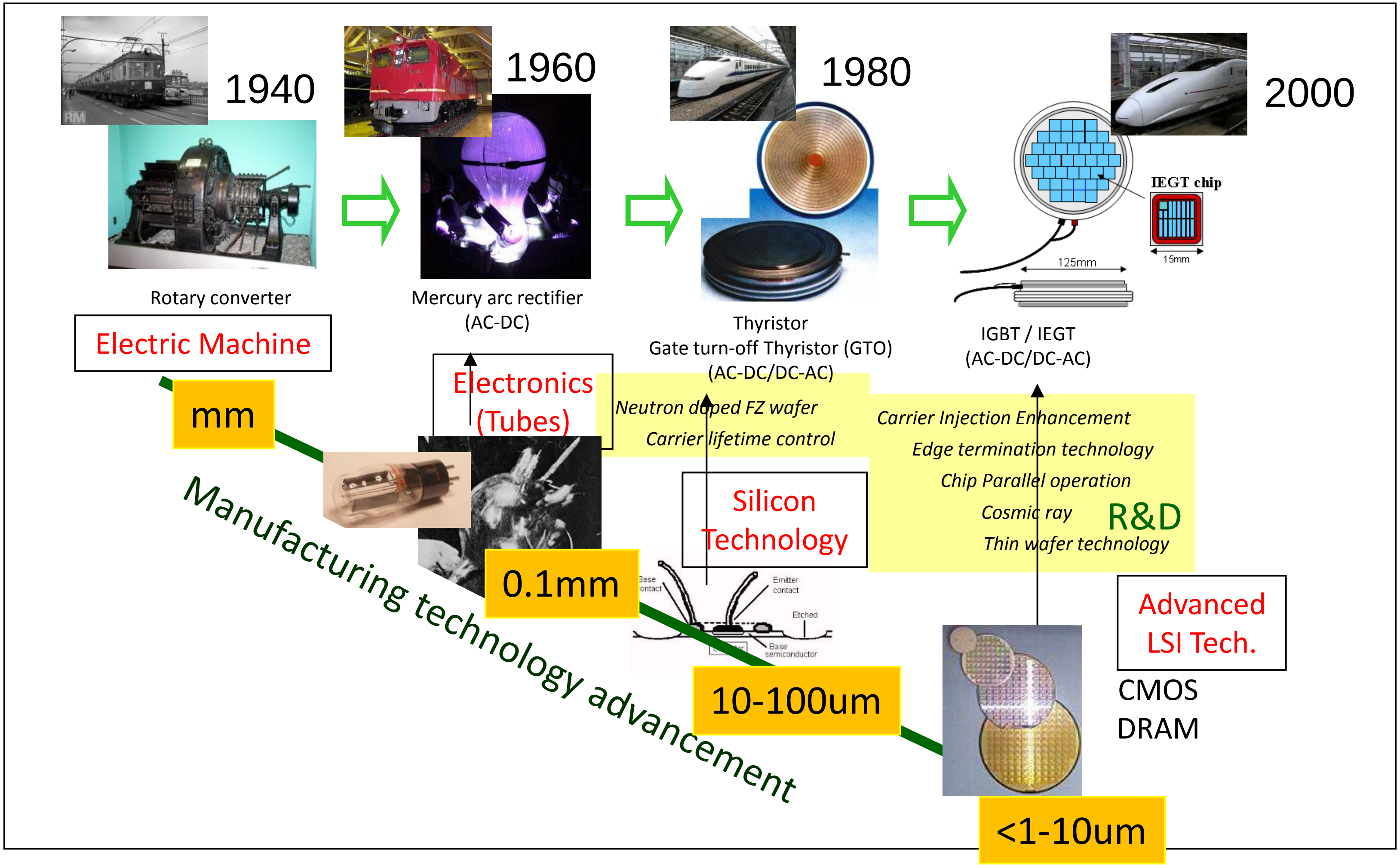
- **Past and Present overview of power semiconductor**
  - Dr. Newell prediction, 1973 talk in PESC
  - Types of discrete devices



- **Present status explanation**
  - Power MOSFET
  - IGBT
  - Lateral Device
  - Wafer technology (Silicon)
  - Simulation technology
- **Future**

100 years of power device development

(High voltage)



William E. Newell, 1973 PESC Keynote

Power Electronics—Emerging from Limbo

WILLIAM E. NEWELL, SENIOR MEMBER, IEEE

Abstract—**Power electronics is a technology which is interstitial to all three of the major disciplines of electrical engineering: electronics, power, and control. Yet its rapidly expanding significance has not been widely recognized, and the historical parochialism of specialists within the technology has stifled communication and cooperation in solving increasingly challenging problems. This paper calls for an end to this parochialism, leading to the emergence of an important new discipline and profession.**

I. Power Electronics Is a Technology Which Now Exists in a Fragmented Limbo

THE BROAD field of electrical engineering is generally segmented into three major areas: electronics, power, and control. When someone uses the word *electronics*, it is quite likely that what he really means is *signal-processing* electronics. Similarly, when electrical power engineering is described, rotat-

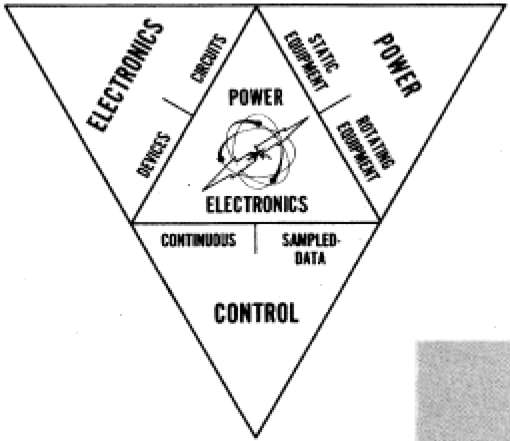
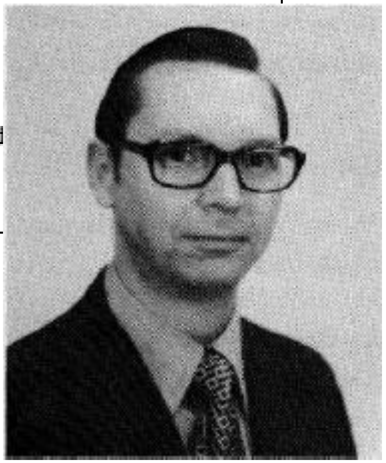
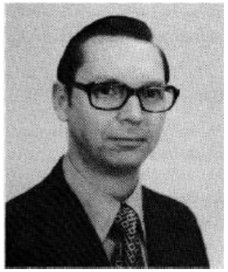


Fig. 1. Power electronics: interstitial to all major d
engineering.



Power Electronics—Emerging from Limbo

WILLIAM E. NEWELL, SENIOR MEMBER, IEEE



POWER ELECTRONICS WILL IN FACT EMERGE AS A FULL-FLEDGED DISCIPLINE AND PROFESSION OF THE FUTURE

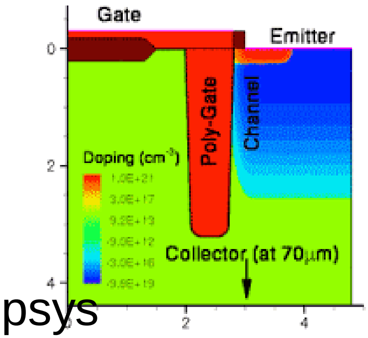
1) Solid-state power control systems will continue to become increasingly prevalent, supplanting electromechanical equipment, and opening new applications never before feasible. Fewer and fewer new applications can be satisfied by the efficiency, the degree of control, the reliability, or the response speed obtainable from anything but a solid-state switch.

Power Electronics—Emerging from Limbo

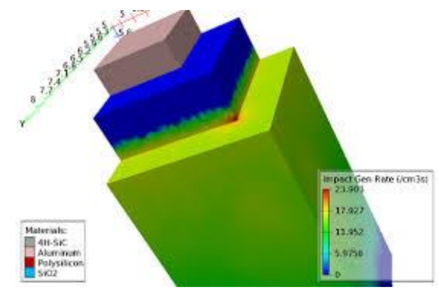
WILLIAM E. NEWELL, SENIOR MEMBER, IEEE

2) Computer-oriented circuit analytical and device modeling techniques will be developed and will displace present design techniques, making possible greater optimization, increased reliability, and reduced cost in both standardized and custom equipment.

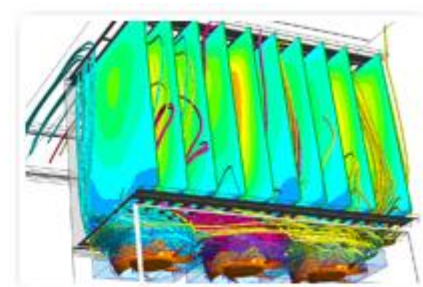
Eventually the insight gained will lead to new unified theoretical approaches suited to the analog versus digital, time versus frequency, device versus circuit, steady-state versus dynamic dilemmas which constrain present approaches. In other words, power electronics will have become a discipline.



Synopsys



Silvaco



Ansys

Power Electronics—Emerging from Limbo

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3) As the dollar volume of the high-power solid-state device market grows, greater research and development in this area will be justifiable. A thorough understanding of charge dynamics and thermal flow will lead to new and improved power device technology, analogous to the rapid evolution which is characteristic of small-signal device technology. Turn-off devices will become commonplace, and conventional devices will be manufactured with smaller spreads in key parameters to permit easier cascading in series/parallel arrays.

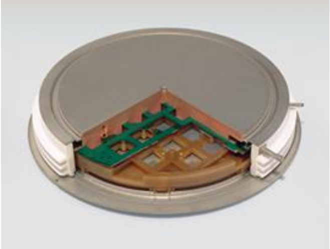

Figure 1: 10kV IGCT module using the HPT IGCT technology

Power Electronics—Emerging from Limbo

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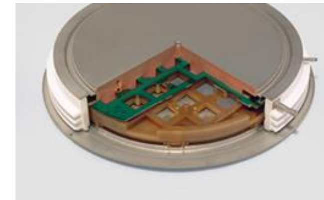
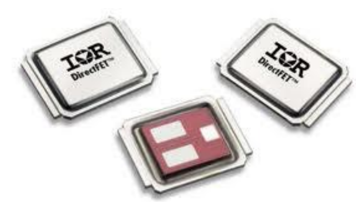


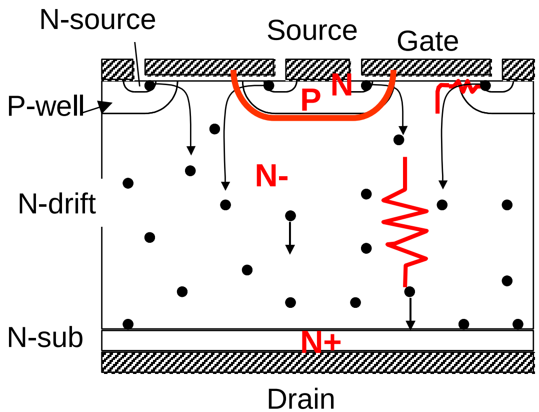
4) Standardized, general-purpose switching modules will become available to serve a greater variety of functions. Increased production runs and the elimination of custom design of many individual units will permit cost reductions without sacrificing reliability. Most low-level control circuits will be assembled from standard types of integrated or hybrid circuits.

5) University education
6) Professional society, conference

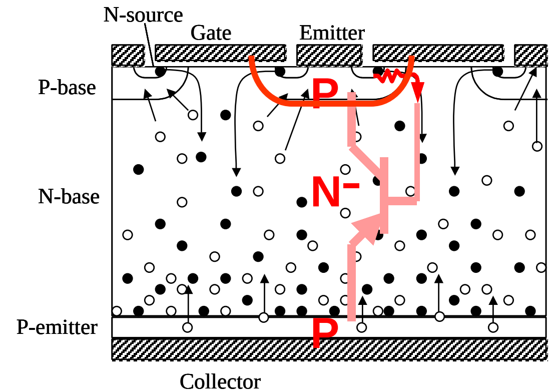


Types of power semiconductors(Switch)

Power MOSFET

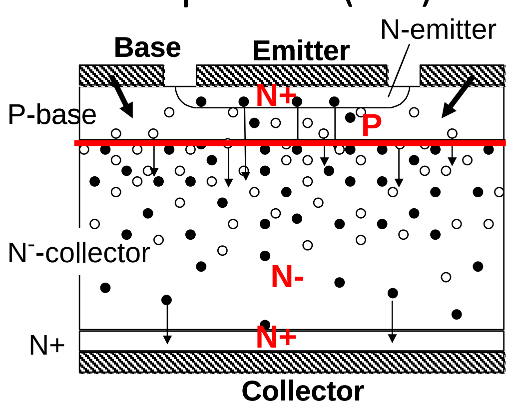


IGBT

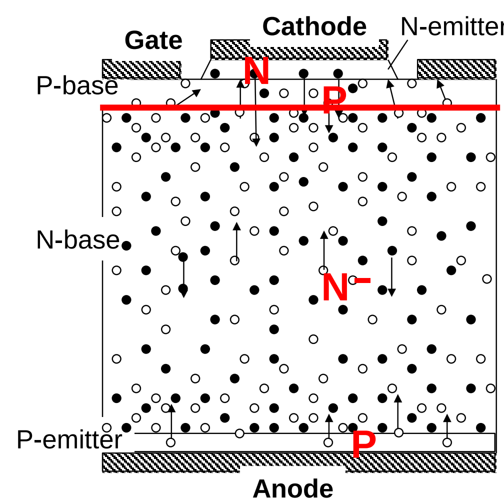


IGBT: Insulated Gate Bipolar Transistor
GTO: Gate Turn-off Thyristor
GCT: Gate Commutated Turn-off Thyristor

Bipolar Tr (BJT)



GTO(GCT)



1. MOS-gate (voltage) control or bipolar gate (current) control
2. Unipolar conduction or bipolar conduction in high resistive layer(N^-)

1988-Proc. of the IEEE

Power semiconductor Devices: An Overview
Phil Hower, Proc. of the IEEE, Vol. 76, No. 4, 1988

Many candidates in 1988

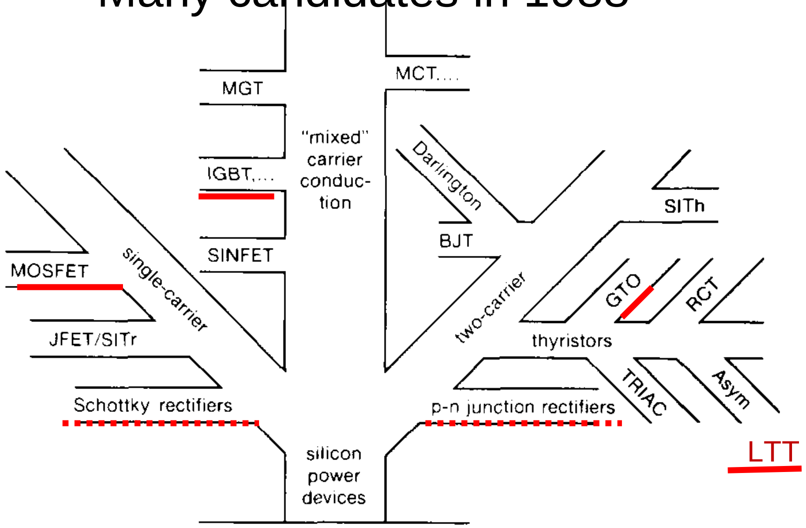
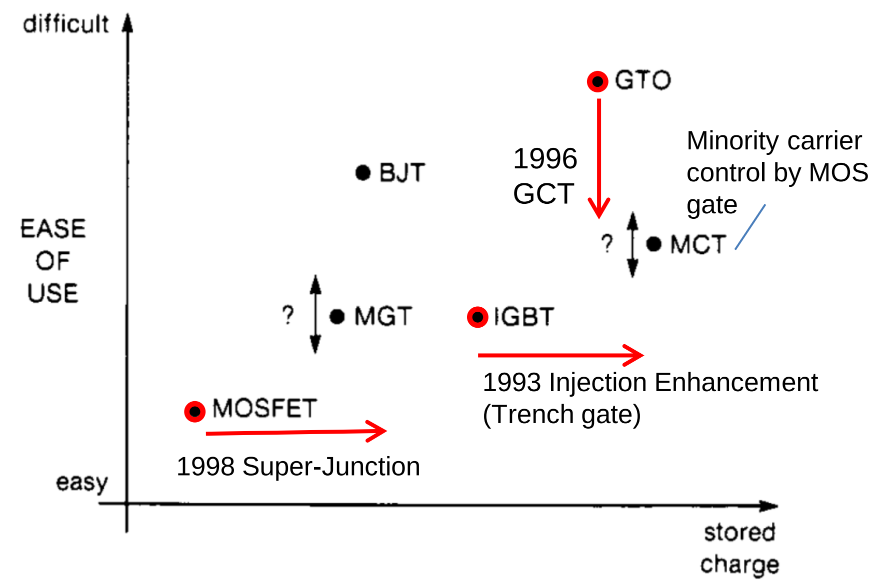


Fig. 5. Silicon power device "tree."



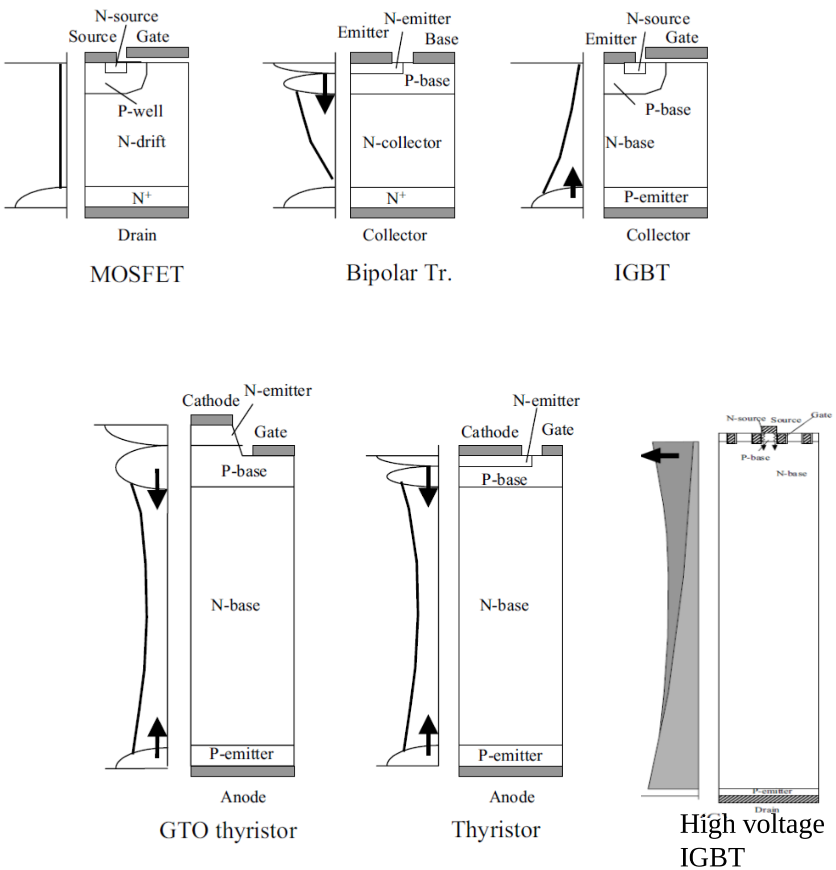
Conduction charge

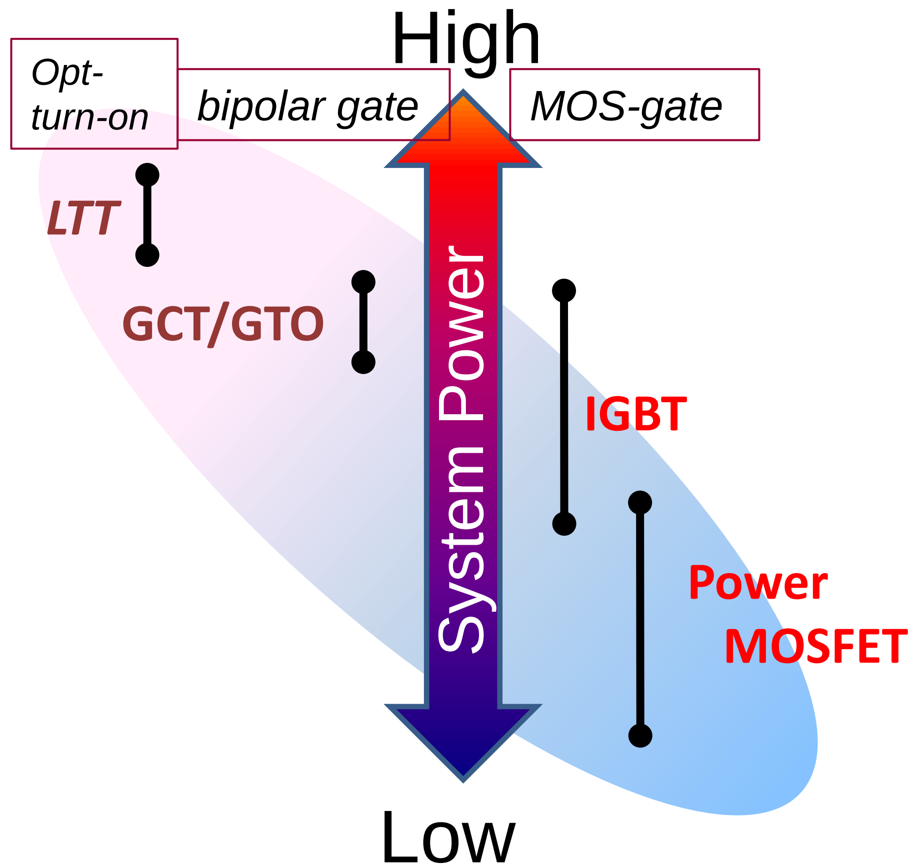
1. Majority carrier control by MOS channel
2. Increase in stored (conduction) charge
3. Integration (Gate drive circuit etc.)

See also, by the same author "Current Status and Future Trends in Silicon Power Devices", Tech. digest IEDM 2010, pp. 13.1.1-13.1.4, 2010

IGBT: Insulated Gate Bipolar Transistor
GTO: Gate Turn-off Thyristor
GCT: Gate Commutated Turn-off Thyristor

Types of Power Semiconductors





IGBT: Insulated Gate Bipolar Transistor
GTO: Gate Turn-off Thyristor
GCT: Gate Commutated Turn-off Thyristor
LTT: Light Triggered Thyrisotor (optical fiber coupled)

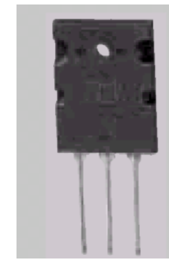
- MOS gate devices cover wide-power range.
- Bipolar gate devices cover very high power applications(>10MW).

Silicon Power Devices (Switches)

Power MOSFET

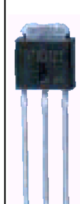
Advanced CMOS (FIVR)

650V-50A

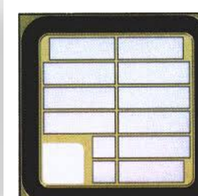


IGBT

200V-600V
5A-40A

SOP-8	DP		TO-220NIS
	straight leads	formed leads	
			

4.5kV-2600A



IGBT：Insulated Gate Bipolar Transistor

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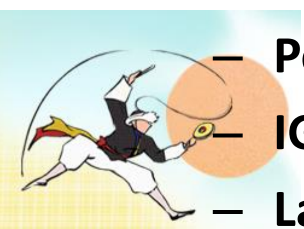
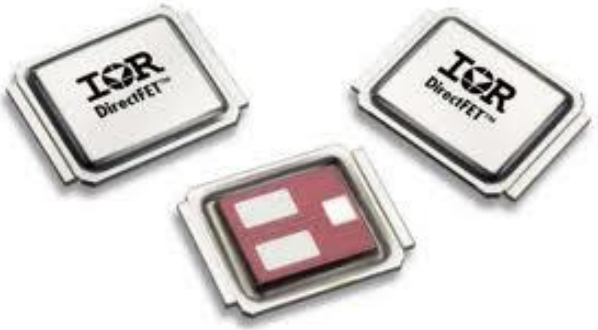
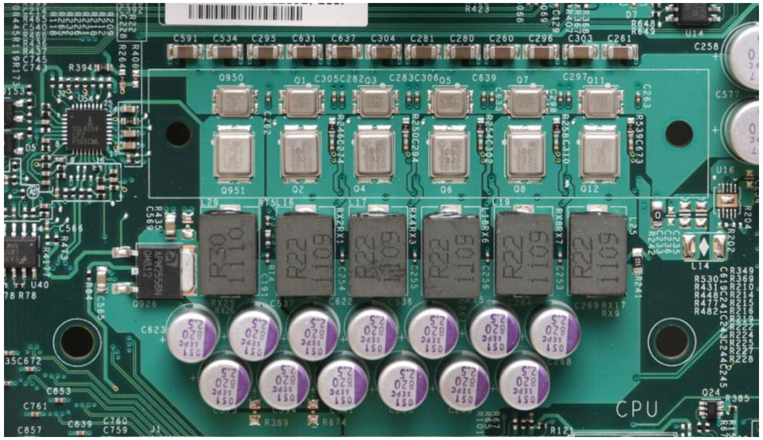
- **Present status explanation**



  - **Power MOSFET**
  - **IGBT**
  - **Lateral Device**
  - **Wafer technology (Silicon)**
  - **Simulation technology**
- **Future**

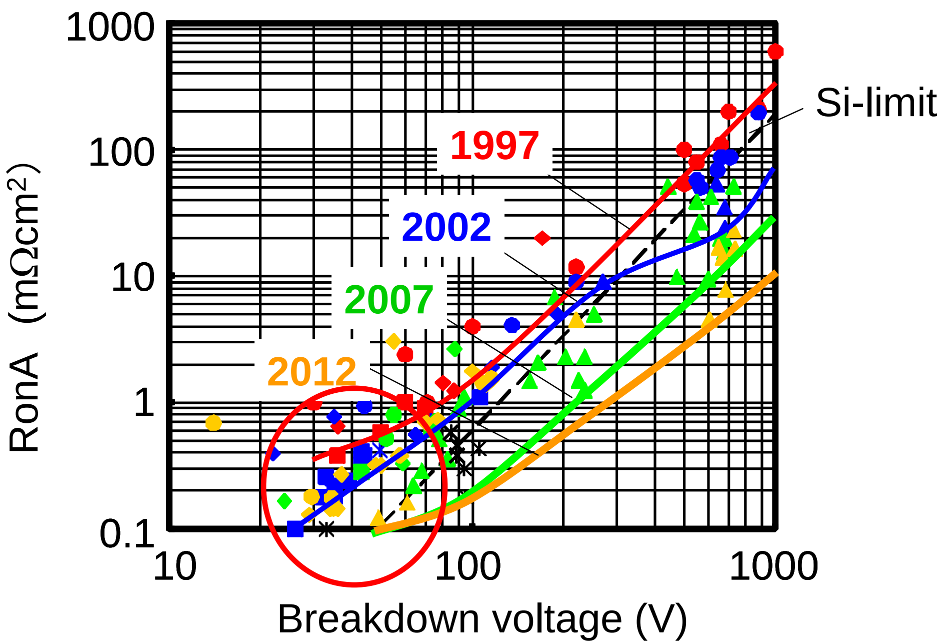


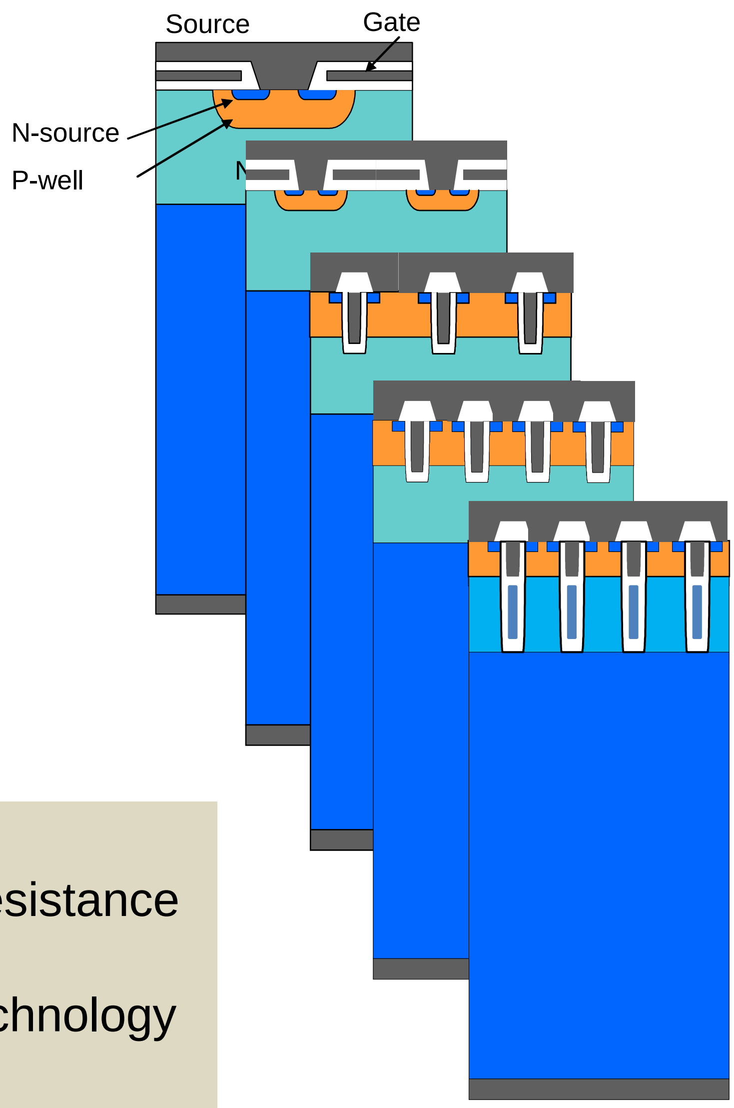
Power MOSFET



Low Voltage MOSFET (Vertical)

Fig from Lecture Slide by
W. Saito, Toshiba

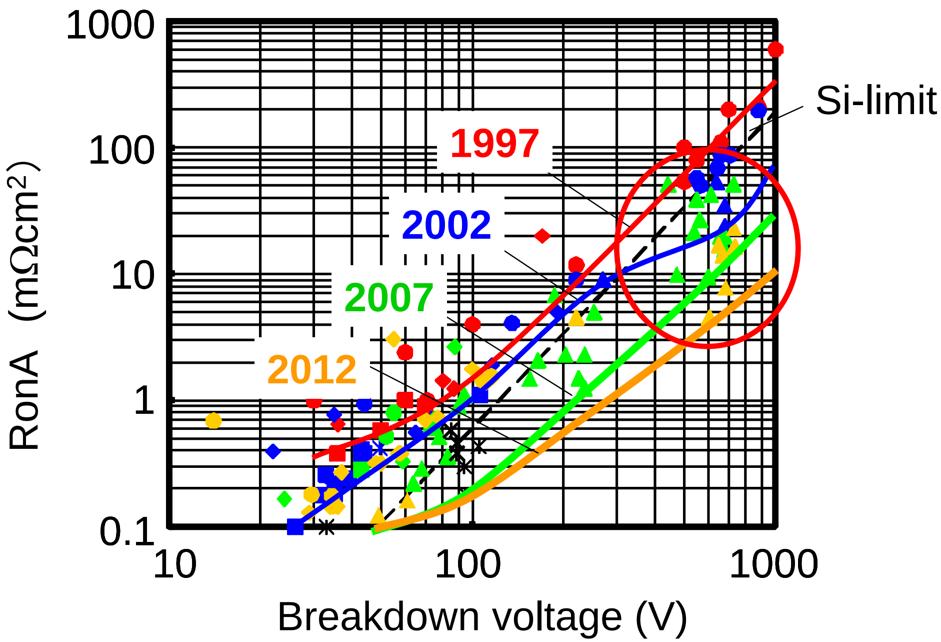




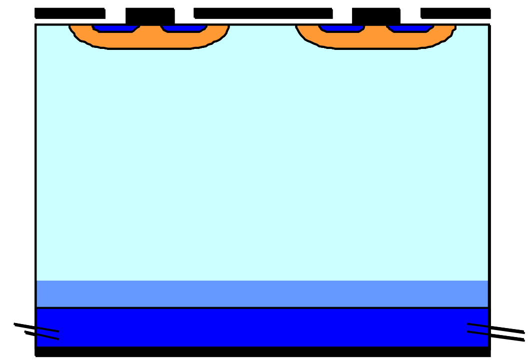
1. Cell size reduction for channel density
2. Trench gate for channel density and JFET resistance removal
3. Charge compensate (Vertical Field Plate) technology for drift resistance reduction.

Super Junction MOSFET

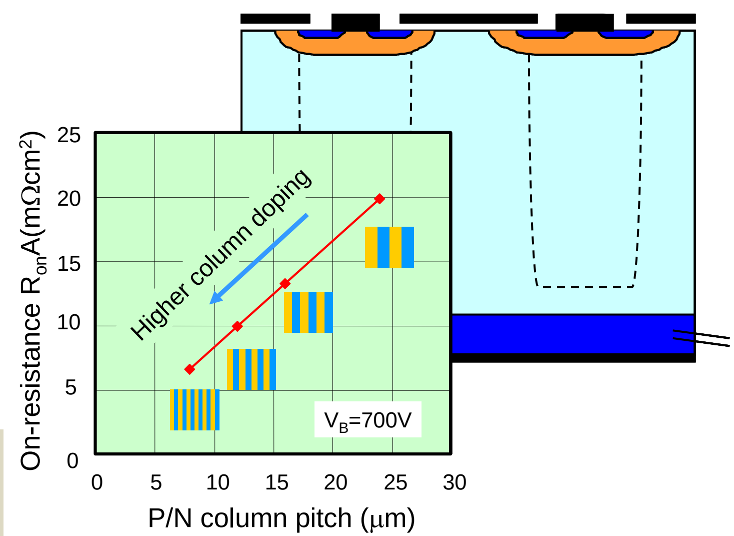
Fig from Lecture Slide by
W. Saito, Toshiba



DMOSFET



SJ-MOSFET



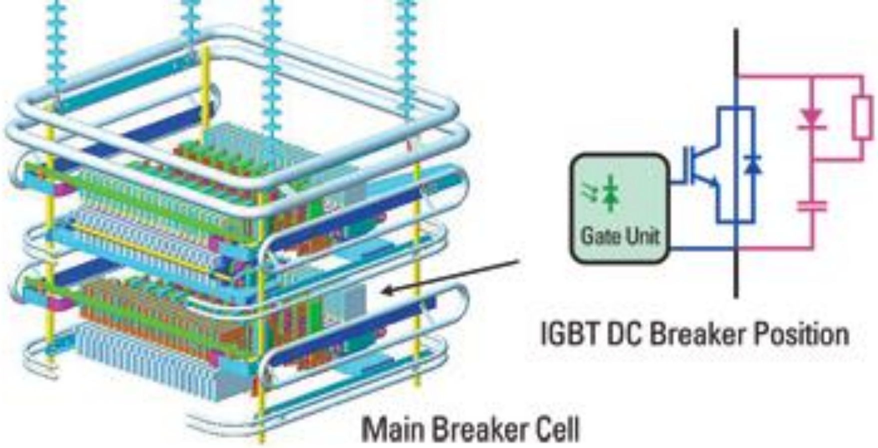
P/N column drift layer

➔Easy to deplete for high impurity concentration

➔Low Ron + High Breakdown Voltage

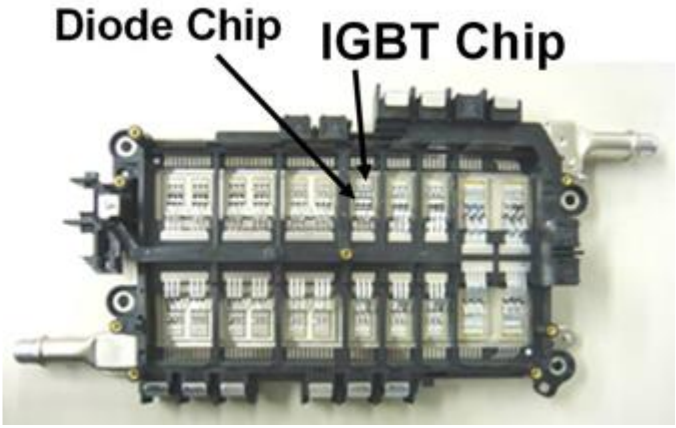
Charge compensate (Super Junction) technology for drift resistance reduction.

=> Fabrication process challenge

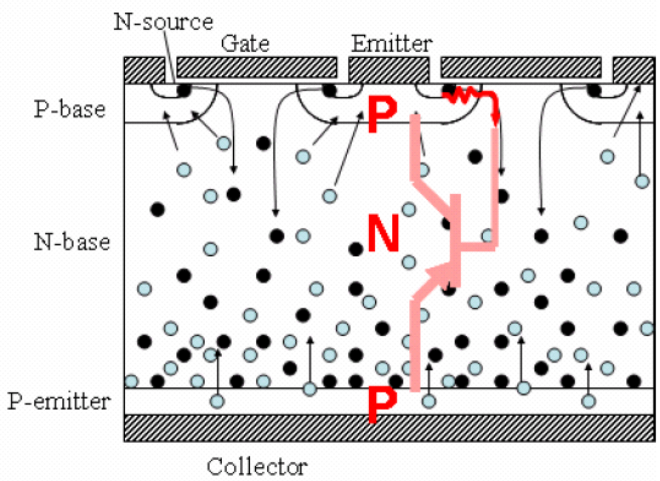


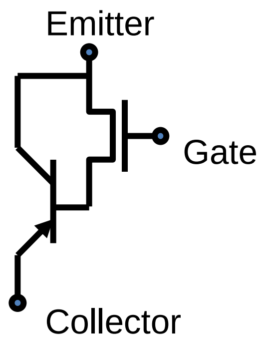
IGBT

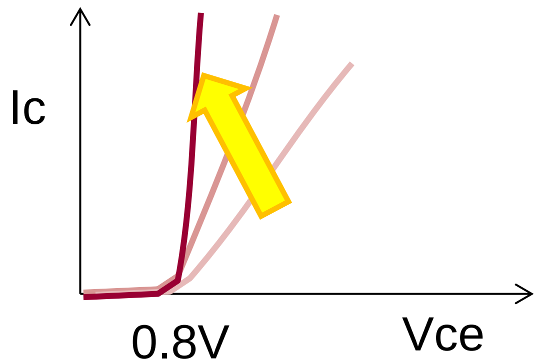
Insulated Gate Bipolar Transistor



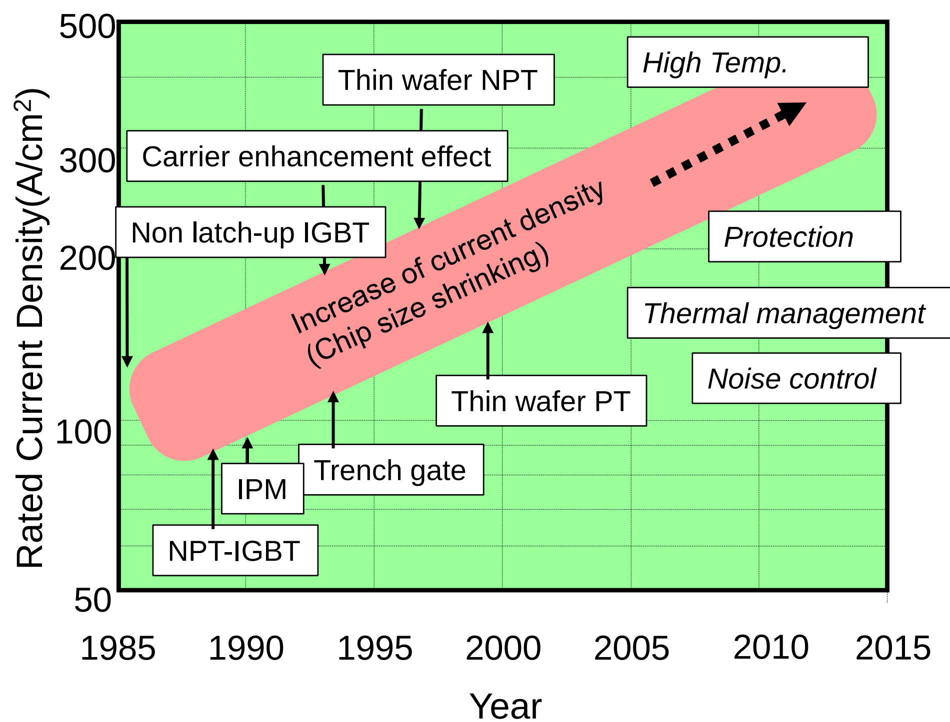
IGBT







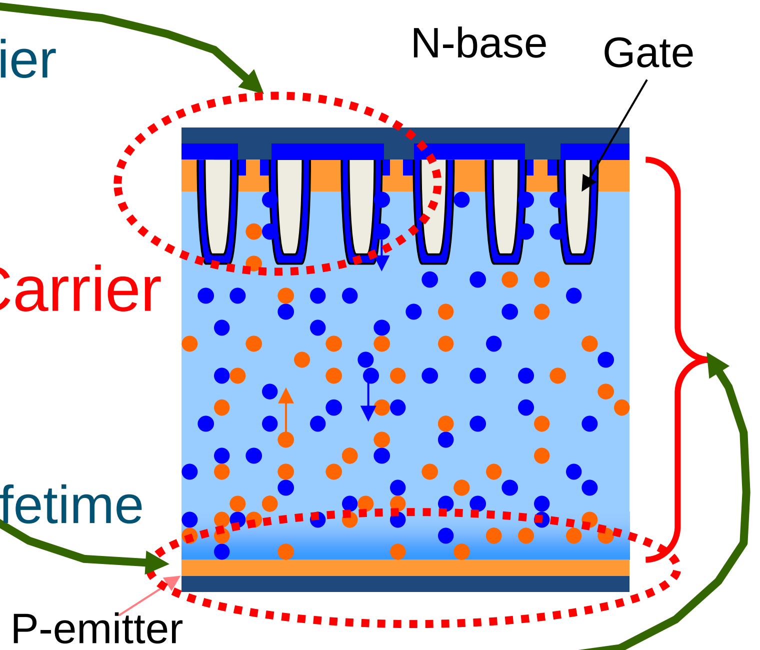
Shen, Omura, "Power Semiconductor Devices for Hybrid, Electric, and Fuel Cell Vehicles" Proc. Of the IEEE, Issue 4, 2007



1. Bipolar Transistor + MOSFET (before IE-effect)
2. High current capability
3. ~0.8V collector-emitter threshold voltage for conduction
4. Medium switching speed (15kHz for motor drive, 100kHz for ICT current supply and FPD driver)

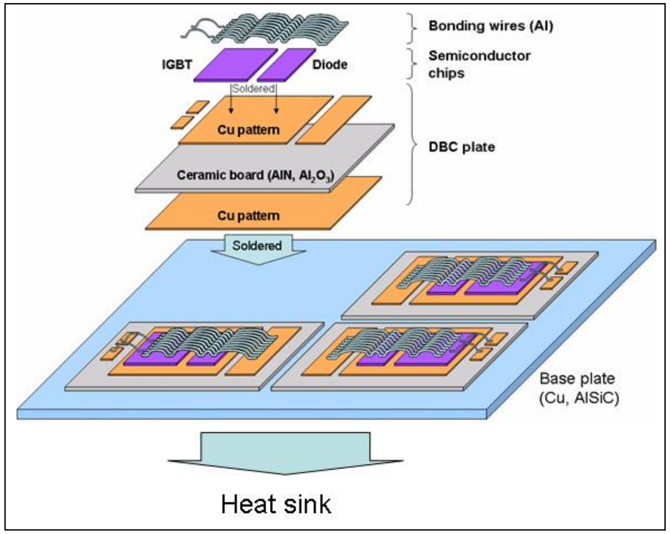
Summary of IGBT Technology

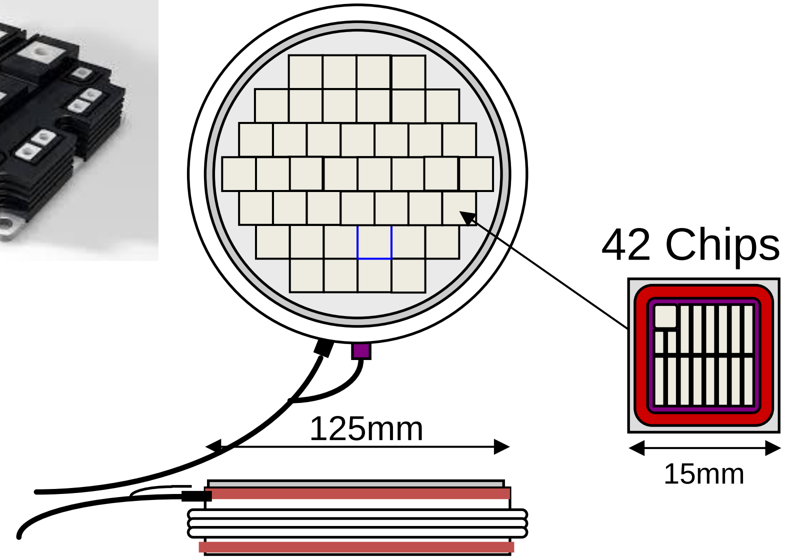
- Trench Gate for Low Vce(sat)
  - –Electron injection enhancement and carrier storing for higher carrier density
  - –Reduction of channel resistance etc.
- Low Hole Injection P-emitter + Long Carrier Lifetime
  - Reduction of turn-off tail current
  - Better thermal coefficient without carrier lifetime killer
- Thin Wafer Technology
  - Reduction of turn-off tail current with short N-base
  - Reduction of conduction loss with short N-base

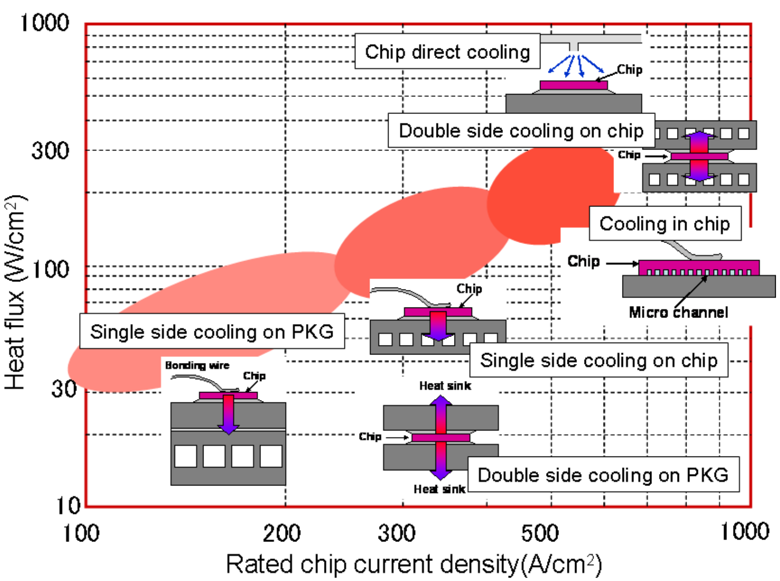


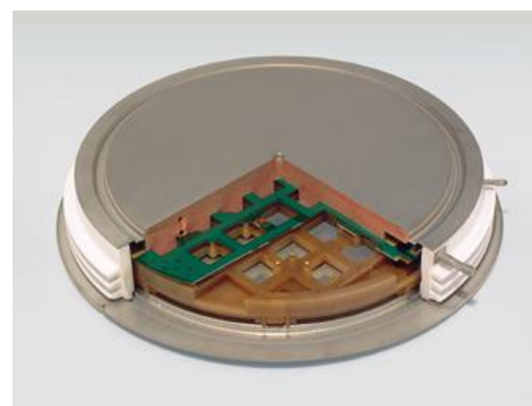
Examples of High Power IGBT Package

Shen+Omura, Proc. of the IEEE, 2007









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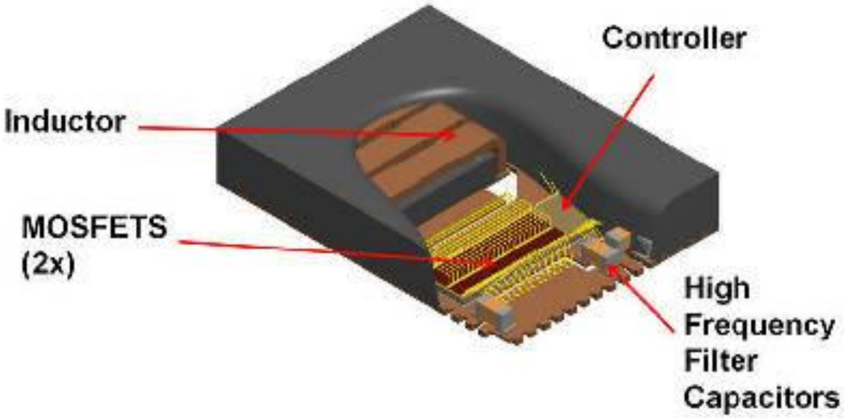
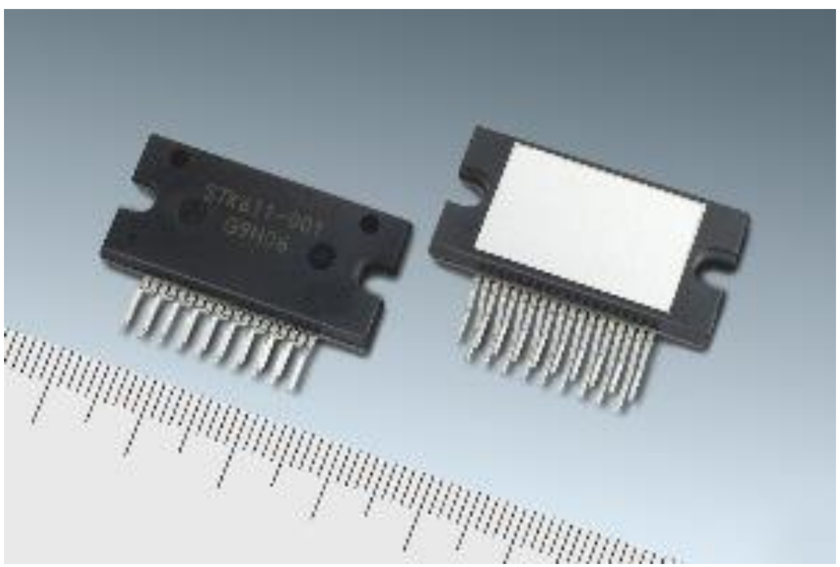


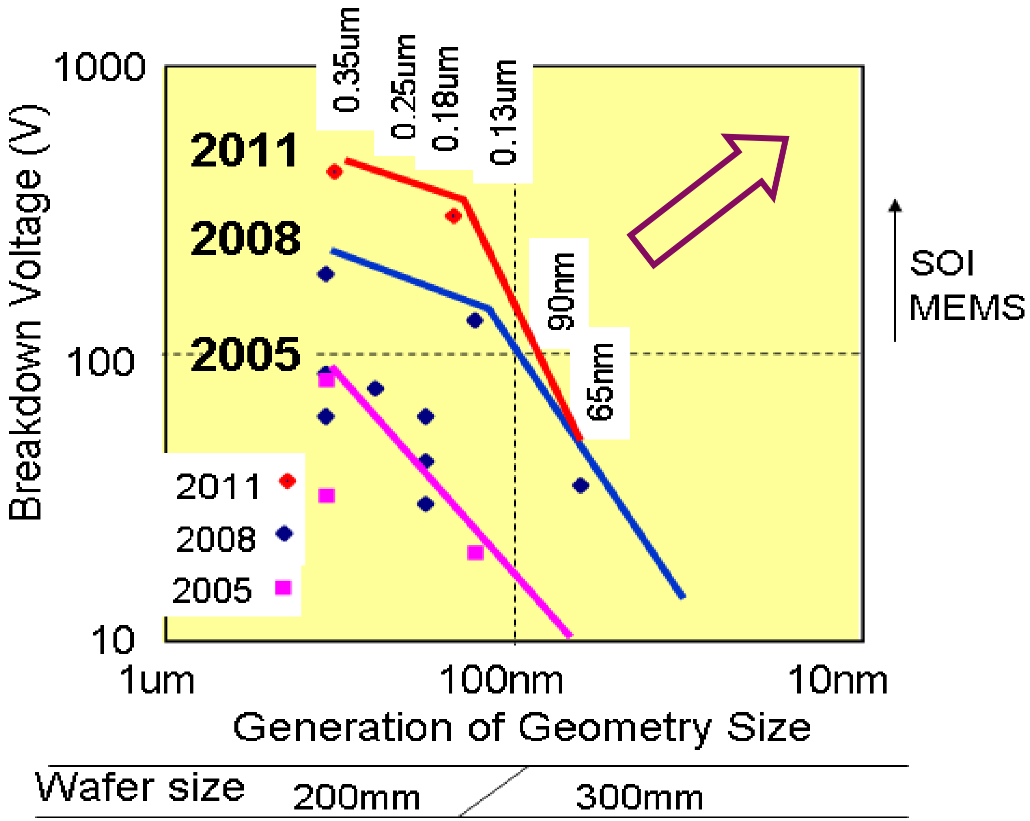
Figure 1: Vicor VI Chip PRM Modules can provide up to 500 W from a 7-cm2 package.

Lateral Power Device



High compatibility to CMOS for high performance and new functions

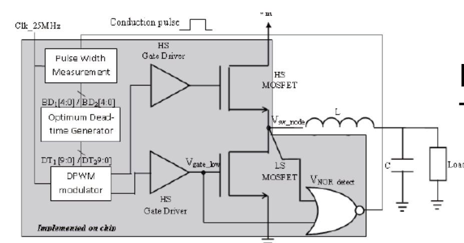
Power IC V_{BK} in ISPSD papers



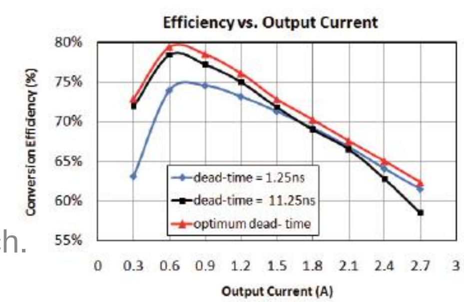
Omura, ECPE workshop Jan. 2012

Future HV Power IC will be …

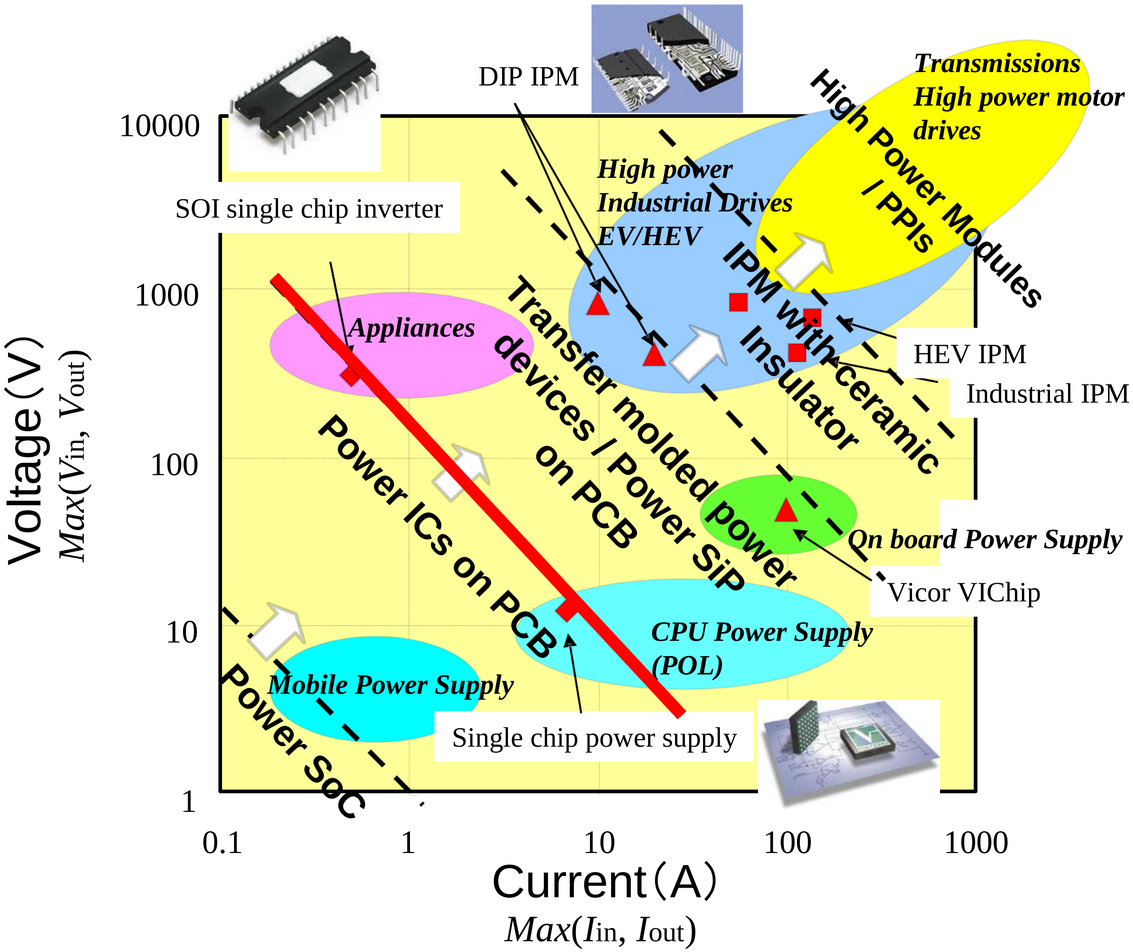
Digital Rich
Power IC



ISPSD 2010
Toronto Univ



Higher power range to cover volume zone



Omura, CIPS 2010

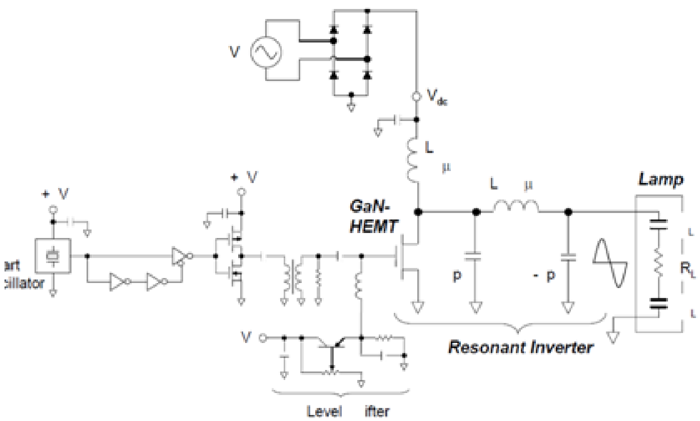
Future HV Power IC will be …

Kilowatt

Power IC

Heat pumping

High switching frequency for new applications



Future HV Power IC will be …

Mega-Hz

Power IC

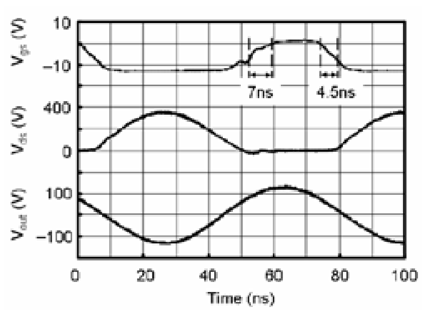
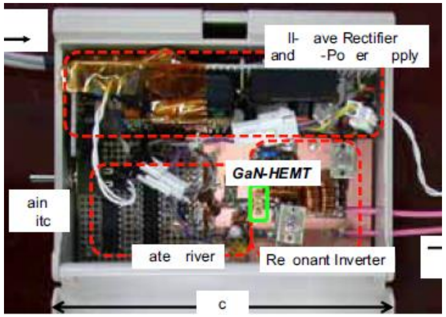
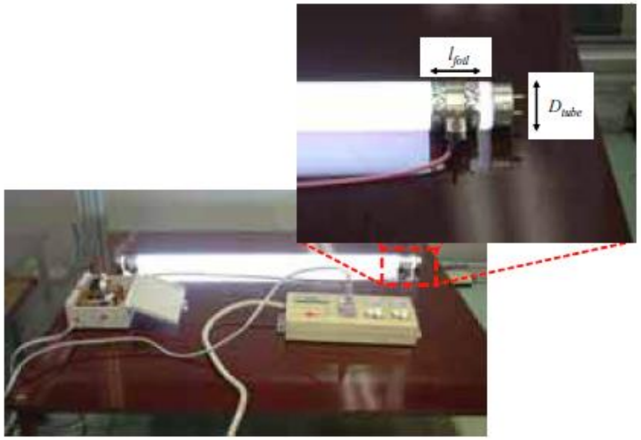


Figure 7. Operating waveform of the demonstrated 13.56 MHz resonant inverter circuit.

13.56MHz
90%

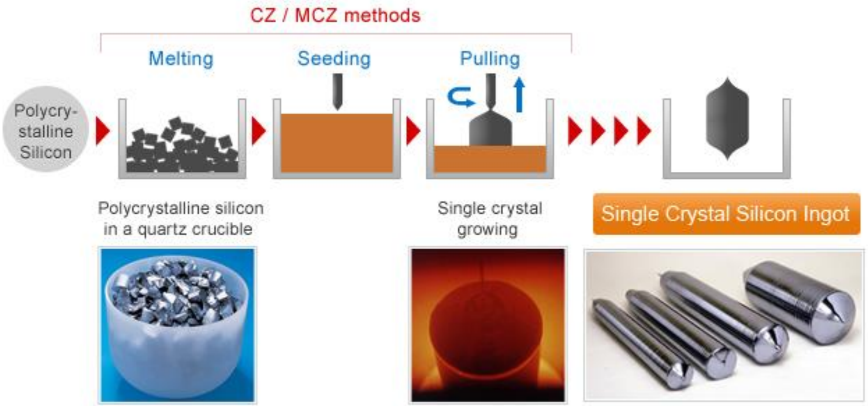
Saito et al.(Toshiba) PESC 2008

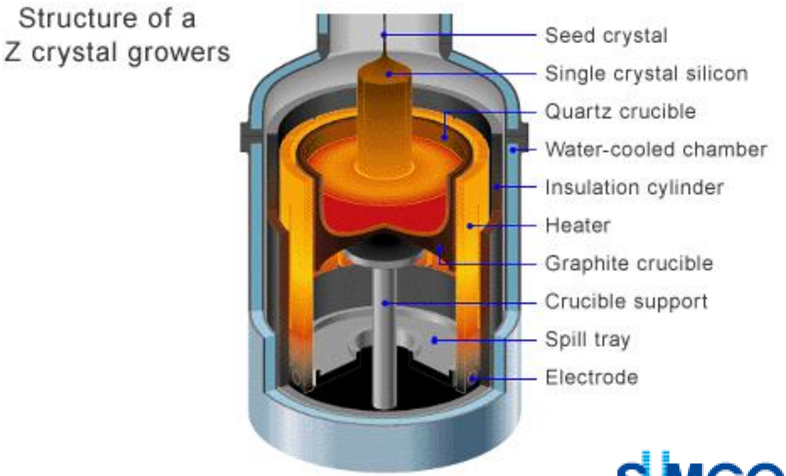




Electrode-less lamp with GaN-HEMT (Toshiba)

Wafer technology





SUMCO

Silicon wafer trend

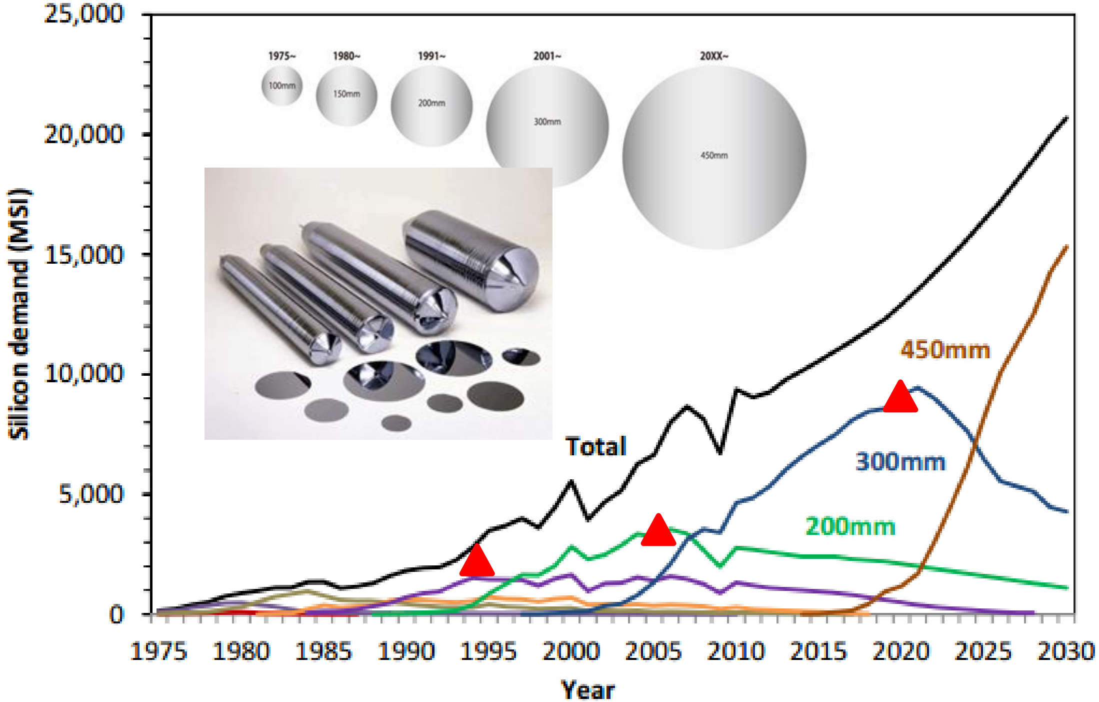
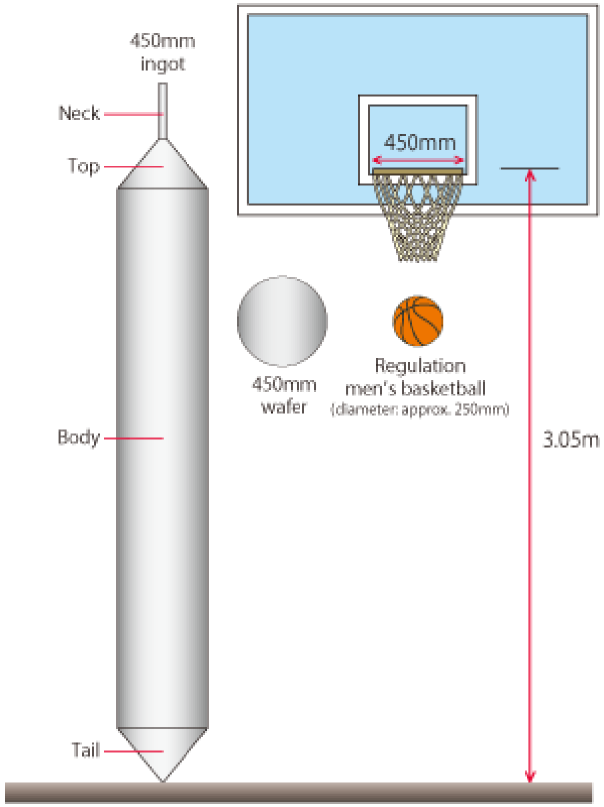


Figure 4. Worldwide Silicon Demand by Wafer Size [2].

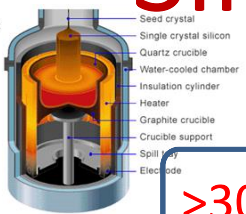


Interestingly, it is estimated that a 450mm silicon ingot would be roughly the same diameter and height as a basketball hoop.

Strong productivity of wafer to meet huge demands

Silicon wafer technology

Structure of a CZ crystal growers



Productivity

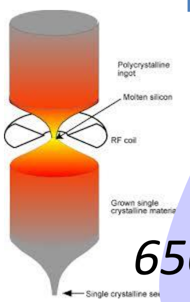
>300mm, **CZ, MCZ**

Large Market, Short time to market

1200V IGBT
1200V PiN diode

Low voltage commodity

Material (wafer) engineering will share the major part of total power device design, fabrication and PE application

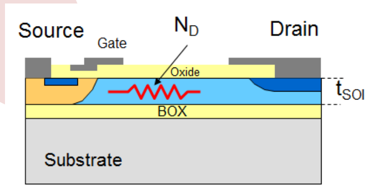


6500V PiN diode

6500V IGBT

Thyrisotrs

High voltage power MOS



Special Power Devices

Quality

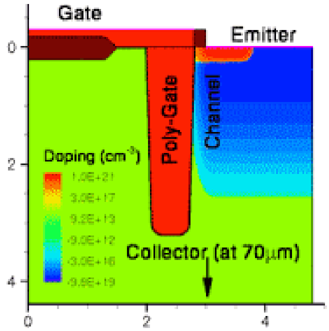
Smaller Market, Long term

Long carrier lifetime
150-200mm **FZ**

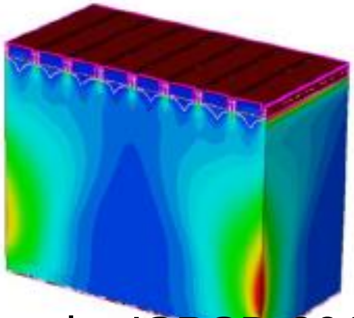
Functionality

Integration, Game change

Epi, SOI, SJ-structure etc
(Pre-structured wafer)

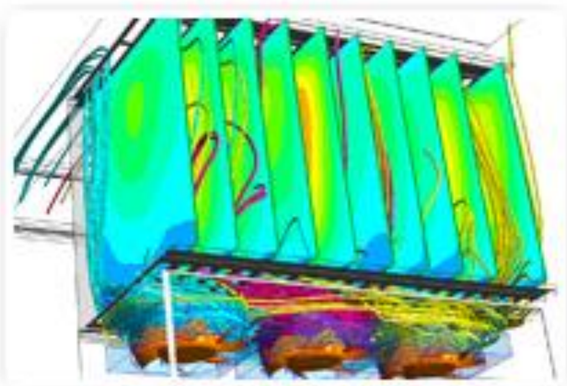


Synopsys

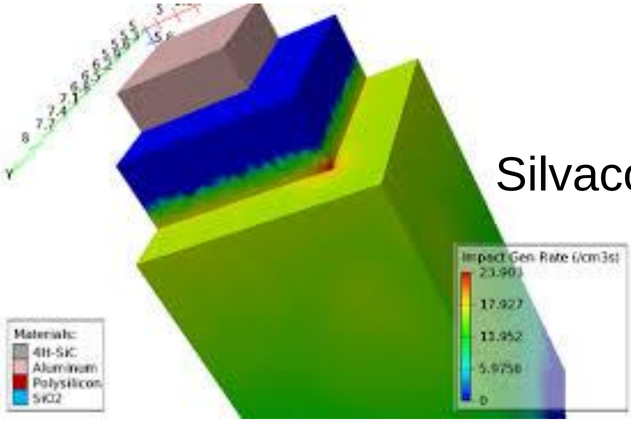


Tanaka ISPSD 2015

Simulation technology

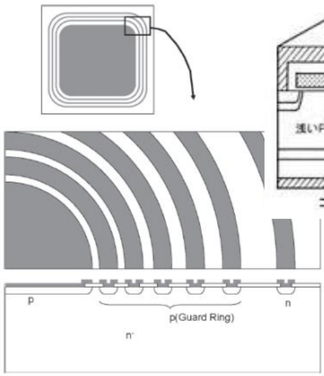


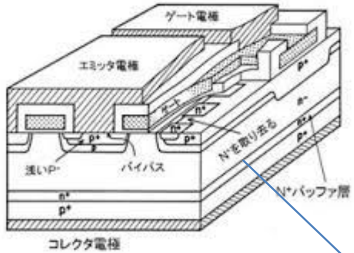
Ansys

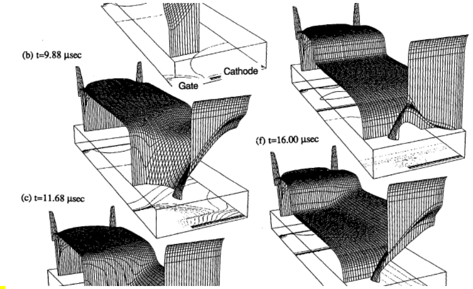


Silvaco

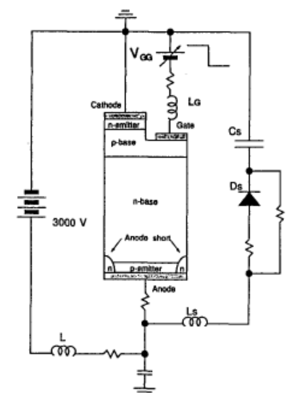
Simulation Technology advancement and new device R&D

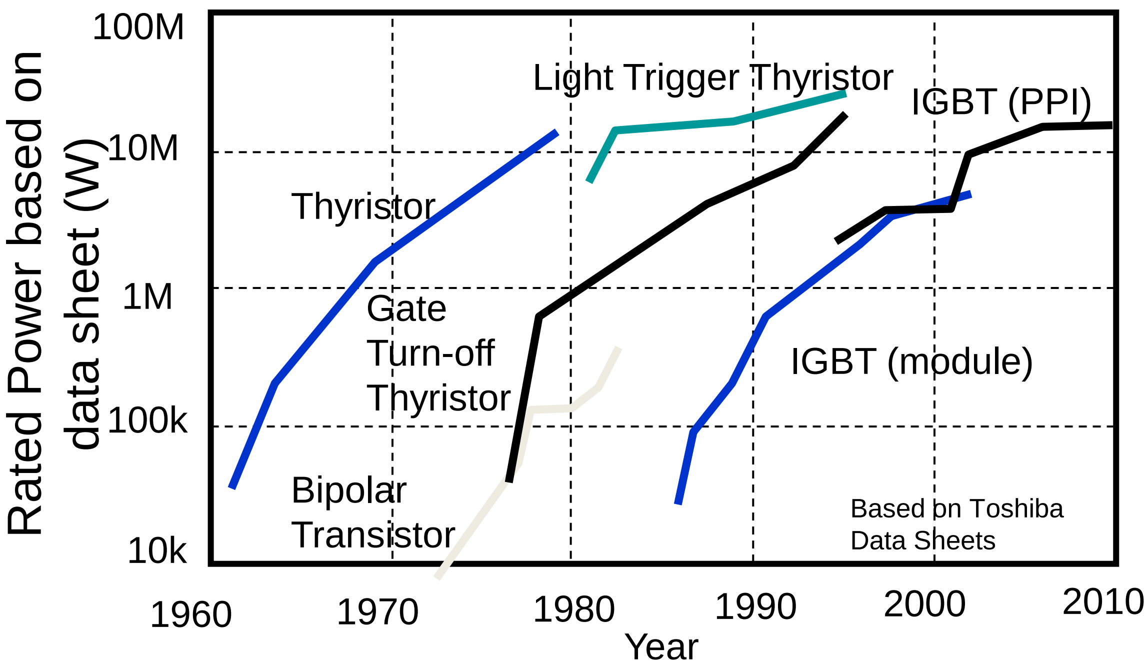






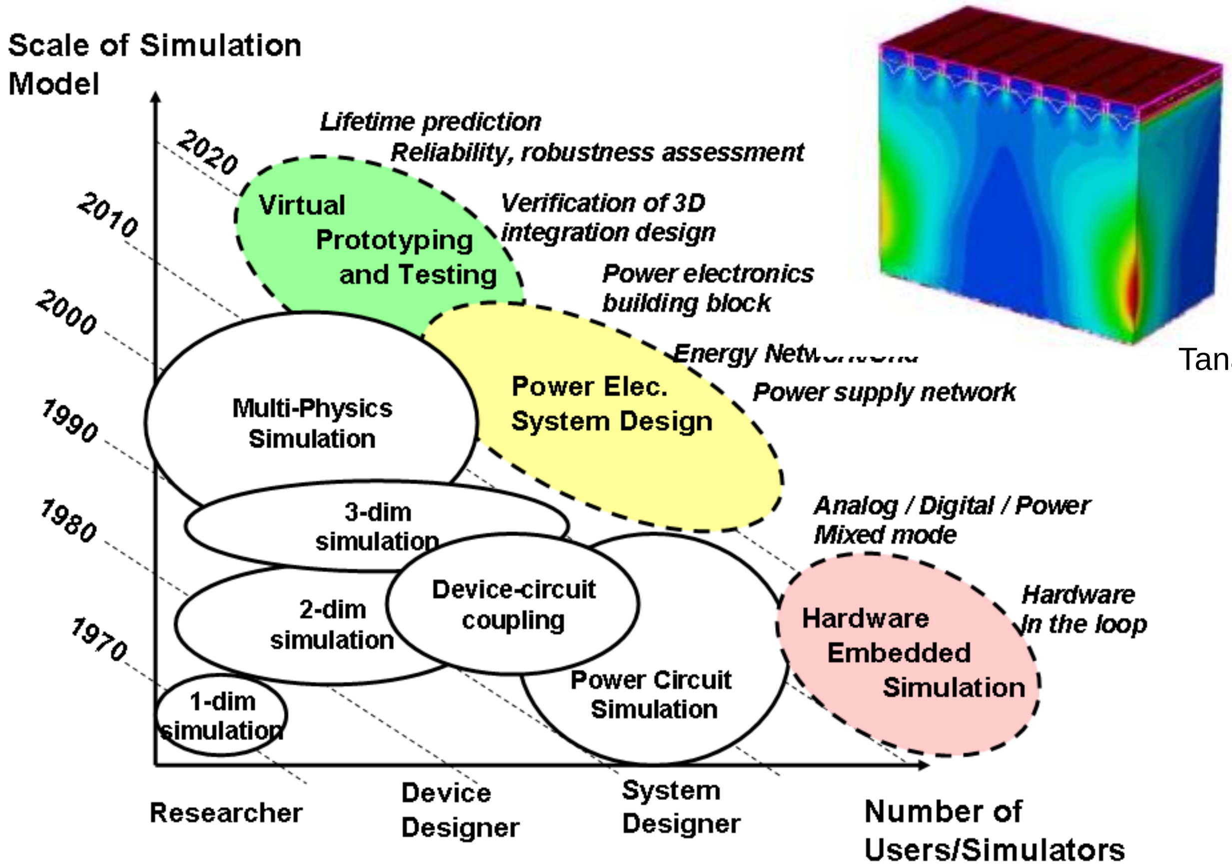
- Device failure simulation
- IGBT compact model
- Non-latch-up IGBT simulation
- 2-D Guard-ring simulation
- 1-D Thyristor numerical simulation
- 1-D PiN diode numerical simulation
- Analytical equation model





Simulation technology

H Ohashi, I Omura - IEEE transactions on electron devices, 2013



Tanaka ISPSD 2015

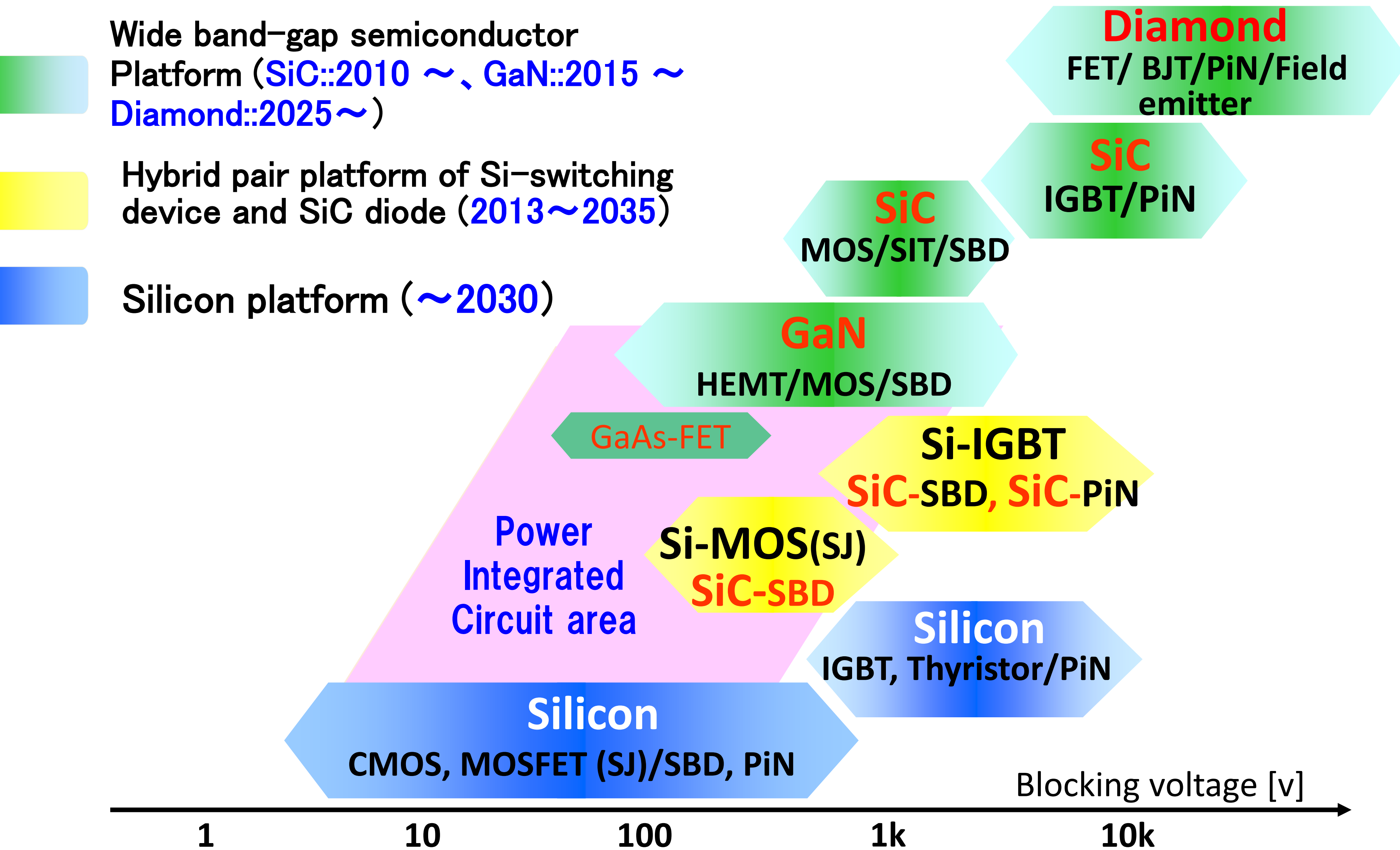
- Virtual prototyping and testing
- Power electronics system design
- Hardware embedded (real-time) simulation

See also Prof. Wachutka, ISPSD 2014 Plenary

Outline

- **Introduction:**
  - **Moore's law**
  - **Power electronics trends and Negawatt cost**
- **Past and Present overview of power semiconductor**
  - **Dr. Newell prediction, 1973 talk in PESC**
  - **Types of discrete devices**
- **Present status explanation**
  - **Power MOSFET**
  - **IGBT**
  - **Lateral Device**
  - **Wafer technology (Silicon)**
  - **Simulation technology**
- **Future**

Advanced power devices Road map



H. Ohashi et al. "Role of Simulation Technology for the Progress in Power Devices and Their Applications," IEEE T-ED, Vol. 60, issue 2, 2013.

Future possibility

- 1) Si-power devices still have much room for development toward ultimate MOSFETs and IGBTs.
- 2) The combination of Si-switching devices and SiC freewheeling diodes will be a significant step not only for strengthening the SiC market but also for Si-device development.
- 3) Si-IGBT will be replaced by SiC MOSFET in the voltage range of more than 1000 V in some applications, and SiC-IGBT has the potential to be used for applications of more than 10 kV. (Si-IGBT for volume market, SiC for high end market)
- 4) GaN power devices will replace some of Si-power ICs and will be used for faster switching applications.
- 5) The unique properties of diamond have potential for new power devices particularly in high-voltage applications.
- 6) The ultimate CMOS has the potential to be used for power integrated devices in ICT applications.

H Ohashi, I Omura - IEEE transactions on electron devices, 2013

H. Ohashi et al. “Role of Simulation Technology for the Progress in Power Devices and Their Applications,” IEEE T-ED, Vol. 60, issue 2, 2013.