III-N Compounds in Devices for Power Electronics

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OUTLINE

(Part 1)

POWER ELECTRONICS

(Part 2)

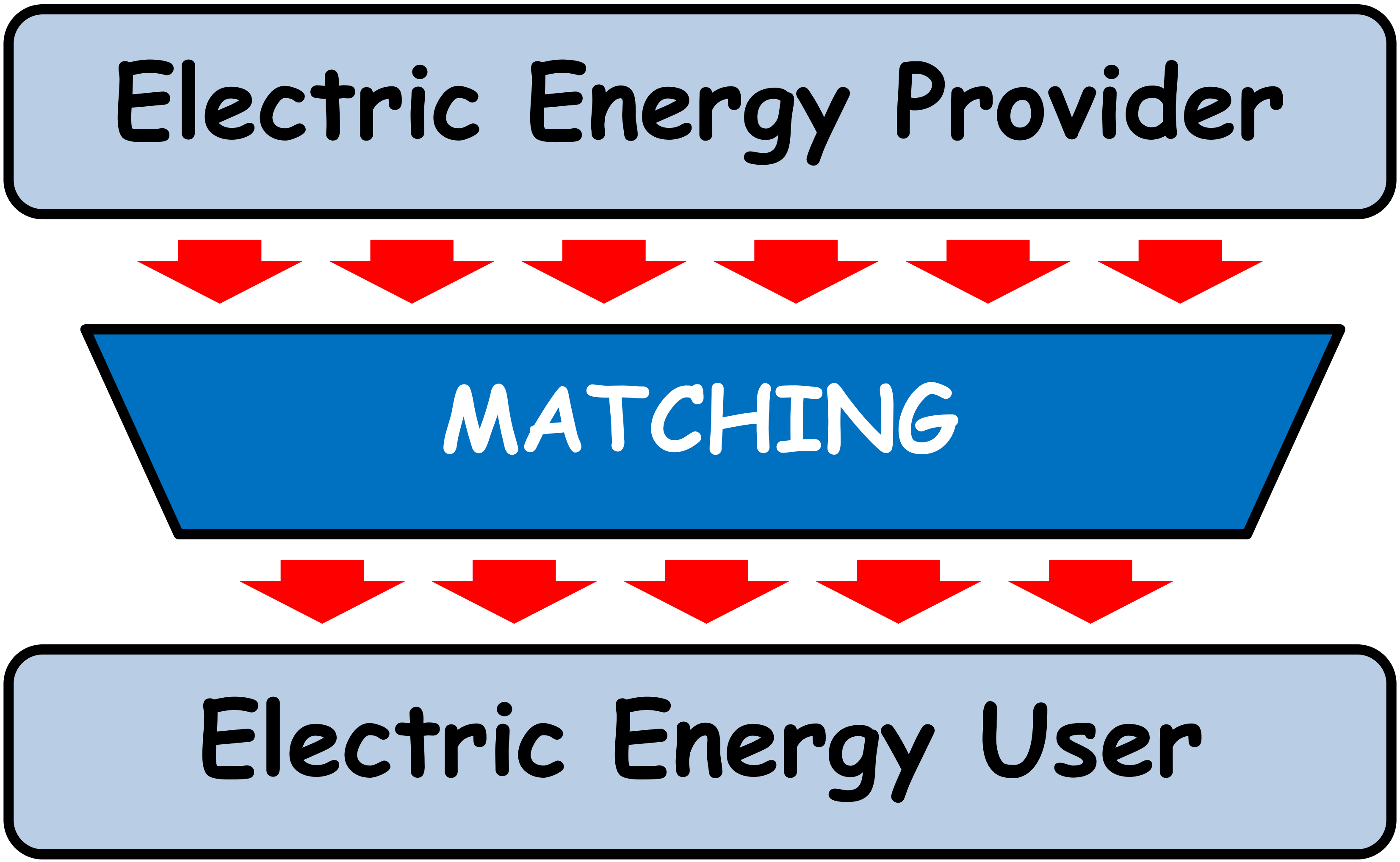
III-N vs OTHERS
for POWER ELECTRONICS

(Part 1)

POWER ELECTRONICS

Electrical Engineering
is all about
Matching
The Electric Energy
from
Source to User

STEP 1 : ELECTRICAL ENGINEERING



Matching What ?

(1)

Voltage / Current Ratio

=> Impedance

(2)

Frequency

Daylife Examples
of
End User's Requirements
for
Electric Energy

EXAMPLE 1

POWER MANAGEMENT

at home :

FIXED FREQUENCY
VARIABLE VOLTAGE

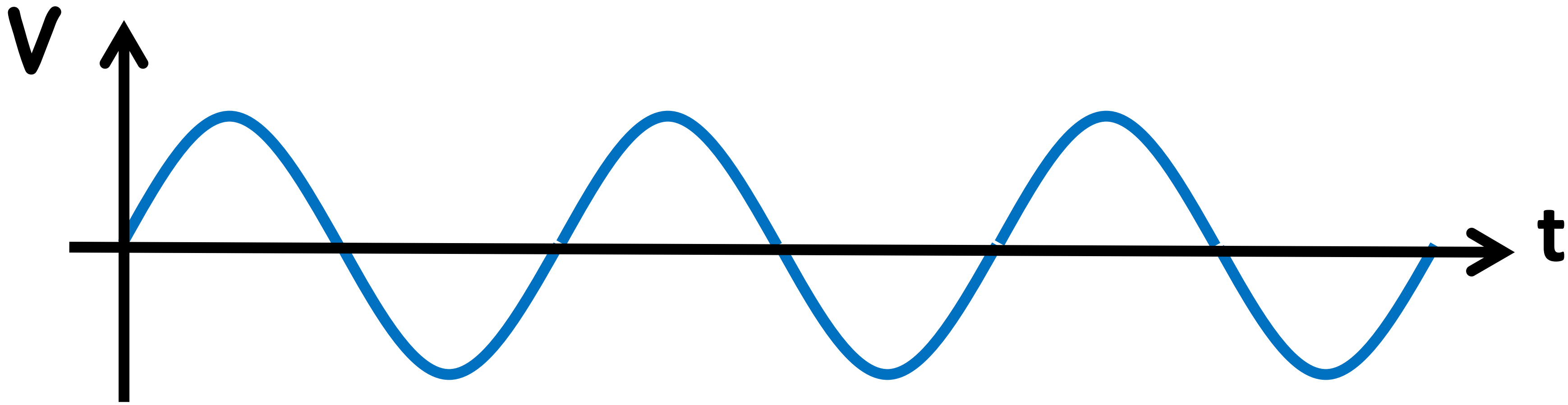
Daylife Systems
which require « Variable Electric Power »
(Variable Average Voltage)
from « Mains Supply »
240 V @ 50 Hz in Europe or 127 V @ 60 Hz in the USA

Halogen Lamp

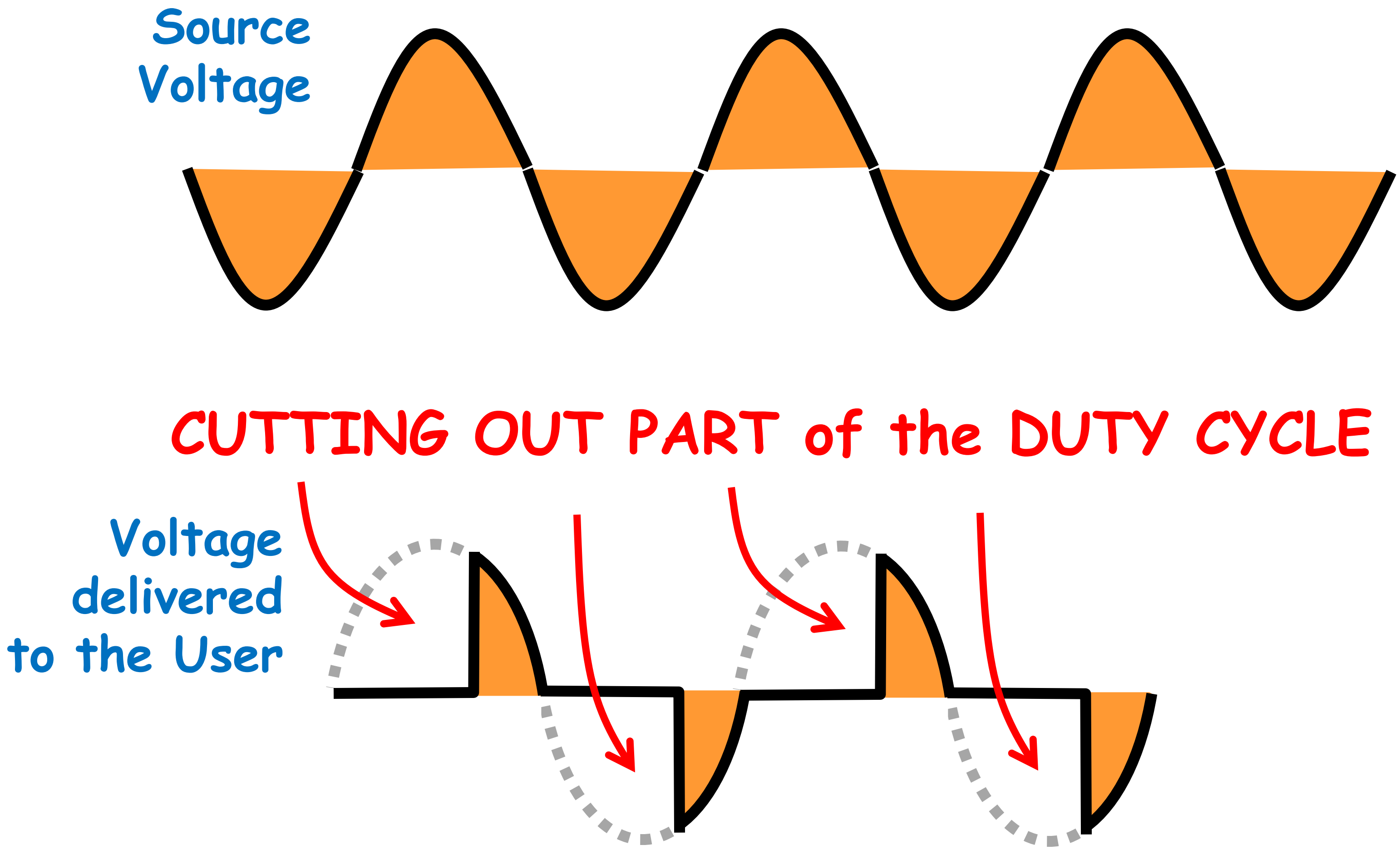
Vaccuum Cleaner

Hand Driller

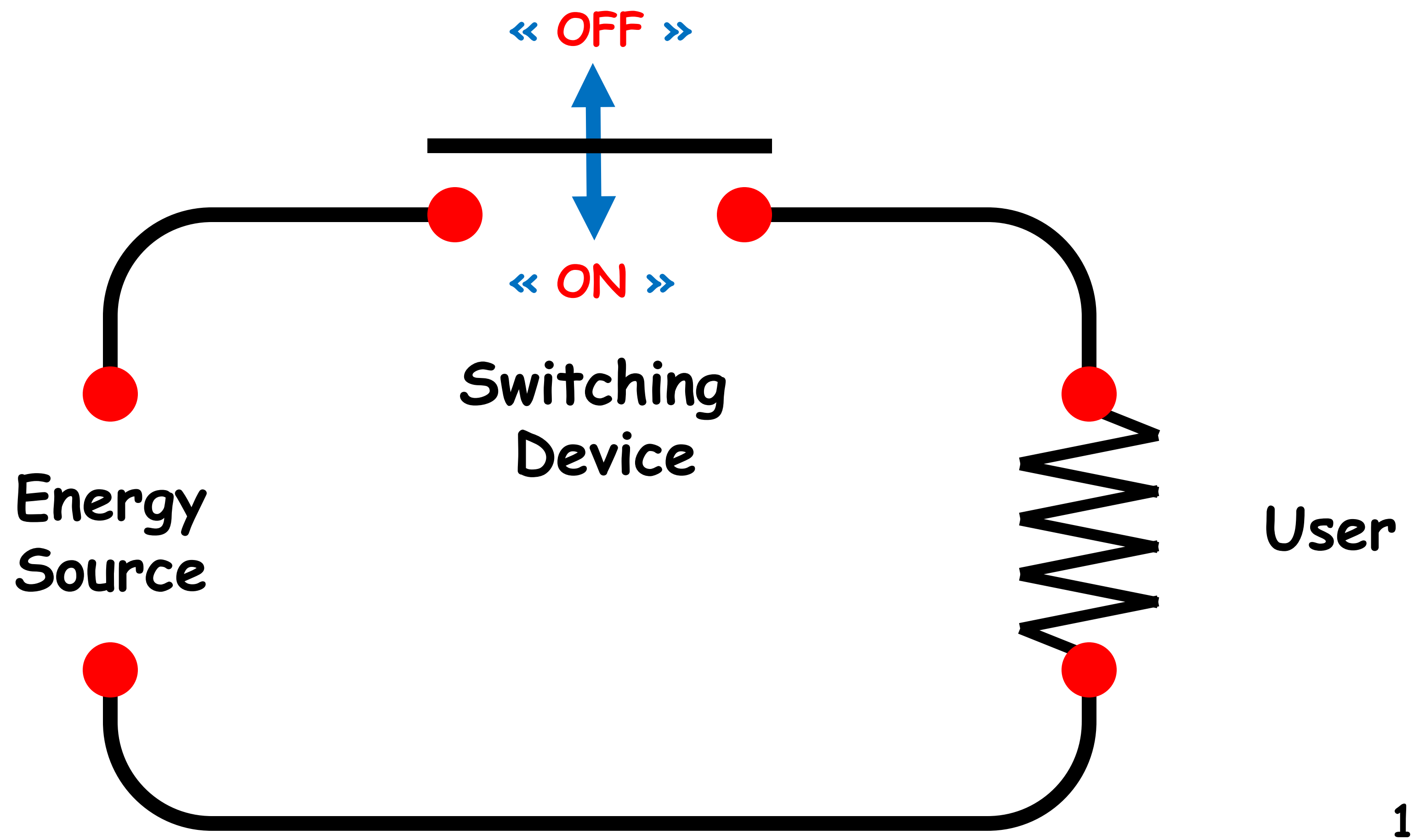
Electric Power Source



CHEAPEST ELECTRIC ENERGY CONTROL SYSTEM
DUTY CYCLE MANAGEMENT



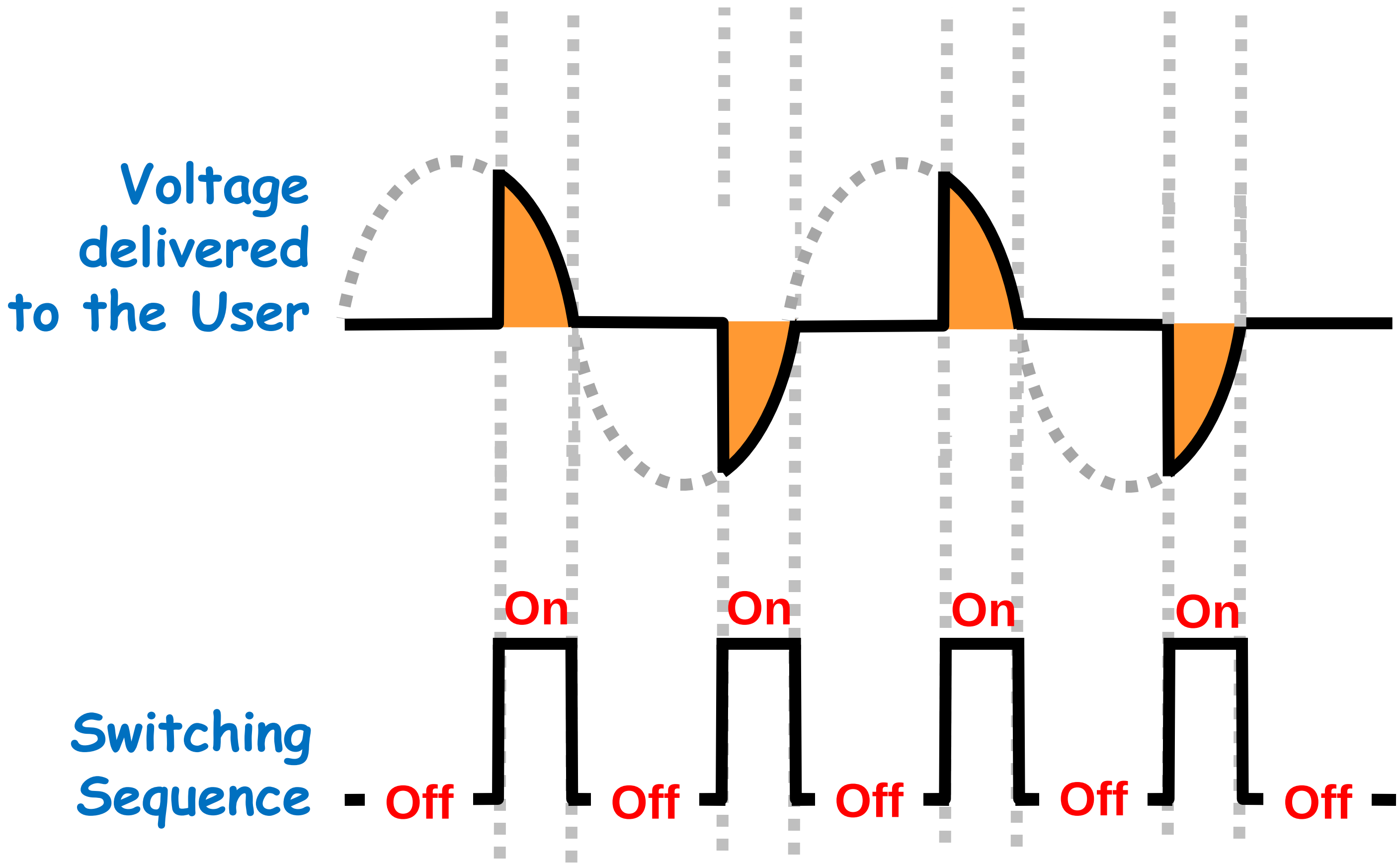
PRINCIPLE of DUTY CYCLE MANAGEMENT
Switching « ON » and « OFF » at the Right Periods



CHEAPEST ELECTRIC ENERGY CONTROL SYSTEM

DUTY CYCLE MANAGEMENT

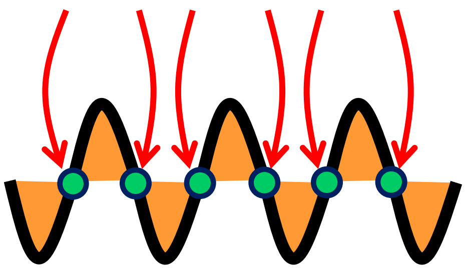
Control of the Average Voltage delivery

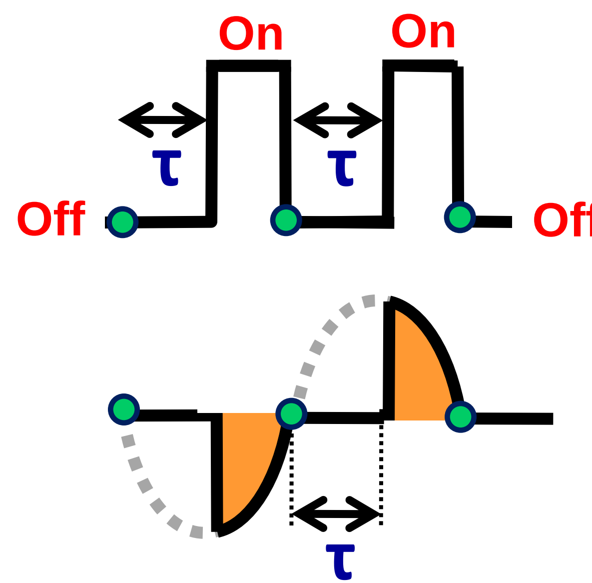


Synoptic of Switching Control System

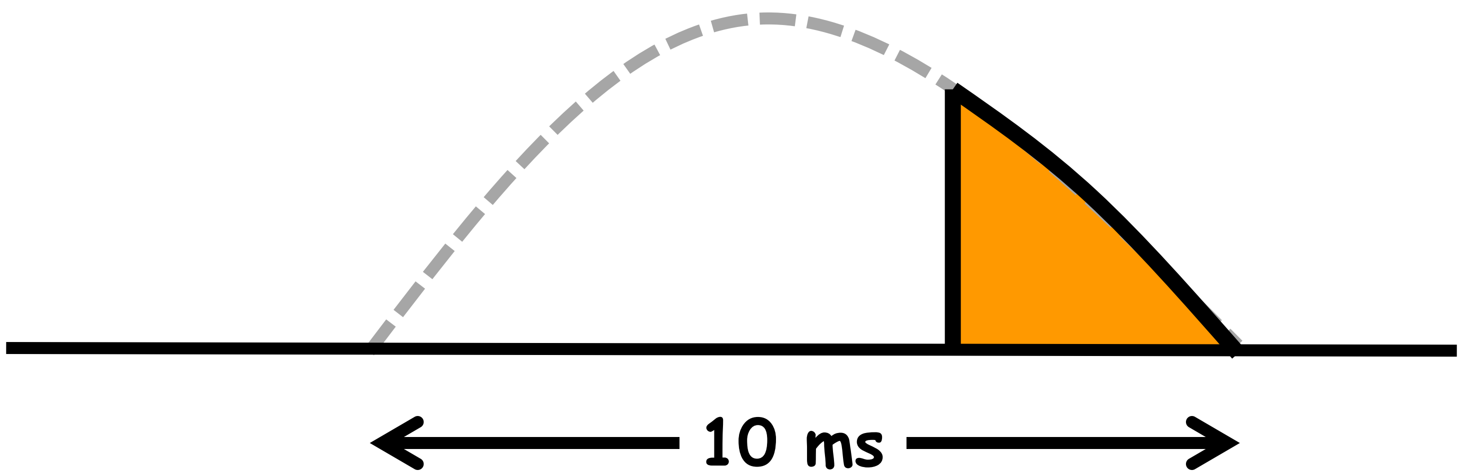
adjusting (τ) leads to variable power delivery

Zero Voltage Detection → Adjustable Delay (τ) → Switching Sequence Synthesis





REQUIREMENTS on SWITCHING TRANSITIONS DURATION « Up » (OFF => ON) and Down (ON => OFF) for 50 Hz ENERGY CONTROL



Switching Transitions Durations should be << 1 ms

Too short for reliable Electromechanical Switches

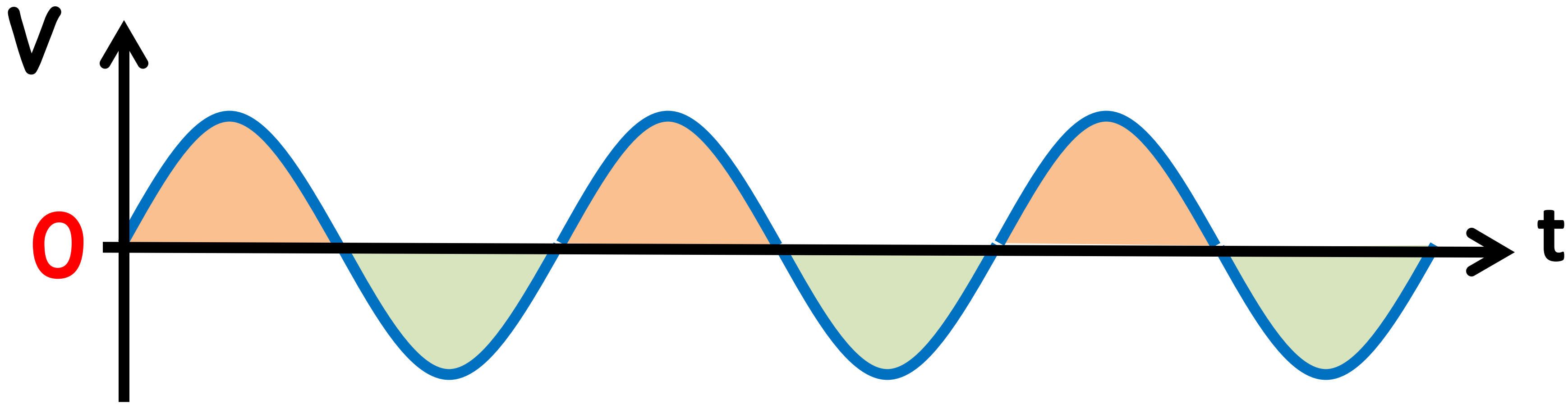
Comfortable for Electronic Switches

EXAMPLE 2

CONVERTING AC ENERGY
into
DC ENERGY

no voltage change

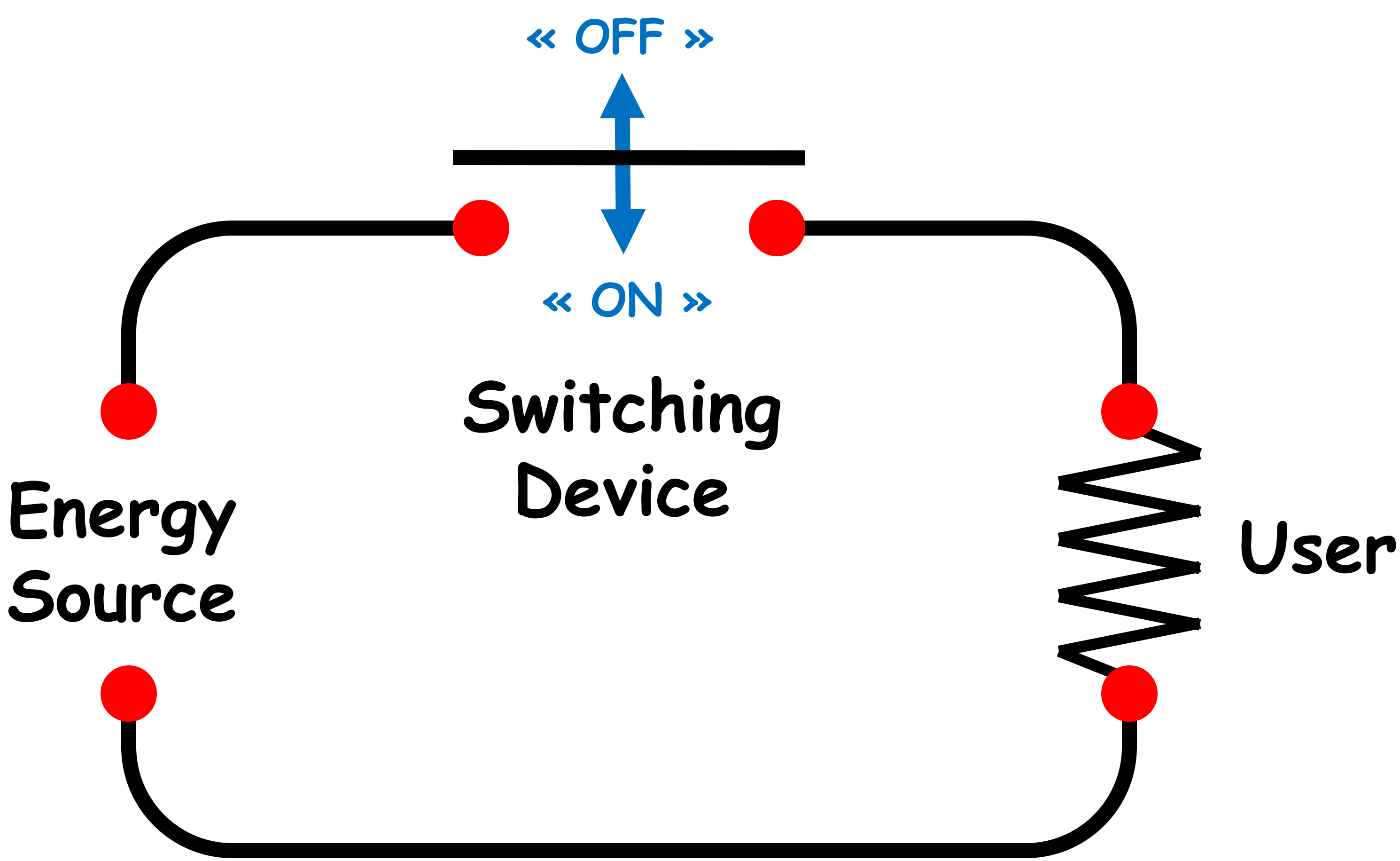
Electric Power Source



Average Voltage is Zero

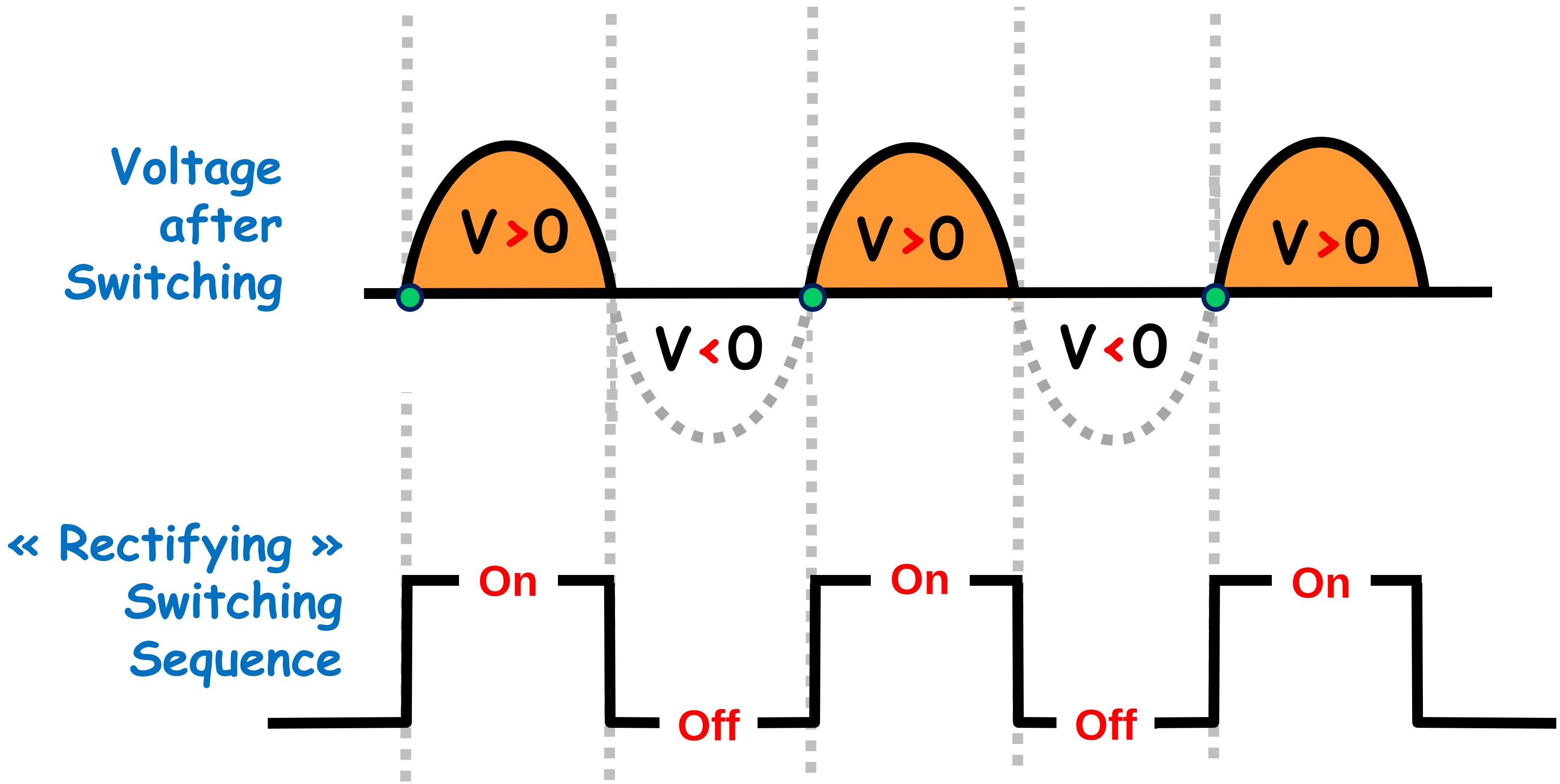
« RECTIFYING » AC POWER

Switching « On » when V>0 and « Off » when V<0

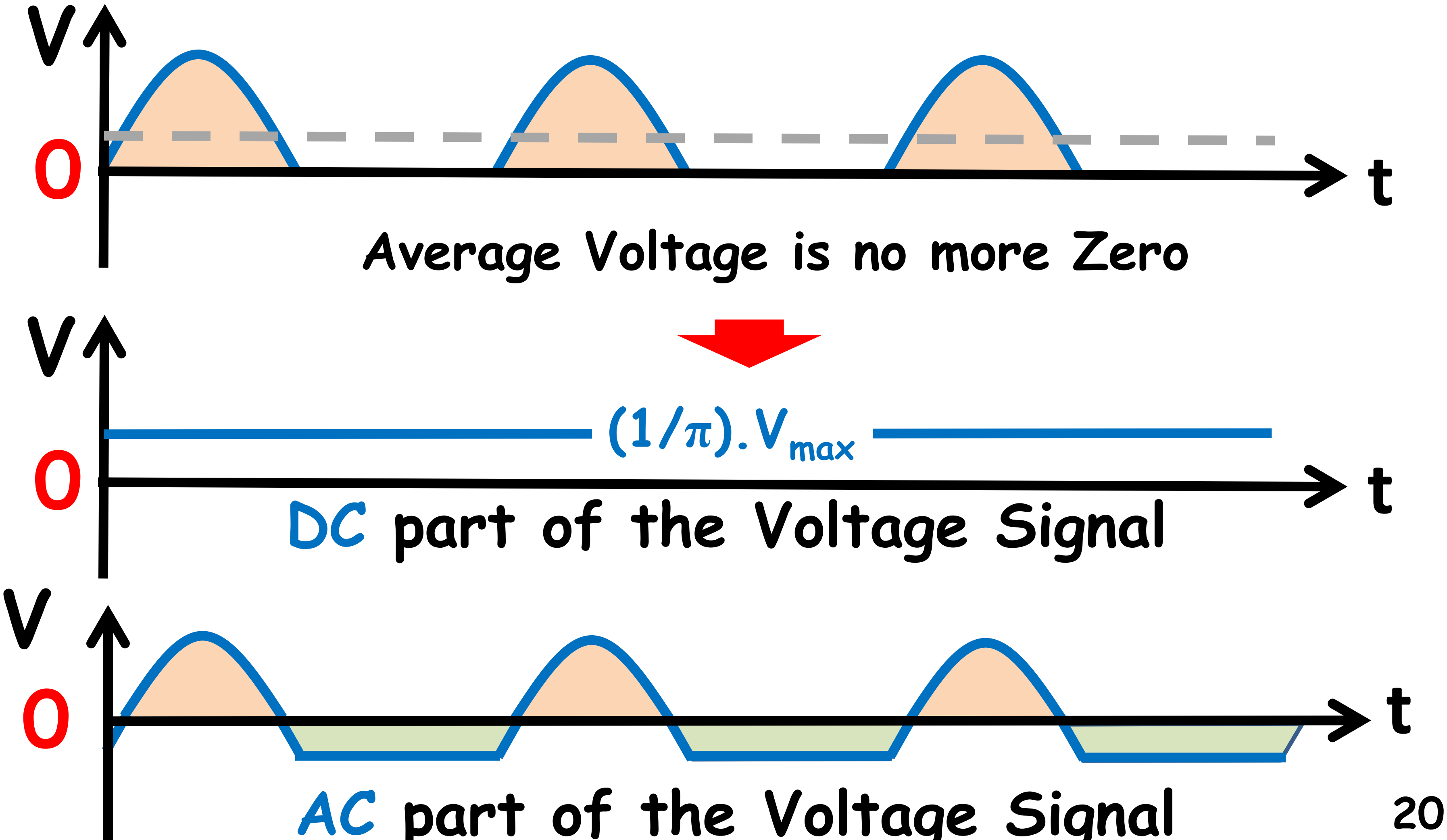


« RECTIFYING » AC VOLTAGE

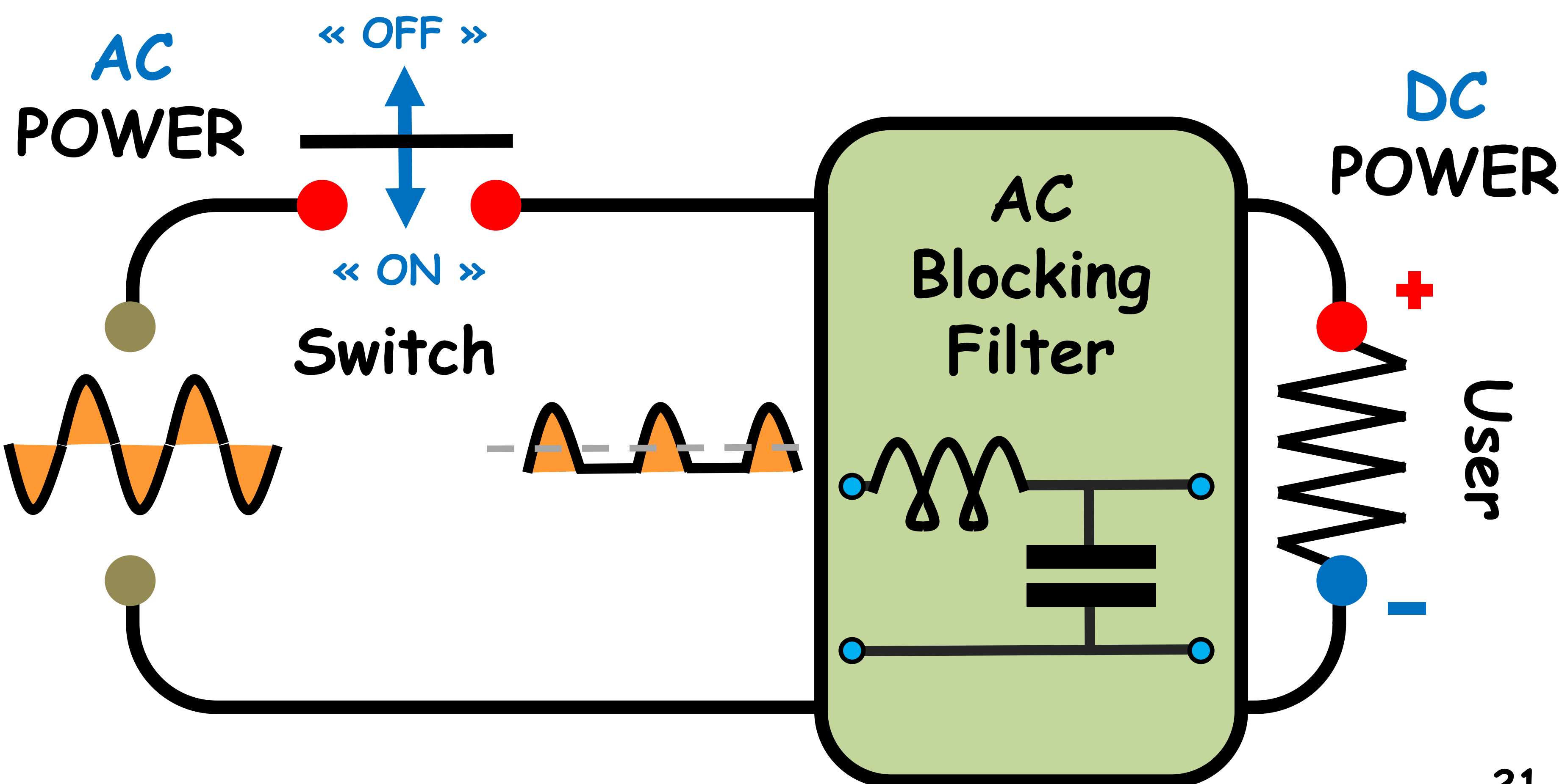
Switching « On » when V>0 and « Off » when V<0



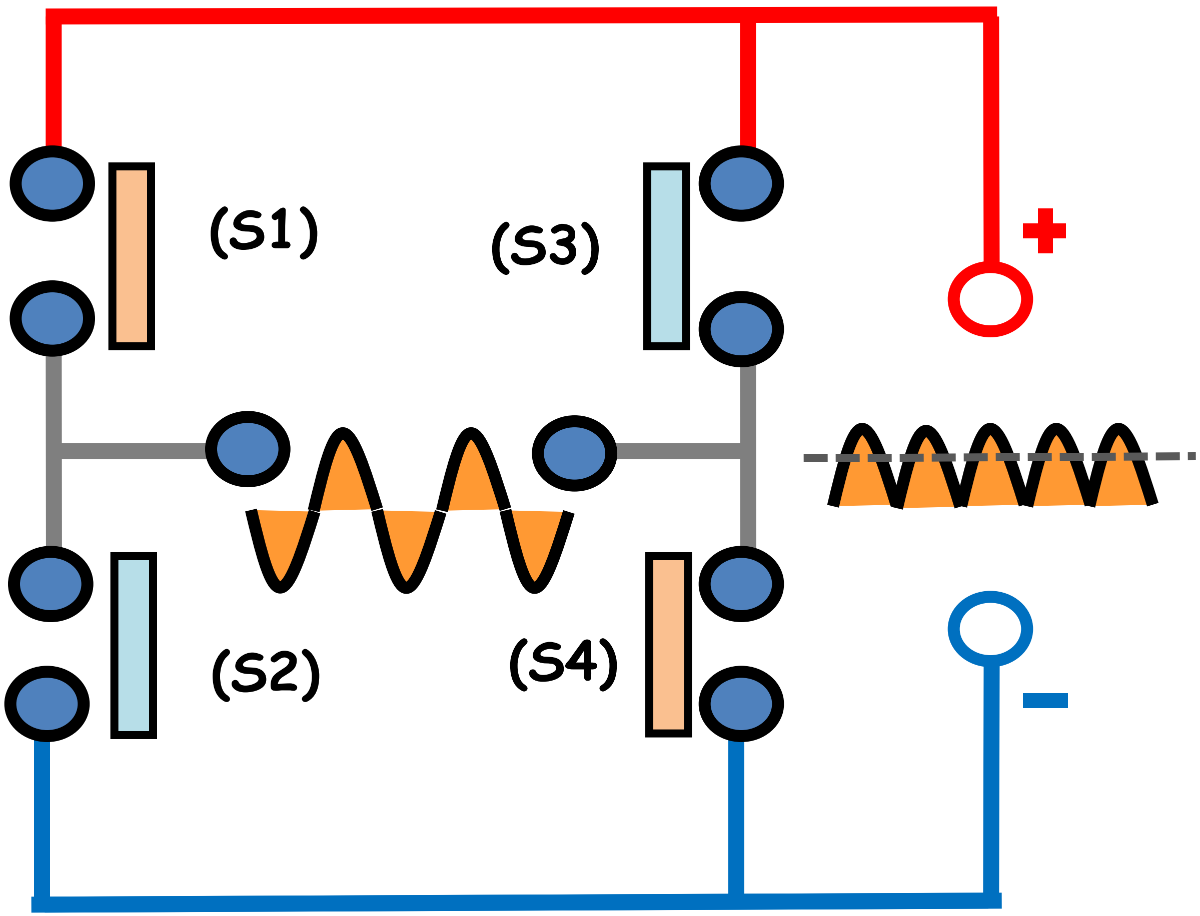
« Rectified » AC Voltage



Transforming AC into DC



More Efficient AC => DC Conversion
"H" or "Bridge" Association of 4 Switches



V>0
S1 and S4 ON
S2 and S3 OFF

Lower AC Voltage
Frequency Doubled

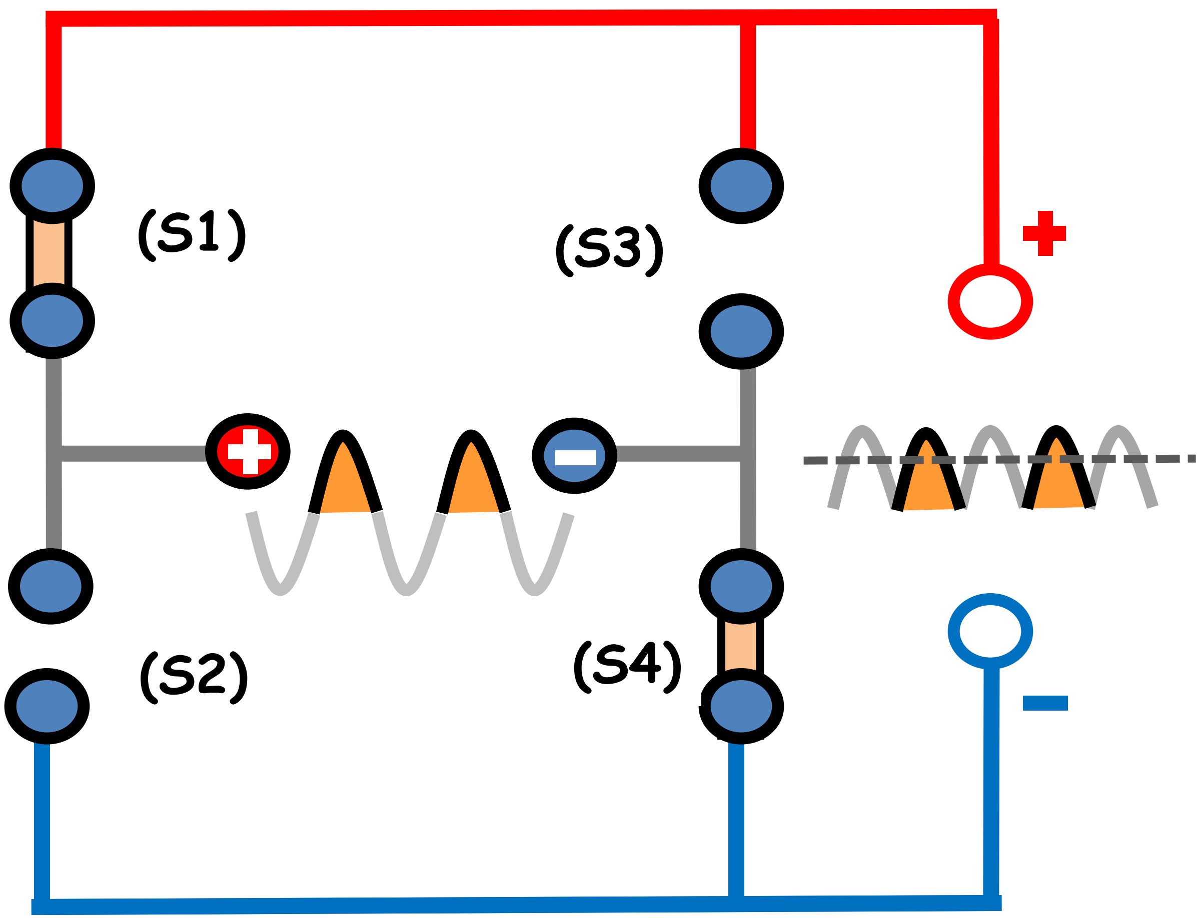
Smaller Filter
required

V<0
S1 and S4 OFF
S2 and S3 ON

Getting Twice More DC Power from the same AC Source

4 Switches Rectifying "Bridge"

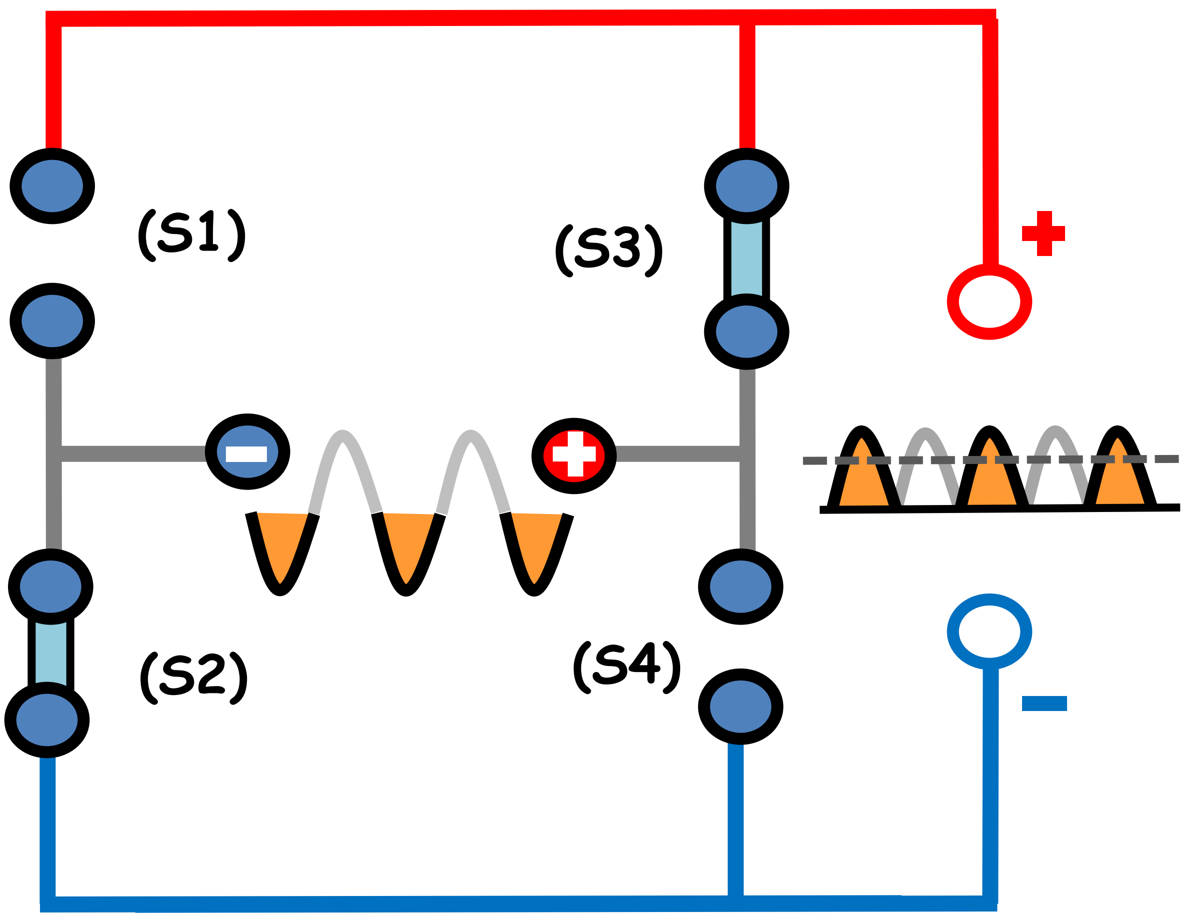
Switching Status during "Positive" Arches



V > 0
S1 and S4 ON
S2 and S3 OFF

4 Switches Rectifying "Bridge"

Switching Status during "Negative" Arches

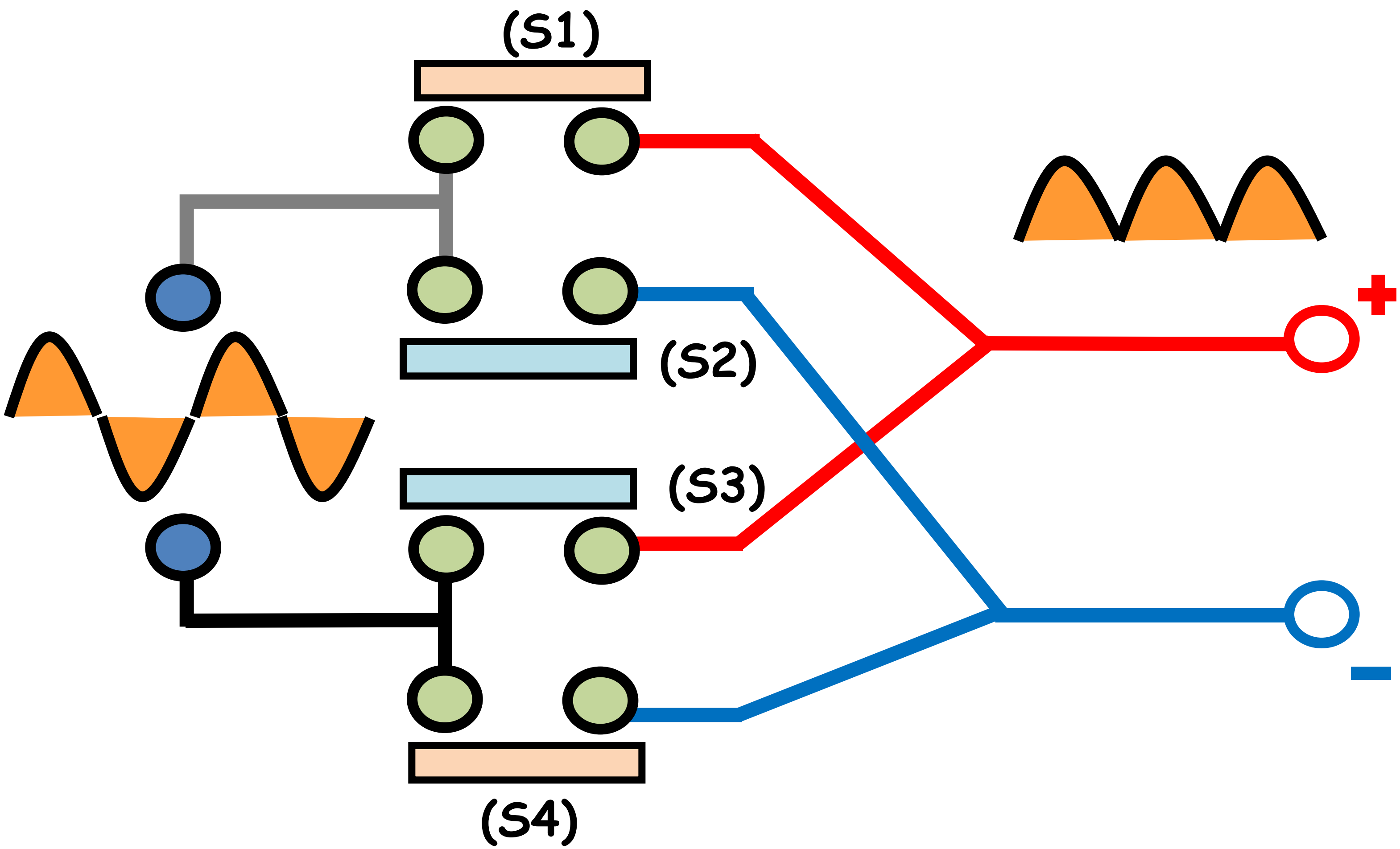


V < 0
S1 and S4 OFF
S2 and S3 ON

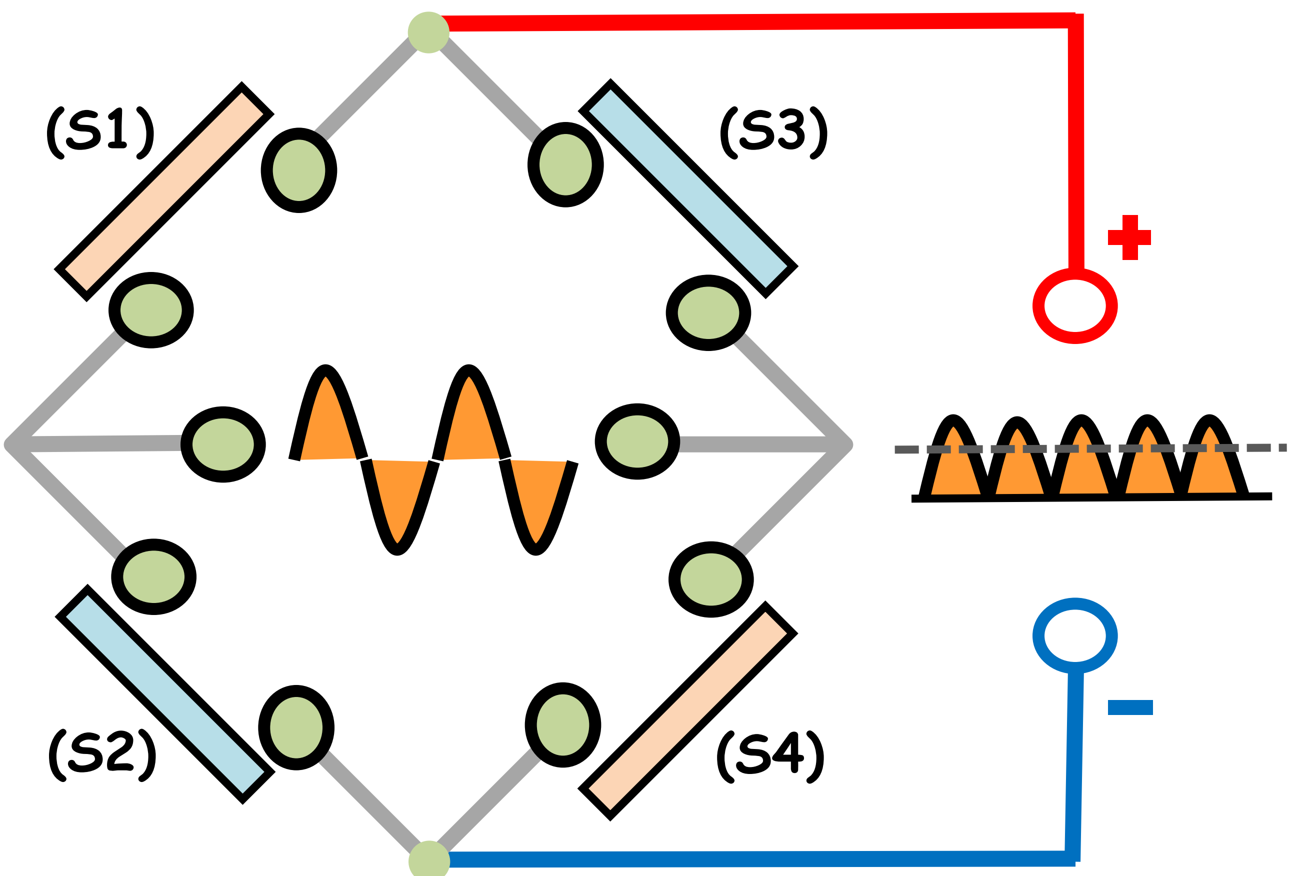
Other Drawing of the Same Bridge

V > 0: S1 and S4 ON   S2 and S3 OFF

V < 0: S1 and S4 OFF   S2 and S3 ON



One More Drawing of the Same Bridge

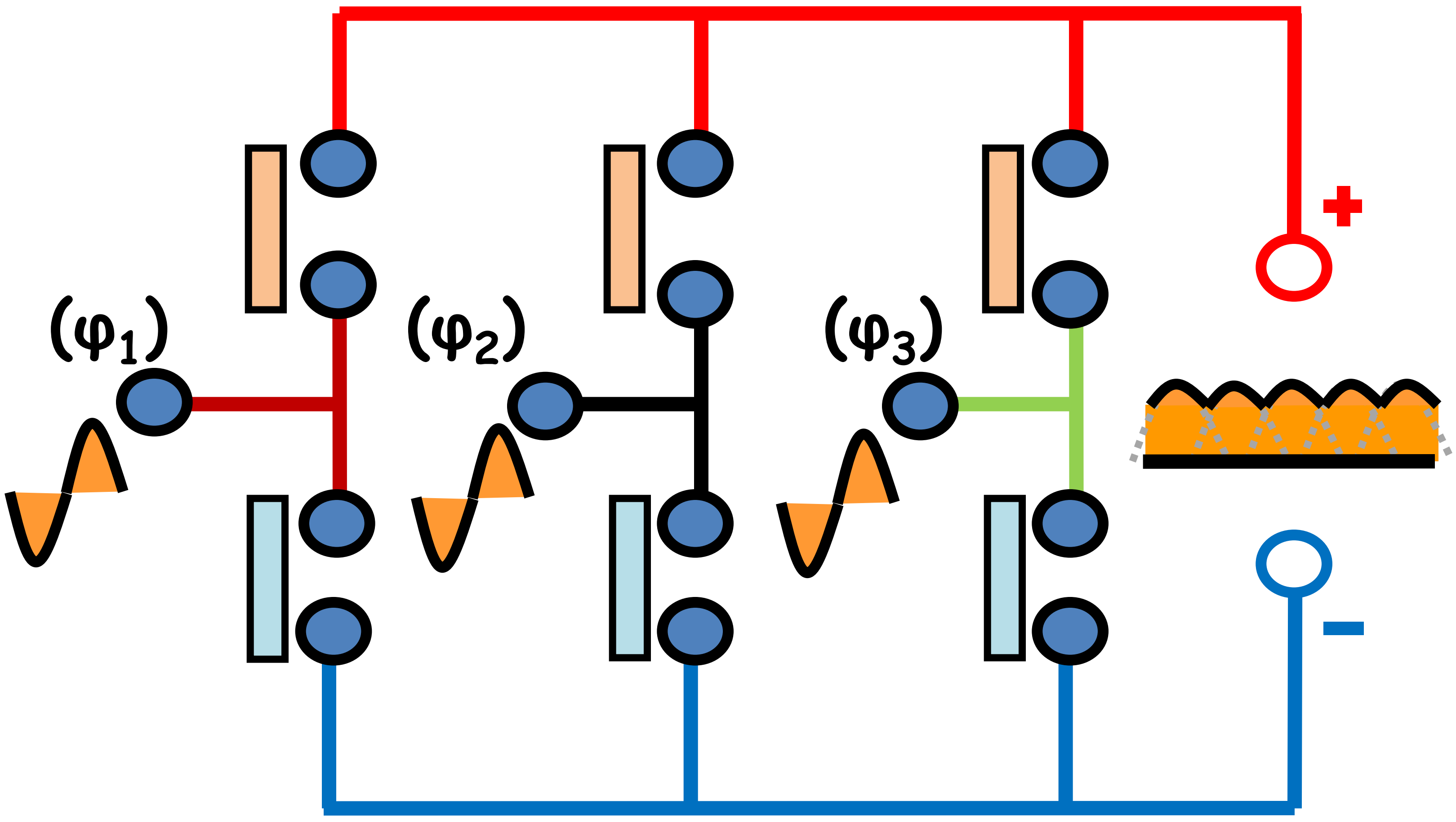


V>0
S1 and S4 ON
S2 and S3 OFF

V<0
S1 and S4 OFF
S2 and S3 ON

Even More Efficient Conversion

3 Phase AC => DC (industrial AC supply)



3 Phase leads to more efficient conversion

=> Higher Average Voltage

=> Higher Fundamental Frequency of the AC signal

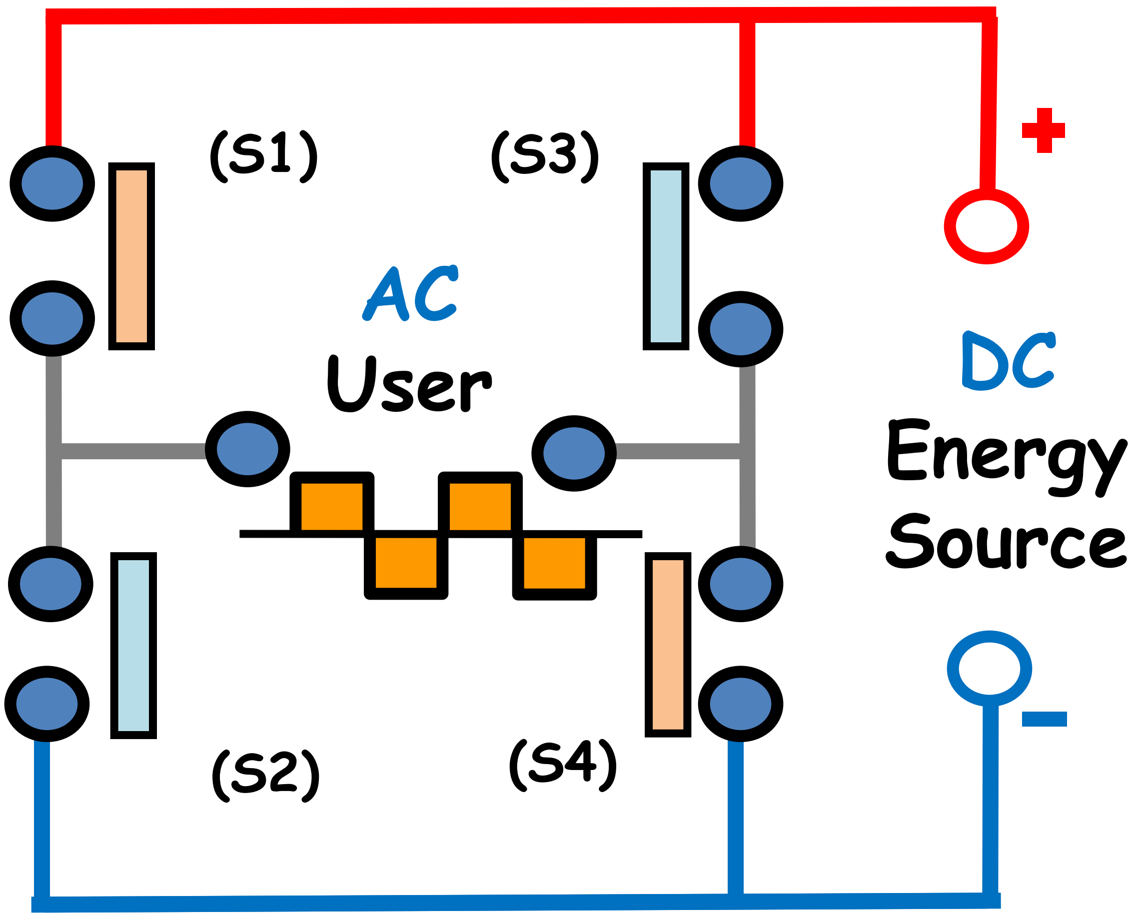
after the Rectifying Bridge

EXAMPLE 3

CONVERTING DC ENERGY
into
AC ENERGY

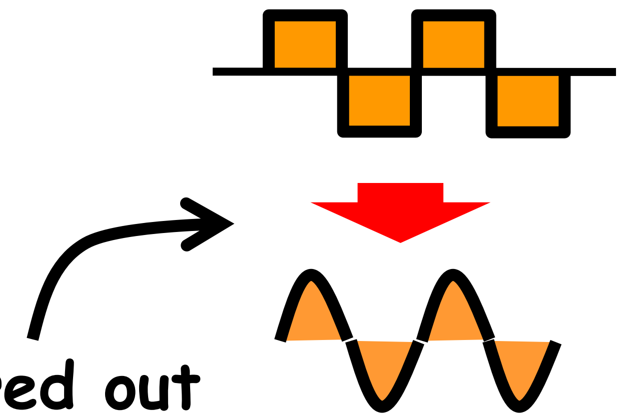
with no voltage change

DC => AC Conversion
"H" or "Bridge" Association of 4 Switches



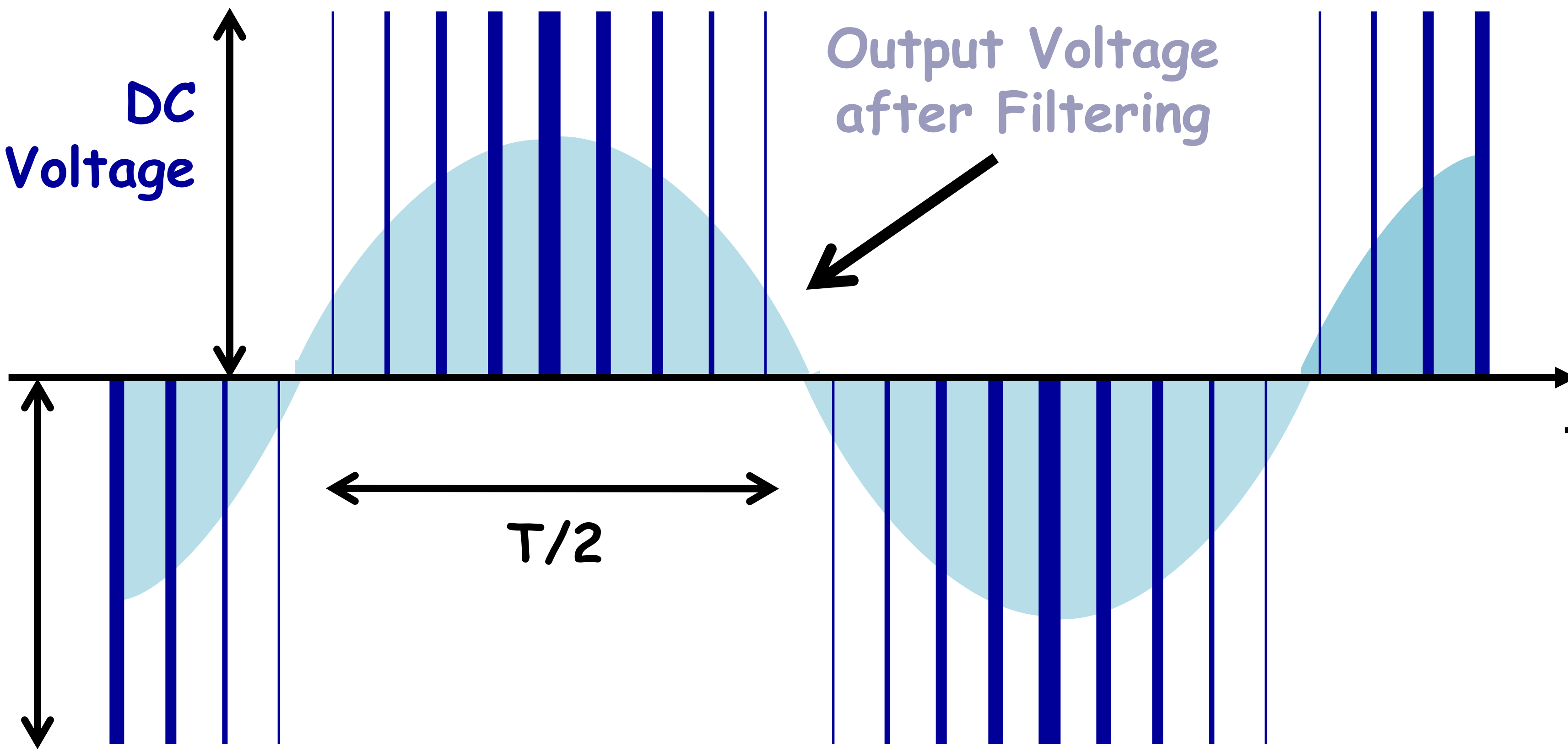
$V_{out} > 0$
S1 and S4 ON
S2 and S3 OFF

$V_{out} < 0$
S1 and S4 OFF
S2 and S3 ON



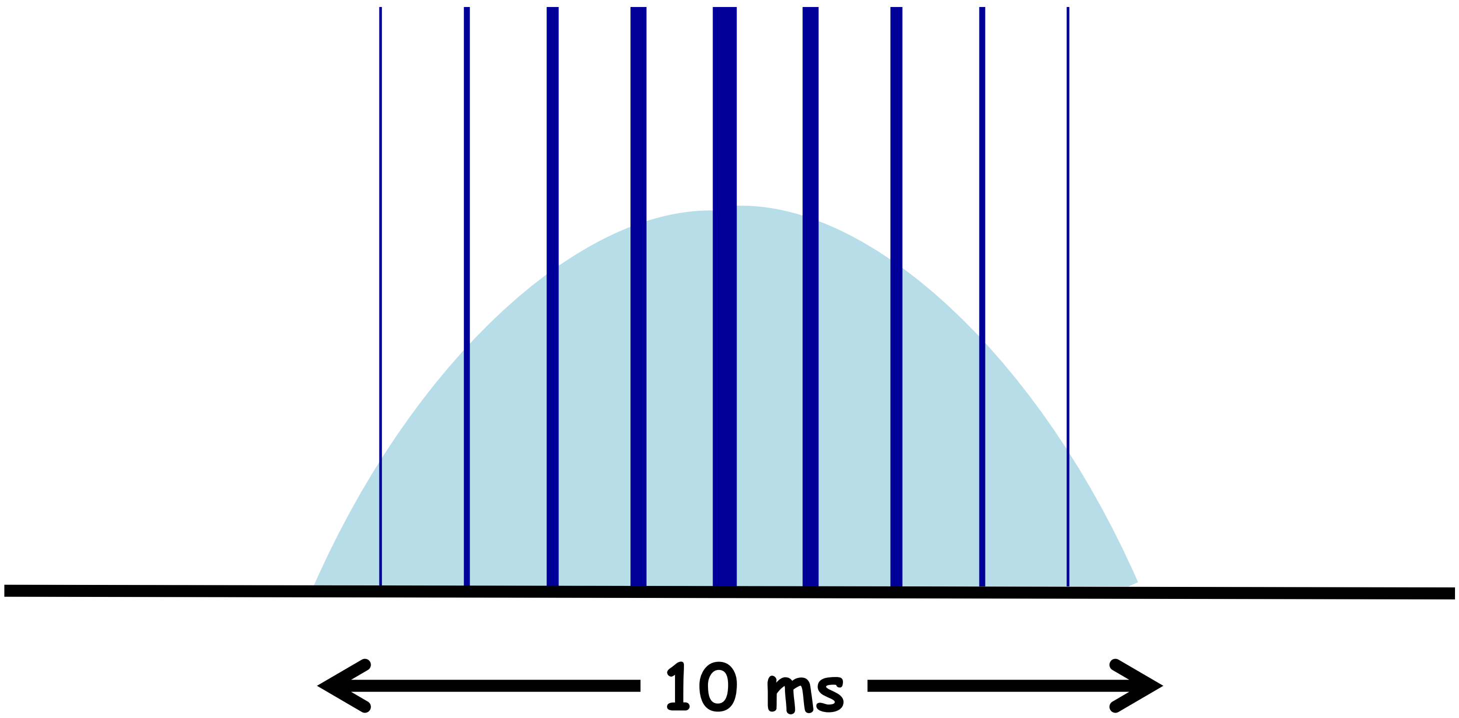
Harmonics (N > 1) have to be filtered out

Sine Voltage Synthesis by Pulse Width Modulation (P W M)
Same Switching Bridge, but Faster Switching required



Very Efficient DC => AC Conversion if switching is abrupt

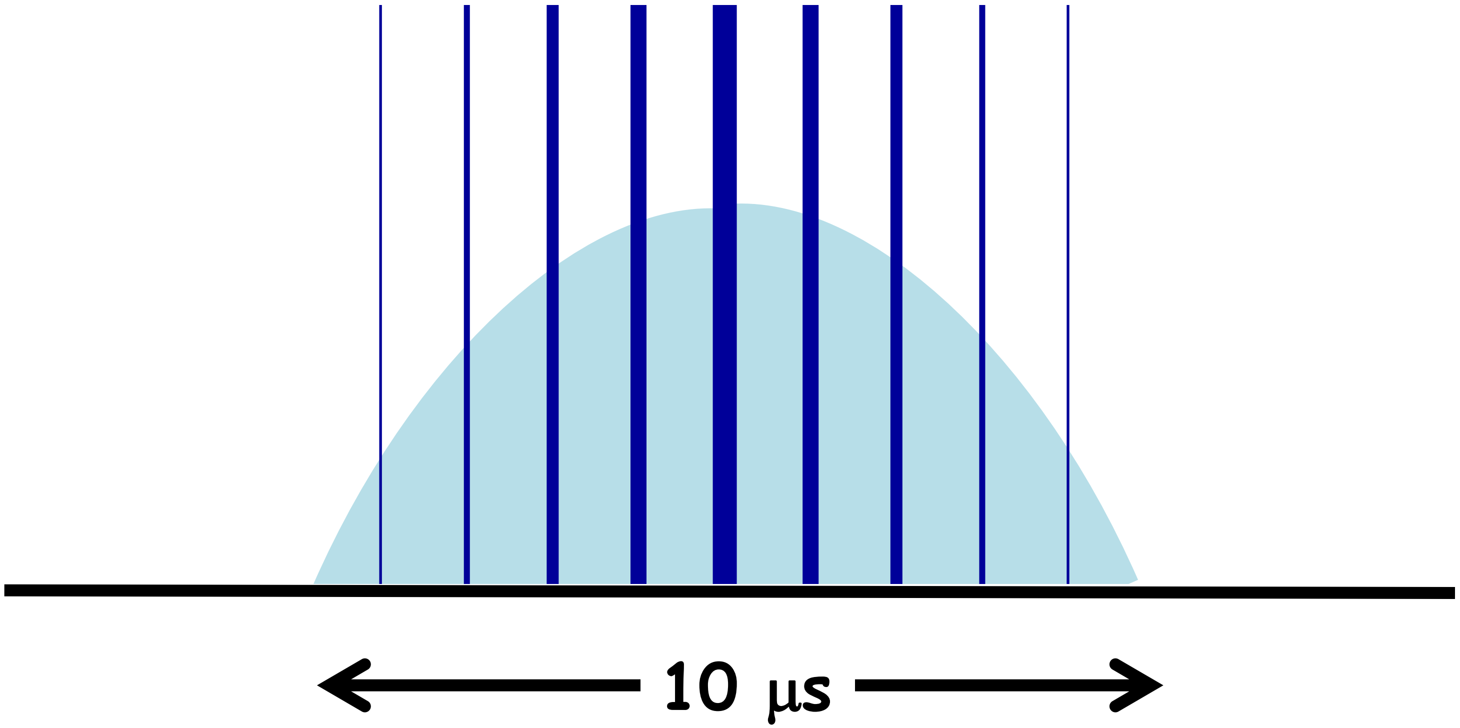
REQUIREMENTS on SWITCHING TRANSITIONS DURATIONS for 50 Hz SINEWAVE SYNTHESIS



Switching Transitions Durations should be << 100 μs

Comfortable for Smart Electronic Switches and V < 1 kV

REQUIREMENTS on SWITCHING TRANSITIONS DURATIONS for 50 kHz SINEWAVE SYNTHESIS



Switching Transitions Durations should be << 100 ns

Severe Requirement on Electronic Switches when V > 100 V

EXAMPLE 4

CHANGING VOLTAGE
of
AC ENERGY

Today, most
Voltage Changing Systems
are based on
Magnetic Transformers

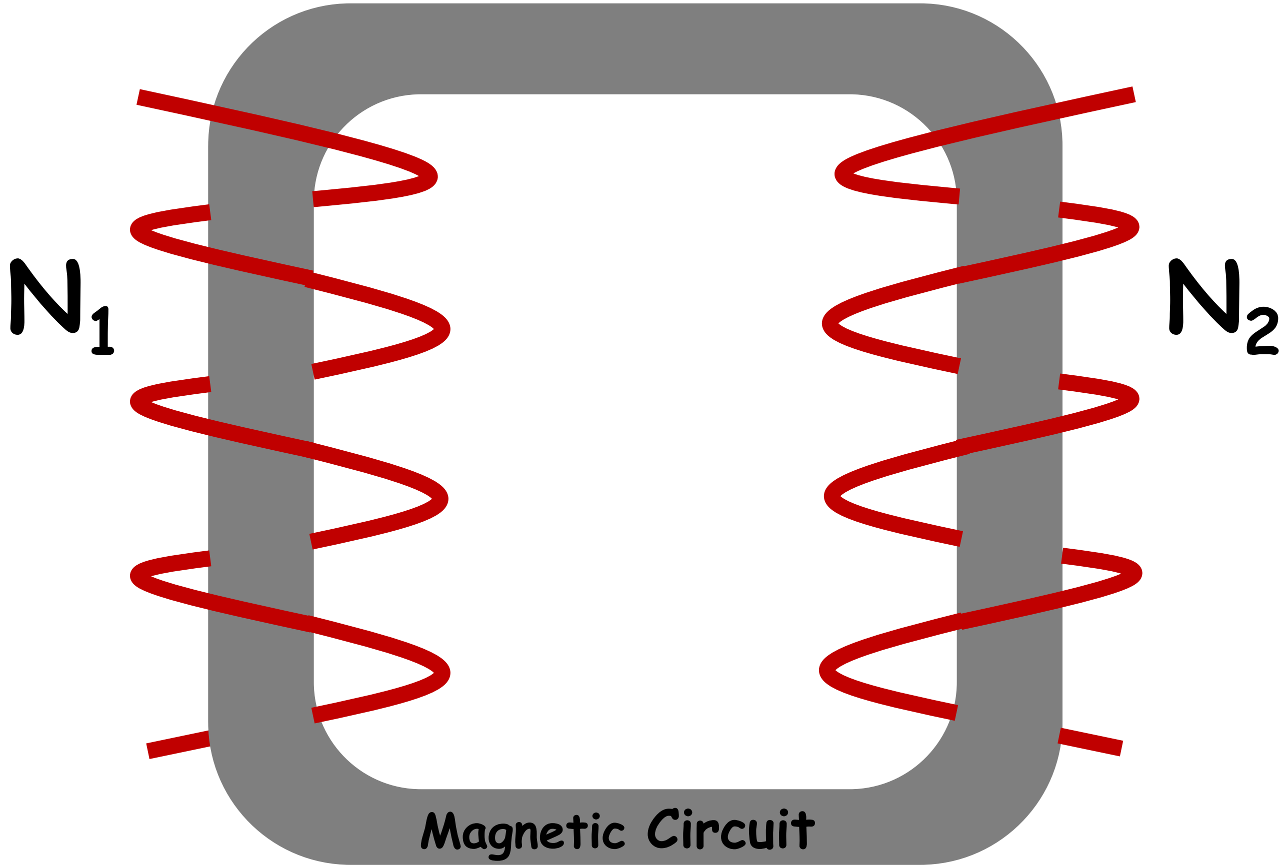
the best
Voltage Transformer
device available so far

. . .

Electromagnetic « Transformer »

2 coils on a Magnetic "Circuit"

$V_2 / V_1 \sim N_2 / N_1 \sim I_1 / I_2$



General Trend for Transformers

↓

Higher Frequency yields Smaller and Lighter Transformer

Electromagnetic Induced Voltage e

$$e = - d\Phi/dt$$

$$| e | \;\alpha\; [\, \Phi_0 \,.\, \omega \,]$$

Φ Magnetic Flux ω = 2π x Frequency

For the same voltage, changing from 50-60 Hz to 50-60 kHz allows to reduce Magnetic Flux within the solenoids by a factor 1 000.

=> 100 times Fewer Wire Turns,
=> 10 times Lower Flux Φ_0 within the Magnetic Circuit

Magnetic Circuits for use at 50-60 Hz

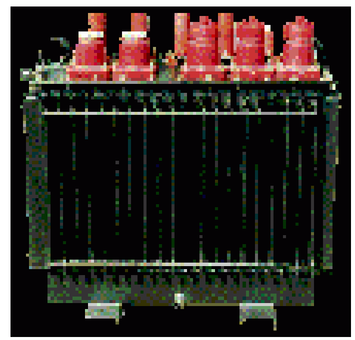
Iron metal (+ Si additive)

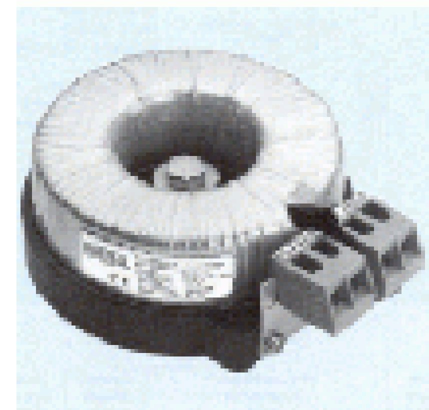
L ~ 1 - 10 μH

Heavy Bulky Magnetic Circuits for use at 50-60 Hz

Iron Metal (+ Si additive)

L ~ 1 - 10 μH

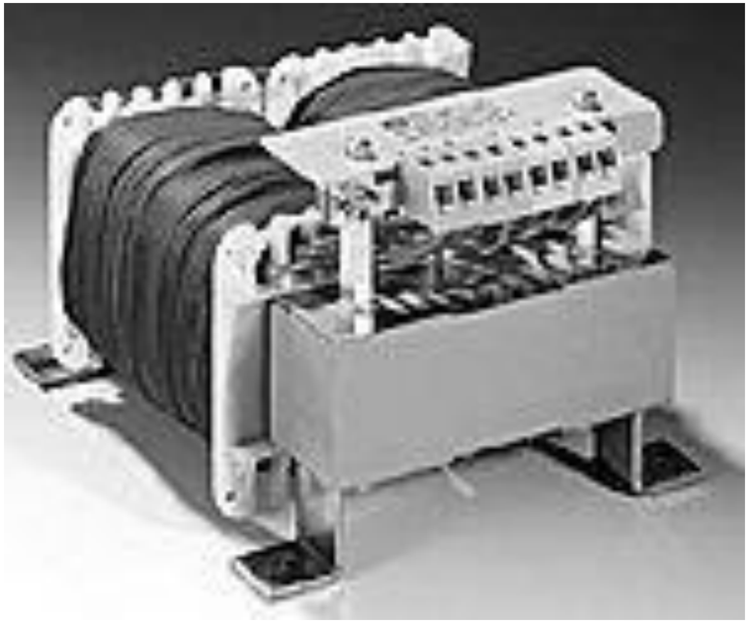




Heavy Bulky Magnetic Circuits for use at 50-60 Hz

Iron metal (+ Si additive)

L ~ 1 – 10 μH



Smaller Lighter Magnetic Circuits for use at 10-500 kHz

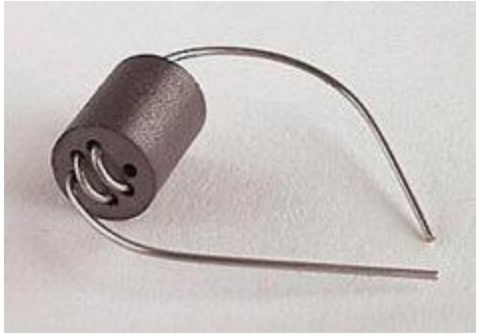
« Ferrite » Oxide

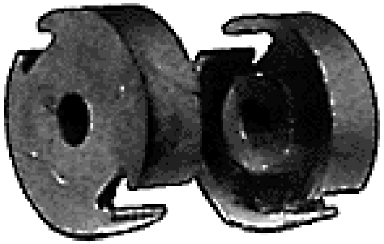
(Fe + Zn + Mn)

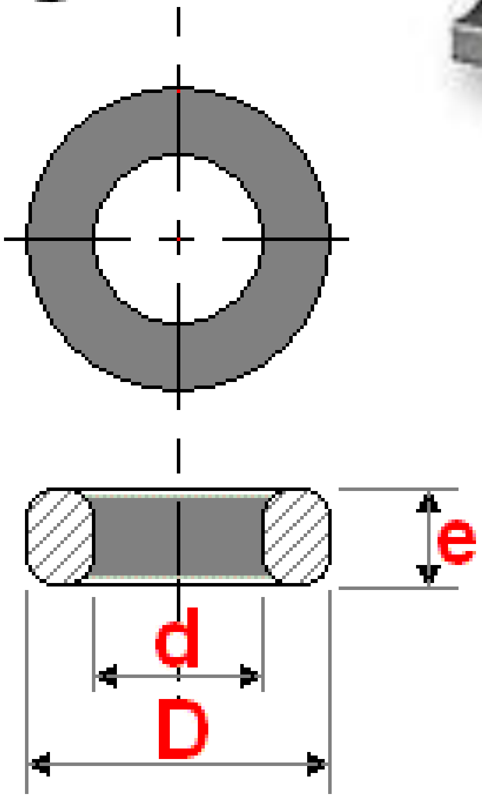
L ~ 0,1 – 1 μH

(10 times lower vs 50-60Hz)

Ferrite Magnetic Circuits







Magnetic Circuits are much Smaller and Lighter at Higher Frequency

Transformers 50 Hz vs 50 kHz 2 kW

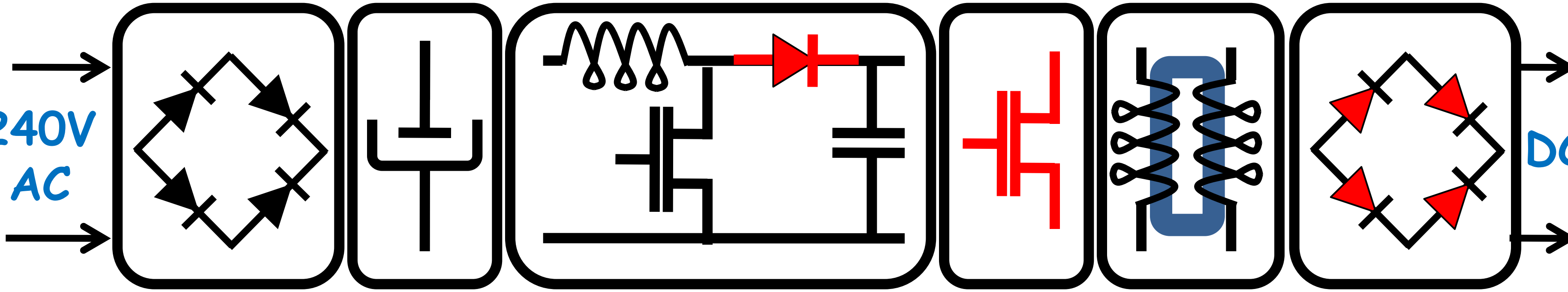
20 cm @ > 10 kg

4 cm @ < 0,2 kg

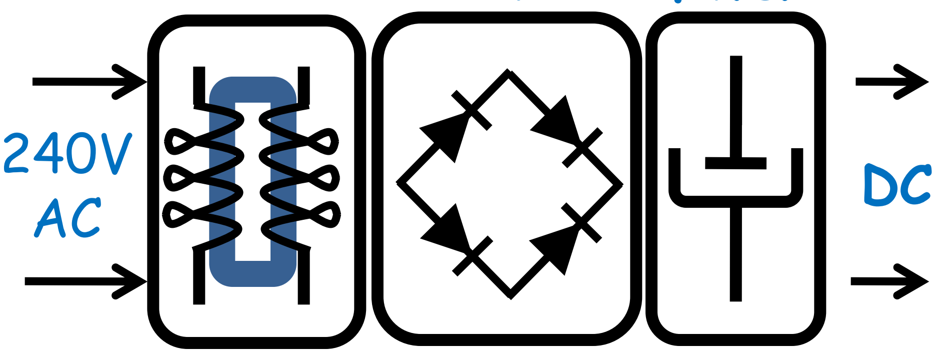
2 kW @ 50 Hz

2,4 kW @ 50 kHz

Modern Power Supply



Old Fashioned Power Supply



Old fashionned Power Supply

240 V AC => Low Voltage 5V DC

240V AC 50 Hz

AC 240V =>AC 5V
50 Hz Magnetic Transformer

5V AC 50 Hz

50 Hz AC=>DC Rectifying Bridge
+ 100 Hz Low-Pass Filter

5V DC

Two-steps, Simple, Reliable, but Bulky - Heavy

Modern Power Supply 240 V AC => Low Voltage 5V DC

240V AC 50 Hz

50 Hz AC=>DC Rectifying Bridge

200V DC

DC =>AC 50 KHz Switching Bridge

200V AC 50 KHz

AC 200V =>AC 5V 50 KHz Magnetic Transformer

5V AC 50 KHz

AC 50 kHz 5V =>DC 5V Rectifying Bridge

5V DC

CONCLUSION (1/3)

A MODERN (2013)

POWER CONVERTER

is an assembly

of

Switching Bridges

HF Magnetic Transformers

High Frequency Filters

CONCLUSION (2/3)

The Higher the Frequency is ...

The Smaller and Lighter
Passive Elements can be :
Magnetic Transformers
Filters
(Capacitors , Inductances)

CONCLUSION (3/3)

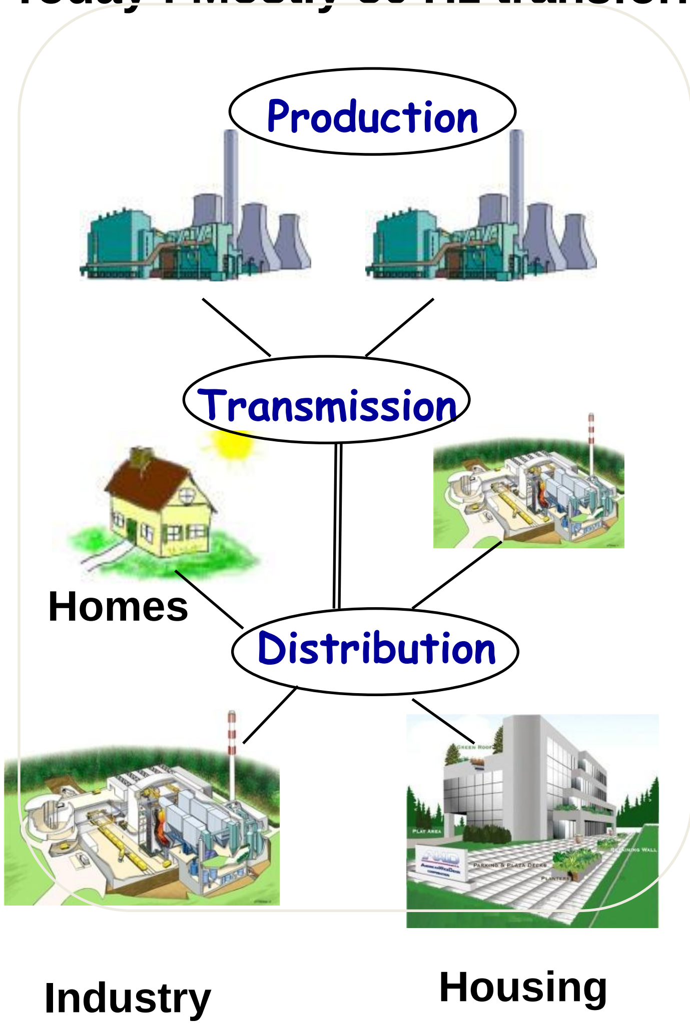
Smart Power Supply

relies on

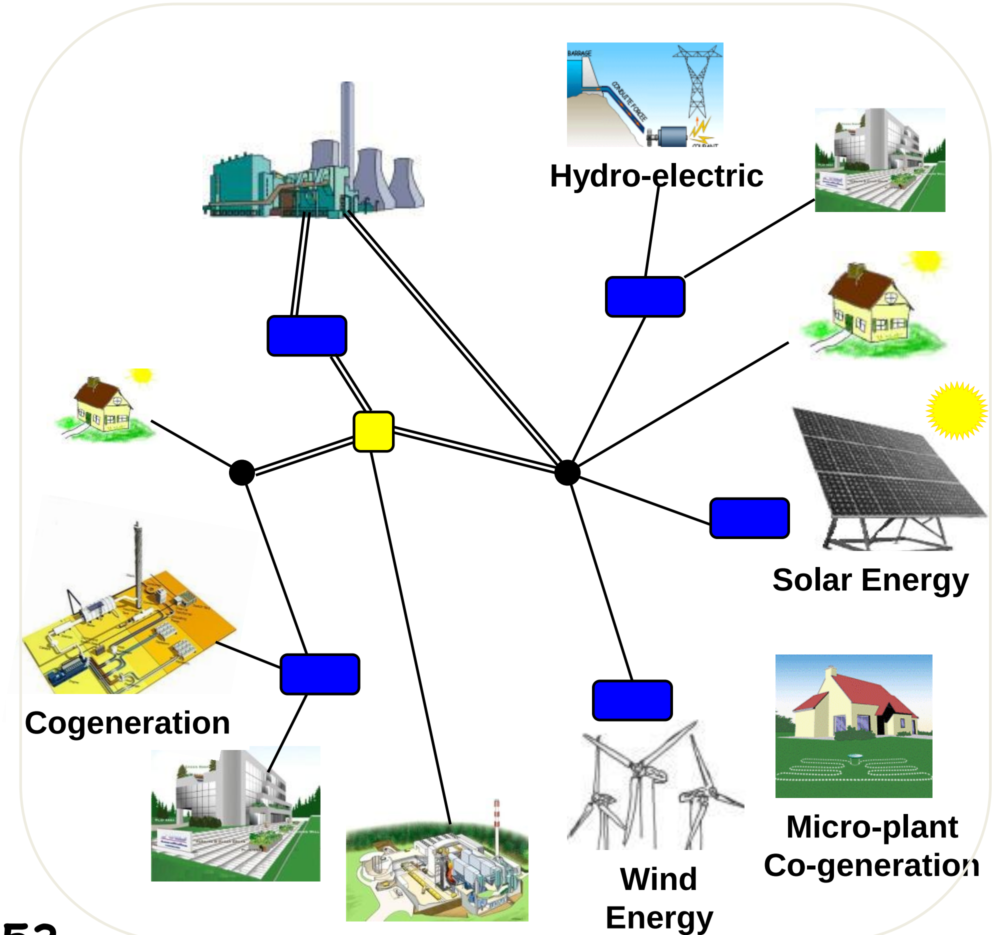
FAST SWITCHING DEVICES

Smart Power Supply is the key of "SMART GRID TECHNOLOGY"

Today : Mostly 50 Hz transformers



Tomorrow : many more « smart converters »



53

Voltage Conventionnal Ranges

0.1 - 1 MV => Very High Voltage

10 - 100 kV => High Voltage

0.5 - 10 kV => Medium Voltage

50 - 500 V => Low Voltage

< 50 V => Very Low Voltage

The Lower Voltage Domain

300 - 600 V 1200 V 1700 V 6,5 kV+

Low Voltage

Medium Voltage

High Voltage

55

Home Voltage Ranges

127 V in USA and Japan
=> 300 V Switch Voltage Handling

240 V in Europe
=> 600 V Switch Voltage Handling

Lowest Industrial Voltage Range

350 - 450 V in most countries
=>1200 V Switch Voltage Handling

The largest Volume Market for Power Electronics Devices

relates to

the Lowest Voltage

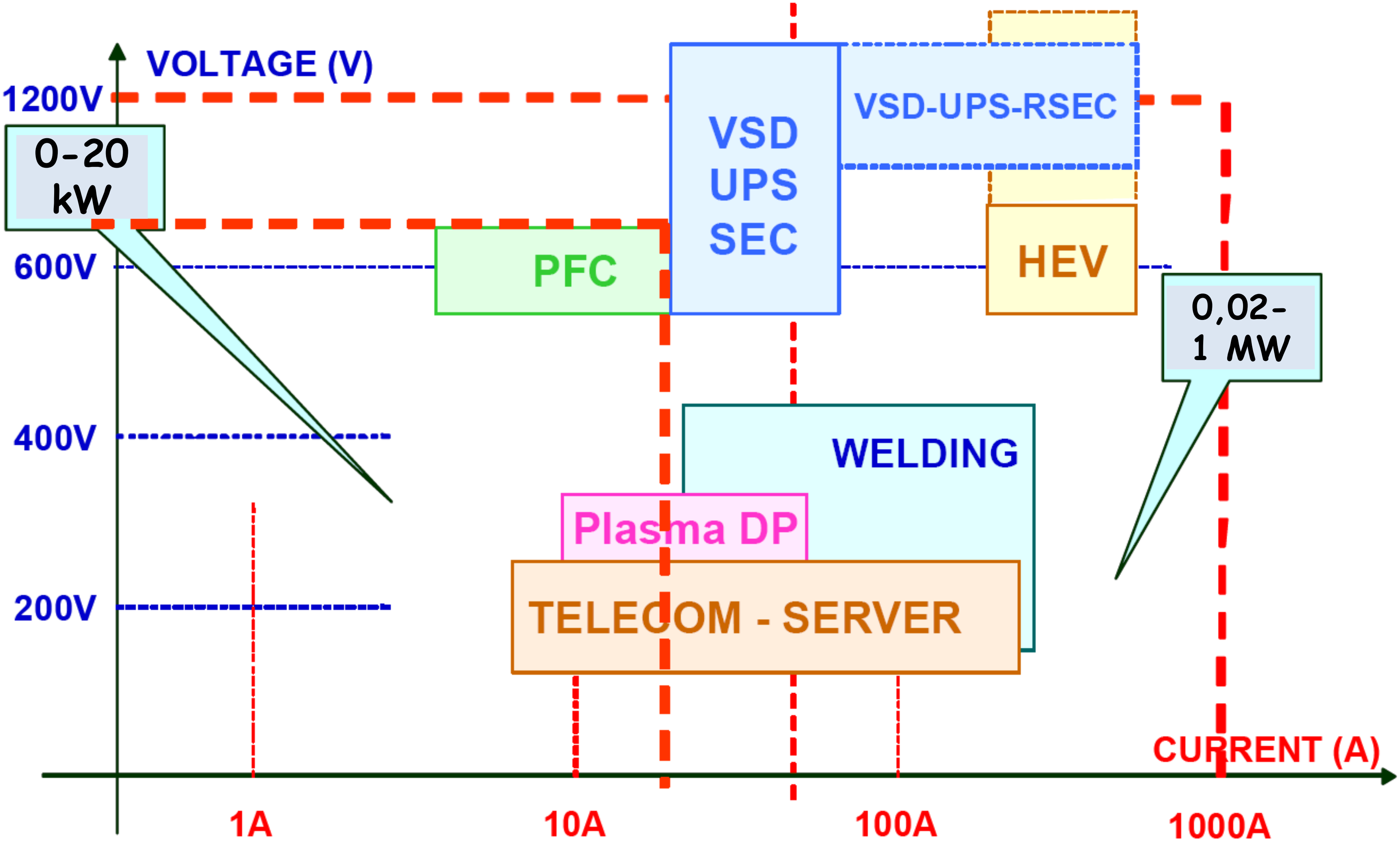
Domestic and Industrial ends

of the Distribution Networks

More than 80 % of the
Power Electronics Market
requires Switch and Rectifier
devices with voltage handling
from 300 to 1200 V

This is just the optimum range for
SiC and GaN Semiconductor
Rectifiers and Switching Devices.

Main Industrial Application Markets in the « Low » Voltage Range 127 – 450 V



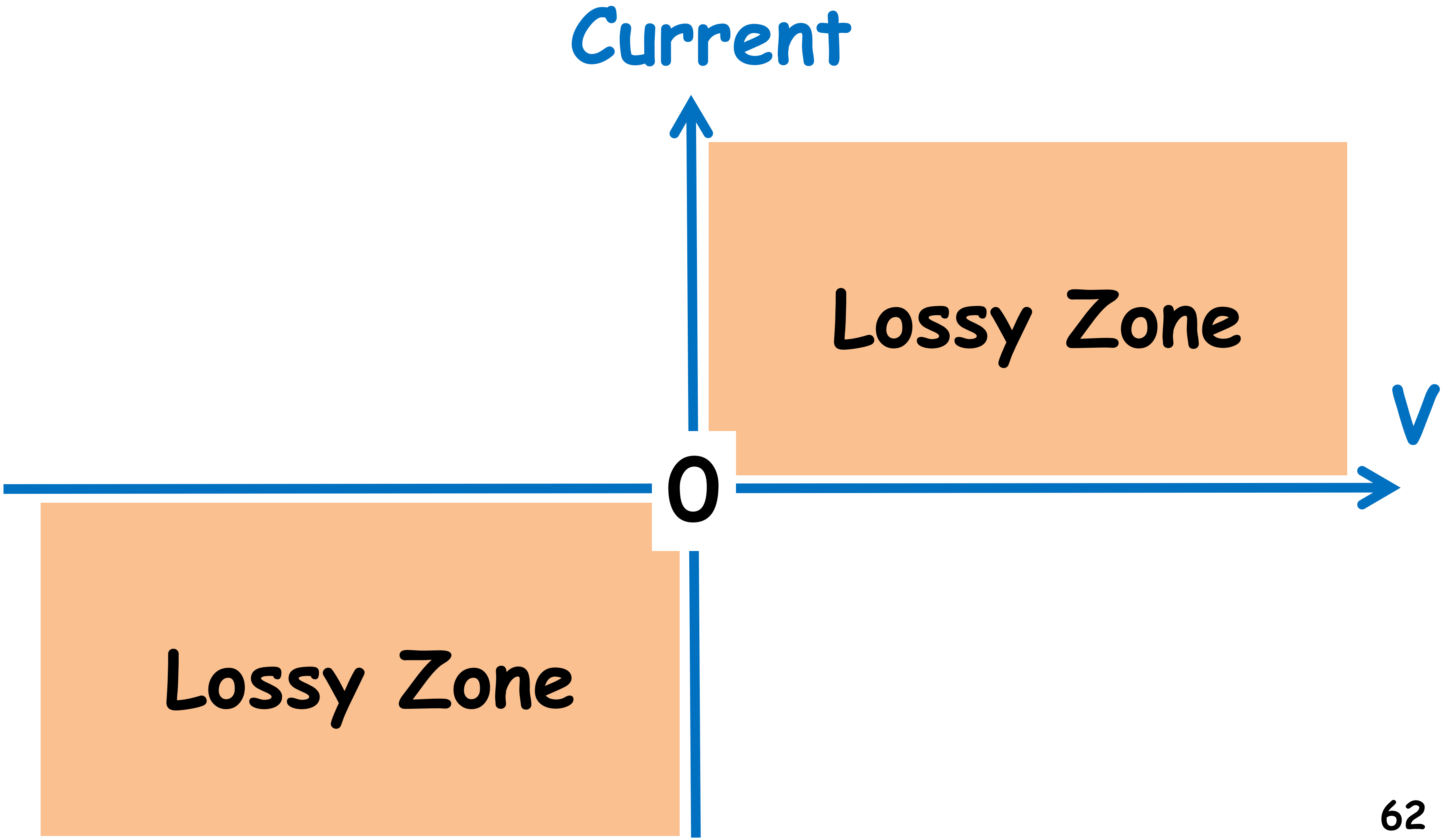
(Part 2)

SWITCHING DEVICES

The Main Goal For Switching Devices

Minimize Energy Losses (Heating)

Current – Voltage Characteristics



The Switching Principles
« Keep Close to the Axis »

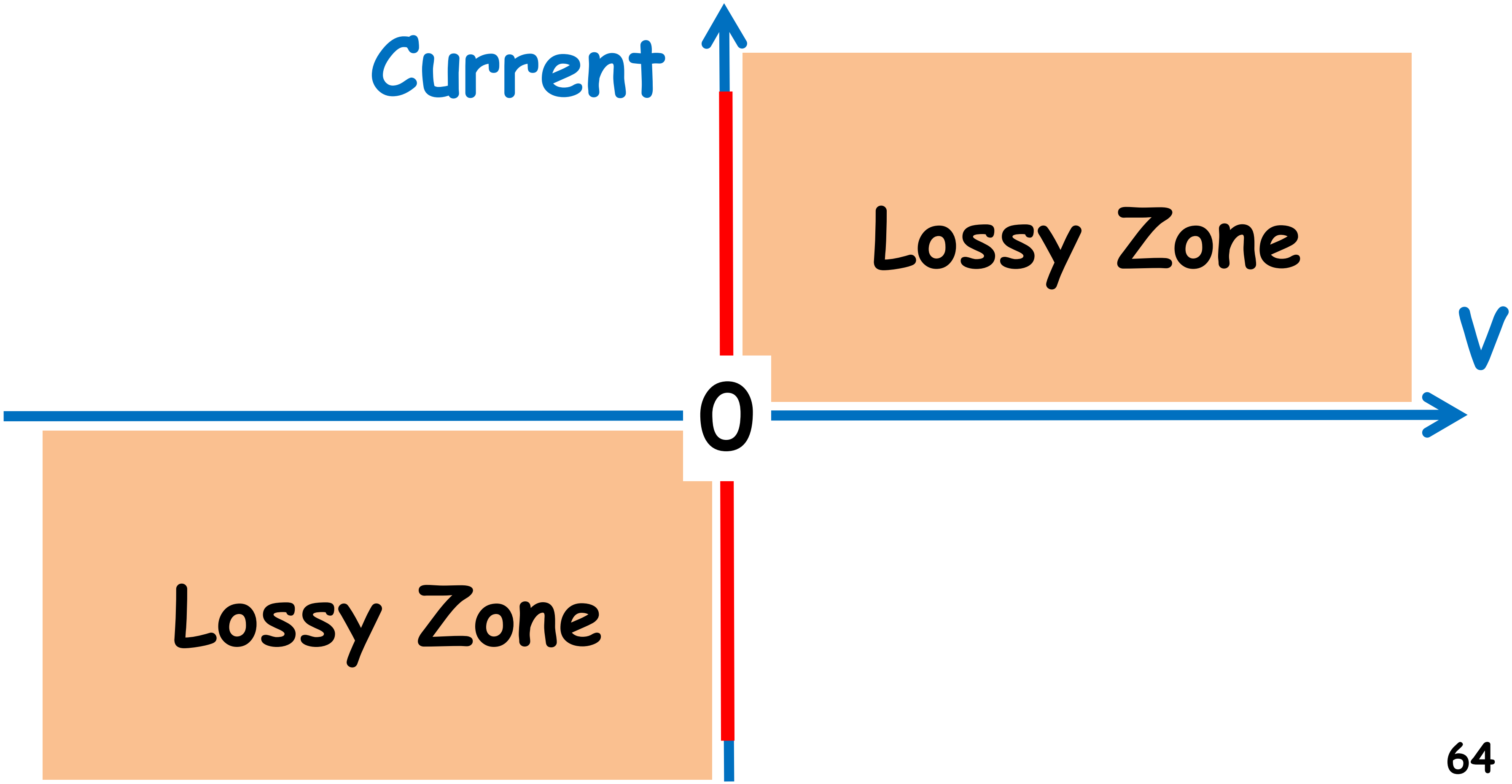
Current x Voltage = Power Loss
Heat Generation

Minimize Current when there is Voltage
(OFF STATE => target I_{OFF} = 0)

Minimize Voltage when there is Current
(OFF STATE => target V_{ON} = 0)

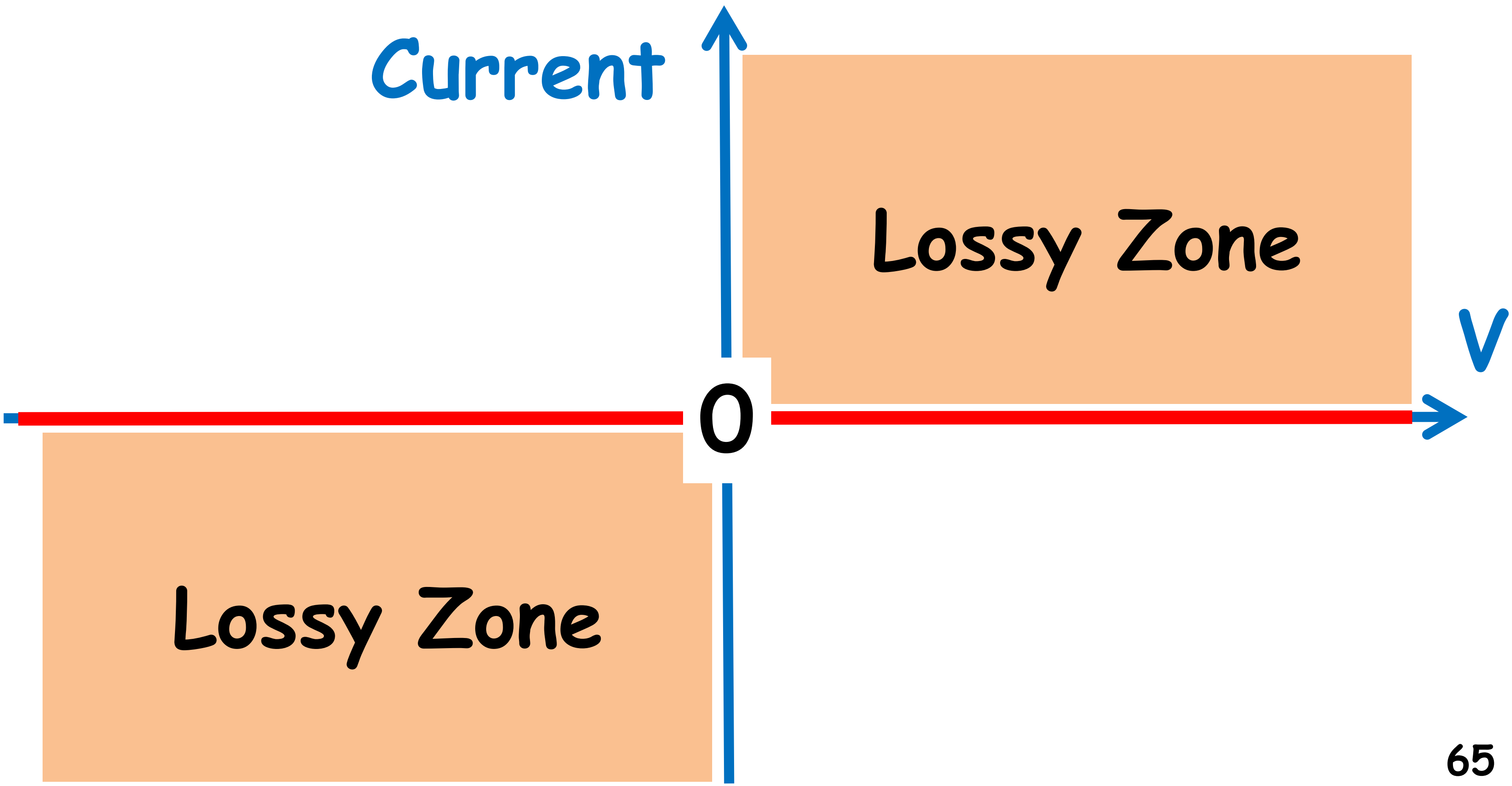
Ideal Switch at « ON STATE »

Zero On-State Voltage Drop V_{ON}



Ideal Switch at « OFF STATE »

Zero Off-State Leakage Current I_{OFF}



The "RECTIFER"
a
SELF-SWITCHING DEVICE

« RECTIFIER »

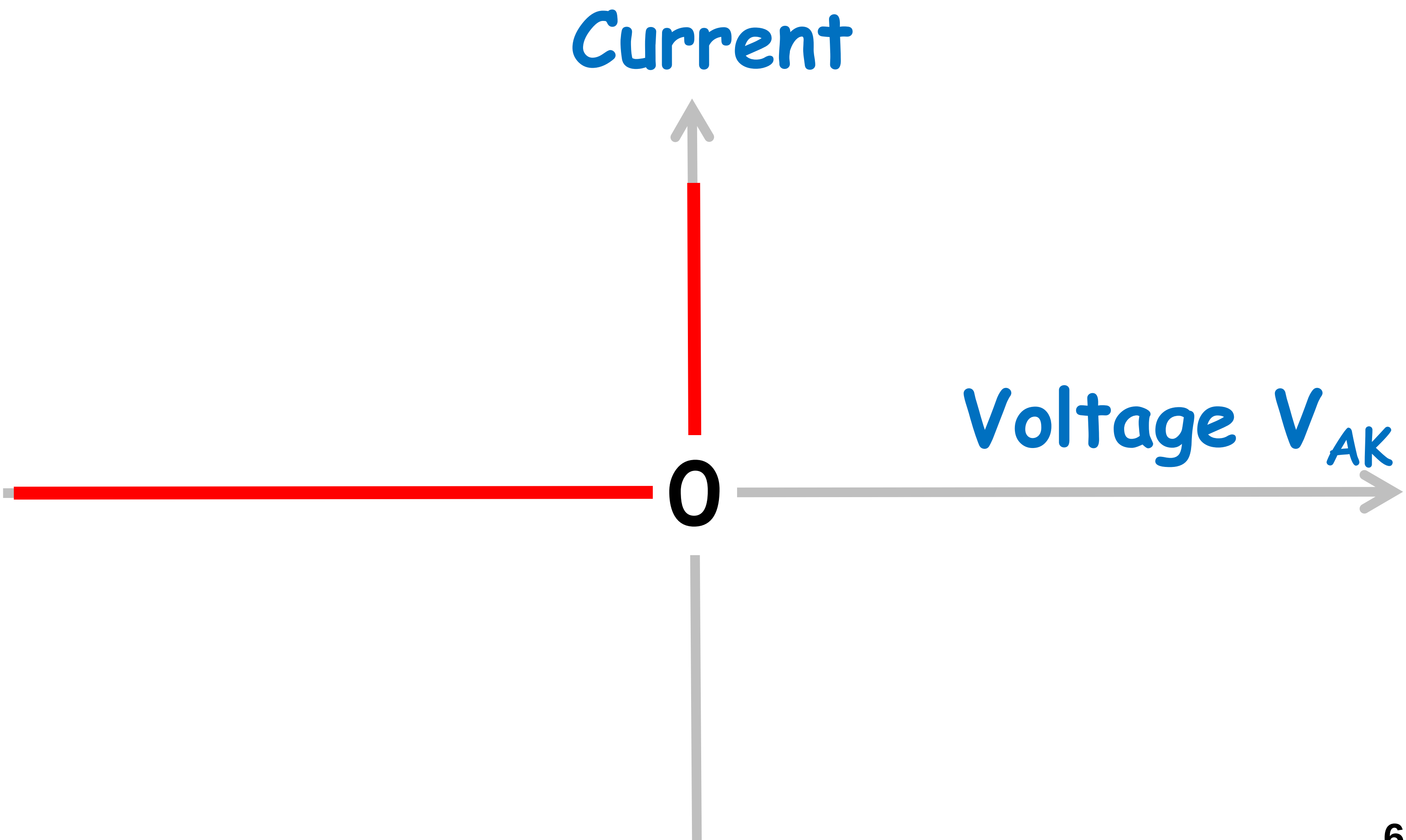
= Switching Device
which spontaneously

turns to ON-STATE when $V_{AK} > 0$
turns to OFF-STATE when $V_{AK} < 0$

=> No need for Control Electrode
=> 2 electrodes are enough

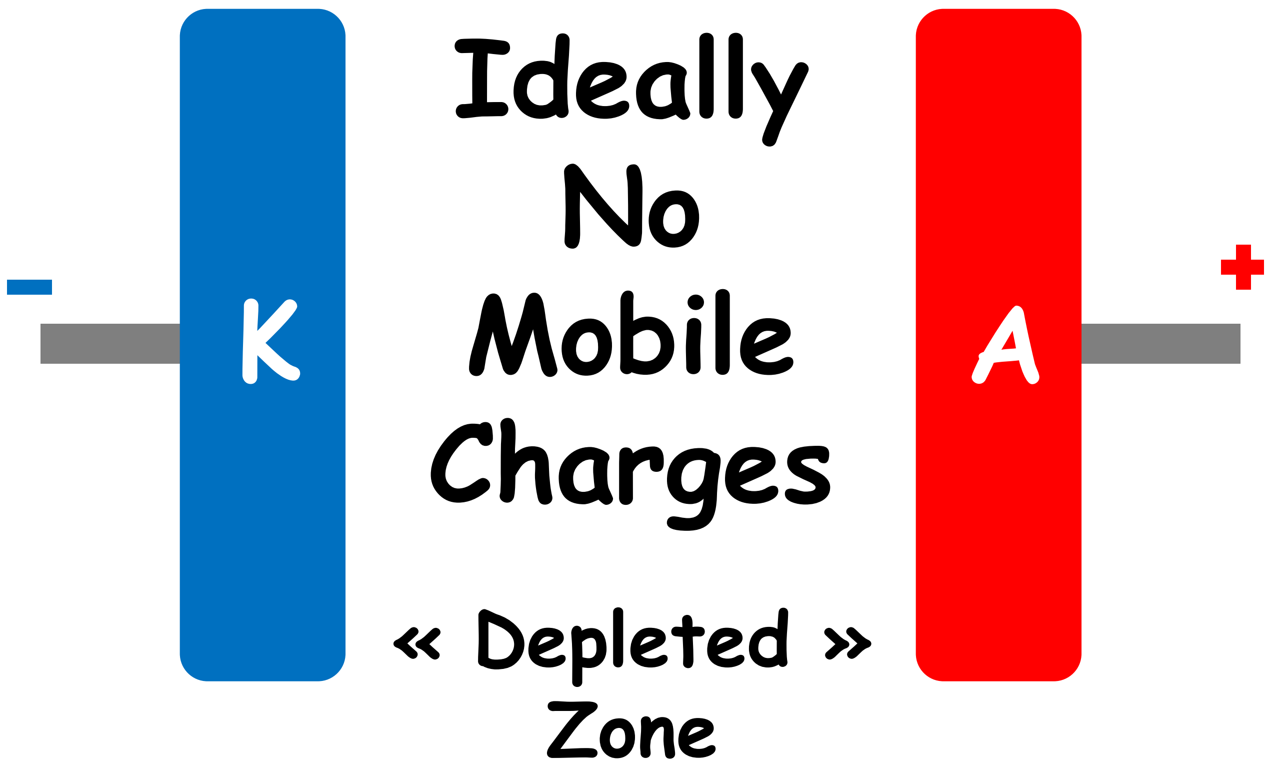
=> It is a DIODE DEVICE

I-V Characteristics of an Ideal Rectifier

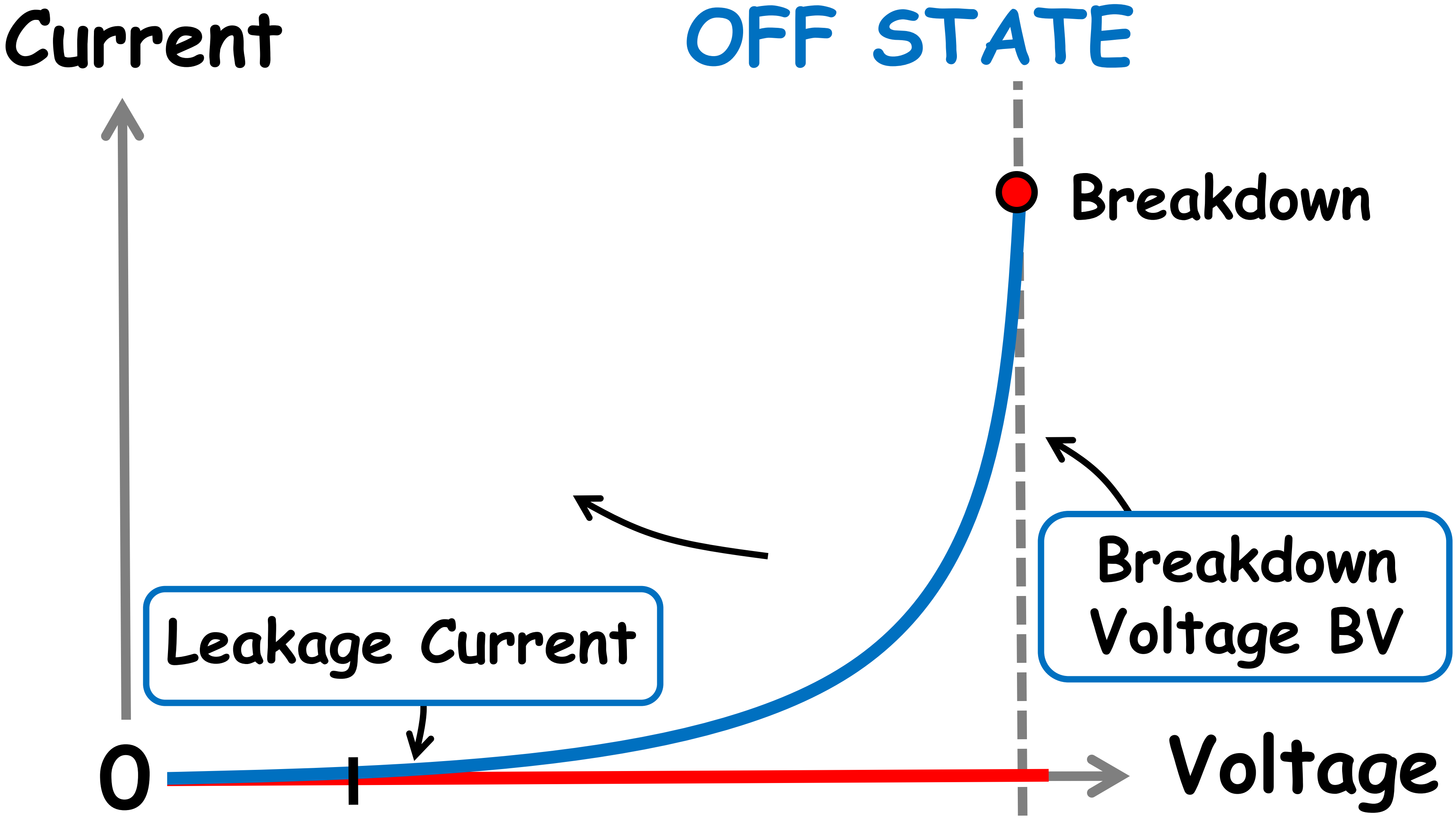


The Switch
at
OFF STATE

The Ideal Switch OFF STATE



The Real Switch
OFF STATE



General Trend

The Higher The Voltage

=> The Higher The Electric Field

=> The Higher The Leakage Current

I_{OFF}

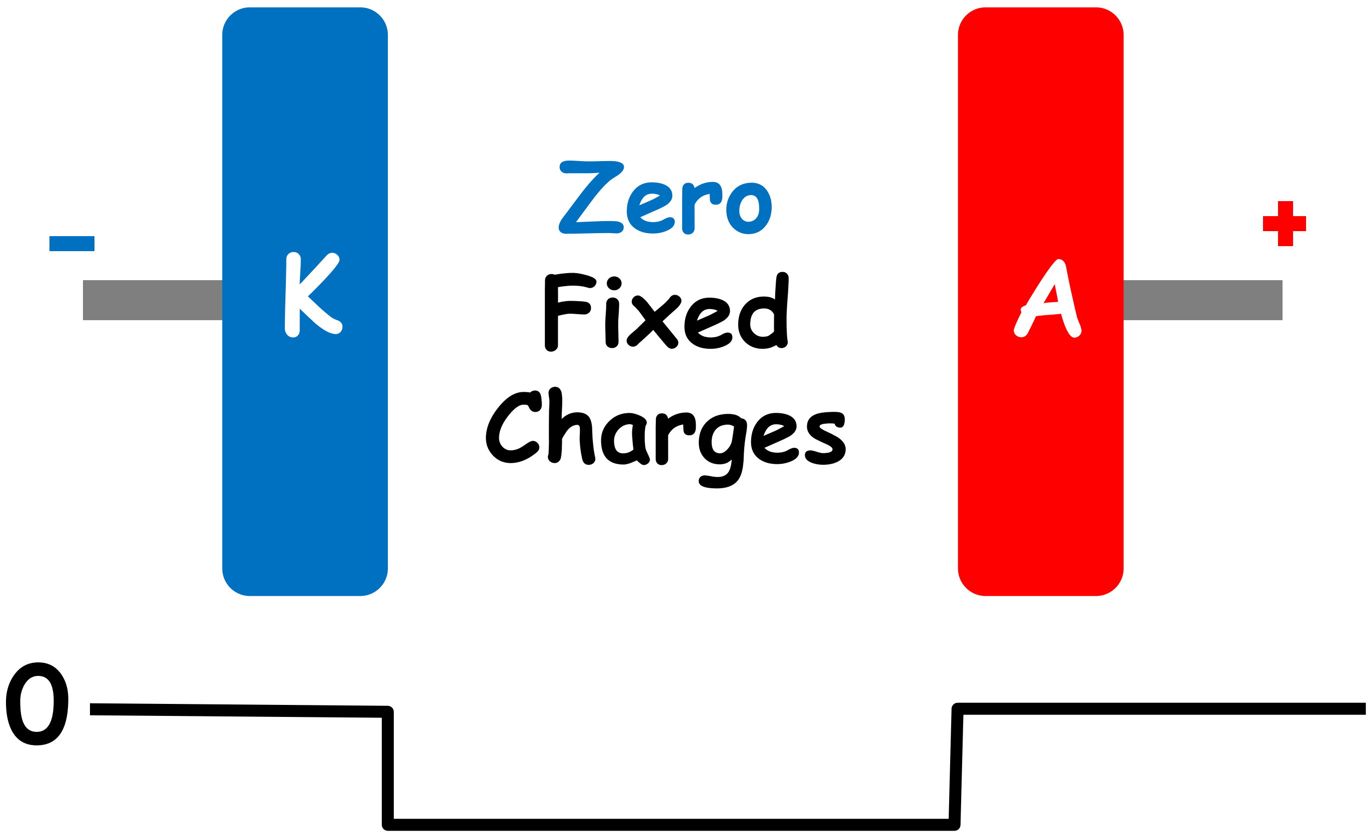
The Real Switch at OFF STATE
3 cases for the
Fixed Charge Density within the Transit Zone

- **Zero Fixed Charges**
  => Vacuum or Undoped Semiconductor

- **Positive Fixed Charges**
  => N-type semiconductor

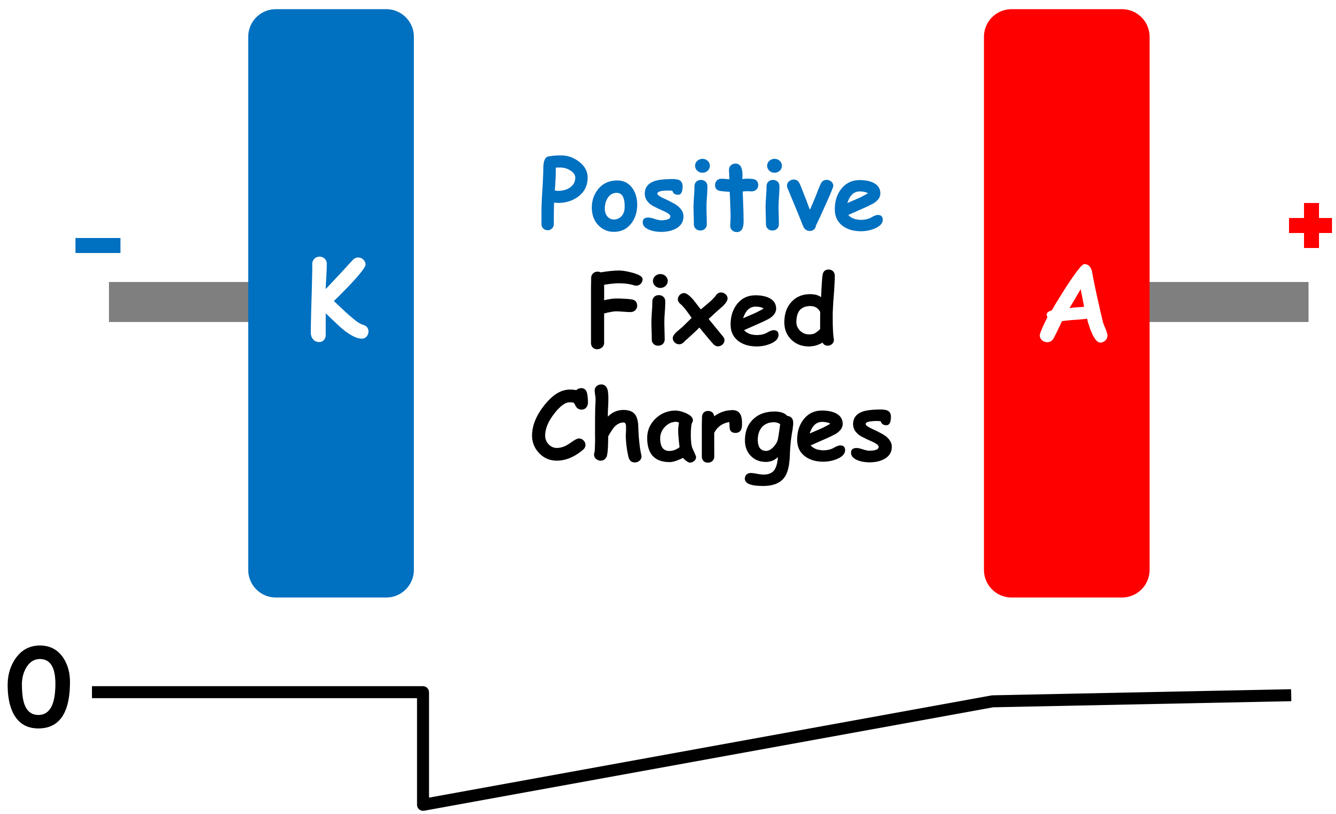
- **Negative Fixed Charges**
  => P-type semiconductor

The Real Switch OFF STATE



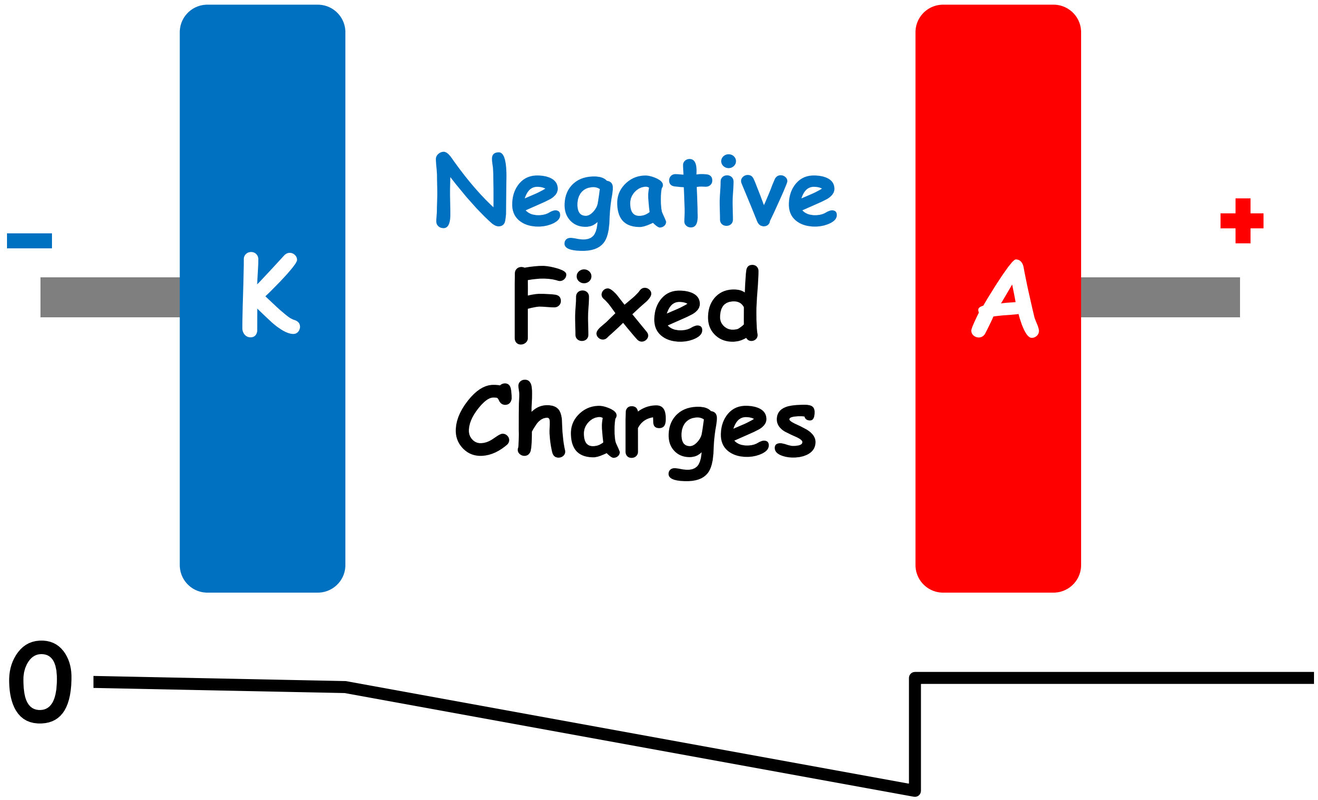
Flat Electric Field Profile

The Real Switch OFF STATE



Electric Field Ramp Profile

The Real Switch OFF STATE

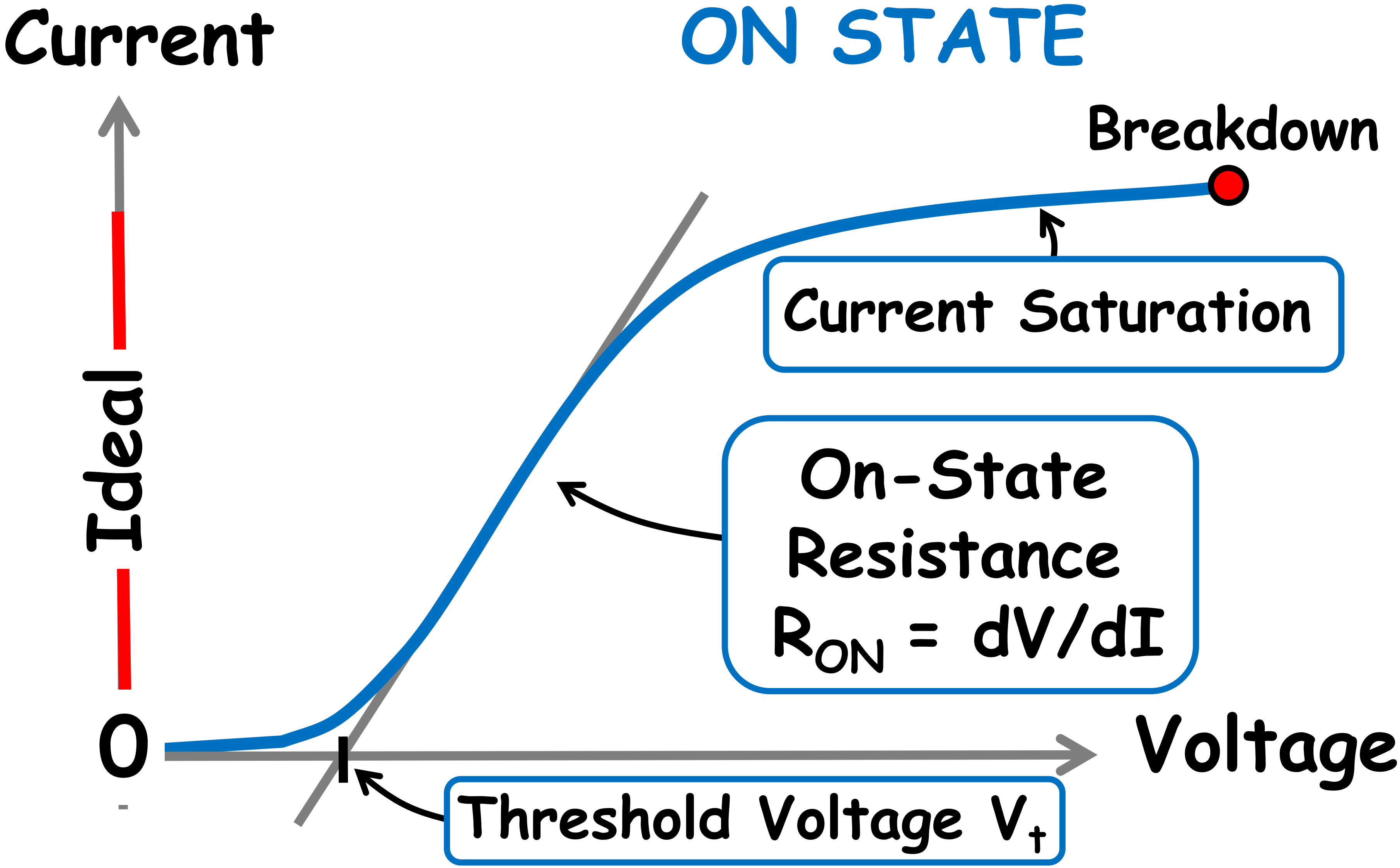


Electric Field Ramp Profile

In the same Semiconductor, Undoped Transit Zone will handle Higher V_{OFF} than Doped Transit Zone

The Switch at ON STATE

The Real Switch
ON STATE



The Real Switch
ON STATE

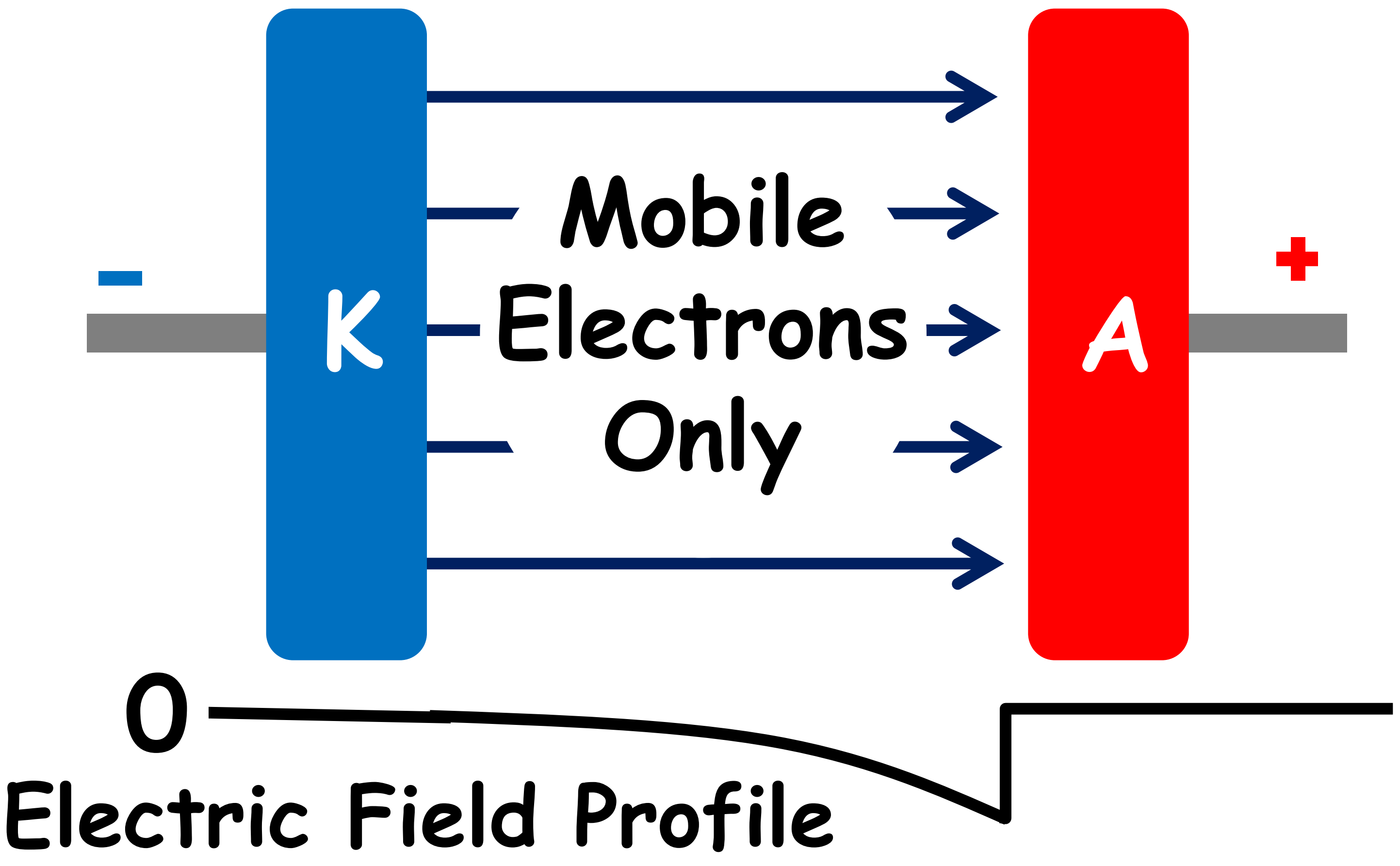
- All switches have a resistance R_{ON}
- Some switches have a Threshold Voltage
- Some switches exhibit Current Saturation
- All switches have a max. available current before breakdown I_{ON} MAX

Unipolar vs Bipolar Switching Devices

In a Unipolar Device
there is only
ONE polarity
of Mobile Charges

Positive OR Negative

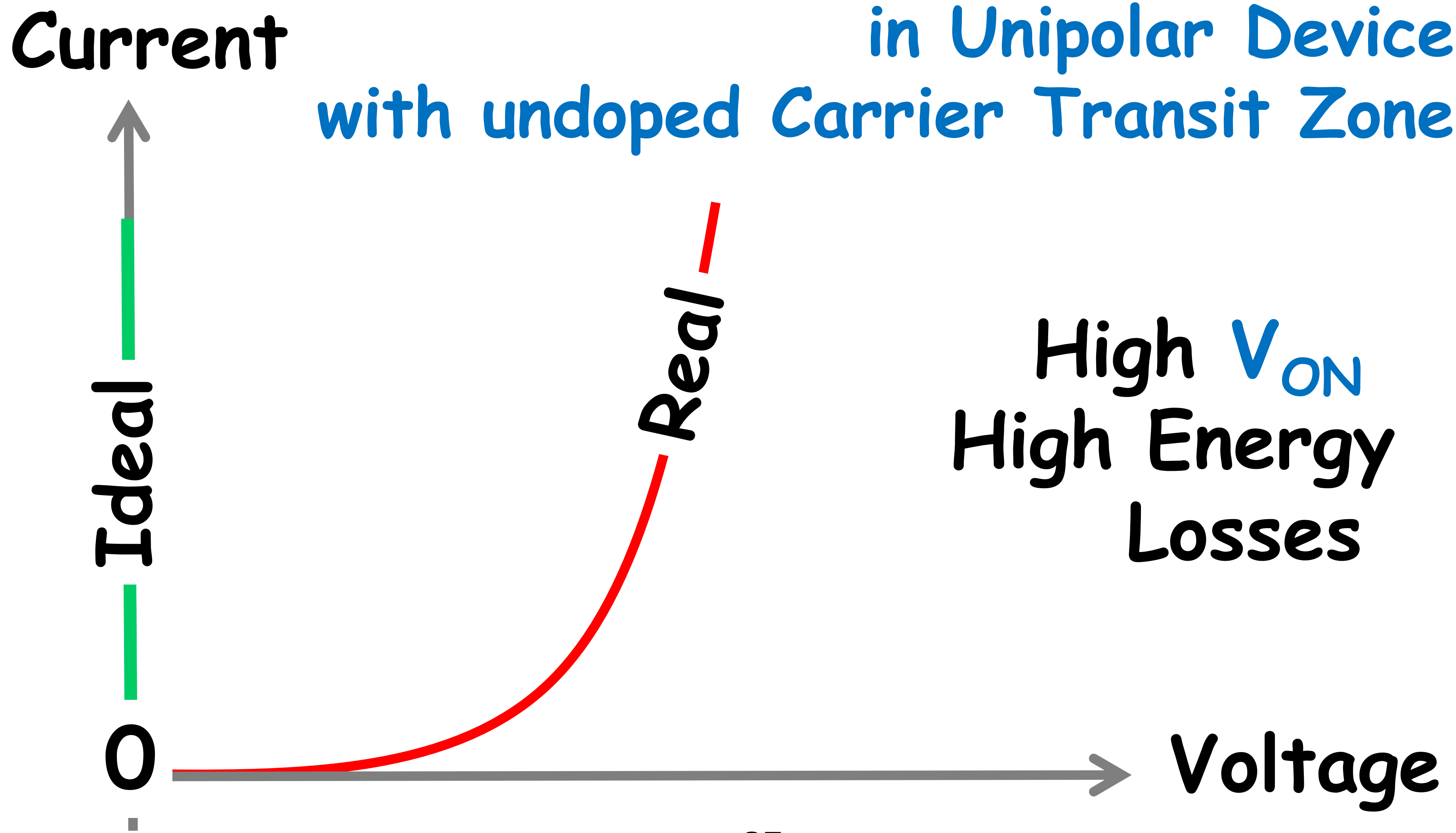
Unipolar Switch « ON » STATE
with no Fixed Charges (Vacuum or Undoped SC)



Space Charge Effect at ON STATE in Unipolar Device with undoped Carrier Transit Zone

- Electric Field is not uniform
- Part of the field accelerates the carriers
- More carrier energy than necessary is lost into heat in the transit zone and the anode
- On-state Voltage V_{ON} is High

Space Charge Effect at ON STATE in Unipolar Device with undoped Carrier Transit Zone



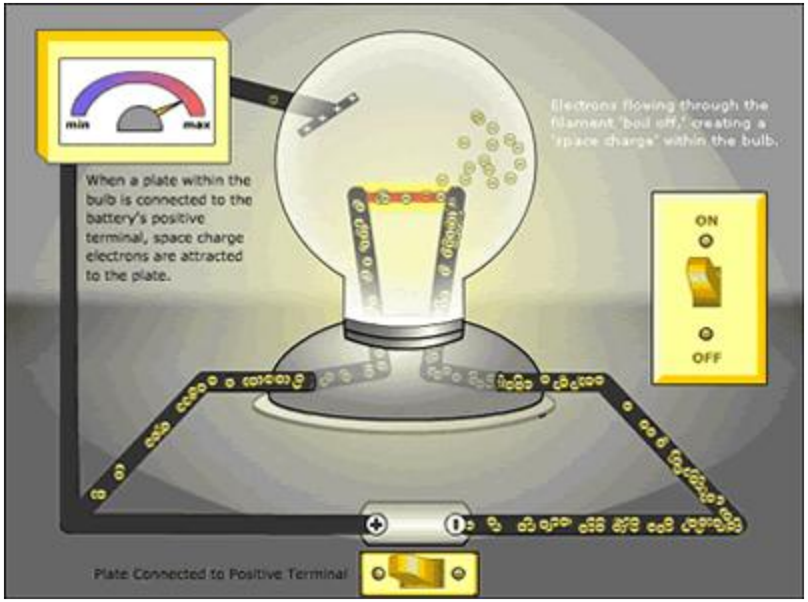
High V_{ON}
High Energy Losses

85

Vacuum Diode

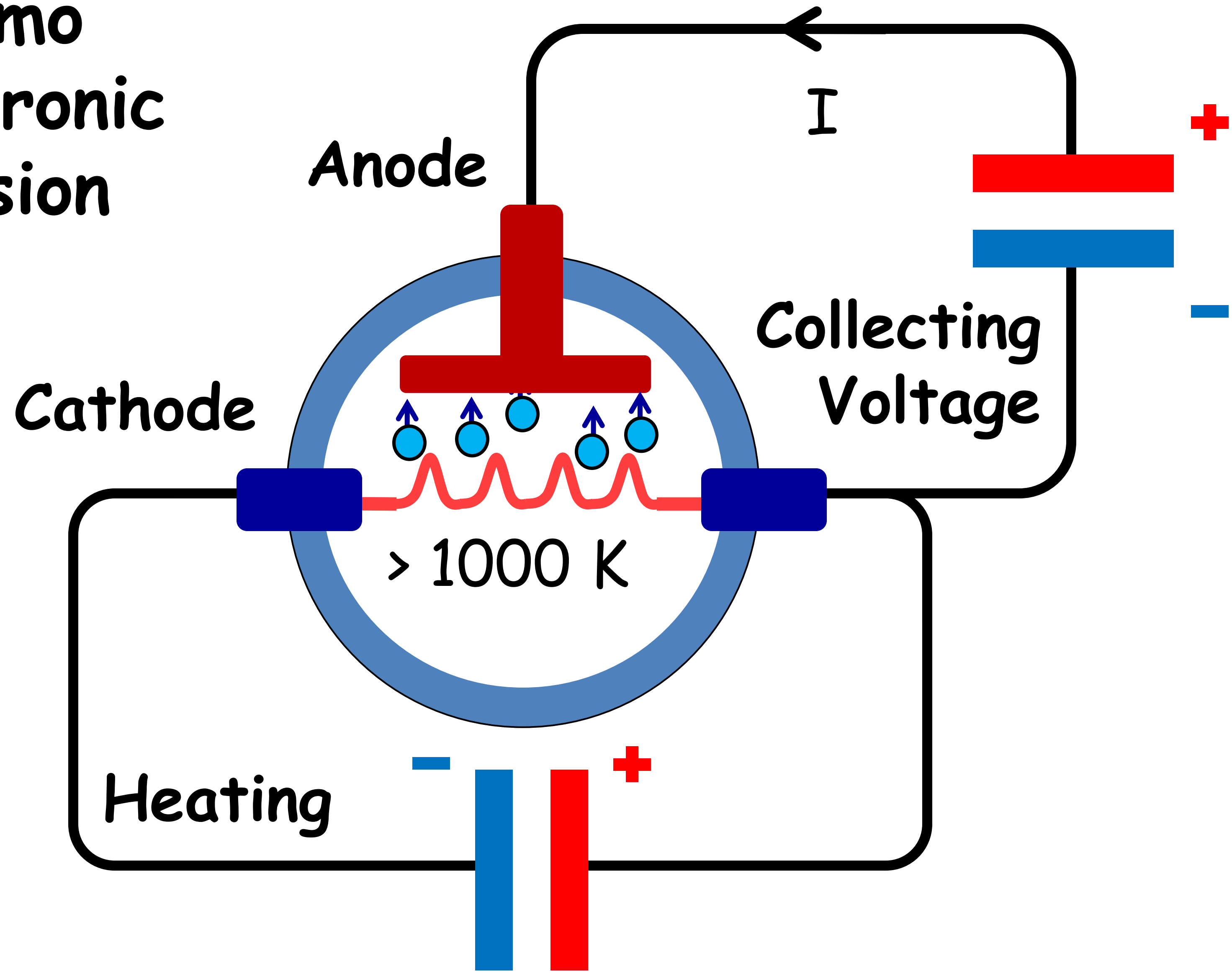
The Ancester
of
All Electronic Switches

1883 : Thomas Alva Edison discovered Thermo-Electronic Emission



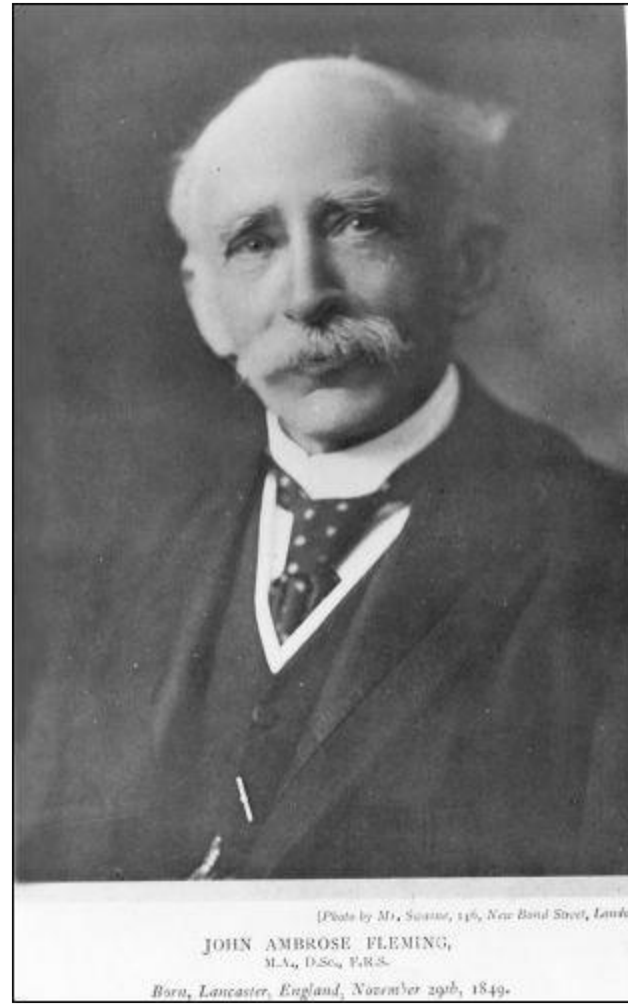
87

Thermo Electronic Emission



1904 : John Ambrose FLEMING invented Vacuum Diode

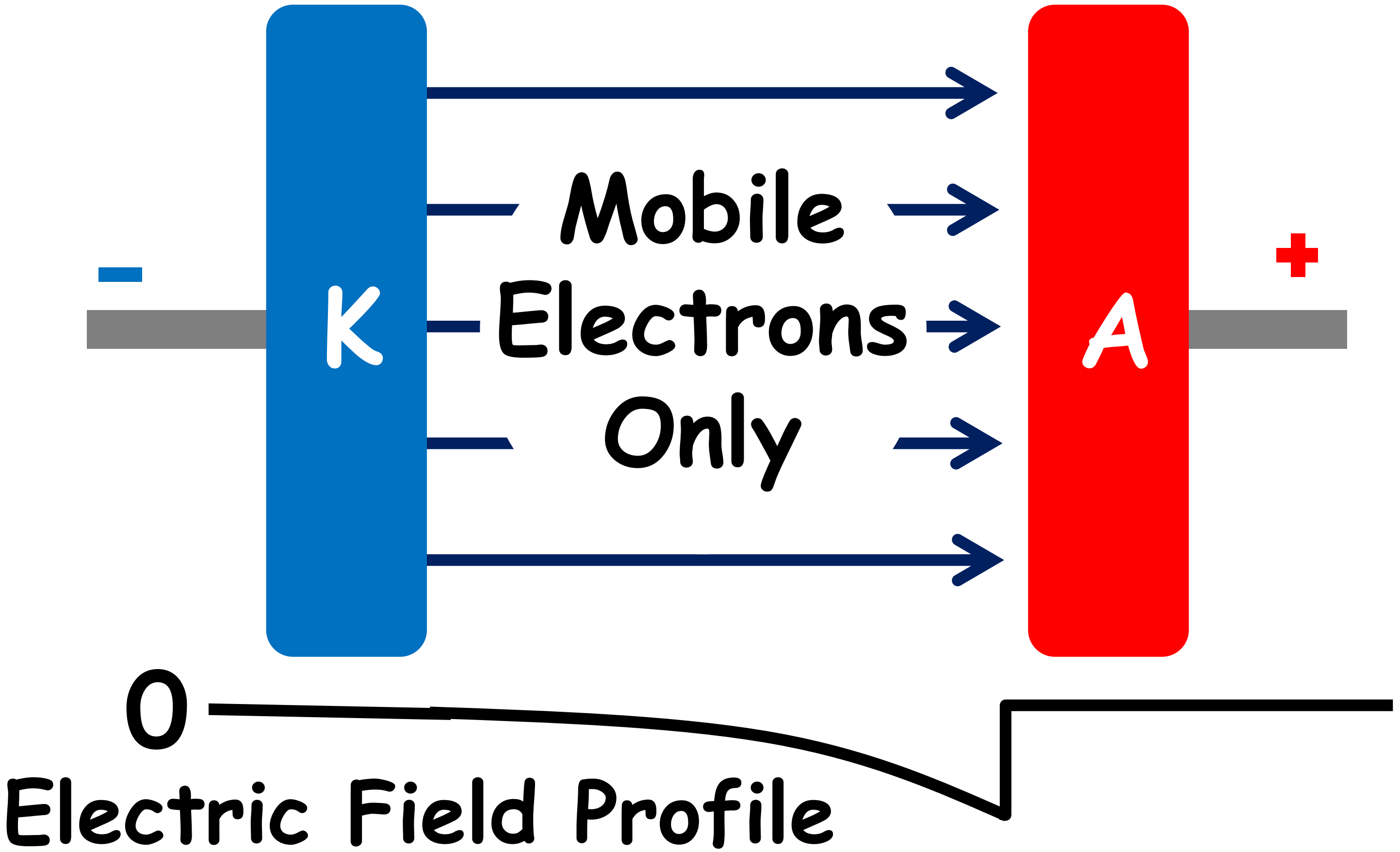
- John Ambrose FLEMING has done research at Cambridge with Maxwell,
- In 1882 He joigned the British Branch of the Edison Company,
- In 1889, he started to work for the « Wireless and Signal Company » of Guglielmo Marconi,
- Fleming invented the « Valve » (Vacuum Diode) in 1904,
- The « rectifying » effect has been rapidly used for the conversion AC => DC,



Vacuum means :

No Fixed Charges
Négative Mobile Charges

Unipolar Switch « ON » STATE
with no Fixed Charges (Vacuum or Undoped SC)



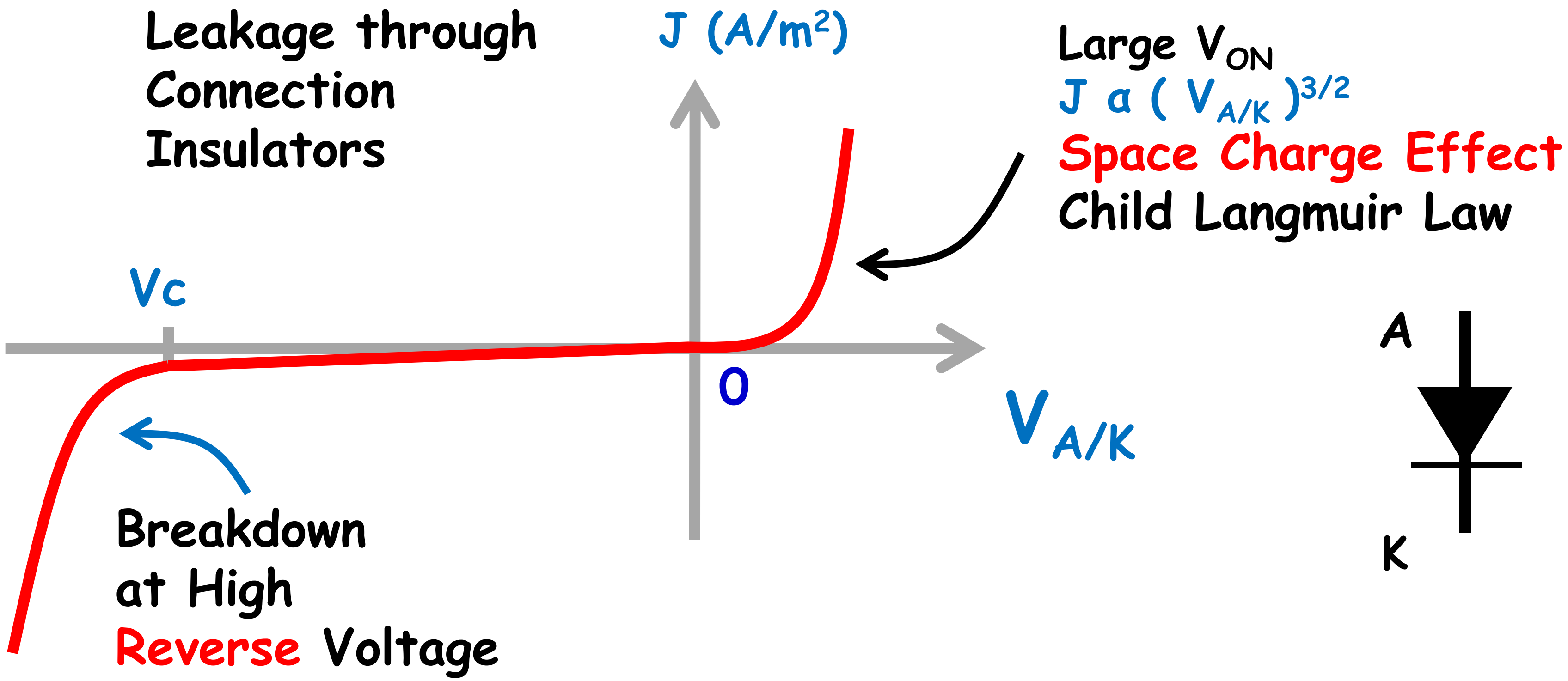
In Vacuum

Space Charge Effect

High Voltage is needed to collect electrons

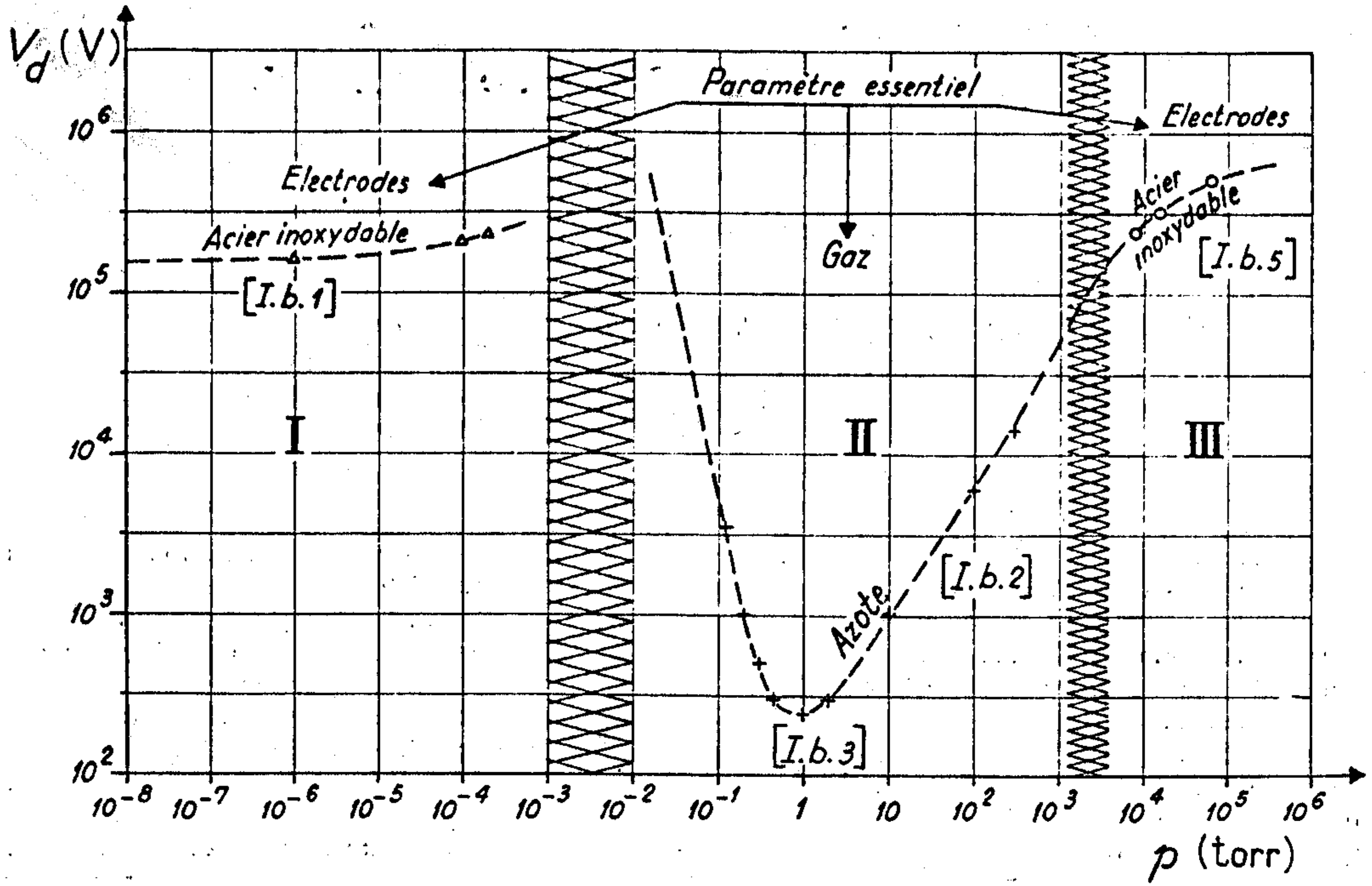
Accelerated Electrons Heat Anode=> energy loss

Current / Voltage Characteristics of a Vacuum Diode Rectifier

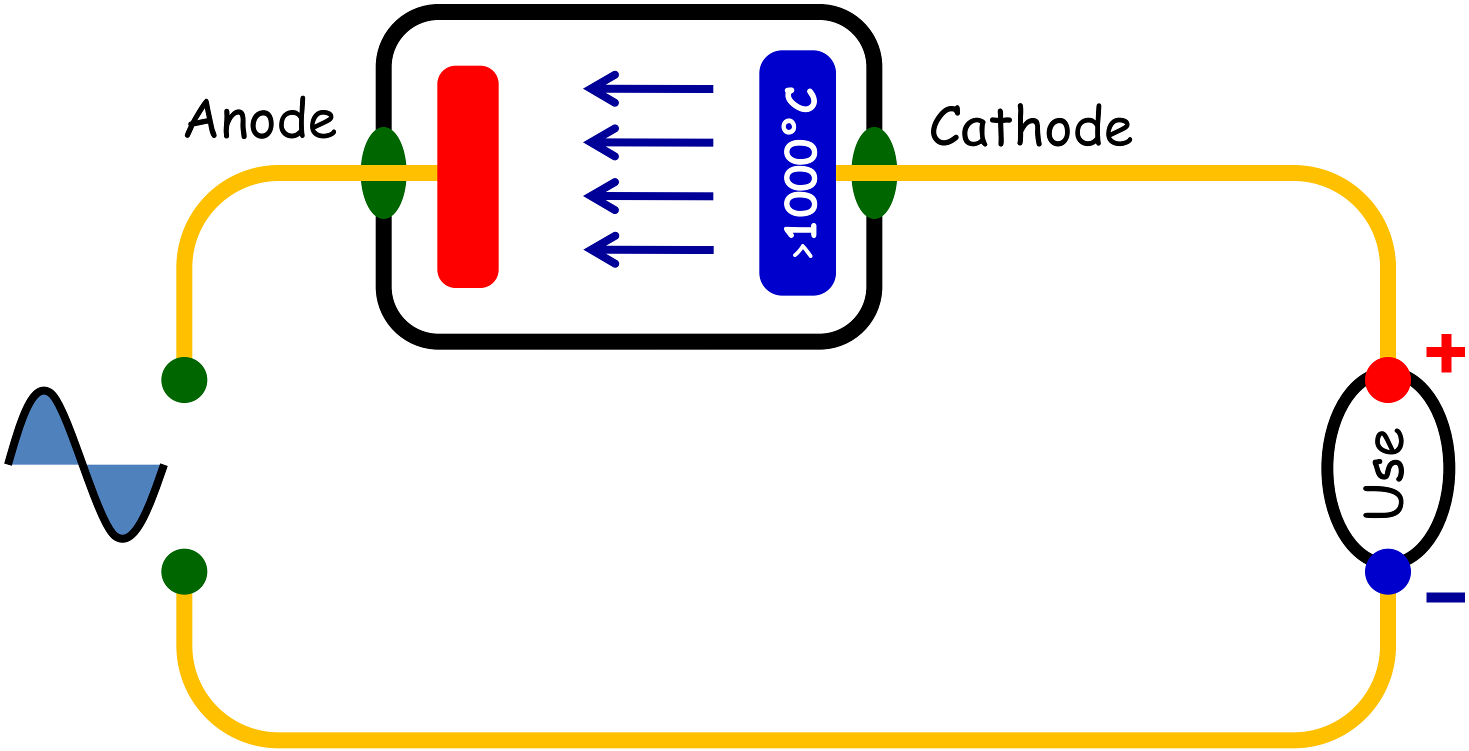


Breakdown Voltage between 2 electrodes (distance : 1 cm) as a function of the Ambiant Pressure in « OFF » State

Breakdown Field is similar (20 V/µm) in good vacuum or in silicon

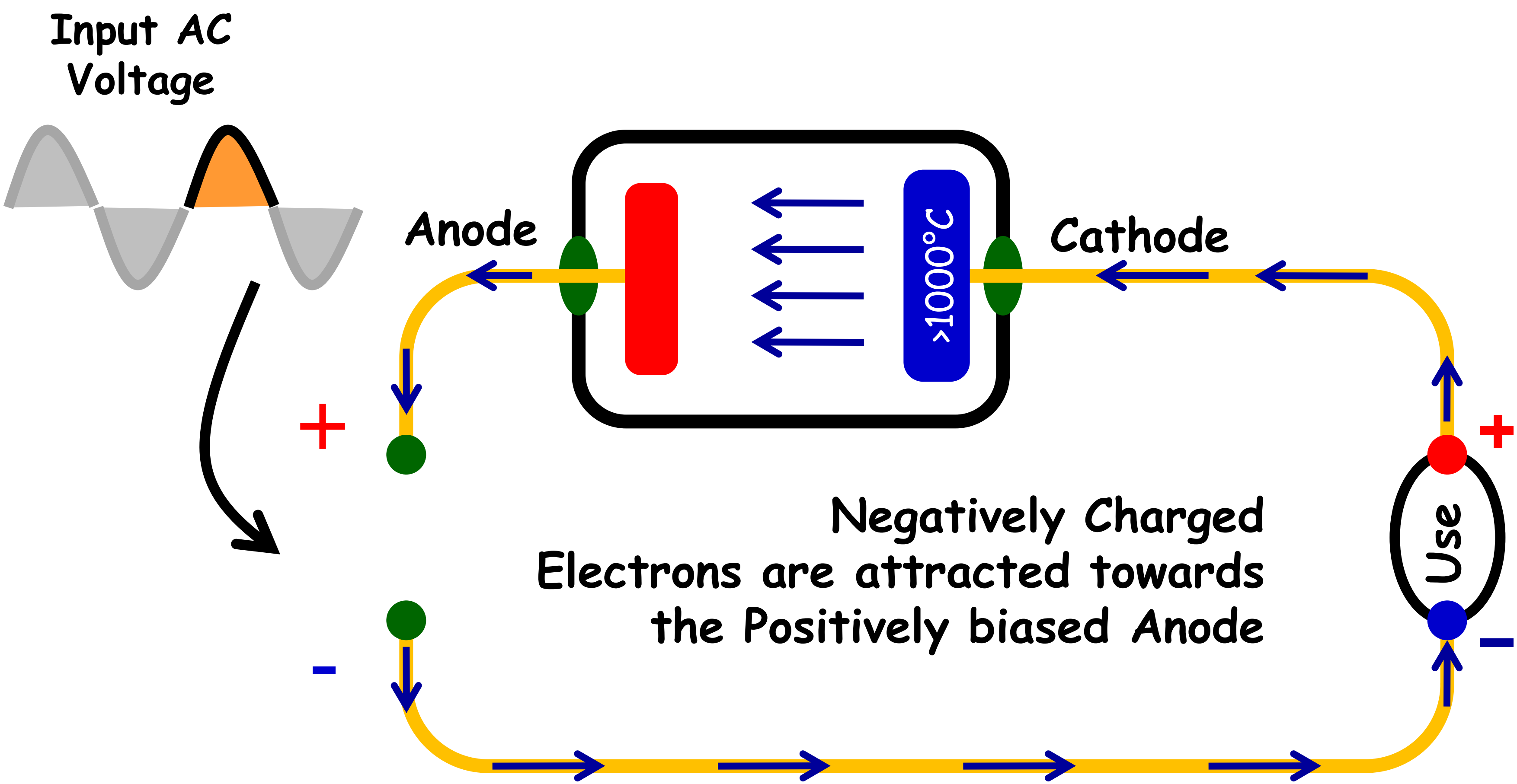


AC => DC Conversion using a Vacuum Diode as a Self Triggered Switch (Rectifier)



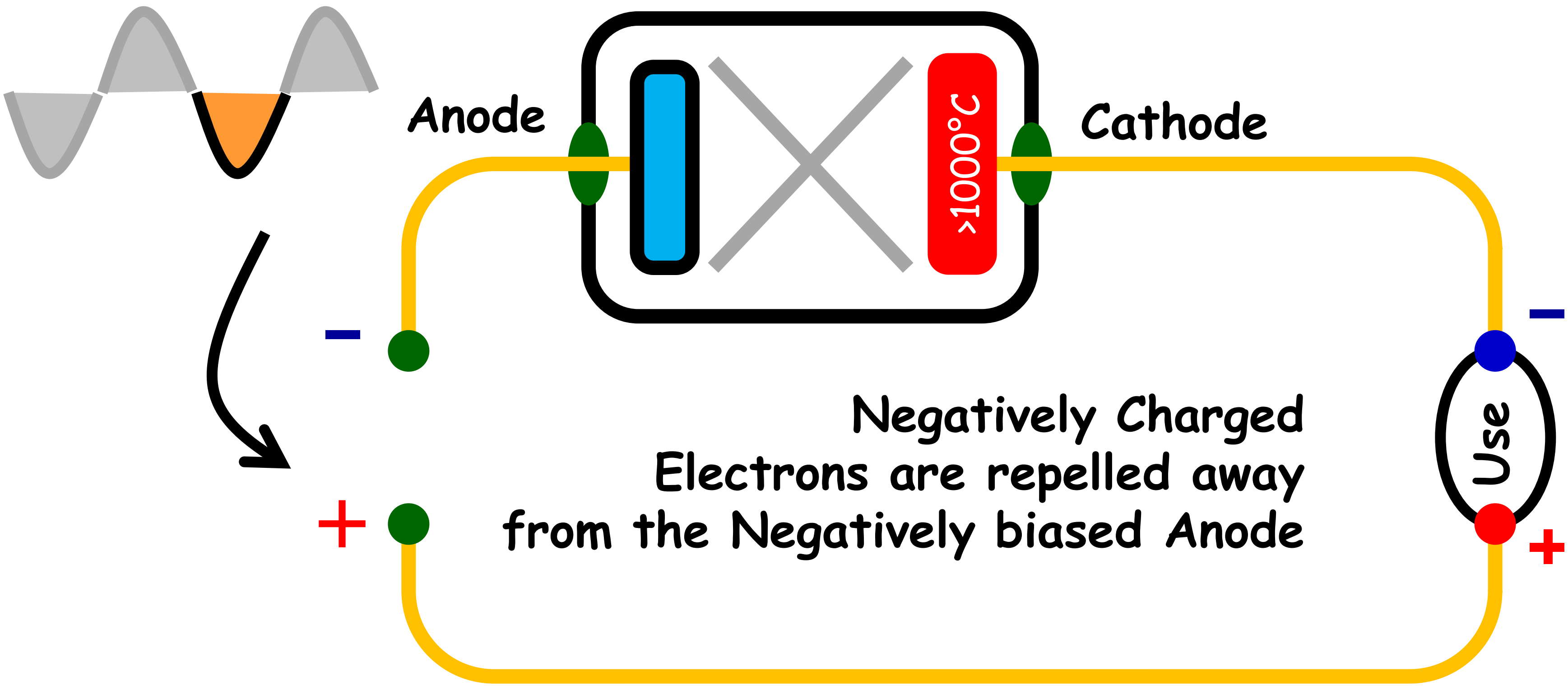
Self Triggered Switching in a Vacuum Diode :

Direct Regime : « ON » when V_{AK} >0

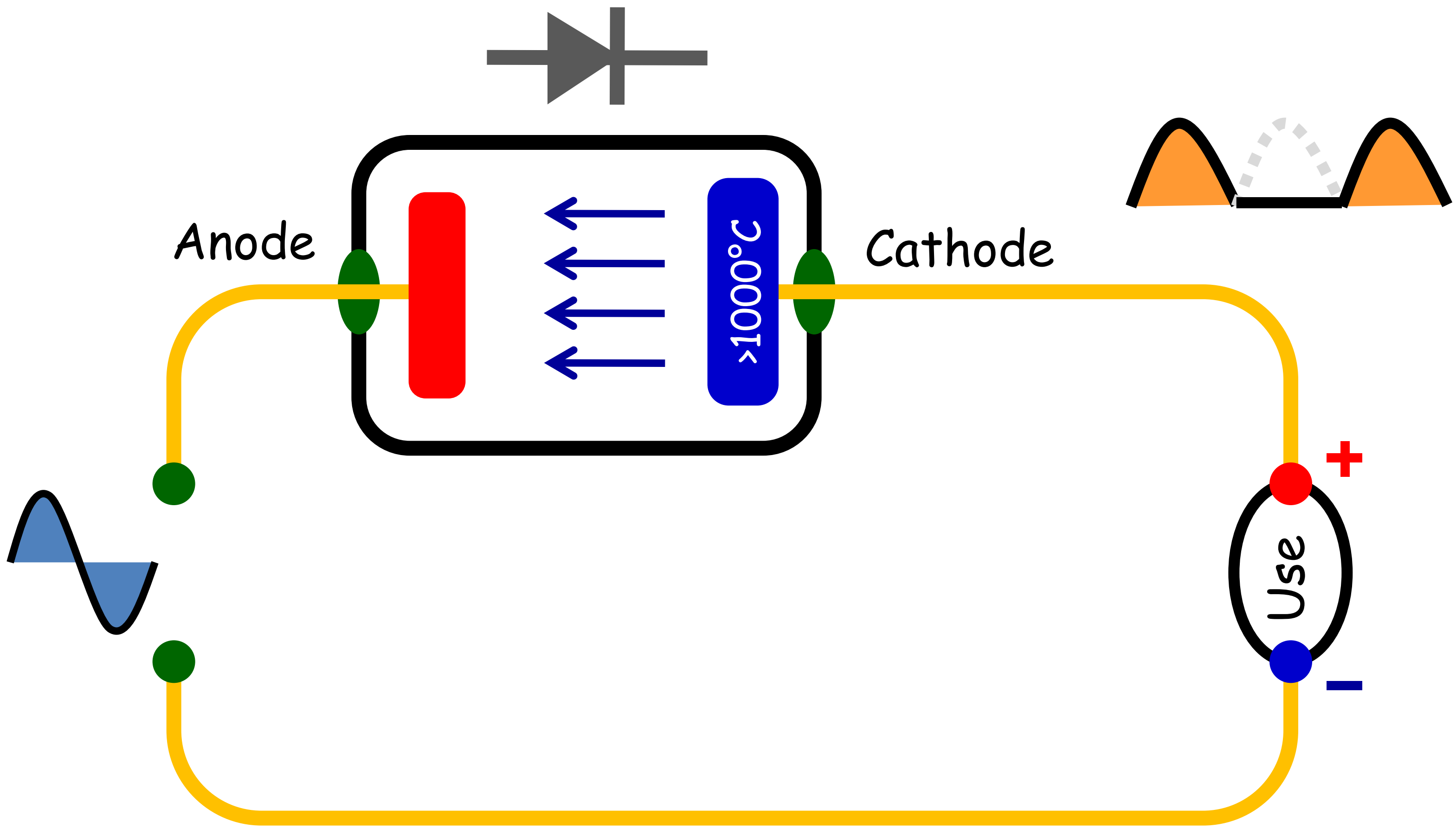


96

Self Triggered Switching in a Vacuum Diode :
Reverse Regime : « OFF » when V_{AK} < 0

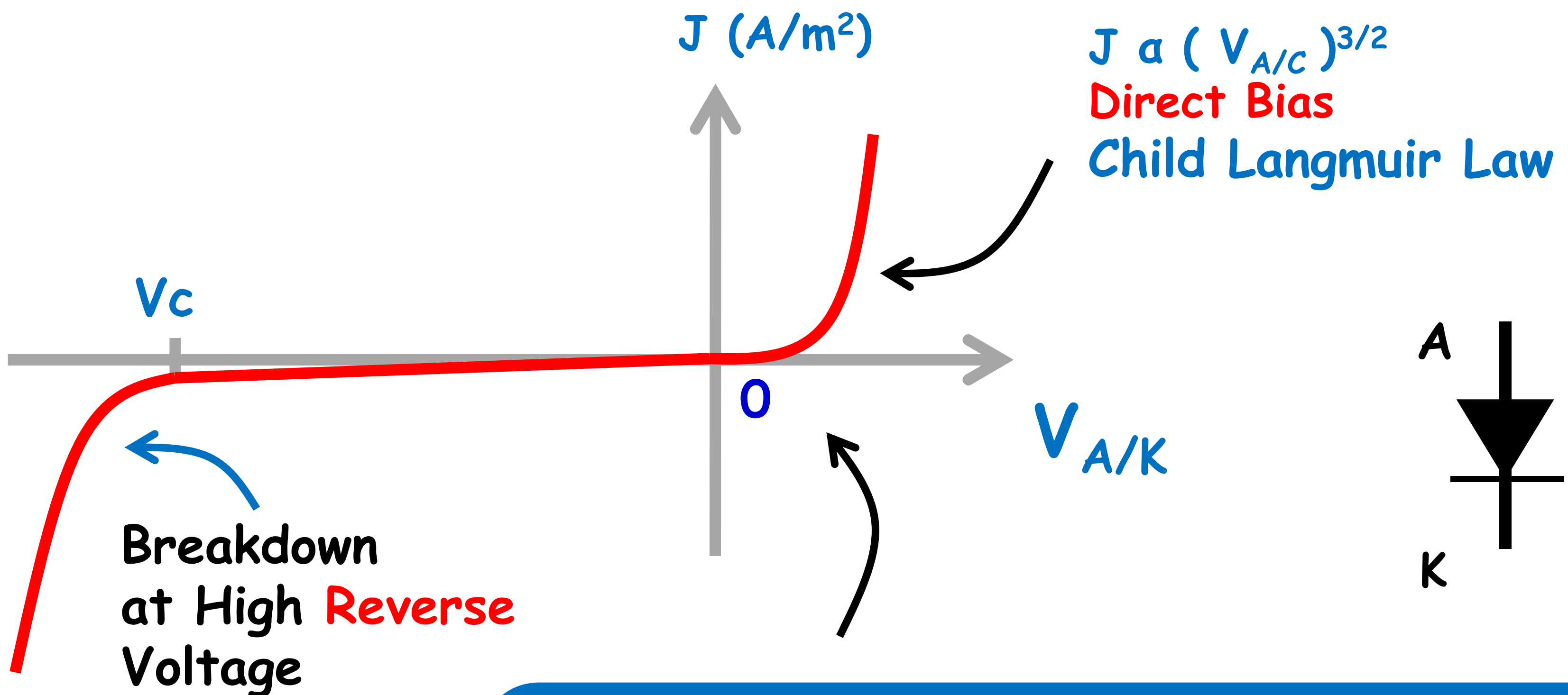


AC => DC Conversion using a Vacuum Diode



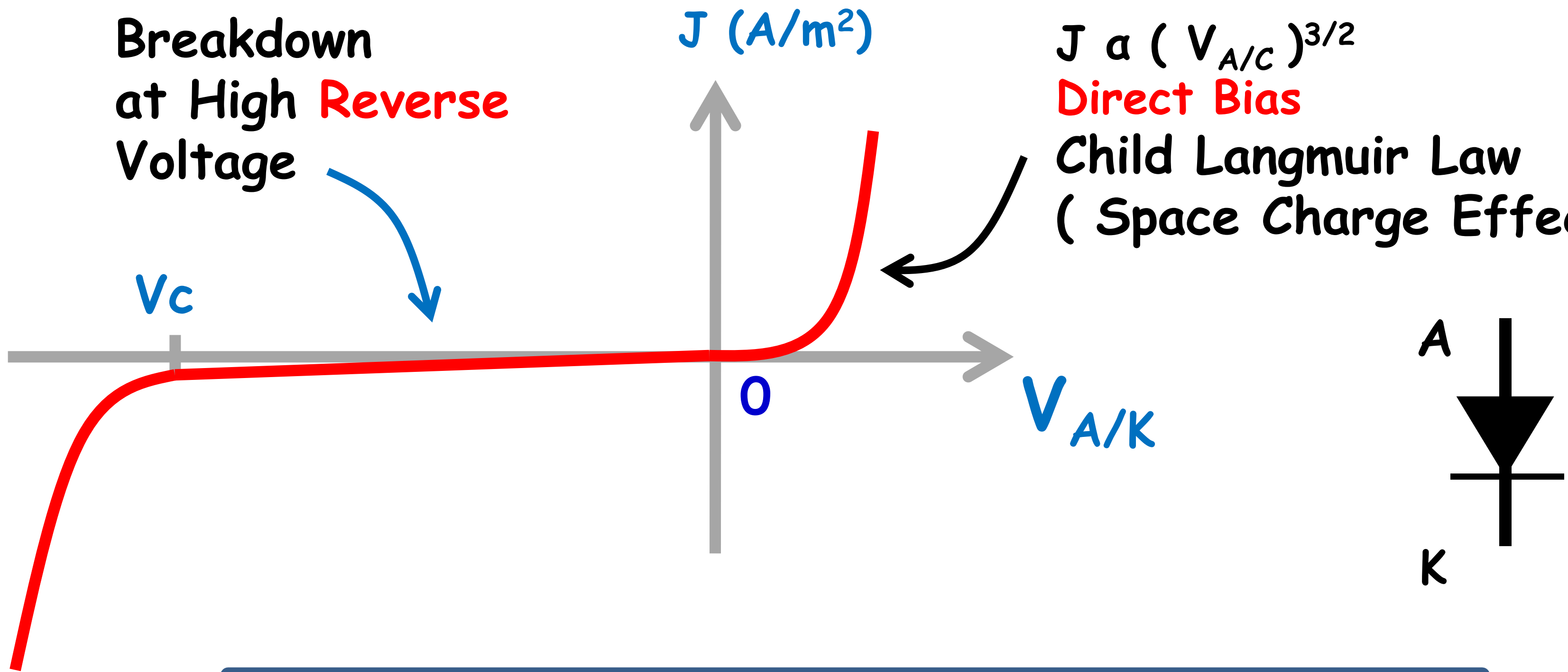
98

Limitations of the Vacuum Diode



High Voltage is required to extract electrons in direct bias regime
(« ON » state)

Limitations of the Vacuum Diode



For A-K distance 10 μm

=> V_{OFF} = 200 V Maximum Reverse Voltage

Child Langmuir Law => V_{ON} ~ 12V @ 1A/mm²

High Losses of Energy (Heating of the Anode)

Vaccum Switches
are Simple
but they are not
Energy Efficient

Undoped Semiconductor Unipolar Switches

have the same problem as Vacuum ones

they are not Energy Efficient

Example :

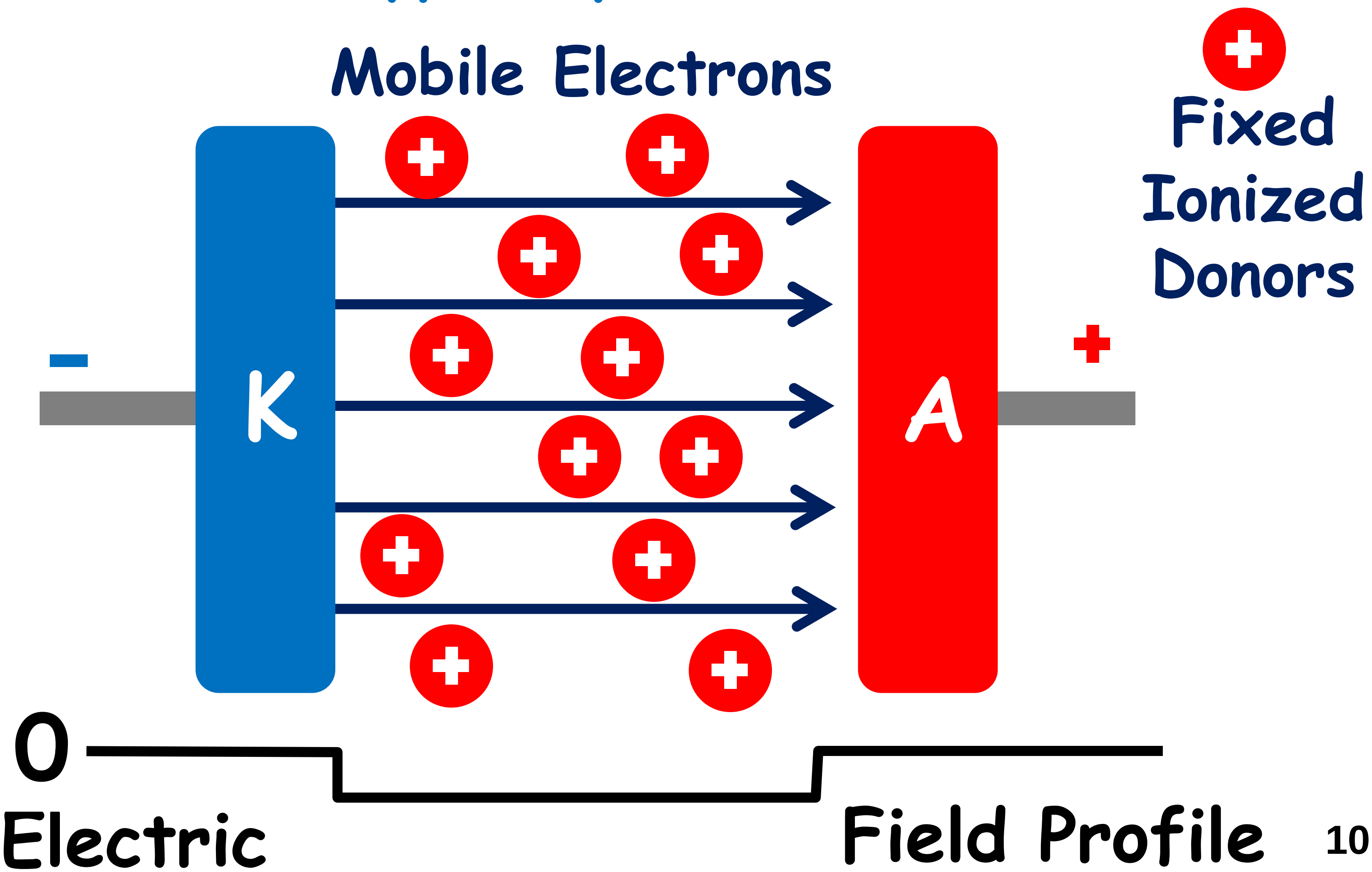
Undoped Diamond Unipolar Switches have excellent V_{OFF} but much too high V_{ON}

they are not Energy Efficient

Conclusion

Semiconductor Unipolar Switches MUST have a Doped Transit Zone

Unipolar Semiconductor Switch « ON » STATE with N-type Doped Transit Zone



Compromise between V_{ON} and V_{OFF}

Baliga's Figure of Merit (BFM) for Unipolar Devices

BFM = best possible V_{OFF} / V_{ON} depends only on semicondutor material, not on device topology.

Baliga's Figure of Merit of Semiconductor Materials For Unipolar Switches

Bkdwn Voltage V_{OFF} / On-Voltage V_{ON}

$$B.F.M = \mu \cdot E_b^3$$

μ Mobility of the Carriers

E_b SC Breakdown Field

Semiconductor Materials for Switching Devices

High Breakdown Field is THE priority

Semiconductor Materials with High Breakdown Field are « Hard Semiconductors »

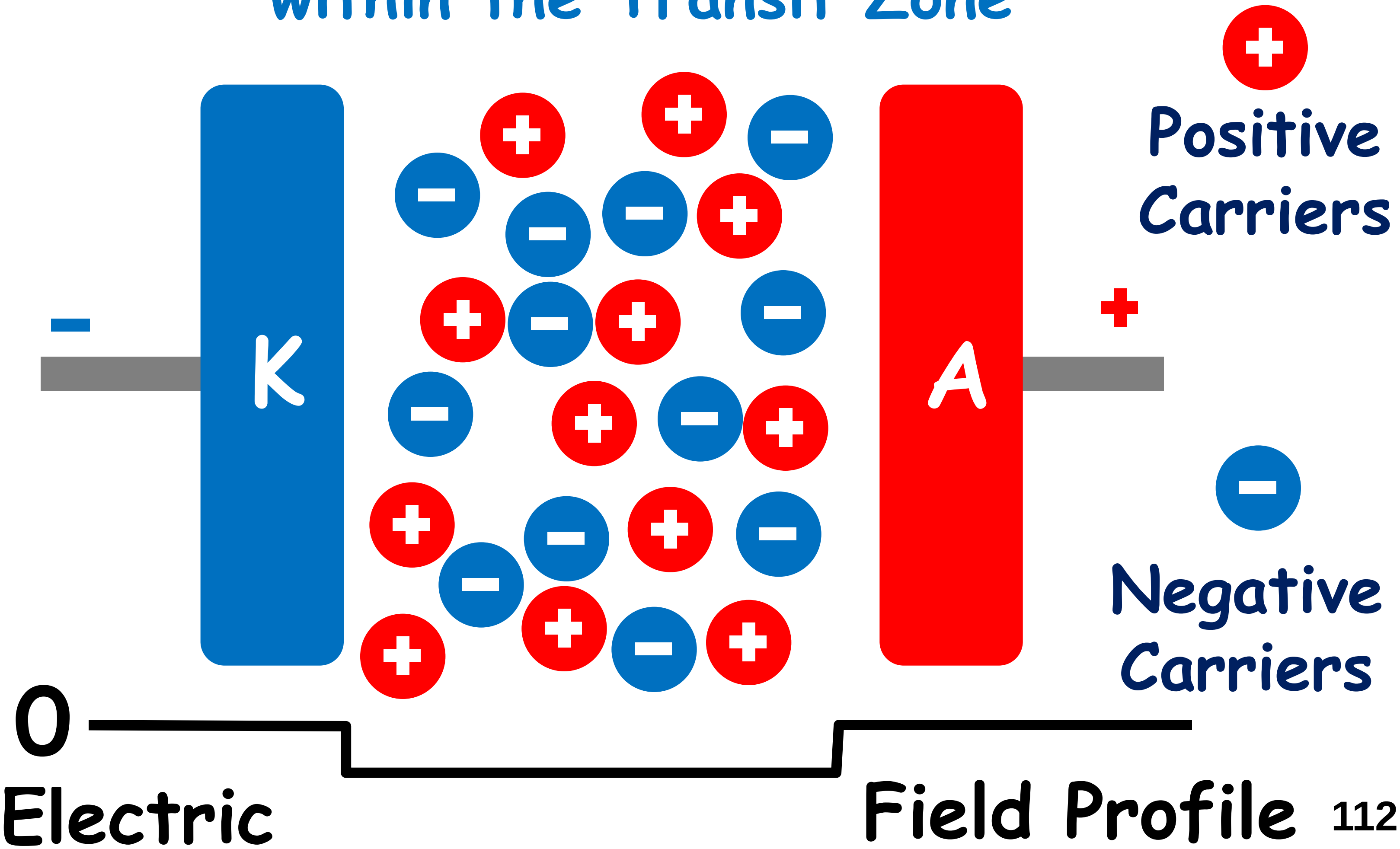
Strong Chemical Bonds provide together :

- Very High Mechanical Hardness,
- Very High Young Modulus,
- Thermal Stability,
- Wide Bandgap,
- High Thermal Conductivity,
- Very High Electric Breakdown Field,
- Low Dielectric Constant,

Bipolar Switching Devices

In a Bipolar Device
BOTH
Positive AND Negative
Mobile Carriers
are present
at ON STATE

Bipolar Switch at « ON » STATE
both Positive AND Negative Carriers within the Transit Zone



In Bipolar Switching Devices :

- Charge Compensation

=> No Space Charge Effect

- High Density of Carriers

=> Low On-State Resistance

Mercury Vapor Plasma Diode

The Ancester of All Bipolar Switches

In Plasma Diodes at ON-STATE

there are

High Densities

of

Positive Carriers

Ions

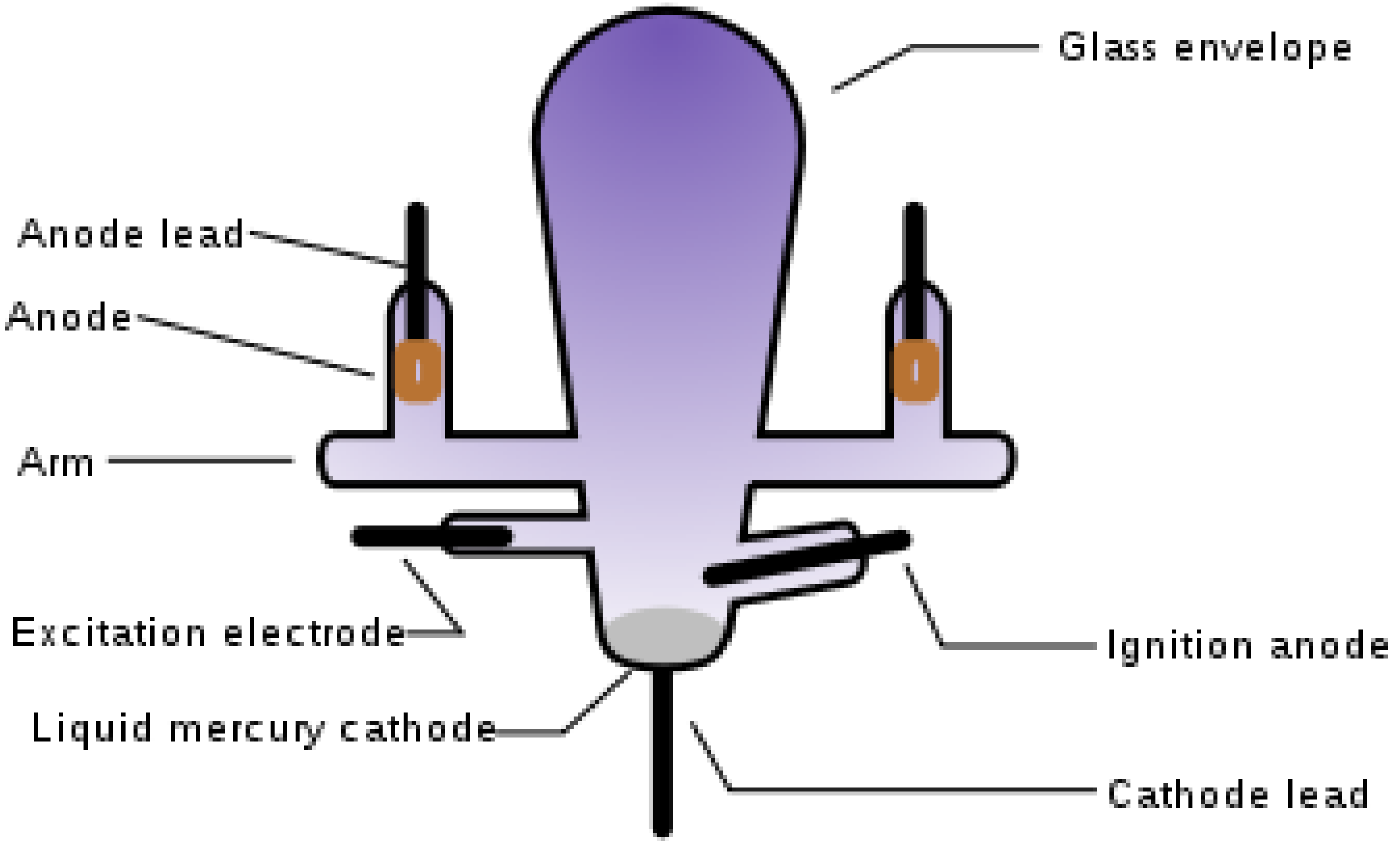
and

Negative Carriers

Electrons

Mercury Cathode Plasma Diodes have been used as « rectifiers » for High Voltage AC => DC up to 1960.

A big one was designed for 180 kV maximum V_{OFF}
V_{ON} ~ 20 V @ 1800 A



Mercury Plasma Diodes

V_{ON} ~ 25V @ 1 kA V_{OFF} up to 180 kV

Visible Light results from

$e^- - Hg^+$

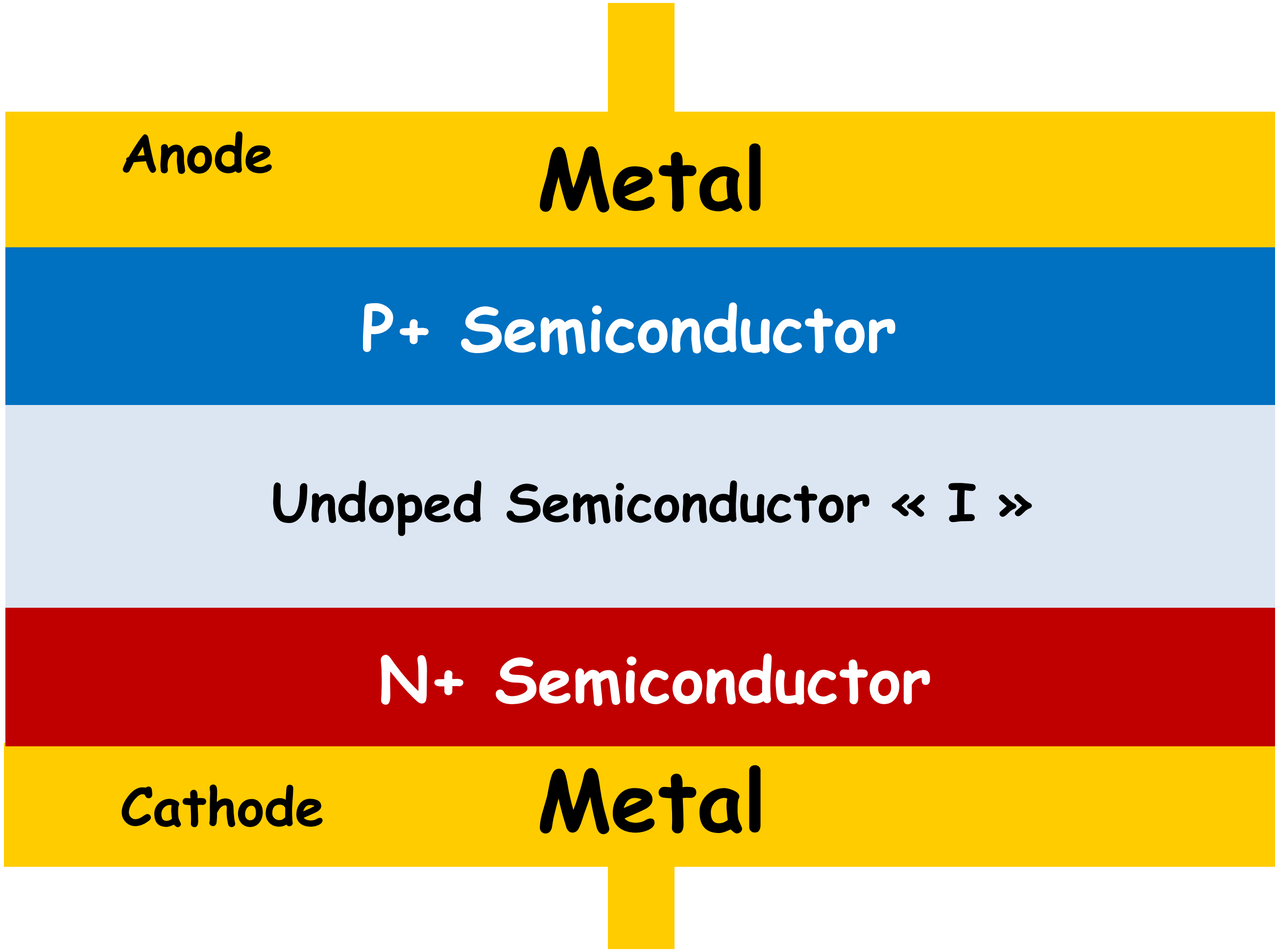
recombinations

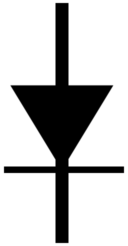
117

Semiconductor PIN Rectifier

The Most Popupar of All Bipolar Switches

Semiconductor P I N rectifier

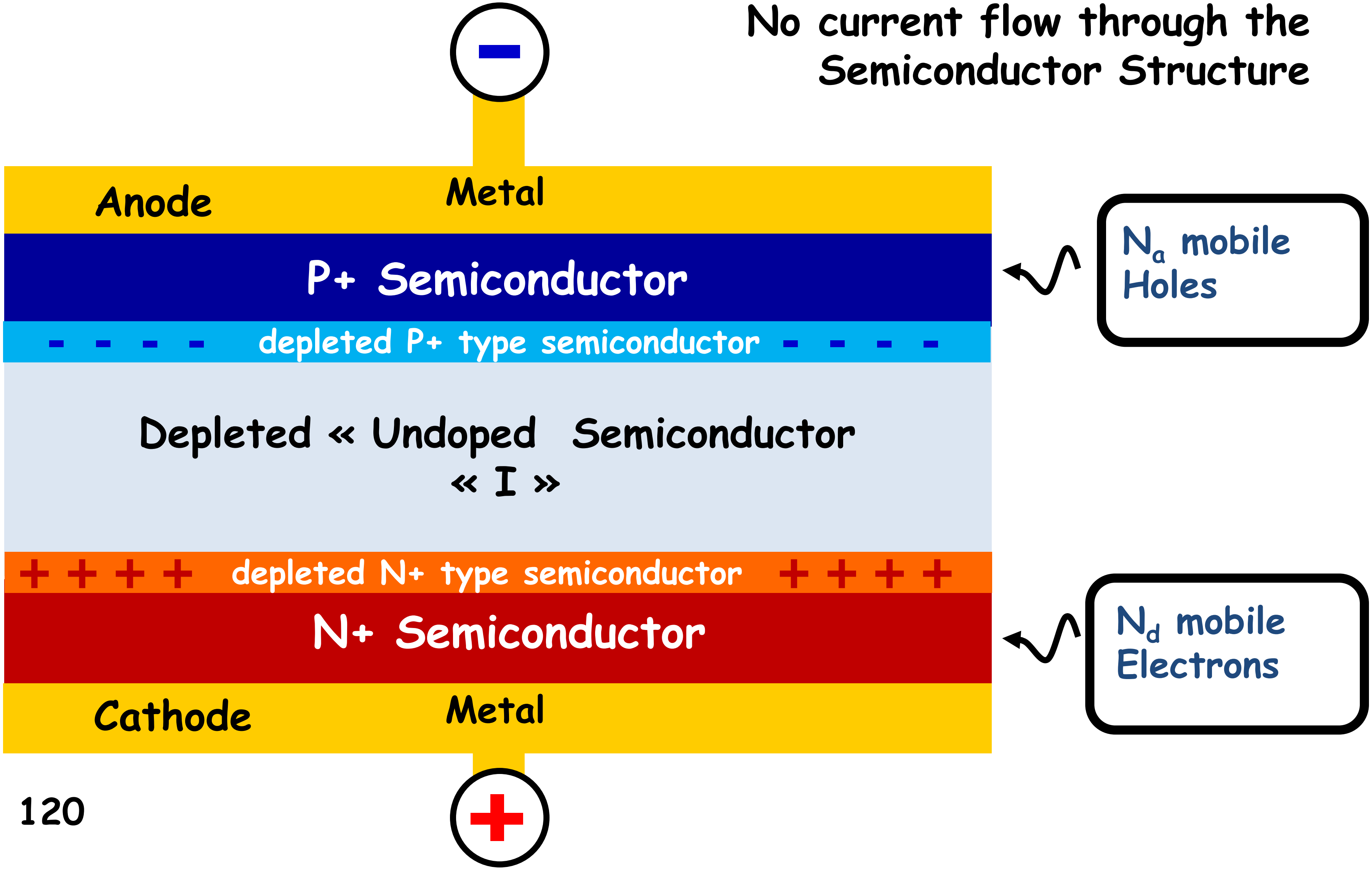




P I N rectifier

Reverse Biased => $V_{AK} < 0$

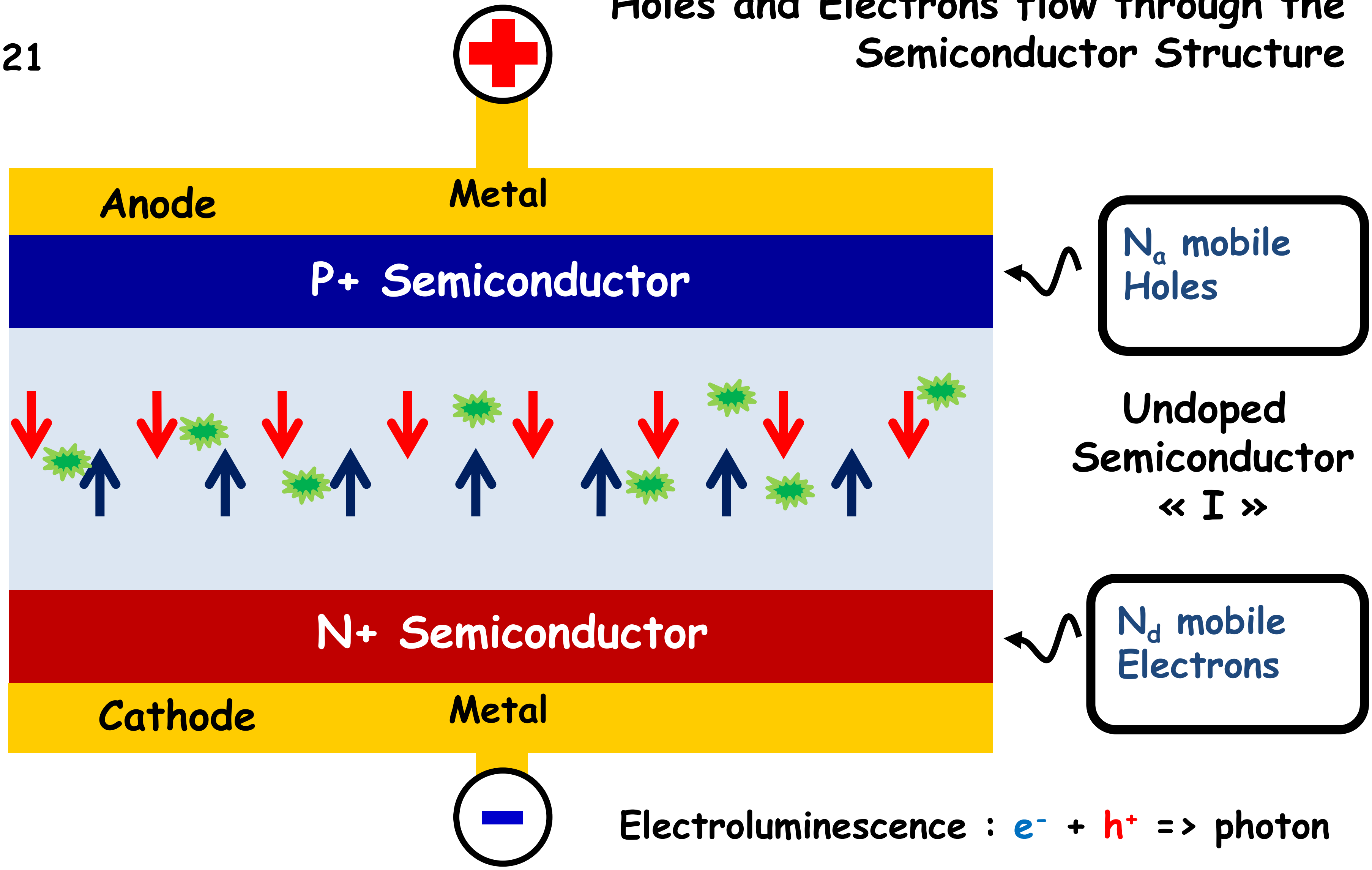
No current flow through the Semiconductor Structure



P I N rectifier

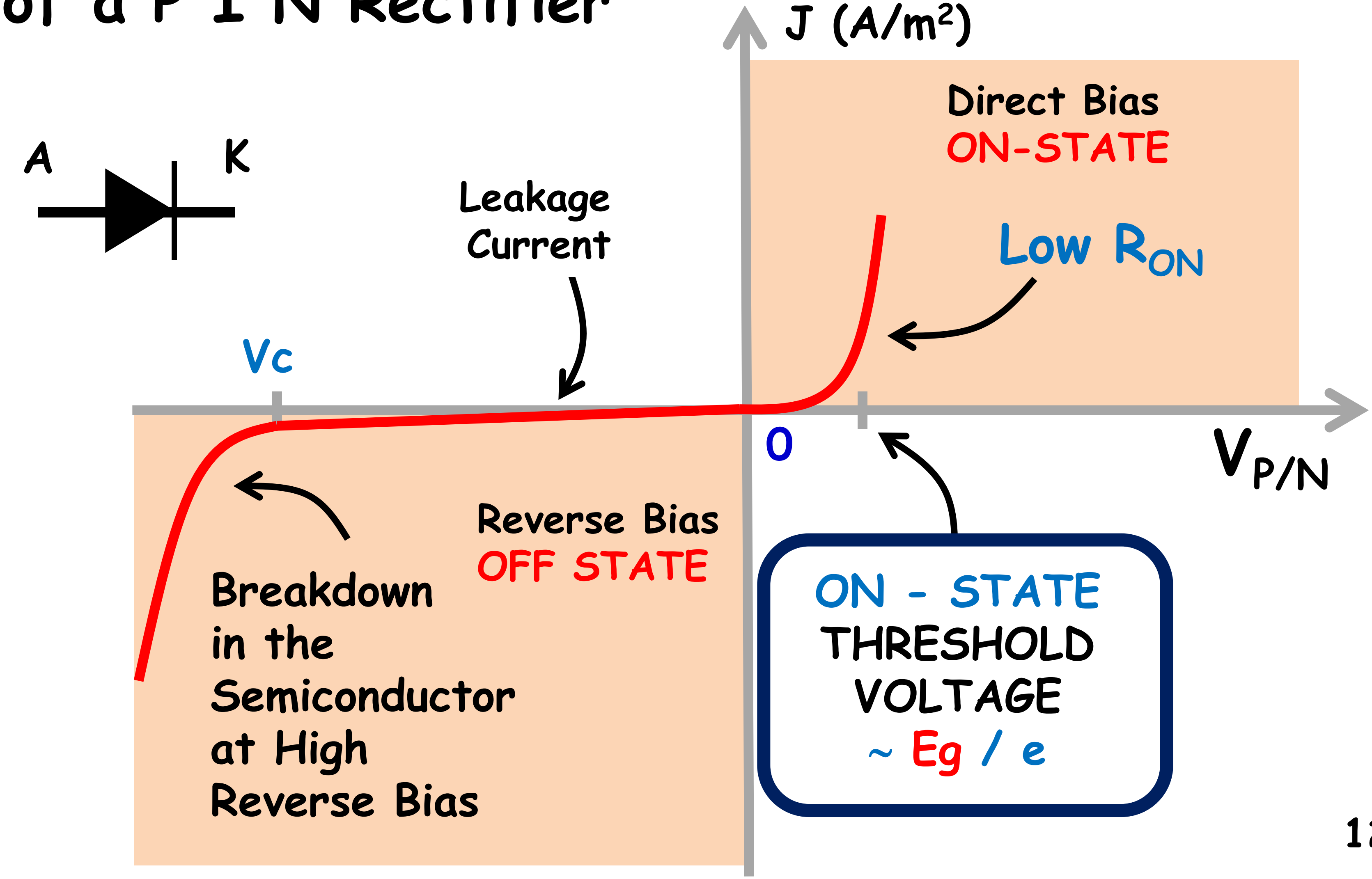
Direct Biased => $V_{AK} > 0$

Holes and Electrons flow through the Semiconductor Structure



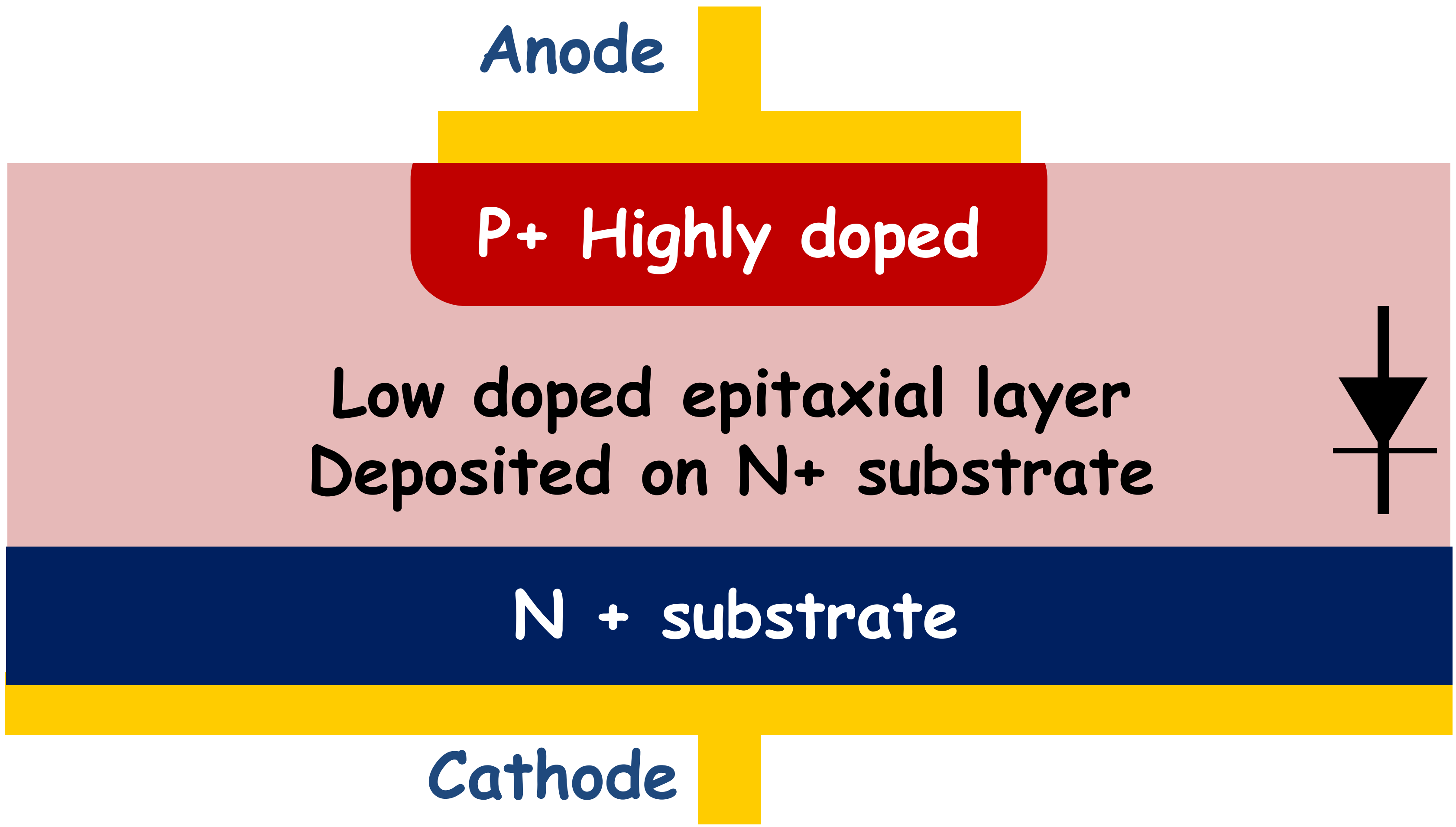
Electroluminescence : e^- + h^+ => photon

Current / Voltage Characteristics of a P I N Rectifier



122

Possible Structure for a P I N rectifier



Silicon PIN Rectifier Ø 100 mm

V_{OFF} ~ 4.5 kV V_{ON} ~ 2 V @ 1 kA

124

On-State Dynamic Resistance in a Bipolar Switching Device

$$R_d = dV / dI = W^2 / 2.\mu.I.\tau$$

W Length of the Transit Zone

μ « Ambipolar » Mobility of the Carriers

I Current Flowing in the Transit Zone

τ Lifetime of the + /- Carriers Pair

GaN Bipolar Devices ?

μ « Ambipolar » Mobility of the Carriers

=> Very low because Hole Mobility in GaN is very Low

τ Lifetime of the + /- Carriers Pair

=> Very low because GaN has direct bandgap

Eg ~ 3,4 eV Bandgap Energy

=> Threshold Voltage Eb/e ~ 3V very High

GaN BIPOLAR DEVICES ?

- Direct Bandgap

=> τ = a few 10 ns at best => High R_{on}

- E_g ~ 3,4 eV => V_{on} > 3V

  => only OK over 3 kV

- Doping Level Control < 10^{15} cm^{-3} very difficult

- « Ambipolar » Mobility of the Carriers

  μ^* => Very low because
  hole mobility in GaN is very Low

127

GaN is not expected to yield Good enough Bipolar Devices

V_{OFF} Very Good
V_{ON} Much too High

=> GaN should focus on Unipolar Devices

SiC Bipolar Devices

μ « Ambipolar » Mobility of the Carriers
=> Not too bad, rather similar as silicon

τ Lifetime of the + /- Carriers Pair
=> A few μs at best => OK

Eg ~ 3,2 eV Bandgap Energy
=> Threshold Voltage Eb/e ~ 3V very High
OK only for V_{OFF} > 3 kV

. . . BUT . . .

Crystal Defects in 4H-SiC turn to 3C-SiC inclusions during PIN operation

=> Shorter τ => Unreliable

Bipolar SiC Devices are still under development after 20 years of research !

At the Moment, 4H-SiC is also limited to Unipolar Devices

The Switching Problems of Bipolar Devices

Example : commercial rectifier ABB

4,5 kV - 900 A

V_{RRM}	=	4500	V	Fast Recovery Diode
$I_{F(AV)M}$	=	900	A	5SDF 07H4501
I_{FSM}	=	16×10^3	A	
$V_{(T0)}$	=	1.8	V	
r_T	=	0.9	mΩ	
$V_{DC\text{-}link}$	=	2400	V	

Doc. No. 5SYA1111-02 Oct. 06

- Patented free-floating silicon technology
- Low switching losses
- Optimized for use as large-area snubber diode in GTO converters
- Industry standard housing
- Cosmic radiation withstand rating

Long Switching Transition ON => OFF : 10 - 20 µs

it takes long time to get rid of the numerous electrons and holes injected during the ON-STATE

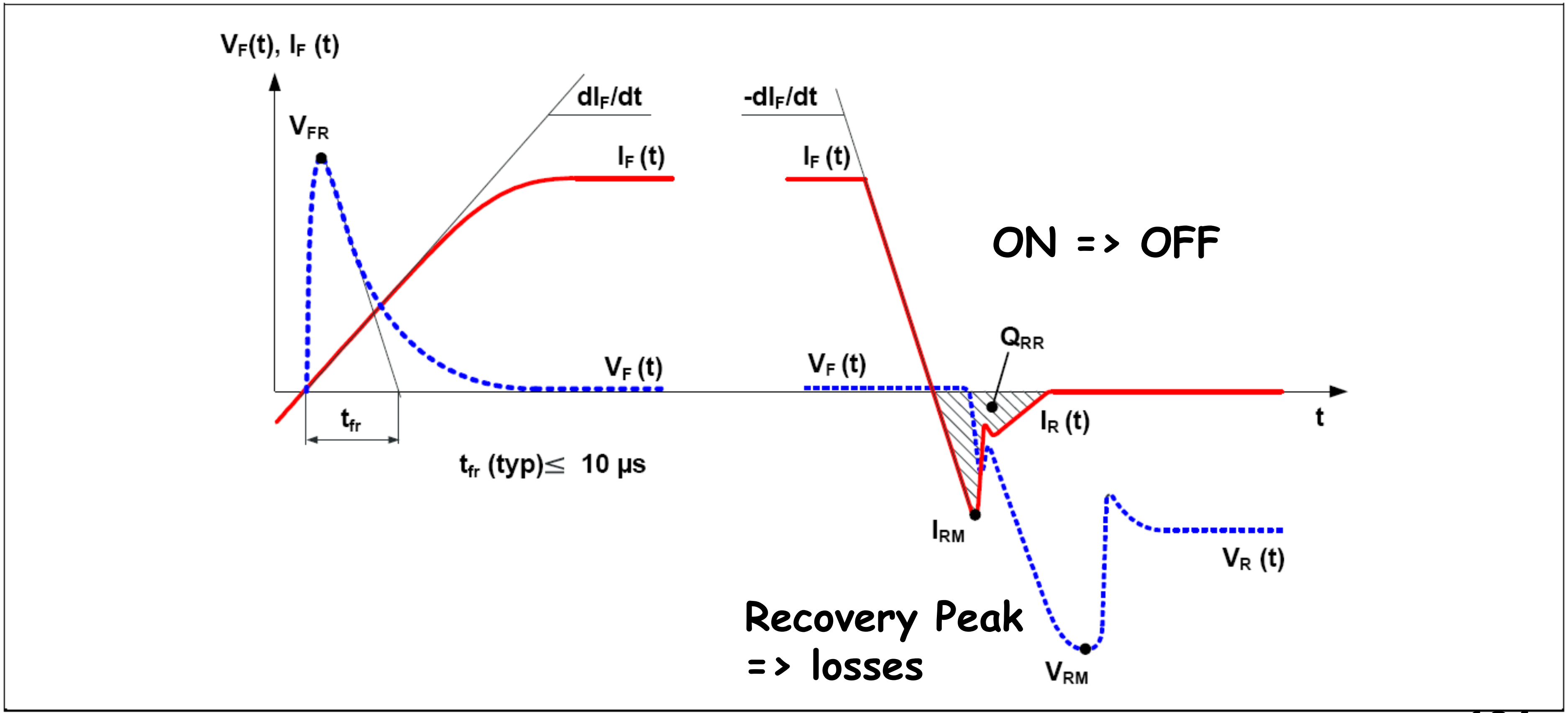
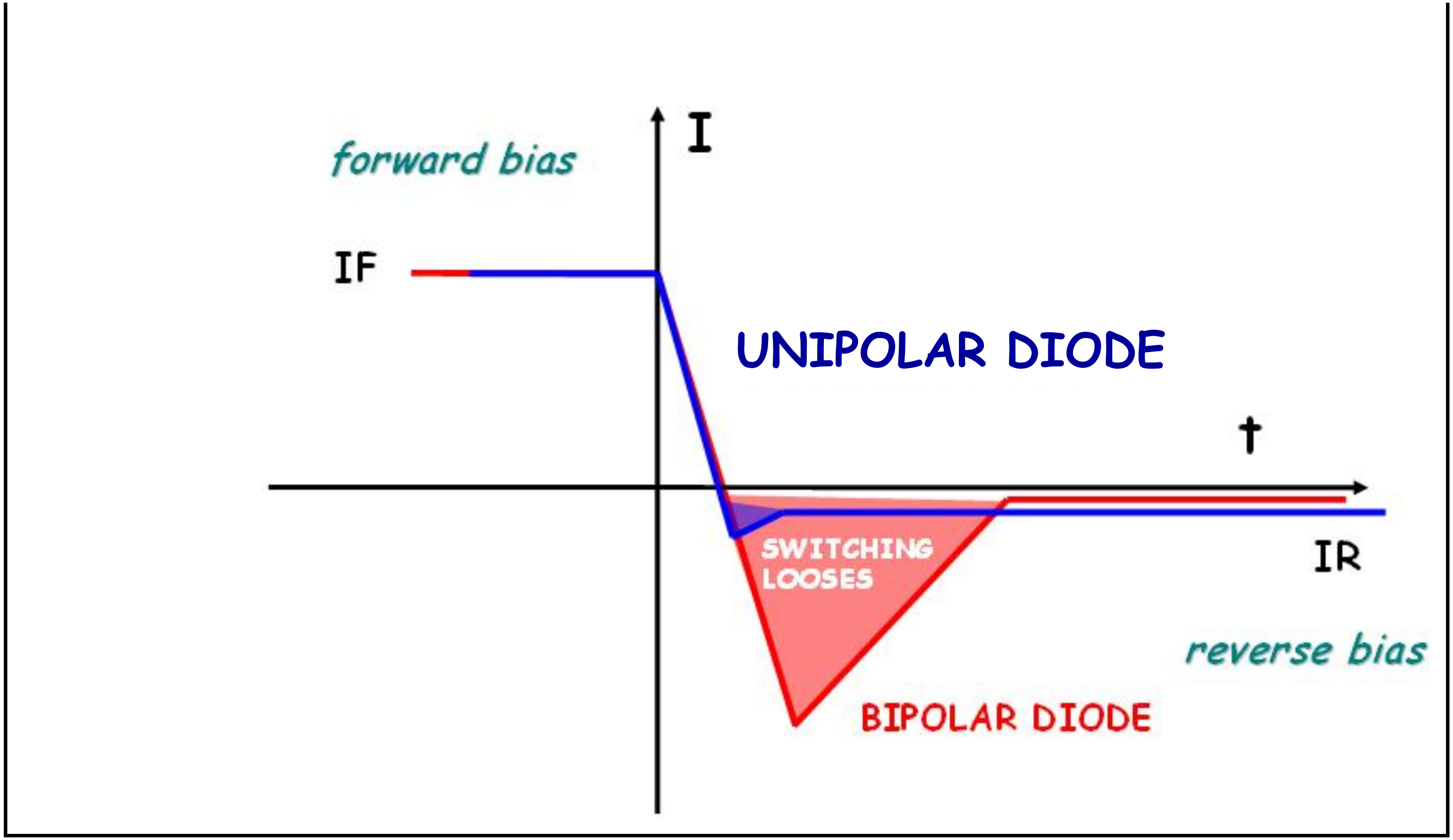
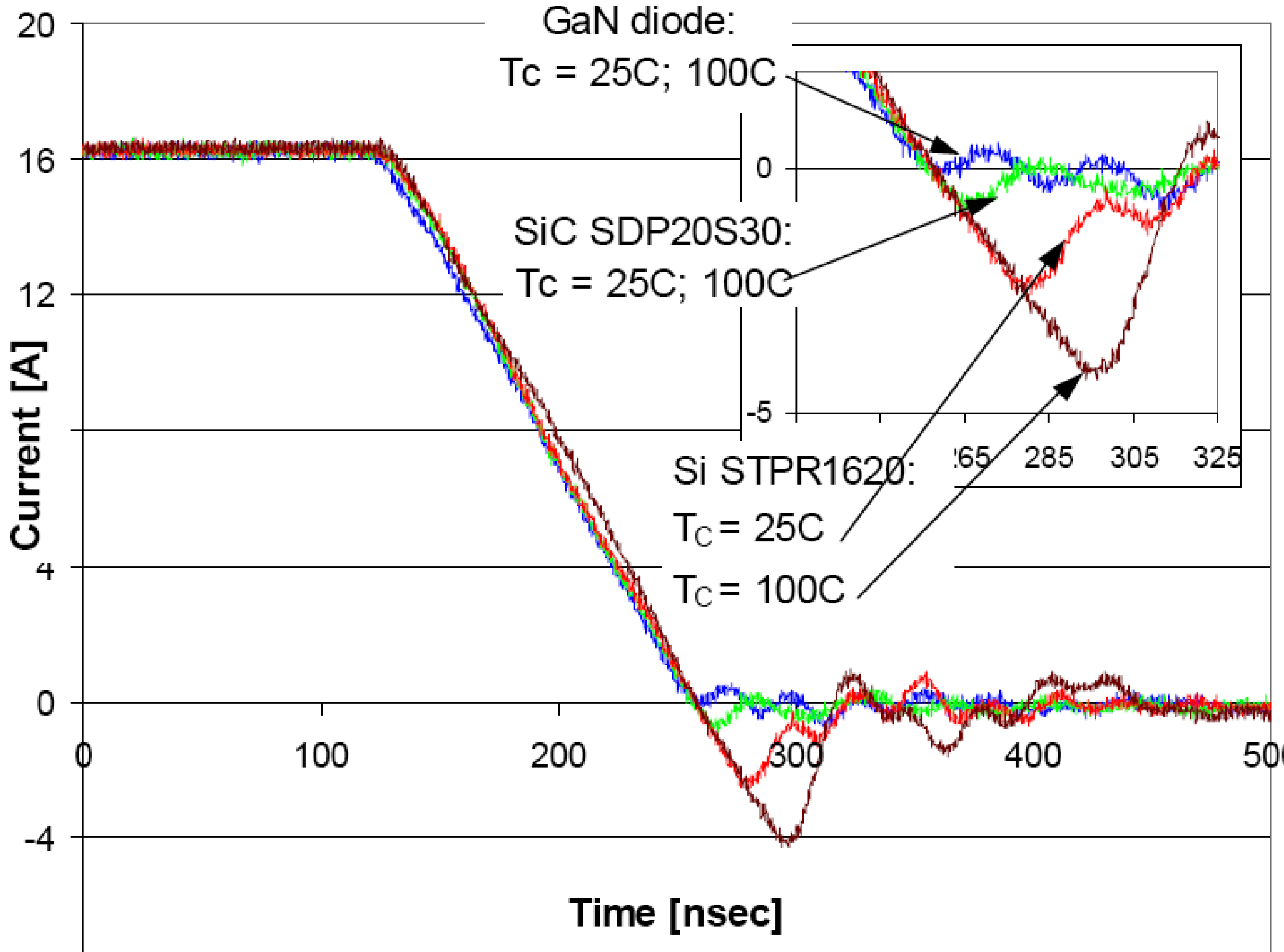


Fig. 6 General current and voltage waveforms

Switching Characteristics
Unipolar vs Bipolar Devices



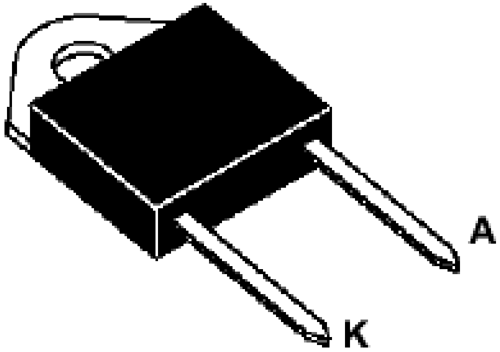
Unipolar (SiC, GaN) vs Bipolar (Si) Rectifiers Switching Characteristics



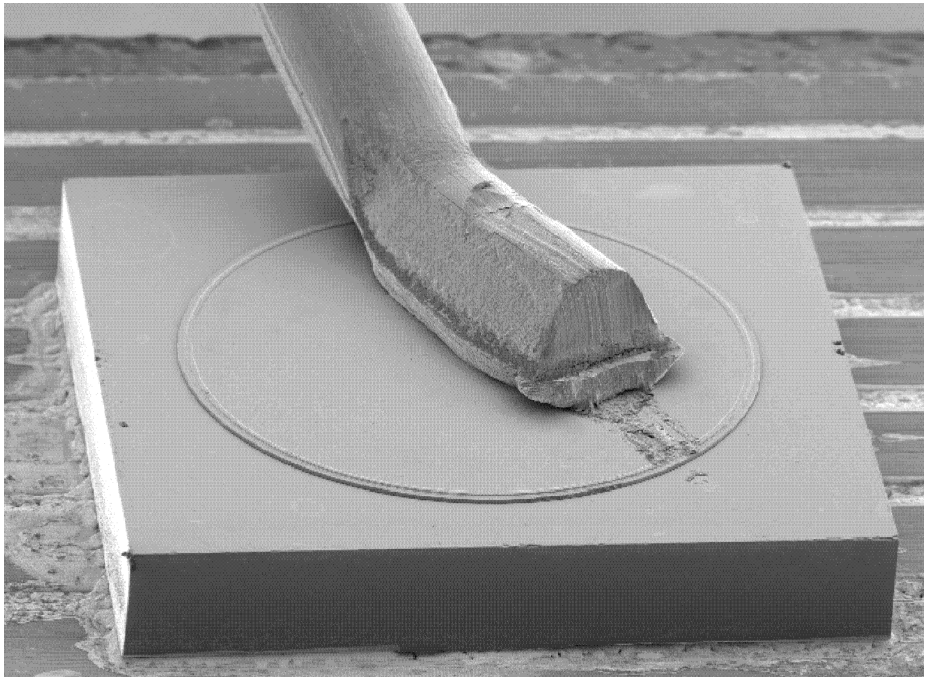
The Simplest Semiconductor Unipolar Switching Device

The Schottky Rectifier

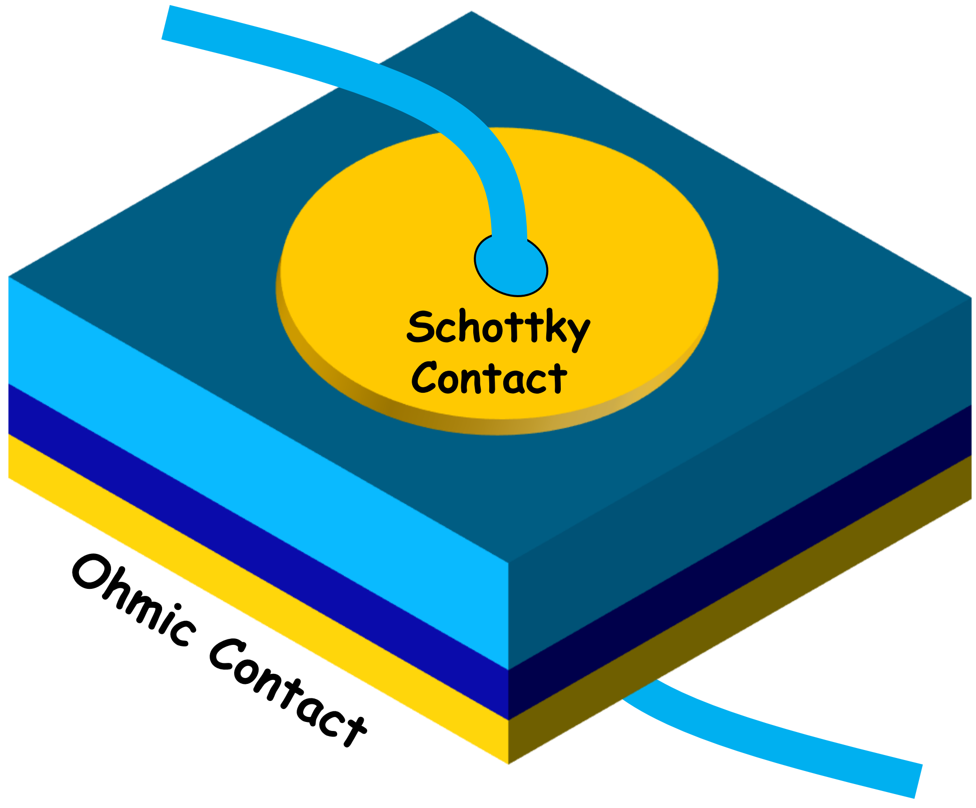
Inside the package : the chip

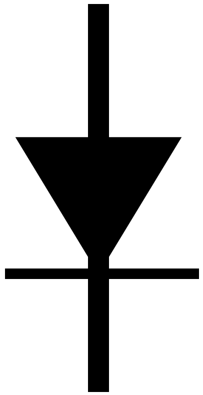


Al wire



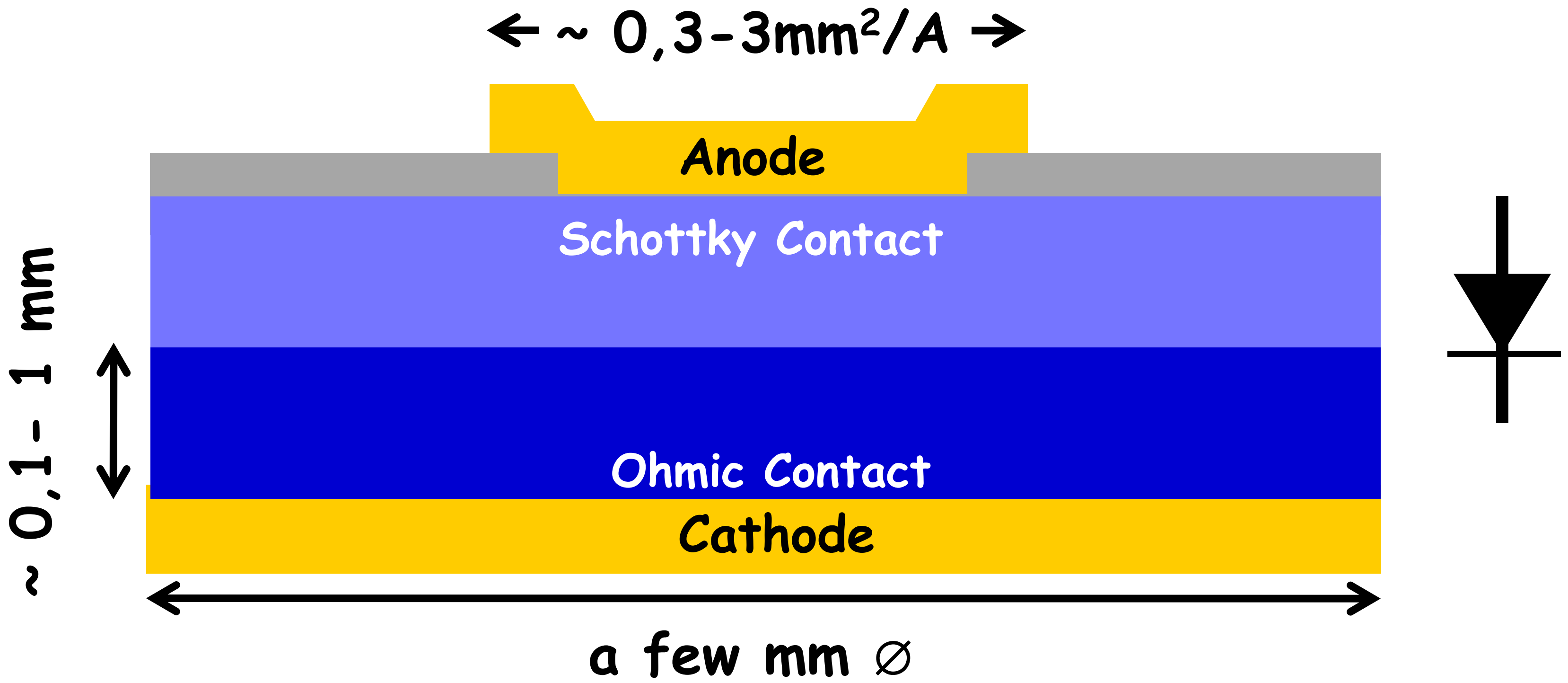
Simplified Schottky Rectifier Structure





Schottky Rectifier Chip on Doped Bulk Semiconductor

Schematic Cross Section (simplified)



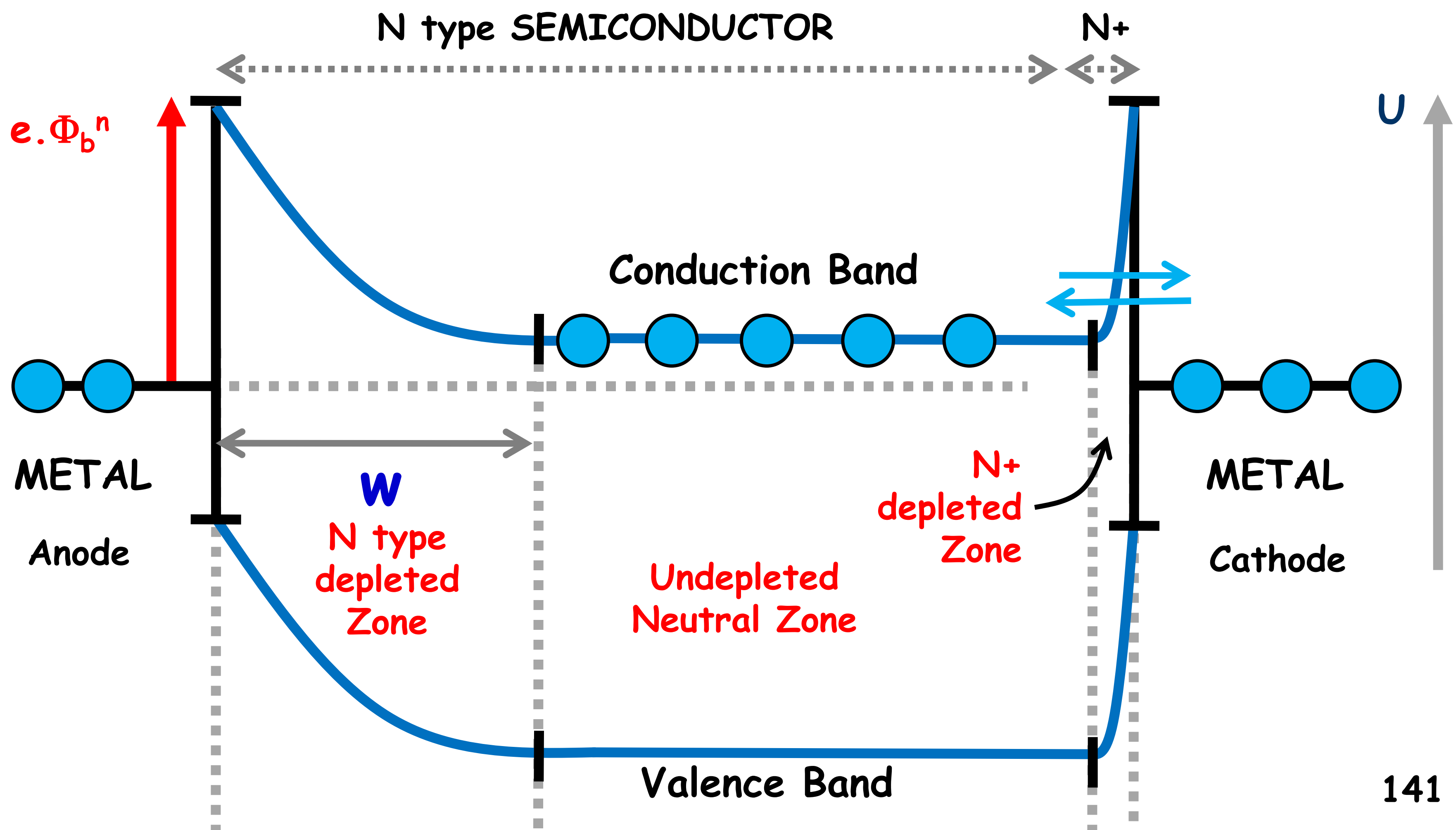
Metal

Insulator => often: amorphous SiO_2

Highly Doped Semiconductor

Low Doped Semiconductor

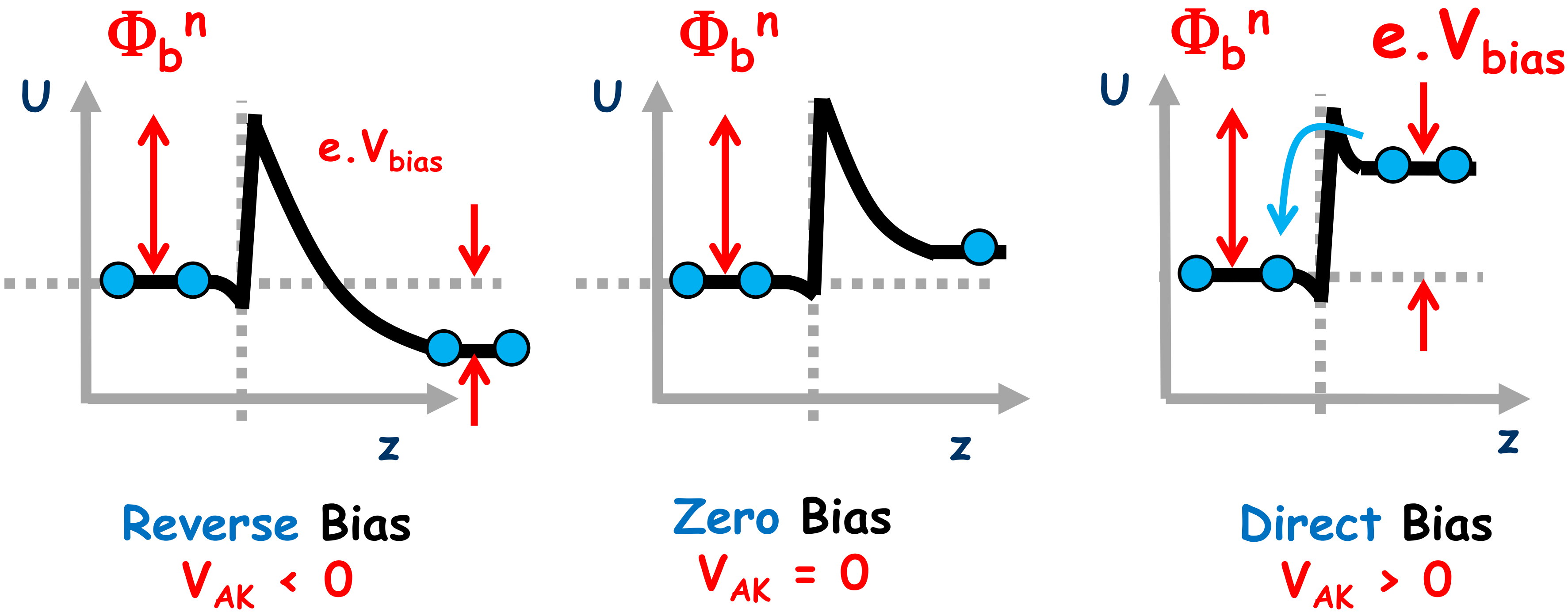
Electronic Energy Potential Profile for a Schottky Rectifier on N type Semiconductor Zero Bias Voltage



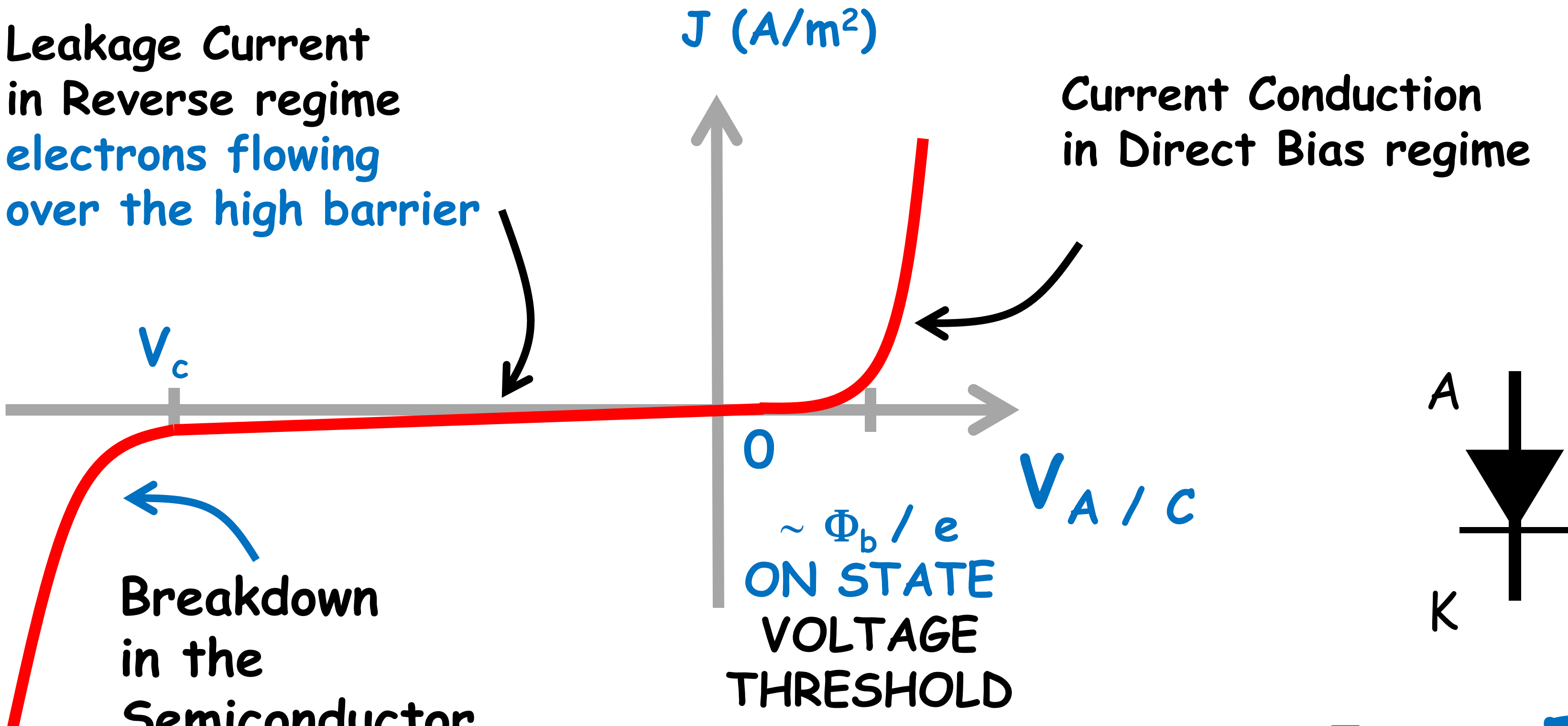
A barrier height Φ_b^n opposes to electron flow both ways

Electrical Profiles for a Schottky Contact

on N type Semiconductor   Variable Bias Voltage



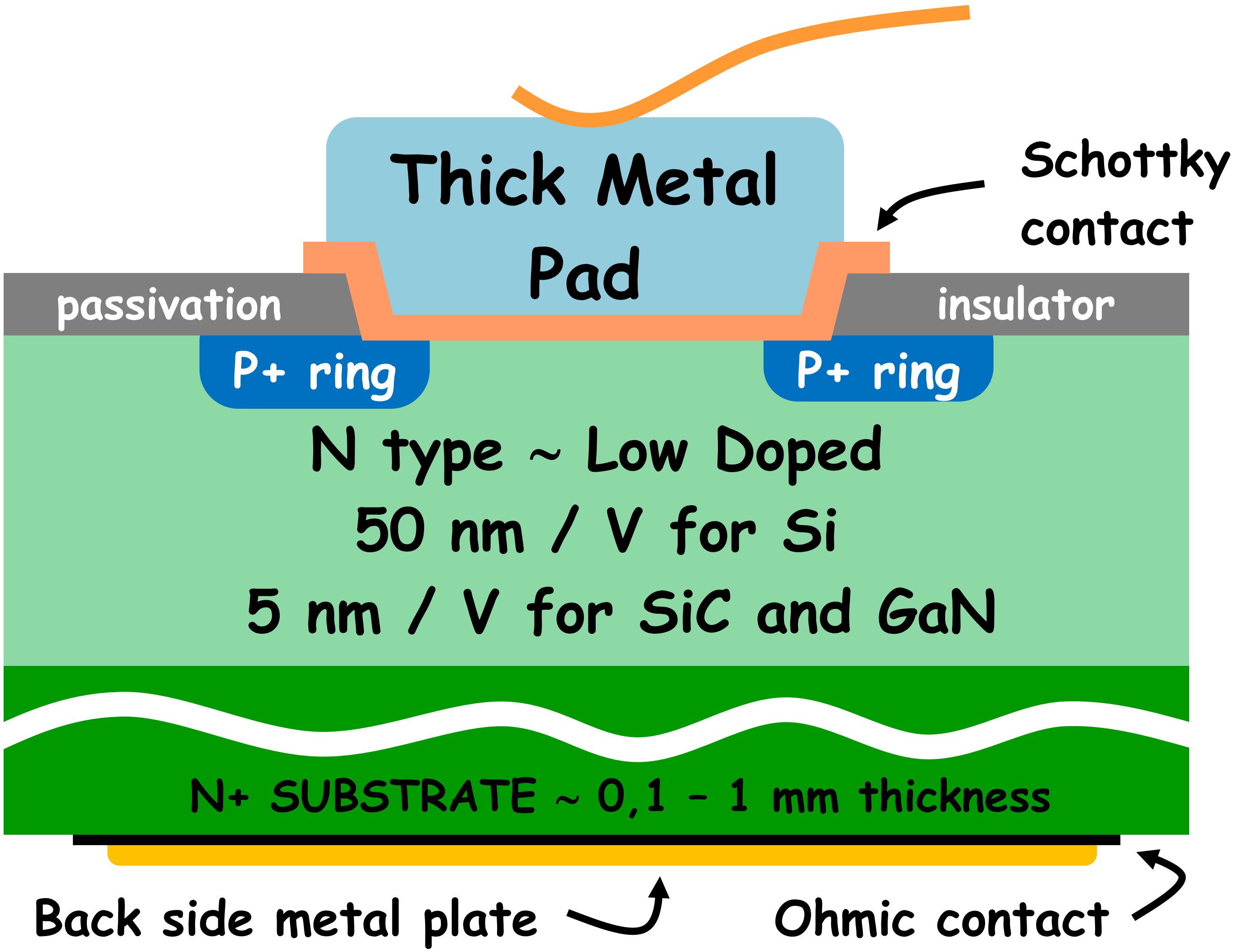
Current / Voltage Characteristics of a Schottky Rectifier Diode



$\Phi_b < E_g$

=> the Threshold V_{ON} is smaller for Schottky diode as for PIN diode

The simplest possible Schottky Rectifier Architecture



Commercial Schottky Rectifiers

Commercial Schottky Rectifiers

- Silicon ones are limited to 150 V
- Commercial 4H-SiC ones are available from 300 to 1700 V
- GaN ones are not available yet. They are future competitors competing with 4H-SiC ones.

600 V - 6A Schottky SiC Rectifiers
for Switching Power Supplies on 240 V mains
(Latest generation with improved reliability)

Standard Case TO 220
4,5 x 10 x 30 mm^3

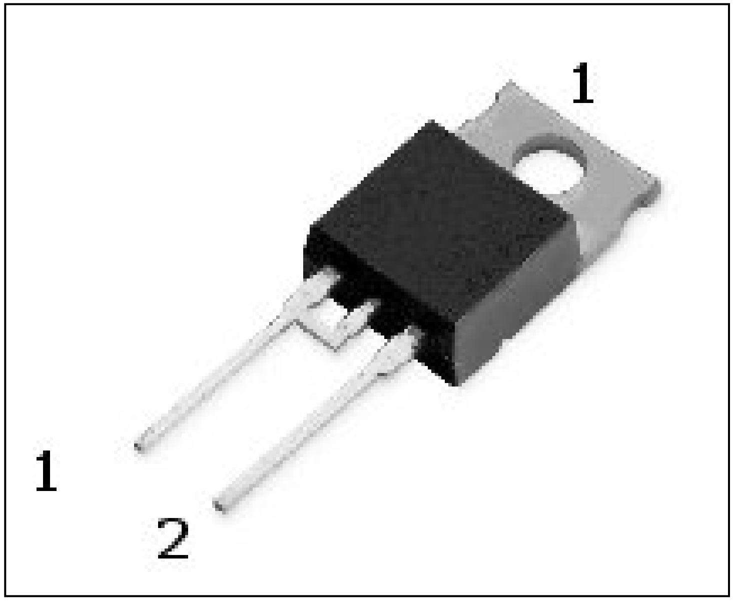
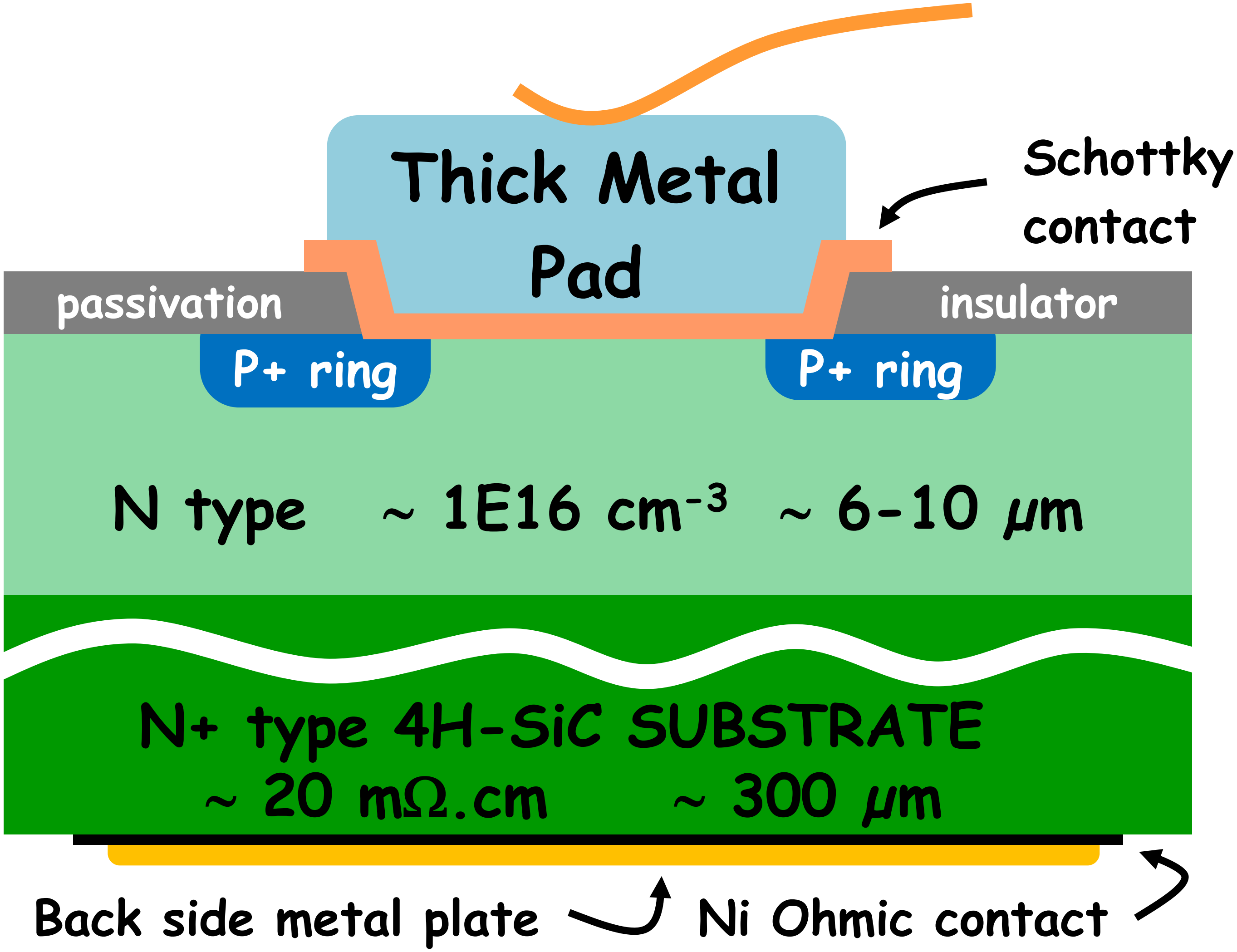


Image : Supplier X

Image : Supplier Y

Probably the simplest possible 600 V SiC Schottky Rectifier Architecture



Key issues for Manufacturing SiC Schottky Rectifiers

(1) 4H-SiC Substrates,

(2) 4H-SiC Homo-epitaxy,

(3) P+ localised doping,

(4) Ohmic and Schottky contacts,

(5) SiC processing line,

4H-SiC

N+ substrates

Status

Status for 4H-SiC N+ substrates

☺ Soon, they will all be Micropipe-Free,

☺ Dislocation Density < 5.10^4 cm^{-2}

☺ Soon, they will all have 150 mm Diameter,

☺ A good polishing process is already available,

☹ There are only few commercial sources
for the best quality substrates : Cree, Sicrystal,

☹ Still, they are quite expensive :
- > 500 € for ONE High Quality 100 mm Wafer

4H-SiC
Homo-epitaxy
Status

Status for 4H-SiC Homo-epitaxy

☹ Very High Temperature > 1500°C

=> complex reactor technology

=> expensive

=> high energy requirements

=> difficult scaling up

=> few reactor suppliers

☺ Fast Epitaxy possible >10 µm/h

Ohmic Contacts on N+ 4H-SiC Status

154

Status for Ohmic Contacts on N+ 4H-SiC

☺ Nickel provides "simple" ohmic contacts,

😐 Annealing around 1000°C => Ni_2Si,

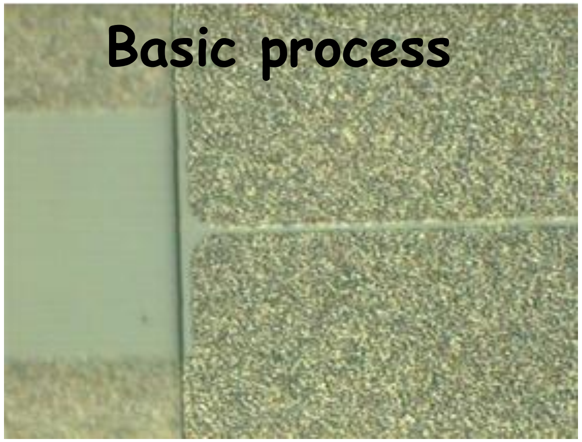
☺ Very Good Conductivity > 0,1 MS/cm^2,

Status for Ohmic Contacts on N+ 4H-SiC

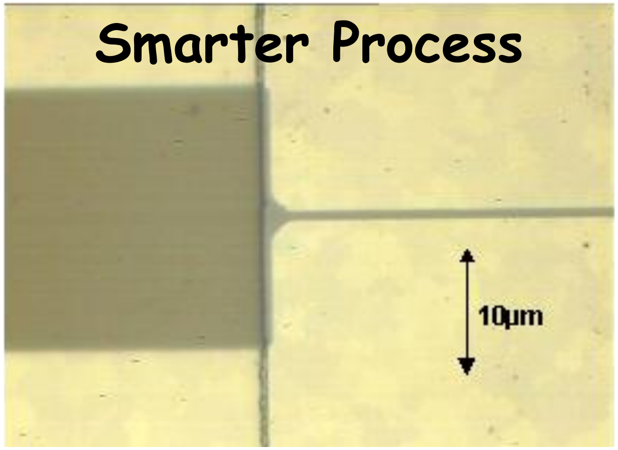
☹ Kirkendall cavities :

=> Weak metal / SiC sticking,

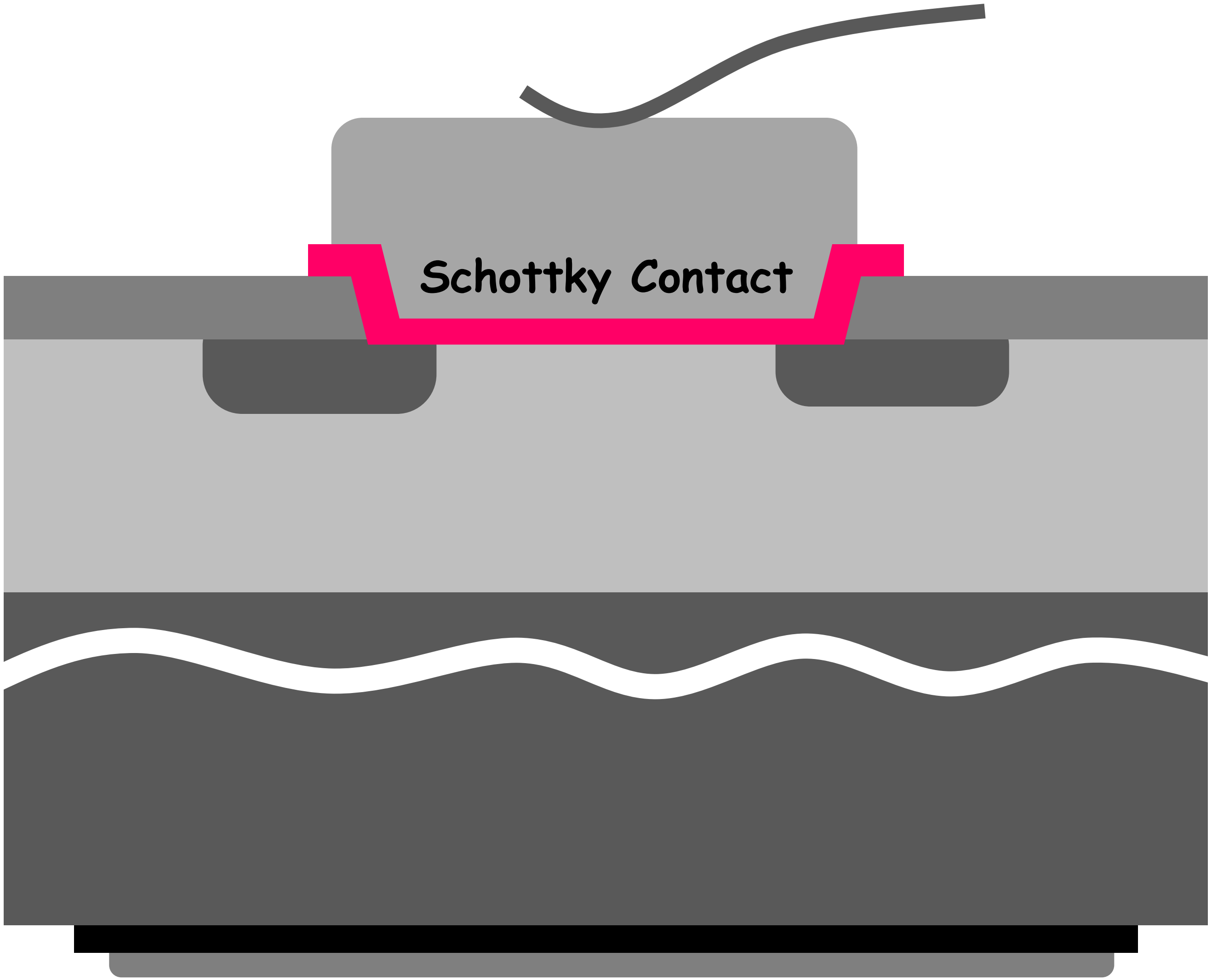
=> More sophisticated metallization required



Every industrial device supplier has developped its own improved process.



Schottky Contacts on N-type 4H-SiC Status


Schottky Contact

Status for Schottky Contacts on N-type 4H-SiC

- Optimum Barrier Height => 1.0 - 1.2 eV,
  - if too high => High V_{on} => High Losses
  - if too Low => High I_{off}
    = High Reverse Leakage Current at High Field,

- Several possibilities for metallization :
  W , Ti , WC , TiC, WN , TiN . . .

- Good enough Ideality Factor n < 1.2
  can routinely be obtained on good 4H-SiC substrates,

GaN
Schottky Rectifiers

Comparative Values for the main SiC and GaN properties relevant for Schottky Rectifiers

10^{16} cm^{-3} 300 K	4H-SiC	GaN
Breakdown Field (MV / µm)	≈ 200	≈ Same
Electron Mobility (cm^2 / V.s)	≈ 600	≈ Same
Thermal Conductivity (W / K.m)	4 - 5	1.3 - 2

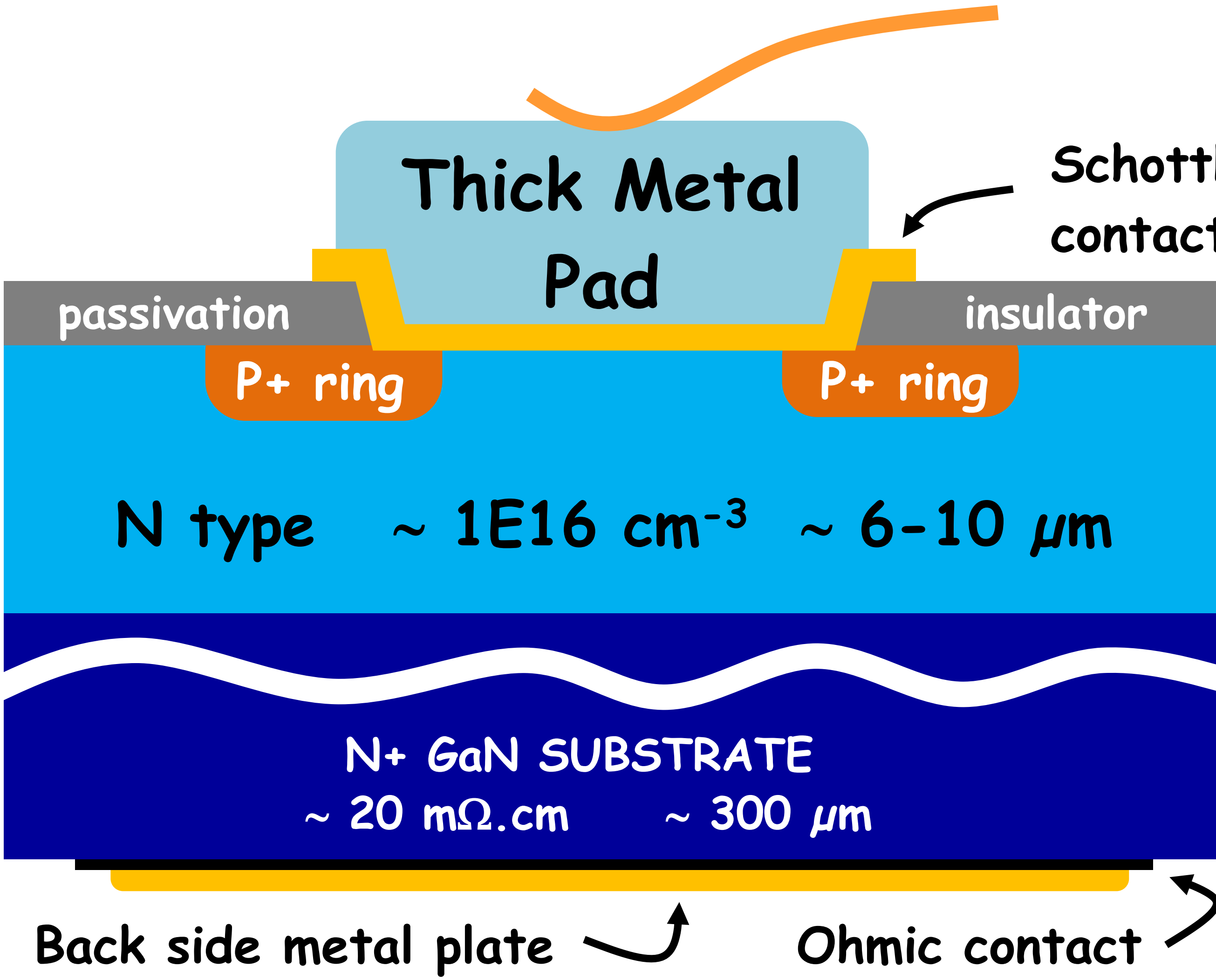
First Idea

GaN Schottky Rectifiers

as similar as possible to

SiC Schottky Rectifiers

Probably today the Simplest Possible 600 V GaN Schottky Rectifier Architecture



Key issues for manufacturing GaN Schottky Rectifiers

(1) GaN N+ Substrates
or "Conductive" Templates,

(2) GaN N- epitaxy,

(3) P+ localised doping,

(4) Ohmic and Schottky contacts,

Ohmic Contacts
on
N+ GaN

Status for Ohmic Contacts on N+ GaN

☺ Ti/Al provides "simple" ohmic contacts,

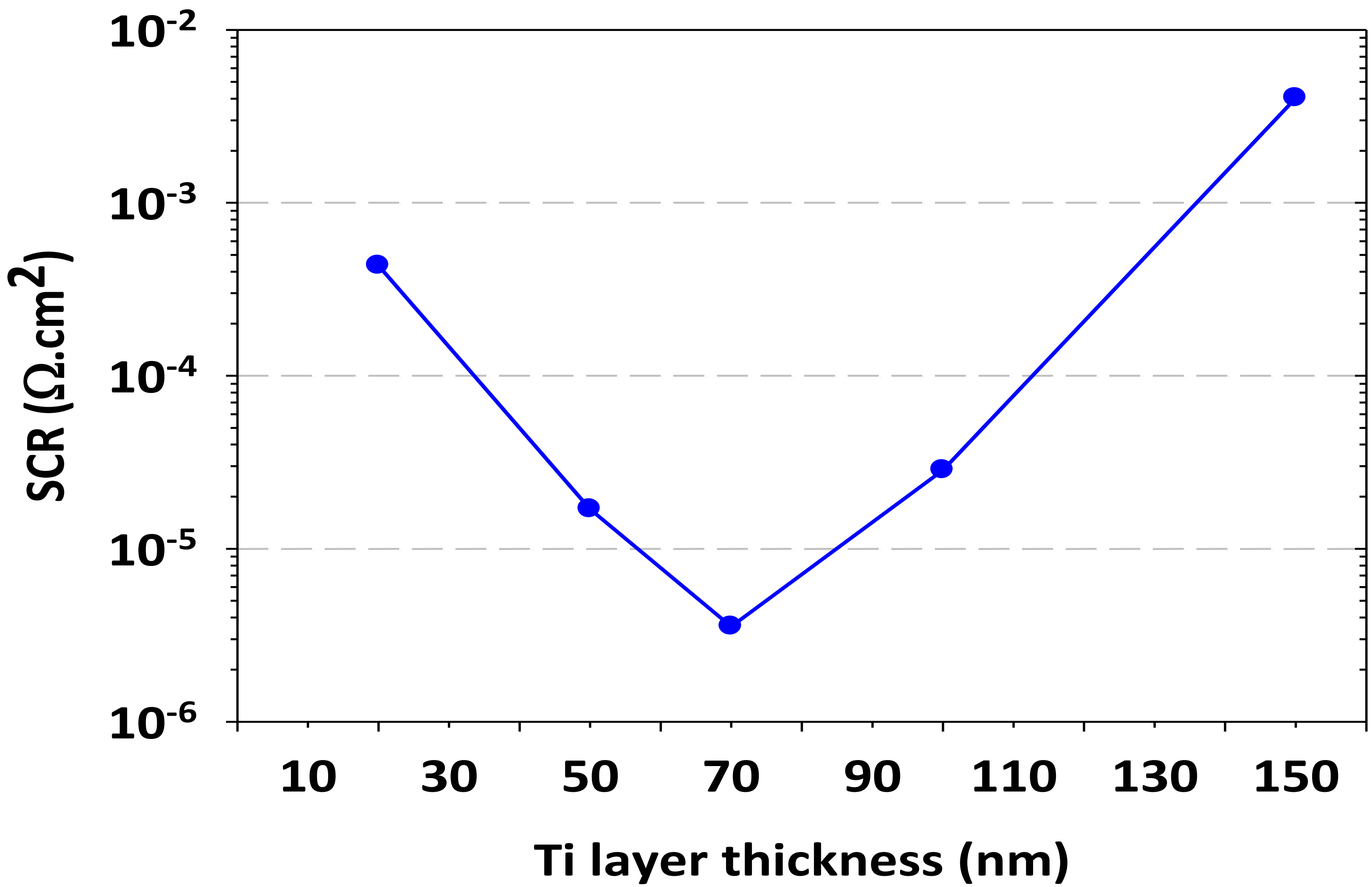
☺ Annealing 600-800°C => Al_3Ti,

☺ Very Good Conductivity > 0,1 MS/cm^2,

☺ No Kirkendall cavity,

OK for Ohmic Contacts
on N+ GaN (N_d >10^{18} cm^{-3}) on "Ga" face
(does not work on "N" face)

Optimizing Ti thickness keeping Al at 200 nm



167

TiAl Contacts

good Specific Contact Resistance (SCR) values are obtained for :

- Optimized Surface Cleaning
- Al (200nm) / Ti (50-70nm) metallization
- 500-650°C RTA annealing 1 -3 min under Ar

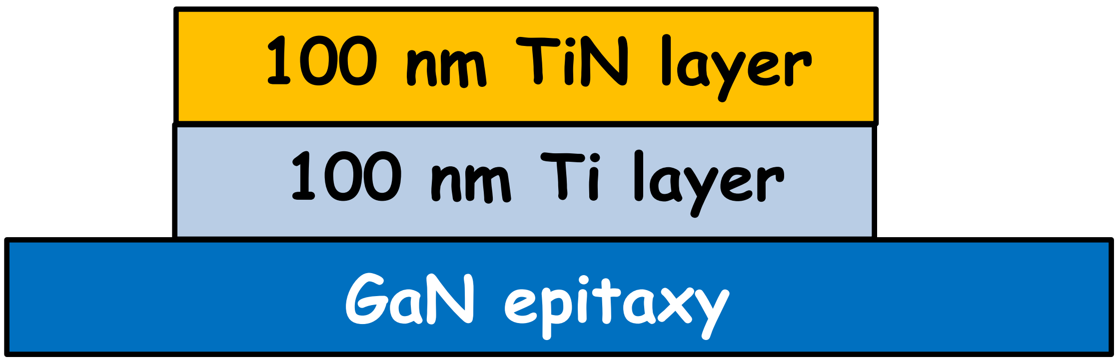
SCR values ($\Omega.cm^2$)	GaN n^+ on sapphire	GaN Si-implanted on sapphire	GaN n^+ (dry etched) on sapphire	GaN n^+ on silicon
	$3x10^{-6}$	$5x10^{-5}$	$5x10^{-6}$	$1x10^{-5}$

Warning" on possible unexpected Ti Diffusion in N-type GaN

"Warning" on possible anomalous Ti Diffusion in N-type GaN

PhD work N. Thierry-Jebali at UCBL

Experiments



(STEP 1)
Sputtering
+ Patterning

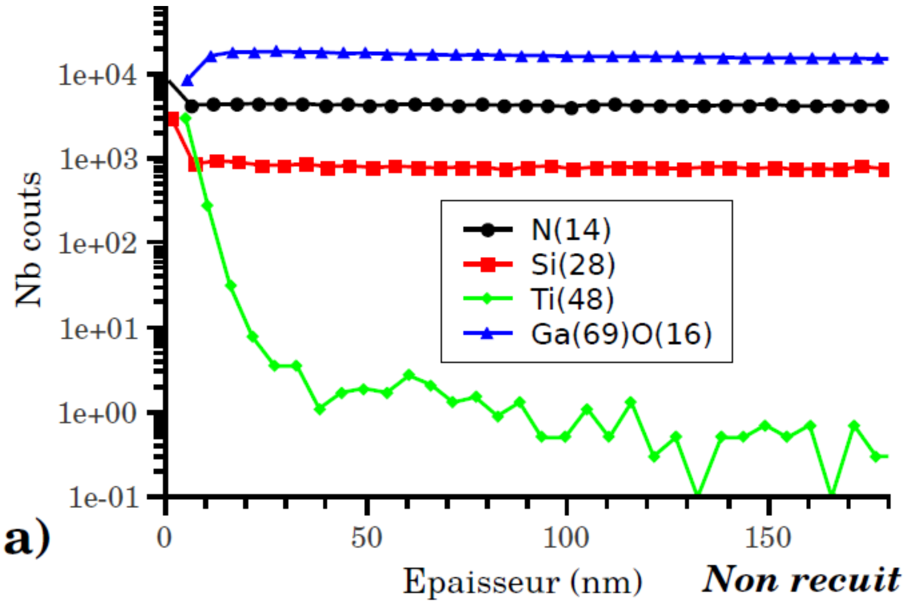
Rôle of TiN : protection
in order to reduce Ti oxidation

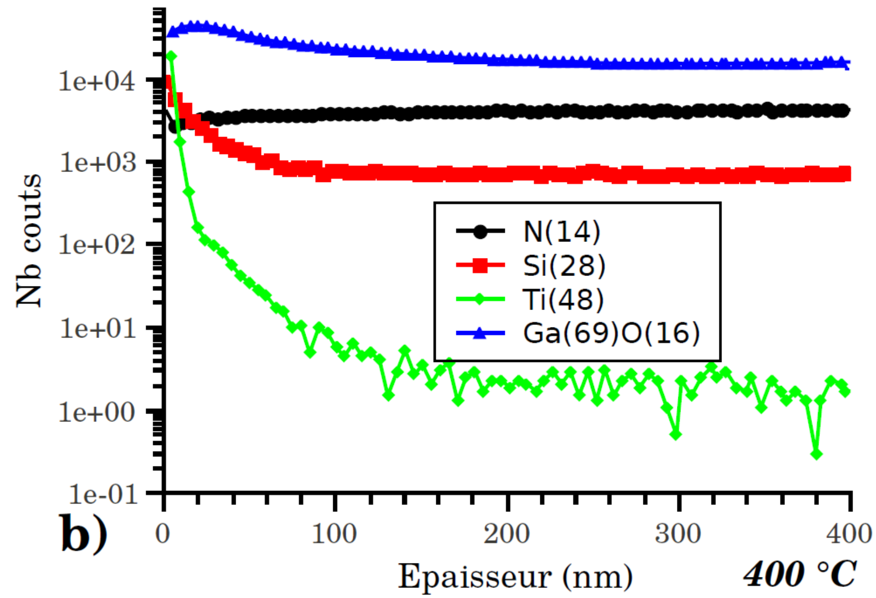
(STEP 2)
Annealing 400°C

(STEP 3)
Removing metals

"Warning" on possible anomalous Ti Diffusion in N-type GaN

PhD work N. Thierry-Jebali at UCBL

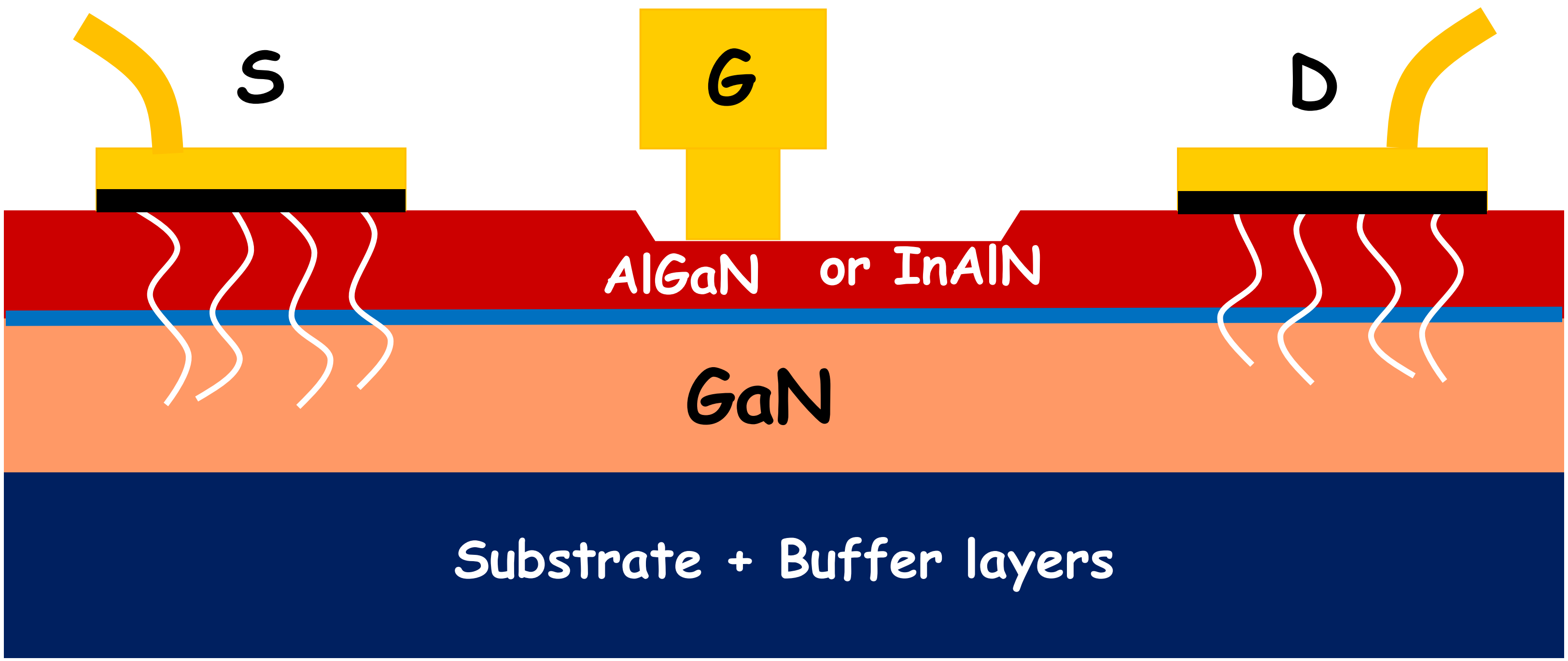




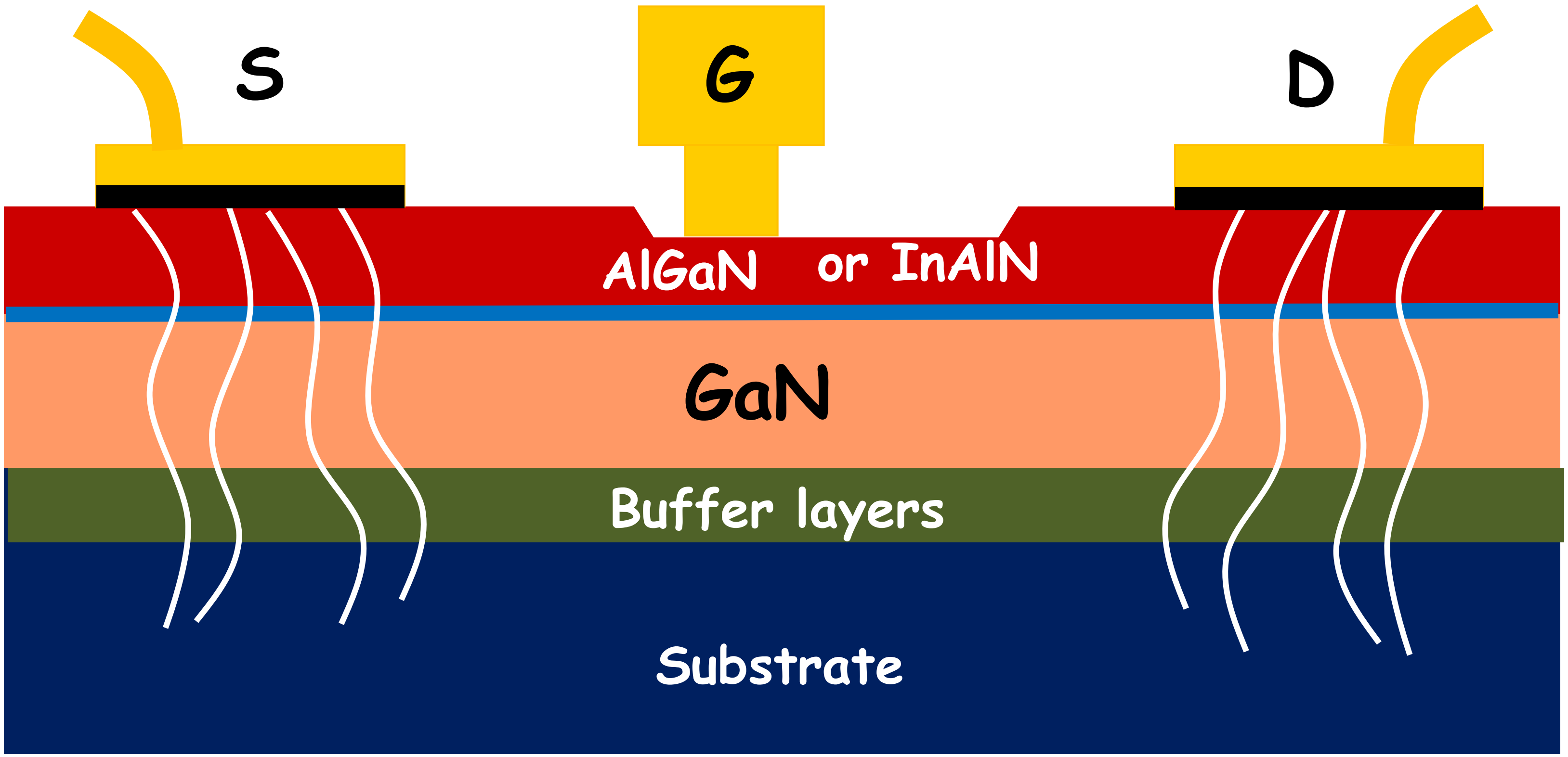
Before Annealing

After Annealing

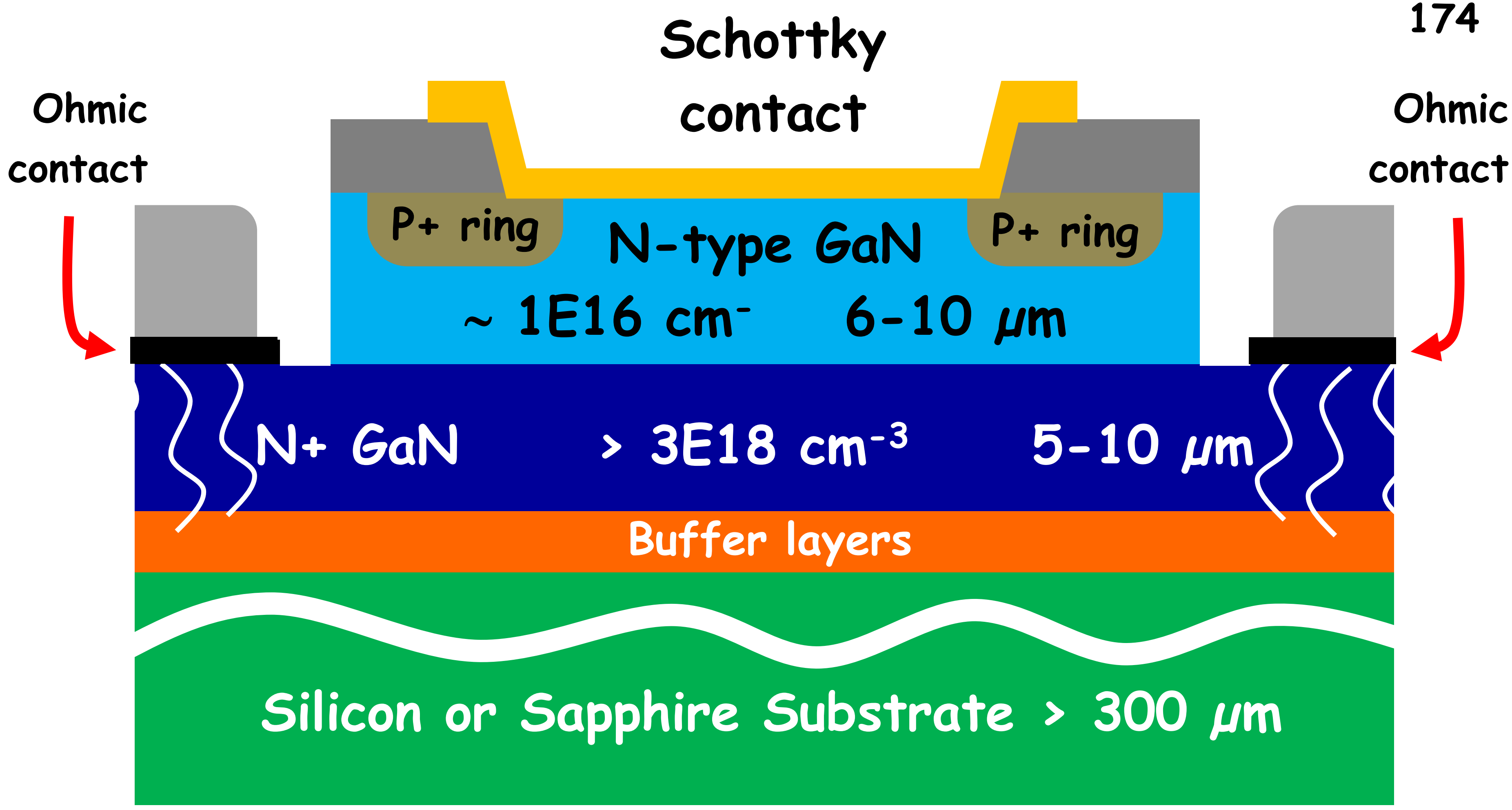
No expected problem for Lateral Devices resulting from Ti diffusion (along threading defects ?)



Except if the diffusion is really deep and the substrate is conductive !



No expected problem from Ti diffusion for Quasi-vertical Devices either



Only true

Vertical GaN devices

could be strongly

affected by

Ti diffusion in GaN

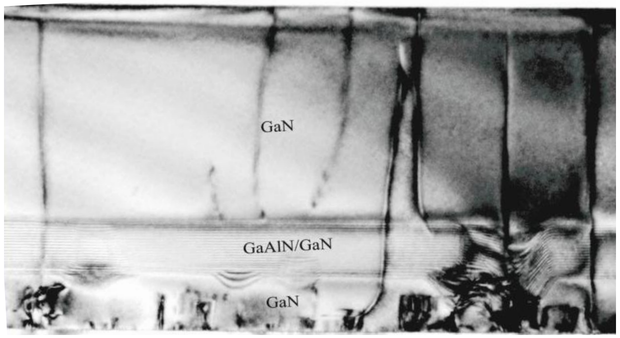
Schottky Contacts
on
N-type GaN

Status for Schottky Contacts on N-type GaN

- ➢ Optimum barrier height => 1.0 - 1.2 eV,
- ☺ ~ 1.0 eV has been achieved using Ni or Mo.

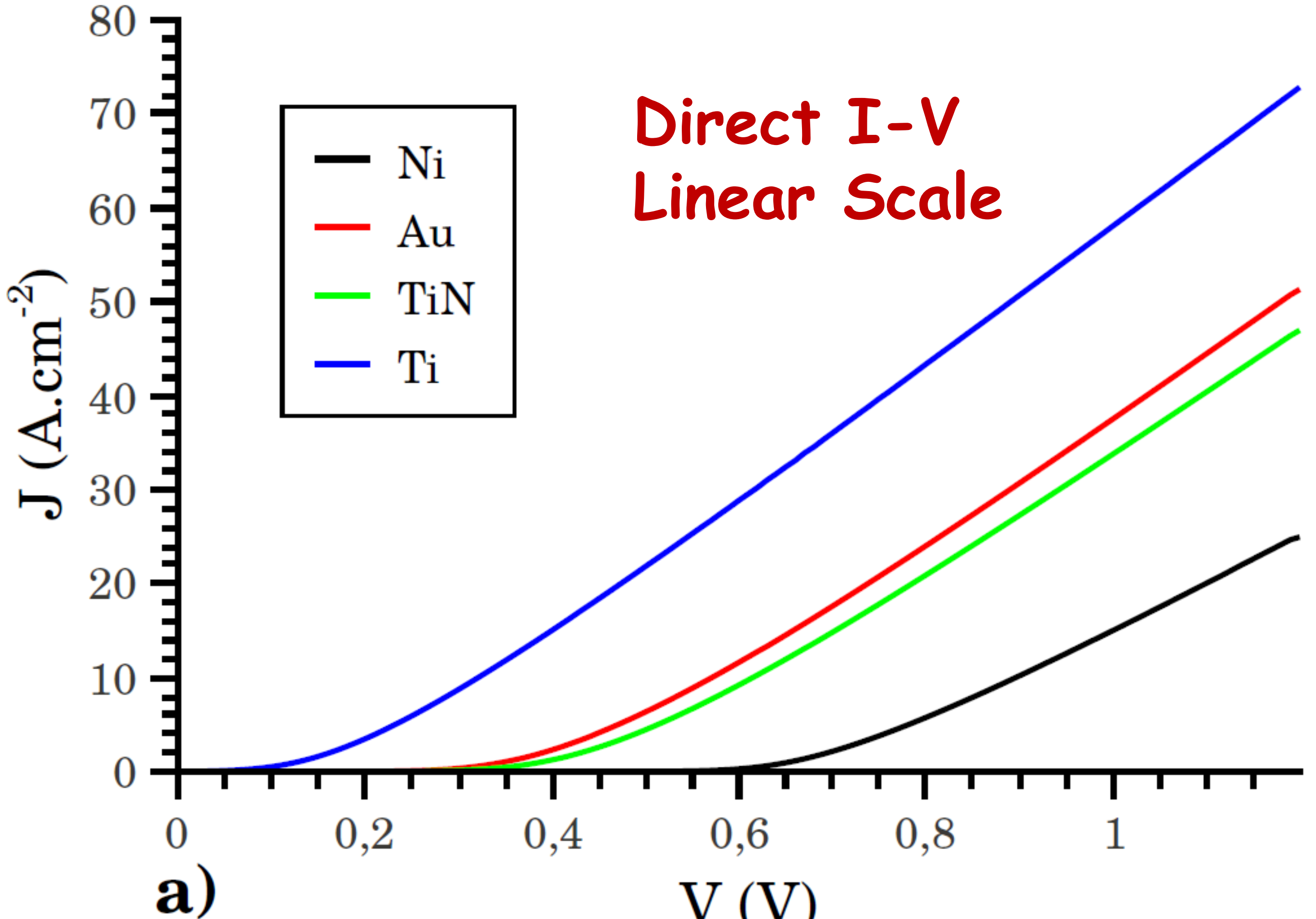
- ☺ (Surprisingly) good enough ideality factor n < 1.2 can be obtained on small diodes (∅ 0.5 mm) on the best GaN epi, though dislocation density is huge

- ☺ The GaN surface preparation seems under control.



- ➢ The contact quality is driven by GaN material quality, not by processing issues.

Ni is preferred for Schottky Contacts on N-type GaN because it provides a Higher Barrier Height



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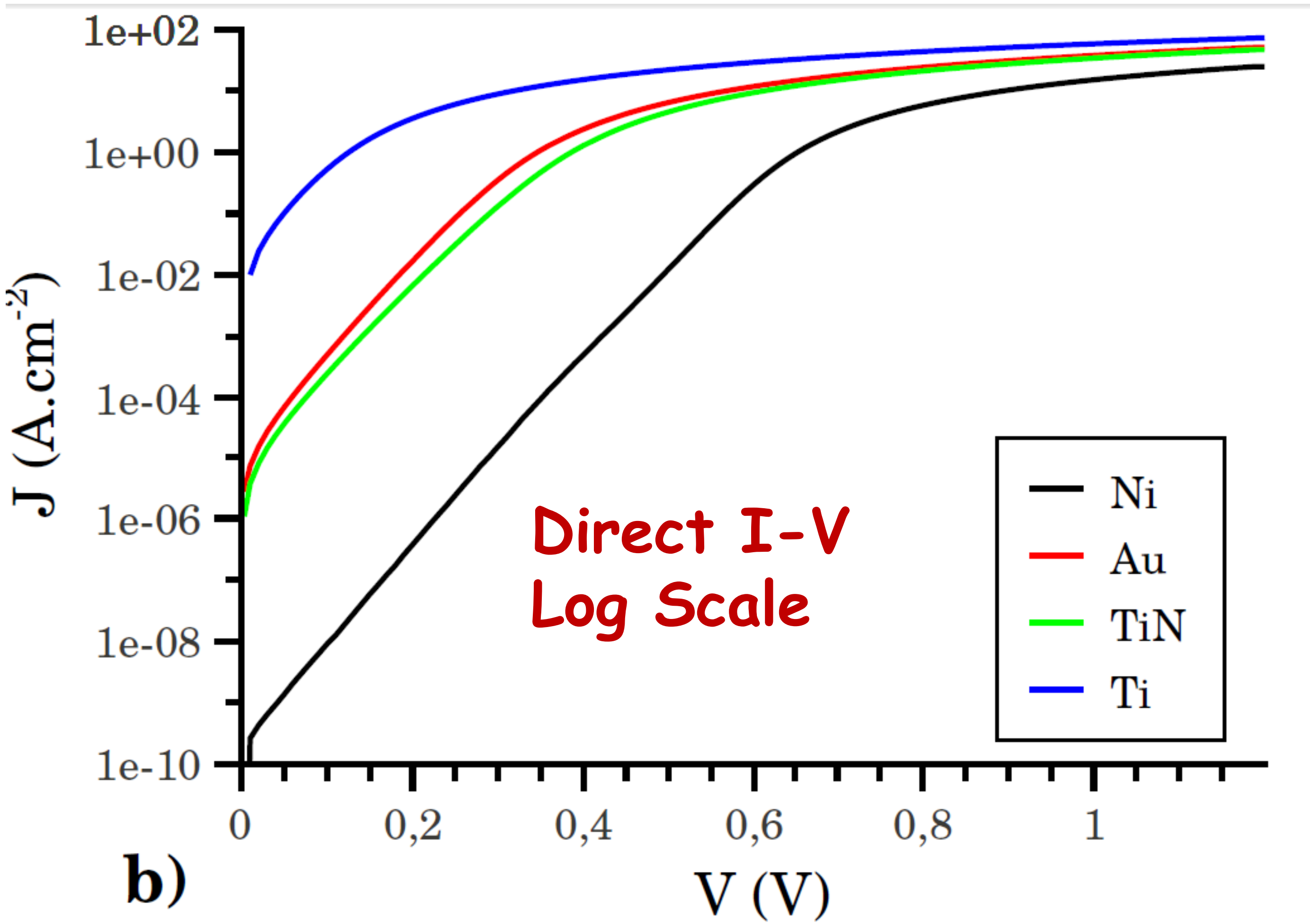
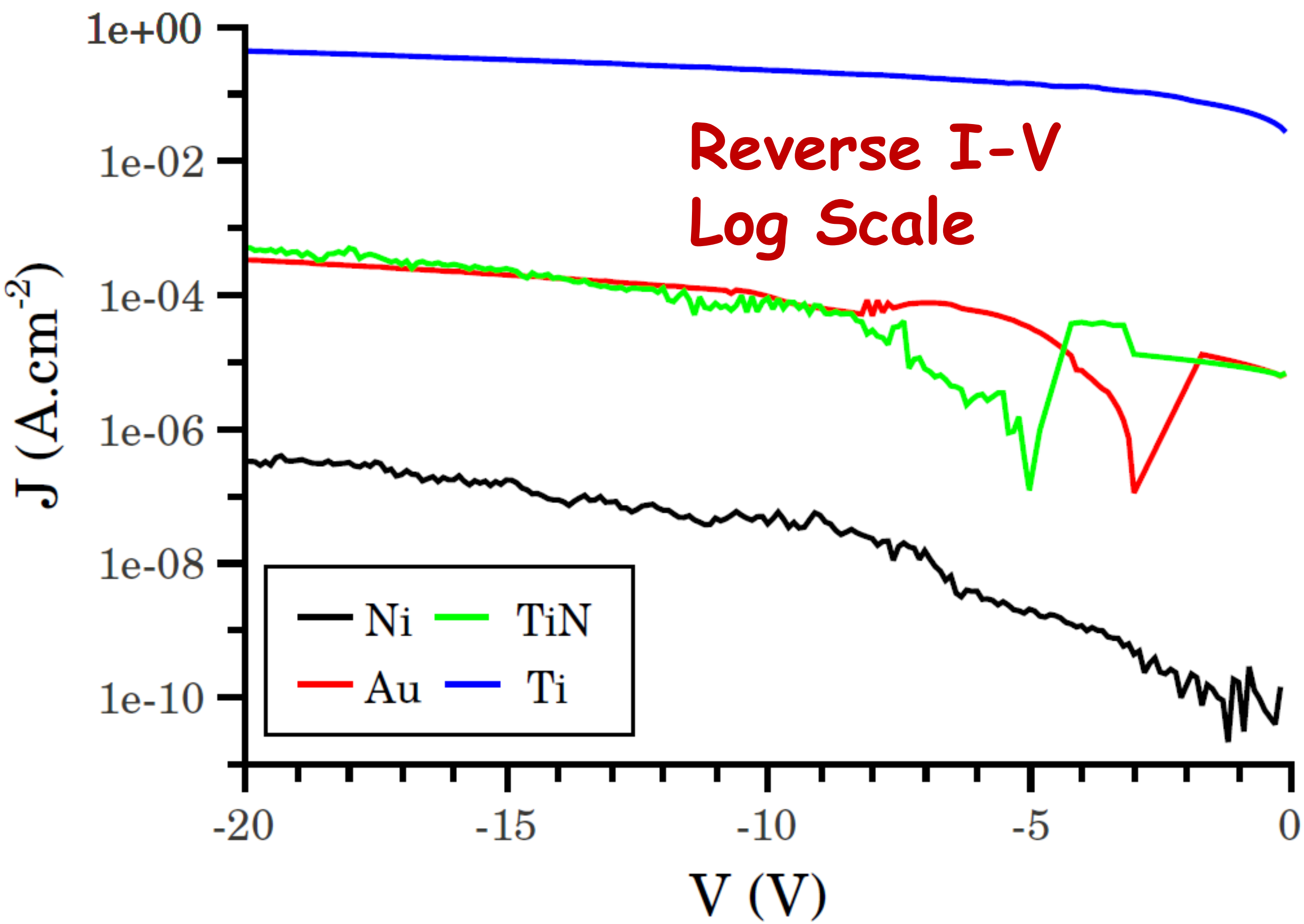
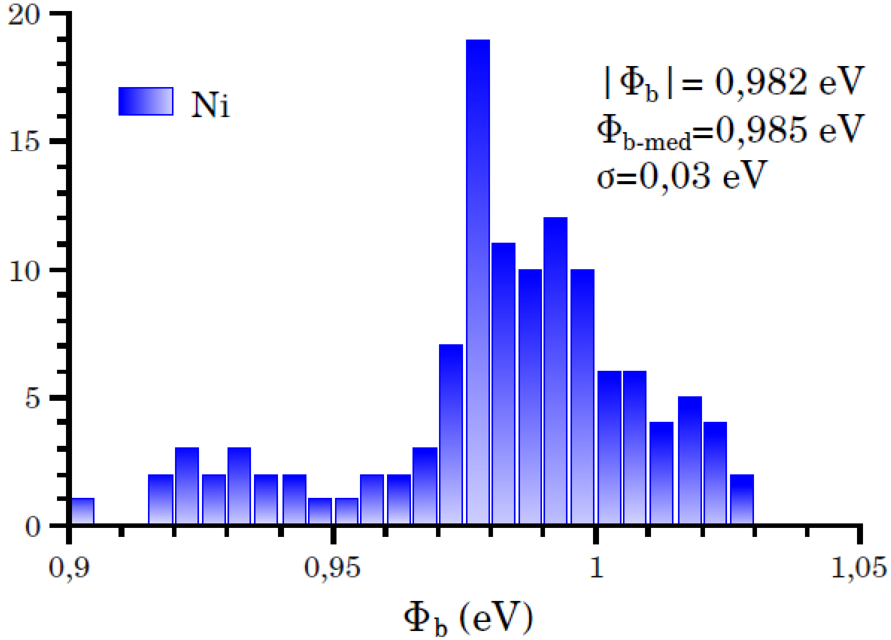
Ni is preferred for Schottky Contacts on N-type GaN because it provides a higher barrier height

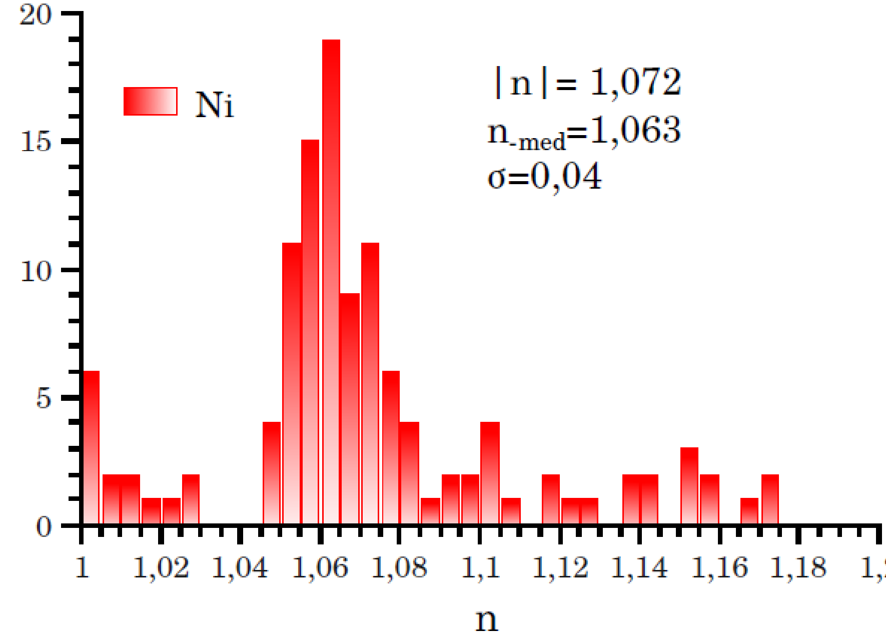


Ni is preferred for Schottky Contacts on N-type GaN because it has a higher barrier height



Ni Schottky Contacts characteristics on N-type GaN on sapphire exhibit rather low dispersion





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GaN

Homo-Epitaxy

MOCVD more usual

MBE works too

Status for GaN MOCVD homo-epitaxy

☺ Typical 1100-1200°C epitaxy => much lower than SiC,

☺ Several suppliers of multiwafers MOCVD reactors,

☺ Easy memory-less n-type doping using diluted silane,

☹ Gallium precursor (TMGa, TEGa) is very expensive,

☹ Cracking of the NH_3 nitrogen precursor
is very inefficient (<< 10%) => huge NH_3 gas flow

GaN
Self Standing
N+ substrates

Status for Self Standing GaN substrates

☹☹ Today 2 inch is the maximum diameter.

> 1 000 € each piece

Difficult scaling up of HVPE crystal growth

=> No perspective for rapid increase of diameter

☹ Crystal is grown from hetero-epitaxial templates on sapphire => minimum dislocation density is still in the range 10^5 - 10^6 cm^{-2}, at best,

☹ Still many macroscopic defects are present within the commercial GaN wafers we have seen,

☹ Ammono-thermal crystal growth => possible alternative

GaN

Schottky Rectifiers

on Self Standing GaN Substrates
cannot compete with SiC devices,
in 2013,
and, probably, it will never ...

GaN Hetero-epitaxy on Silicon or Sapphire ?

Issues related to Sapphire substrate

☺ 150 mm sapphire wafers exist, 100 mm common, 200 mm under development

☺ Rather cheap, potentially event cheaper,

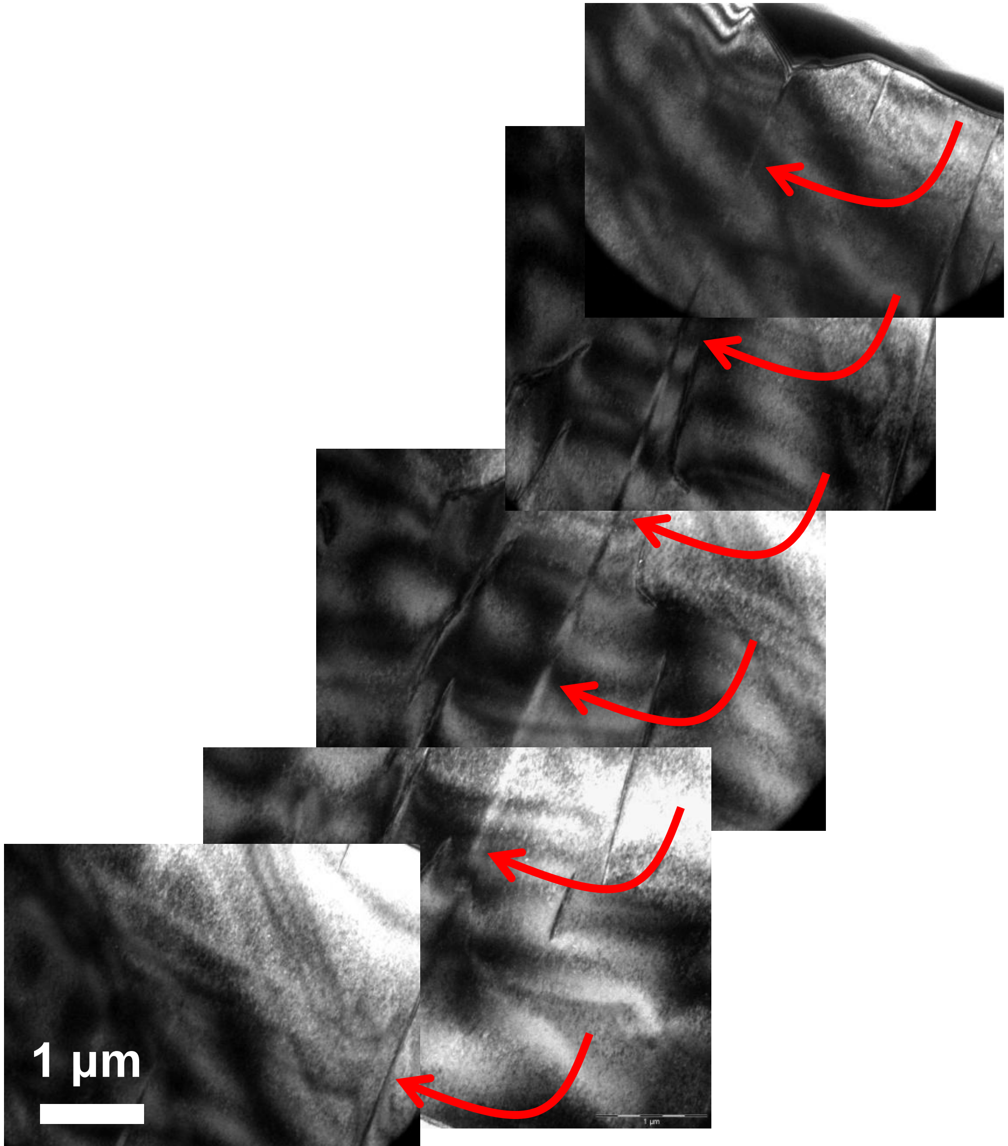
but

☹ Electrically Insulating. Cannot be made conductive,

☹ Rather low thermal conductivity K_{th}^{300K} ~ 50 W / K.m,

☹ Chip dicing difficult :
mechanical => fuzzy , laser => expensive,

TEM View of Nanopipe seeded on sapphire substrate defect and propagating all along GaN 10 µm epitaxy on Sapphire



for GaN Rectifiers

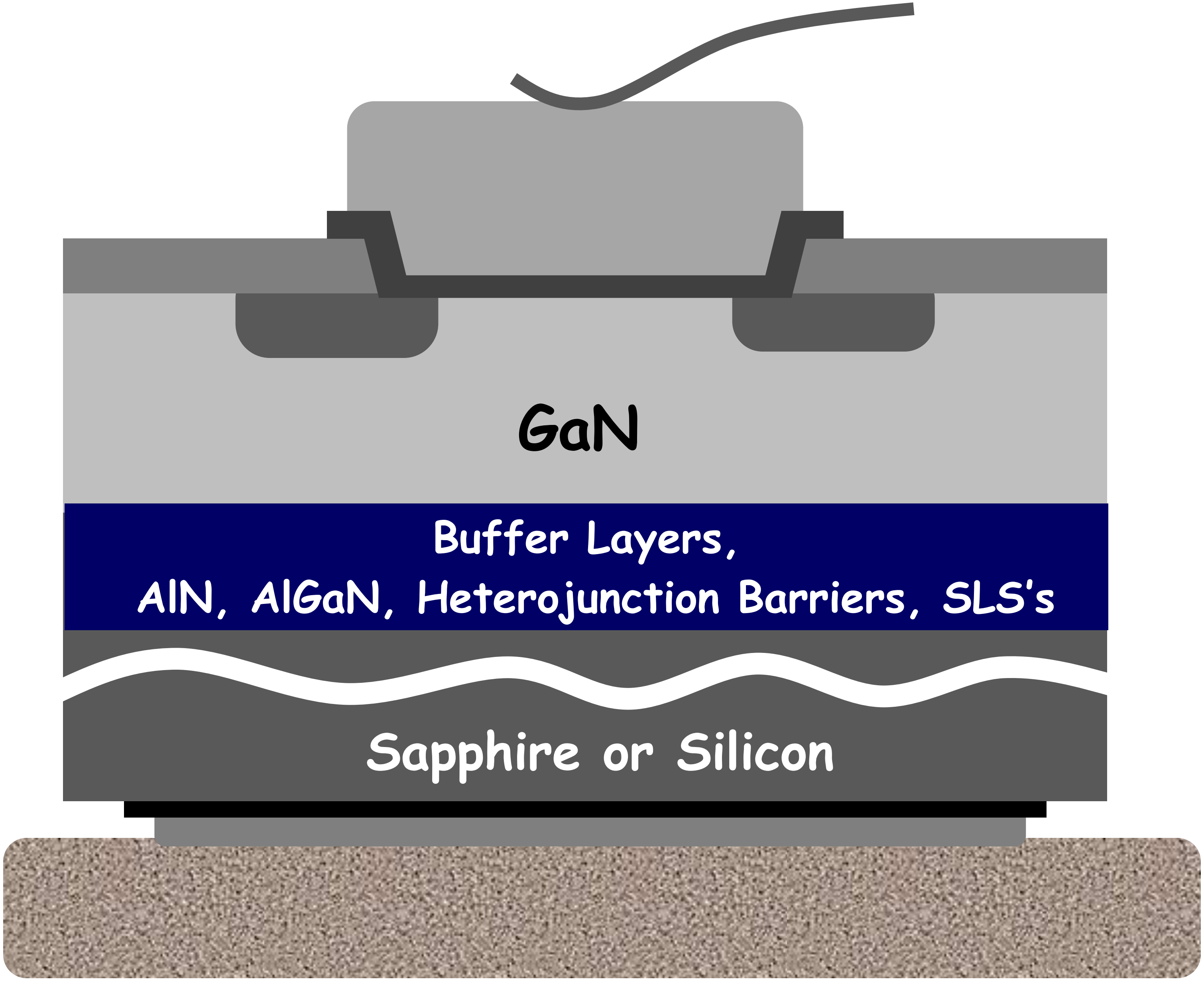
whatever

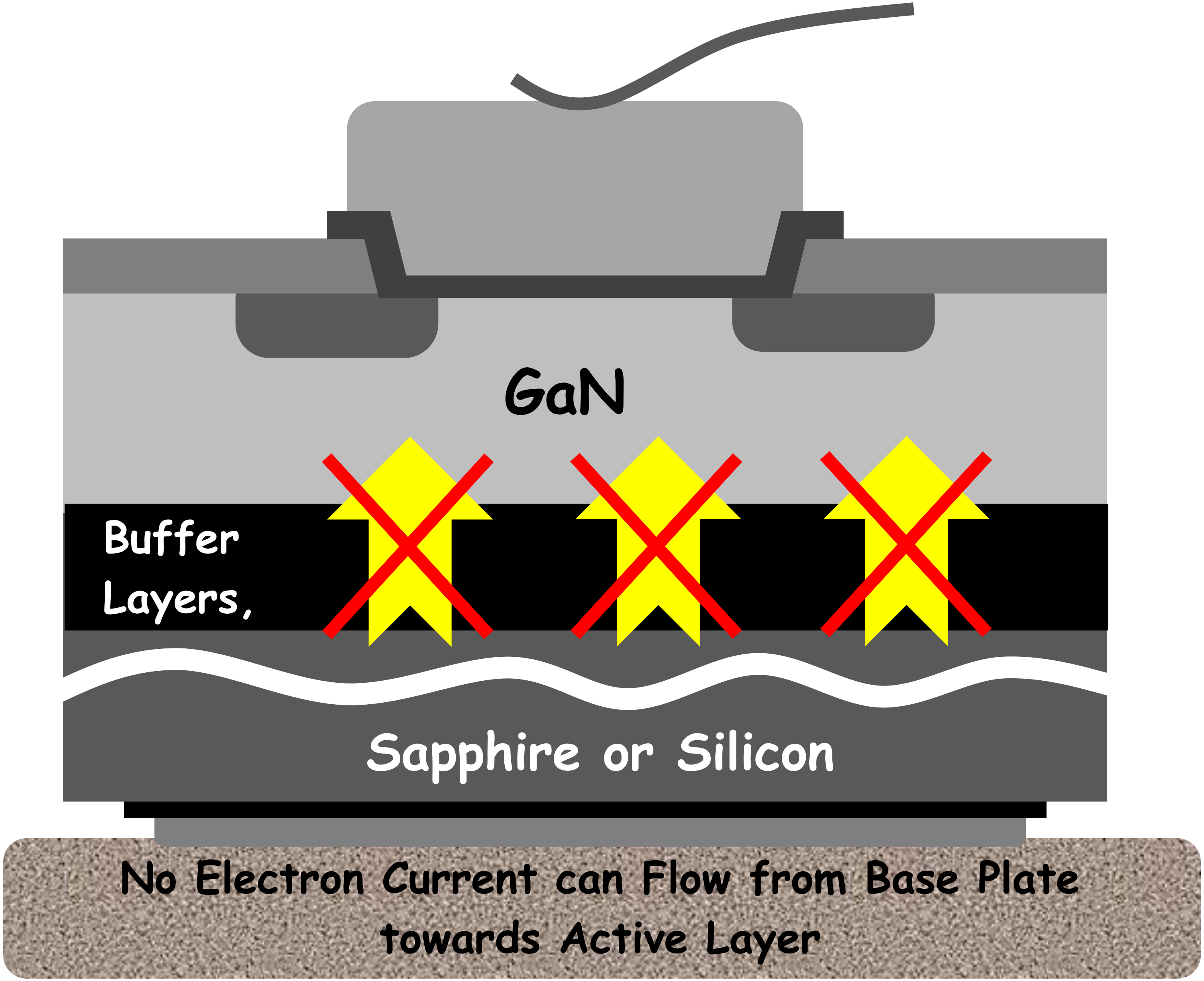
on Sapphire or Silicon

There is a Concern
about the Backside Access
to the Cathode

GaN epitaxy
on
Sapphire or Silicon

requires
Complex Buffer Layers


GaN
Buffer Layers,
AlN, AlGaN, Heterojunction Barriers, SLS's
Sapphire or Silicon


GaN
Buffer
Layers,
Sapphire or Silicon
No Electron Current can Flow from Base Plate
towards Active Layer

On
Sapphire or Silicon
substrate,
we cannot use the same
Vertical Device Topology
as for
4H-SiC Schottky Rectifiers.

Change of Topology

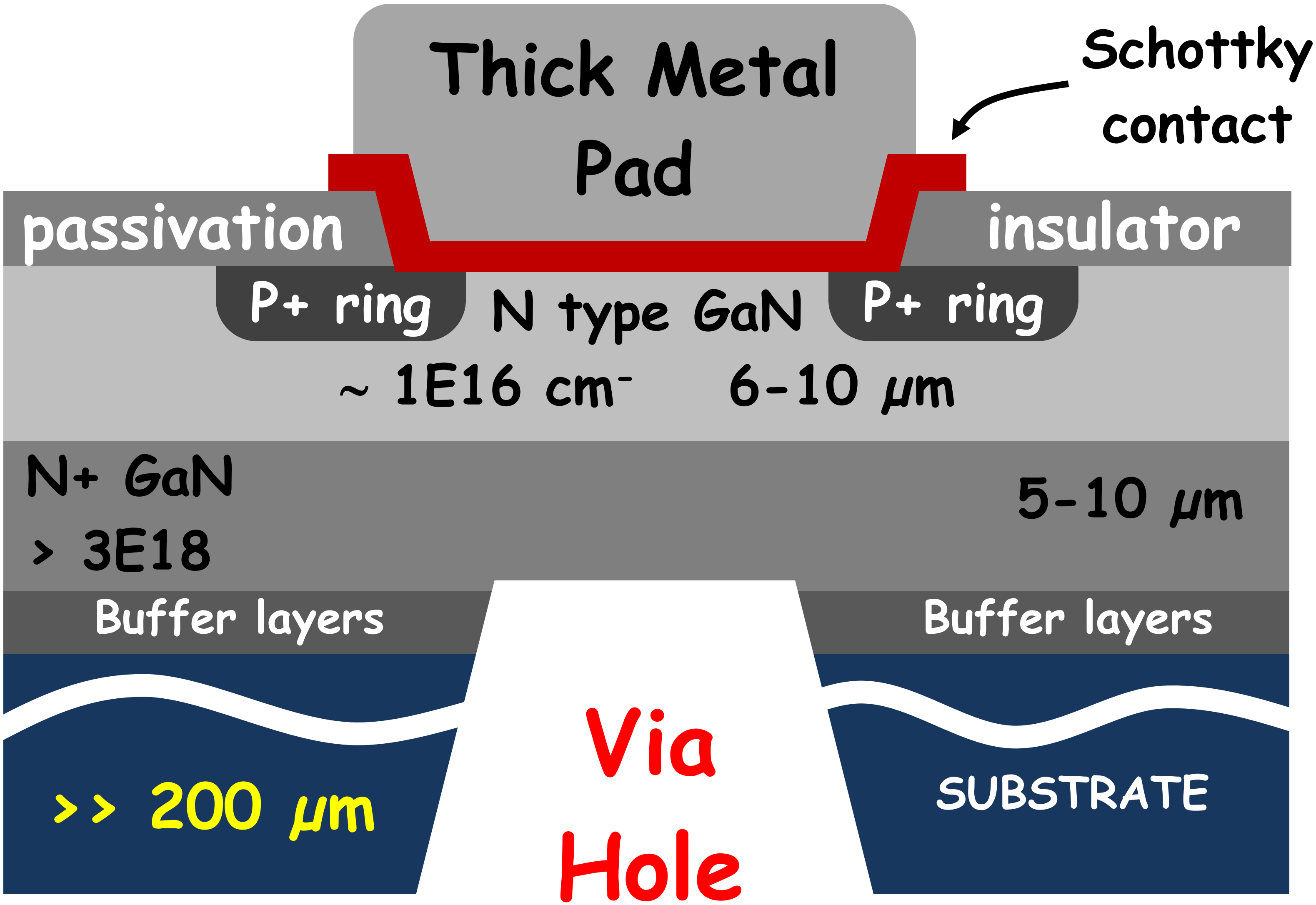
Option 1

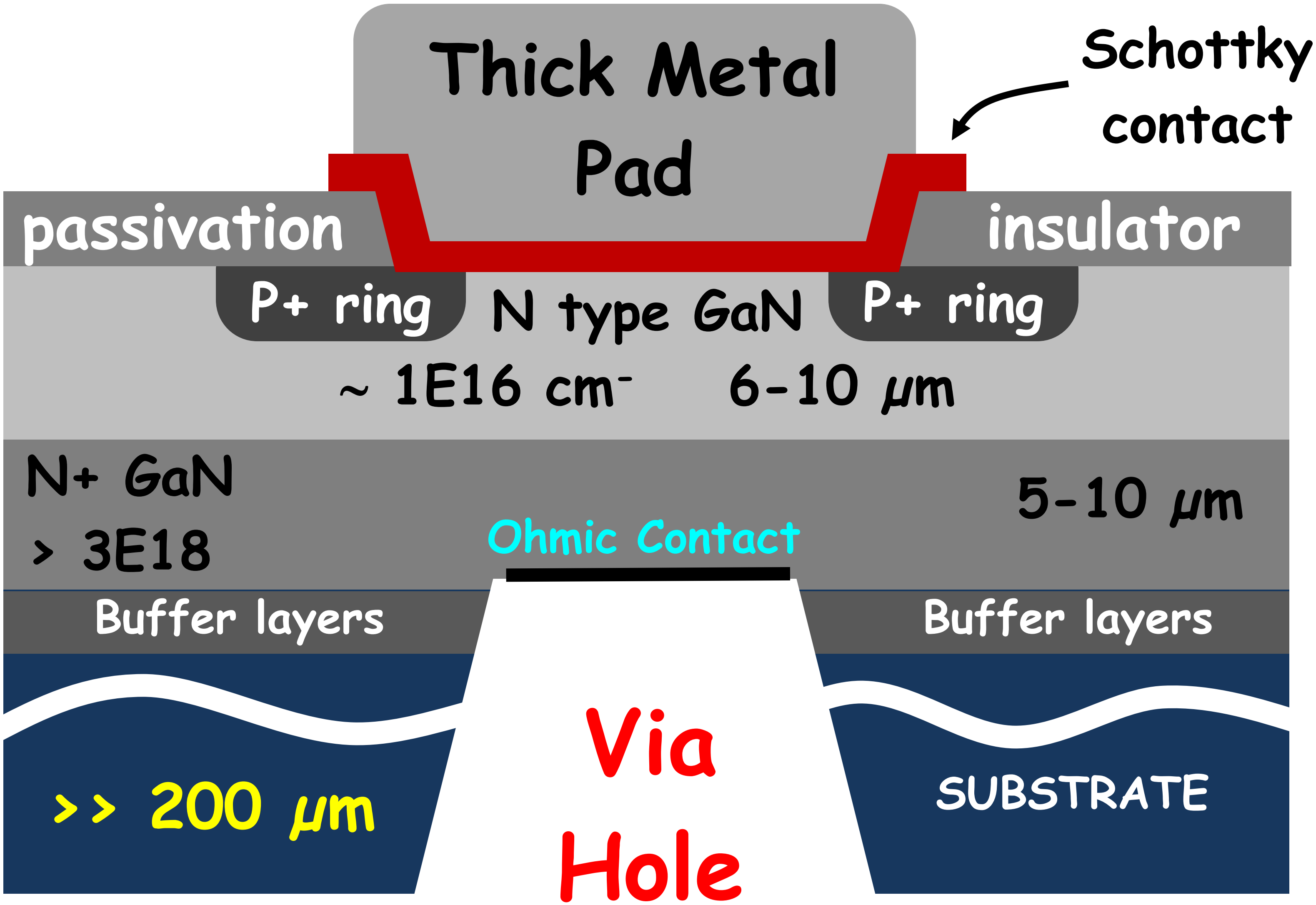
VIA HOLES

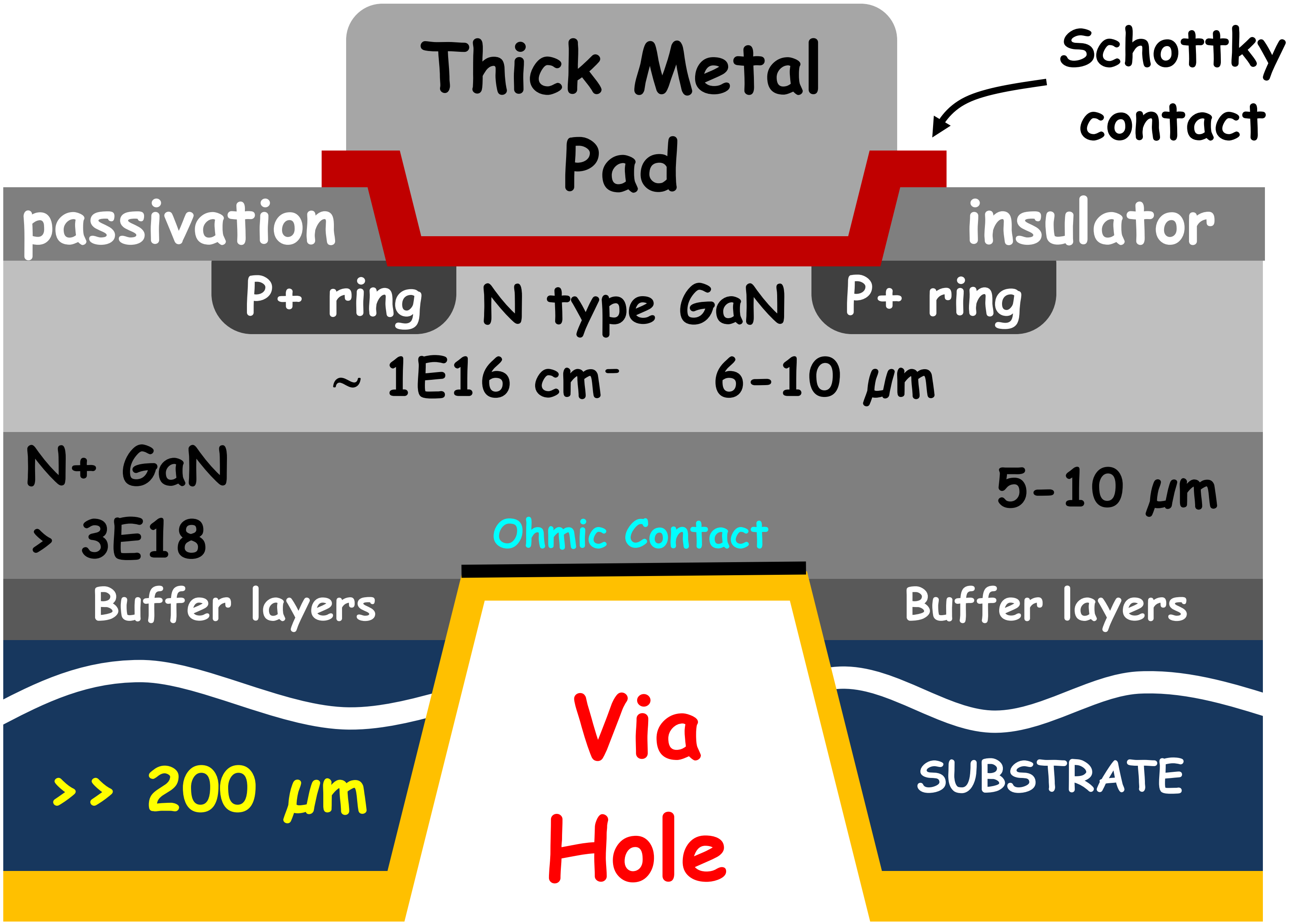
through the substrate

for cathode

BACKSIDE ACCESS


Thick Metal Pad
Schottky contact
passivation
insulator
P+ ring
N type GaN
P+ ring
~ 1E16 cm-
6-10 µm
N+ GaN
> 3E18
5-10 µm
Buffer layers
Buffer layers
Via Hole
>> 200 µm
SUBSTRATE


Thick Metal
Pad
Schottky
contact
passivation
insulator
P+ ring
N type GaN
P+ ring
~ 1E16 cm⁻
6-10 μm
N+ GaN
> 3E18
5-10 μm
Ohmic Contact
Buffer layers
Buffer layers
>> 200 μm
Via
Hole
SUBSTRATE


Thick Metal Pad
Schottky contact
passivation
insulator
P+ ring
N type GaN
P+ ring
~ 1E16 cm⁻
6-10 μm
N+ GaN
> 3E18
5-10 μm
Ohmic Contact
Buffer layers
Buffer layers
Via Hole
>> 200 μm
SUBSTRATE

Issues related to the "Via Hole" option on Sapphire

☹ The Deep Etching of Sapphire is difficult, long, and expensive,

☹ "Over Heating" of Schottky Contact during Ohmic Contact Annealing,

☹ Risk for epi Layer "Blow-up"

Deep etching of Sapphire

requires high density plasma etching with specific chemistry.

It is a slow and expensive process

<< 1 µm / mn

Addressing the masking issue for this etching is also a real challenge ...

Issues related to the Via Holes option

"Over Heating" of Schottky Contact

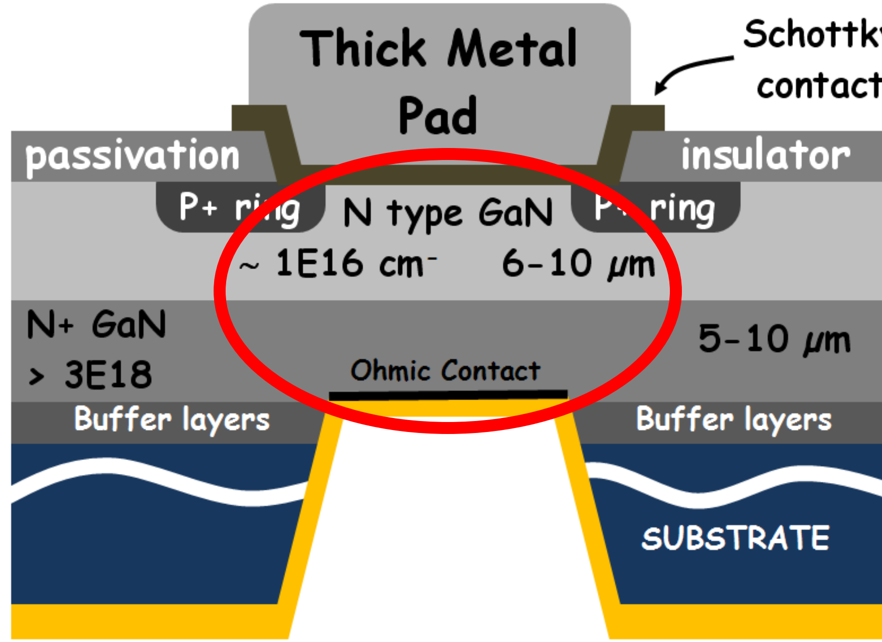
☹ Usually, Via Hole process is performed
at the end of the device processing,
after the active device is finished,

=> For via holes, backside Ohmic contact
has to be performed after Schottky contact,

=> Schottky Contact must survive the high-temperature
ohmic contact annealing => very demanding constraint
on Metal / Semiconductor interface chemistry,

Issues related to Via Holes in Sapphire or Silicon

Epi Layer "Blow-up"



☹ After via holes etching, the thin active layer is self-standing => fragile

☹ Due to the stress in the hetero-epi layers, there is a strong risk the active layer will simply explode during via hole etching or wafer un-glueing, or during wafer dicing

Change of Topology

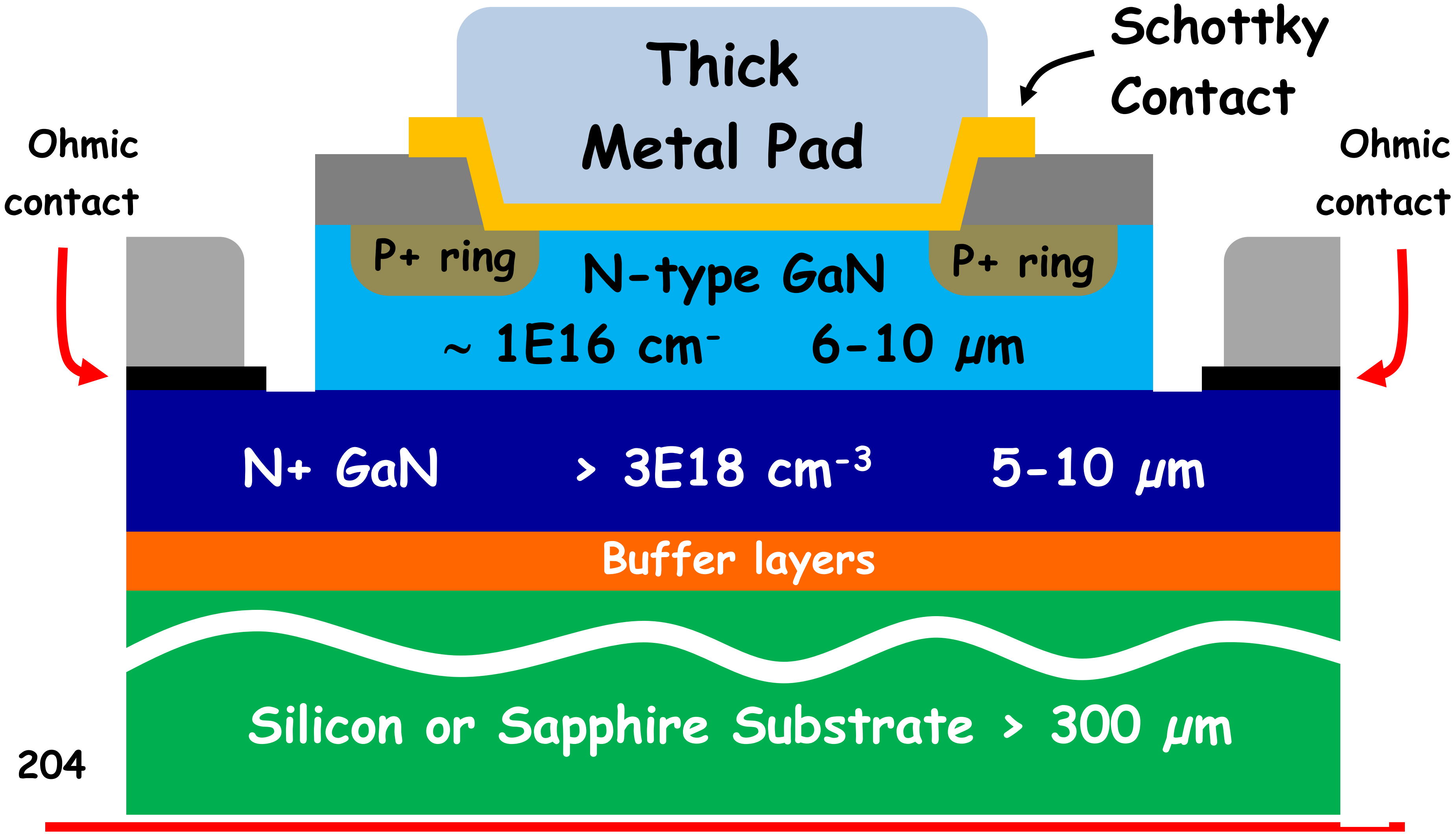
Option 2

both

Anode **AND** Cathode

access from the epi side

MESA Topology with both the Anode and Cathode Access from the Epi side



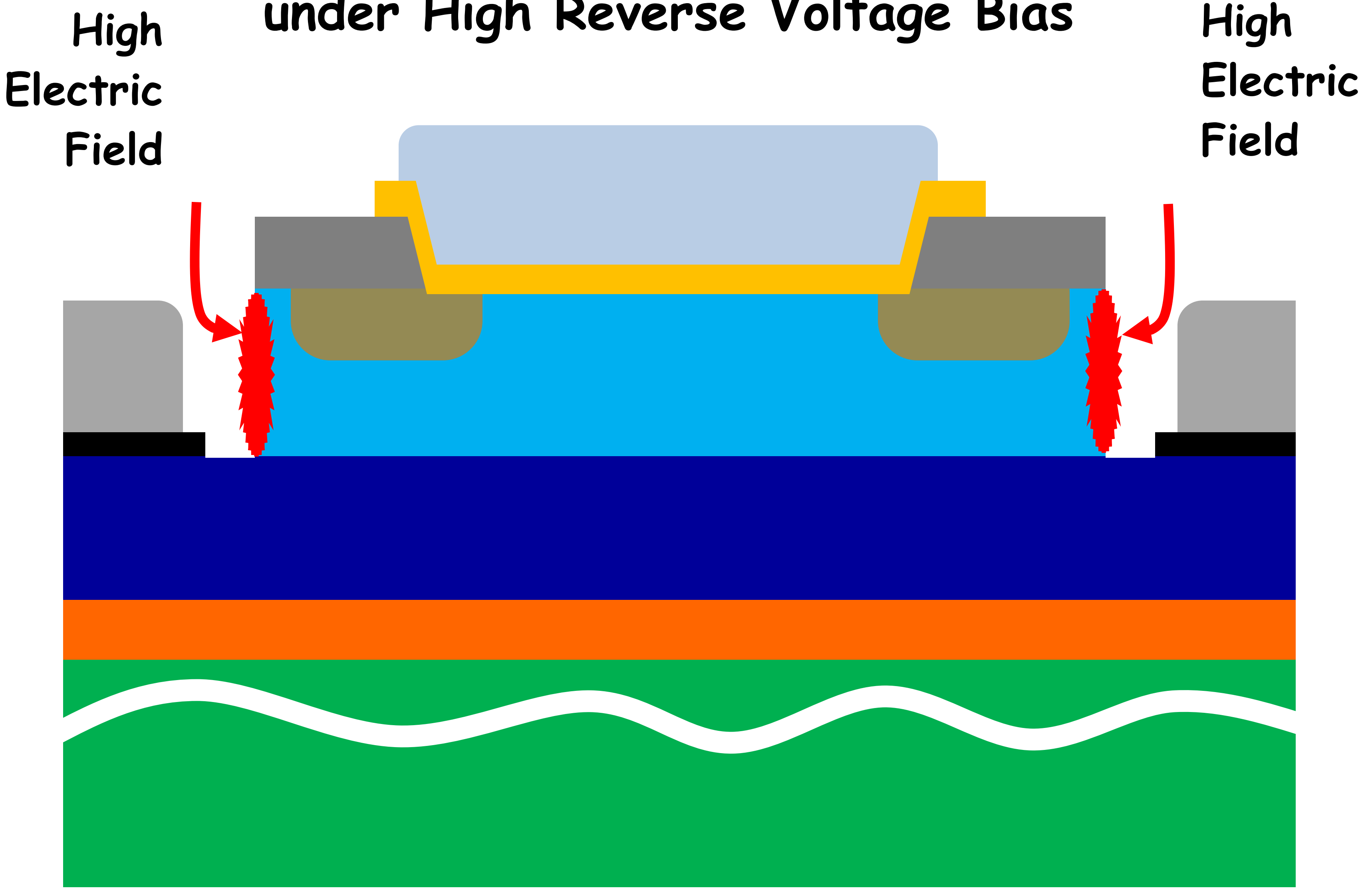
Issues related to MESA Topology

☹ Deep GaN etching required => long process
=> high density ICP chloride chemistry plasma

☹ High electric field on mesa edge => risk
=> demanding for the Mesa Edge Passivation

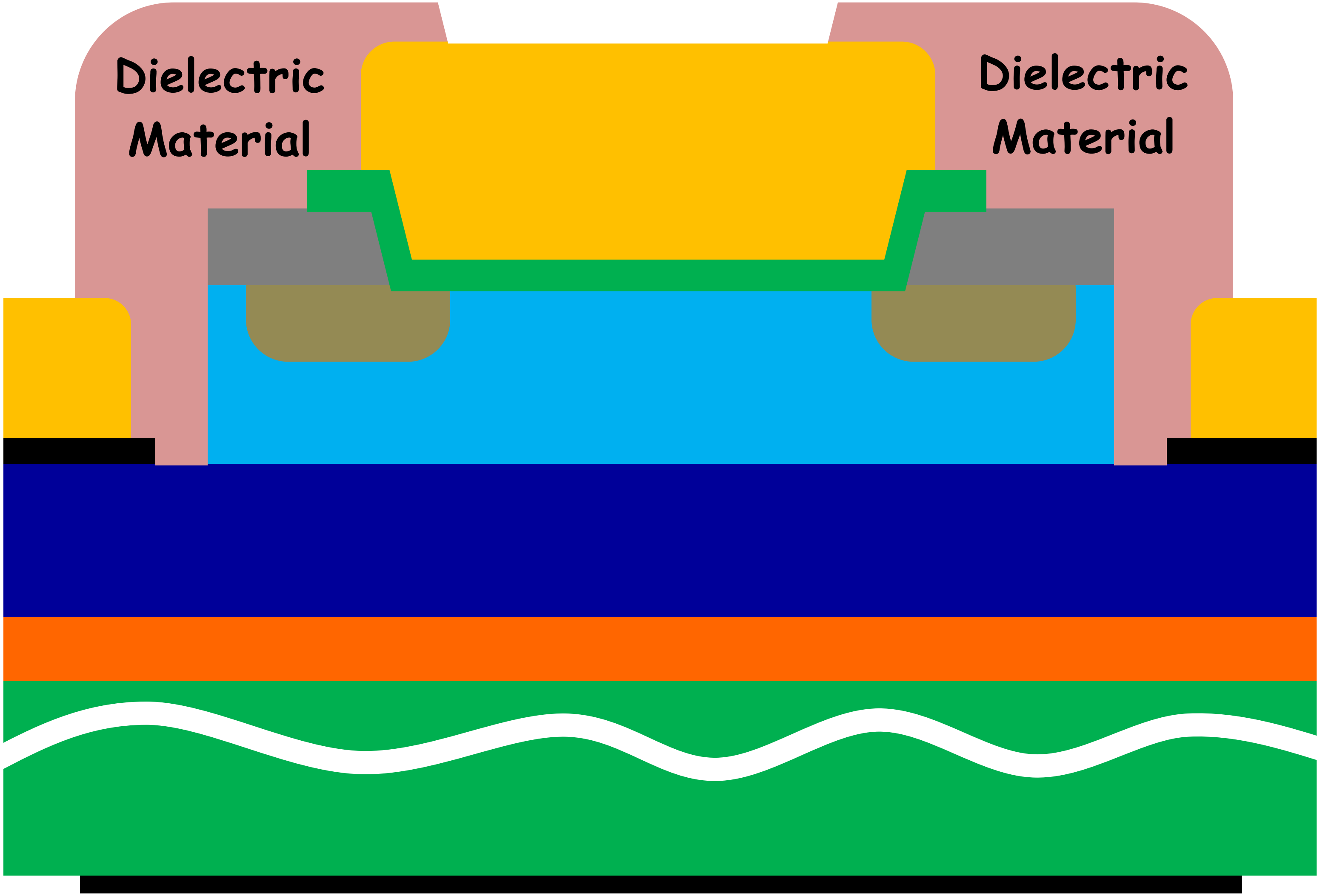
☹ Complex management of High Voltage Isolation
between nearby electrodes on the epi side,

High Electric Field Zones on the MESA edge under High Reverse Voltage Bias



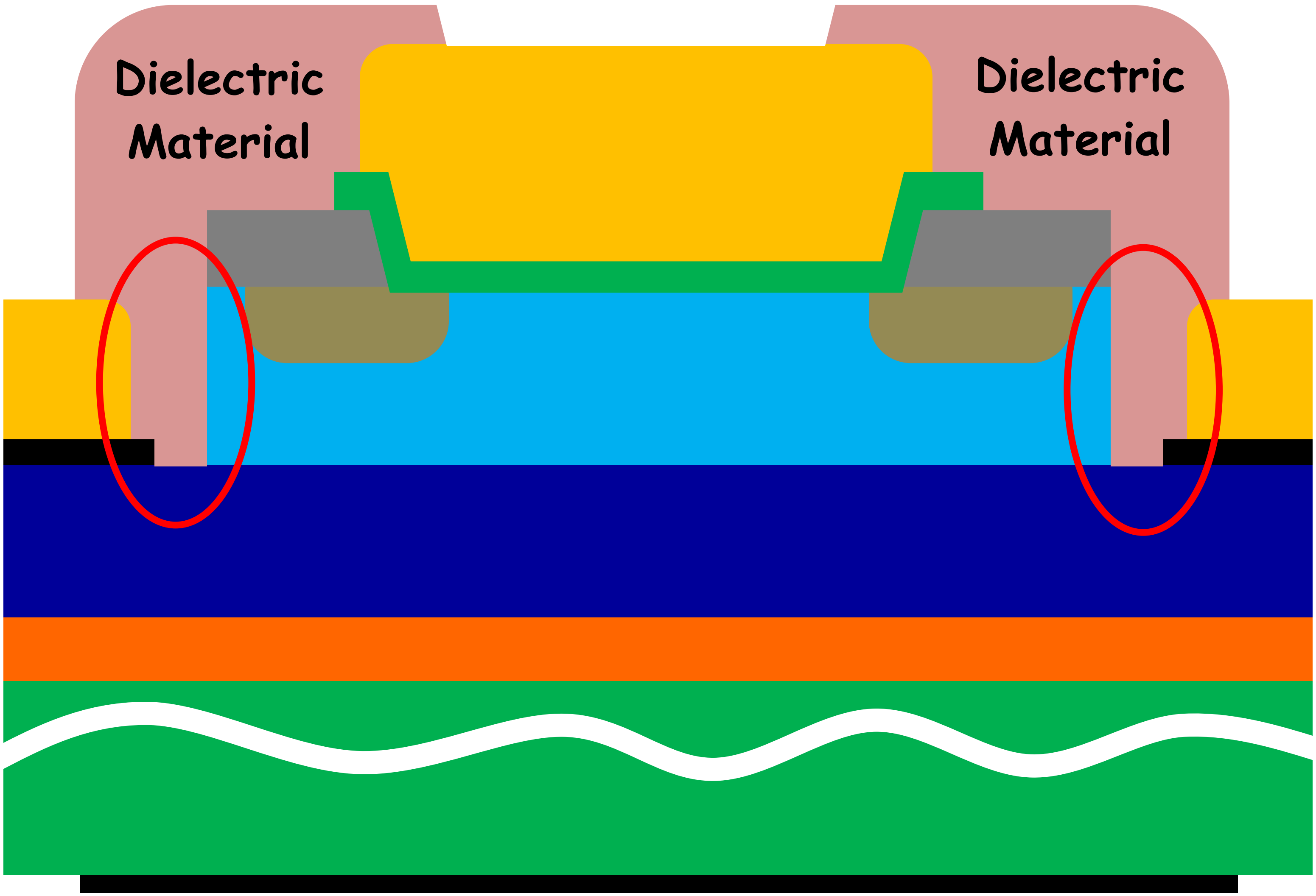
Long Term Reliable Isolation

between 2 nearby electrodes is difficult ...



Long Term Reliable Isolation

between nearby electrodes is difficult ...



Issues related to both MESA and VIA HOLE options

☹ Thick N+ sub-layer required
with sheet resistance $R_{\square} < 30$ ohm
=> $N_d > 5.10^{18}$ cm^{-3} and thickness > 5 µm
=> Silicon doping brings high stress
on hetero-epitaxial GaN
=> Other donor should be used
=> Ge is the simplest

☹ Total epi thickness > 10 µm for 600 V diode
=> > 5 hours epitaxy duration

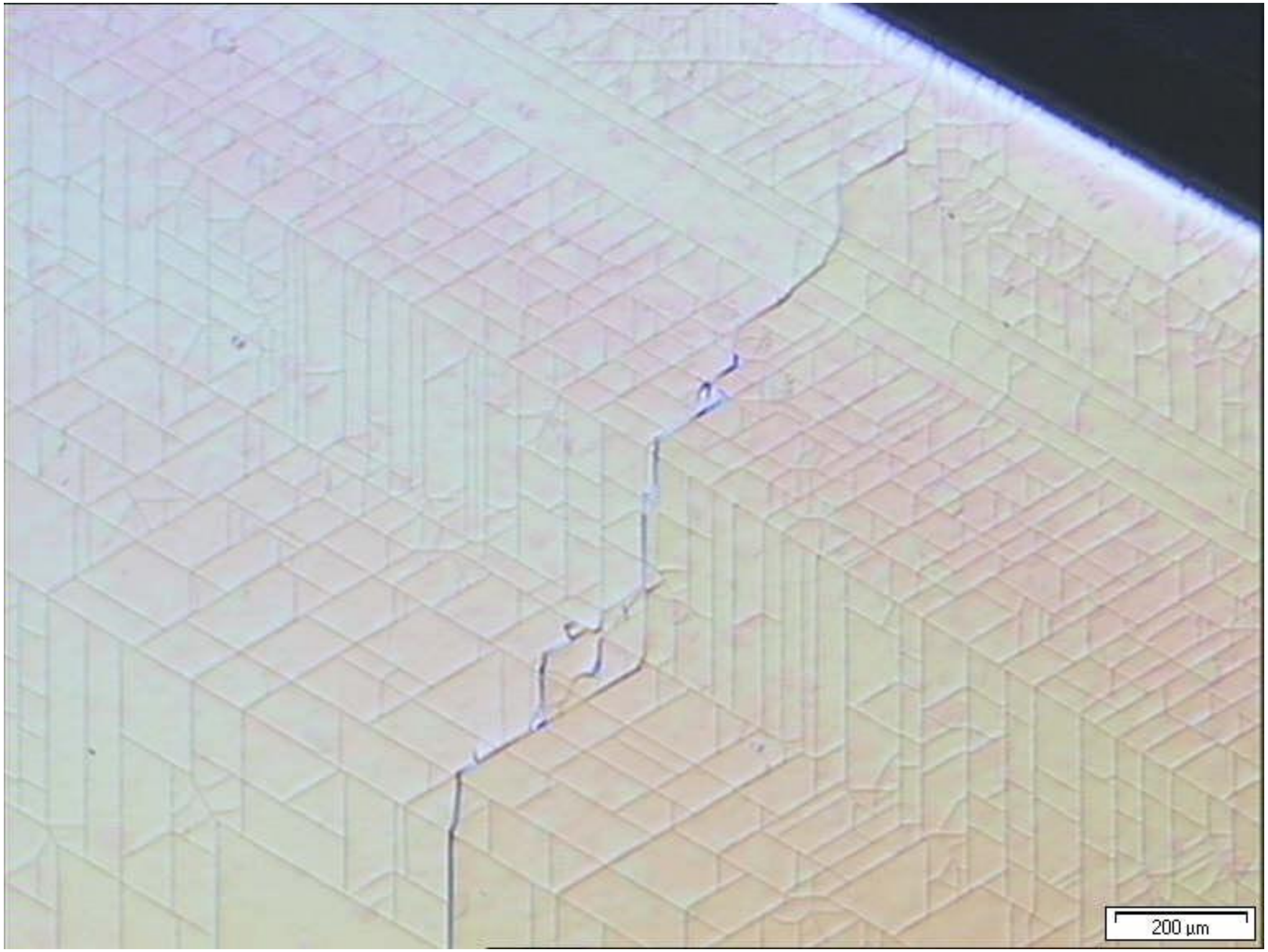
Specific problems related to Silicon Substrate

- ☹ Thick GaN epi layers grown on Silicon get easily cracked,

- ☹ N+ GaN:Si layers / Si substrate are extremely stressed

Example of Cracked GaN / Si epi layer

=> Optimizing the epitaxy is still a heavy work



Conclusion :

Can
GaN Schottky Rectifiers
really compete with
4H-SiC ?

212

The lowest risk approach today for SiC-like GaN Schottky Rectifiers

Substrate : Silicon

MOCVD epitaxy faster,

MESA Topology,

Mesa edge passivation (high risk),

TiAl ohmic contacts,

2 electrodes on front epi side

Industrial Risk :

GaN epitaxy

on

Sapphire or Silicon

requires

Complex Buffer Layers

Problem :

There is no

Standard GaN Material

today.

Every III-N epi grower keeps its own Buffer recipe secret.

Change of Epi Grower

⇕

Change of GaN material properties.

Final Conclusion on GaN Rectifiers

(1) GaN Schottky Rectifiers are much more difficult to fabricate than 4H-SiC.

(2) The main reasons for trying to develop GaN rectifiers => SiC substrates

- Expensive
- Lower diameter (Ø 150 mm sampled today)
- Lower crystal quality than Si

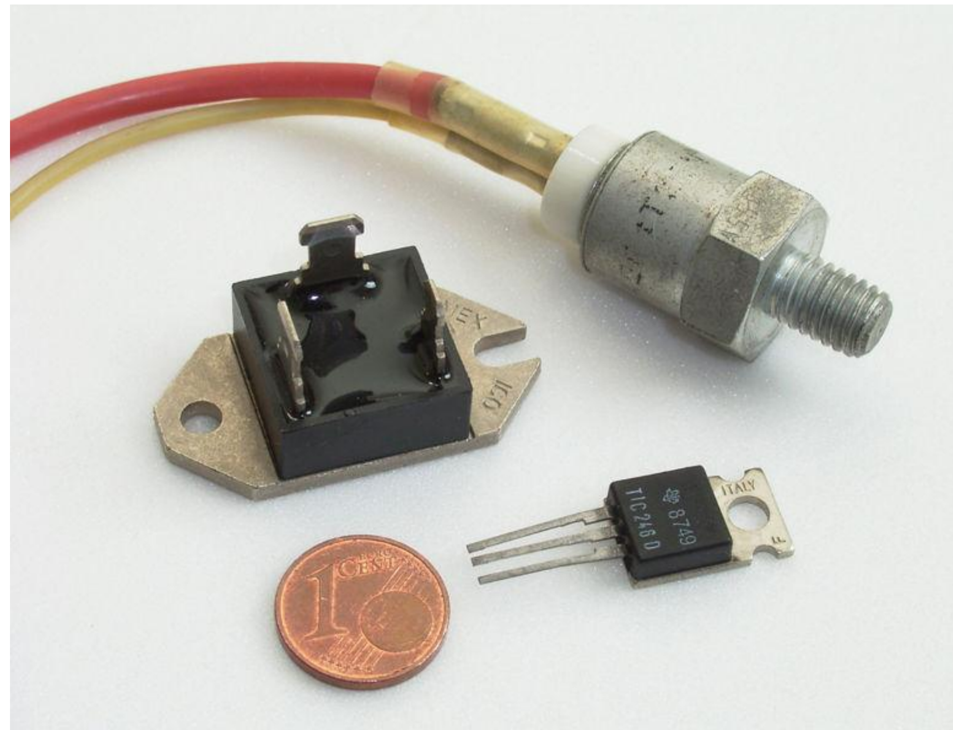
A Quick Panorama of Gated Switching Devices

Silicon

The Cheapest Switching Device

SILICON TRIAC

Cheapest Available Devices « TRIAC »
=> 1 Silicon Chip for Direct Control
over 50-60 Hz Energy without Change of Voltage

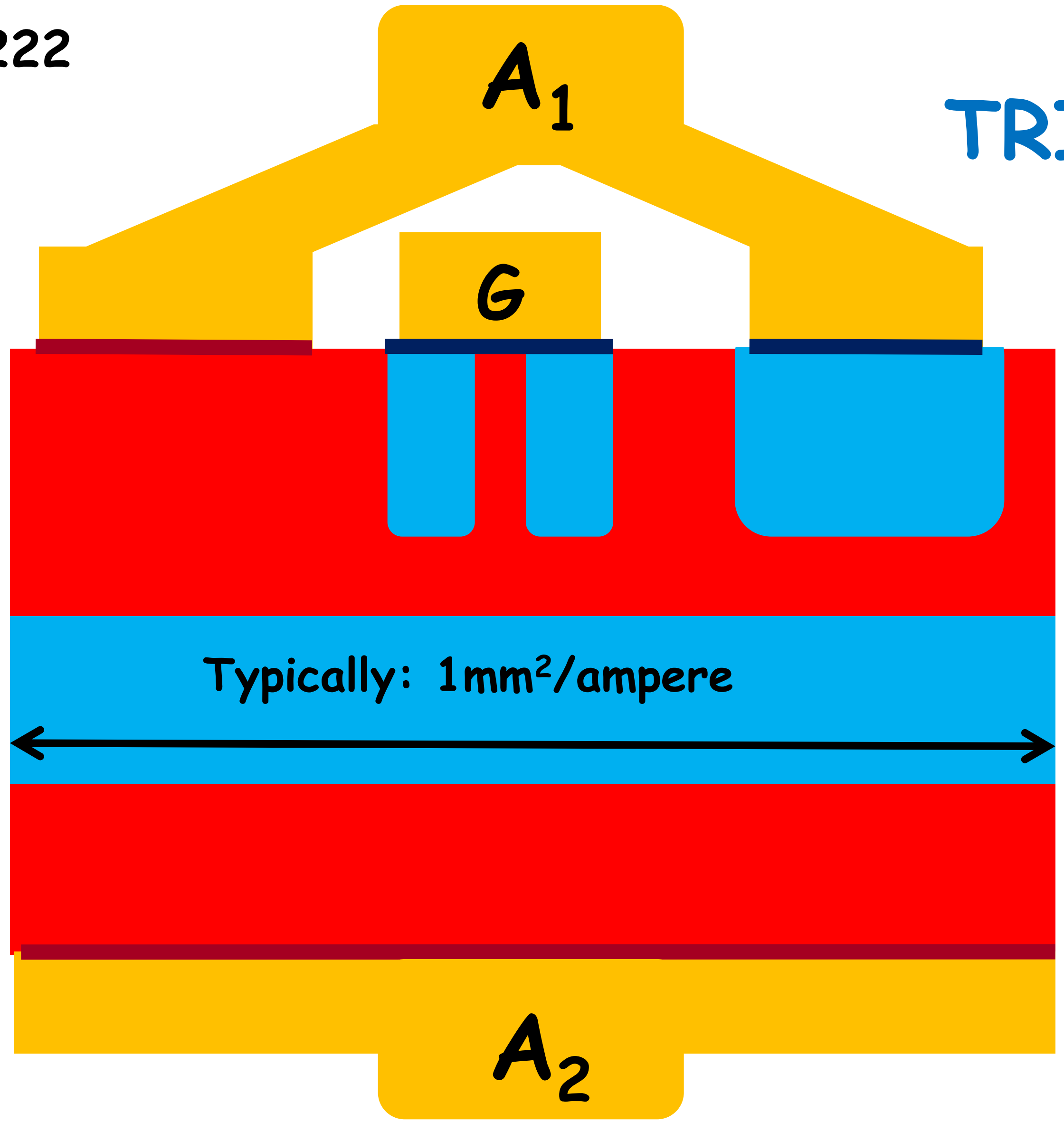


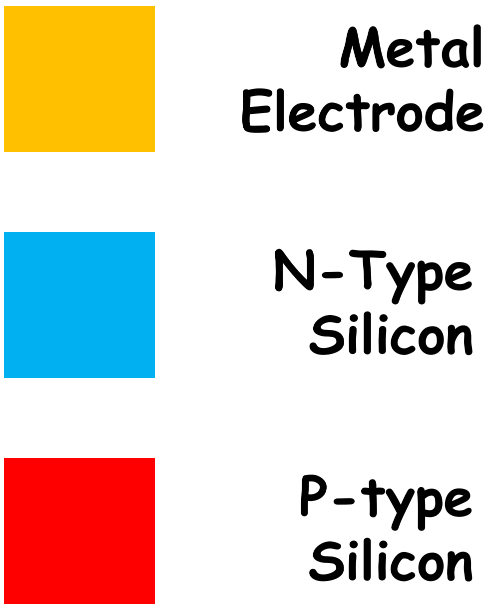
Control Module

« TRIAC » devices

« TRIAC » are not ideal devices, but they are cheap

Structure of TRIAC device chip





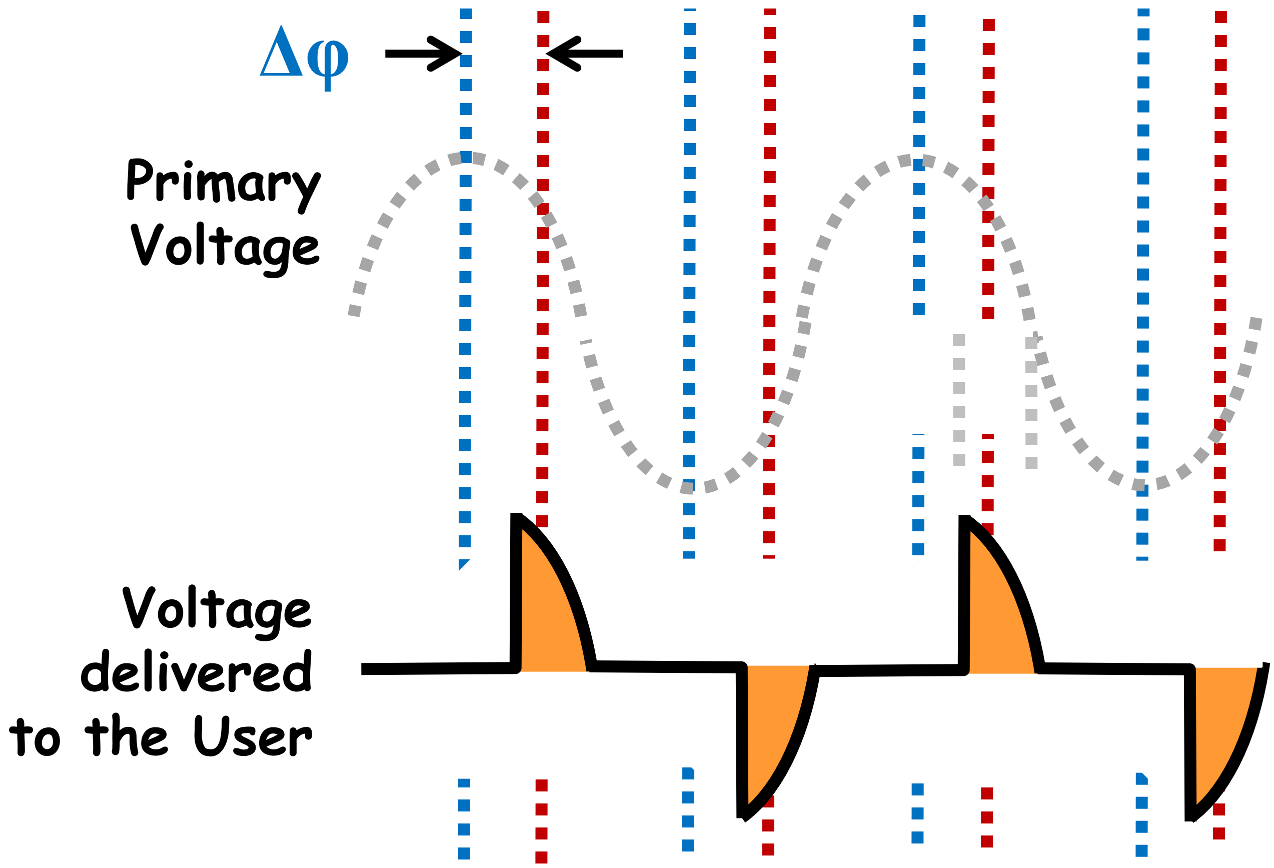
100 Hz maximum

SILICON TRIAC
has plenty of drawbacks

- It is a bipolar switch
  => Slow switching
  => High V_{ON}, threshold is around 1V

- It is a « latch-up » switch
  => cannot be stopped from On-State
  => Switches Off only when V =0

CONSEQUENCE of On State « Latch up » in TRIAC => Phase Shift Δφ => Energy Losses

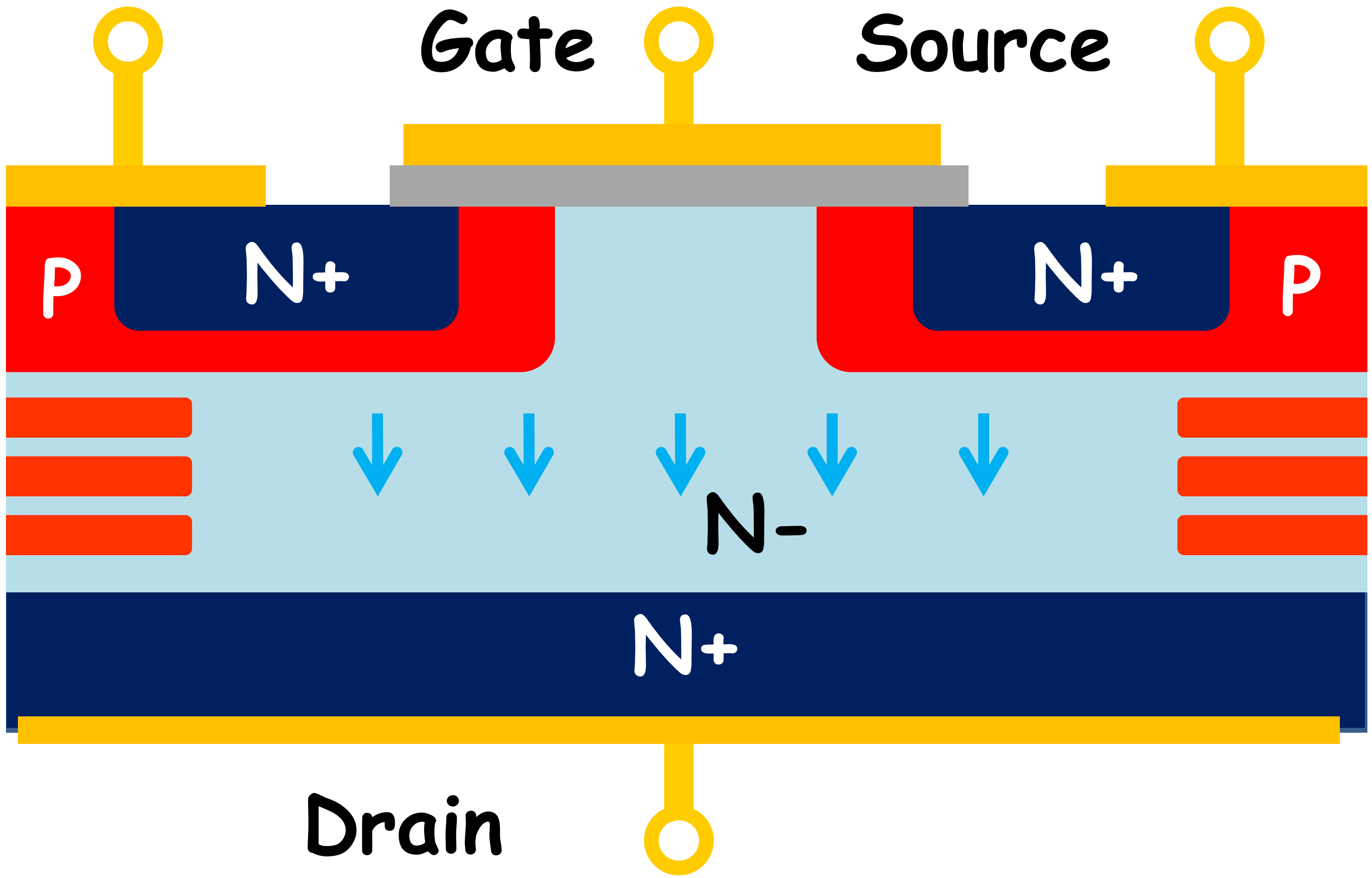


22
4

The Fastest
Silicon Switching Device
(more expansive)

SILICON
VERTICAL MOS

Vertical MOS (up to 1MHz)
Si Unipolar Switch used from 0 to 1 kV in 2013

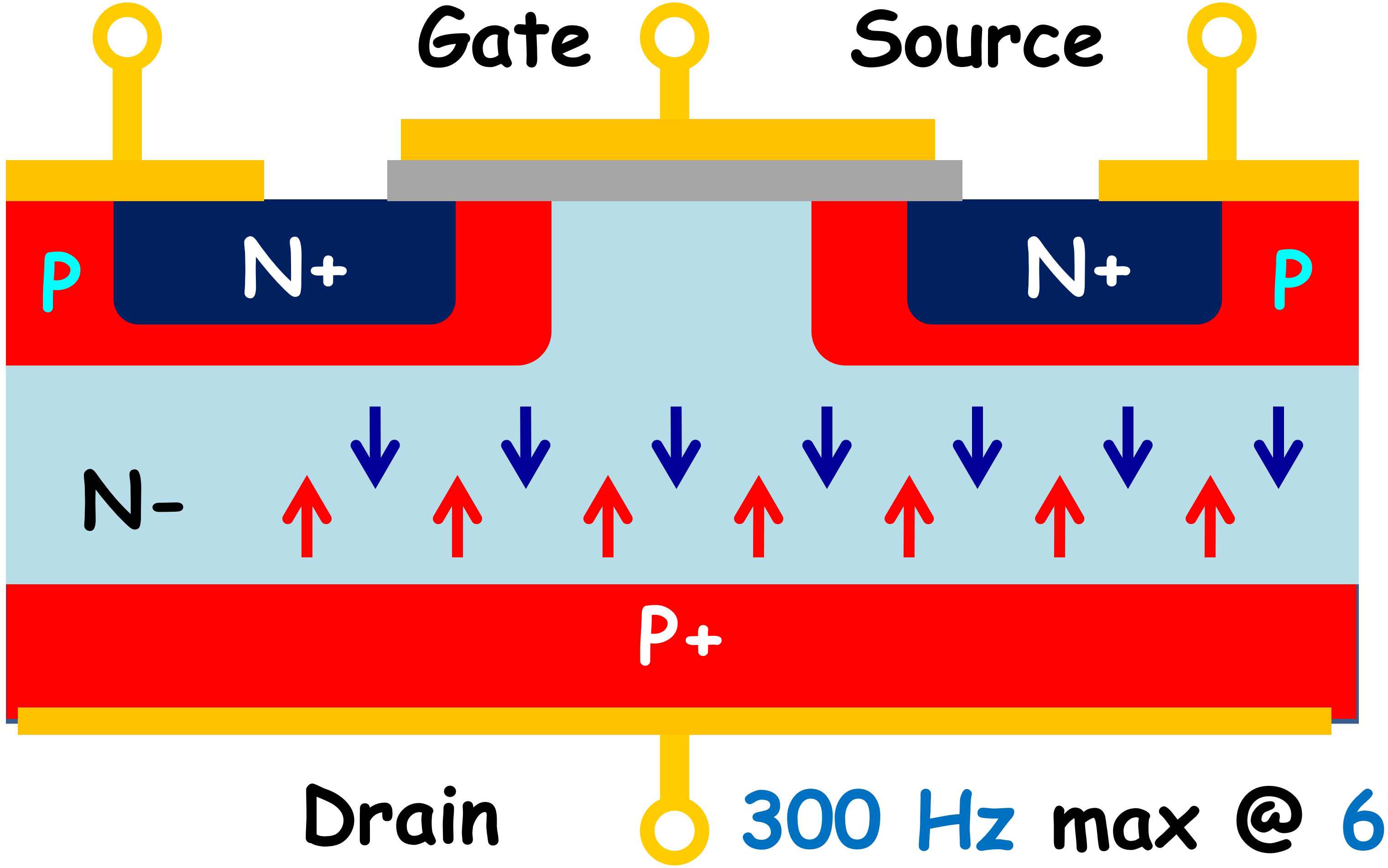


The Bipolar Silicon Switching Device adapted to High Voltage (up to 6 kV)

Insulated Gate Bipolar Transistor (IGBT)

Insulated Gate Bipolar Transistor (IGBT) 228

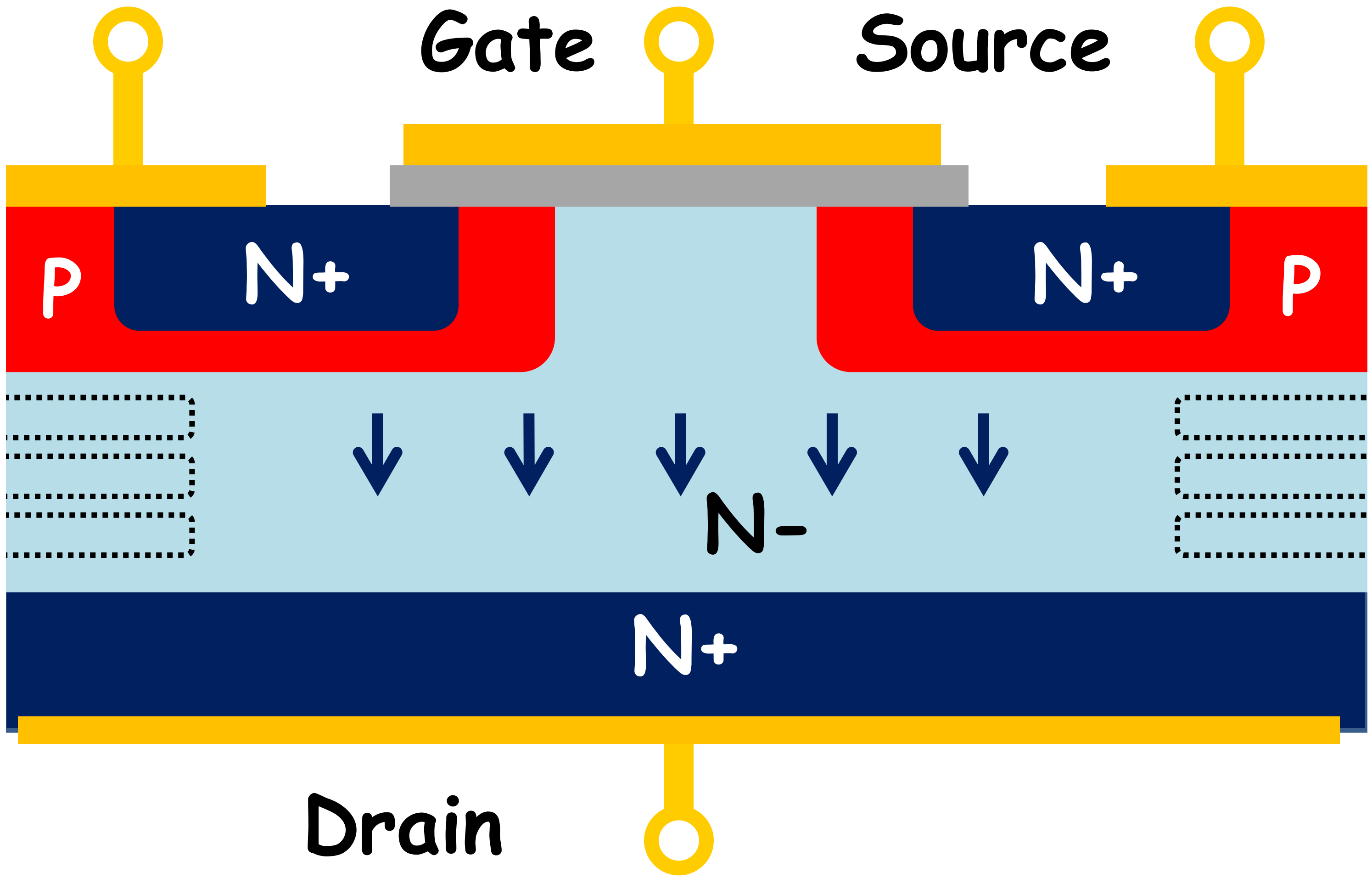
Si Bipolar Switch used from 1 to 6 kV in 2013



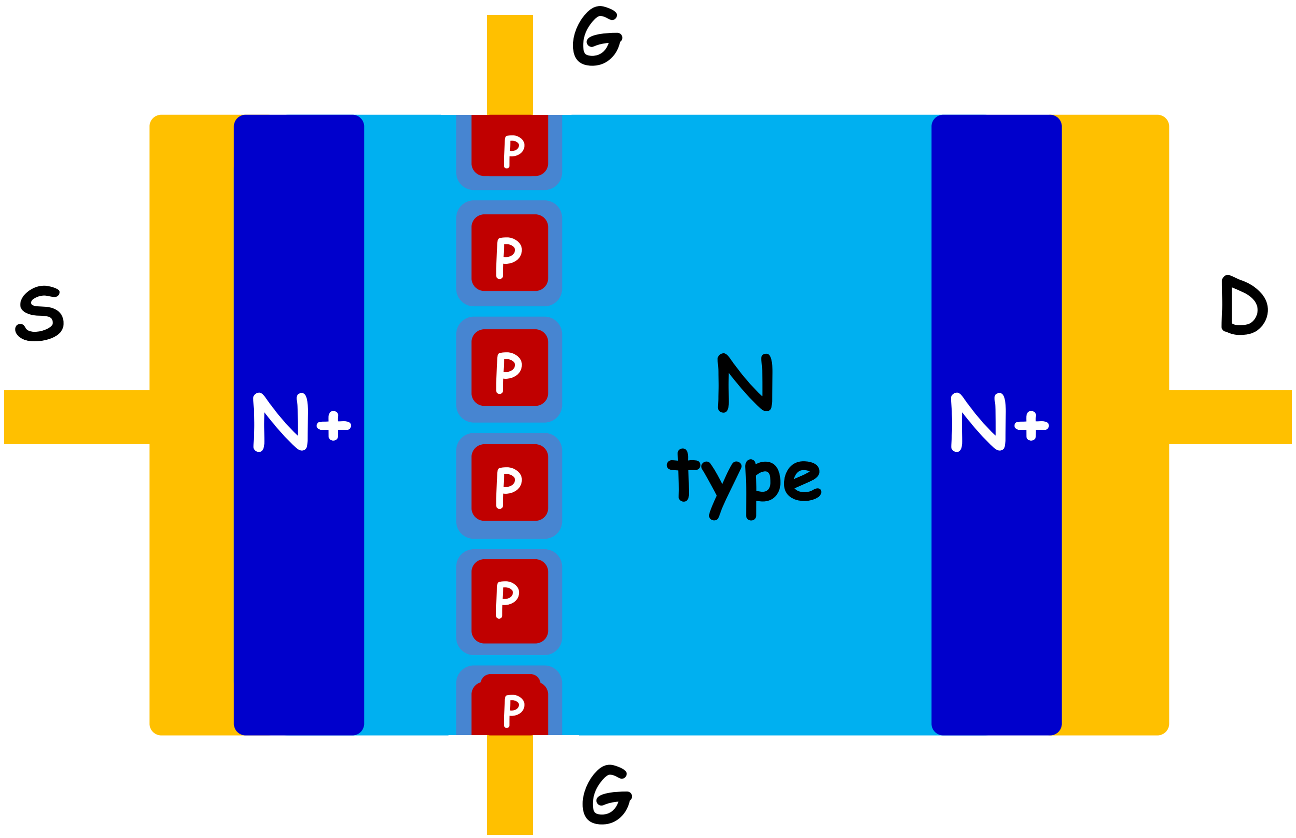
300 Hz max @ 6 kV

SiC

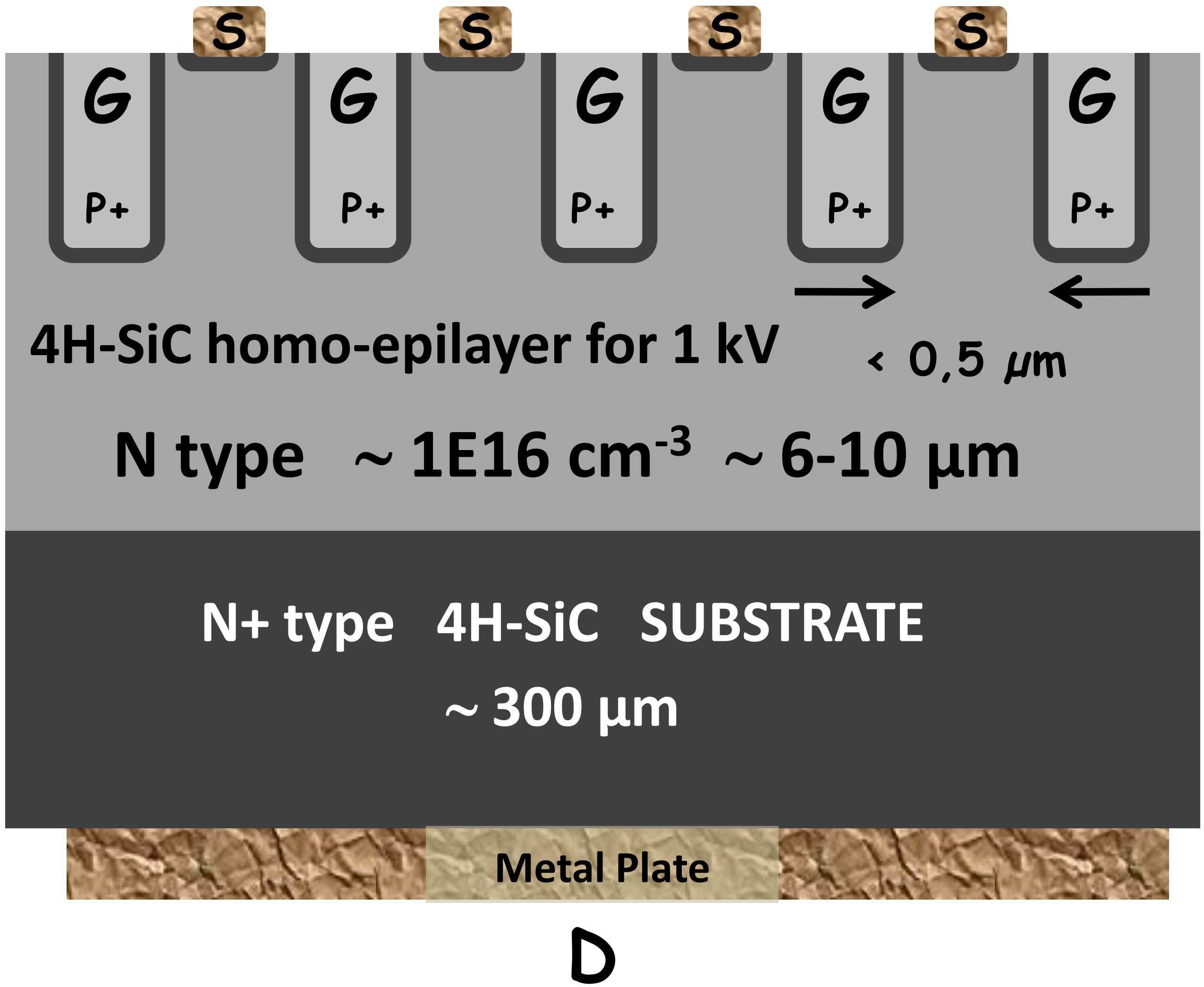
Vertical MOS SiC Unipolar Switch prototypes 1 to 10 kV in 2013



JFET Unipolar Switch Principle
(mostly Normally On)



VERTICAL J-FET SiC up to 3 kV



No Perfect SiC

Gated Switching Devices yet :

JFET

More reliable – Normally ON

MOSFET

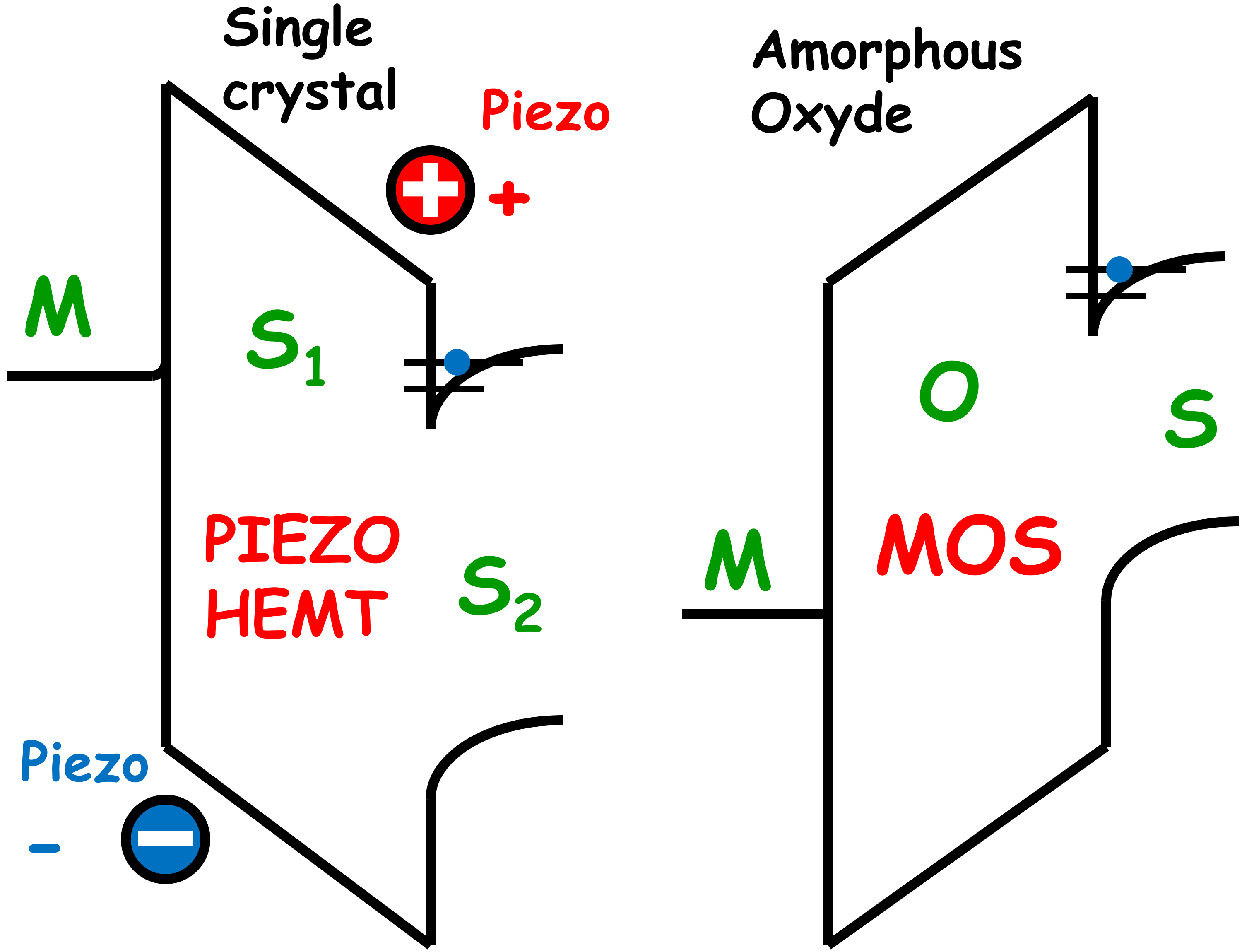
Less reliable – Normally OFF

III-N

High Mobility 2d Electron Gas

is the main driver towards

III-N Unipolar Switches



Single crystal
Piezo
+
M
S_1
PIEZO HEMT
S_2
Piezo
-
Amorphous Oxyde
O
S
M
MOS

2d Electron Gaz Properties at AlGaN or InAlN / GaN interface

Electron Mobility
1000 to 2000 $cm^2/V.s$

Much Higher than on any Si or SiC FET

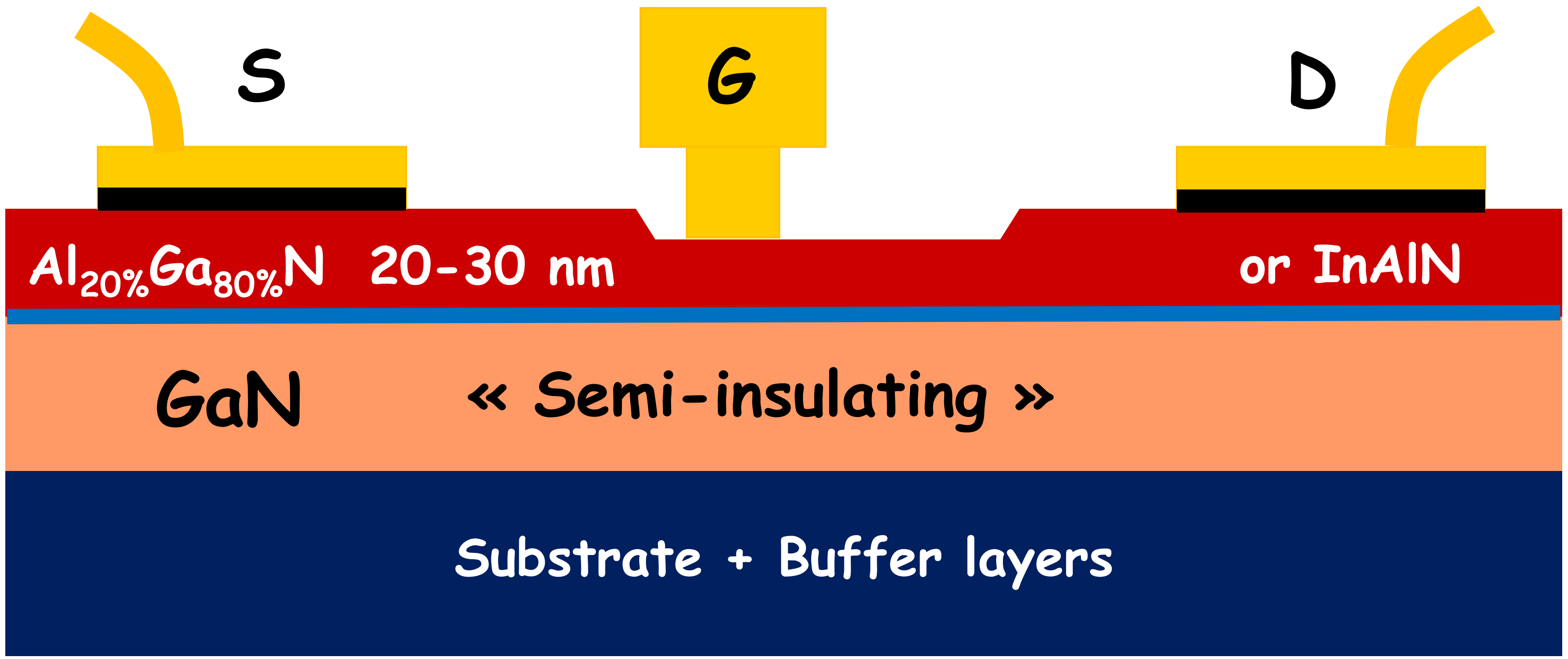
Electron SheetDensity
1 to 2 E13 cm^{-2}

III-N

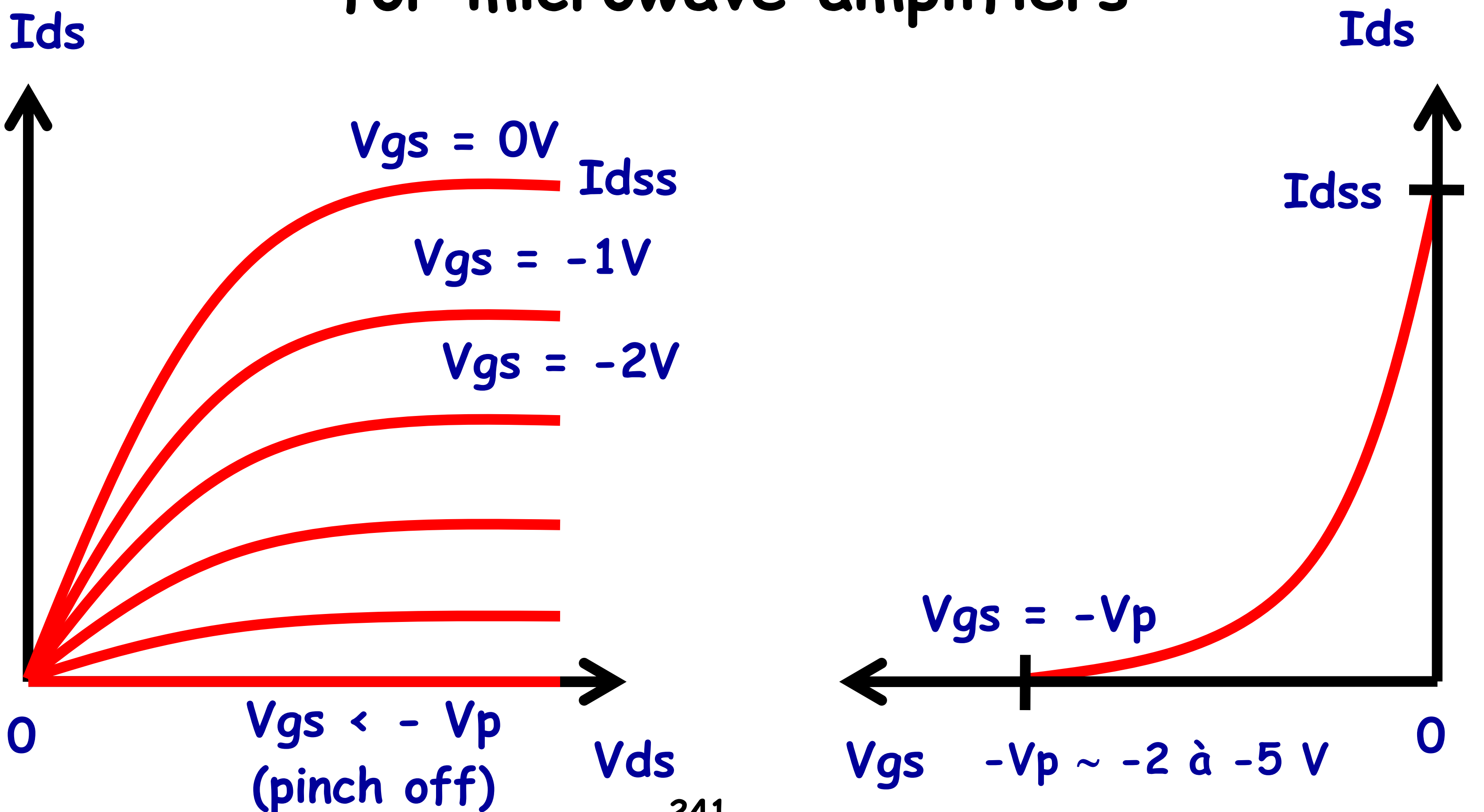
from
Microwave HEMT
to
Unipolar Switch

(0)
Starting Point :
Piezo-Electric HEMT
for
Microwave Amplifiers
=> Normally On

Typical Piezo-Electric HEMT for Microwave Amplifiers (Normally On)



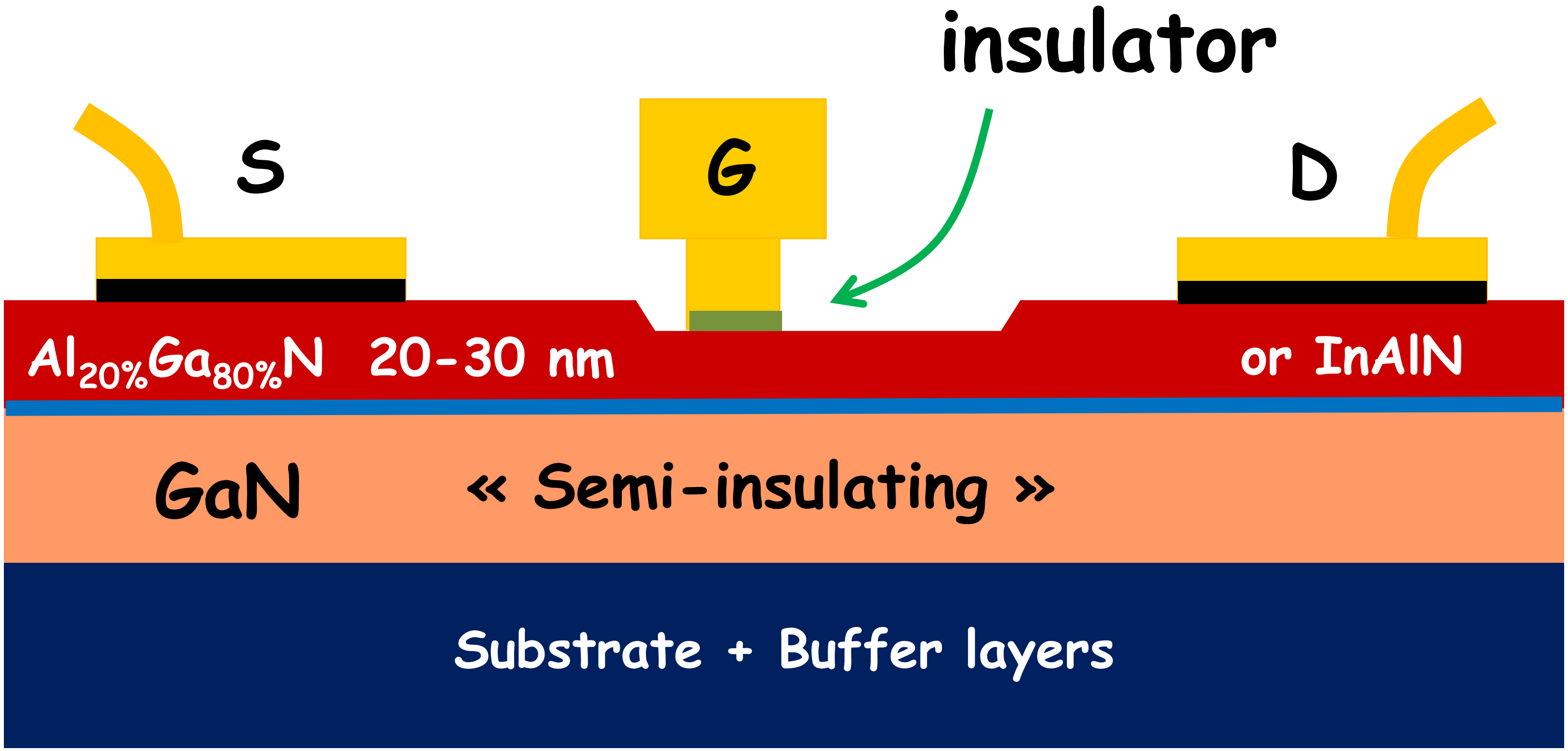
I-V characteristics of a typical AlGaN / GaN HEMT piezo-electric transistor for microwave amplifiers



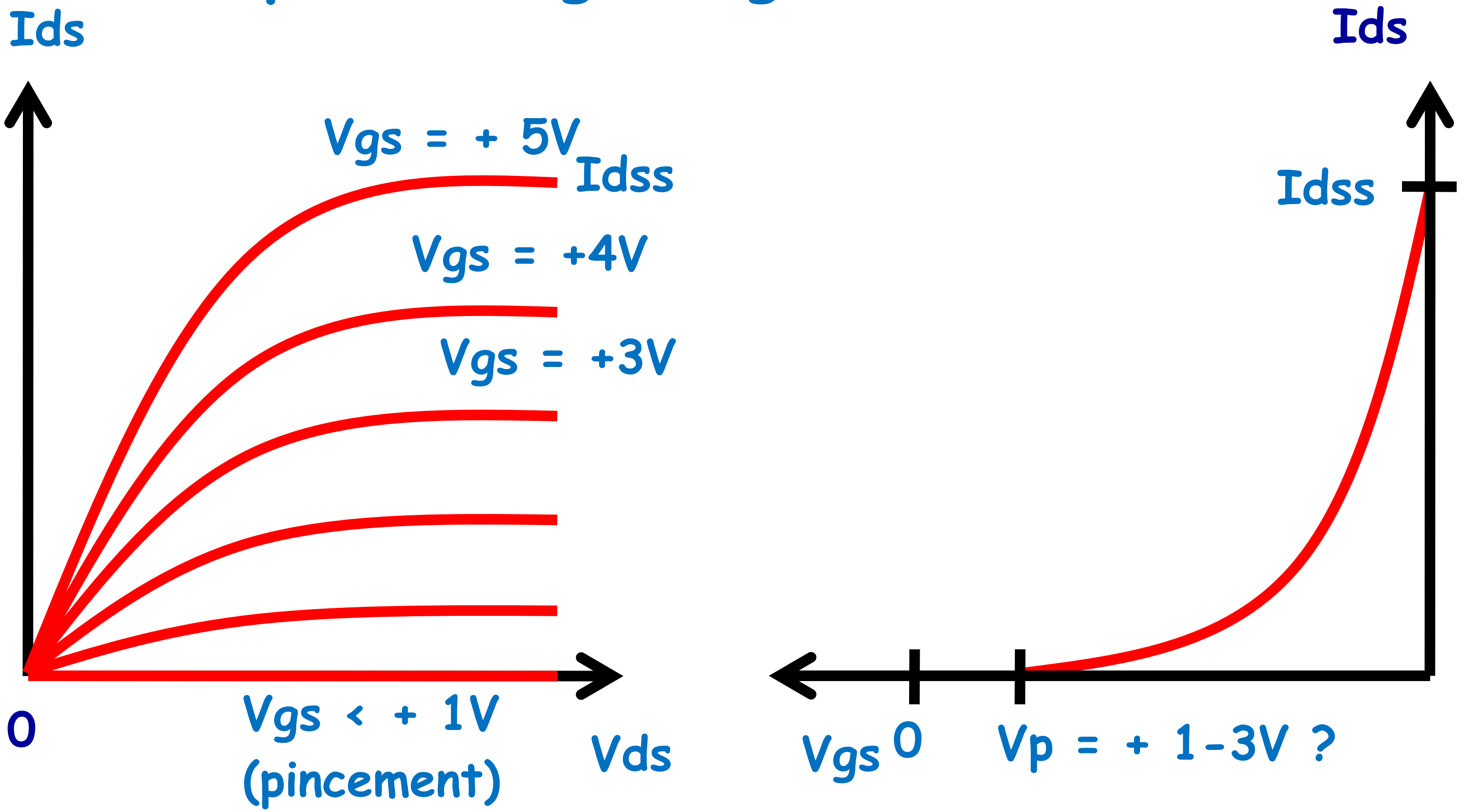
(1)
Turn to Normally OFF

(heavy work)

Modified Piezo-Electric HEMT
(Normally Off)

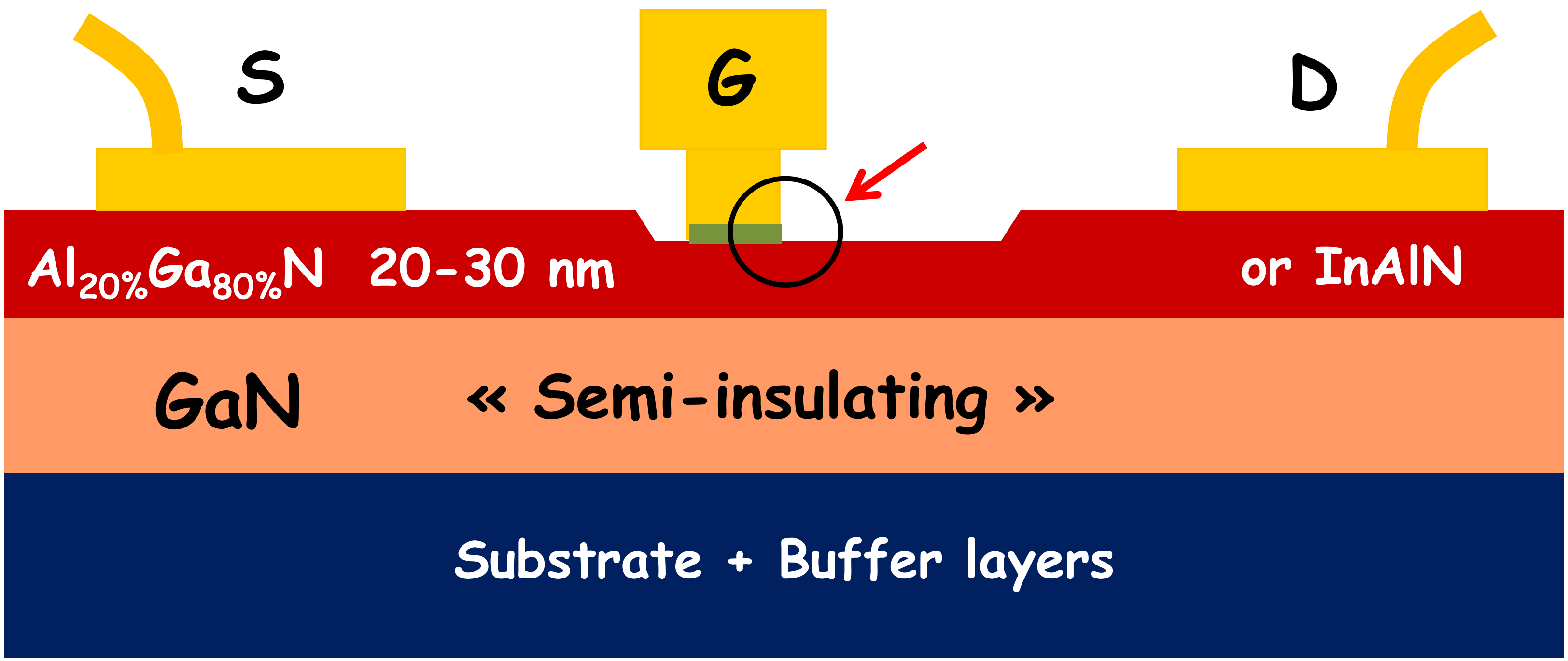


I-V characteristics of a modified III-N HEMT piezo-electric transistor adapted for getting HEMT rectifier



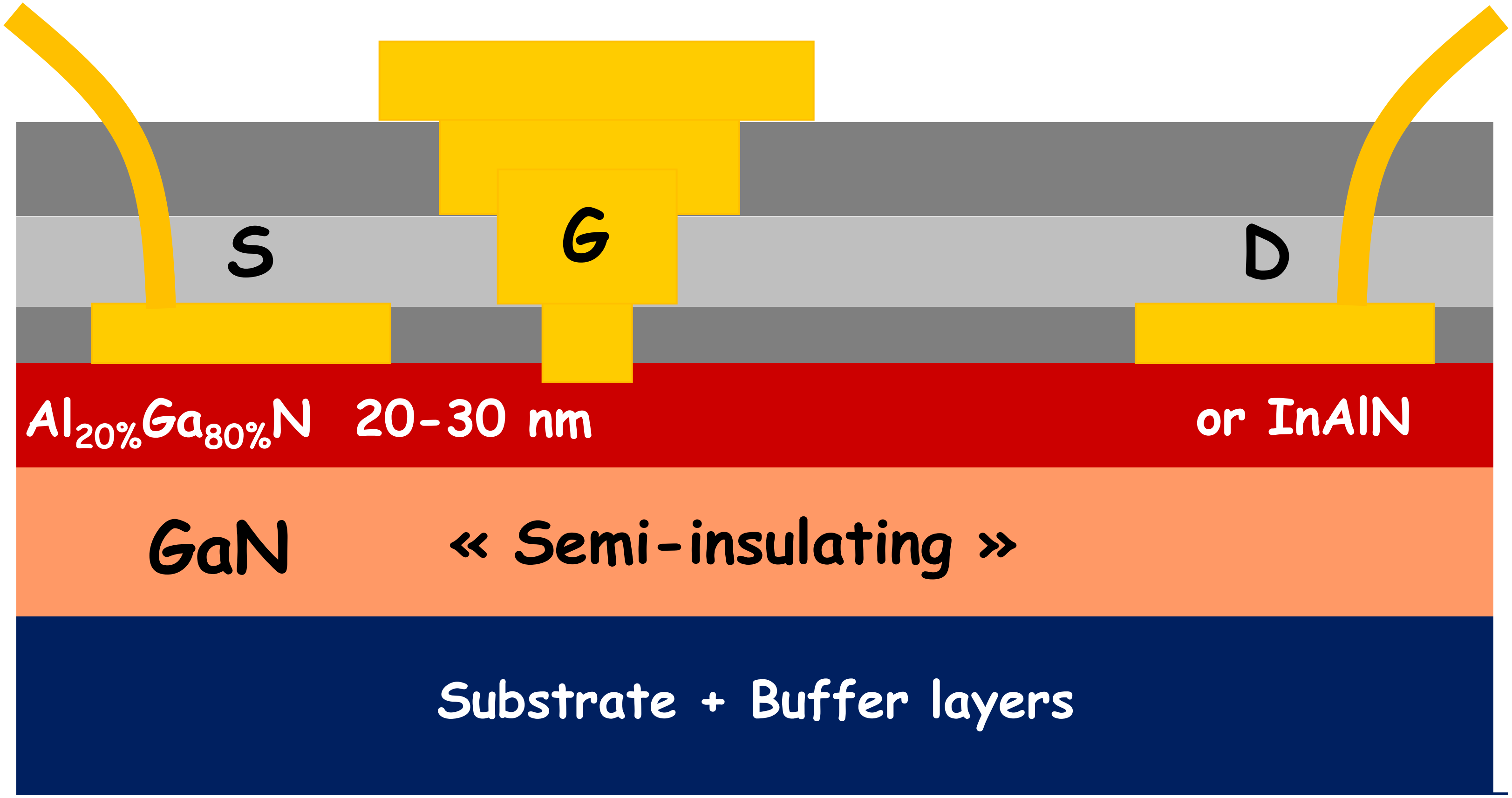
(2)
Organize
Peripheral Protection

Typical Piezo-Electric HEMT for Microwave Amplifiers : Field Concentration at Gate Edge



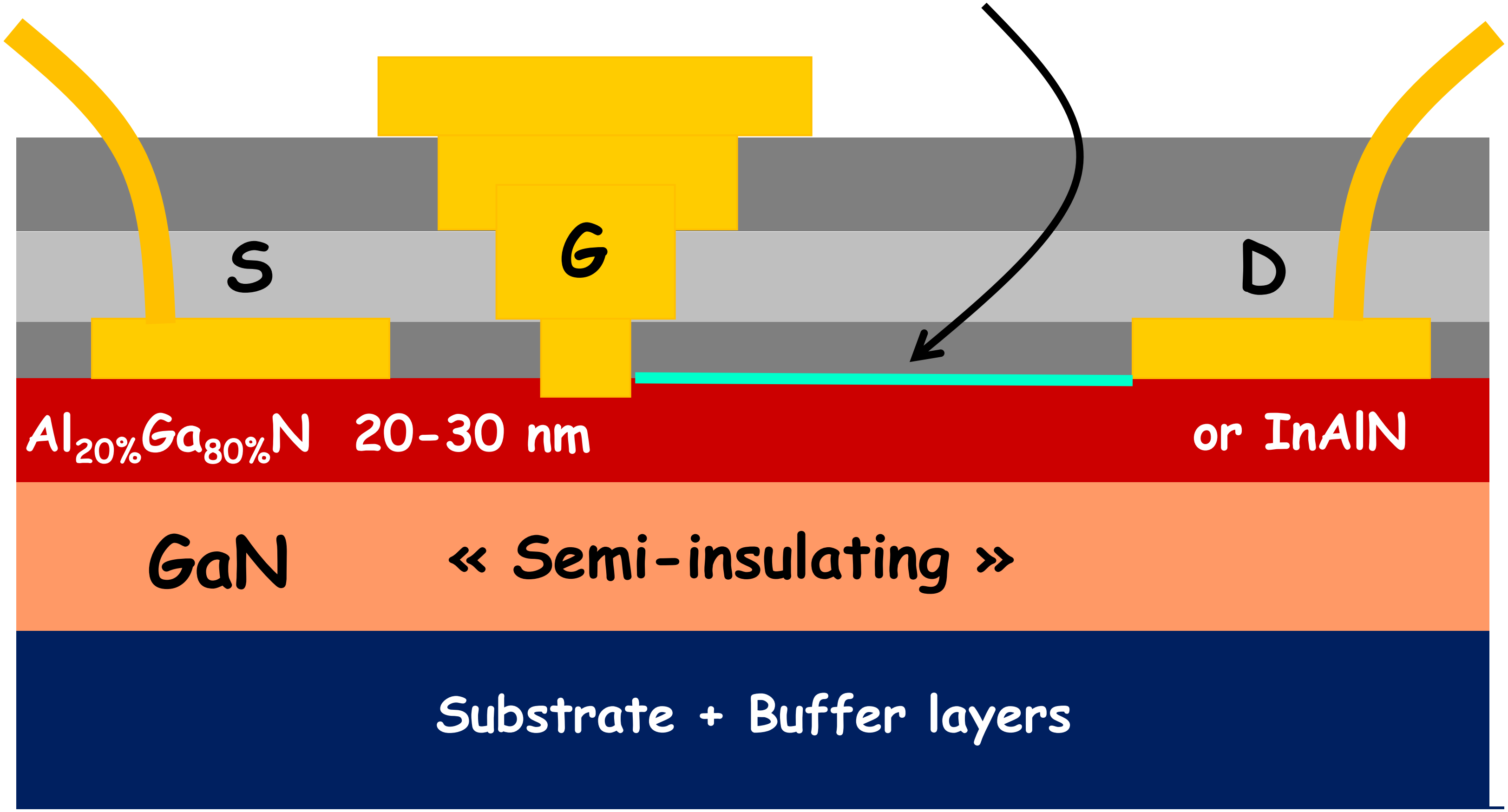
Multiple Field Plates bring Improvements for Higher Voltage Handling

> 2kV handling at best today



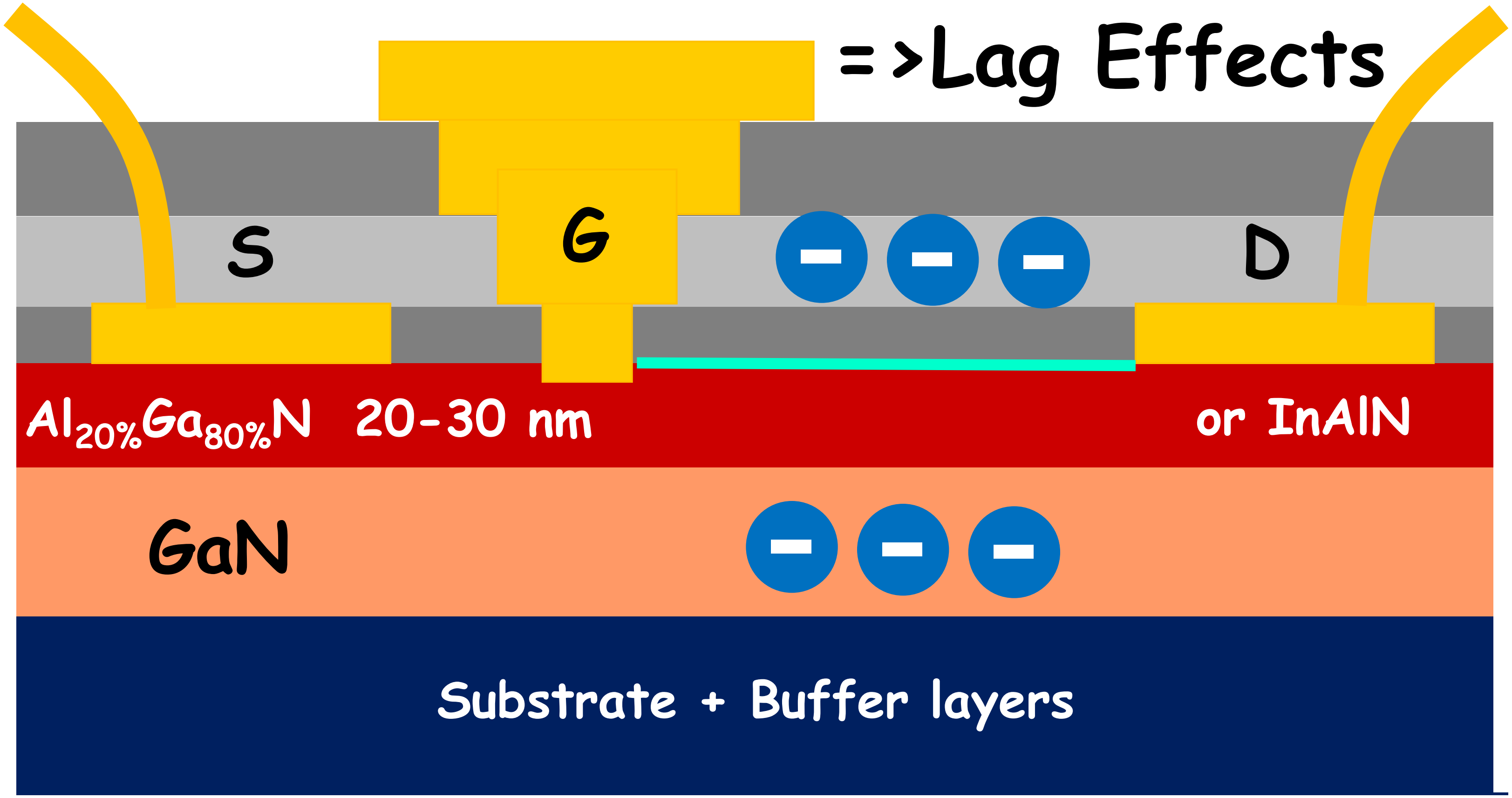
(3)
Vulnerability of III-N HEMT
as
High Voltage Switch

Vulnerability of III-N HEMT
As High Voltage Switch
The Lateral Channel



Vulnerability of III-N HEMT as High Voltage Switch

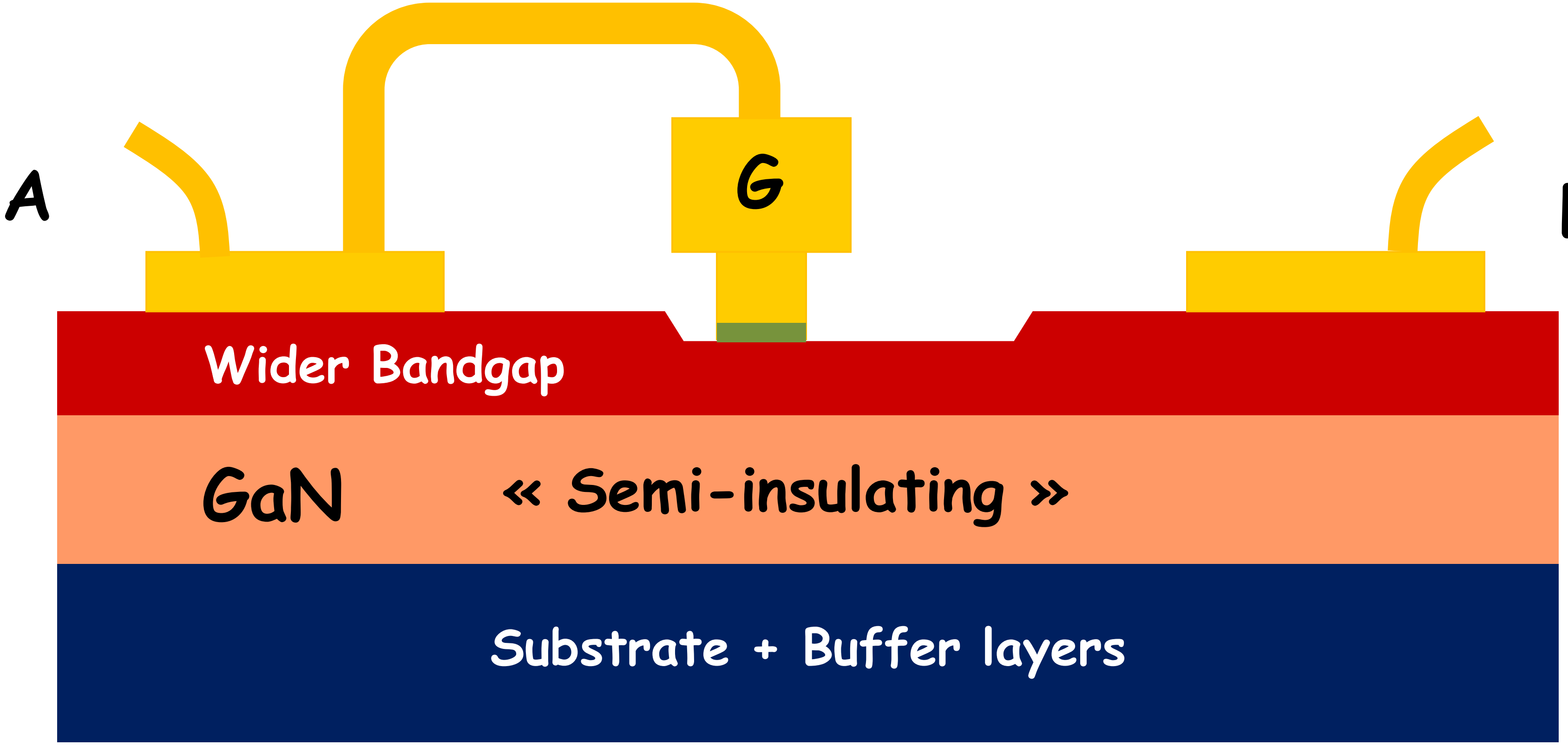
Electron Trapping in Buffer or Passivation



Tentative
Schottky Rectifier Topology

based on
III-N
Piezo-Electric HEMT
topology

First Approach : Tentative Rectifier based on N channel Normally Off FET structure

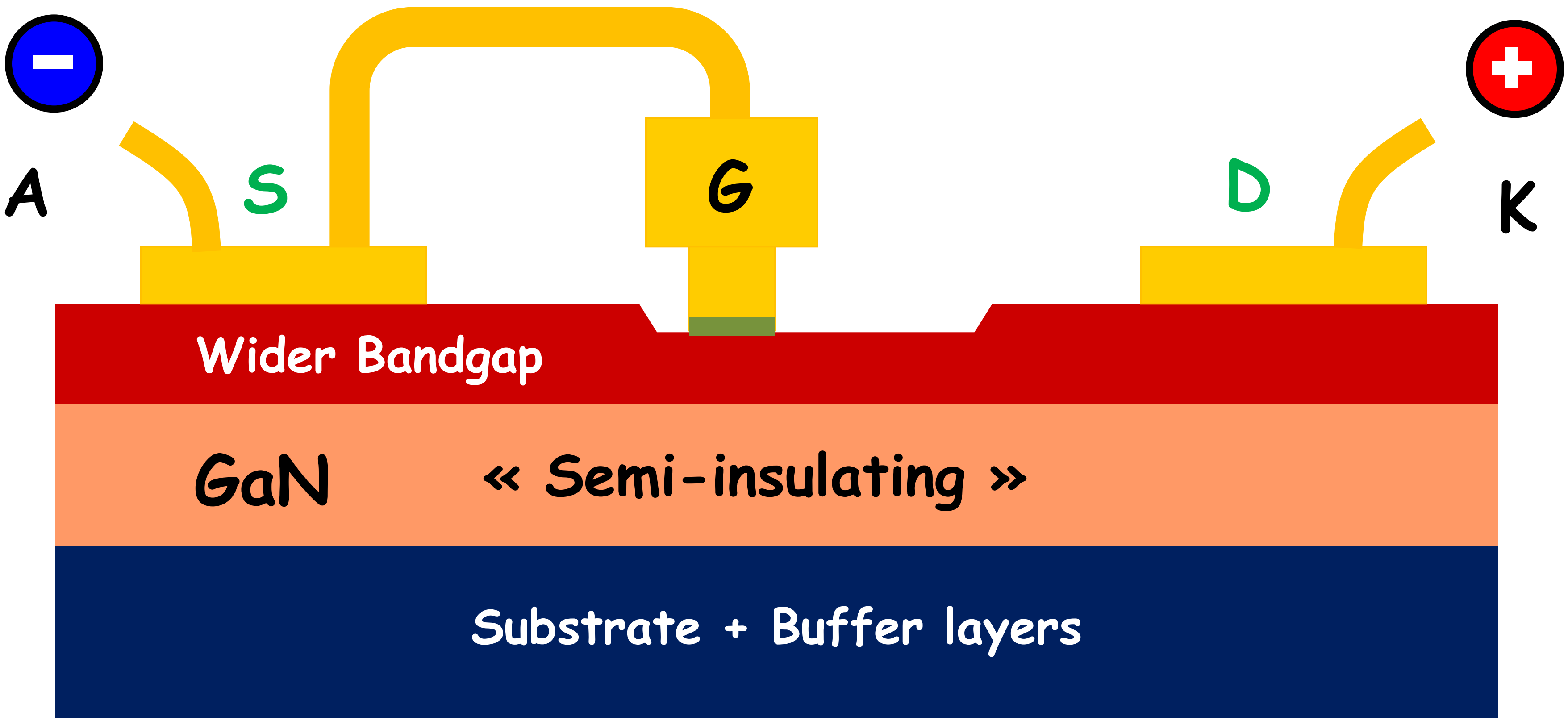


Tentative Rectifier

from a N channel Normally Off FET structure

Vgs = 0 => device « OFF »

HIGH Vth required

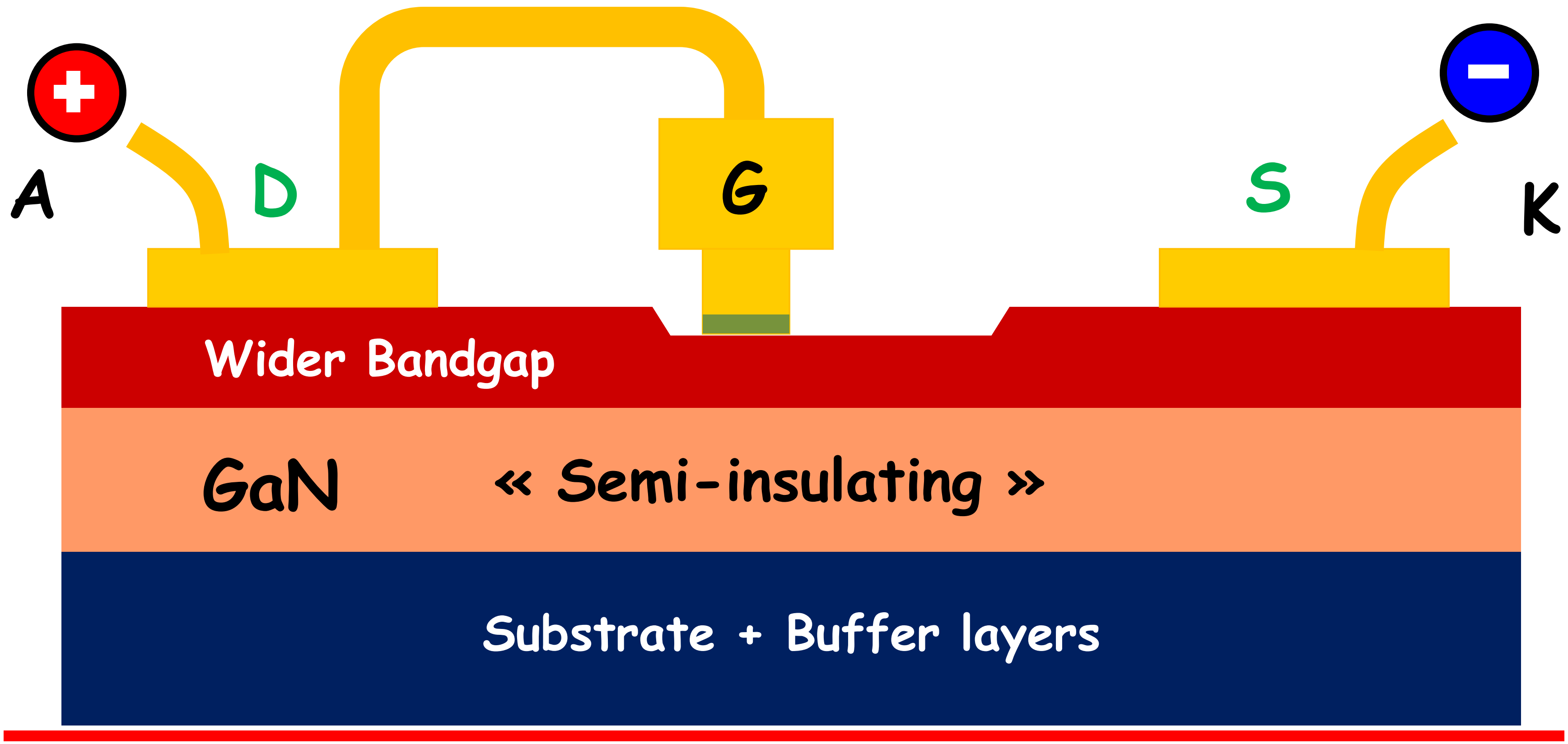


Tentative Rectifier

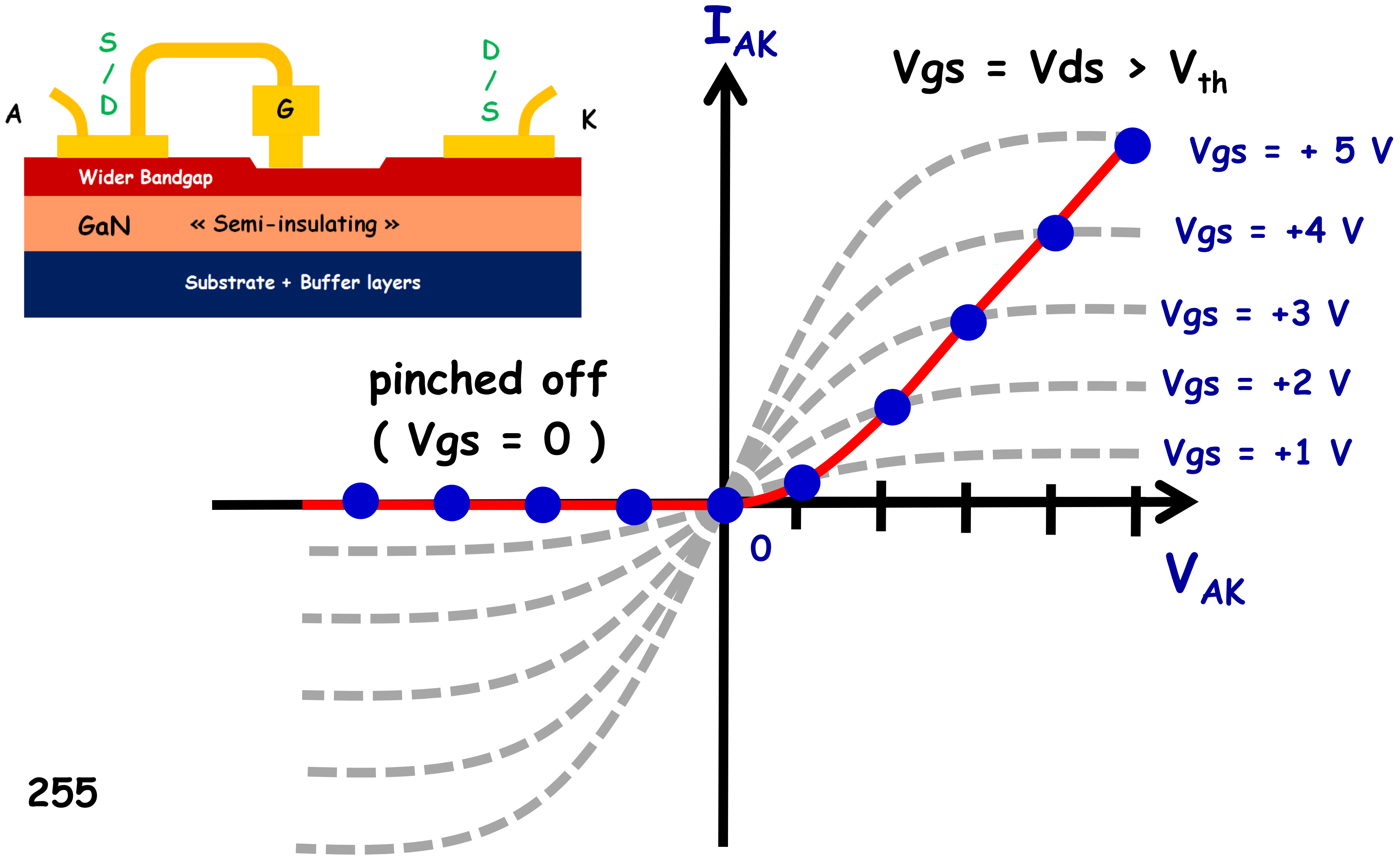
from a N channel Normally Off FET structure

Vgs > 0 => device « ON »

LOW V_{th} required



Ideal I-V characteristics of a tentative rectifier structure based on Normally OFF FET



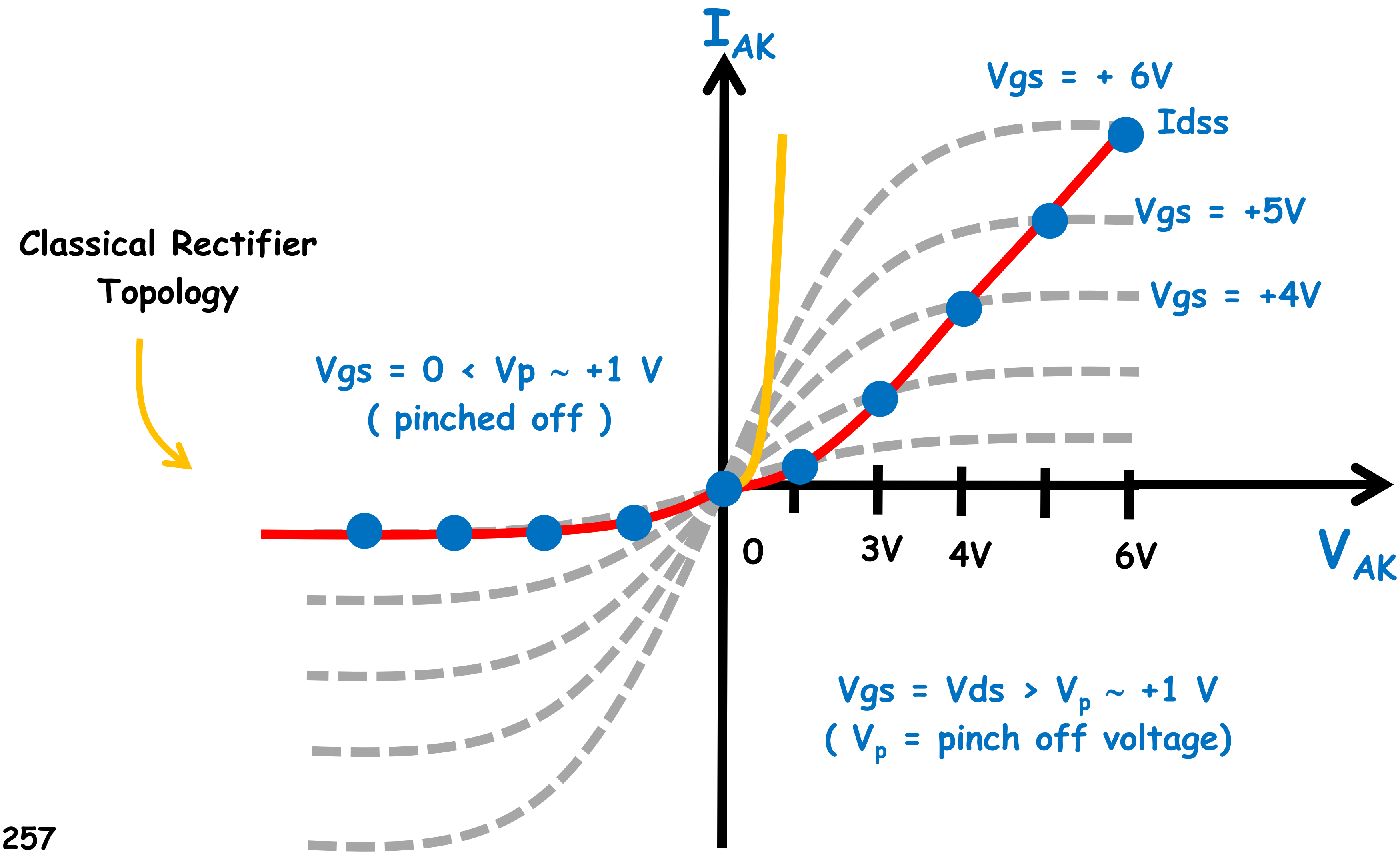
Problem : Ideal Threshold Voltage

there is no good compromise

Basically, you would have to make V_{th}
Negative AND Positive
on the same device …

I-V characteristics of a tentative piezo-electric HEMT rectifier

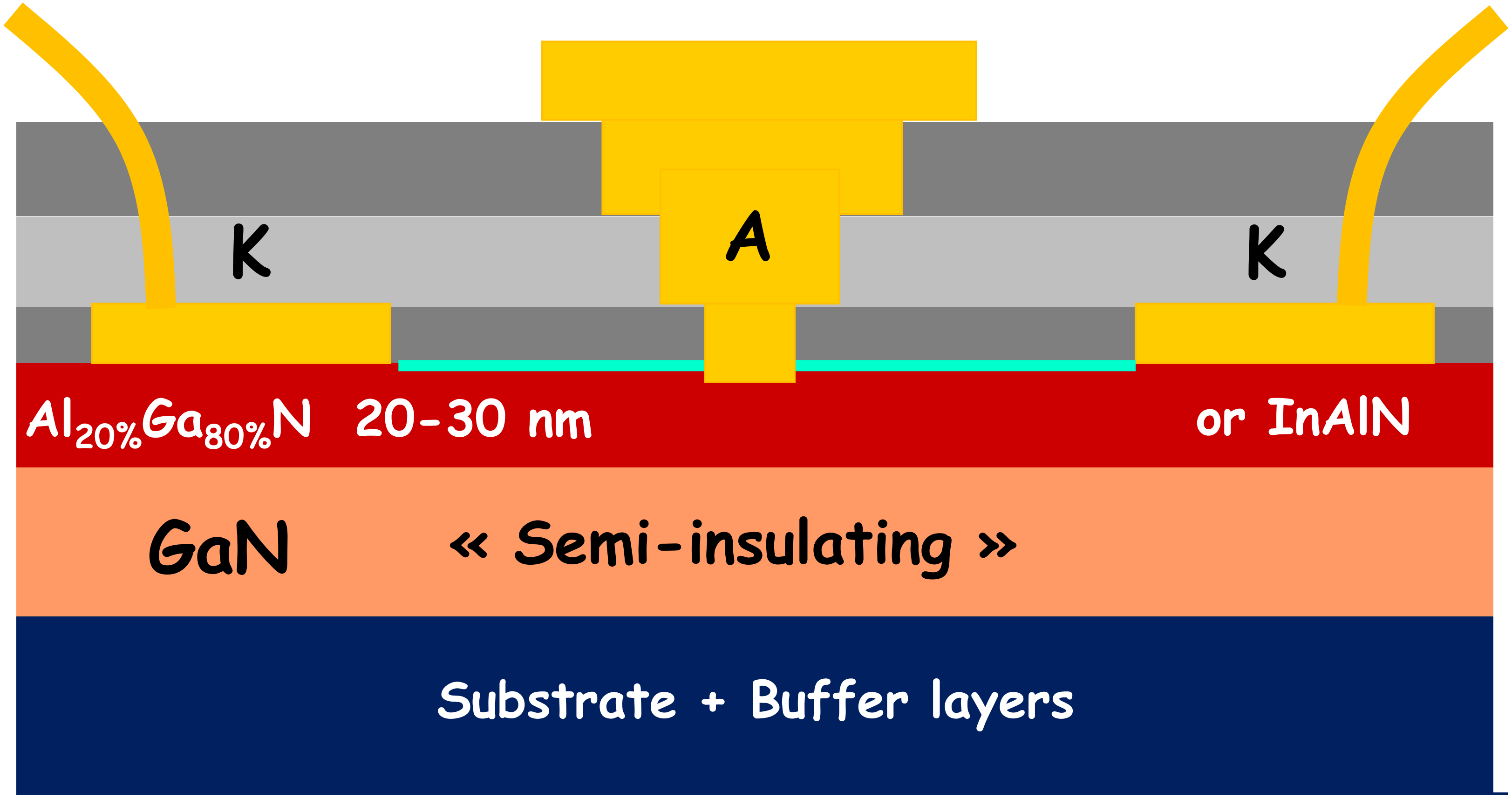
High V_{on} + High Risk of High Reverse Leakage Current



This first approach towards III-N rectifier is hopeless

Another HEMT approach towards III-N rectifiers

Second Approach : III-N rectifier using Schottky Gate Anode



Thanks for your attention !