HIGH TEMPERATURE RESISTANT MATERIALS

HIGH-TEMPERATURE ELECTRONIC

ELECTRONIC SYSTEM

Electronics system is an integration of multiple, diverse materials with specially designed functionality based on their properties

ELECTRONIC SYSTEM

Term „electronics" deals with groups of electronic circuits as well as components wich are designed to:

- build up complex measurement,
- control or power-supplying functional systems
- signal detection and processing,
- data storage and display
- computation
- power distribution, and many others

INFORMATION PROCESSING

Information processing can be realized by manipulation of voltage and electric current:

- rectification (diode, thyristor, triac)
- amplification (transistor)
- oscillation (quartz oscillator)
- switching of electronic signals (transistor)

INFORMATION PROCESSING

Information processing by means of conversion of information form:

- Optoelectronics (electric ↔ optical)
- Thermoelectric (electric ↔ thermal)
- Electromechanical (electric ↔ move)

BASIC ELEMENTS OF ELECTRONIC SYSTEM

The electronic circuit basic components:

- Resistors
- Capacitors
- Diodes
- Transistors
- Integrated circuits (ICs)

Semiconductors

BASIC ELEMENTS OF ELECTRONIC SYSTEM

Types of semiconductor devices:

- Diode (PN, Schottky)
- Transistor (pnp, npn)
- MOS Field Effect Transistor (MOSFET)
- Junction Field Effect Transistor (JFET)
- Insulated Gate Bipolar Transistor (IGBT)
- Thyristor (npnp)

SEMICONDUCTOR MATERIALS USED IN MODERN ELECTRONIC DEVICES

- Silikon (Si)
- Germanium (Ge)

SINGLE ELEMENT SEMICONDUCTORS

- Galium arsenide (GaAs)
- Indium phosphide (InP)
- Cadmium telluride (CdTe)
- Silicon-germanium alloys ($Si_XGe_{(1-X)}$)
- Alluminium gallium arsenide ($Al_XGa_{(1-X)}As$)

COMPOUNDS

SEMICONDUCTOR MATERIALS USED IN MODERN ELECTRONIC DEVICES

Silicone is dominant material due to its:

- Abundance
- Safety
- Electronic functions

MOST IMPORTANT PARAMETERS OF SEMICONDUCTING MATERIALS

- Energy band gap (E_g)
- Fermi level (E_f)
- Effective energy band density of states (N_C, N_υ)
- Intrinsic carrier concentration (n_i)
- Mobility of carriers (μn, μp)
- Electron saturation drift velocity (v_{sat})
- Carrier lifetime (τ_{HL}, τ_{SC})
- Breakdown electric field strength (E_C)

TYPES OF JUNCTION DEVELOPED FOR SEMICONDUCTOR DEVICES

- **p-n** junction (*p-type/n-type* layered structure)
- **m-s** junction (metal-semiconductor contact)
- **MOS** junction (metal-dielectric-semiconductor)

AREAS OF APPLICATION OF HIGH TEMPERATURE ELECTRONIC SYSTEMS

- Exploration nad monitoring petroleum and geothermal wells (inside the bore hole, deep in the ground temperature can reach 300°C)
- „Fly-by-wire" system sensors in civilian and military aircrafts located in „high-temperature" areas (temperature up to 300°C)
- Exploration of Solar System

HOT ENVIRONMENTS

- **Example 1:** during exploration of petroleum and geothermal wells the ambient temperature can be as high as 300°C
- **Example 2:** in military or civilian aircrafts electronics systems are working in locations where ambient temperature is greater than 300°C (close to an engine, etc.)
- **Example 3:** electric motor drivers applied in electric cars with power as high as 100kW require components with max. operating temperature close to 200°C.

ADVANTAGES OF MOUNTING ELECTRONICS CLOSE TO SENSORS/ACTUATORS

- Reduction in mass
- Saving in space
- Sharing the same cooling loop
- Reduction of component materials usage
- Reduction of the system cost and volume

HIGH-TEMPERATURE ELECTRONICS

TEMPERATURE INFLUENCE ON THE ELECTRONIC COMPONENTS PERFORMANCE

OPERATING TEMPERATURE OF MODERN ELECTRONIC SYSTEMS

Some properties of an electronic system can change to certain extent with temperature:

- Electrical
- Mechanical
- Chemical

In most cases lose of the functionalities occur before structural damage

CRITERIA FOR THE LOWEST AND THE HIGHEST TEMPERATURE LIMITS OF AN ELECTRONIC SYSTEM ARE BASED ON FUNCTIONALITY AND STRUCTURAL INTEGRITY.

HIGH TEMPERATURA IN MODERN ELECTRONIC SYSTEMS

Increase of temperature in electronic systems can be caused by:

- Hot environment
- Self heating

Raise the temperature of a component

Reduction of processing efficiency

HIGH TEMPERATURA IN MODERN ELECTRONIC SYSTEMS

- Normal operating temperature (systems comprised mostly on silicon and semiconductors): from -55 to 125°C
- High temperature electronics (HTE's) systems: >125°C

TEMPERATURE LIMITS

- Maximum known temperature of operation of discrete semiconductor devices in laboratory conditions reaches 700°C (diamond Schottky diode)
- SiC-based MOSFET transistors could operate in temperatures up to 650°C
- GaAs-based ICs can operate in temperatures as high as 400-500°C
- Si-based ICs have been reported to operate for 1000 hours in temperature of 300°C
- Passive semiconductor elements can work in temperatures as high as several hundreds of °C

PERFORMANCE IN HIGH TEMPERATURE – RESISTORS

- Thin-film/metal-film resistors (Ni-Cr, Ta2N/Ta-N, Cr-Si) can work up to about 200-250°C because of aging problems
- Thick-film resistors have good stability at high temperatures (500°C) and better aging characteristics (up to 300°C) - developed mainly for high temperature applications
- Carbon resistors - not suitable for high temperature applications

PERFORMANCE IN HIGH TEMPERATURE – CAPACITORS

- Capacitors with polymer dielectrics - use in high temperature conditions limited to about 200°C (polymer decomposition). Low influence of temperature changes on capacitance.
- Ceramic capacitors - can operate to at least 300°C. Behavior with change in temperature depends on dielectric material used.
- Electrolytic (solid electrolytic) capacitors at high temperature capacitance may increase noticeably depending on the type of electrolyte.

TEMPERATURE LIMITS OF BASIC SEMICONDUCTOR MATERIALS

Factors limiting the upper temperature limit for semiconductor devices:

- properties of the basic material (Si, GaAs, SiC, …)
- type of device (diode, bipolar transistor, field-effect transistor, …)
- design of the device (materials, geometry and dimensions)
- materials and designs of the contacts and interconnections
- assembly and packaging techniques and materials
- type of circuit (analog or digital) and the circuit design
- the particular application
- time of operation at maximum temperature

TEMPERATURE LIMITS OF BASIC SEMICONDUCTOR MATERIALS

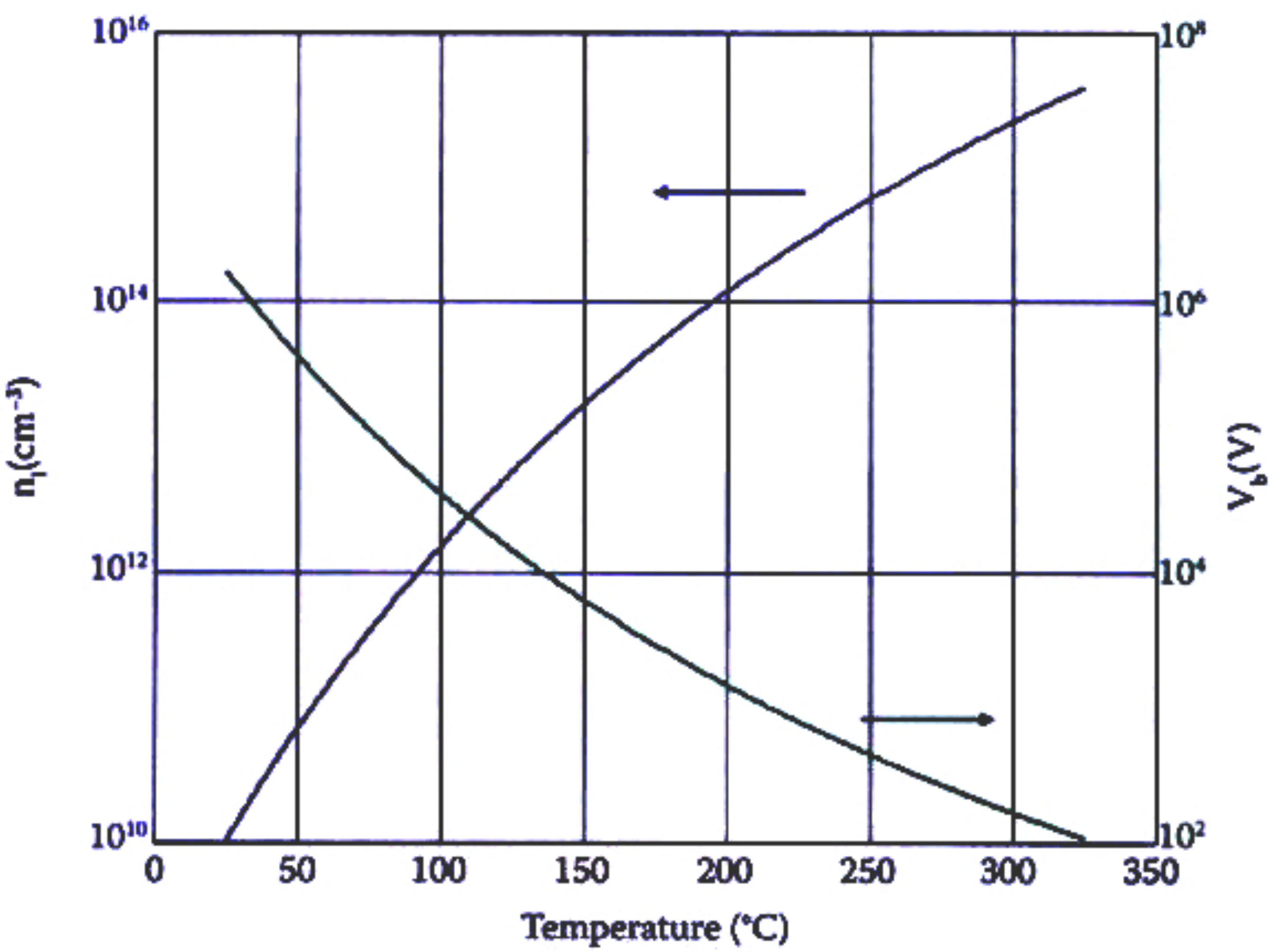
- Charge carriers (electrons and holes) movement controls the semiconductor device operation - example: *p-n* junction allows carrier movement only in one direction because of different doping on the two sides of the junction
- At sufficiently high temperatures the electrical difference between the two regions (*p* and *n*) disappears and as a consequence *p-n* junction cannot control the carriers movement
- The main effect that limits the temperature in high temperature region is leakage in *p-n* junction of a device
  - Leakage effect can be reduced by:
    - reduction of the p-n junction area
    - elimination of the junction (*silicon-on-insulator* wafers used in MOSFET transistors)

INTRINSIC CARRIER CONCENTRATION

- Intrinsic carriers: **electrons** (-) and **holes** (+)
- Carriers generated due to thermal excitation
- In semiconducting materials $n = p = n_i$
- (n – electron concentration, p – hole concentration)
- In semiconductor devices majority carriers are generated by introducing „impurity" additions (donors and acceptors)
- Concentration of carriers determined by dopant density (mostly 10^{13} to 10^{19} cm^{-3}).

THERMALLY INDUCED FAILURE

Intrinsic carrier concentration n_i and breakdown voltage vs. temperature in Si



Intrinsic carrier density:

$n_i = 10^{10}\ cm^{-3}$ at room temperature

increases exponentially with temperature

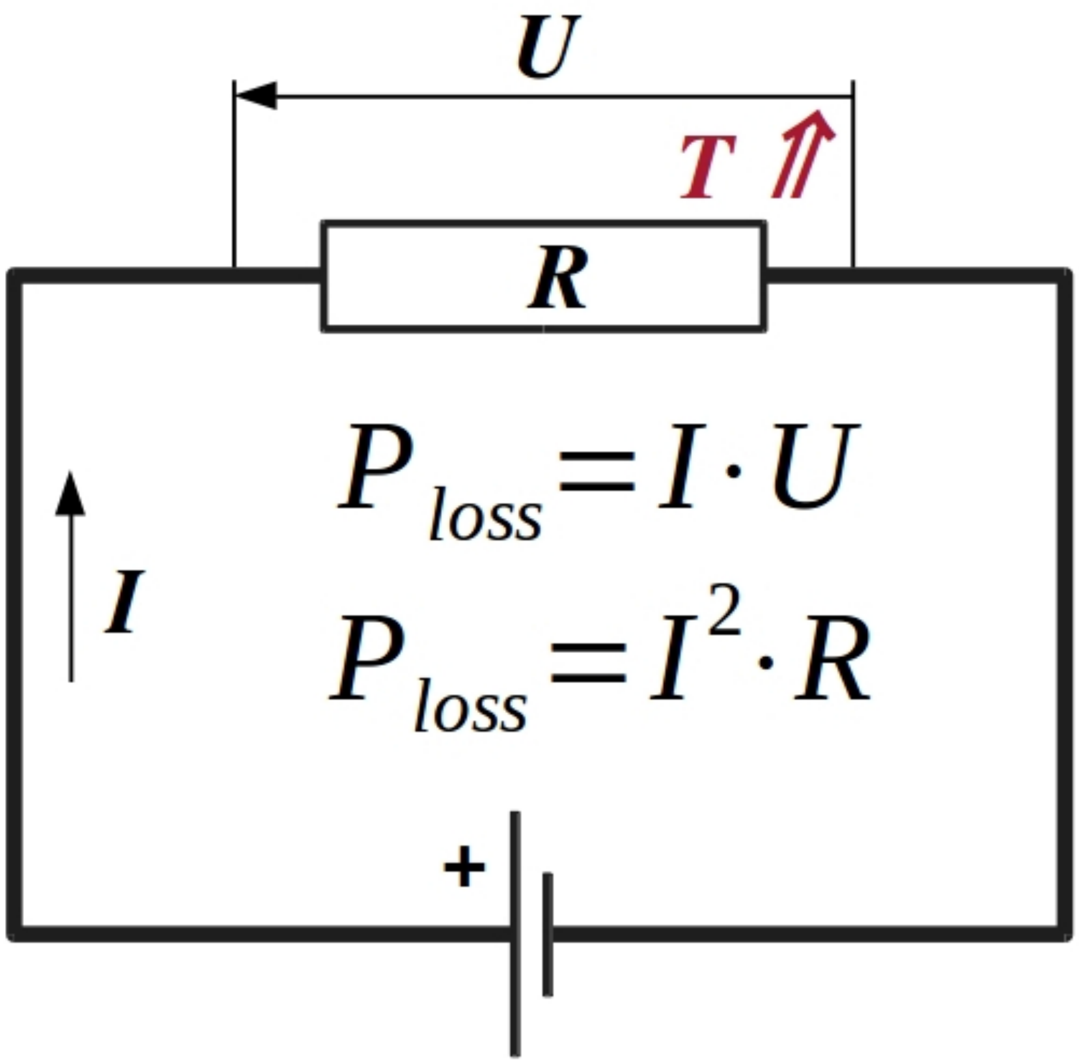
Effects:

- disappearance of carrier barriers in bipolar devices
- loss of gate control on carrier channel in field effects devices

INTERCONNECTION BETWEEN SEMICONDUCTOR MATERIAL AND OUTER WORLD

- Electrical contacts to semiconductor material are done by metallization (unwanted interactions or barriers to charge transfer)
- At high temperatures the contact may have an effect on temperature capabilities and determine upper temperature limit for the device.
- Detrimental processes at contact areas:
  - Interdiffusion
  - Electromigration
  - Restructuring (e.g. voids formation)
  - Oxidation and corrosion

ELECTRONIC COMPONENT SELF HEATING



P_{loss} – electric power loss in the component

I – electric current

V – voltage drop on the component

R – resistance

Power loss will be absorbed by components and generated heat

Heat must be removed from element to the ambient to prevent overheating and damage.

ELECTRONIC COMPONENT SELF HEATING

Cooling of the electronic components utilizes convection and/or radiation to transfer the thermal energy from the component to the ambient

Electrothermal relationship between temperature and the power loss in a component:

$$T_j = T_a + \theta_{ja} \cdot P_{loss}$$

T_j – max. operating temperature of the core element in a component

T_a – ambient temperature of an electronic subsystem (usually a baseline temperature of the cooling system

θ_{ja} – thermal characteristics of both the package and thermal management system

P_{loss} – electric power loss in the component

Si TEMPERATURE-RELATED PARAMETERS

Temperature Dependence of Si Electrical Properties and Device Parameters

Serial Number Electrical Parameter	Formula	Parameter Value @25°C (T_0)	Parameter Value @125°C	Parameter Value @200°C
1. Energy bandgap	$Eg = 1.18\text{-}9 \times 10^{-5}(T_j)\text{-}3 \times 10^{-7}(T_j)^2$	1.12 eV	1.09 eV	1.06 eV
2. Intrinsic carrier concentration	$n_i = (N_c N_V)^{1/2} \cdot \exp(\text{-}Eg/2kTj)$ $= 1.042 \times 10^{15}(T_j)^2 \exp(\text{-}6884/T_j)$	$1.01 \times 10^{10} \times cm^{-3}$	$5.59 \times 10^{12} \times cm^{-3}$	$1.19 \times 10^{14} \times cm^{-3}$
3. Electron mobility	$\mu_n = 1500(T_0/T_j)^{2.5}$	1500 $cm^2/V \cdot s$	739.92 $cm^2/V \cdot s$	475.51 $cm^2/V \cdot s$
4. Electron mobility near surface	$\mu_{ns} = 400(T_0/T_j)^{2.5}$	400 $cm^2/V \cdot s$	197.31 $cm^2/V \cdot s$	126.80 $cm^2/V \cdot s$
5. Hole mobility	$\mu_p = 450(v/T_j)^{2.5}$	450 $cm^2/V \cdot s$	221.98 $cm^2/V \cdot s$	142.65 $cm^2/V \cdot s$
6. Electron diffusion coefficient	$Dn(T_j) = \mu_n k T_j/q$ $= 2.0187 \times 10^5(T_j)^{-1.5}$	38.8572 cm^2/s	25.23 cm^2/s	19.50 cm^2/s
7. Hole diffusion coefficient	$Dp(T_j) = \mu p k T_j/q$ $= 6.0561 \times 10^4(T_j)^{-1.5}$	11.66 cm^2/s	7.57 cm^2/s	5.85 cm^2/s
8. Ambipolar diffusion coefficient	$Da(T_j) = 2Dn(T_j)Dp(T_j)/$ $(Dn(T_j) + Dp(T_j))$ $= 9.3171 \times 10^4(T_j)^{-1.5}$	17.93 cm^2/s	11.65 cm^2/s	8.9972 cm^2/s
9. Ambipolar (high-level) lifetime	$\tau_{HL}(Tj) = \tau_{HL0}(T_j/T_0)^{1.5}$ $= 1.9245 \times 10^{-4}(T_j)^{1.5}\ \tau_{HL0}$	0.9 μs	1.385 μs	1.793 μs
10. Built-in potential	$Vbi = (kT/q)\ln(N_A N_D/n_i^2)$ $= V0\text{-}2.1\ mV/(Tj\text{-}T_0)$	700 mV	490 mV	332.5 mV
11. PN junction reverse current	$Jr = a\ ni^2 + b\ ni/\tau_{sc}$ $= Jro.2^{(T-T0)/11}$	1 μA	545 μA	61,147 μA
12. PN junction breakdown voltage	$Vbr = Vbr0(1 + 0.001/K)$	1000 V	1100 V	1175 V
13. Threshold voltage	$V_{TH}(T_j) = V(T_0)\text{-}0.009(T_j\text{-}T_0)$	4 V	3.1 V	2.43 V
14. Thermal conductivity	$\kappa = \kappa_0(T_0/T)^{1.3}$	1.56 $W/cm \cdot K$	1.07 $W/cm \cdot K$	0.86 $W/cm \cdot K$

THERMAL MANAGEMENT IN ELECTRONIC SYSTEMS

- Forced air/liquid cooling (high efficiency)
- Remotely located from high temperature region electronics systems
- Actively cooled with air or liquid coolant pumped from a distant
- **Disadvantages:**
  - long wires,
  - large number of connectors and/or cooling system plumbing
  - gain in the mass and complexity of the system

HIGH TEMPERATURE RESISTANT MATERIALS

THERMALLY INDUCED FAILURES

THERMALLY INDUCED FAILURES

Temperature influences on performance of electronic devices

Most semiconductor parameters will change with temperature

Forms of thermally induced failure of semiconducting materials:

- Degradation caused by chemical reactions
- Uncontrolled increase in intrinsic carrier concentration
- Leakage current

DEGRADATION DUE TO CHEMICAL REACTION

Arrhenius model of thermally induced degradation of electronic components. R describes the chemical reaction rate of degradation:

$$R = A \cdot e^{\left(\frac{-E_a}{R \cdot T}\right)}$$

E_a quantifies the minimum amount of energy needed to allow a certain chemical reaction to occur.

The failure modes with smaller E_a will occur easily.

Temperature will accelerate the chemical reaction => quick degradation.

E_a – activation energy (eV)

k – Boltzmass's constant

T – absolute temperature (K)

The lifetime of a semiconductor device drastically decreases with elevated operation temperature. Therefore, an operating temperature limitations are introduced based on reliability (lifetime) requirements.

DEGRADATION DUE TO CHEMICAL REACTION

Typical failure mechanisms and corresponding activation energy values within conventional Si devices

Main Failure Mechanisms and Activation Energy Values (Examples)

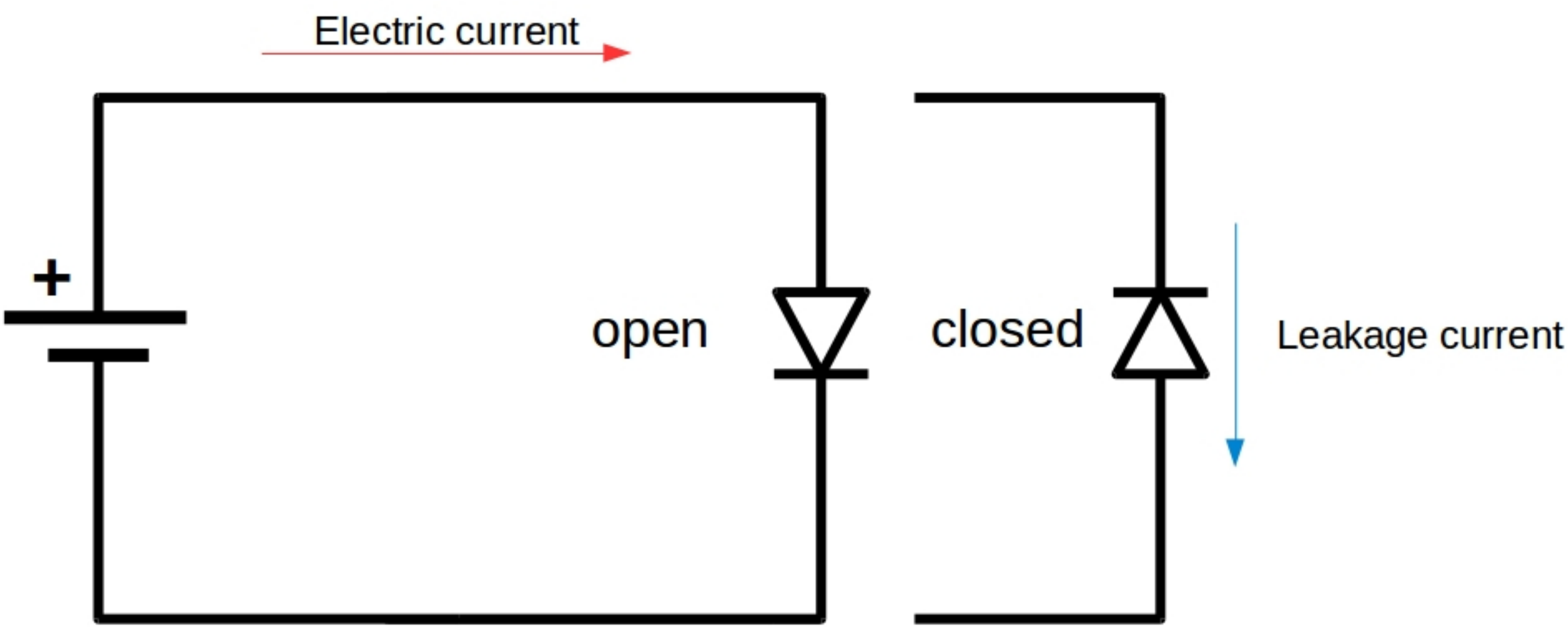
Failure Mode	Failure Mechanism	Activation Energy (eV)
Metal trace failure (open, short, corrosion)	Al metal electromigration	0.4–1.2
	Al metal stress migration	0.5–1.4
	Au–Al alloy growth	0.85–1.1
	Cu metal electromigration	0.8–1.0
	Al corrosion	0.6–1.2
Oxide film breakdown (leakage current increase, short circuit)	Oxide film breakdown	0.3–0.9
h_{FE} degradation	Ion movement acceleration due to moisture	0.8
Parameter value fluctuation	Degradation by NBTI	0.5 and up
	Na ion drive in SiO_2	1.0–1.4
	Slow trapping of Si–SiO_2 interface	1.0
Increased leakage current	Inversion layer formation	0.8–1.0

THERMALLY INDUCED FAILURE

In some cases:

- increase of temperature can have positive influence on the device's performance
- In Si-based rectifier diodes voltage drop decreases with temperature
- Outcome: lower power loss

LEAKAGE CURRENT

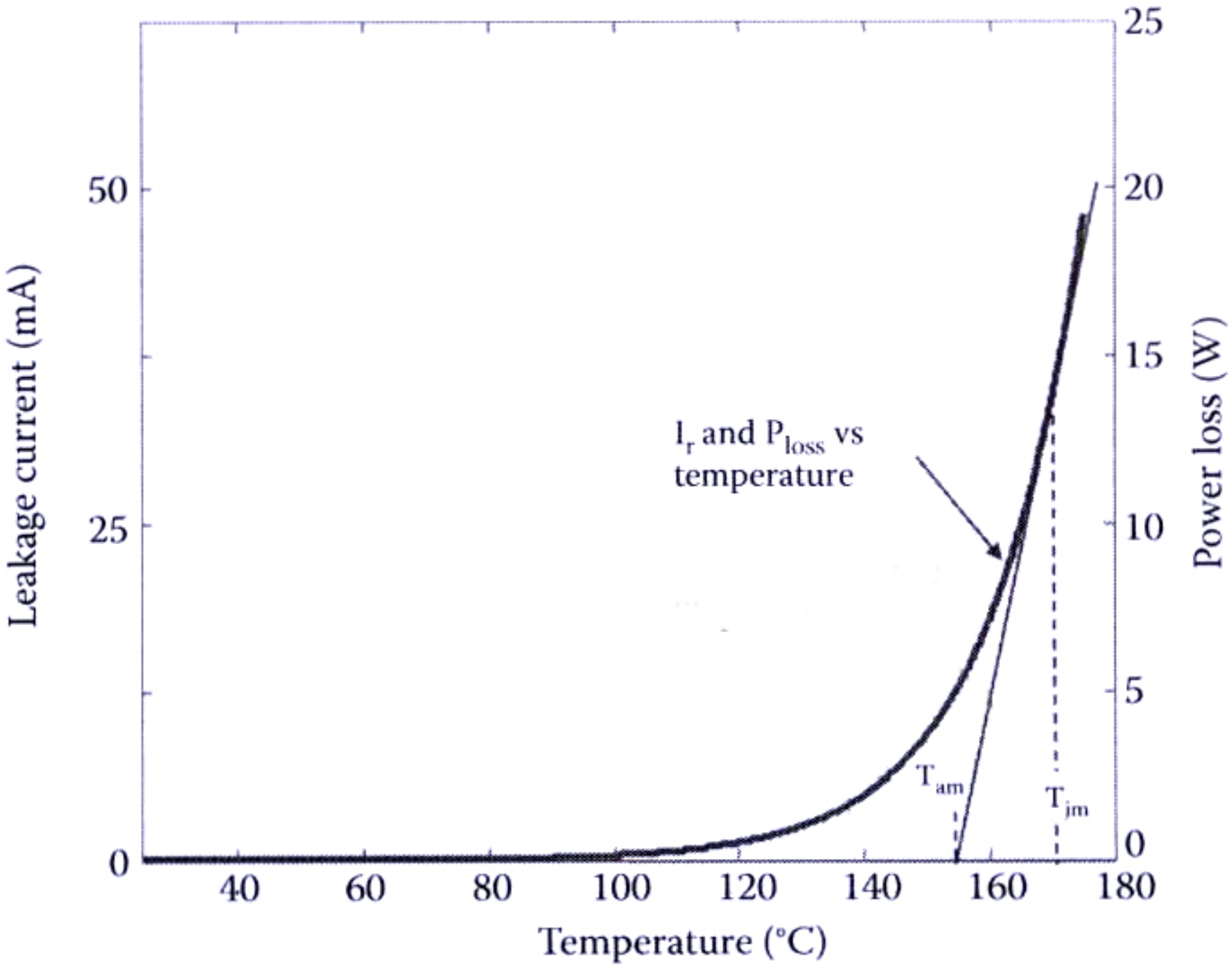


p-n junction diode works like electric one-way valve

LEAKAGE CURRENT

- Leakage current increases dramatically with temperature
- Leakage current double in magnitude with temperature rise of every 10 degrees.
- Power loss is large enough to heat up the device itself
- As the temperature increase the device is getting hotter which again leads to further increase of leakage current
- Unless heat is constantly removed, the device will be destroyed
- Thermal instability phenomenon called „thermal runaway"

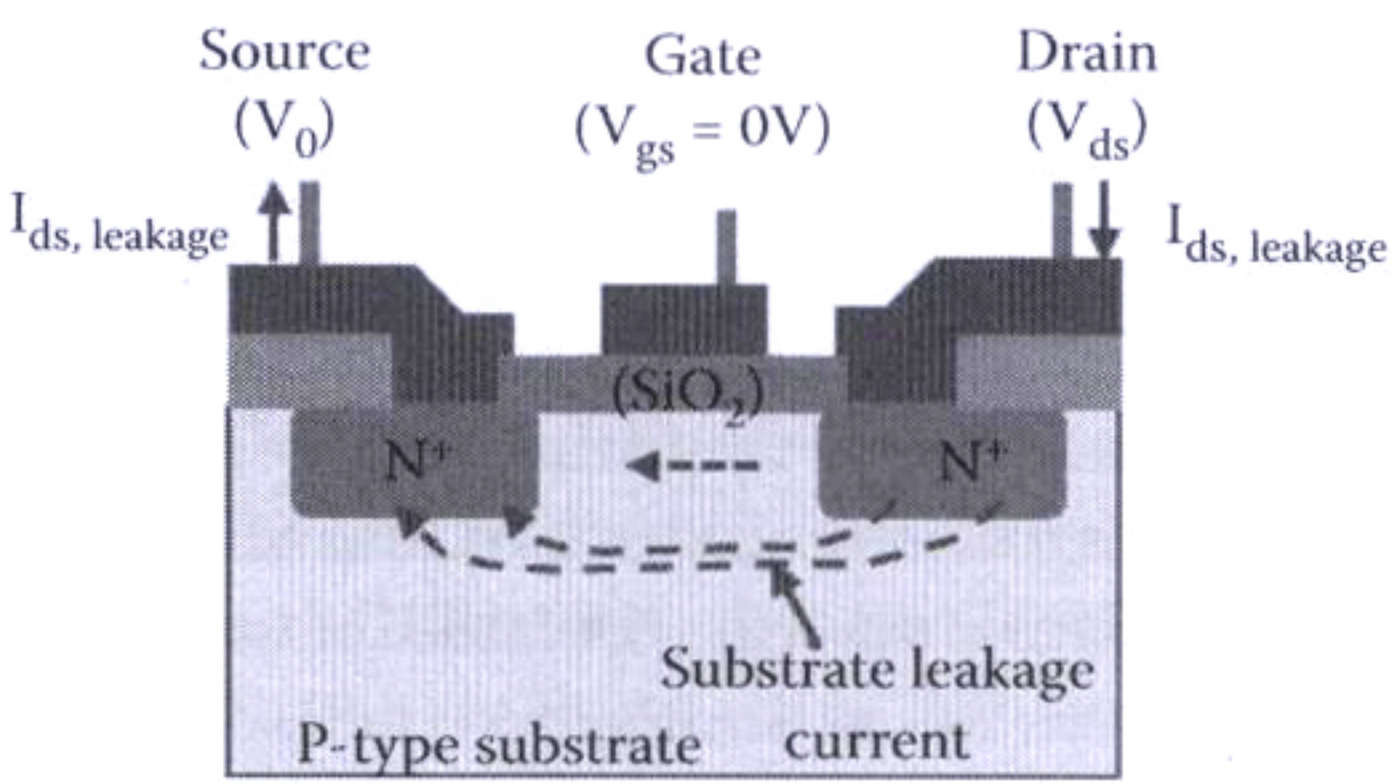
LEAKAGE CURRENT

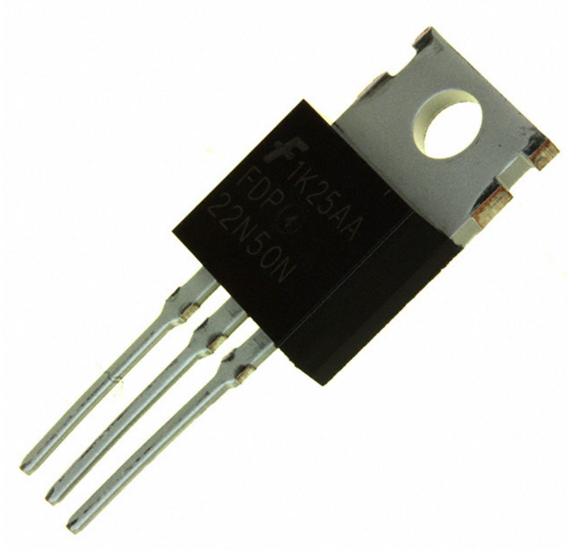


Power loss in *p-n* Si diode induced by leakage current.

LEAKAGE CURRENT

Problem: temperature-driven leakage current in MOSFET transistor structure



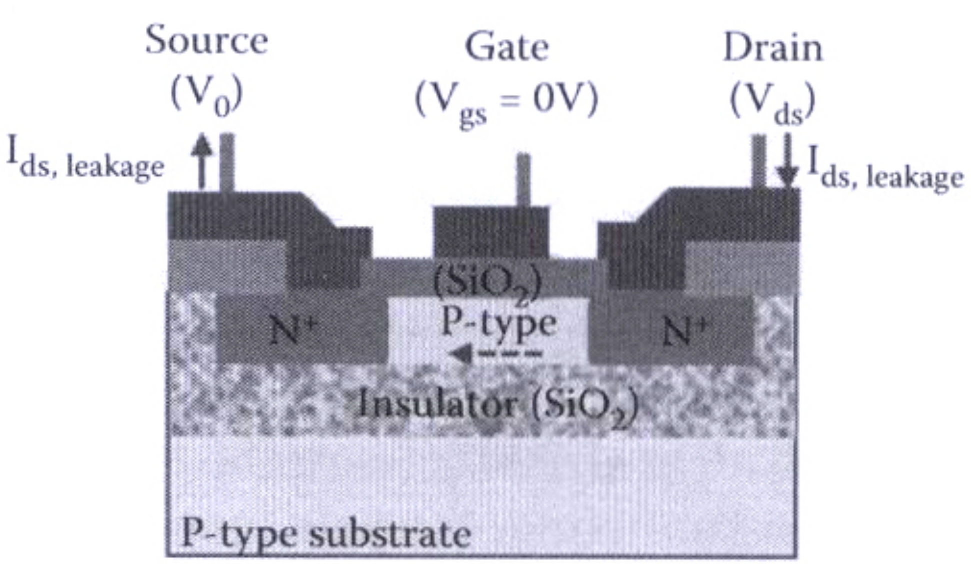


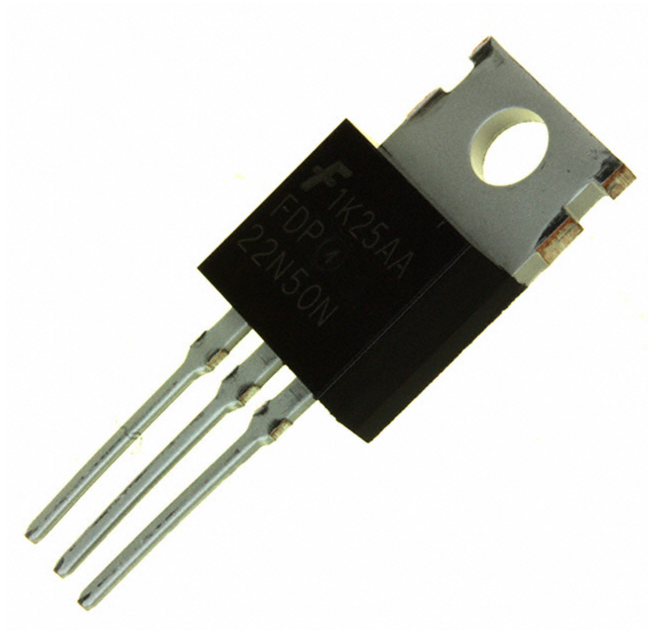
Source: https://dmohankumar.files.wordpress.com/2011/08/mosfet-2.jpg?w=100&h=100

Limitation in operational range of temeratures of MOSFET-based electronics

LEAKAGE CURRENT

Overcome of the problem: additional insulation in the transistor structure; new transistor structure called "Semiconductor On Insulator" (SOI)





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Result: increase in maximum operational temperature to over 200°C

ALTERNATIVE HIGH-TEMPERATURE SOLUTIONS

- New class of high temperature materials (Wide Energy Bandgap, WBG)
- For high power, high-temperature semiconductor switches
- Made of silicon carbide (SiC) and gallium nitride (GaN)
- Energy band gap up to 5 times higher than for Si
- 7 times higher breakdown electric field
- 15 orders lower intrinsic carrier concentration in WBGs at room temperature
- Reduction of leakage current by tens of order of magnitude
- <u>Electric properties strongly dependent over temperature</u>

ALTERNATIVE HIGH-TEMPERATURE SOLUTIONS

- Although some limits existing in SiC-based semiconductors, the combination of necessary material properties can meet the demanding high-temperature and high-power application requirements

- After special design, the new junction structures can have low reverse leakage at temperatures up to 600°C

- Still some technical challenges are to be overcome

REFERENCES

1. Bar-Cohen, Y., 2014, High temperature materials and mechanisms,CRC Press, Taylor & Francis Group

2. http://www.extremetemperatureelectronics.com

THANK YOU FOR THE ATTENTION

THE END