Welcome !

INDO-GERMAN WINTER ACADEMY 2005

COURSE 3: SEMI-CONDUCTORS

FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

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FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

OUTLINE

- Outline
- Ferro electricity
- Properties of Ferroelectrics
- Material & Device designing
- Dielectric Capacitors
- Ferroelectric Memories
- Pyroelectric Devices
- Piezoelectric Devices
- Electro optic Devices
- PTC Materials & Devices
- Composite Materials
- Summary

FERROELECTRICITY

- Electric Polarization
  - Electronic Polarization [THz-PHz]
  - Ionic Polarization [GHz-THz]
  - Dipole Reorientation [MHz-GHz]

- Ferroelectric materials with permanent dipoles cannot be used for microwave dielectric materials.
- Ferroelectric: Spontaneous polarization can be reversed by an electric field.

- Dielectric
  - Piezoelectric
  - Pyroelectric
  - Ferroelectric

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FIELD INDUCED STRAIN

- **Electric Field Induced Strain:** Deformation caused in insulating materials by application of electric field.

Electrostriction	Converse Piezoelectric Effect
Secondary electromechanical coupling effect.	Primary electromechanical coupling effect.
$x = M*E^2$	$x = d*E$

ELECTRO-OPTIC EFFECT

- Electric field of light electronically polarized, thus $\varepsilon = n^2$
- When an external electric field is applied to the crystal, ion displacement is induced, deforming the shape of the electron cloud, and consequently the refractive index is changed. This is called **Electro-optic effect.**

GRAIN SIZE DEPENDENCE OF FERROELECTRICITY:

- Below critical particle/ grain size, the material ceases to be ferroelectric (i.e. becomes paraelectric.

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APPLICATIONS OF FERROELECTRICS

APPLICATION	PHYSICAL PROPERTY UTILIZED
Capacitor Dielectrics	Peak dielectric cons –tant around Curie temperature.
Memory Applications	Material must be ferroelectric at room temperature.
Pyroelectric Sensors	A large temperature dependence of spon-taneous polarization below Tc.
Electrooptic devices	Electrooptic property
PTC thermistors	Positive temperature coefficient of semi-conductor ferroelectric ceramics.

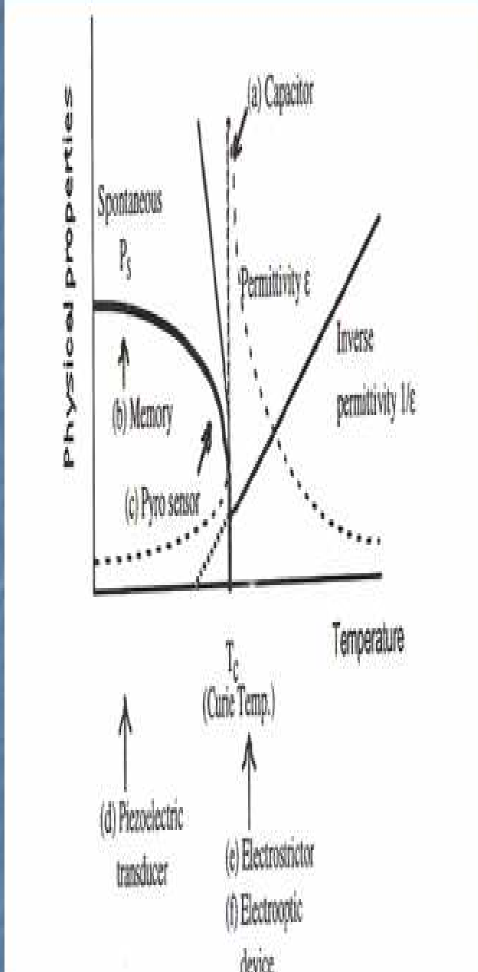

Fig. 1.12 Temperature dependence of the spontaneous polarization and permittivity in a ferroelectric material. (a) - (f) indicate the temperature ranges for each application. In other words, if we can shift such temperature range closer to room temperature, a practical material is obtained.

FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

MATERIAL DESIGNING :

- **Critical Factors in Material Designing :**
  - Composition Selection
  - Dopant Effects on Ferroelectricity
  - High Power Characteristics

Doping Effects on Ferroelectricity in PZT:

Acceptor: Domain Pinning -> " hard " piezoelectricity

Donor: Pb deficiency compensation -> " soft " piezoelectricty

- **Fabrication of Ceramic Powders :**

  1] Preparation of Ceramic Powders
  - Solid State Reaction
  - Coprecipitation
  - Alkoxide Hydrolysis
  - Oxide-mixing technique

  2] Sintering Process

  3] Single Crystal Growth

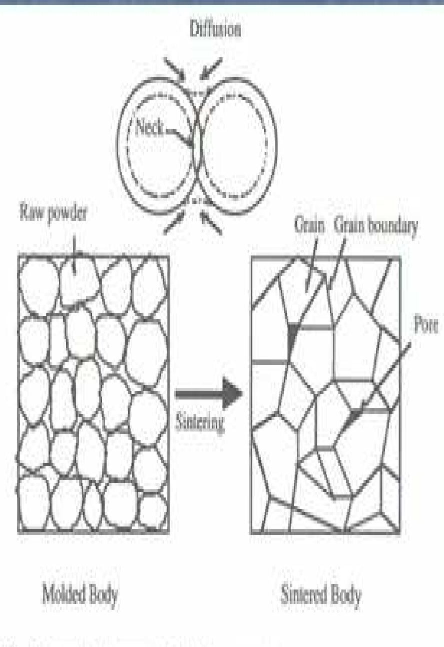

Fig. 3.12 Schematic diagram of sintering process.

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DEVICE DESIGNING :

1] Single Disks

2] Multilayers

  -Cut & bond method   - Tape-casting method

3] Bimorphs/ Moonies

4] Flexible composites

5] Thin/ Thick films

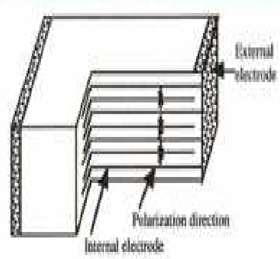

Fig. 3.15 Structure of a multilayer actuator.

Fig. 3.16 Fabrication process for a multilayer ceramic actuator.

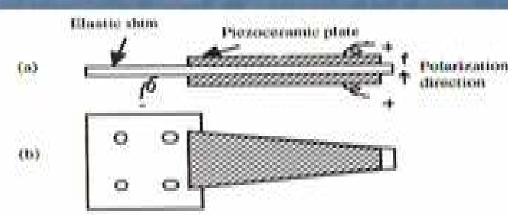

Fig. 3.18 Fundamental structure of a piezoelectric bimorph.

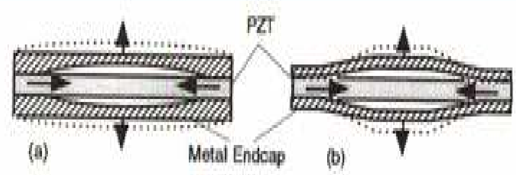

Fig. 3.21 Structures of a Moonie (a) and a modified Moonie (Cymbal) (b).

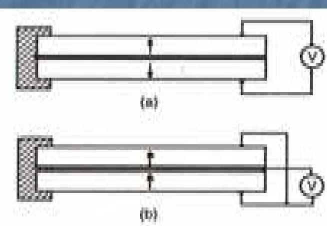

Fig. 3.19 Two types of piezoelectric bimorphs: (a) the anti-parallel polarizatio[n] type and (b) the parallel polarization type.

DEVICE DESIGNING (contd.) :

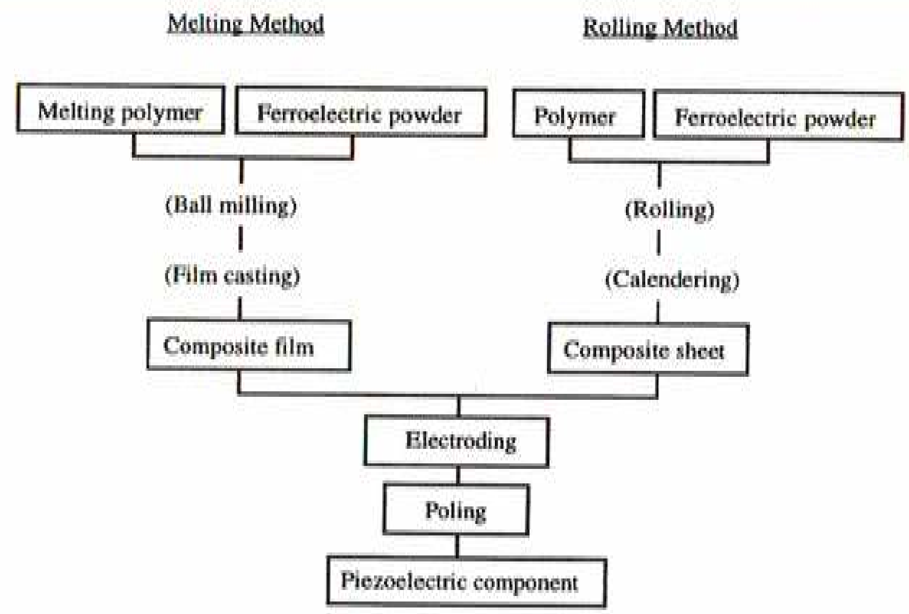

Fig. 3.23 Fabrication process for PZT: polymer composites.

Techniques for fabrication of oxide thin films:

a) Physical Processes:
- Electron beam evaporation
- RF sputtering, DC sputtering
- Ion beam sputtering
- Ion plating

b) Chemical Processes:
- Sol-gel method
- Chemical vapour deposition
- MOCVD
- Liquid phase epitaxy

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CERAMIC CAPACITORS :

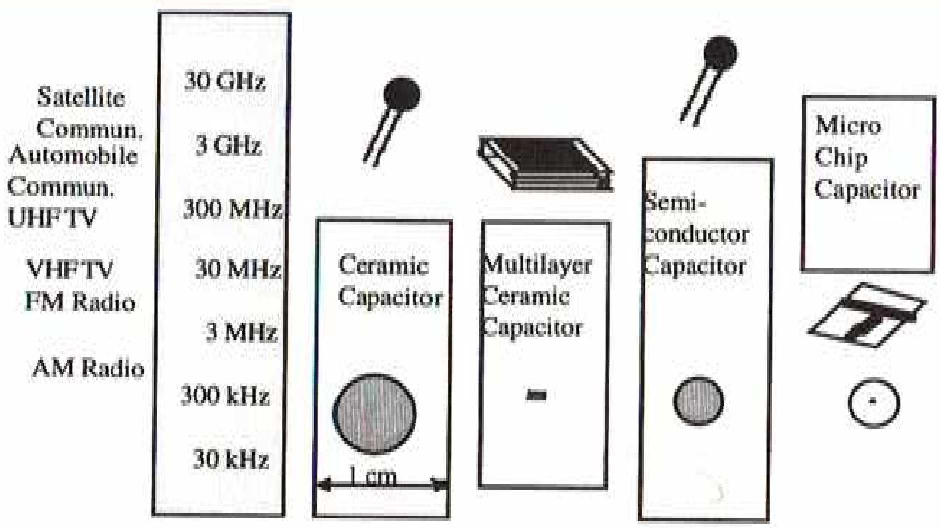

Fig. 4.1 Various capacitor types classified according to their sizes and operating frequency ranges.

Basic specifications required for capacitors:

❑ **Small size, large capacitance :** Materials with a large dielectric constant are desired.

❑ **High frequency characteristics :** Ferroelectrics with a high dielectric constant are sometimes associated with dielectric dispersion, which must be taken into account for practical applications.

❑ **Temperature characteristics :** Material should stabilize temperature characteristics.

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CHIP CAPACITORS :

- High-frequency applications
- Formed using multi-layer structures

$$C = n\varepsilon_0\varepsilon S / (L/n)$$

Where, n -> number of layers

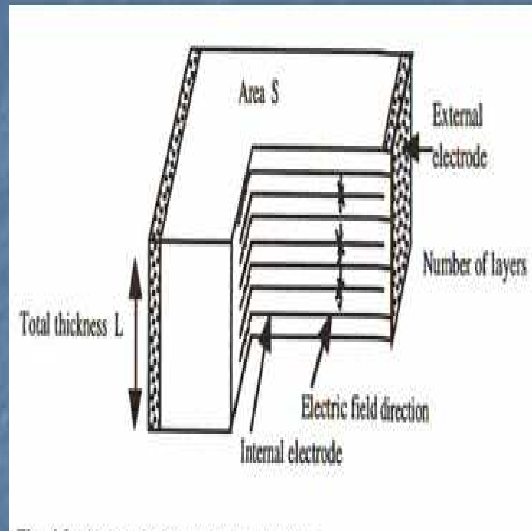


Fig. 4.2 Structure of a multilayer capacitor.

RELAXOR FERROELECTRICS :

- **Application :** Compact chip capacitors.
- **Properties :**
  - High Permittivity
  - Diffuse Phase Transition (temperature-insensitive characteristics)
  - Dielectric Relaxation (frequency dependence of permittivity)

FERROELECTRIC MEMORY DEVICES :

FERROELECTRIC DRAM :

- Volatile memory
- Requires Refreshing
- Minimum memory capacitance: 30fF

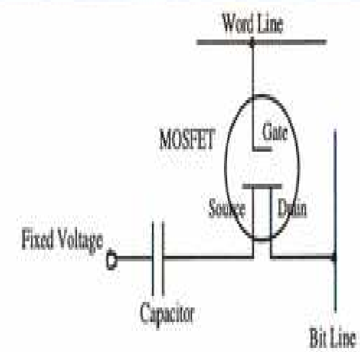


Fig. 5.1 Fundamental structure of a DRAM, composed of a MOSFET and a capacitor.

- **General Requirements for DRAM Capacitor:**
  - high dielectric constant in a thin film configuration
  - low leakage current
  - micro-machinability
  - low diffusion into semiconductor substrate
  - Low contamination during the fabrication process

- **256 Mbit level prototype DRAMs have been manufactured.**

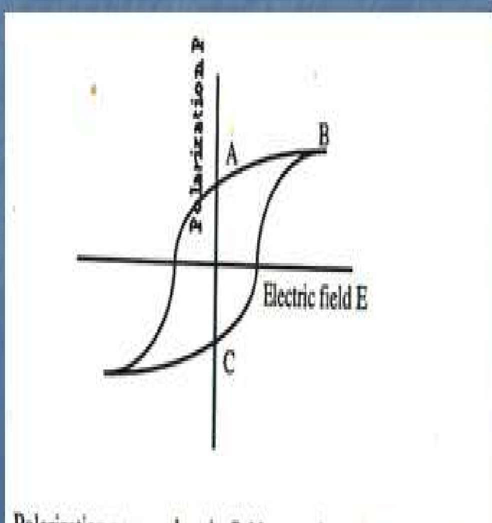
FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

NON-VOLATILE FERROELECTRIC MEMORY :

FRAM (Inversion Current Type) :

- Ferroelectric thin film with a large polarization-electric field hysteresis used as a memory capacitor.
- The observed current amount for a positive pulse indicates initial polarization state.
- Reading Process is destructive.

- **Fatigue :** Large voltage applied on a ferroelectric film at every reading process, degrades polarization hysteresis characterisitic.



Polarization versus electric field curve for a ferroelectric film.

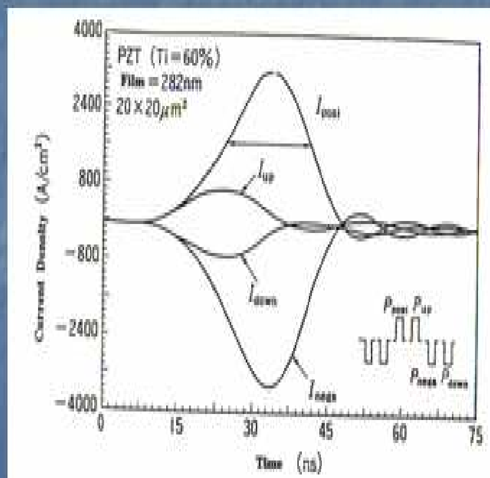
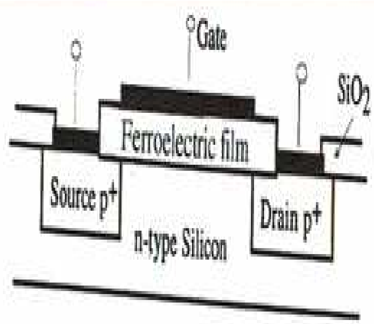


Fig. 5.10 Current responses to a series of pulses (two positive pulses followed by two negative pulses) on a PZT film with 20 x 20 μm² electrodes.

MFSFET (Metal-Ferroelectric-Semiconductor FET) :

- Ferroelectric film replaces Gate oxide.

- Advantages:
  - No fatigue.
  - Non-destructive Reading.
  - Small polarization density required to control the Si surface potential.



Structure of an MFSFET.

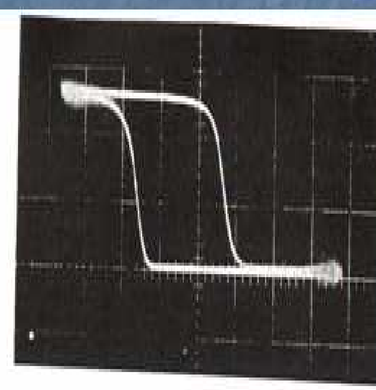


Fig. 5.13 Drain current versus gate voltage relation in an MFSFET with a $PbTiO_3$ film fabricated on a SiO_2/Si substrate

- **64 kbit level non-volatile memory devices have been used.**

PYROELECTRIC DEVICES :

- **Pyroelectric Effect : Temperature dependence of the spontaneous polarization of a polar material.**

- **Merits of Pyrosensors :**
  - wide range of response frequency
  - use at room temperature
  - quick response in comparison with other temperature sensors
  - high quality (optical grade homogeneity,etc.) materials for the pyrosensors are unnecessary.

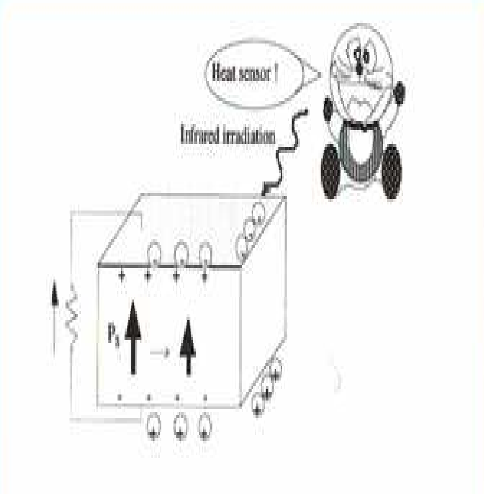


Fig. 6.1 Principle of a pyroelectric sensor: a temperature increase due to the infrared irradiation (such as human body) --> Spontaneous polarization decrease --> Variation in electric charge (or current).

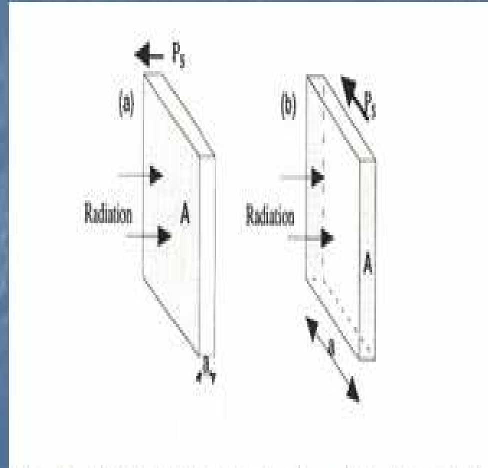


Fig. 6.2 Typical geometric configurations for pyroelectric detectors: (a) face electrodes with the polarization direction parallel to the infrared irradiation, and (b) edge electrodes with the polarization direction perpendicular to the irradiation.

FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

PYROELECTRIC DEVICES (contd.) :

➢ Figures of Merit for Pyroelectric Materials

Table 6.1 Figures of merit for pyroelectric materials.

Figure of Merit	Application
p/c_p	low impedance amplifier
$p/(c_p\varepsilon)$	high impedance amplifier
$p/(c_p\alpha\varepsilon)$	thermal imaging device (vidicon)
$p/c_p(\varepsilon \tan\delta)^{1/2}$	high impedance amplifier when the pyroelectric element is the main noise source

p: pyroelectric coefficient; c_p: specific heat; ε: relative permittivity
α: thermal diffusivity

➢ Applications :

- Temperature/ Infrared Light Sensors
- Infrared Image Sensors

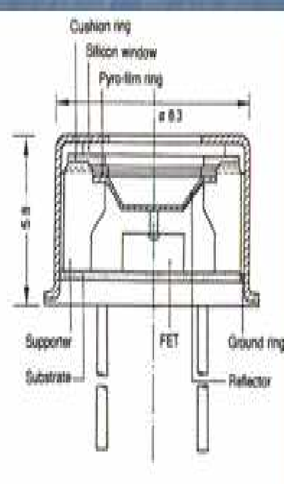


Fig. 6.6 A polymer-based (PVDF) pyroelectric infrared sensor.

FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

PIEZOELECTRIC DEVICES :

- **Piezoelectric Effect :** Electric charges produced on the surface on application of mechanical stress.
- All Piezoelectric materials have geometric strain proportional to an applied electric field: **Converse Piezoelectric Effect**.

- **PIEZOELECTRIC MATERIALS:**

<u>SINGLE CRYSTALS</u>

- **Applications:** frequency stabilized oscillators, surface acoustic devices.
- Single-crystal piezoelectric materials: quartz, lithium niobate ($LiNbO_3$).
- Anisotropic materials

<u>POLYCRYSTALLINE MATERIALS</u>

- $BaTiO_3$: dielectric & piezoelectric properties affected by its own stoichiometry, microstructure, and dopants entering onto A or B site in solid solution.
- $Pb(Ti,Zr)O_3$ (PZT) : Zr content determines crystalline symmetry. With increase in Zr content structure changes from Tetragonal to Rhombohedral Symmetry.

FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

PIEZOELECTRIC MATERIALS:

RELAXOR FERROELECTRICS:

- Polycrystalline or single crystals
- Properties: broad phase transition from paraelectric to ferroelectric, strong dielectric relaxation, weak remanent polarization.
- Show induced piezoelectric effect. Large electromechanical coupling effect.
- Example: PMN-PT, PZN-PT.

POLYMERS:

- Characteristics of Piezoelectric polymers:
  - a) small piezoelectric d constants (for actuators) and large g constants (for sensors),
  - b) light weight and soft elasticity, good acoustic impedance matching with water or the human body.
  - c) low mechanical quality factor Q_M, allowing for a broad resonance bandwidth.
- Example: Polyvinylidene difluoride (PVDF), PVDF-TrFE.

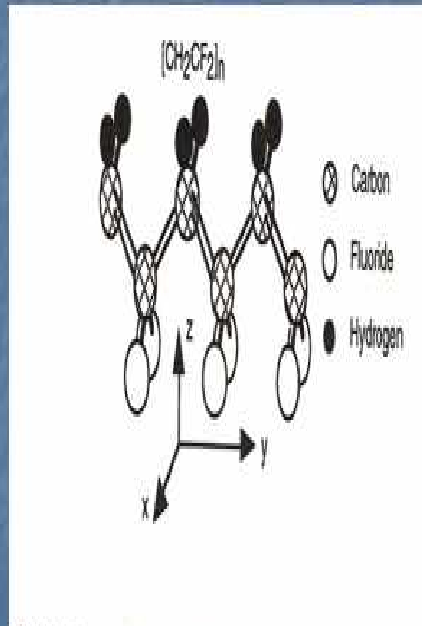


Fig. 7.5 Structure of polyvinylidene difluoride (PVDF).

FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

PIEZOELECTRIC MATERIALS:

COMPOSITES:

- Piezoelectric ceramic + Polymer phase
- 1-3 piezocomposite, e.g. PZT-rod / polymer composite widely used.
- Acoustic match to tissue or water of piezoceramic improved by forming a composite structure.
- Applications: underwater sonar, medical diagnostic ultrasonic transducer applications.

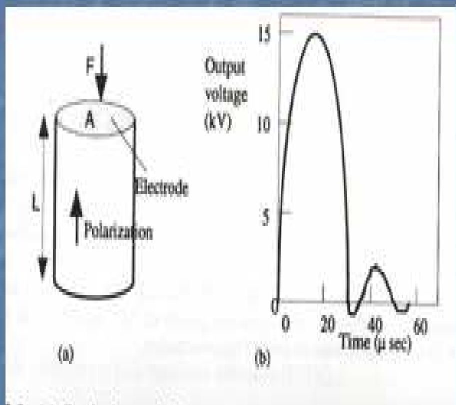
THIN-FILMS

- ZnO and AIN used for thin film depositing.
- Applications: bulk acoustic and surface acoustic wave devices, micro-transducers and actuators.

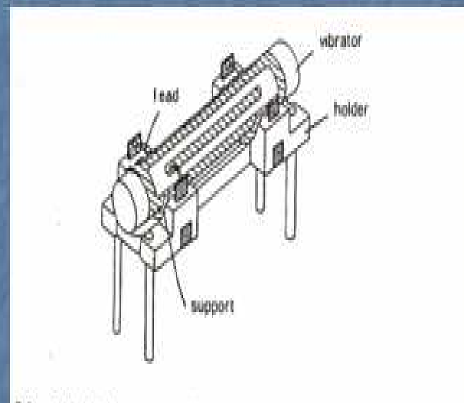
FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

PIEZOELECTRIC DEVICES :

A] Pressure Sensors / Accelerometers / Gyroscopes :



7.6 (a) Gas igniter and (b) output voltage.



7.9 Cylindrical gyroscope (by Tokin).

B] Piezoelectric Vibrators / Ultrasonic Transducers :

The resonance and antiresonance modes are both mechanical resonances.
Max. Electrical admittance- resonance
Min. Electrical admittance- antiresonance

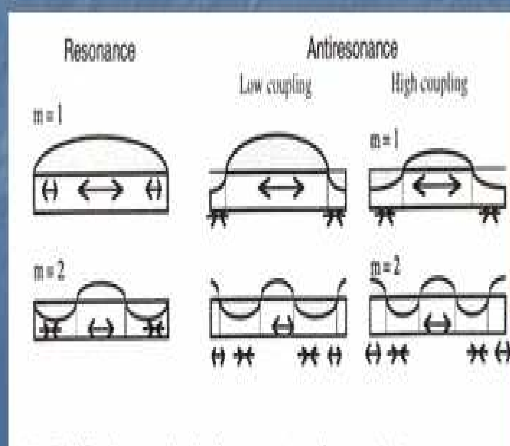


Fig. 7.13 Strain generation in the resonant or antiresonant state.

FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

PIEZOELECTRIC DEVICES :

Piezoelectric Vibrators

- Size & shape of device important (both vibrational mode & ceramic material)
- Hard piezoelectric ceramics preferred (high mechanical quality factor)

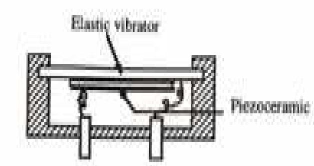


Fig. 7.16 Piezoelectric buzzer.

Ultrasonic Transducers

- Employs piezoceramics as well as magnetostrictive materials
- Hard piezoceramics with high Q_M preferred
- Liquid medium used for sound energy transfer

Resonators/ Filters

- At resonant frequency, piezoelectric body absorbs more energy than at other frequencies resulting in a dramatic decrease in impedance.
- bandwidth of filter $\propto k^2$, k-coupling coefficient
- Sharpness of passband depends on Q_M

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PIEZOELECTRIC DEVICES :

C] Surface Acoustic Wave Devices:

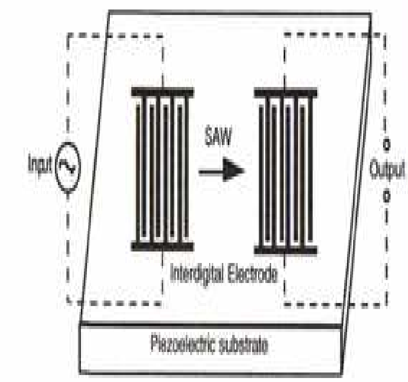


Fig. 7.20 Fundamental structure of a surface acoustic wave device.

➢ **Materials used for Saw devices:**
lithium niobate & lithium tantalate.

➢ **Advantages:**

1) The wave can be electro acoustically accessed and tapped at the substrate surface and its velocity is approximately 10000 times slower than em wave.
2) The SAW wavelength is on the same order of magnitude as line dimensions produced by photolithography and the lengths for both short and long delays are achievable on reasonably sized substrates.

D] Piezoelectric Transformers:

➢ Input/Output terminals fabricated on piezo-device.

➢ Input/Output voltage is changed through vibration energy transfer.

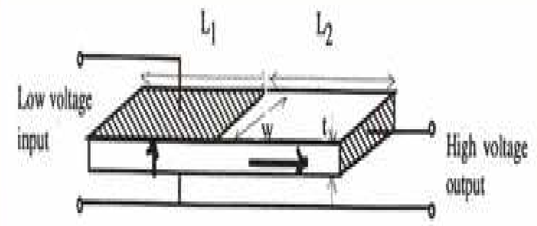


Fig. 7.21 Piezoelectric transformer proposed by Rosen.

FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

PIEZOELECTRIC DEVICES :

D] Piezoelectric Actuators:

➢ **Classification of ceramic actuators:**

Displacement	Drive Technique	Actuator Category	Materials
Rigid displacement	Servo displacement transducer	Servo displacement transducer	Electrostrictor
	On/Off drive	Pulse drive motor	Soft piezoelectric
Resonant displacement	AC drive	Ultrasonic motor	Hard piezoelectric

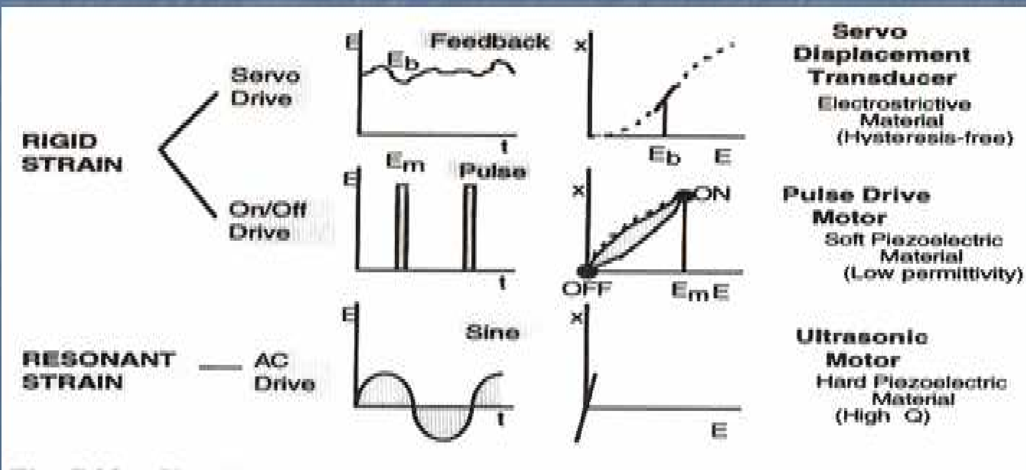


Fig. 7.29 Classification of piezoelectric/electrostrictive actuators.

FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

PIEZOELECTRIC DEVICES :

E] Ultrasonic Motors:

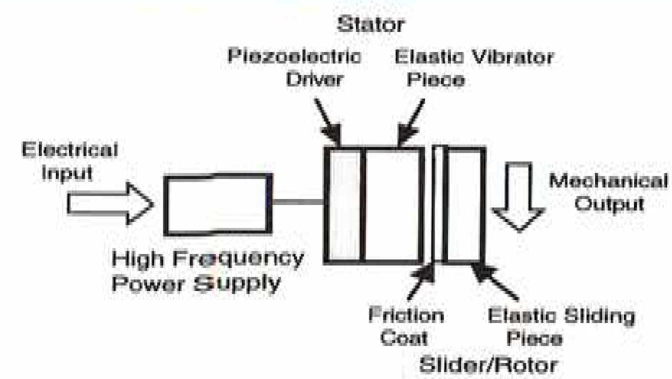


Fig. 7.42 Fundamental construction of an ultrasonic motor.

Merits :

1.Low speed & high torque

2.Quick response, wide velocity range, hard brake and no backlash.

3.High power/ weight ratio & high efficiency

4.Compact size & lightweight

5.Simple structure and easy production process

6.Negligible effect from external magnetic or radioactive fields

Demerits:

1.Necessity for high frequency power supply

2.Less durability due to frictional drive

3.Drooping torque vs speed characteristics.

FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

ELECTROOPTIC DEVICES :

- **Electrooptic effect :** Change in refractive index with an external applied electric field.

- **Applications:** light valves, beam deflectors, optical displays for optical communications, solid state laser chips, optical fibers.

- Ceramic electrooptic components possess advantages over LCDs in terms of their response speed (micro-sec), falling time, contrast ratio (100), gray scale (16 scales), ability to withstand high intensity illumination.

- **Demerit:** high drive voltage (1 kV) and production cost ($100).

TRANSPARENT ELECTROOPTIC CERAMICS:

- Polycrystalline microstructure of ferroelectric ceramics sintered to a pore-free state.
- Relaxor ferroelectric- non-linear optic applications.

FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

TRANSPARENT ELECTROOPTIC CERAMICS:

- **Examples:**

1] $(Pb,La)(Zr,Ti)O_3$ –PLZT

-good transparency in a wavelength range extending from visible to infrared
-optical anisotropy with an applied electric voltage
-voltage required for electrooptic shutter is much less

2] $Pb(Zn_{1/3}Nb_{2/3})O_3$ –PZN

-relaxor ferroelectric
-single crystal form
-At transition temperature, can be depoled without any remanent polarization.

3] $Pb(Mg_{1/3}Nb_{2/3})O_3$ –$PbTiO_3$ –PMN-PT

-Curie temperature increases gradually with $PbTiO_3$ content crossing room temperature at x=0.12

- **Desired Properties in a new ceramic electrooptic material:**

a) ceramic transparency requires almost zero birefringence in zero-field state (i.e. a pseudo-cubic structure) to supress light scattering,
b) large fracture toughness may be obtained in a sufficiently dense structure,
c) large electrooptic effect is manifested by relaxor ferroelectrics.

FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

BULK ELECTROOPTIC DEVICES :

1] Ferpic (Ferroelectric Picture Memory Device) :

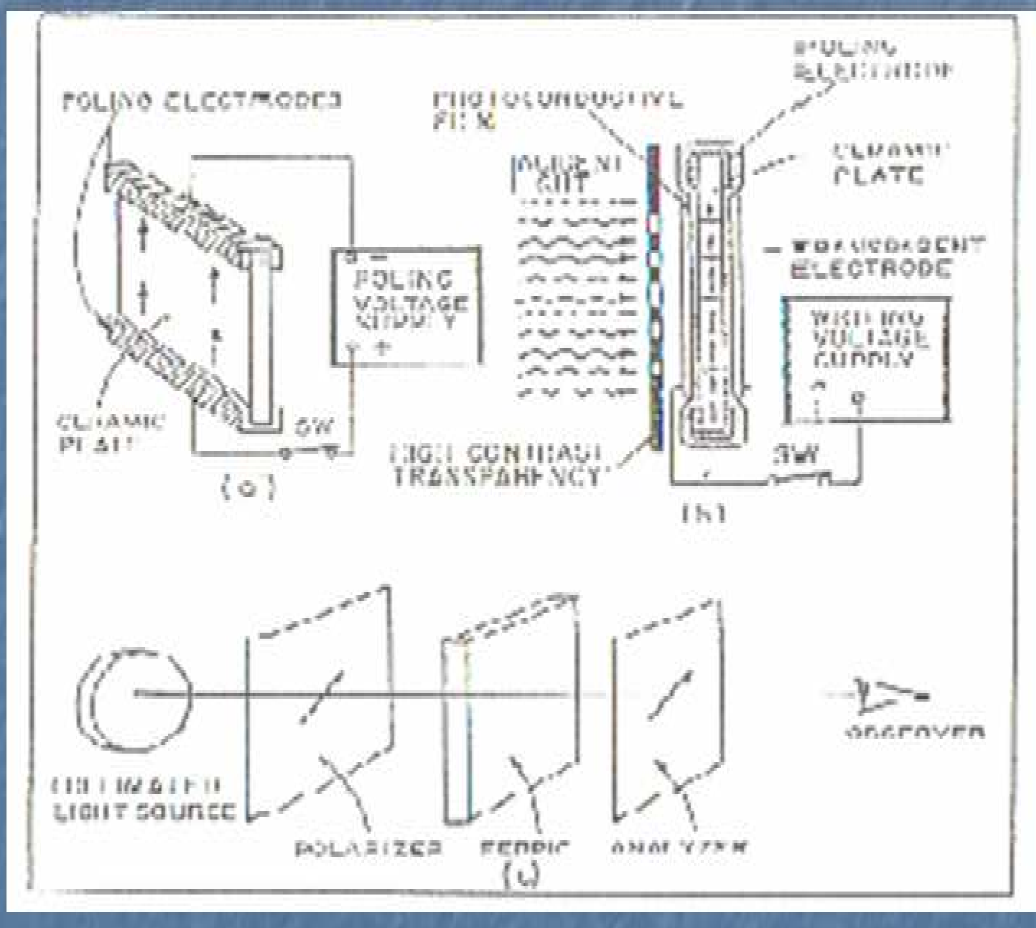


Fig. Principle of Ferpic (a) initial DC Poling, (b) writing process using a photoconductive film, © reading process using a pair of parallel polarizers.

FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

BULK ELECTROOPTIC DEVICES :

2] Eye Protection Application :

- PLZT goggles for the U.S. Air Force to provide thermal & flashblindness protection

3] Stereo TV Application :

- lenses consist of pair of optically isotropic PLZTdiscs sandwiched between two crossed polarizers.
- At zero voltage between electrodes, light not transmitted.
- transmitted light intensity increases with applied voltage, maximum at phase difference of 180deg. between PLZT disc.

4] Two-dimensional displays :

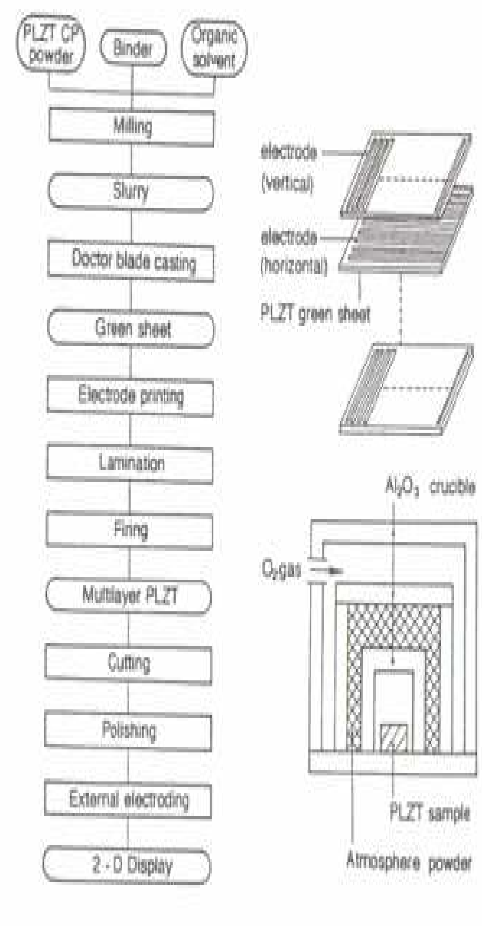


Fig. 8.13 Fabrication process for the two-dimensional PLZT optical display.

FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

ELECTROOPTIC DEVICES :

WAVEGUIDE MODULATORS :

- **Fabrication:** deposition of a high refractive index layer on a substrate
- Nb diffused $LiNbO_3$ single crystal commonly used.
- Transmitted light intensity is easily modulated by applying a relatively low voltage. (e.g. 0.3V -> modulation by 1 rad)

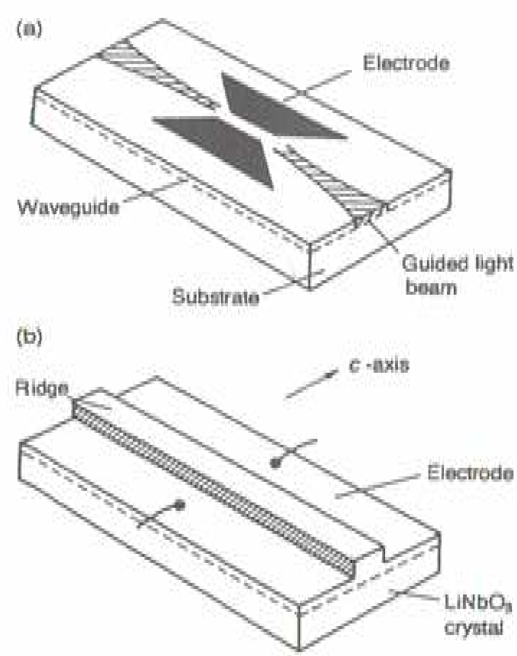


Fig. 8.20 Electrooptic waveguides: (a) planar-type and (b) ridge-type.[12]

FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

PTC MATERIALS :

PTC PHENOMENON (Positive temperature coefficient of resistivity effect) :
Drastic increase in resistivity with increasing temperature around Curie point.

➢ The PTC dopants have higher ionic valence than
- Ba (replaced by La, Sm, Ce or Gd ions)
- Ti (replaced by Nb, Ta or Bi ions)

1] PTC THERMISTORS :

➢ Temperature change detection, Active current controllers

➢ When self-heated, exhibit a decrease in the current owing to a large increase in resistivity.

➢ Applications: over- current/ voltage protectors, starting switches for motors, automatic demagnetization circuits for color TVs.

2] GRAIN BOUNDARY LAYER CAPACITORS :

➢ capacitors made of semiconductive $BaTiO_3$ ceramics with highly resistive grain boundaries.

➢ exhibits excellent freqency characterisctics

➢ used as a wide bandpass filter.

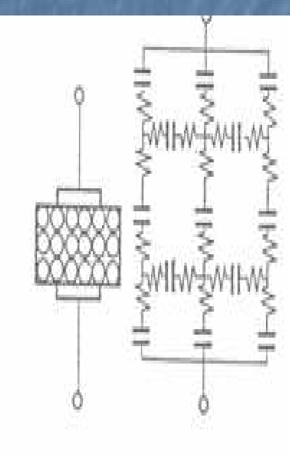


Fig. 9.9 Model of the grain boundary layer capacitor.

COMPOSITE MATERIALS :

- Connectivity
- Composite Effects :
  - Sum effect
  - Combination effect
  - Product effect

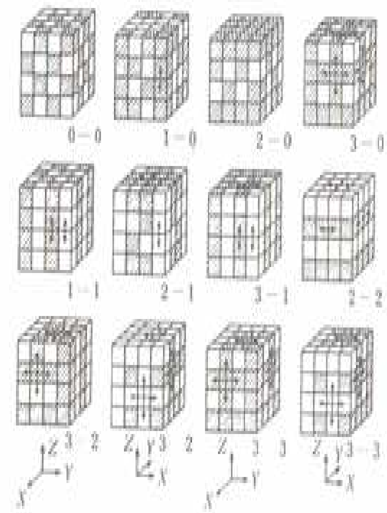
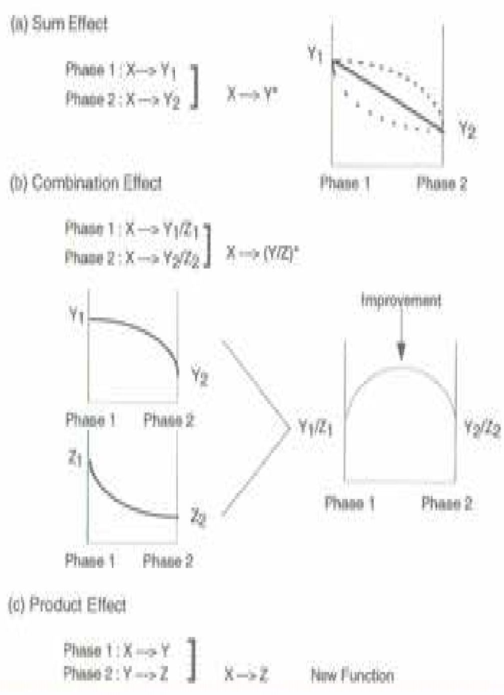


Fig. 10.1 Classification of two-phase composites with respect to connectivity.[1]

Table 10.1 Composite effects: sum, combination and product effect.



PZT-POLYMER COMPOSITES :

- Polymer PVDF used for sensor applications.
- PVDF not used for avtuators or high power transducers due to small piezoelectric d constants and small elastic stiffness
- Advantages of PVDF-PZT composites: high coupling factors, low acoustic impedance, good matching to water/ human tissue.mechanical flexibility, broad bandwidth.

PZT COMPOSITE DAMPERS :

- **Principle :**

1] vibration transmitted to piezoelectric material
2] vibrational energy converted into electrical energy through piezoelectric effect
3] If a proper resistor is connected, the energy converted into electricity is consumed as Joule heat by the resistor.
4] The energy converted back into mechanical energy is reduced, so that vibration can be rapidly damped.
5] Damping takes place most rapidly when the series resistor is selected such that the impedance matching condition R=1/2*pi*f*C , is satisfied.

FERRO-ELECTRIC MATERIALS IN MICROELECTRONICS

SUMMARY :

Applications of Ferroelectrics :

-High permittivity dielectrics
-Ferroelectric memories
-Composite materials
-Piezoelectric devices
-Electrooptic devices
-PTC materials
-Pyroelectric devices

Present market shares of ferroelectric devices :

Capacitors, Piezoelectric devices, Thermistors.

Promising areas :

-Electromechanical devices (piezoelectric actuators, ultrasonic motors)
-Thin film hybrid sensors
-Electrooptic devices

Reliability issues of ferroelectric devices :

-Reliability of ceramics
-Reliability of devices
-Drive techniques

Thank You !