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Manufacturing Technologies for MEMS and SMART SENSORS

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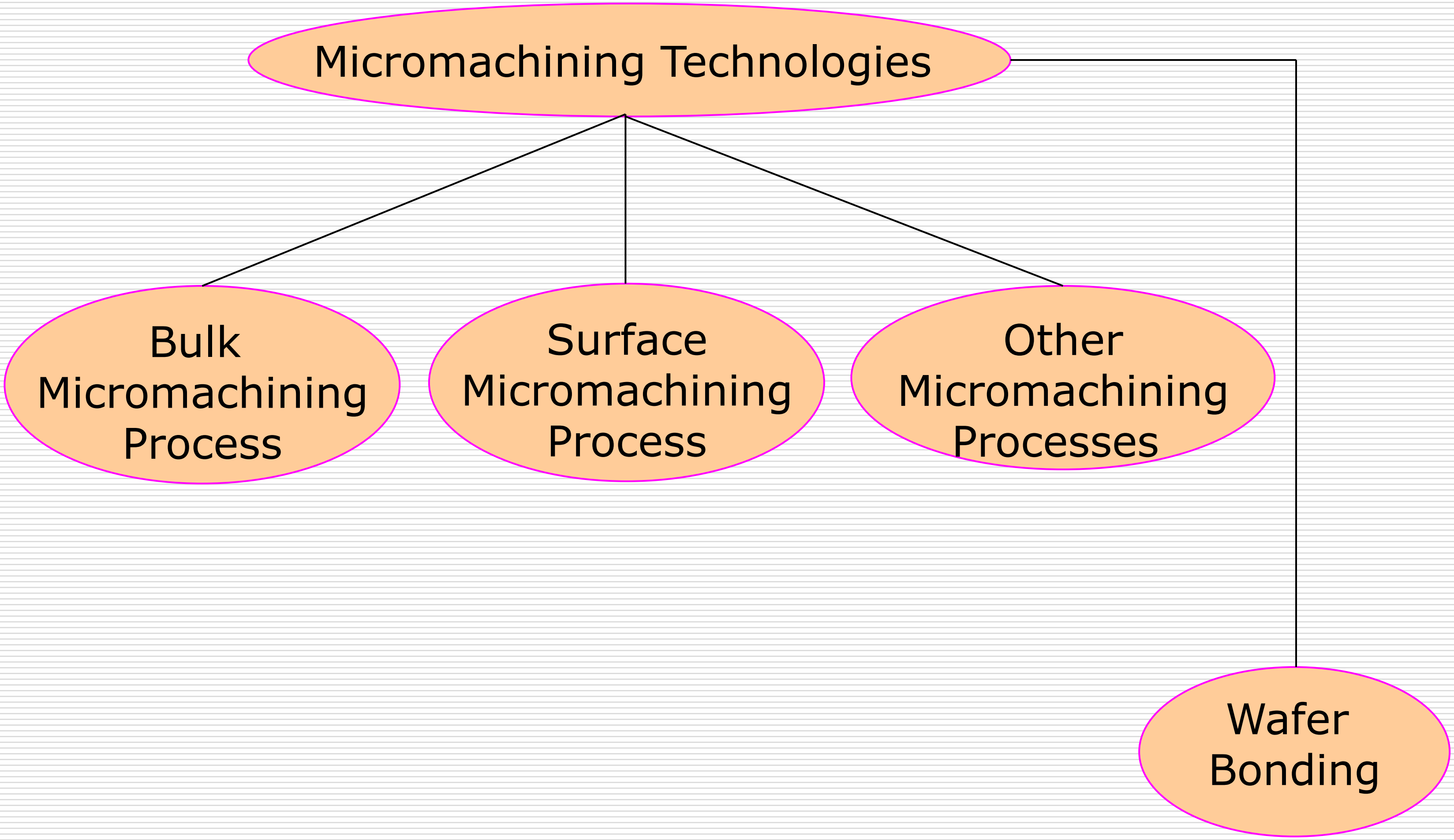
Grouping of Manufacturing Technologies

Two groups of manufacturing technologies used:

- ❑ **Micro-machining Technologies**
  - ➢ Originally developed for producing micro-mechanical components and systems
  - ➢ Now used in the production of all MEMS-based devices for making the MEMS element
- ❑ **Integrated-Circuit (IC) Technologies**
  - ➢ Originally developed for producing integrated circuits (ICs)
  - ➢ Now used in the production of **all smart sensors** (including smart MEMS sensors) for making the micro-electronic circuit
  - ➢ Can also produce at the same time any **electrical or electronic micro-sensor** required in the smart sensor.

Micro-Machining Technologies

Micromachining Technologies



Micromachining Technologies

Bulk Micromachining Process

Surface Micromachining Process

Other Micromachining Processes

Wafer Bonding

Bulk Micromachining

- Process is meant to remove a bulk (significant amount) of material from substrate (wafer) by chemical etching
- Substrate is usually a silicon crystal
- Sometimes, glass, quartz, germanium or gallium arsenide are used
- Substrate (wafer) can be etched **from one or both sides**
- Etching is done selectively with **a mask and an etchant**
- A thin layer of SiO_2 is formed in the top of substrate
- A mask is formed in this SiO_2 layer
- Two types of etching processes are used in bulk-micro-machining:
  - Isotropic etching
  - Anisotropic etching

Mask Formation

- Masks are needed in all micro-machining and IC processes at several steps
- Mask is made in a SiO_2 (or sometimes Si2N3) layer
- The layer needs to formed **in** the top of substrate
- Mask is made by photo-lithographic etching technique

Photo-Lithographic Etching: Process

Steps in Photo-lithographic etching process:

I. Generate desired pattern (photo-mask with appropriate clear and opaque regions) computer-aided design (CAD) tools

II. Make a layer of a photo-resist (photo-sensitive material) on SiO_2

III. Transfer pattern from photo-mask to photo-resist layer using light (process is called as photo-lithography)

IV. Develop photo-resist layer in a specified chemical solution

V. Etch the wafer using a suitable chemical etchant to transfer pattern from photo-resist to SiO_2

Thus, a SiO_2-mask has been created on the top surface of the substrate.

Photo-Lithographic Etching: Photo-Resist

Two types of photo-resist are used:

A. Positive photo-resist

Produces same pattern as on photo-mask

B. Negative photo-resist

Produces reverse of the pattern on photo-mask

Isotropic Etching

- Etchants used have equal etching rate for all crystallographic orientations of silicon wafer (crystal)

- Common Etchants (examples)
  - Sulfur hexa-flouride (SF_6)
  - Hydrogen flouride (HF)

- Structures Produced (examples)
  - Semi-spherical cavity
  - Rim-cantilever

Anisotropic Etching

- Etchants used have **unequal** etching rates for **different** planes of silicon crystal (wafer)

- Common Etchants (examples)
  - Ethylene-diamine pyrocatechol (EDP) for SiO_2 mask
  - Potassium hydroxide (KOH) for Si_3N_2 mask

- Structures Produced (example)
  - Diaphragm

Merits and Limitations of Bulk Micro-Machining

- Merits of Bulk Micro-Machining:
  - Fast etching rate
  - Material can be removed in bulk.
  - Etching can be done from both sides, if required.
- Limitations of Bulk Micro-Machining:
  - Intricate features can’t be produced.
  - Material of substrate can be only removed, but no external material can be added (deposited).

Surface Micromachining

- ❑ Process meant to build intricate 3-dimensional structures by **depositing and removing (etching) materials in layers one over the other with the help of masks**
- ❑ All etching and deposition processes are carried out from one surface only
- ❑ Layers are deposited using:
  - ➢ Vacuum evaporation, or
  - ➢ Chemical vapour deposition
- ❑ Two types of layers are used:
  - ➢ Structural Layer: Retained in the final structure
  - ➢ Sacrificial Layer: Sacrificed selectively during the process
- ❑ Substrate is usually Si; glass also used
- ❑ SiO_2 or Si3N2 layer used for masking

Merits and Limitations of Surface Micro-Machining

- ❑ Merits of Surface Micro-Machining:
  - ➢ Intricate features can be produced.
  - ➢ Not only the material of substrate can be removed, but external materials can also be added (deposited).

- ❑ Limitations of Surface Micro-Machining:
  - ➢ Because of the slow-etching rate, this technique is not suitable for removing large quantities of materials.
  - ➢ Addition and removal of materials are possible from the top side only.

Other Micromachining Processes

- LiGA Process
- DRIE Process
- Plasma etching
- Micro-milling

Other Micromachining Processes

LiGA Process

- LiGA stands for Lithographie, Galvanik und Abformung
- Process combines lithography, electroplating and moulding
- Uses electroplating to build mechanical structural parts
- For etching, LiGA uses UV-rays (upto 20 μm), or laser (upto 200 μm) or X-rays (upto 500 μm)
- A mould is prepared for mass replication using injection moulding, stamping or some other process.

Advantage: Compared to surface micro-machining, it is capable of thicker structures and faster etching.

Other Micromachining Processes
DRIE Process

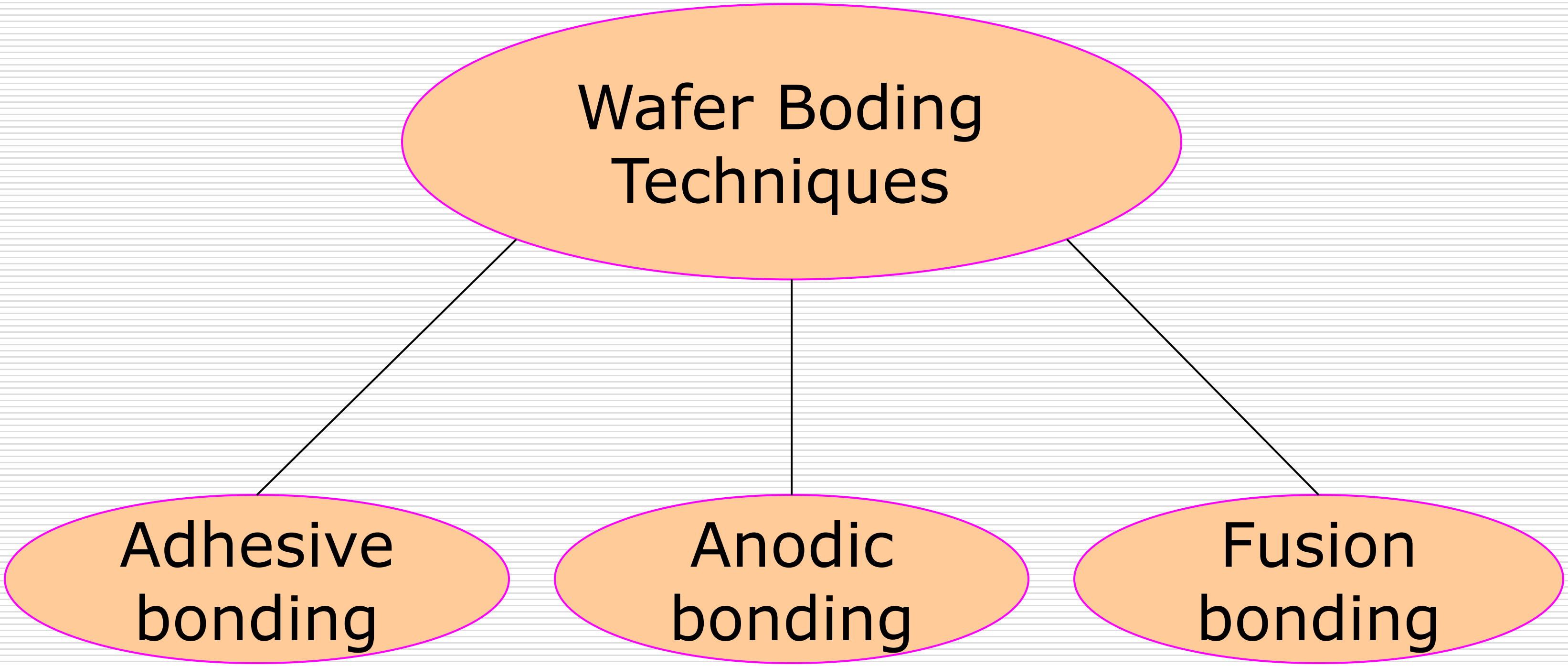
- DRIE stands for Deep Reactive Ion Etching
  - A highly anisotropic etching process
  - Used to create deep penetration, steep-sided holes and trenches in wafers/substrates, with high aspect ratios
  - Developed specially for MEMS requiring these features

- Cryogenic-DRIE process:
  - The wafer is chilled to −110°C
  - This low temperature slows down the chemical reaction that would have produced isotropic etching
  - But ions continue to bombard upward-facing surfaces and etch them away
  - Consequently, the process produces trenches with highly vertical sidewalls.

Wafer Bonding

- Used for bonding two wafers of same or different materials to produce complex structures
- Common situations of bonding in micro-machining are:
  - Silicon-on-silicon bonding
  - Silicon-on-silicon dioxide bonding
  - Silicon-on-glass bonding

Wafer Bonding Techniques



Wafer Boding Techniques

Adhesive bonding

Anodic bonding

Fusion bonding

Adhesive Bonding

- Applicable to bonding of wafers of any materials
- An adhesive is applied between two surfaces to be bonded
- Adhesives used: glass frit, polymer pastes
- Apply pressure around 1 bar
- Heat at around 400 ^{0}C

Anodic Bonding

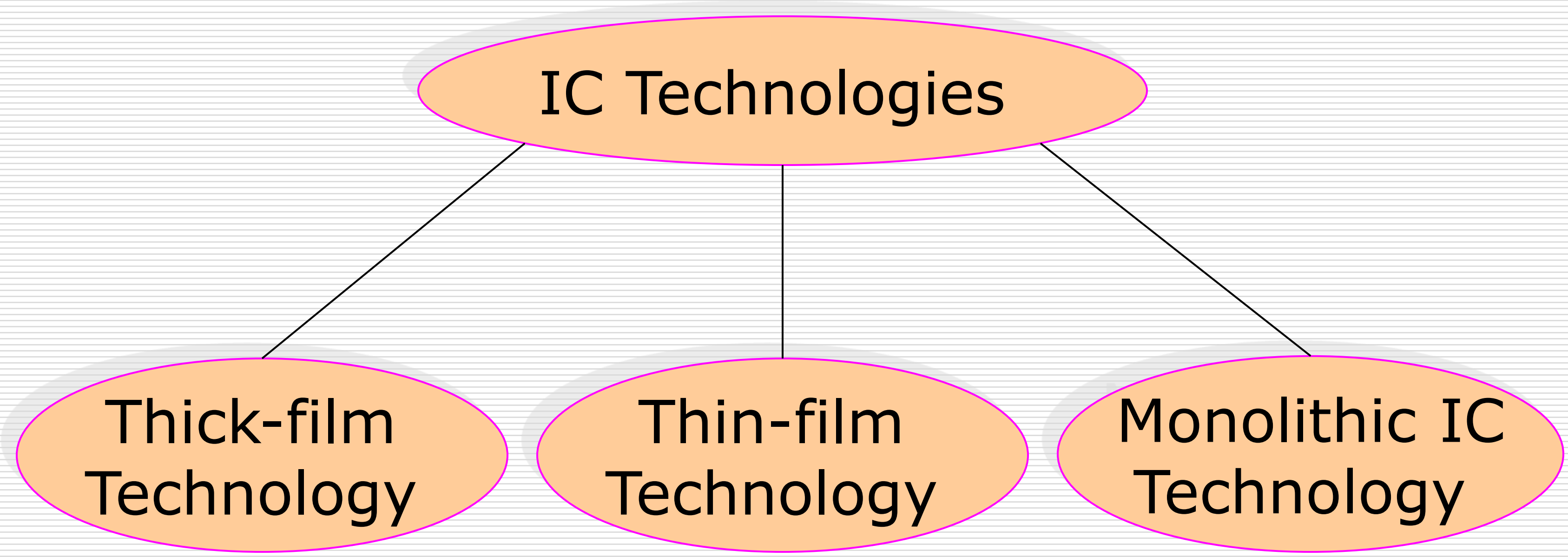
- Applicable to bonding of wafers of any materials
- Apply a potential difference of around 500V between two surfaces to be bonded
- Heat at around 400 ^{0}C
- No adhesive
- No pressure

Fusion Bonding

- Applicable to silicon-on-silicon bonding and silicon-on-silicon dioxide bonding
- Finish the two surfaces to be joined
- Place the two surfaces together
- Heat at around 1000 ^{0}C in oxygen
- No adhesives
- No pressure
- Bonding takes place at atomic level through fusion of one silicon dioxide layer with another silicon dioxide layer (either present or created by oxidation)

Integrated-Circuit Technologies

IC Technologies & Capabilities



IC Technologies

Thick-film Technology

Thin-film Technology

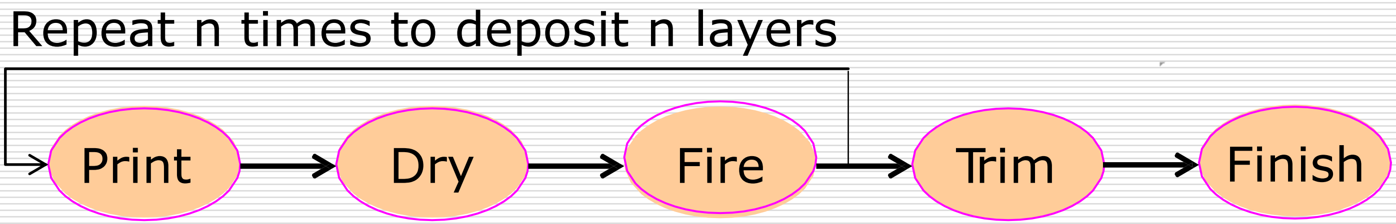
Monolithic IC Technology

Capabilities:
- R, C & L
- Conductors
- Sensing elements
- Sensor supports

Capabilities:
- R & C
- Conductors
- Sensing elements

Capabilities:
- R & C
- Diodes & transistors
- Conductors
- Sensing elements

Thick-Film Technology



Repeat n times to deposit n layers

Process : Print → Dry → Fire → Trim → Finish

Materials for printing: Substrate + Paste or Ink + Printing screen

Components of paste :

Suspended particles of selected material

\+

Organic solvent (to make paste)

\+

Glass frit (binding material)

Particle Materials for Thick-Film Pastes

Conductive → For interconnections and small inductances

Resistive → For resistances and resistive sensors

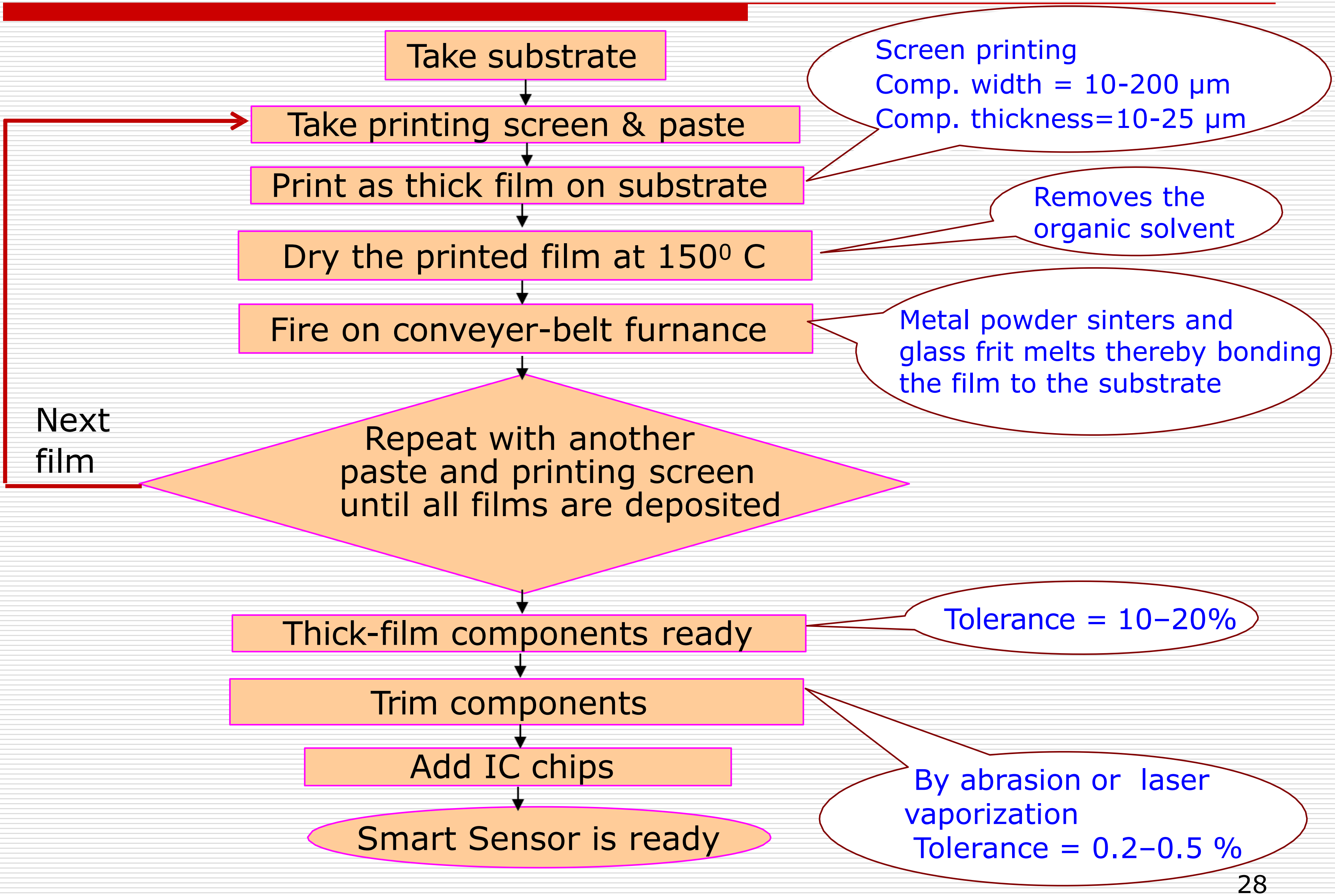
Dielectric → For capacitors and capacitive sensors

Other materials → For other sensors and sensor supports

Paste Types & Compatible Substrates

- Low-Temperature Pastes
  - Melting Point: Less than 250 ^{0}C
  - Substrate : Plastic materials
    Glass fibre with epoxy
    Anodized aluminum
- Medium-Temperature Pastes
  - Melting Point: 500 – 600 ^{0}C
  - Substrate: Low carbon steel with porcelain enamel coating
- High-Temperature Pastes
  - Melting Point: 800 – 1000 ^{0}C
  - Substrate : Ceramic

Thick-Film Process



Take substrate

Take printing screen & paste

Print as thick film on substrate

Screen printing
Comp. width = 10-200 µm
Comp. thickness=10-25 µm

Dry the printed film at 150^0 C

Removes the organic solvent

Fire on conveyer-belt furnance

Metal powder sinters and glass frit melts thereby bonding the film to the substrate

Repeat with another paste and printing screen until all films are deposited

Next film

Thick-film components ready

Tolerance = 10–20%

Trim components

By abrasion or laser vaporization
Tolerance = 0.2–0.5 %

Add IC chips

Smart Sensor is ready

Thick Film Components

1. Thick-film resistors (any value)
2. Thick-film capacitors (any value)
3. Thick-film inductors (small values only)
4. Conductors
5. Thick-film sensors (see next slide for details)
6. Sensor supports, heaters etc.

Thick-Film Sensors

- Temperature Sensors: Thick-film RTD
  Thick-film thermistor
  Thick-film thermocouple
- Pressure Sensors: Thick-film diaphragms
  Thick-film capacitors
  Thick-film piezo-resistive sensor
  Thick-film piezo-electric sensor
- Light Sensors: Photo-conductive sensors
- Magnetic Sensors: Magneto-resistive sensors
- Humidity Sensors: Organic-polymer based sensors
- Gas Sensors: Metal-oxide sensors (e.g. SnO_2, ZnO_2)

Advantages of Thick Film Technology

- Almost any material can be deposited as thick film
- Several electrical (resistive and capacitive) sensors can be made using this technology
- Low-value resistances and high-value capacitances possible
- Small inductances are also possible
- Components can withstand high temperatures
- Large voltage / current excitation can be used
- Heaters can also be integrated
- Economical for low-volume production
- Suitable for R & D work on micro-sensors

Limitations of Thick Film Technology

- Active components cannot be produced
- Size of components is very large
- Not suitable for medium and large-scale production

Thin-Film Technology

- Film thickness: Less than 1μm to 25μm
- Process: Deposit thin-films by vacuum evaporation or some other technique on a substrate
- Patterns: By masking
- No printing, drying, firing and trimming

Substrate for Thin-Film Components

- High–purity alumina
- Low–alkalinity glass
- Silicon
- Silicon oxide

Thin-Film Deposition Techniques

- Vacuum evaporation
- Chemical vapour deposition
- Sputtering
- Plasma deposition
- Reactive growth
- Spin casting

Thin-Film Components

- Thin-film resistors (any value)
- Thin-film capacitors (any value)
- Thin-film conductors
- Thin-film sensors

Thin-Film Materials and Sensors

- For conductors: Aluminium or gold
- For resistors: Nichrome
- For dielectrics: Silicon dioxide
- For sensing elements (examples):
  - Strain gauge: Nichrome, polycrystalline silicon
  - RTD: Platinum
  - Gas sensor: Zinc oxide
  - Piezo-resistive pressure sensor: Nichrome, polycrystalline silicon
  - Thermo-anemometric flow sensor: Gold

Advantages of Thin-Film Technology

- Almost any metal can be deposited to produce thin-film sensors
- Several electrical (resistive and capacitive) sensors can be made using this technology
- Miniaturization (smaller dimensions than thick-film devices)
- Suitable for low as well as high volume production.
  - Because of the former advantage, it is suitable for R & D work on micro-sensors.
  - Because of the latter advantage, it is used for adding low-value resistances, high-value capacitors and certain micro-sensing elements, not feasible with monolithic IC technology, to monolithic ICs to produce special smart sensors on a mass scale.

Limitations of Thin Film Technology

☐ Active components cannot be produced.

☐ Size of thin-film components is much larger as compared to monolithic IC components.

2.4 Monolithic IC Technology

- Dimensions: Sub-micrometric, nano-metric
- Substrate: Wafer of silicon (less used are Ge and GaAs)
- Capability: R, C, diodes, transistors, conductors and electronic/electrical sensing elements
- Basic Processes:
  1. Epitaxial growth
  2. Silicon-oxide layer formation
  3. Photolithographic etching
  4. Planar diffusion of dopants
  5. Metallization
  6. Stitch bonding

Monolithic IC Process: Steps

Step I: Epitaxial growth

Step II: Isolation diffusion

Step III: Base diffusion

Step IV: Emitter diffusion

Step V: Metallization

Step VI: Packaging

Advantages of Monolithic IC Technology

- Both active and passive devices can be produced
- Electronic micro-sensors (transistors or diodes used as sensors) and electrical micro-sensors (resistive and capacitive sensors) can be produced simultaneously with micro-electronic circuit
- Very high density of devices
- Highly economical for mass production

Limitations of Monolithic IC Technology

- Only electronic and electrical micro-sensors (not MEMS) can be produced using this technology
- Resistances in medium-range only
- Capacitances of small values only
- Uneconomical for producing smart sensors in small quantities.

Comparison of IC Technologies

Feature	Thick –Film Tech.	Thin-Film Tech.	Monolithic IC Tech.
Passive components	R, C, L	R, C	R & C with limitations
Active components	No	No	Yes
Conductors	Yes	Yes	Yes
Dimensions	Largest	Large	Small
Electrical sensing elements	Most of materials	Most of materials	Si only
Electronic sensing elements	No	No	Yes
Economic level of production	Small scale only	Small & large scales	Large scale only
Suitability for R&D work	Yes	Yes	Expensive