Mechanical Properties of thin-films used in Semiconductor Devices

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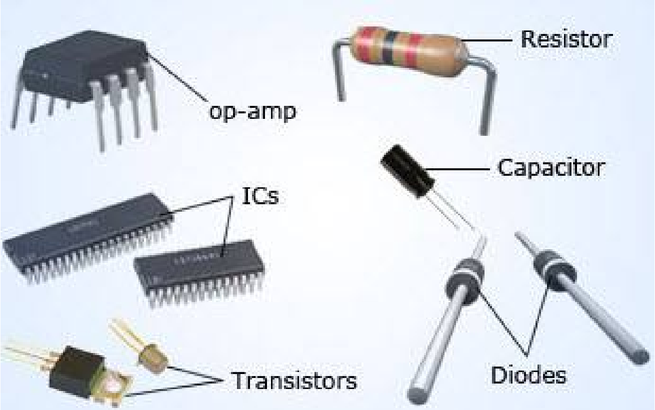
Outline

- Fabrication of Semiconductor devices
- Thin Films
- Mechanical Behavior Problems
- Mechanical Testing Techniques
  - Micro-Tensile testing
  - Nano-Indentation test
- Data Analysis
- Applications

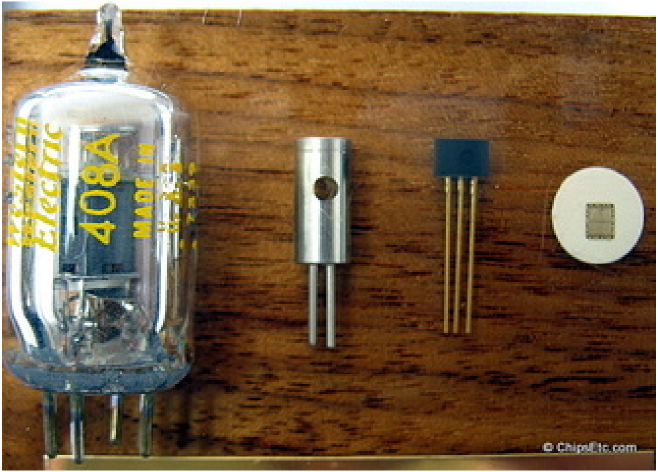
Semiconductor Devices



History of semiconductor devices

Images from https://en.wikipedia.org/wiki/Transistor and /Cat's-whisker$_{d}$*etector*

Evolution of IC Devices and Technology



MOSFET

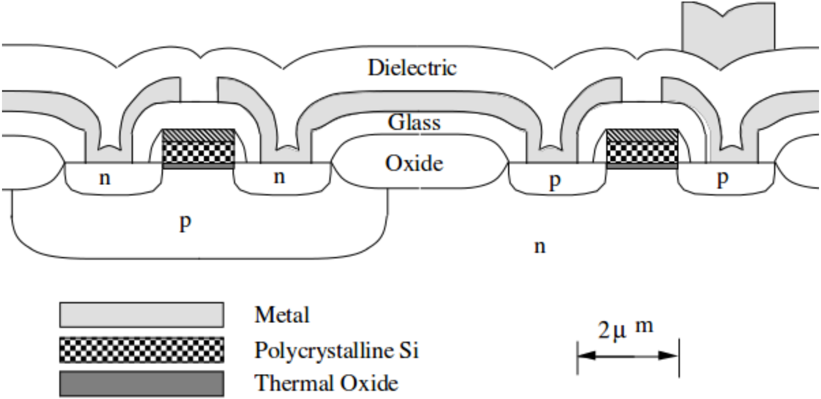
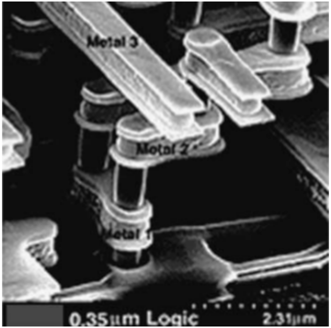
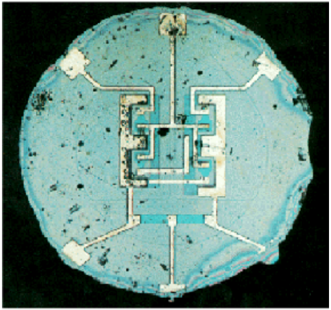


Figure1:Complimentary Metal-Oxide Semiconductor Transistor[1]

Evolution of IC Devices and Technology





Fairchild Semiconductor, 1959

Figure2:Aluminum interconnections [4] and First generation semiconductor chip[1]

Thin Films

- **Defination:** A thin film is a 2 dimensional layer of material ranging from fractions of a nanometer (monolayer) to several micrometers in thickness.
- **Characteristics of Thin Films:**
  - size
  - cost consideration
  - complex interconnections
  - low or prescribed temperature coefficients
  - low noise
  - wide range of resistor and capacitor values
  - Reproducibility
  - compatibility with silicon
  - finer grain size

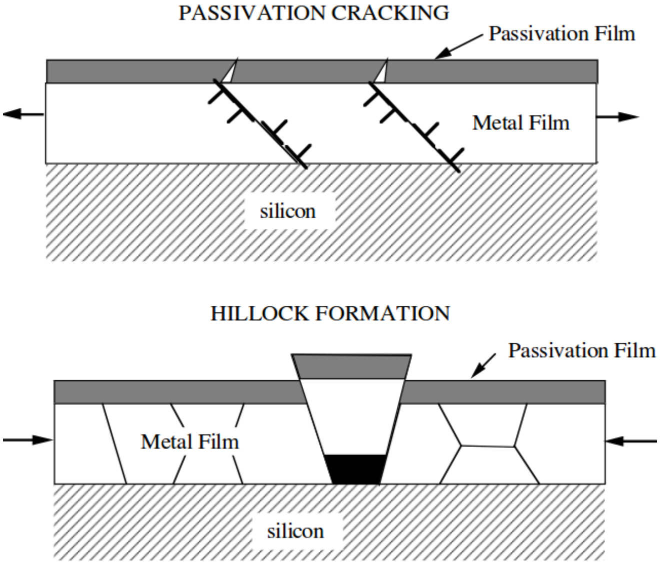
Mechanical Behavior Problems[1]

- Plastic Deformation
- Wafer Cracking
- Thin Film Peeling
- Metal Crack Problem
- Electromigration and voiding

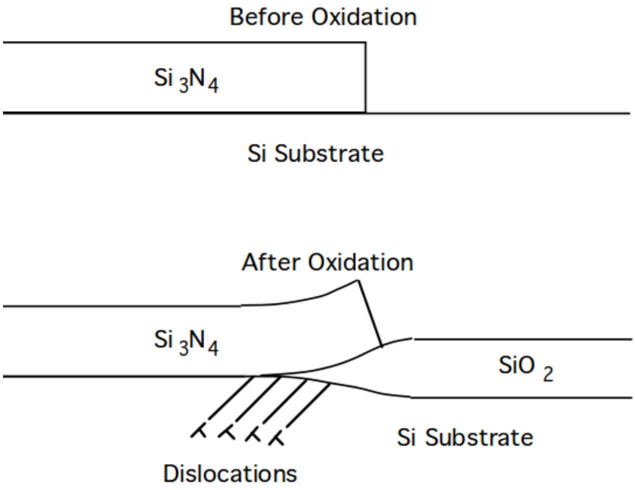
Considerations in Mechanical Behavior

- Thin Film Stresses
  - Residual stresses
  - Lattice Misfit (epitaxial film)
  - Thermal stresses
  - External stresses
- Finer Grain size
- Dislocations ($10^{11} cm^{-2}$)
- Impurities
- Voids

Failure associated with inhomogeneous plastic flow



Bird's Beak and Dislocations



MOSFET

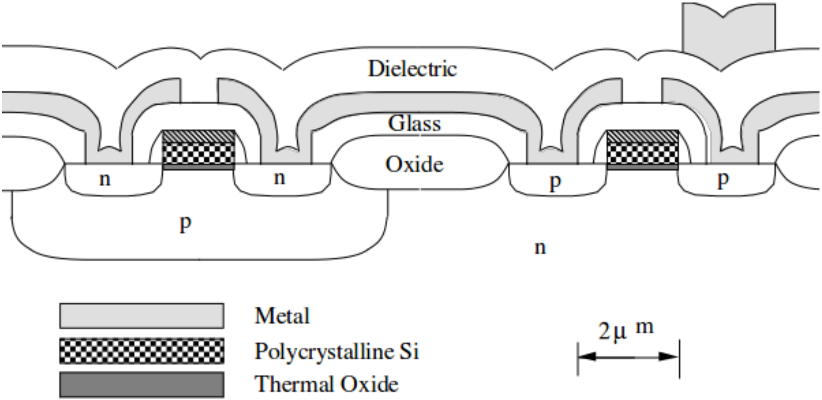
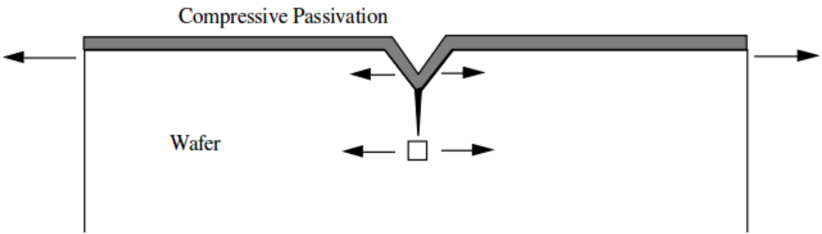


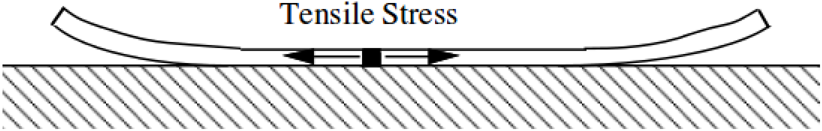
Figure1:Complimentary Metal-Oxide Semiconductor Transistor[1]

Wafer Cracking

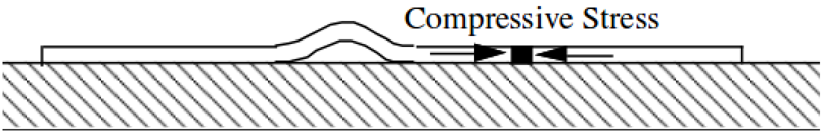


Thin Film Debonding

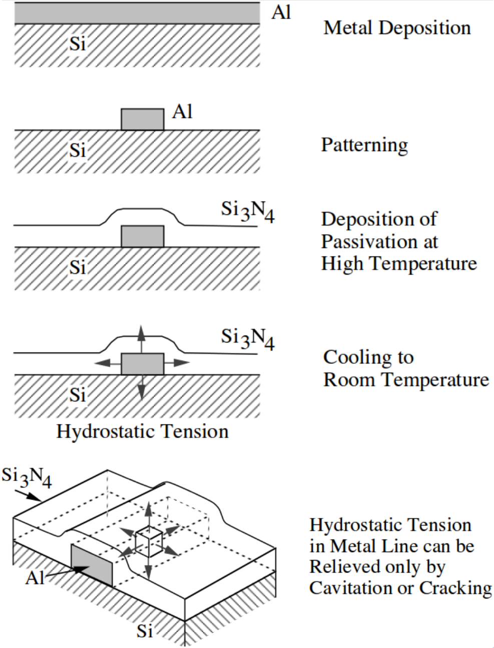
- Thin Film Peeling



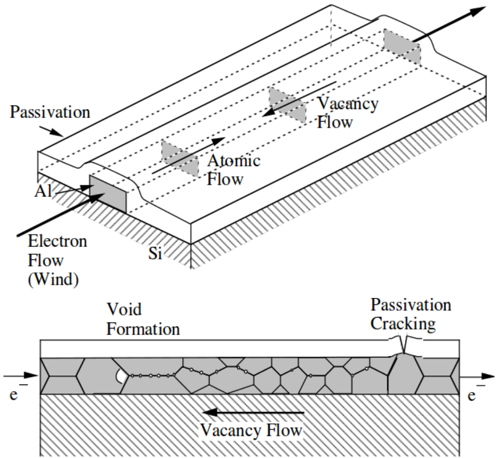
- Thin Film Buckling



Metal Crack Problem in Interconnect Metals



Electromigration Problem for Interconnect Metals



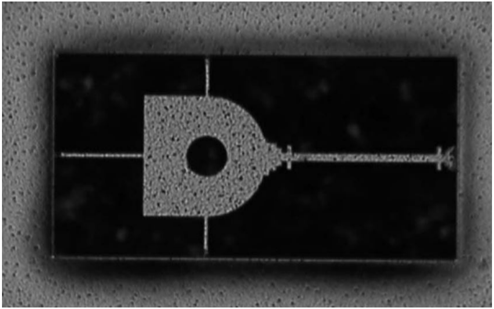
Methods for Mechanical Characterization of Thin Films

- At present there are no specific ASTM Standards for testing of Thin films
- Standard methods for bulk materials are scaled down to fit the thin film specimen geometry
- Some of the Testing techniques presently used are:
  - Micro-Tensile Testing
  - Nano Indentation method
  - Wafer/Substrate Curvature Testing
  - Pressurized Bulge Test
  - Adhesion Testing (Thin films to its Substrate)

MICRO TENSILE TESTING

- Problems with conventional testing methods
  - thin film separation
  - gripping of the sample
  - sensitivity
  - stress and strain measurements
- Fabrication of Micro-Tensile test specimen
  - Silicon frame tensile specimen
  - Photo lithographic patterning
  - Selective etching of Silicon substrate
  - Silicon frame cutting
- Force measurement - using load cells
- Displacement measurement - using interferometric techniques

Micro-Tensile test specimen



Fabrication of Micro-Tensile test specimen.[4]

- Silicon frame tensile specimen
- Photo lithographic patterning
- Selective etching of Silicon substrate
- Silicon frame cutting

Micro-Tensile testing

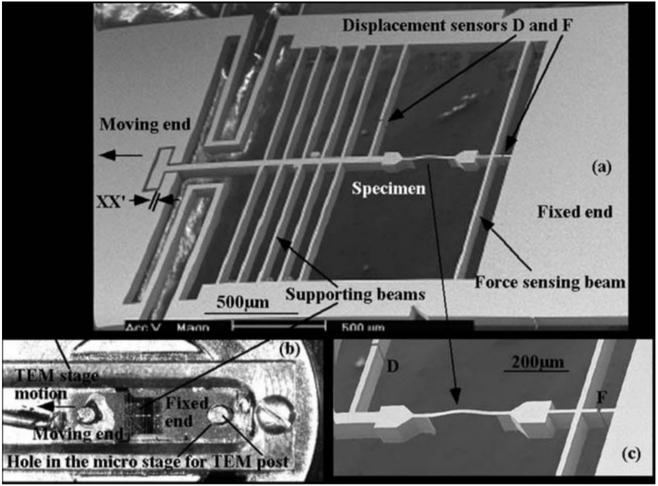
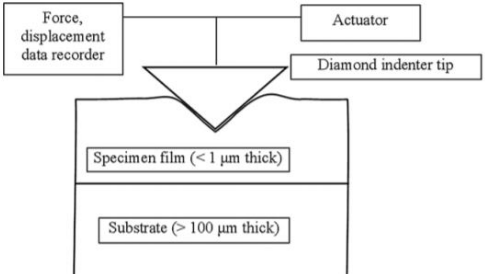


Figure3:Tensile specimen assembly including aluminum tensile specimen and MEMS support assembly and force gage for use in the TEM.[4]

NANO INDENTATION TESTING

- Similar to the conventional hardness test, but is performed on a much smaller scale by use of specialized equipment
  - A nano-intender
- The force(P) required to press a sharp diamond indenter into tested material is continuously recorded as a function of the indentation depth(h)



Nano Indentation Testing

- Measurement of Elastic Modulus of Thin Film

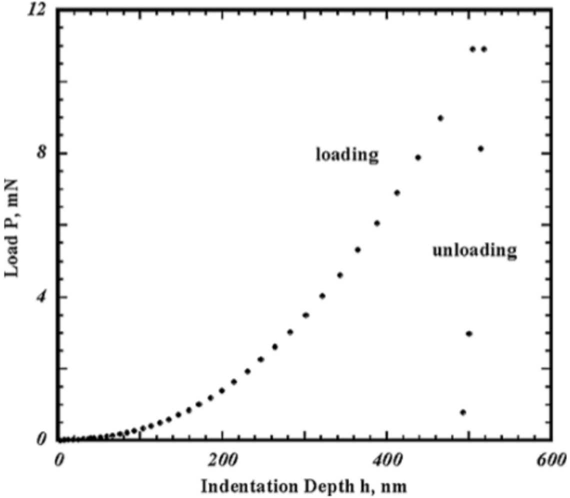


Figure4:Load-depth record from an instrumented indentation test of an electrodeposited Cu film $1\mu m$ thick.[4]

Nano Indentation Testing

- $E_r = \frac{\sqrt{\pi}}{2} * \frac{dP}{dh} * \frac{1}{\sqrt{A}}$
  E_r is the reduced Elastic modulus of the sample
  S is stiffness $\frac{dP}{dh}$, taken for unloading portion of curve.
  A is contact Area
- $\frac{1}{E_r} = \frac{1-\nu_i^2}{E_i} + \frac{1-\nu_f^2}{E_f}$
  ν_i is the Poisson's ratio of the intender
  ν_f is the Poisson's ratio of the thin film
  E_i is the indenter's elastic modulus
  E_f is the thin film's elastic modulus

Nano Indentation Testing

- Hardness is defined as the ratio of indentation load and projected contact area:
  $H = \frac{P_{max}}{A_{projected}}$
- For a metal film the yield stress, σ_{ys}, can be taken as the $1/3$ of the hardness measured by nano-indentation, or more accurately it can be extracted from the extent of the plastic zone size around the indenter, c:
  $\sigma_{ys} = \frac{3P_{max}}{2\pi c^2}$

Interpretation of Experimental Values

Material	Fabrication Method	Thickness(μm)	Yield Strength(MPa)	UTS(MPa)/Hardness(GPa)	Young's Modulus(GPa)
Microtensile Test[2]					
Al	e-beam evaporated method	1	94	151	24-30
Cu	e-beam evaporated method	1	160	-	125-129
Au	e-beam evaporated method	1	90	-	53-55
Nano Indentation Test[4]					
Cu	electro-deposited annealed	0.5	-	1.04-1.27	121-132
Cu	electro-deposited annealed, polished	0.5	-	1.21-1.29	131-138

Reviews of the mechanical properties of thin films have appeared over the years. The general conclusions formulated are still relevant:

- The elastic properties of thin films ordinarily do not differ greatly from bulk properties, and Youngs moduli measured by various techniques do not differ greatly.
- The thinner the films, the greater are the hardness and strength.
- Specimen preparation methods and the structure of the films have a significant effect on the mechanical properties of the films.

Grain size and structural size effects

- Hall-Petch rule
  - Strength increases with the inverse square root of the grain size
  - Thin films(up to certain small grain size) have higher strengths than bulk materials of the same chemical composition.
- Low Elongation to Failure
  - Very low values are not commonly interpreted to mean that the film lacks the capacity for plastic deformation, but rather is considered to be a geometric effect.
- Young's modulus
  - young's modulus values generally match with the bulk materials but significantly depend on the experimentation method.[4]

Grain Size Effects

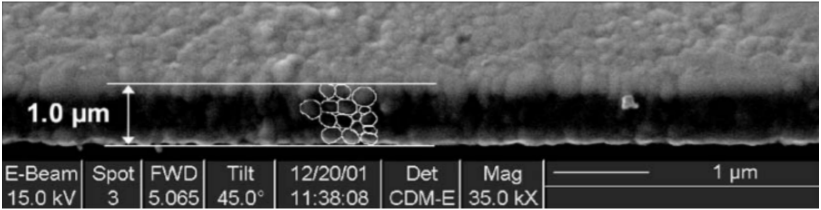


Figure5:SEM image of Au membrane highlighting the number of grains through the film thickness. average grain size is 250-300nm.[2]

Structural Size Effects

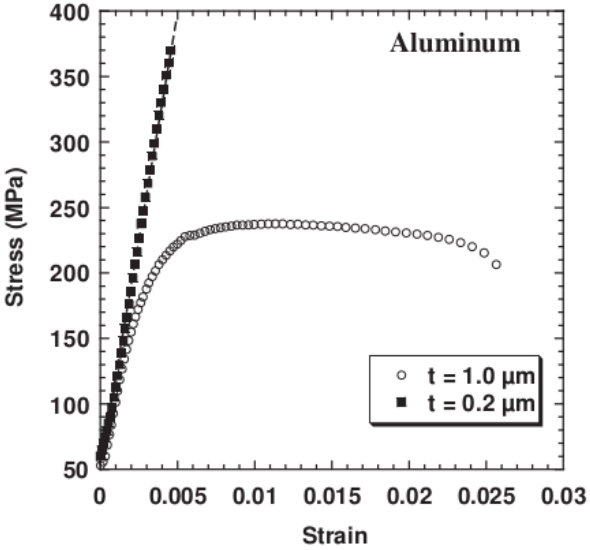


Figure5:Stress strain plots for Al membranes showing effects of specimen thickness[2]

Thin Films in Modern Microprocessor

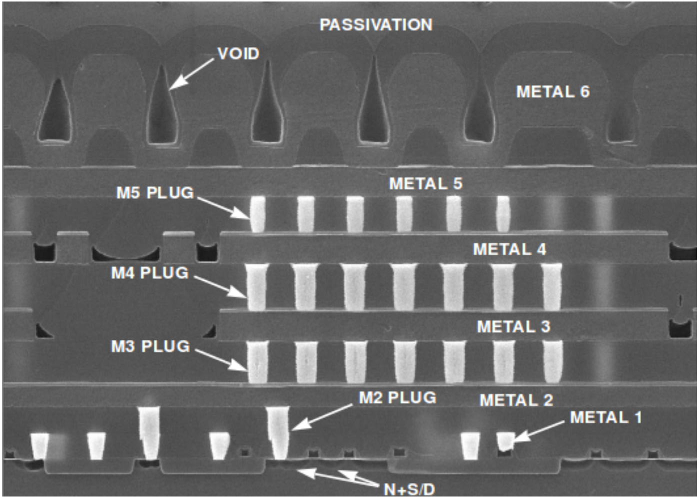


Figure6:SEM section view of AMD K6 Microprocessor[1]

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