Low- κ Dielectrics

Prof. Krishna Saraswat

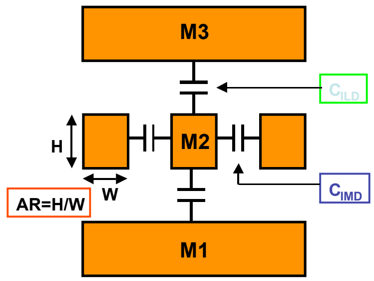
Department of Electrical Engineering
Stanford University
Stanford, CA 94305
saraswat@stanford.edu

Performance Metrics

- **Signaling**
  - Delay
  - Power dissipation
  - Bandwidth
  - Self heating
  - Data reliability (Noise)
  - Cross talk
  - ISI: impedance mismatch
  - Area
- **Reliability**
  - Electromigration
- **Clocking**
  - Timing uncertainty (skew and jitter)
  - Power dissipation
  - Slew rate
  - Area
- **Power Distribution**
  - Supply reliability

- **Depend on R, C and L !**
- **Function and length dictates relative importance**

Interplay Between Signaling Metrics



RC-Delay

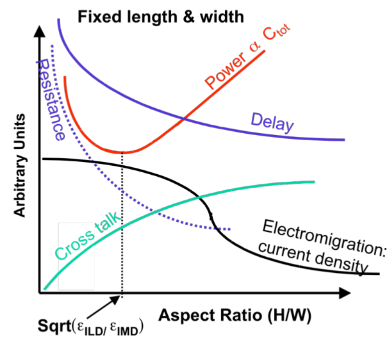
$$\tau \propto RC_{inttot}$$

Power

$$P = \alpha C_{inttot} V^2 f \propto C_{inttot}$$

Crosstalk

$$X_{talk} \propto \frac{C_{IMD}}{C_{inttot}} = \frac{1}{1 + \frac{\left(\varepsilon_{ILD}/\varepsilon_{IMD}\right)}{AR^2}}$$



- AR increase (tradeoffs)=>
  - Better delay and electromigration
  - Worse power and cross talk
- Increasing aspect ratio may not help

•Pay attention to different metrics simultaneously
•Design window quite complex
•Capacitance very important

Dielectric Constant

- The dielectric constant, κ, is a physical measure of the electric polarizability of a material
- Electric polarizability is the tendency of a material to allow an externally applied electric field to induce electric dipoles (separated positive and negative charges) in the material. Polarization **P** is related to the electric field **E** and the displacement **D** by

$$\mathbf{D} = \varepsilon_o \mathbf{E} + \mathbf{P}$$

- ***P** is related to **E*** through χ_e the electric susceptibility of the dielectric

$$\mathbf{P} = \varepsilon_o \chi_e \mathbf{E}$$

$$\text{Therefore } \mathbf{D} = \varepsilon_o (1+\chi_e)\mathbf{E} = \varepsilon_o \kappa \mathbf{E}$$

where ε_o is the permittivity of the free space.

Note that **P** *also* is the density of atomic electric dipole per unit volume

$$\mathbf{P} = \Sigma \mathbf{p}/V = N\mathbf{p}$$

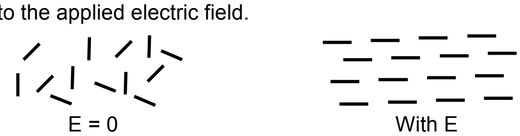
where **p** is the dipole moment and *N* is the density of dipoles

Components of Dielectric Polarization

- In solid state matter, there are three polarization mechanisms:
  1. **Electronic polarization** occurs in neutral atoms when an electric field displaces the nucleus with respect to the electrons that surround it.
     - Example: Hydrogen atom, Si, Ge

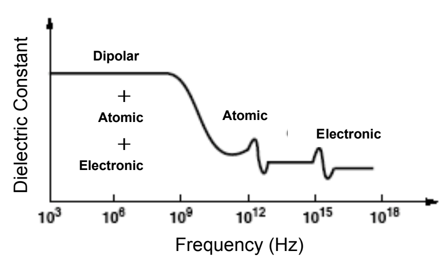
  2. **Atomic or ionic polarization** occurs when adjacent positive and negative ions stretch under an applied electric field.
     - Example: NaCl, most dielectrics
     - Compond semiconductors (GaAs, SiC have both electronic and ionic polarization)

  3. **Dipolar or orientational polarization** occurs when permanent dipoles in asymmetric molecules respond to the applied electric field.
     - Example: H_2O



Components of Dielectric Polarization

- In a perfect vacuum, there are are no atoms to polarize, making $\chi_e = 0$ and k = 1.
- Each polarization mechanism has an associated response time and therefore will not contribute to k beyond some corresponding frequency.
- At the frequency of interest to us all 3 mechanisms contribute to polarization but relative contributions may vary from material to material



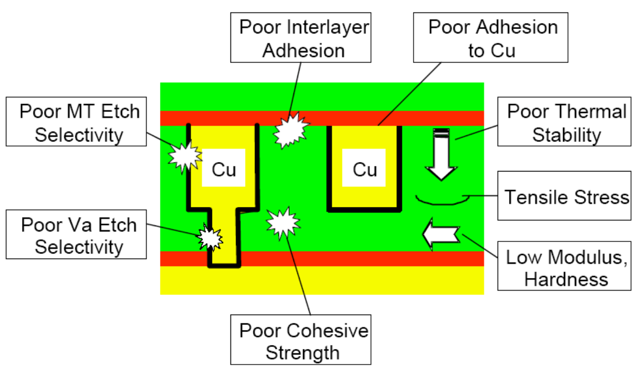
Low Dielectric Constant

A low- k dielectric is an insulating material that exhibits weak polarization when subjected to an externally applied electric field. A few practical approaches to design low- k materials are:

- Choose a nonpolar dielectric system. For example, polarity is weak in materials with few polar chemical groups and with symmetry to cancel the dipoles of chemical bonds between dissimilar atoms.
- Since k_{air} = 1, dielectrics can also have lower effective k with the incorporation of some porosity into the chemical structure.
  - ➢ Materials where atoms are far apart (remember $\boldsymbol{P} = N\boldsymbol{p}$)
  - ➢ Add physical porosity
- Minimize the moisture content in the dielectric or alternatively design a dielectric with minimum hydrophilicity. Since k *water* ~ 80, a low-k dielectric needs to absorb only very small traces of water before losing its permittivity advantage.

Challenges for Low-κ Materials

Weak Thermo-Mechanical Strength: 10x worse than SiO_2 in almost every category of thermo-mechanical properties.



Ref: C.-H. Jan, IEDM Short Course, 2003

Dielectric Constant Reduction Methods

- **Reduce polarization strength and density.**
- **Reduce Si-O density: SiO_2 (k=4)**
- **Incorporate F: SiOF(k =3.7)**
- **Incorporate CH3-: SiOC(H) (k=2.8)**
- **Use low polarization polymer:**

Bond	C–C	C–F	C–O	C–H	O–H	C=O	C=C	C≡C	C≡N
Polarizability (Å)	0.53	0.56	0.58	0.65	0.71	1.02	1.64	2.04	2.24

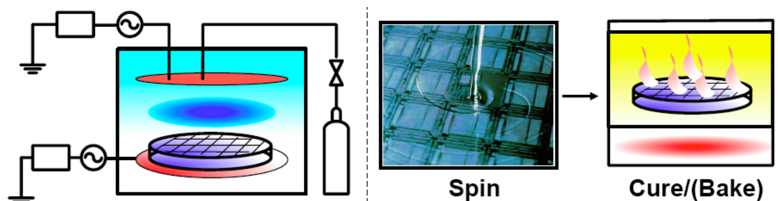
(Ref.: K.J. Miller et al., Macromolecules, *23*, 3855 (1990).)

Low Dielectric Constant (Low-k) Materials

Oxide Derivatives	
F-doped oxides (CVD)	k = 3.3-3.9
C-doped oxides (SOG, CVD)	k = 2.8-3.5
H-doped oxides (SOG)	k = 2.5-3.3
Organics	
Polyimides (spin-on)	k = 3.0-4.0
Aromatic polymers (spin-on)	k = 2.6-3.2
Vapor-deposited parylene; parylene-F	k ~ 2.7; k ~ 2.3
F-doped amorphous carbon	k = 2.3-2.8
Teflon/PTFE (spin-on)	k = 1.9-2.1
Highly Porous Oxides	
Xerogels/Aerogels	k = 1.8-2.5
Air	k = 1

Deposition Methods –CVD vs. Spin-on

Industry split between CVD and spin-on. Currently CVD dominates for k > 2.5 and spin-ons dominate at k < 2.5 porous films (< 65 nm).



CVD:
- Proven technology
- No cure step.
- Mechanical strength ↑.
- Easier integration.
- By equipment vendors

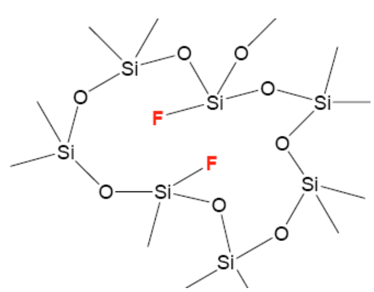
Spin-on:
- Done on track.
- Need post treatment.
- Mechanical strength ↓.
- By materials suppliers.

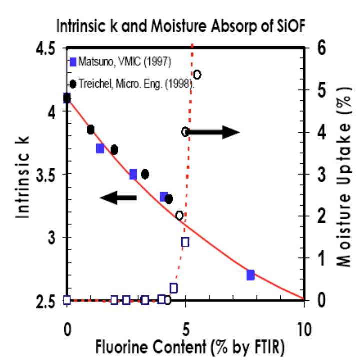
Ref: C.-H. Jan, IEDM Short Course, 2003

SiOF (F-Silicate Glass) k ~ 3.5 –4.5

- **Basic Process Chemistry:**

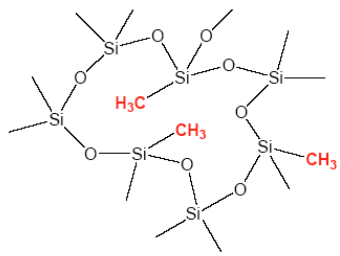
  SiH4+ SiF4+O2→$SiO_xF_y(H)_z$ (HDP/PECVD, T> 450 °C)
- **Structure: F substitution of O in the 3D network of Si and O.**
- **Properties:**
  - **k: 3.6 –3.9.**
  - **k <3.5 and F > 4% not stable with high moisture adsorption.**





CVD Organo Silicates k ~ 2.5 –3.5

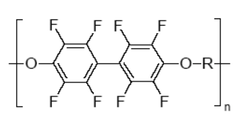
- CDO (Carbon Doped Oxide), OSG (Organo Silicate Glass), SiOC
- Proven CVD technology for 90 nm node.
- k ~ 3.5 to 2.5 with decreasing mechanical strength



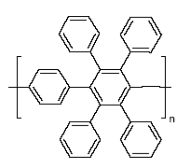
Structure

Spin-on Organics: k ~ 2.5 –3.5

SOP (Spin-On Polymer)



F-PAE
(F-Poly Arylene Ether)
k ~ 2.6,
T_{dcomp}< 540 °C'
(FLARE™)

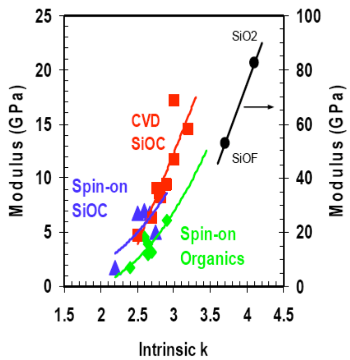


Polyimide, BCBTM, ---

Aromatic Polymer
k ~ 2.6,
T_{dcomp}> 500 °C'
(SiLK™)

Issues: Weak mechanical strength (hardness, modulus), poor thermal stability, poor adhesion (can be improved with adhesion promoter), high CTE.

Mechanical Properties

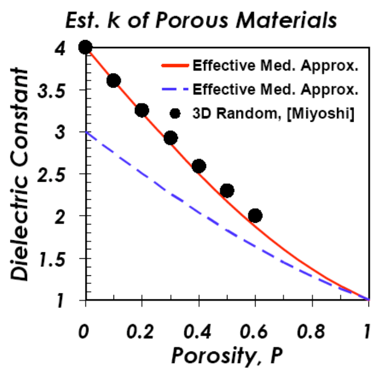


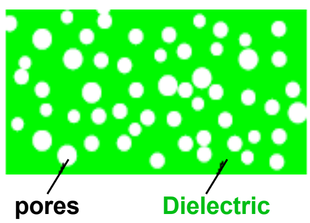
Mechanical Strength:
- CVD SiOC > Spin-on SiOC > Spin-on Organics
- SiO_2, SiOF 10x of low k

Adhesion:
- SiO_2, SiOF 10x of low k
- Spin-on Organic > CVD SiOC
- Blister, Cracking and Delamination.

Dielectric Constants and Porosity

Dielectric constants can be lowered via porosity (air = 1).





Ref: C.-H. Jan, IEDM Short Course, 2003

Porous Materials

Material Options:

- Porous Silicate Glass
- Xerogel/Aerogel
- Porous Organo Silicate Glass
- Porous SSQ
- Porous Organics
- Porous SiLK

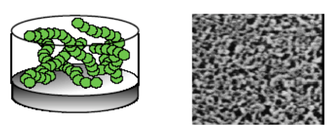
Spin-on Sol-Gel is the most common approach.

<u>Sol-Gel Process:</u>

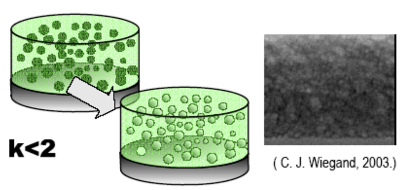
- Sol: (Organo) Silicate or Organic matrix forming a 3-D polymerization network in solvent.
- Gel: Organic solvent and “structure directing” molecules (templates, porogen(pore generator)) blend in polymerization network.
- Heat treatment to remove solvent and porogen, and leave porous framework.

Synthesis Methods

- **Solvent Extraction**
  - **Gel = solvent**
  - **Random structures**
  - **Open, non-uniform pores**
  - **Ex.: Aerogel/Xerogel, k<1.5**

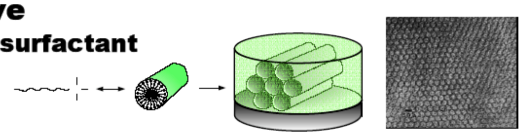


- **Molecular Template**
  - **Gel = solvent+porogen**
  - **Ordered amorphous**
  - **Non-uniform pores**
  - **Ex.: P-MSQ, p-Organics, k<2**



(C. J. Wiegand, 2003.)

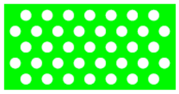
- **Molecular Sieve**
  - **Gel = solvent+surfactant**
  - **Ordered X’tal**
  - **Open pores**
  - **Ex.: MCM-41™**



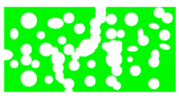
(J.S. Beck, et al., JACS (1992).)

Pores Distribution

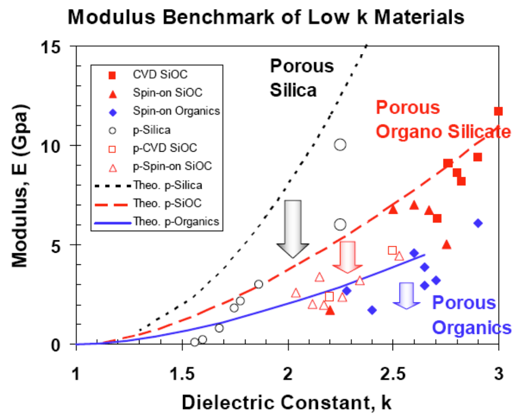
Poor pores distribution ⇒ weak mechanical strength



Desired:
- Uniform
- Ordered
- Small
- Closed



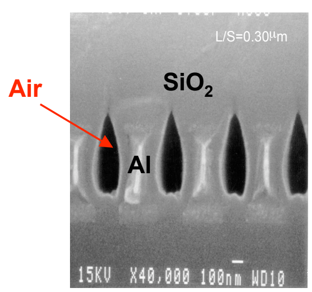
Undesired:



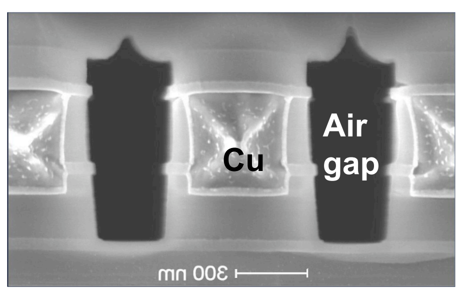
Ref: C.-H. Jan, IEDM Short Course, 2003

Air-gap as Low-k Dielectrics

Air-Gap Interconnect Structure



Ref: Shieh, Saraswat & McVittie. IEEE Electron Dev. Lett., January 1998



Source: Werner Pamler, Infinion

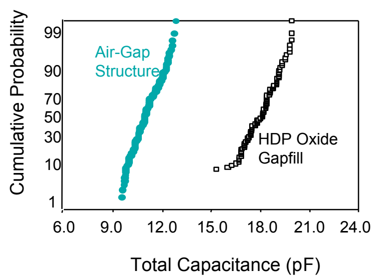
Old dielectric SiO_2 K = 4

Ultimate limit is air with K = 1

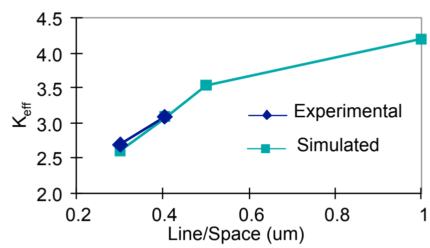
Air-gap Experimental Data

0.3μm line/space

Capacitance



K_{eff} vs. Feature Size

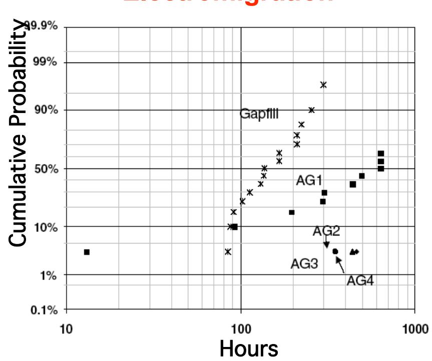


Significant reduction in capacitance

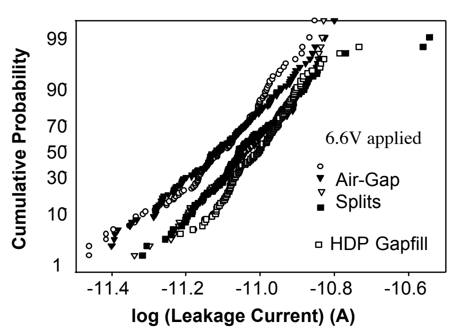
Ref: Shieh, et al., IEEE IITC, 1998

Air-gap Reliability

Electromigration



Leakage



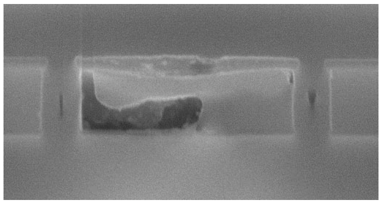
✓ Air-Gap splits show significantly longer lifetimes than Gapfill split
✓ Leakage data indicates no breakdown well above operating voltage.

Ref: Shieh, et al., IEEE IITC, 2002

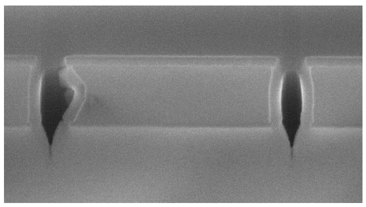
Reduced Stress in Air-gap Structures

FIB Mill Cross-Section

HDP Gapfill Dielectric



Air-gap Dielectric



- Rigid gapfill dielectric unable to deform and reduce stress during electromigration.
- Flexible air-gap sidewall deforms
- Air-gaps lower the effective modulus of the dielectric.
- Lower modulus reduces stress during electromigration.
- Effect of air-gap on modulus is greater in high aspect ratio lines.

Ref: Shieh, et al., IEEE IITC, 2002