Glass and Glass-Ceramics for Wireless Communication

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LTCC devices for RF Front-end

- Chip L, C
- LPF
- Switch
- Diplexer
- (Antenna-Switch Module)
- ANT
- A_Rx
- A_Tx
- B_Rx
- B_Tx
- VCO/PLL
- VCO
- Coupler
- PA
- Balun
- Balance BPF
- LNA
- BPF
- BPF
- Balun
- Coupler
- Switch
Why Ceramics ????????
Dielectric Constant

- FR4/Cu: 4.0
- LTCC/Ag: 5-100

@4GHz
Dielectric Loss

FR4/Cu: 2.5%  
LTCC/Ag: 0.02-0.25%

@4GHz
Temp. Coefficient of Resonant Frequency ($T_f$)

$T_f \approx -\frac{1}{2} T_k \frac{1}{T_{CE}} \text{ m/K}$

$T_k$: Temperature coefficient of capacitance

TCE: Thermal expansion coefficient

FR4/Cu  LTCC/Ag
Thermal Expansion Coefficient

- Plastics: 25 ppm/k
- Ceramics
- Si: 10 ppm/k
- GaAs: 5 ppm/k
Why LTCC ?????
Low Temperature Cofired Ceramics

<1000 °C

One fire

Ceramic base
Electrical Resistivity of Conductors

1/\(Q_t\) = \(1/Q_m\) + \(1/Q_c\)

Resitivity (x10^{-6} ohm-cm)

- W
- Ni
- Cu
- Ag
- Au
Melting Point of Conductors

<table>
<thead>
<tr>
<th>Metal</th>
<th>Melting Point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>3300</td>
</tr>
<tr>
<td>Ni</td>
<td>2000</td>
</tr>
<tr>
<td>Ag</td>
<td>1000</td>
</tr>
<tr>
<td>Cu</td>
<td>1000</td>
</tr>
<tr>
<td>Au</td>
<td>1000</td>
</tr>
</tbody>
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LTCC Materials and Processes

Dielectric:
  * Glass-Ceramics, Glass+ceramics
  * Dielectric Constant: 5-100
  * Dielectric Loss: 0.01-0.5%

Conductors: Ag, Cu and Au

Resistors: RuO$_2$+Glass

Firing conditions:
  * Temp.: $800-1000^\circ$C
  * Time: 10-60 min
  * Atmosphere: Air, H$_2$+N$_2$+H$_2$O
Low Temperature Cofired Ceramics

<1000 °C
One fire
Ceramic base

Diagram:
- Raw Materials
- Slurry
- Tape Casting
- Blanking
- Via Punching
- Via Filling
- Screen Printing
- Laminating
- Cutting
- Co-firing
- Terminating
- Electroplating
Integrated RF Module

- Resistor Wire-bonded bare chip
- Soldered flip-chip
- Buried capacitor (high-K tape or paste)
- Thin-film capacitor
- Via
- MIM capacitor
- Buried resistor
- Mixed-K Substrates
- Shielding or GND pad
- Inductor or interconnect line
- SMT I/O
- GND
- SMT I/O
- Thermal via
Cofiring Defects
LTCC Solutions to Bluetooth

- Chip Antenna
- Band Pass Filter
- Low Pass Filter
- Coupler
- Balun
- Module
- Inductors
LTCC Market in Wireless Communication

- Bluetooth: 2001, 2005
- Handset: 2001, 2005
- WLAN: 2001, 2005
Design of LTCC Compositions

Type 1: Glass+Ceramics
e.g., DuPont 951

Type 2: Glass-Ceramics
e.g., Ferro A6

Type 3: Glass±Ceramics
e.g., Heraeus CT2000

Diagram:
- Green: Glass
- Sintered: Crystalline phase
- Filler
- \( \text{Al}_2\text{O}_3 \)
Type I: Glass+Ceramics

Glass: PbO, K₂O, B₂O₃, SiO₂
\[ V_{\text{glass}} : 60-70\% \]

Ceramic Filler: Al₂O₃
\[ V_{\text{Al₂O₃}} : 30-40\% \]

\[ \frac{1}{Q_m} = (V/Q)_{\text{glass}} + (V/Q)_{\text{alumina}} \]
\[ Q_m = 200-300 \]

\[ \frac{1}{K_m} = (V*K)_{\text{glass}} + (V*K)_{\text{alumina}} \]
\[ K_m = 4-8 \]

Dielectric Mixture

Sintering
\[ 850 \sim 900 \, ^\circ C \]

Glass
\[ K = 6-7 \]
\[ Q = 100-150 \]
\[ V_{\text{glass}} = 60-70\% \]

Al₂O₃
\[ K = 10 \]
\[ Q = 10000 \]
\[ V_{\text{Al₂O₃}} = 30-40\% \]
Uniaxial Viscosity (Ep)

Processing robustness
--“Fool-Proof” systems

Heating rate
**Type II: Glass-Ceramics**

Glass: CaO, K₂O, B₂O₃, SiO₂  
\( V_{\text{glass}} : 100\% \)

Sintering  
850~900 °C

Residual glass: B-rich  
K=5-6  
Q= 100-150  
\( V_{\text{glass}} =20-40\% \)

Wollastonite  
K = 5-6  
Q = 1000  
\( V_{\text{Al}_2\text{O}_3} =60-80\% \)

Dielectric Mixture  
\[
1/Q_m = (V/Q)_{\text{glass}} + (V/Q)_{\text{alumina}} \quad Q_m = 500-700
\]
\[
1/K_m = (V*K)_{\text{glass}} + (V*K)_{\text{alumina}} \quad K_m = 5-6
\]
Effect of heating rate on densification

![Graph showing the effect of heating rate on densification. The graph plots temperature (°C) on the x-axis and free uniaxial strain at Z axis on the y-axis. Three curves are shown for different ramp rates: 1 °C/min (red), 5 °C/min (green), and 10 °C/min (blue). The curves indicate an increase in strain with increasing temperature.]

- High
Effect of Crystallization on Viscosity & Densification

Smart System
Interfacial Reaction between Ag and LTCC
Type III: Glass±Ceramics

Glass: $K_2O, B_2O_3, SiO_2$  
$CaO, SrO, BaO$

Ceramic Filler  
$Al_2O_3$

$T_f$ Adjuster  
$TiO_2$

Sintering 850~900 °C

Residual Glass  
$Q \sim 350$

$V_{glass}$

CaAl$_2$Si$_2$O$_8$, $Q=1300$  
SrAl$_2$Si$_2$O$_8$, $Q=1300-10000$  
BaAl$_2$Si$_2$O$_8$, $Q=10000$

$V_{cryst.}$

Al$_2$O$_3$, $Q = 10000$  
$V_{AI2O3}$

$TiO_2$

Dielectric Mixture

$1/Q_m = (V/Q)_{glass} + (V/Q)_{alumina}$  
$Q_m = 900-1200$

$1/K_m = (V*K)_{glass} + (V*K)_{alumina}$  
$K_m = 8-10$
Prevention of Bloating

Pure glass

40 vol% Al$_2$O$_3$
Effect of Al$_2$O$_3$ on Crystallization

- Pseudowollastonite
- Cristobalite

- Alumina
- Anorthite

- 10 µm

- 500 nm
Effects of Alumina Content and Size on Densification
Effects of Alumina Content and Size on Densification

- Alumina Content (vol%)
- Al₂O₃ Size (µm)

- bloating
- poor densification

- 800°C
- 850°C
- 900°C
Effect of Heating Rate on Densification

![Graph showing the effect of heating rate on densification. The graph plots temperature (°C) against shrinkage (%). The x-axis represents temperature ranging from 600 to 1100 °C, and the y-axis represents shrinkage ranging from -25% to 0%. The heating rate is indicated by different colors and ranges from 0.5 °C/min to 20 °C/min.](image-url)
Effect of Crystallization on Dielectric Properties

The graph shows the change in dielectric constant and loss over time. As the crystallization time increases, the dielectric constant increases, while the loss decreases. The anorthite content also shows a significant change, increasing with time.
Glasses in LTCC

* $K = 5-100$
* $Q > 1000$
* Low-fire: 850-900°C
* Non-crystallizable preferred
* Lead-free
* Insignificant reaction with Ag
* Excellent leaching resistance