Integrated Passives Technology Embedded Capacitor Films (ECFs) and Ink-Jet Resistors

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Integrated Passives Technology Embedded Capacitor Films (ECFs) and Ink-Jet Resistors

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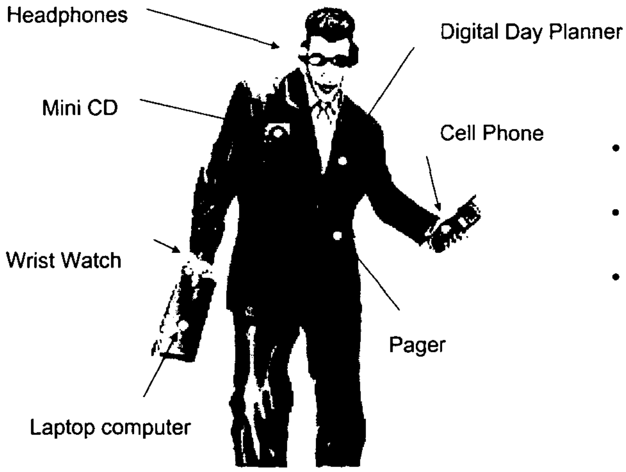
Outline

- **Introduction**
  - ✓ Embedded Capacitors & Resistors
- **Embedded Capacitors**
  1. Embedded Capacitor Films(ECFs) Fabrication
  2. Properties of ECFs
     - ✓ Tolerance
     - ✓ Dielectric Constant
     - ✓ Leakage Current
     - ✓ Adhesion Strength
- **Embedded Resistors**
  - ✓ Ink-jet resistors fabrication

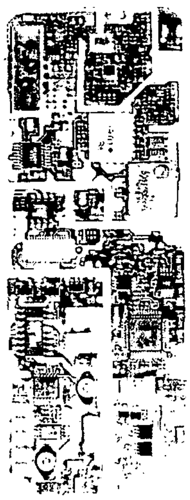
Trends of Electronic Packaging



- ***Miniaturization***
- ***Light Weight***
- ***High Performance***

Active Components vs. Passive Components

- **Cellular phone**



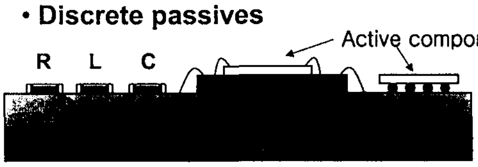
제품	수동소자 수	전체 IC 수	비율
<u>휴대폰</u>			
Ericsson DH338 Digital	359	25	**14:1**
Ericsson H237 Analog	243	14	**17:1**
Philips PR93 Analog	283	11	**25:1**
Nokia2110 Digital	432	21	**20:1**
Motorola Mrl 1.8 GHz	389	27	**14:1**
Casio PH-250	373	29	**13:1**
Motorola StarTAC	993	45	**22:1**
Matsushita NTT DoCoMo	492	30	**16:1**
<u>휴대용 전자 제품</u>			
Motorola Tango Pager	437	15	**29:1**
Casio QV10 Digital Camera	489	17	**29:1**
1990 Sony Camcorder	1226	14	**33:1**
Sony Handy Cam DCR-PC7	1329	13	**31:1**
<u>기타 통신 제품</u>			
Motorola Pen Pager	142	3	**47:1**
Infotac Radio Modem	585	24	**24:1**
Data Race Fax-Modem	101	8	**13:1**
<u>**PDA**</u>			
Sony Magic Link	538	74	**7:1**

휴대폰의 경우 수동 소자가 PCB 면적의 50% 이상 차지

Embedded Passives

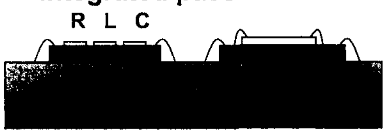
❑ What is Embedded Passives?

- Discrete passives



- Embedded passives

- Integrated passives



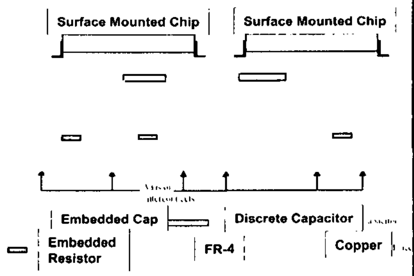
❑ Advantages of Embedded Passives

- Smaller area
- Shorter interconnection length (low parasitic loss)
- Less solder joints

⇨

- Miniaturization
- Higher electrical performance
- Better reliability

Applications of Embedded Passives

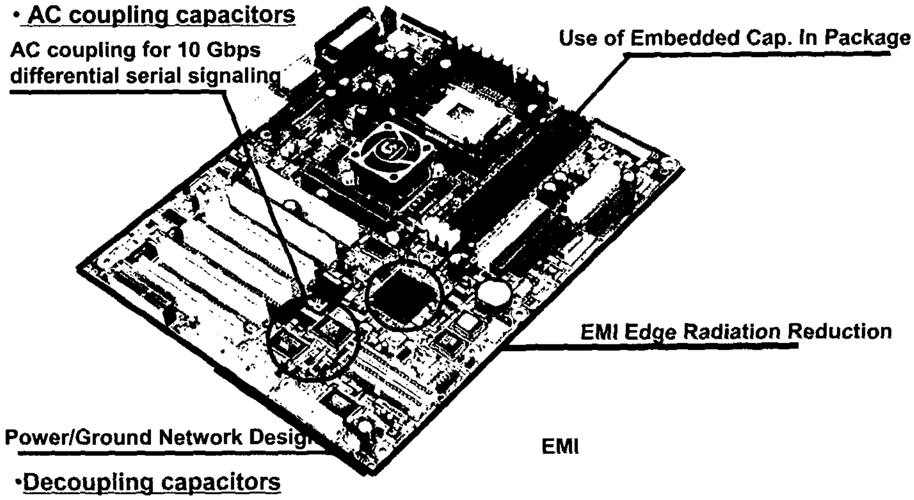


◆ Resistors (50%)
- Termination resistors (20~100 Ω)
- Pull-up/down resistors (1~30 KΩ)

◆ Capacitors (40%)
- Decoupling capacitor for simultaneous switching noise(SSN) suppression (10~100 nF)
- Bypass, EMI filter, timing capacitor (10~100 pF)

◆ Inductors (10%)

Applications of Embedded Capacitors



Embedded Capacitors

Material Candidates for Embedded Capacitors

▪ **Requirements for embedded capacitors materials for organic substrate**

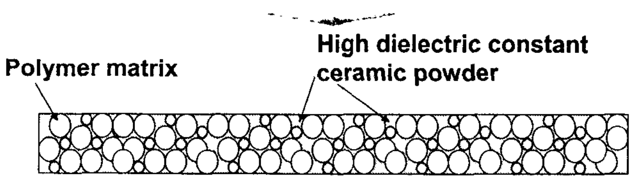
- High dielectric constant (high capacitance)
- Processability (low process temperature)
- Low tolerance (< ±5%)
- Low cost

$$\frac{C}{A} = \varepsilon_0 \varepsilon_r \frac{1}{d}$$

Type	Materials		공정온도	유전상수	두께	Specific Capacitance
Thin film	Al_2O_3		moderate	6~9	200~500 nm	20 (nF/cm^2)
	DLC					
	Ta_2O_5			25	200~500 nm	100
	TiO_2			98	Poor insulation properties	
	$Pb(Zr,Ti)O_3$ -PZT		Very high	Very high	-	-
	$(Ba,Sr)TiO_3$ -BST					
Thick film	$BaTiO_3$ Powder	Epoxy resin	low	High	2.5 μm	22
	PMN-PT powder	Polyimide				

Why Polymer/Ceramic Composite?

High dielectric constant of ceramic powders + **Good processability & Low cost of polymers**



- **Epoxy/$BaTiO_3$ composite**
  - $BaTiO_3$: well-known high dielectric constant ceramic powder
  - Epoxy: compatible with PWB

Current Status in Polymer/Ceramic Composite Capacitors

- **Spin coating method using colloidal solution**
  - ➢ **Thin dielectric layer formation**
  - ➢ **High waste of materials (>90%)**
  - ➢ **Large capacitance tolerance**
    - Non-uniform coating thickness over large area

- **유사 제품 상용화 현황 - 초보적 수준**
  - ➢ **3M : 유전상수 15~23의 제품 상용화 - 낮은 유전상수**
  - ➢ **Dupont: 유전상수 10의 제품 상용화 - 낮은 유전상수**
  - ➢ **Sanmina 특허**

New Capacitor Materials are needed!!!

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➢ Embedded Capacitors

1.Embedded Capacitor Films(ECFs) Fabrication

2.Properties of ECFs

✓**Tolerance**
✓**Dielectric Constant**
✓**Leakage Current**
✓**Adhesion Strength**

Material Formulation for ECFs

❑ Ceramic powders & Polymers

❖ High dielectric constant $BaTiO_3$ nano-powder

❖ Specially formulated polymer resin

- Thermosetting Epoxy
  - Thermal stability & Adhesion strength after curing
- Thermoplastic
  - Good film formation capability
  - Film flexibility in B-stage

- Epoxy curing agent
- Dispersion agent
- Solvent

Film formation process

❑ ECF fabrication procedure

BT powder, dispersant, solvent mixing

↓

Ultrasonic & ball milling

↓

Polymer resin & curing agent mixing

↓

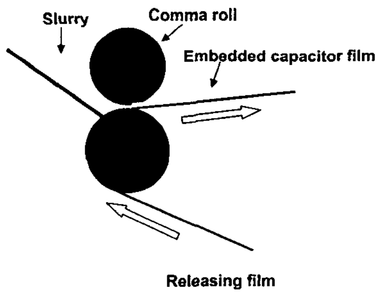
Ball milling

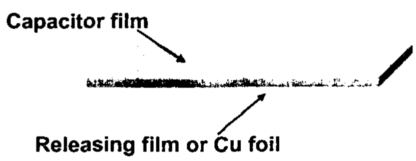
↓

Film coating on releasing film or metal foil

↓

Solvent drying

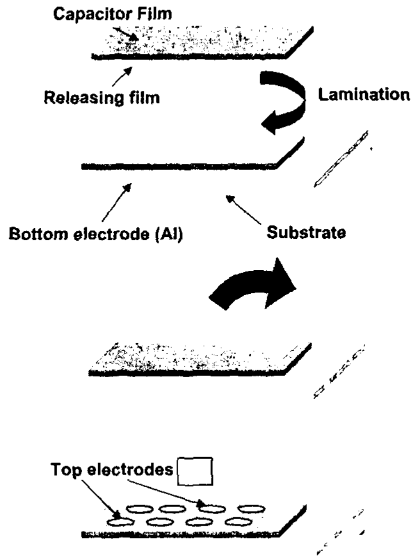




Capacitors Fabrication Process

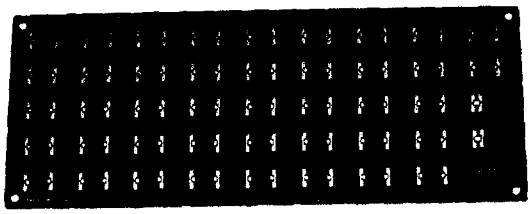
❑ Capacitors fabrication & measurement

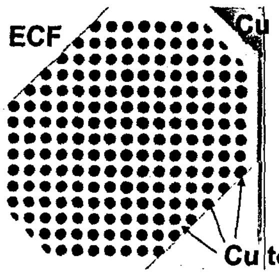
Lamination 50psi, 180°C for 10min
Top electrodes deposition Cu sputtering: 1μm
Capacitance measurement 42 dots, 100kHz

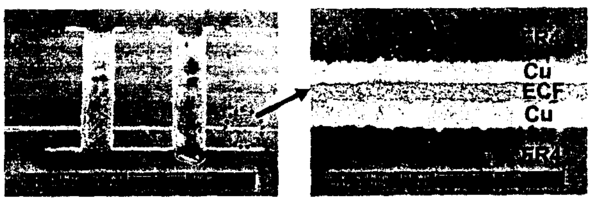


ECF Fabricated on PCB

14 cm × 5.5 cm







×50 ×500

➢ Embedded Capacitors

1. Embedded Capacitor Films(ECFs) Fabrication

2. Properties of ECFs

- ✓ Tolerance
- ✓ Dielectric Constant
- ✓ Leakage Current
- ✓ Adhesion Strength

Characteristics of ECF Capacitors

❑ Typical tolerance of ECF capacitors

	Bimodal
Thickness	10 μm
Thickness Tolerance(3σ)	± 2.9%
Dielectric constant	93
Dielectric loss	0.03
Specific capacitance	8.24 nF/cm^2
Capacitance tolerance (3σ)	± 4.8 %
Leakage current (A/cm^2)at 10V	5.0×10^{-8} A/cm^2

Test conditions

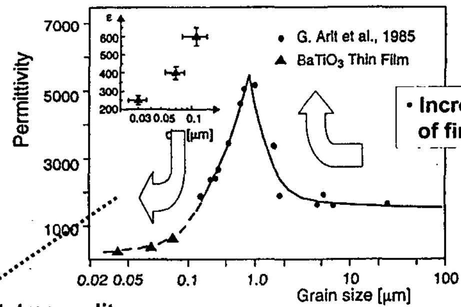
- Test sample size: 10cm×10cm
- Number of dots: 50
- Total number of dots tested: 200
- Dot area: 0.126 cm^2

$$Tolerance(\%) = 100 \times 3\sigma / \overline{R}$$

➢ Embedded Capacitors

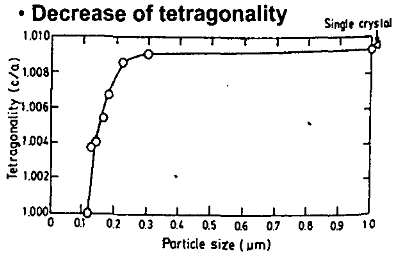
1. **Embedded Capacitor Films(ECFs) Fabrication**
2. **Properties of ECFs**
   - ✓ Tolerance
   - ✓ Dielectric Constant
   - ✓ Leakage Current
   - ✓ Adhesion Strength

Dependence of Dielectric Constant of $BaTiO_3$ on Grain Size



• Increase of 90° domain wall of fine grained $BaTiO_3$

• Decrease of tetragonality



• K. Uchino et al., *J. Am. Ceram. Soc.*, 72 (1989)

• G. Arlt et al., *J. Appl. Phys.*, 58 (1985)

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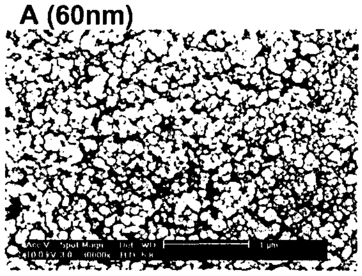
$BaTiO_3$ Powder Size

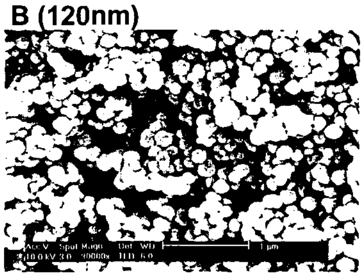
Powder #	Particle size (μm)		Spec. surface area (m²/g) by BET
	Median dia.(d_m)	Average dia. (d_a)	
A	0.06 (0.1)		16
B	0.12 (0.2)		8.2
C	0.151	0.173	13 ± 3
D	0.254	0.334	7.1
E	0.319	0.411	4.0 ± 0.4
F	0.832	0.873	2.4
G	0.916	0.975	2.3

$BaTiO_3$ particles SEM

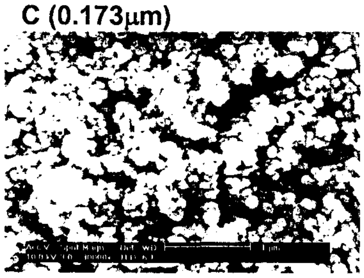
A (60nm)



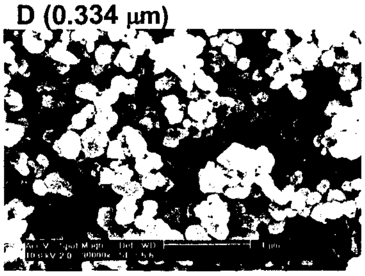
B (120nm)



C (0.173μm)

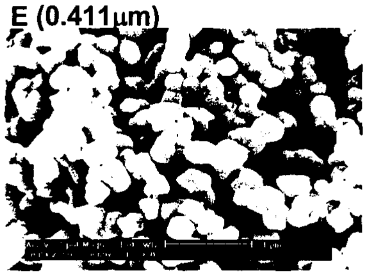


D (0.334 μm)

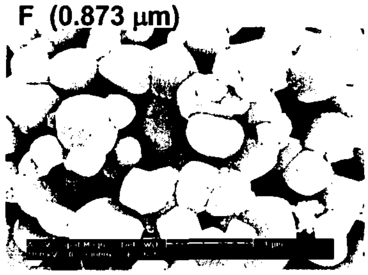


$BaTiO_3$ particle size: SEM

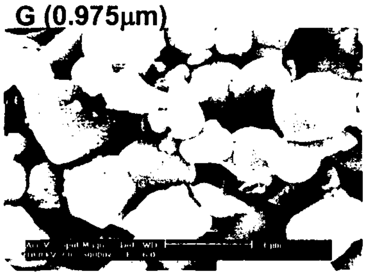
E (0.411μm)



F (0.873 μm)



G (0.975μm)



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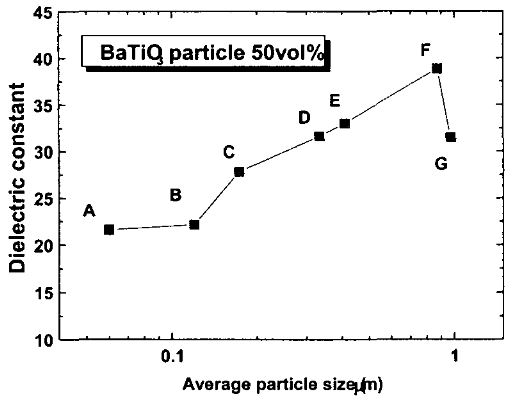
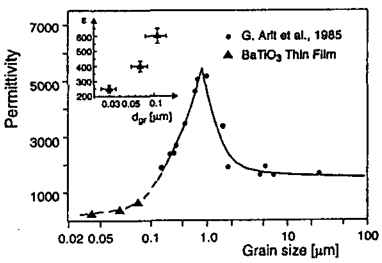
Particle size effects on dielectric constant

- Particle volume fraction: 50vol%





- F (0.87μm) powder showed the highest dielectric constant

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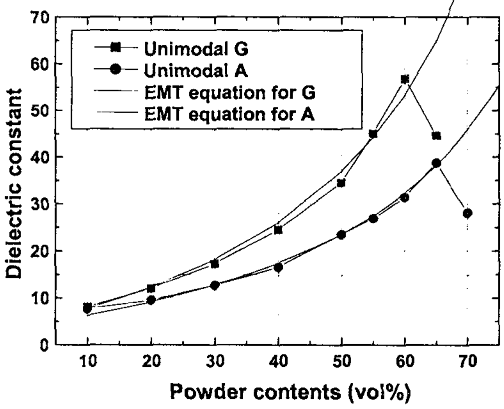
Particle volume fraction effect: Unimodal

G: 0.97μm, A : 0.06μm



• Maximum packing density
G: 60vol%, A: 65vol%

• Modified EMT equation

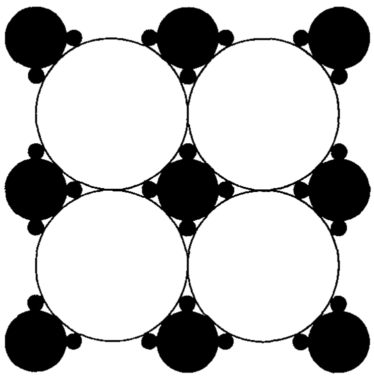
$$\varepsilon = \varepsilon_p [1 + \frac{f_c(\varepsilon_c - \varepsilon_p)}{\varepsilon_p + n(1-f_c)(\varepsilon_c - \varepsilon_p)}]$$

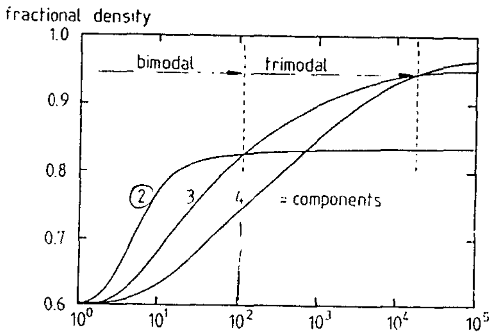
ε_p: dielectric constant of polymer
ε_c: dielectric constant of ceramic
f_c: ceramic particle volume fraction
n: morphology factor

If ε_p=4
For G (0.97μm)
n=0.12, ε_c=5000
For A (60nm)
n=0.18, ε_c=300

Particle volume fraction effect: Multimodal

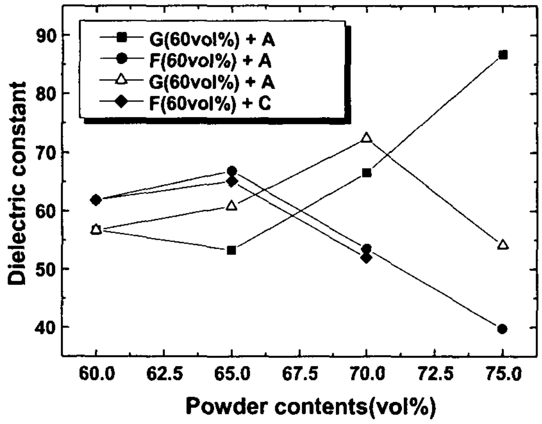
■ Multimodal Packing





• Using trimodal powders, over 90vol% packing is possible
• Size ratio between coarser particle and smaller particle is important

Bimodal Combination



- F(0.87μm) is better for unimodal, but G(0.97μm) was more effective for higher volume loading of bimodal distribution.

➢Embedded Capacitors

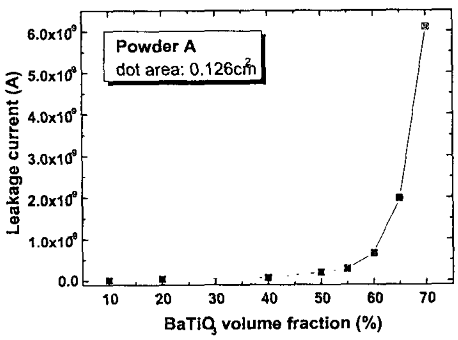
1. Embedded Capacitor Films(ECFs) Fabrication

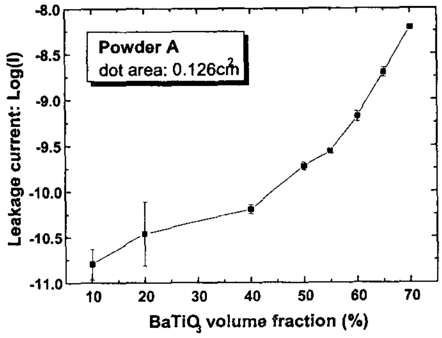
2. Properties of ECFs

- ✓ Tolerance
- ✓ Dielectric Constant
- ✓ Leakage Current
- ✓ Adhesion Strength

BaTiO$_3$ Volume Fraction Effects

- **Measurement condition**
  5MV/m=5V/μm, step 1V from 0V
  equipment: Keithley 236 SMU





- Leakage current increased as particle volume fraction increased.

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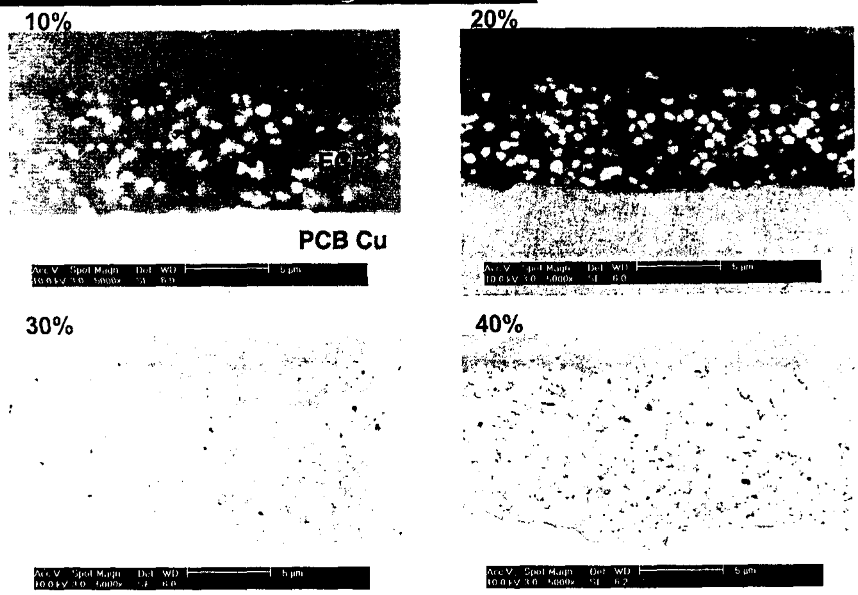
Cross Section Images of ECFs



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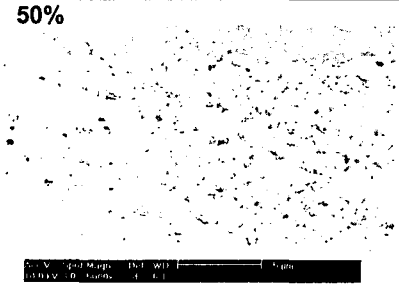
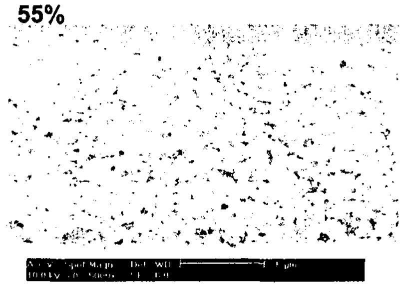
Cross Section Images of ECFs

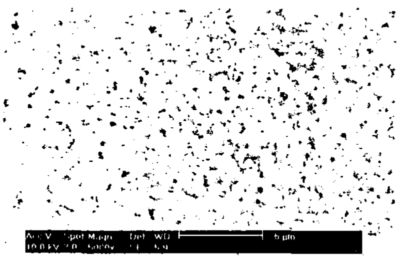
50%



55%

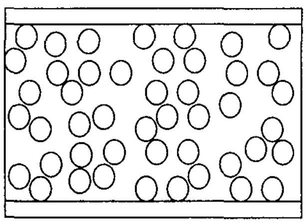


60%



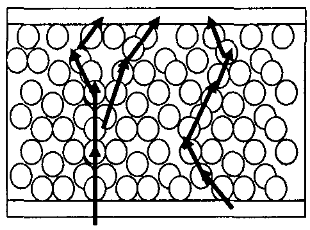
Leakage Current Conduction in ECFs

Below percolation threshold



No connected path

Over percolation threshold



Conduction path formation

- $BaTiO_3$ is more conductive than epoxy, so it acts as stepping stones
- Epoxy surrounding the particles act as conduction barrier

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2. Properties of ECFs
   - ✓ Tolerance
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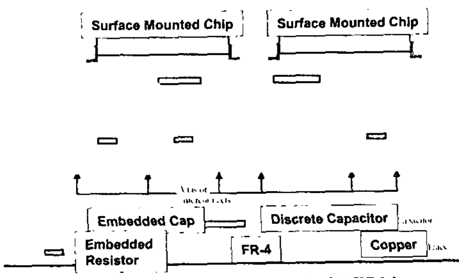
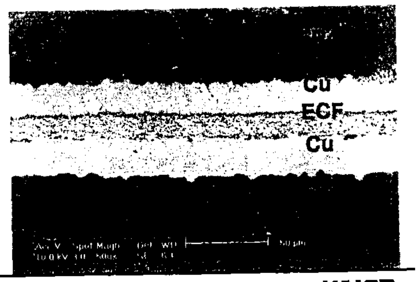
Adhesion of ECFs on Cu

Variables

Required peel strength: 0.8kgf/cm

1. Solvent drying effects
   - Drying condition: 100°C, 30min
2. Effects of $BaTiO_3$ powder volume fraction
   - G powder(0.97μm) : 10 ~ 65vol%
3. Effects of $BaTiO_3$ particle size
   - 7 powders: 20vol%, 50vol%





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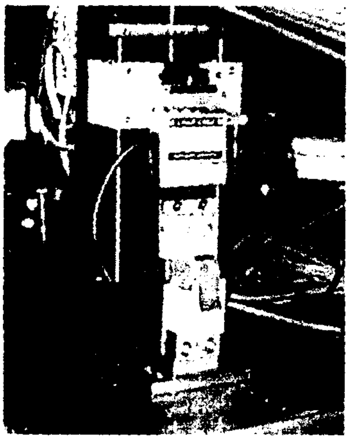
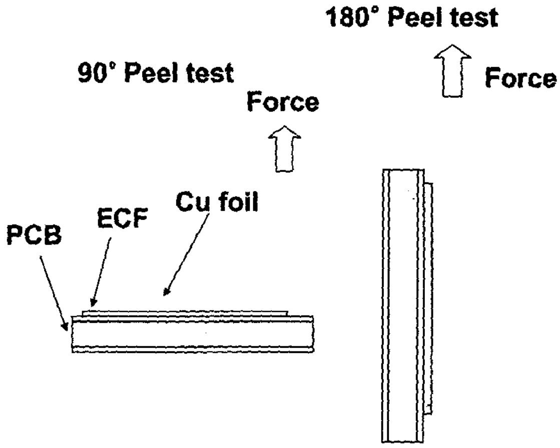
Peel Strength Measurement





- Interface adhesion strength between ECF and Cu foil
- Smooth surface of Cu foil was used.
- Thickness: Cu foil-18μm, ECF- 10~20μm

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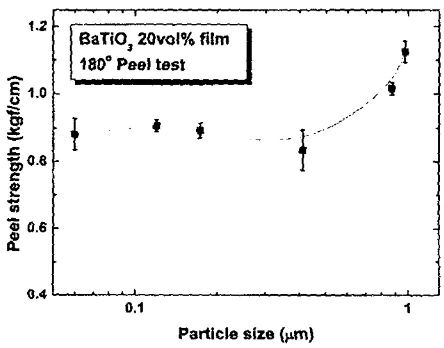
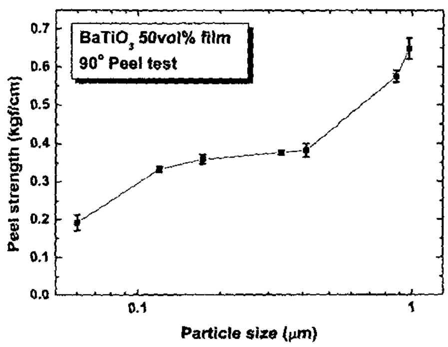
Particle Size Effects

- **Lamination: 180°C, 50psi, 10min**
- **Shiny surface of Cu foil**





- **Peel strength increased as particle size increased.**

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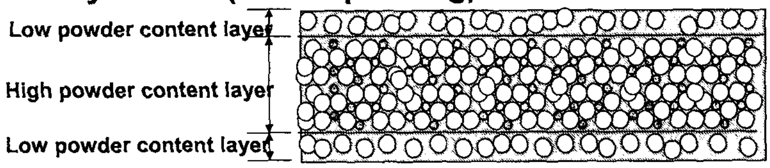
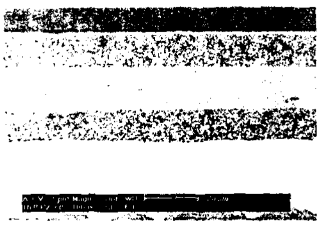
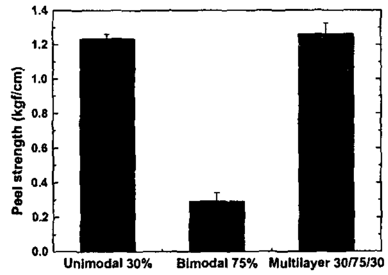
3-layered ECFs (1)

➢ **3-layer ECF (Patent pending)**



- **Low powder content layer:**
  → **Conduction barrier & adhesion layer**
- **High powder content layer:**
  → **Main dielectric layer**





Summary of ECFs

1. Embedded Capacitor Films with excellent properties were newly developed.

   ECF capacitors with low tolerance (less than ±5%) and high dielectric constant of 93 were successfully demonstrated on PCBs.

   60% of discrete capacitors (<100nF) for cell phones applications can be replaced by embedded capacitors.

2. For higher dielectric constant ECFs,

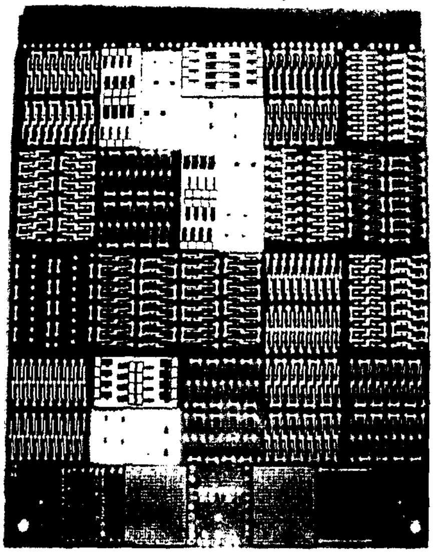
   Optimum $BaTiO_3$ particle size for unimodal was 0.87μm,

   and Higher powder loading over 75% is needed.

   However, adhesion and leakage current problem should be optimized.

Printed Embedded Resistors

Conductive Polymer Resistors, <200Ω/sq, ~1mm long



- Polyimide resistors
- Resistor size: 0.125-1.375 mm
- Daisy chain vs. Isolated
- 125, 250 and 500 μm Cu conductors

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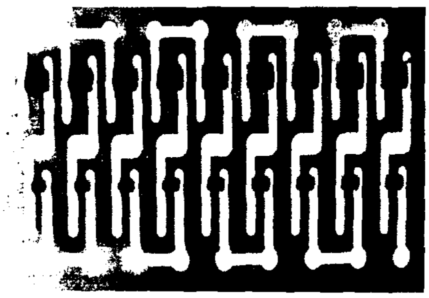
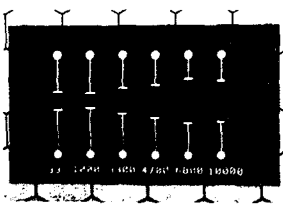
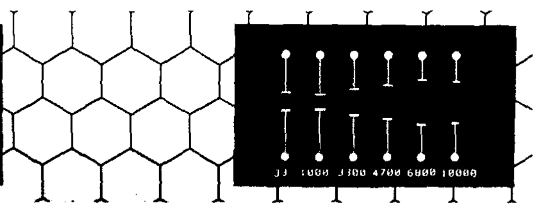
Printed Embedded Resistors



- Well defined printed edges
- Additive, non-contact, digital printing process
- Easy set up and modification





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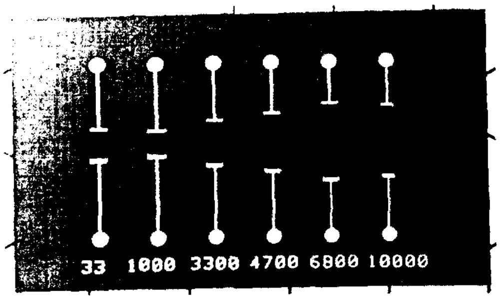
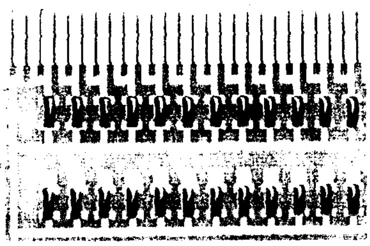
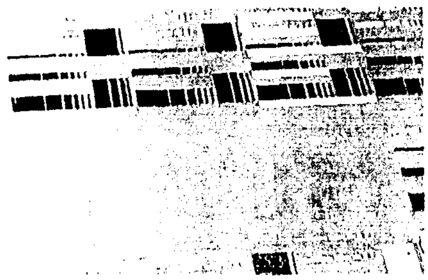
Printed Embedded Resistor



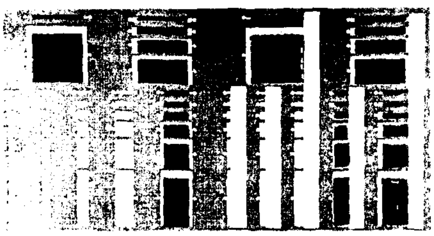


UV-curable resistor

Embedded Resistor Trimming



- Ni/P plated trimmed by ICP.
- Demonstrated trim down: up to 35%
- Resistor size trimmed
  - 10 mil – 330 mil



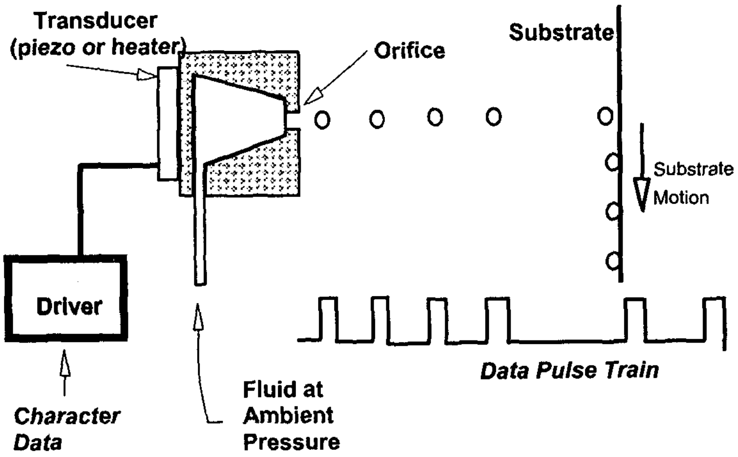
A portion of Ni/P plated Test Vehicle inner layer trimmed down using ICP and Ink jet printing

Trimming Target: 40 ohm/square

TV-2R Inner Layer-4				
Size	Before Trimming		After Triming	
mil	Average	Std Dev	Average	Std Dev
320X170	51.4	8.1	38.7	5.8
160X170	54.4	11.4	42.2	9.6
80X170	53.9	9.3	40.9	9.1
40X170	53.7	9.3	38.9	7.2
20X170	55.7	12.0	40.4	9.4
10X170	53.9	6.3	42.8	9.5

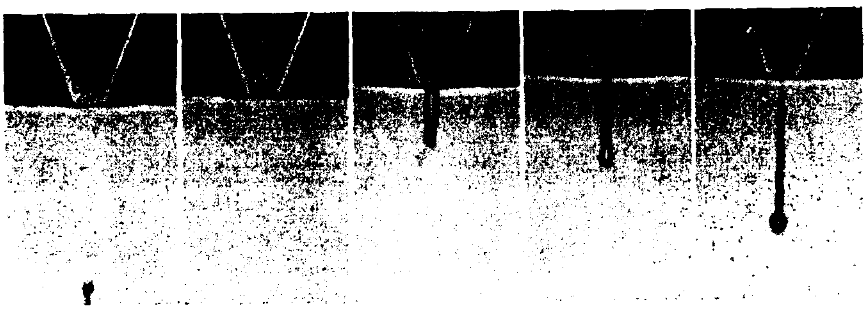
Ink-Jet Resistor Technology

15-150µm droplets, 0-25kHz

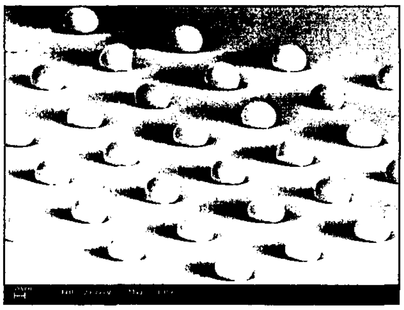


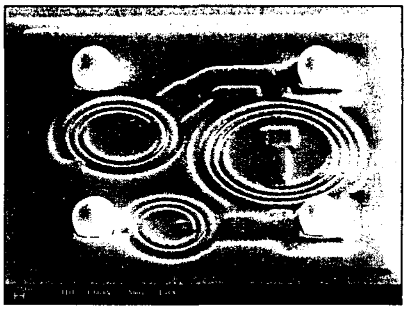
Drop-on-Demand Technology

60µm droplets of alcohol, 4kHz



Solder Jet





- Eutectic Pb/Sn solder bumps
- Various bump size

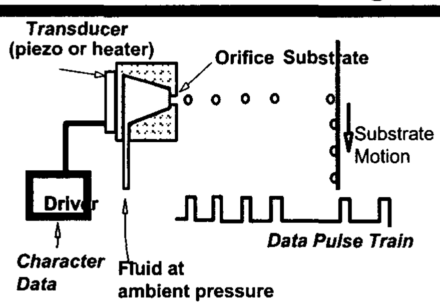
Micro-Electronic Packaging Lab.(MEPL) KAIST

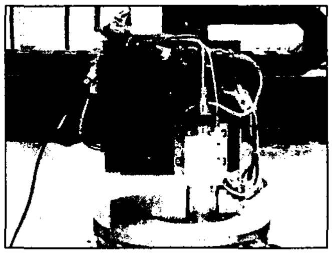
Ink-Jet Microdispensing Advantages

- Direct-write of materials
  - data-driven (flexible, low cost)
  - additive (environmentally friendly, low cost)
  - non-contact
  - thick films possible
- Wide range of materials
  - biological, metals, polymers, fluxes ...
  - wide operating temperature range (0-370C)
- Wide range of resolutions
  - 15-120um drops + N drops per spot
- Wide range of rates
  - 1Hz - 1MHz

Micro-Electronic Packaging Lab.(MEPL) KAIST

Embedded Resistors Printing using Drop-on-Demand ink-jet





▪ Solder/Polymer Jetting Machine

Embedded Passives

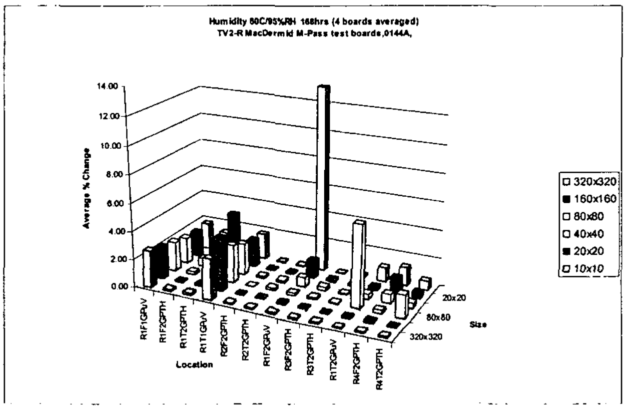
- Miniaturization
- Higher electrical performance
- Better reliability

Drop-on-Demand ink-jet printing

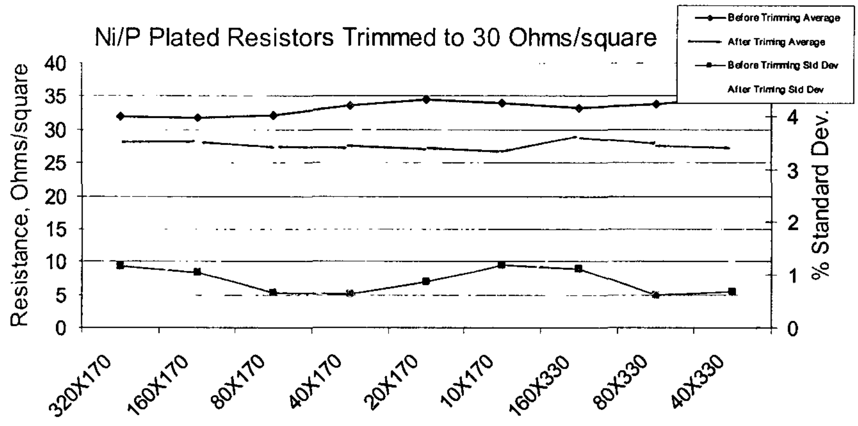
- Low cost
- Low tolerance of resistance
- Easy application for resistors of variable size and complex patterns

➤ ***Study for Embedded Resistors Printing is necessary !!***

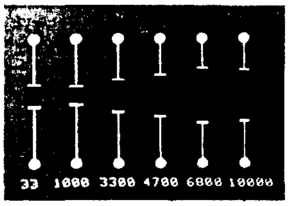
Temperature/Humidity Test Results
Boards with No Ink Jet Trimming

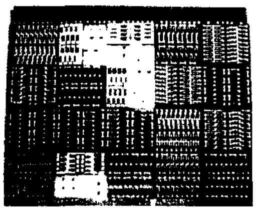


Embedded Resistor Trimming Results



Embedded Resistors Printing/Trimming using Drop-on-demand





• Ink-jet printed embedded resistor using conductive polymer (*From AEPT consortium*)

TV-2R Inner Layer-4 (Ni/P plated resistor using ICP)				
Size (mil)	Before Trimming		After Trimming	
	Avg (Ω/sq)	STD(%)	Avg	STD(%)
320 x 170	51.4	8.1	38.7	5.8
160 x 170	54.4	11.4	42.2	9.6
80 x 170	53.9	9.3	40.9	9.1
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20 x 170	55.7	12.0	40.4	9.4
10 x 170	53.9	6.3	42.8	9.5

• Embedded Ni/P resistor trimmed by ICP

Key points of Embedded Resistors Printing

- Development of new resistor materials for ink-jet printing
  - Investigation of Fluid viscosity(<40cps), Surface tension(20-70dyne/cm), Stable droplet dispersion
- Demonstration of resistor printing and curing processes
  - Dispensing temp, Volume control of dispensed droplets, Curing parameters
  - Resistor properties : Resistance, Tolerance, TCR (Temp. Coeff. of Resistance)