Adhesives in Microelectronics and MEMS Applications

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Monosized polymer particles

Polymer particles with exceptional properties

- Mono sized particles
- Size 1 – 200 µm
- Polymer composition
- Surface chemistry
- Functional groups
- Porosity
- Magnetic
- Metal plated
- Core & shell
Adhesion

- Adhesion relates to the interface between adherent and adhesive
- The most important mechanism for adhesion is inter-molecular and surface forces
  - Van-der Waal (dispersion forces)
  - Hydrogen bonds
  - Very short range (sub nm)
- Generally no chemical bonds
- Other factors like mechanical “interlocking” have very little importance in typical electronic systems
- Cohesion: Internal “strength” of the adhesive (often chemical bonds)
Adhesive / cohesive

Adhesive failure

Chip

Substrate

Cohesive failure

Chip

Substrate
Contact angle

Medium A

Medium B

$\gamma_{AB}$

$\gamma_{AC}$

$\gamma_{CB}$

Contact angle

$\theta$
Criteria for wetting

• Force balance (along interface)

\[ \gamma_{AB} = \gamma_{AC} + \gamma_{CB} \cdot \cos \theta \]

- \( \gamma_{A(B)} \): Surface energy solid (-air) [N/m], [J/m²]
- \( \gamma_{C(B)} \): Surface energy adhesive (-air)
- \( \gamma_{AC} \): Surface energy solid-adhesive

• For a good wetting

\[ \gamma_A > \gamma_B \]
Polymer properties

- Low weight (0.9 - 1.5 g/cm³)
- High thermal expansion
- Hygroscopic
  - Affects mechanical and electrical properties
- Glass transition
  - Introduces new degrees of freedom in the material
  - Increases thermal expansion
  - Reduced mechanical strength
Polymer

- Long chains of monomers
- Linear or branched
- Thermoset
  - Best chemical and mechanical stability
  - Epoxies, polyurethane, silicone
- Thermoplastic
  - Simplifies rework
  - Teflon, polyesters
Thermoplastics

- Reversible melting ↔ solidifying
  - Heating provides thermal energy for polymer chains to move “freely”
  - Cooling reduces the molecular motion
- Linear molecular chains
  - Entanglement
  - Inter-molecular forces
  - No chemical cross bonding
- Mechanical anisotropy
  - Preferential orientation of molecules
- Polyesters, acrylics
# Properties of thermoplastics

<table>
<thead>
<tr>
<th>Fillers</th>
<th>Tg °C</th>
<th>Bond Temp °C</th>
<th>Rework min. °C</th>
<th>Die Shear MPa</th>
<th>Thermal W/m°C</th>
<th>Modulus GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>-40</td>
<td>100 - 150</td>
<td>110</td>
<td>11</td>
<td>0.20</td>
<td>0.4</td>
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<tr>
<td>Ag, AIN, None</td>
<td>25</td>
<td>150 - 200</td>
<td>160</td>
<td>14</td>
<td>0.3-3.0</td>
<td>0.4</td>
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<tr>
<td>Ag, AIN, None</td>
<td>45</td>
<td>160 - 220</td>
<td>170</td>
<td>17</td>
<td>0.3-3.0</td>
<td>3.2</td>
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<tr>
<td>Ag, AIN, None</td>
<td>85</td>
<td>160 - 250</td>
<td>170</td>
<td>19</td>
<td>0.3-3.0</td>
<td>2.5</td>
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<tr>
<td>None</td>
<td>145</td>
<td>200 - 230</td>
<td>210</td>
<td>24</td>
<td>0.22</td>
<td>1</td>
</tr>
<tr>
<td>Ag, Au, AIN, None</td>
<td>180</td>
<td>325 - 400</td>
<td>350</td>
<td>25</td>
<td>0.3-3.0</td>
<td>2.2</td>
</tr>
<tr>
<td>None</td>
<td>280</td>
<td>350 - 450</td>
<td>400</td>
<td>31</td>
<td>0.25</td>
<td>2.3</td>
</tr>
</tbody>
</table>
Thermoset

- Do not melt upon heating
- Forms links or chemical bonds between adjacent chains, during curing (intra-molecular bonds)
- Three dimensional rigid network
- Properties depend on the molecular units, and the length and the density of the cross-links
- Thermosetting resins are usually isotropic
- Epoxies, silicones, urethanes
Glass temperature

- Second order phase transformation
- Discontinuous volume expansion, heat capacity and mechanical properties
- Thermal energy sufficient to allow rotation about chemical bonds
  - Depends on bond (Carbon or silicone)
  - Adjacent molecular groups (dipoles, bulkiness and symmetry)
Different classes of organic adhesives

- **Solvent-based adhesives:** The adhesive is solved in a suitable solvent or dispersed in water. The adhesive solidifies during drying (not curing).

- **Thermoplastic adhesives:** Based on thermoplastic materials, that is solid to liquid is a reversible phase change. Typically polyimide- and polyester (easily oxidized).

- **Thermosetting adhesives:** Improved mechanical properties, high temperature and chemical resistance.
Structural adhesive

- Good load-carrying capability
- Long-term durability
- Resistance to heat, solvent, and fatigue
- 6 main types:
  - Urethanes
  - Acrylics
  - Epoxies
  - Silicones
  - Anaerobic adhesives
  - Cyanoacrylates
Structural adhesives

- **Cyanoacrylate**
  - Cyanoacrylates adhesive bonds quickly to plastic and rubber but have limited temperature and moisture resistance.
  - Cured by humidity present on surfaces

- **Acrylics**
  - Acrylics, a versatile adhesive family that bonds to oily parts, cures quickly, and has good overall properties.
  - Cure at room temperature when used with activators.
    - The adhesive and activator can be applied separately to the bonding surfaces. Often a low viscosity activator
    - The adhesive and activator premixed in a static mixer prior to application. Anaerobic

- **Anaerobics, or surface-activated acrylics**
  - Bonding threaded metal parts etc.
Silicones

- Solvent born resins
  - Evaporation of solvent
  - Curing at elevated temperature
- Room Temperature Vulcanisation RTV
  - One part RTV systems generally cured by moisture
    - Give of by-products during cure
  - Two part RTV generally cured by a platinum complex
- UV cured
- Very wide temperature range
  - -50 – 200 °C
Silicones (II)

- Soft, low modulus material
  - Very low Tg (typically -65 °C)
- Very high CTE (Typically 350 ppm/ °C)
- Very low dielectric constant
  - Low dielectric loss
- Easily modified to provide a range of physical and mechanical properties, cure system, and application techniques.
- Very low surface tension (24 mN/m)
- Very mobile, vapor attaches to all surfaces
  - Wire bonding problems
Silicones (III)

- Good water and moisture resistance
  - However, very high water permeability If adhesion is good, a continuous water film is not obtained at the interface
  - NB! Oxygen bridge bonding to die surface prevents Al corrosion
  - Relatively low equilibrium moisture content
  - Very low levels of mobile ions
- Good sealing properties
  - Very durable for glass sealing
- Weather well out-of-doors
- Low surface tension expels liquid water
(Poly)urethanes

• One or two component systems
• Often solvent based
• Low stress materials
  ■ Good flexibility and elasticity
  ■ High thermal shock resistance
  ■ Good peeling characteristics
• Moisture curing system (~ 50%RH)
• Good adhesion to many organic materials
Epoxies

- Thermoset
- Thermal cure (UV or light cure optional)
- Relatively high E-modulus
  - Brittle
- Generally good adhesion
  - Hydrogen bonding (NB! Except gold, due to lack of oxygen at the surface)
  - Mechanical interlocking
- Typical shrinkage upon curing is in the order of 1 to 2 percent
- Relatively low moisture permeability
The selection of a curing agent is as important as the choice of the resin:
- Rate of reactivity
- Degree of exothermal
- Gel time
- Curing time
- Mechanical properties of the cured adhesive.

The number of epoxide groups in the molecule determines the “functionality” of the resin:
- Increasing glass transition temperature
- Decreasing Thermal Coefficient of Expansion (TCE)
Epoxide group
Modification of properties

- Choice of resin system
- Choice of hardener
- “Fillers”
  - Electrical (dielectric) properties
  - Mechanical properties
  - Possible ionic contamination
Fillers

- **Plasticizers, flexibilizers or elastomers**
  - Plasticizers (an additive that is physically blended into the resin (do not become part of the polymer). Plasticizers in epoxies are typically rubber or thermoplastic particles. They have to be > 1 micron to be efficient
  - Flexibilizers are chemically reacted into the epoxy system (often thermoplastic polymers)
    - Reduces solvent and moisture resistance and lowers Tg
  - Elastomers remains as a distinct second phase (two separate cross-linked networks)
Plasticisers

- Absorbed liquids (soft solids), decrease the glass temperature
- Increased “free volume”
  - Reduces the internal viscous friction

\[
\frac{1}{T_g(PF)} = \frac{w_p}{T_g(P)} + \frac{w_L}{T_g(L)}
\]

- Ex. Glass temperature of water: approx. –135 °C.
Influence of water

![Graph showing the relationship between water content and glass temperature. The graph indicates a downward trend as the water content increases.](Image)
Silver epoxies

- Low impact strength
  - High loading of silver particles

- Solutions
  - Reducing filler rate by use of porous silver particles (Fraunhofer)
  - Randomise particle orientation, by making conductive composite particles (Georgia Tech)
  - Introduce plastizisers, to increase the ability to absorb mechanical energy (Ablestik)
  - Polymer spheres with silver coating
Mechanical properties

- E-modulus [GPa]
- Coefficient of thermal expansion [ppM/K]

Filler content silver [weight %]

Graph showing the relationship between E-modulus and coefficient of thermal expansion with varying filler content silver.
Criteria for adhesive selection

- Means of “dispensing” of adhesive
  - Screening, film, dispensing, stamping etc...
    - Viscosity / rheology:
    - Unwanted flow (capillary driven), leaching

- Good adhesion to parts:
  - What is the main components to be bonded (surface!!)
  - Surface cleaning

- Demands for mechanical properties
  - Strength - flexibility
    - E-module / Elongation before break
  - Sensitivity to mechanical stress
  - Requirements for temperature cycling
Criteria for adhesive selection

- Processing temperature
- Thermal expansion adhesive:
  - High CTE will often increase stress in adhesive joint due to the increased miss-match with the components to be bonded
  - High thermal expansion is likely to increase diffusion of humidity etc..
- Low ionic contamination
- Thermal (and electrical) conductivity
- Void free bond line
  - Local stress concentration (crack initiation)
  - Poor local thermal contact
Requirements from application (I)

- **Glass transition temperature** relative to operational (and storage) temperature of the device.
  - Radical change of mechanical properties
    - Reduced “E-modulus”
    - Increased thermal expansion
  - Increased diffusivity above Tg.
- **Water absorption:**
  - Changes mechanical properties (plasticizer)
    - Reduced $T_g$
  - Changes dielectric properties
Resin bleed

- Resin bleed is the unwanted capillary action of low viscous parts of the adhesive
- Contamination of bond pads
  - Destroy the ability to perform wire bonding
- Relatively low molecular weight thermoset
  - During initial heating
  - Ultra clean surfaces (high surface tension)
  - Rough surfaces (large surface area)
E-modulus of different die attach adhesives

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>T_g [°C]</th>
<th>E-modulus (dynamic) [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>@ -65</td>
<td>@ 25</td>
</tr>
<tr>
<td>A</td>
<td>53</td>
<td>2,68</td>
</tr>
<tr>
<td>B</td>
<td>30</td>
<td>1,81</td>
</tr>
<tr>
<td>C</td>
<td>88</td>
<td>5,78</td>
</tr>
<tr>
<td>D</td>
<td>40</td>
<td>5,40</td>
</tr>
<tr>
<td>E</td>
<td>67</td>
<td>6,27</td>
</tr>
<tr>
<td>F</td>
<td>98</td>
<td>2,40</td>
</tr>
<tr>
<td>G</td>
<td>245</td>
<td>6,90</td>
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</tbody>
</table>
Stress in “Die attach”

<table>
<thead>
<tr>
<th></th>
<th>Chip</th>
<th>Substrate</th>
<th>Adhesive</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-modulus</td>
<td>190 GPa</td>
<td>20 GPa</td>
<td>-</td>
</tr>
<tr>
<td>CTE</td>
<td>2,6 ppM/K</td>
<td>18 ppM/K</td>
<td>50 ppM/K</td>
</tr>
<tr>
<td>Thickness</td>
<td>0,4 mm</td>
<td>2,0 mm</td>
<td>0,03 mm</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0,25</td>
<td>0,4</td>
<td>0,45</td>
</tr>
</tbody>
</table>
Shear stress in adhesive

Shear stress [Pa]

Distance from centre [mm]

- 30 GPa
- 10 GPa
- 3 GPa
- 1 GPa
- 0.3 GPa
- 0.1 GPa
Normal stress in die

![Graph showing normal stress in die]

- Normal stress [Pa]
- Distance from centre [mm]

Key:
- 30 GPa
- 10 GPa
- 3 GPa
- 1 GPa
- 0.3 GPa
- 0.1 GPa
Measured stress in silicon die

- Silicon chip onto copper substrate
- Compressive stress along the centre-line
- Measured with Piezo-resistors
Measured stress in silicon die (II)

- Compressive stress normal to the centre-line
- Measured with Piezo-resistors
## Measured and calculated stress

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Cure temp</th>
<th>Strain calc.</th>
<th>Strain meas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>958-2</td>
<td>150°C</td>
<td>1740·10⁻⁶</td>
<td>543·10⁻⁶</td>
</tr>
<tr>
<td>H20E-175</td>
<td>160°C</td>
<td>1880·10⁻⁶</td>
<td>343·10⁻⁶</td>
</tr>
<tr>
<td>K/5022-81</td>
<td>210°C</td>
<td>2570·10⁻⁶</td>
<td>105·10⁻⁶</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Stress calc.</th>
<th>Stress meas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>958-2</td>
<td>429 MPa</td>
<td>132 MPa</td>
</tr>
<tr>
<td>H20E-175</td>
<td>457 MPa</td>
<td>84 MPa</td>
</tr>
<tr>
<td>K/5022-81</td>
<td>629 MPa</td>
<td>26 MPa</td>
</tr>
</tbody>
</table>
Comments: Measured stress

- Observed strain (stress) much lower than calculated!
- K/5022-81 (polyimide based): problems with the curing of the adhesive
- What is the effective “Zero-stress” temperature?
- Plastic deformation?
Transient Hot Wire

\[ y = 0.006375 \ln(x) + 0.36764 \]

\[ \lambda = \frac{\alpha \cdot R^2 \cdot I^3}{4\pi \cdot h \cdot b} \]
Results

- \( \lambda \) increase with increased amount of conductive filler

- For Nano scale particles \( \lambda \) increase more than theory suggest:
  - 0% 0.20 W/mK
  - 10% 0.35 W/mK
  - 20% 0.56 W/mK

- Surface treated alumina better:
  - Untreated: 0.26 W/mK (10%)
  - Treated: 0.32 W/mK

- Nanoscale particles better than micro scale particles:
  - Micro: 0.26 W/mK
  - Nano: 0.35 W/mK (10%)
Silver epoxy

- Silver flake distribution in Ablebond 952-8
- Elongated particles
Thermal interface resistance

- Ablebond 958-2
- Silicon chip onto molybdenum substrate
Thermal interface resistance (II)

- Epo-Tek H20E-175
- Silicon chip onto copper substrate!
Temperature cycling of die attach

Temperature cycling of die attach

Thermal resistance [Kcm²/W]

Adhesive 1

Adhesive 2

10 - 150 °C, 8x8 mm test-chip on copper substrate
Adhesive as underfill

- Bump lifetime under thermal cycling decreases with induced strain
- Bumps without underfill:
  - CTE mismatch => cyclic shear strain
  - Crack growth
- Bumps with underfill
  - Strain reduction
  - Lifetime increase 10X

Si chip (CTE=2.6 ppm /K)

FR4 (CTE= 18 ppm /K)
Effect of Underfill

- Mechanical coupling chip/substrate
  - Reduces bump shear strain
  - Strain highest at chip edge
  - Strain depends on shear modulus of underfill
- Introduces axial strain
  - CTE mismatch solder/underfill
  - Depends on underfill CTE
  - Affects all bumps equally
- Impact on lifetime?

Shear mode

Tensile mode
Measurement of bump lifetime - Aims

- Measure number of thermal cycles to failure
- Two underfill materials (different CTE)
- Measurements as function of distance to chip centre
  - No variation: Axial strain dominates
  - Lifetime decreases with distance: Shear strain
- Establish simple analytical model for bump lifetime
- Compare experimental lifetimes with model
Experimental method

- Test sample:
  - Silicon test chip with eutectic solder bumps
  - Reflowed to FR4 substrate
  - Underfill applied and cured
- Thermal cycling
  - -55 - 145 °C
  - 2 cycles per hour
Lifetime measurements

- Daisy chain connections on chip/substrate
  - Grouped in “rings” with similar distance to centre
  - Continuity of each ring monitored
    - In situ
    - For each 50 cycles (at RT)
  - Resistance increase = failure
Underfill characteristics

- Two different types used:
  - Filled: CTE = 28 ppm/K
  - Unfilled: CTE = 58 ppm/K
  - Tg: 120 °C
  - CTE and Tg measured by DMA
- Curing: 150 °C
- Maximum cycling temperature (145 °C) exceeds Tg!
ACA technology
Overview

- Introduction
- Anisotropic conductive adhesive
  - Z-axis conductive film
- Typical products
- Joint quality
- Reliability
- Different FlipChip techniques
- Conclusions
ACF History

- First ACF in industry
- Fine pitch connection 250 µm
- First thermo-setting ACF 200 µm
- COG, ACF with insulated layer 100 µm
- Fine pitch COG connection 50 µm

Timeline:
- 1976
- 1980
- 1984
- 1988
- 1992
- 1996
- 2000
Anisotropic Conductive Adhesive

- The adhesive film is applied uniformly
- Pressure is applied during curing, giving conduction only between pads
- Thermoplastic or thermosetting
- Film (tape) or paste
Particle compressed between bump and pad

![Image of compressed particle](image.png)

**Figure 11:** Close-up view of a deformed Au coated DVB-PS polymer particle in ACF film after bonding.
Driving force

• Possibly higher reliability
  ■ Right choice of adhesive and bonding surface

• Fewer process steps
  ■ No fluxing or cleaning

• Finer pitch
  ■ Anisotropic Conductive Adhesive
  ■ Non-conductive Adhesive

• Environmental friendly
  ■ No lead
Introduction

- Lower temperature processing
  - Lower thermal stress
- New materials in packaging
  - Polyester based flex circuits
  - Low cost plastics
- Non solderable surfaces
  - ITO conductors (LCD’s)
Optimising process conditions

- Large number of particles on pad
- Low particle density between neighbouring pads
- Fast process time
- Reliable and uniform connection resistance
Curing cycle

Connection resistance

Heat

Pressure

T 1

T 2

T 3

T 4

T 5

T 6

Time
Curing cycle (II)

- T 1: Start of pressurisation
- T 2: Start of heating
- T 3: The resistance increase depending on electrode material
- T 4: End of heating
- T 5:
- T 6: End of pressure
  - If curing is insufficient, the resistance may start to increase
Bonding force

- The applied bonding force is counter balanced by
  - Squeezing of the adhesive film
  - Compression of particles

- Squeeze film pressure
  - Film thickness
  - Chip dimension
  - Viscosity of adhesive
  - Rate of squeezing

\[ F = \int_{A_{\text{Chip}}} p dA + \sum_{i} \kappa_{\text{p}} \varepsilon \]
Squeezing of adhesive film

- Flat silicon surfaces
- 1st stage: squeeze of adhesive only
- 2nd stage: compression of particles
Factors influencing on joint quality

- Coplanarity.
- Bump height and uniformity
- Pressure and pressure distribution.
- Particle distribution
- Cure temperature and cure time
- Temperature ramp rate
- Alignment accuracy
Contact stability (I)

- Stable contact
  - Uniformly deformed particles
  - Adequate pressure

- Unstable contact
  - Too low pressure during connection
Contact stability (II)

- Uneven particle size
  - Not uniformly deformed particles

- Uneven bump-height
  - Not uniformly deformed particles
Degradation mechanisms

- Oxidation and hydration of conductors
- Polymer degradation by moisture or UV-light
- Adhesive failure due to humidity adsorption
- Crack formation
- Thermal and mechanical fatigue
Failure mechanisms I

- Adhesive
  - Thermal and mechanical fatigue
  - Humidity
  - UV light
- Cohesive
  - Humidity
  - Thermal and mechanical fatigue
Failure mechanisms II

- Oxidation of metal surfaces
  - Humidity
  - Corrosive gases
- Expansion / swelling
  - Thermal and mechanical fatigue
  - Humidity
Typical reliability tests

- Temperature cycling from -40 to +125 °C
- Constant humidity test: 85 °C, 85%RH
- High temperature ageing at 125 °C
- Temperature cycling from -40 to +125 °C
- NB!: Tests are typically adopted from solder
  - Different failure mechanisms
The use of ACA Technology

- Typical applications:
  - Flat panel displays
  - Smart cards
  - Single or multi-chip modules
  - Piezo electric components (printer heads etc.)
  - Micro mechanical and Micro optical components

- Low temperature bonding
  - Plastic, clothing
Mounting trends

- Large size LCD
- COG
- Super slim TAB
TAB connection

- ITO
- Chip
- ACA connection
- PWB
Chip on Glass

- Chip
- Flexprint
- LCD panel
- ACA connection
Chip on Glass; Sharp DVD player
ACF applications

- Chip on Flex
- Flex on Glass
ACF Flip Chip on rigid board

- Personal digital assistant (PDA) by Casio Computer
- Six IC’s (Microcontroller, Gate Array, Memory, decoder and amplifier) are mounted with flip-chip.
- Minimum pitch is 124 µm
- Sequential build-up substrate.
Key factors for Chip on Glass

- More than 5 particles per bump
- Ensure insulation
  - Insulated particles for low pitch?
- Development of more elastic binder material
- Higher $T_g$ material
- Less moisture absorption
Sharp; “ELASTIC”

- Conductive particle
- Tacky adhesive
- Cured adhesive
- Adhesive
- Glass substrate
- Glass

IC
Sharp; “ELASTIC “

- ELASTIC: Electrical interconnection using light-setting adhesive
- Placing particles on tacky adhesive
  - Photo process
  - Gold plated plastic spheres
  - No need for bump plating
- 50 micron pitch demonstrated
Mitsubishi

- Photo process with conductive particles
  - UV transparent substrate
  - Non transparent pads
- Waste of conductive particles?
Matsushita; Stud “wire” bumps
“Isotropic Conductive Adhesive”
Casio; “Microconnector”

- Insulating layer
- Metal layer
- Polymer ball
- Bump
- Adhesive
- Chip
- Substrate
- Electrode pad
Mitsubishi

Opaque electrode pad

Uncured photoresist

Glass substrate

UV Light
Hitachi: Double layer ACA

Diagram showing a chip with bumps, an adhesive layer, and a particle layer.
Conductive particles

- Volume fraction 5 to 10 %
  - Responsible for the electrical contact
  - Pure metals such as gold, silver or nickel
  - Metal-coated particles with plastic or glass cores.
- Typically 3 to 10 micron in size,
- Treating particles separately from the adhesive.
  - Small volume fractions of particles in the ACA, gives minor changes in mechanical behaviour, at least in the case of metallised polymer particles.
Conductive particle

Elementary composition

%  100  50  0

Gold
Nickel

Styrene

Diam. 5-10 µm
Particle development

- 1\textsuperscript{st} generation (Dyno Specialty Polymers), focus on
  - Different polymer compositions
  - Cross-linking densities
- 2\textsuperscript{nd} generation, focus on
  - Adhesion between metal and polymer core
  - Added chemical groups for bonding to the metal
Testing of mechanical properties
Results, mechanical testing (@RT)

![Graph showing force vs. deformation with different markers for AU 54, Commercial, AU 128, AU 15, and AU 11.]
2\textsuperscript{nd} generation particle (@ 150 °C)
SEM picture of 2nd generation particle (tested at 150 °C)

- Very good adhesion between polymer and metal
  - Adhesion promoters included in polymerisation process
- High reliable contacts due to integrity of particles
Commercial particles (testing at 150 °C)

- Particles fully des-integrated
- Lack of adhesion between polymer and metal
Measurement of contact resistance

- 4-wire measurement
- Ensemble of free particles
- Au-Pt electrodes
Electrical resistance AU-54

- Contact resistance versus “contact force”
- 4-point measurement
- “Free” particles
- Gold electrodes
Contact resistance versus cycling