Advanced Metal-Eutectic Bonding for High Volume MEMS WLP

Sumant Sood
SUSS MicroTec Inc

IEEE MEMS Bay Area Meeting,
26 Feb 2014

Contents

Contents

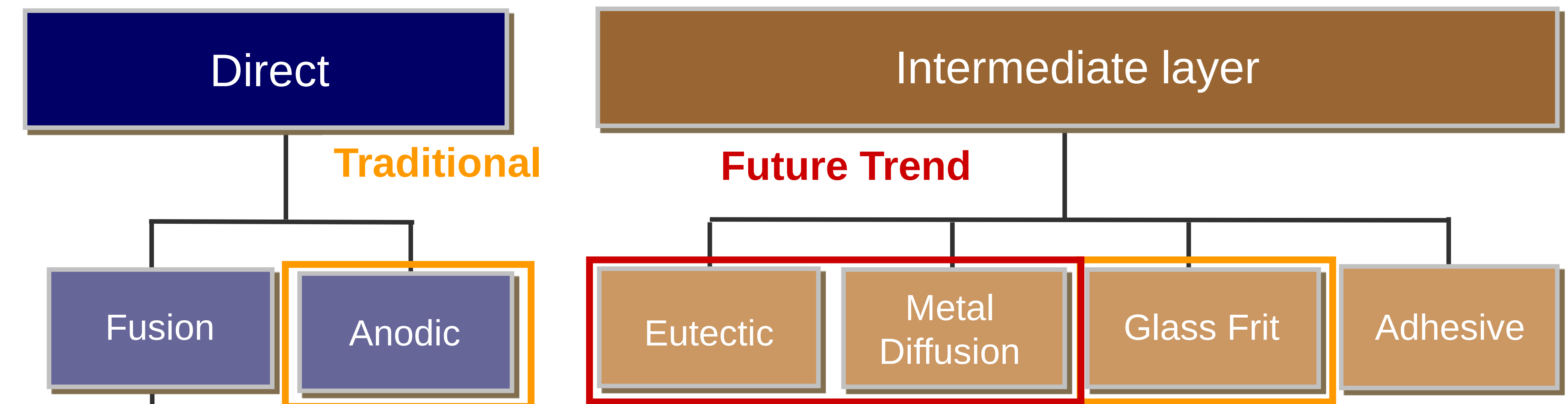
Main MEMS WL Packaging Processes

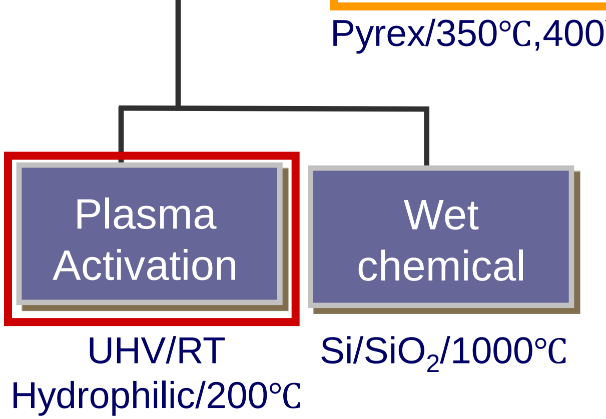
- **Anodic Bonding**
  - Si to glass
  - Special cases (glass-glass, glass-metal etc)
- **Metal Diffusion Bonding**
  - Cu to Cu
  - Au to Au
  - Ti to Ti/Si
  - Al-Al
- **Eutectic Alloy Bonding**
  - Au/In
  - Cu/Sn
  - Au/Sn
  - Au/Si and Au/Ge
  - Al/Ge
- **Direct Bonding**
  - Si to Si, SiO_x, Si_xN_y, Glass etc
  - Glass to glass
  - Si to piezoelectric materials (Quartz, $LiNbO_3$, $LiTaO_3$)
  - Compound Semiconductors Bonding (InP, GaAs, GaN, SiC etc)
- **Glass Frit Bonding** (traditional and lead-free)
- **Adhesive/Polymer Bonding**
  - Cyclotenes (BCB 3000 and 4000 series)
  - SU8
  - Polyimides
  - UV and heat curable Epoxies

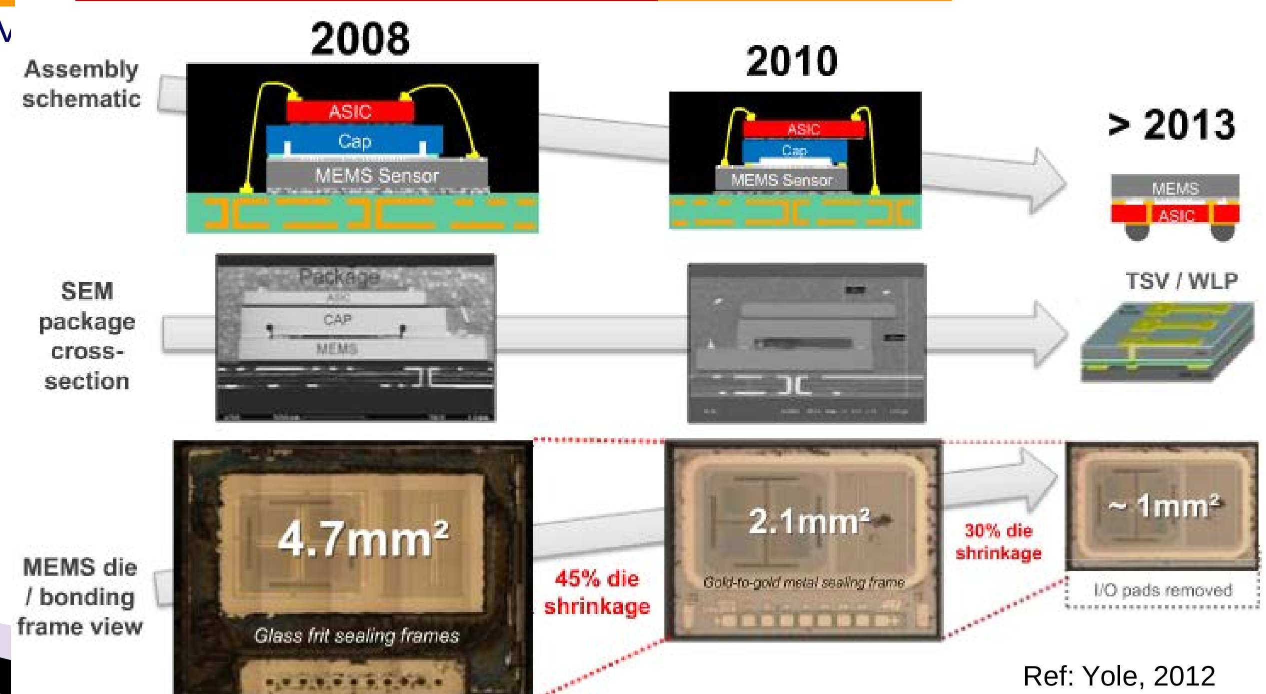
Head-Head Comparison

Factor	Criteria	Anodic	Glass-frit	Direct	Metal Diffusion	Adhesive	Eutectic
Bond Force	<10KN	↑	↑	↑	↓	↑	↑
Bond Temp	Large temp Range	↓	↓	↑	↓	↑	↑
Alignment capability	<2um	↓	↓	↑	↑	↑	↑
Hermetic Seals	Should be hermetic	↑	↑	↑	↑	↓	↑
Heterogeneous integration	Should be possible	↓	↑	↓	↑	↑	↑
Roughness requirement	>10nm	↑	↑	↓	↓	↑	↑
Potential Issues		Not CMOS/ FEOL compatible	Dirty process, large bond line width, high temp	Requires clean particle-free surfaces	Requires metal CMP.. Issues with severely bowed wafers	Not hermetic, large seal width	Potential oxidation of metal layers

WLP Processes Evolution







More MEMS per Wafer
Low Temp Req.
Hermeticity Req.

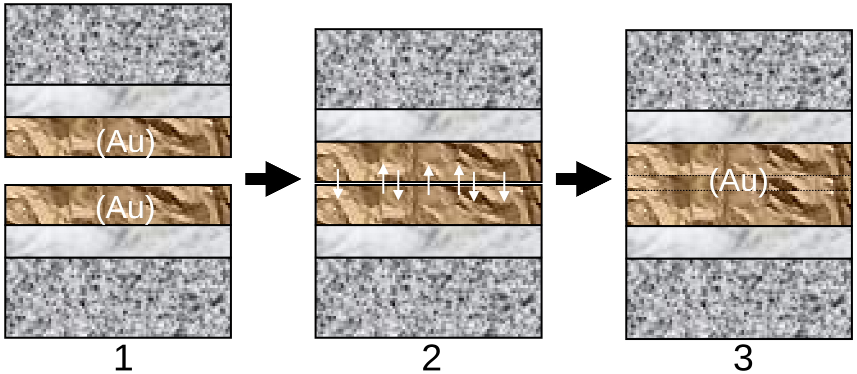
Ref: Yole, 2012

Contents

Metal Inter–Diffusion Bonding

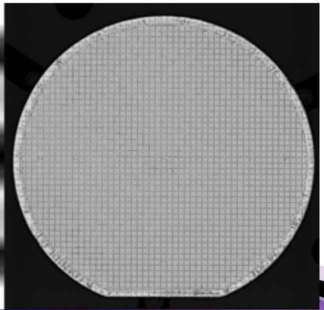
+ Bonding Mechanism

- Smooth, clean metal surface critical
- Intimate contact of bonding layer
- Solid phase metal inter-diffusion
- surface oxide removal needed
- Homogeneous high force requirement

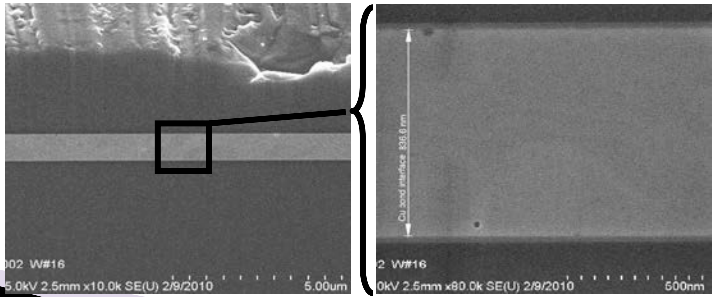


+ Bonding Conditions (6"/8" wafers)

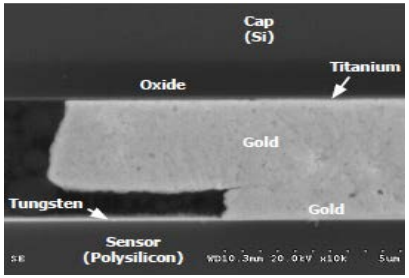
Bond Type	Bond Temp	Force*	Pre–clean
Cu–Cu	250–400C	20–40kN	Oxide removal–wet cleans and In–situ forming gas
Au–Au	250–400C	40–70kN	Organics removal via O2 plasma/UV treat
Al–Al	400–480C	50–90kN	Oxide removal/cracking– Ar ion–milling and In–situ
Ti–Ti	300–400C	25–50kN	Organics removal– Minor cleaning

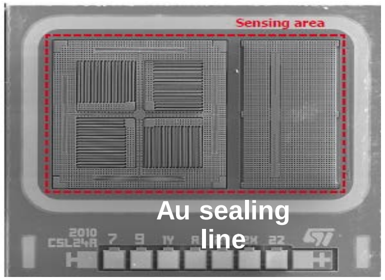


SAM image of a 6" Au-Au bonded pair.



SEM cross-section of a bonded Cu blanket pair. Each wafer has 300nm of ECU Cu/ 100nm PVD Cu/ 20nm Ti seed layer.



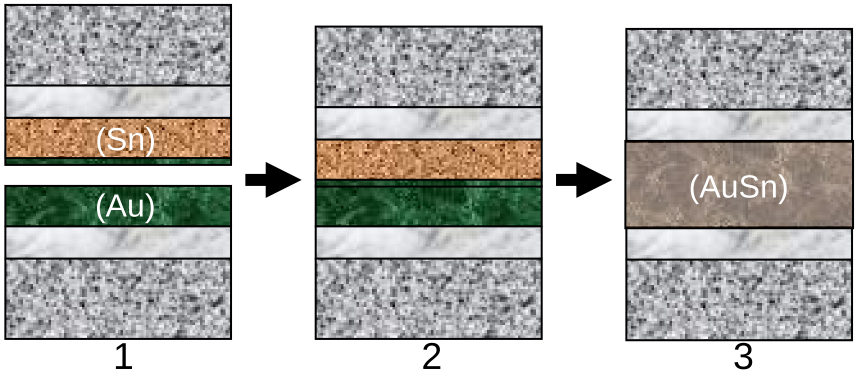


Au-Au bonding used in a 3-axis accelerometer.

Metal Eutectic Bonding

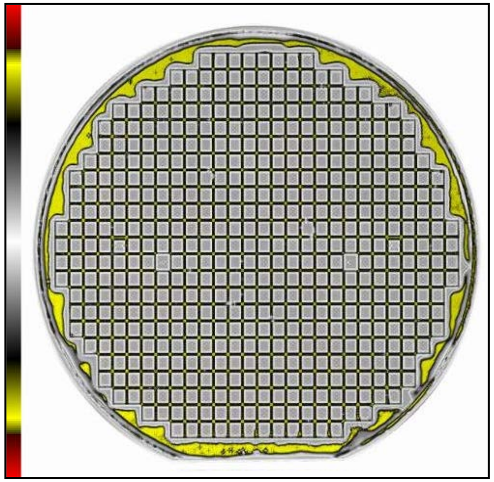
+ Bonding Mechanism

- Heat up to 20 – 30 °C higher than eutectic point (T_e)
- Two metals are melted and mixed
- Cool down to below T_e
- Homogeneous temperature < +/- 2 %
- Homogeneous pressure
- Faster heating > 30^{o}C/min



+ Bonding Condition (6”/8” wafers)

Eutectic Alloy	Eutectic Comp.	Eutectic Temp	Bond Temp*	SLID/TLP
Au-In	0.6/99.4 wt%	156C	180-210C	Yes
Cu-Sn	5/95 wt%	231C	240-270C	Yes
Au-Sn	80/20 wt%	280C	280-310C	Yes
Au-Ge	28/72 wt%	361C	380-400C	No
Au-Si	97.1/2.9 wt%	363C	390-415C	No
Al-Ge	49/51 wt%	419C	430-450C	No

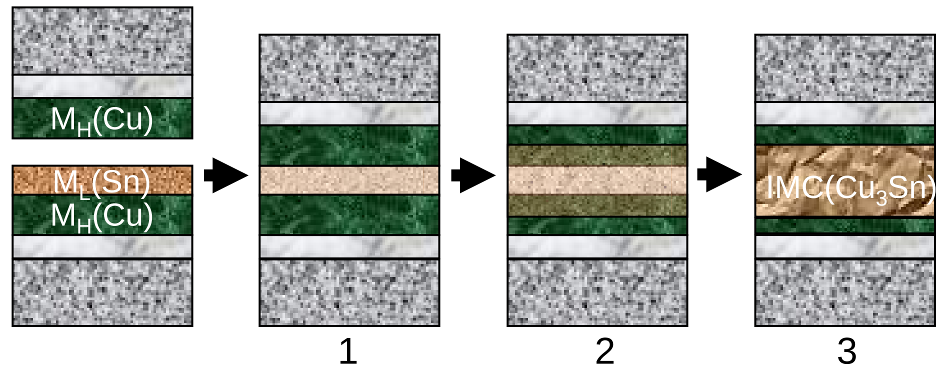


SAM image of an aligned 6” AuSn bond.

TLP (Transient Liquid Phase) Bonding

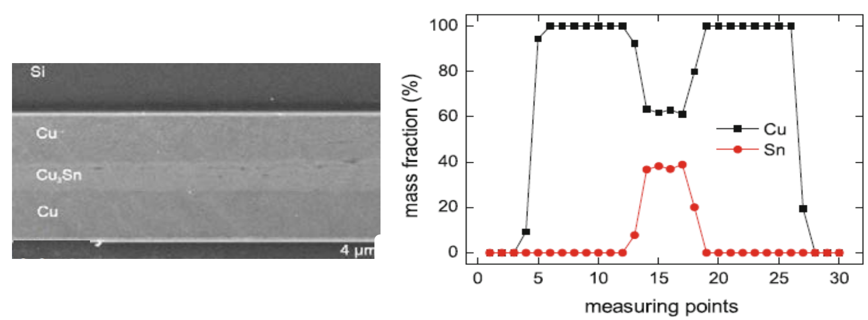
+ Bonding Mechanism

- Heat up to slightly higher than melting point (T_m) of low-melting point metal (M_L)
- M_L melts and mixed with high-melting point metal (M_H)
- Form intermetallic compound (IMC)
- Homogeneous temperature < +/- 2 %
- Homogeneous pressure



+ Bonding Condition

Material	Bond Temp. (°C)	Force @8" (N)	Duration (min)	Pre-treatment
Au-In	180 – 200	1-10k	1-5	Organics Ashing for Au
Cu-Sn	240 – 280	5-15K	10 – 20	Oxide removal of Cu
Au-Sn	240-280	5-15K	10-20	Organics Ashing for Au



SEM Micrograph and corresponding EDX line scan show a Cu/Cu-Sn/Cu sandwich which are confirmed by EDX. The measured 32wt % corresponds to the target IMC

Contents

Al-Ge Eutectic Bonding

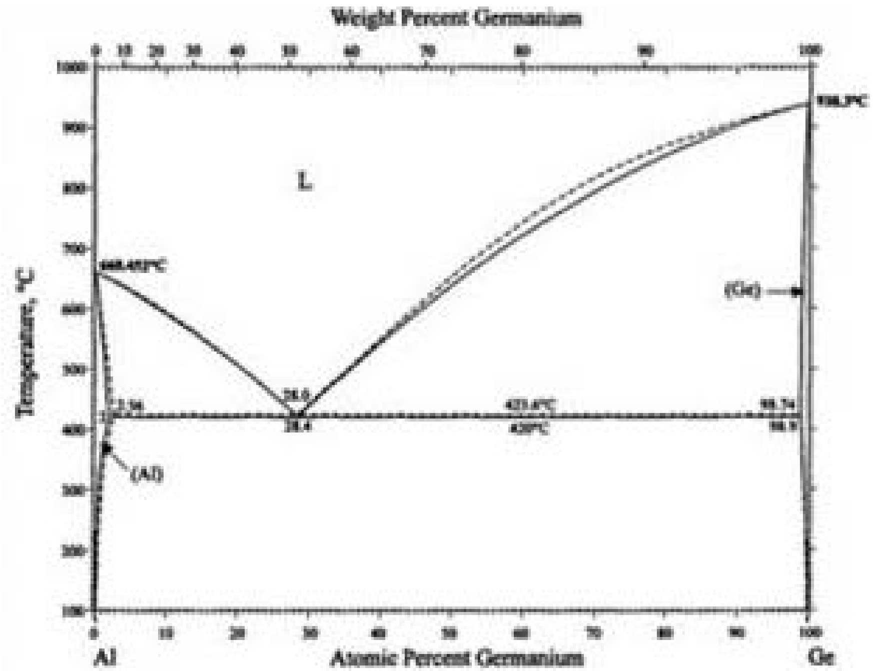
Advantages

- Low Cost & CMOS compatible fab friendly materials
- Relatively small frame structure
- Higher hermeticity
- Good fit for MEMS process standardization
- <450C Temp (no degradation of metal interconnects)

Challanges

- Aluminum-oxide grows almost instantaneously
- Complex process chain and machine parameters greatly influences the quality of eutectic bond

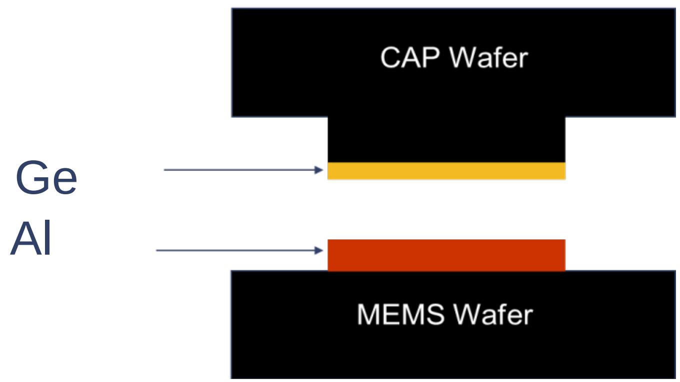
Al-Ge Eutectic System for CMOS-MEMS Integration



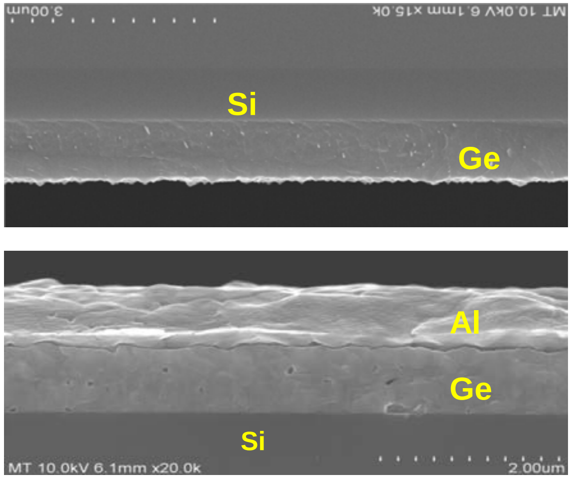
The Aluminum- Germanium system is a simple eutectic system with three phases (a) liquid (b) fcc (Al) solid solution and (c) diamond cubic (Ge) solid solution with eutectic point of 420ºC ± 4ºC *(Ref: Crnogorac et al, 2009)*

$$\frac{t_{Ge}}{t_{Al}} = \frac{at\%_{Ge}}{at\%_{Al}} \frac{\rho_{Al}}{\rho_{Ge}} \frac{A_{Ge}}{A_{Al}} = 0.59$$

Ideal Ge /Al thickness ratio is ~0.59 based on 71% at. Wt. Al and 29% at. wt. Ge

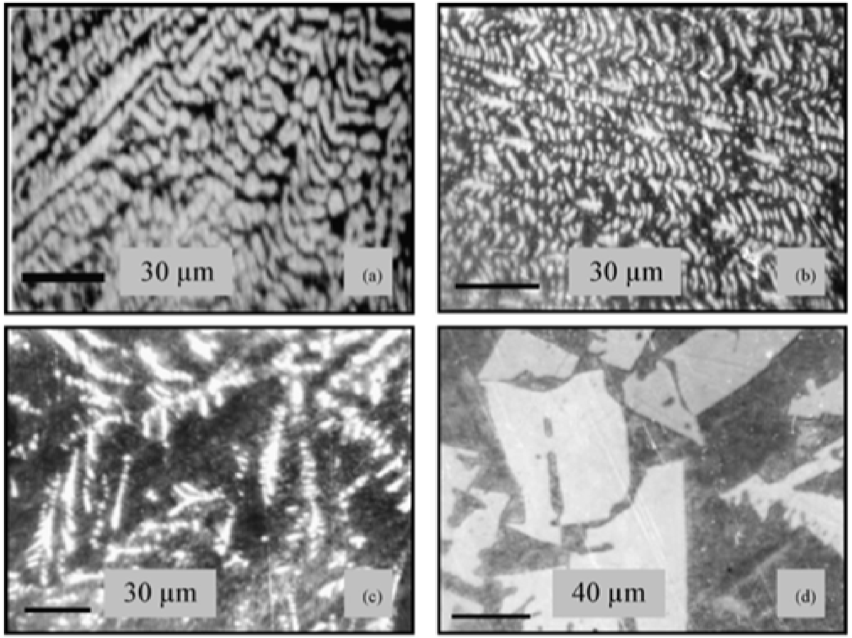


Typical Al/Ge stack for MEMS capping with Al on device wafers



SEM images of pre-bonded wafer stacks used for initial study (a) Substrate 1: Si/0.1µm TEOS/0.5µm Ge (b) Substrate 2: Si/0.1µm TEOS/0.5µm -1um Ge /1µm Al

Understanding the Al–Ge Eutectic Bond



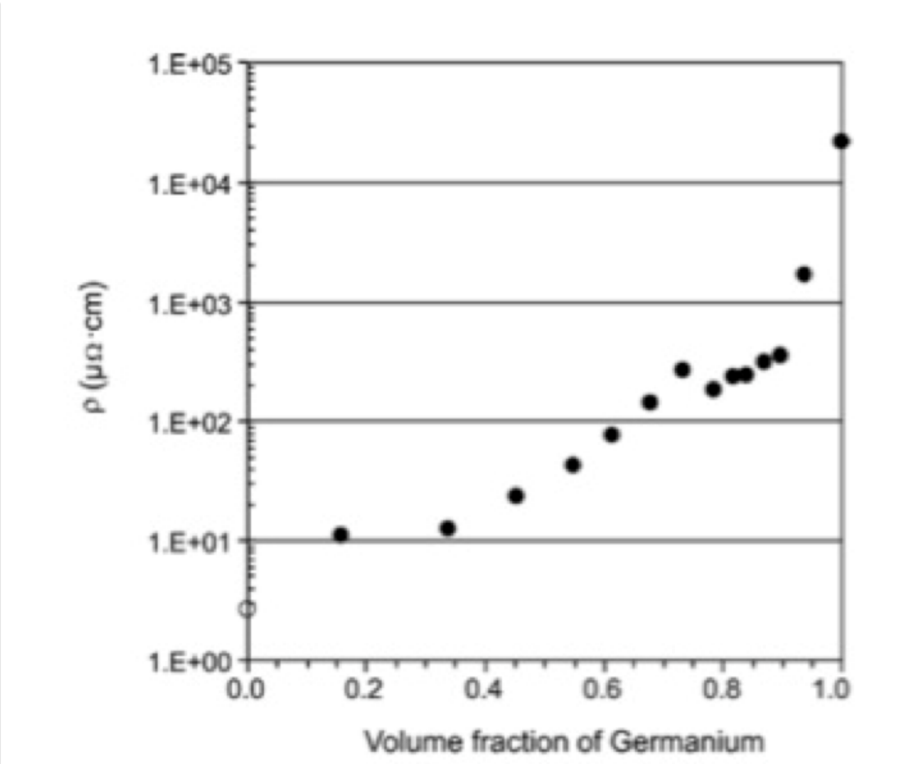
Microstructure of Al–Ge alloys: (a) 10 at.% Ge; (b) 20 at.% Ge; (c) 28.4 at.% Ge; (d) 40 at.% Ge

- AES Analysis identified Ge dendrites (light grey) embedded in an Al matrix (dark)
- This geometric structure is typical of Al-Ge system in which solidification takes place at the eutectic temperature where tow distinct liquidus curves meet.
- At this temperature both Al and Ge solid phases must deposit on the grain nuclei until all the liquid is converted into the solid.
- The simultaneous deposition results in a distinct microstructure unique to the alloy and is usually observed in slowly cooled samples.

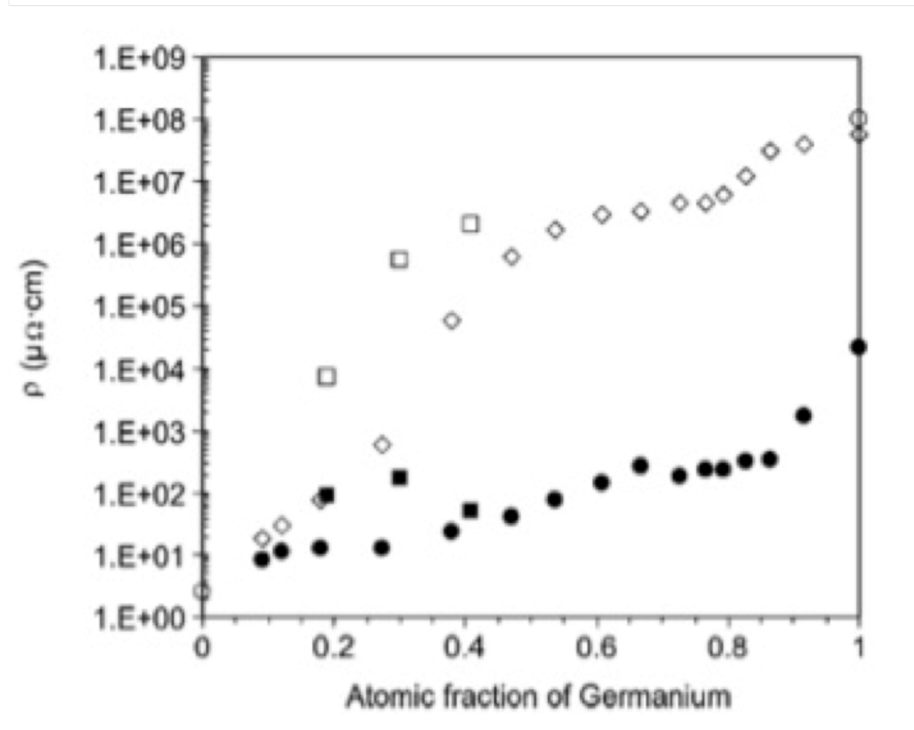
Alloy	Density 10^3 kg / m^3	Young's modulus (GPa)
Al-10 at.% Ge	3.06 ± 0.01	76.1 ± 0.8
Al-20 at.% Ge	3.30 ± 0.02	83.1 ± 0.8
Al-28.4 at.% Ge	3.49 ± 0.02	90.0 ± 0.9
Al-40 at.% Ge	3.77 ± 0.02	96.5 ± 0.9

(S.P. Nikanorov et al. / Materials Science and Engineering A 442 (2006) 449–453)

Al–Ge Electrical Resistivity



Resistivity of crystallized Al-Ge alloys as functions of the volume fraction of Ge



Resistivities at room temperature of sputter-deposited Al–Ge alloy films in the amorphous and crystallised state as a function of the atomic fraction of Ge.

(Ref: A. Boogaard, J.J. van den Broek / Thin Solid Films 401 (2001) 1–6)

Process Design Phases

Phase A

Metal Stack and seal ring width optimization

- Seal ring widths varied between 30 and 120um
- Single Wafer with deposited Al-Ge layers
- Al/Ge thickness ratio varied between 1.5 and 2.2

Phase B

Bond Process Parameters and Machine Optmization

- Determine optimum process parameters for
  - Minimal Squeeze-out
  - Improved Bond morphology
  - Improved Shear strength

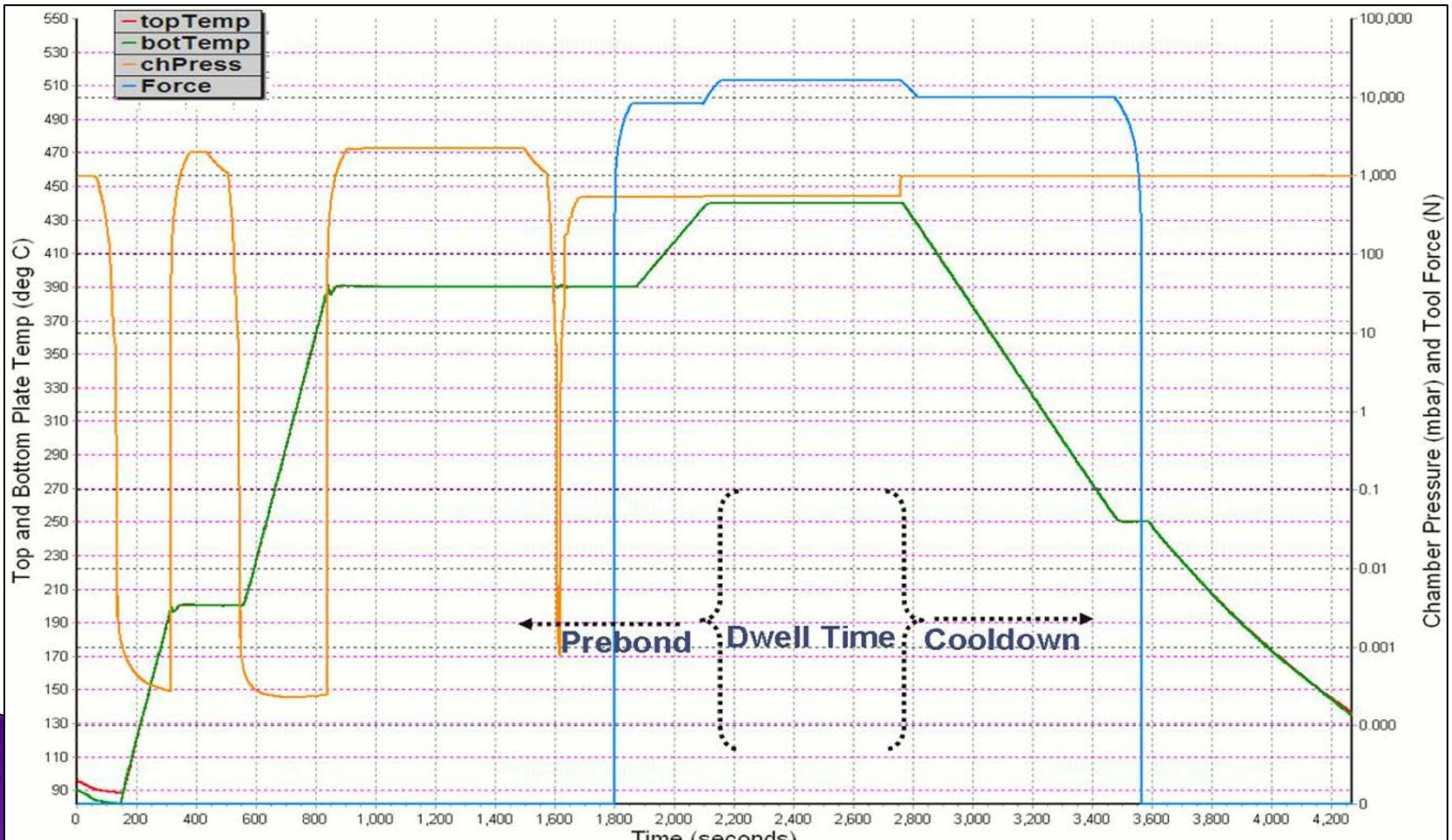
Phase C

HVM Process Qualification

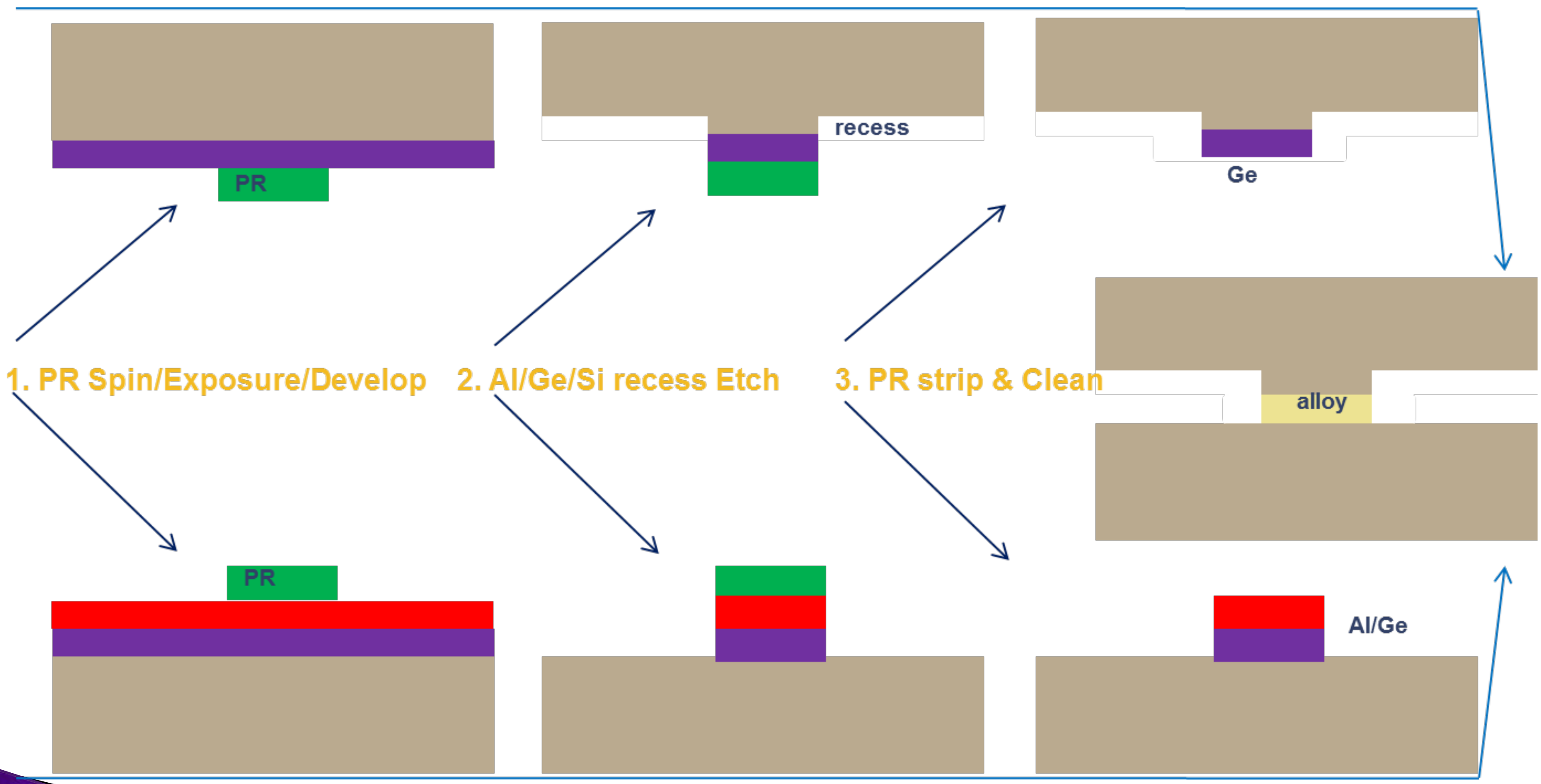
- Minimize cap-fly off
- Al cleaning optimization
- Maximize device yield
- Optimize throughput

General Process Parameters for Al-Ge Bonding

- Temperature: 420C-450C
- Bond Force: 15- 50 kN
- Bond Time : 3-30 minutes

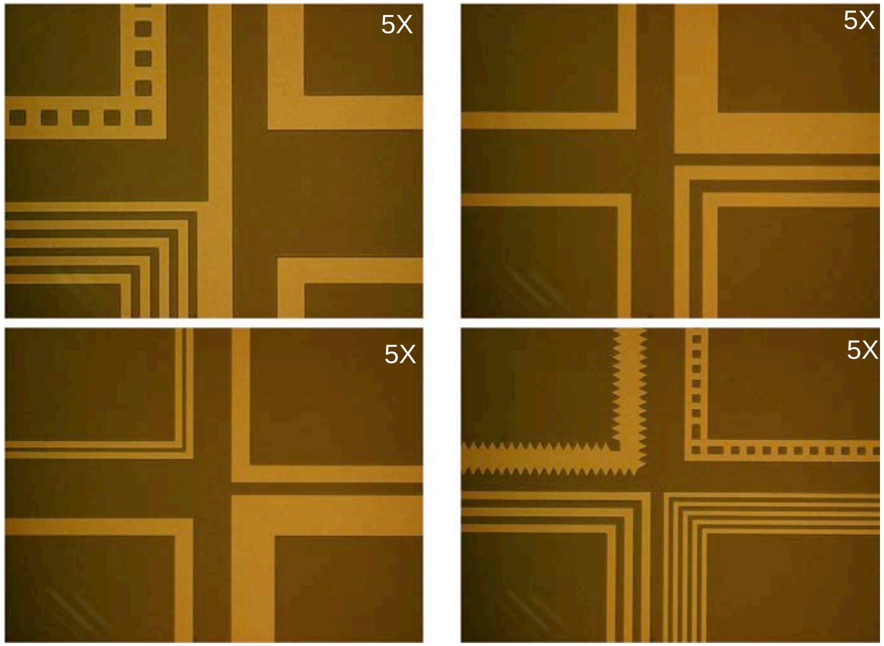


Al–Ge Patterning, Alignment & Bonding

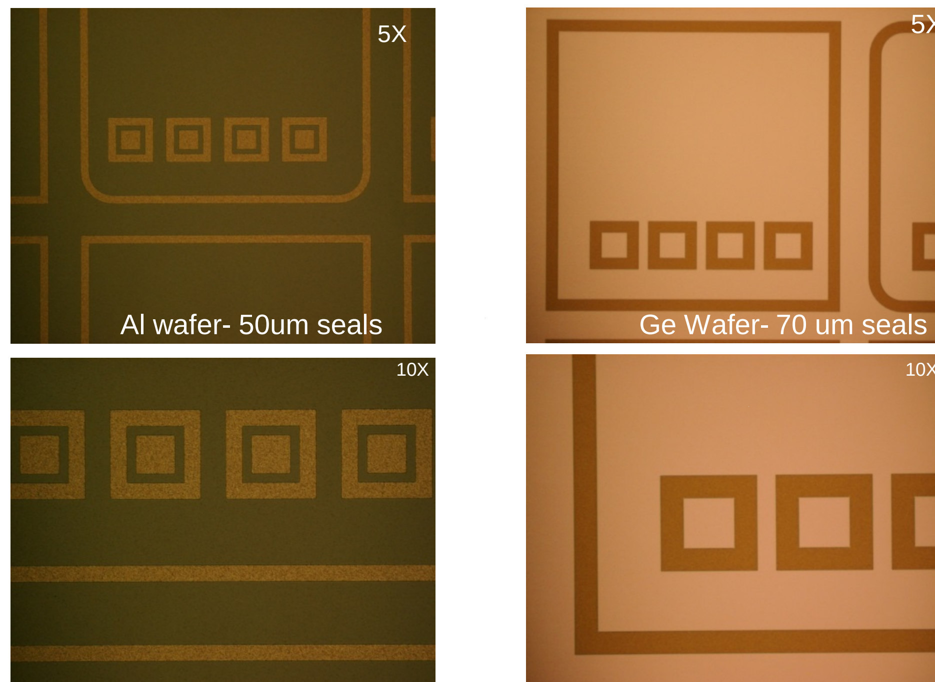


The process includes a mirrored-pair mask design, lithography, etch, pattern alignment and eutectic metal bonding:

Metal Seal Ring Design



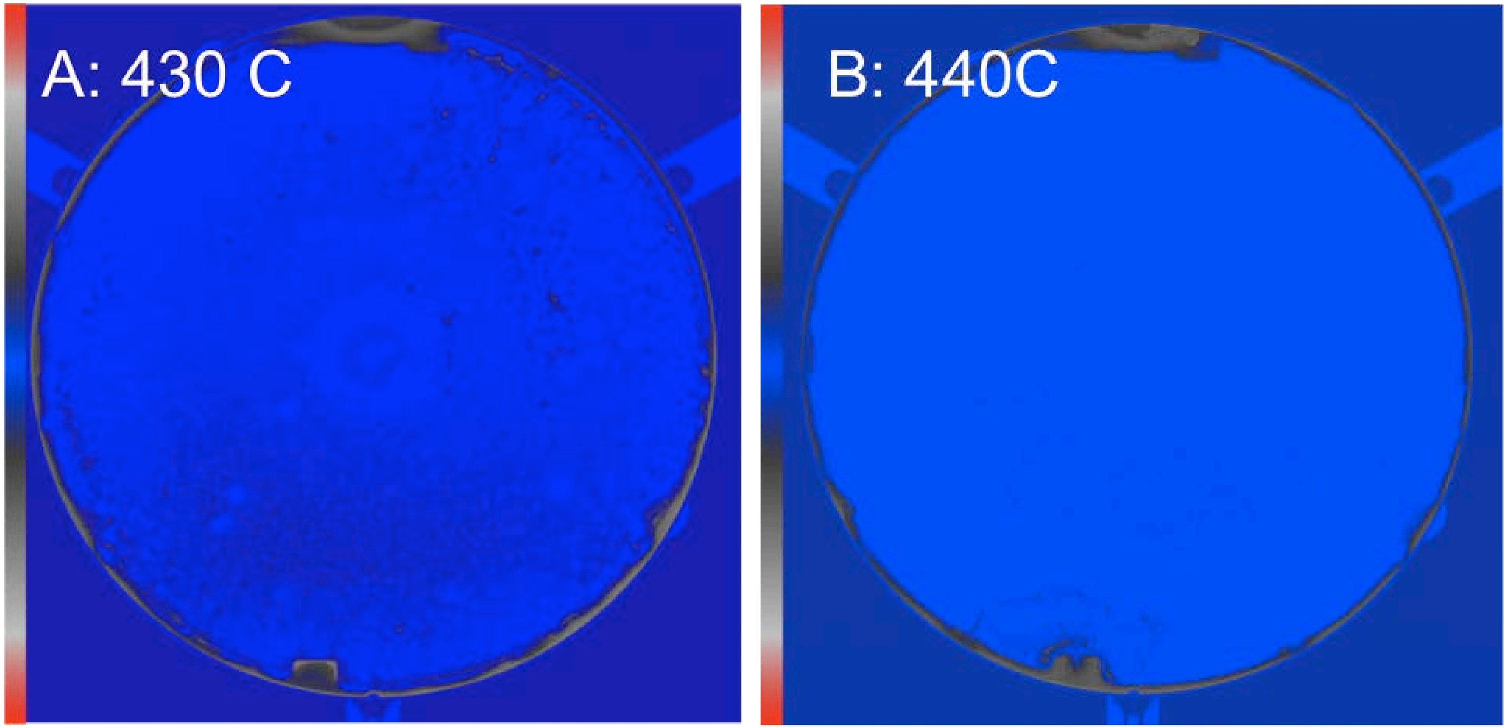
Phase A– Images showing Seal Rings of Varying widths (30um to 120um) on both Al and Ge wafers



Phase B/C –wafer design: 50um Al and 70um Ge seals

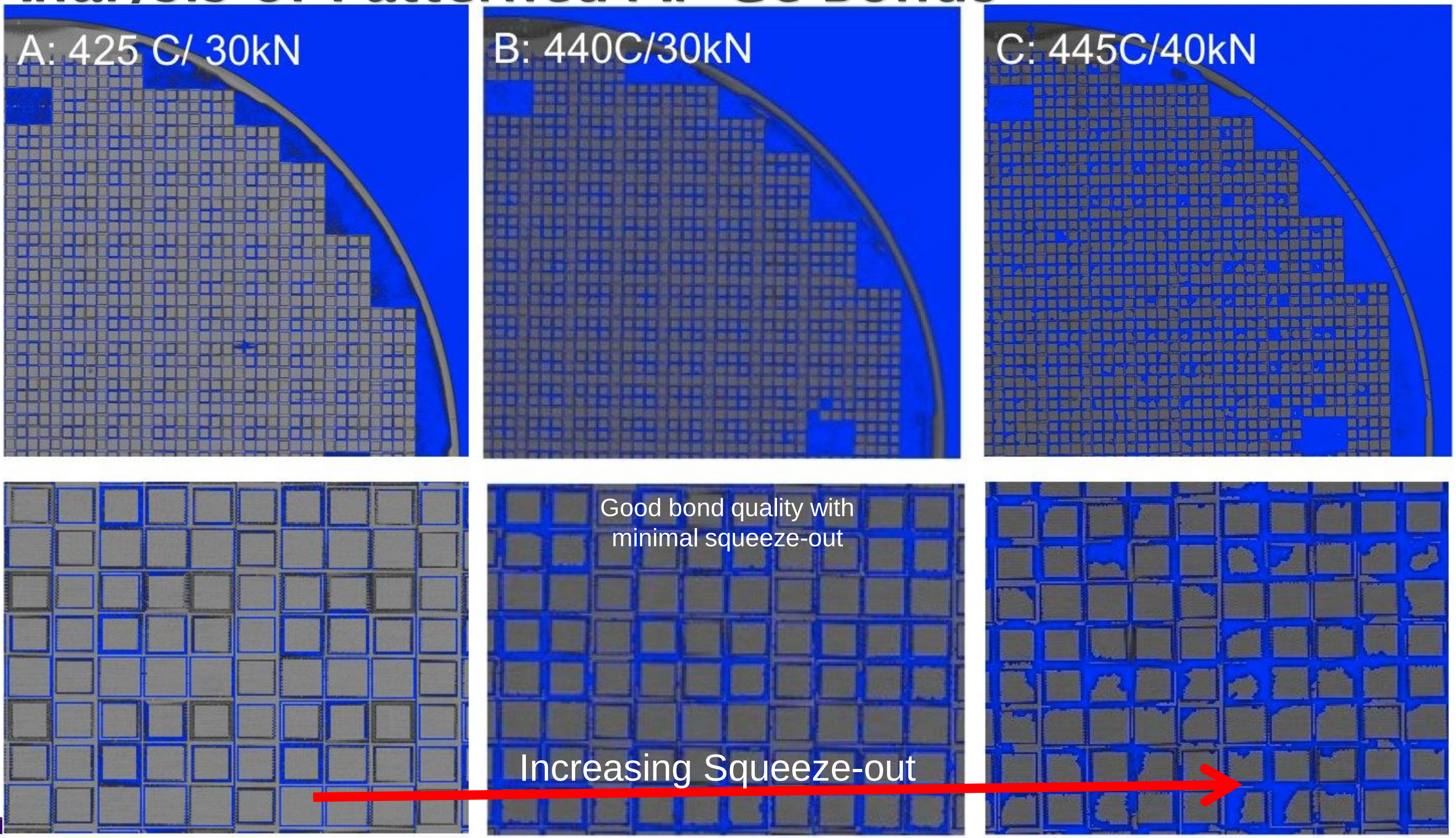
Contents

Bond characterization– blanket wafers SAM analysis



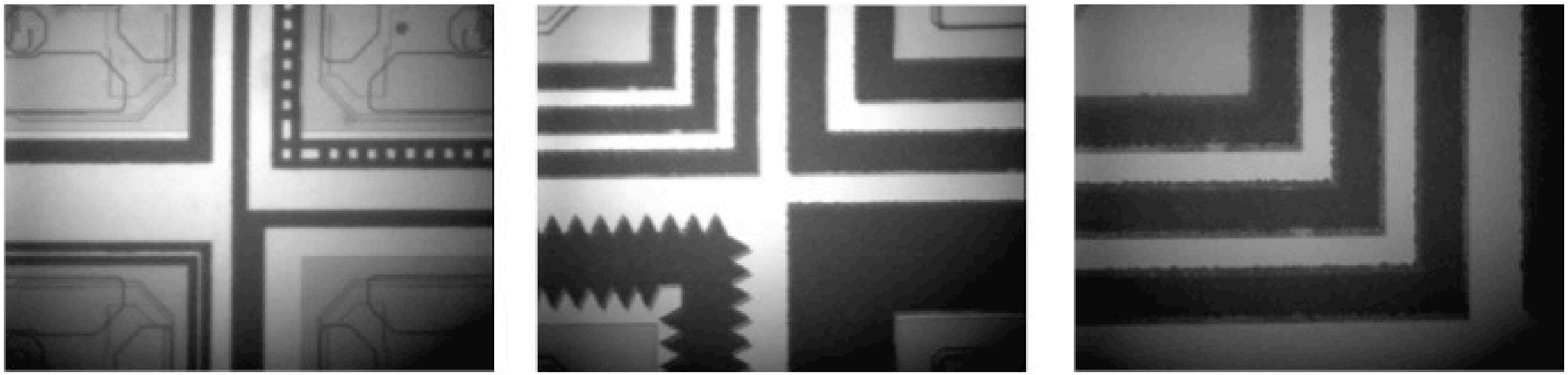
SAM images of a blanket Al-Ge bonded pairs showing a void-bonding.
The two artifacts at 6’o clock and 12’o clock position are from wafer clamping for Al deposition during upstream processes

Phase A: Bond characterization– SAM Analysis of Patterned Al–Ge Bonds

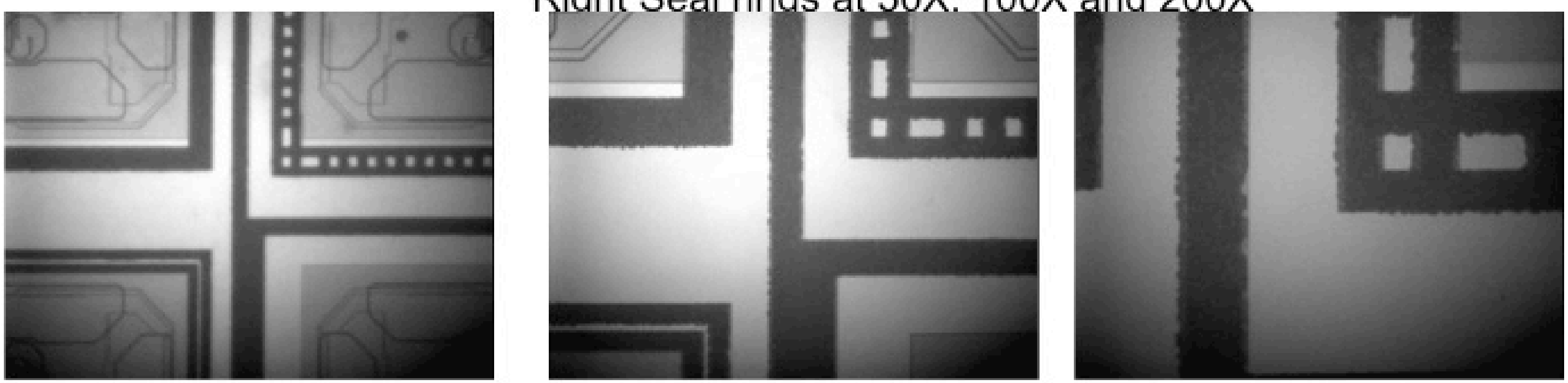


SAM images of a patterned Al-Ge bonded pairs at 425-445°C/ 30-40kN/ 9 minutes

Bond characterization:- Post Bond IR analysis (optimized process)



Right Seal rings at 50X, 100X and 200X

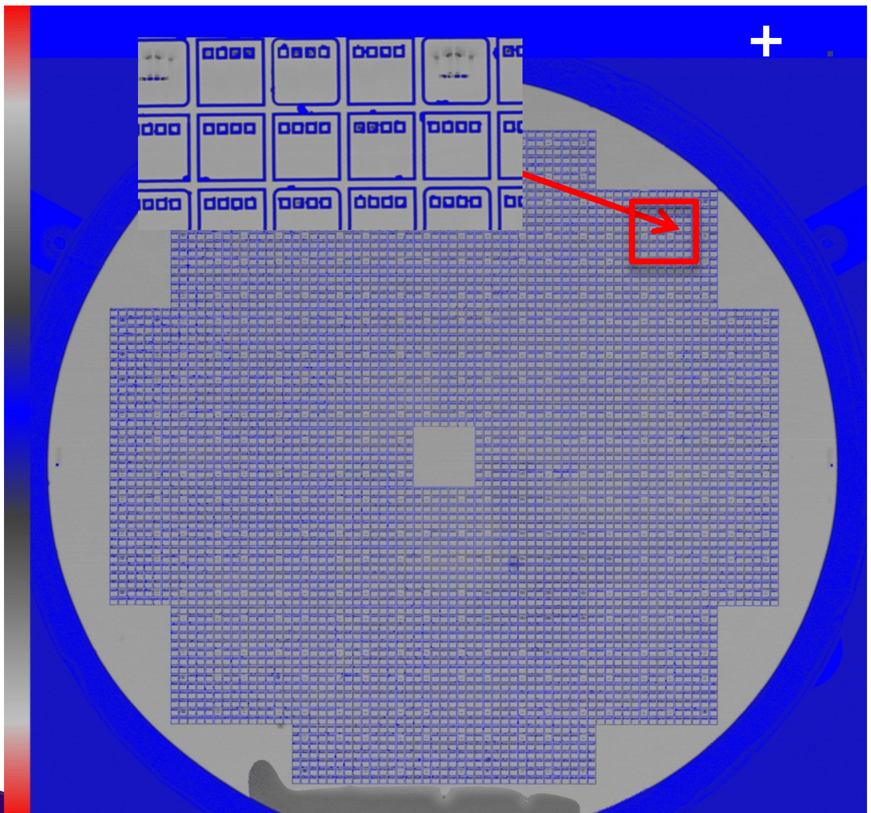


Left Seal rings at 50X, 100X and 200X

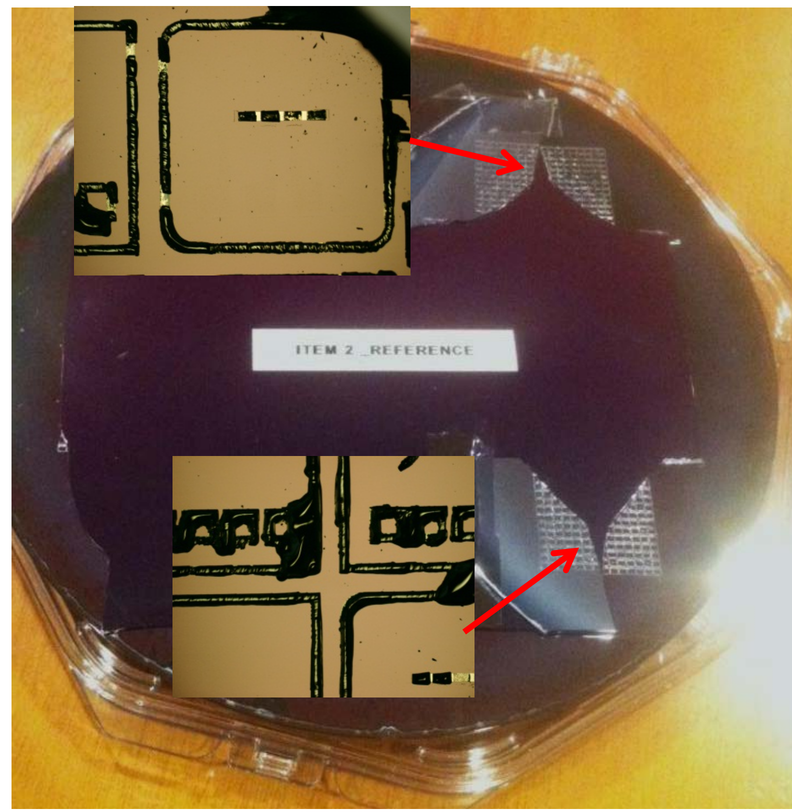
Transmission IR images from an offline IR microscope shows seal-rings from aligned and bonded Al-Ge substrates bonded with an optimized process

Bond Characterization

Post SAM Analysis, razor blade testing of was conducted to correlate SAM data with bond strength testing (done by inserting a razor blade at the bond interface)



SAM Image of aligned and bonded Al-Ge pair



Razor blade testing followed by optical microscope inspection showing strong bond interface

Bond characterization: Shear strength

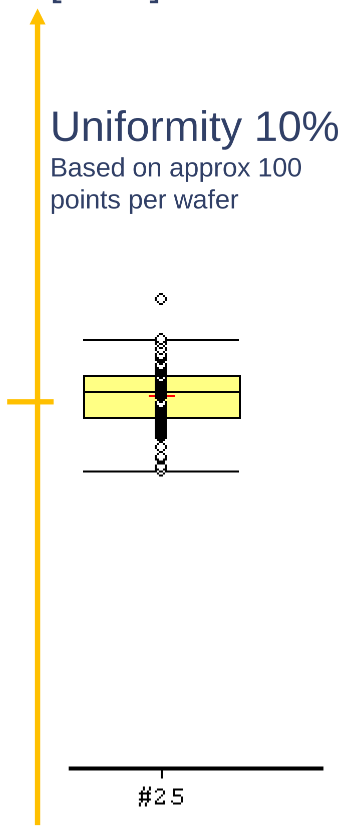
Shear strength [MPa]

Uniformity 10%

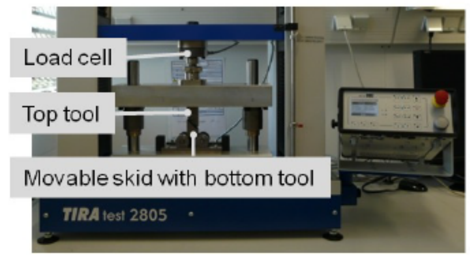
Based on approx 100 points per wafer

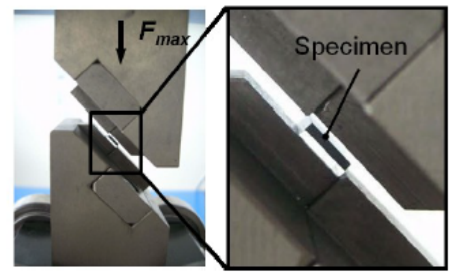
Mean value 75..120

depends on design



- Shearing the sample with an angle of 45°

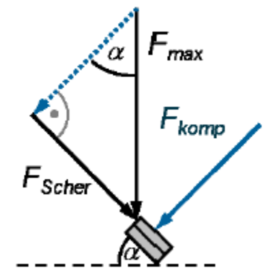




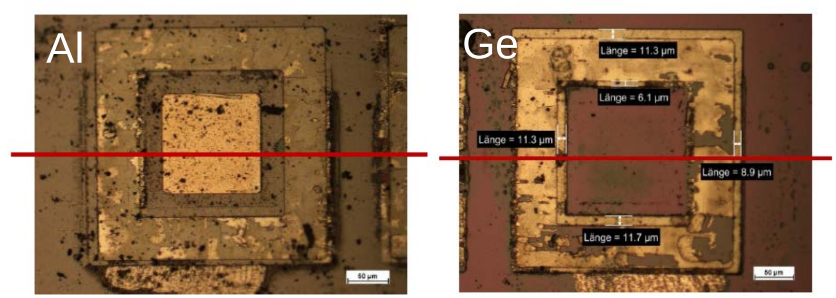
→ Shear stress interacts with compression

Shear strength

$$\tau_{Shear} = \frac{F_{Shear}}{A_{bond}}$$



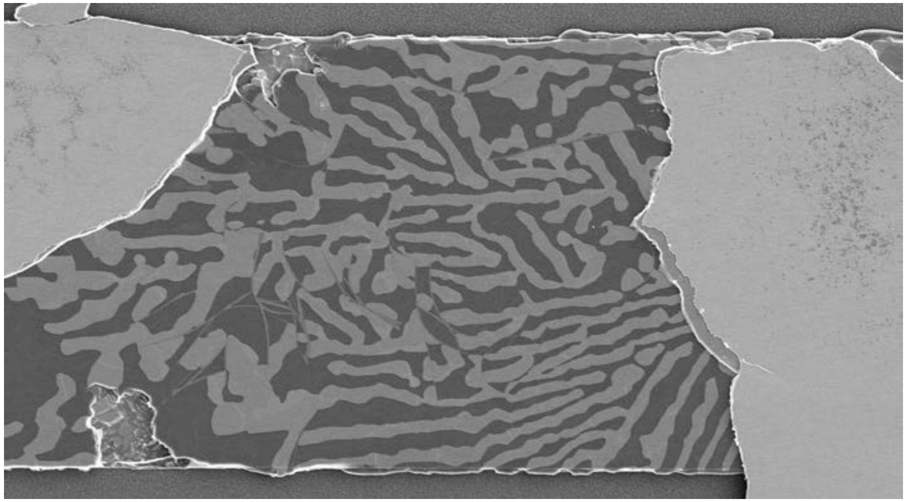
- Previous sample preparation → dicing in chips



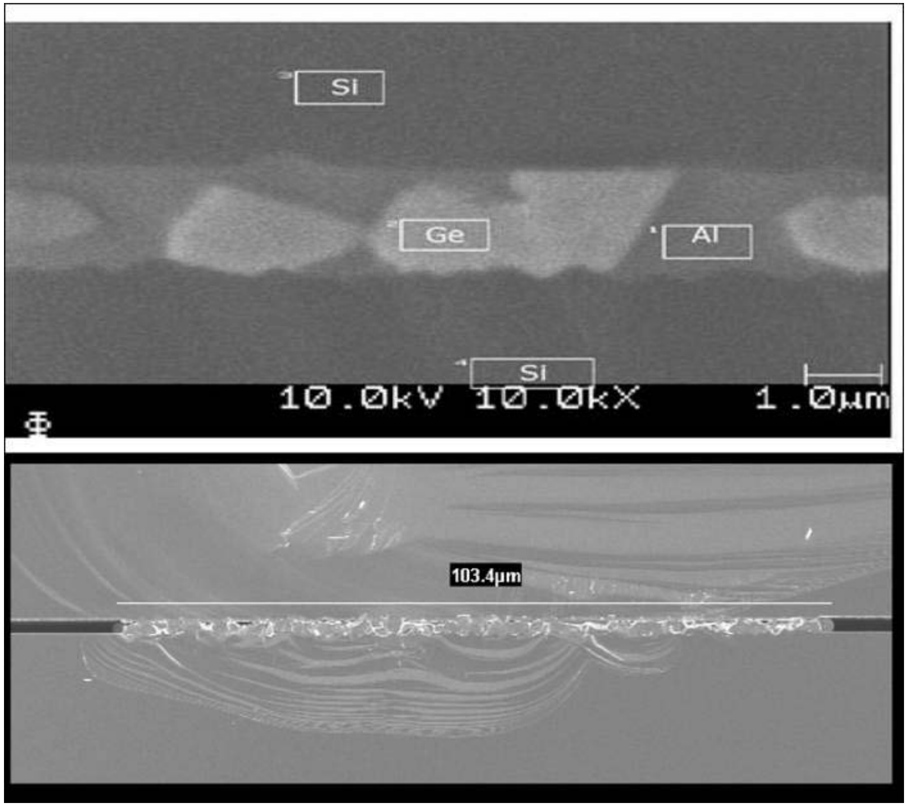
Al transferred over to Ge side. Failure at either Al/Ox interface

Bond characterization: SEM analysis of Bonded Wafers

- Bond interface cannot be identified due to good eutectic melt
- Al-Ge phases are nearly pure (low solid solubility)
- Strong mechanical properties at the interface (Fracture energy in excess of 40J/m^2)

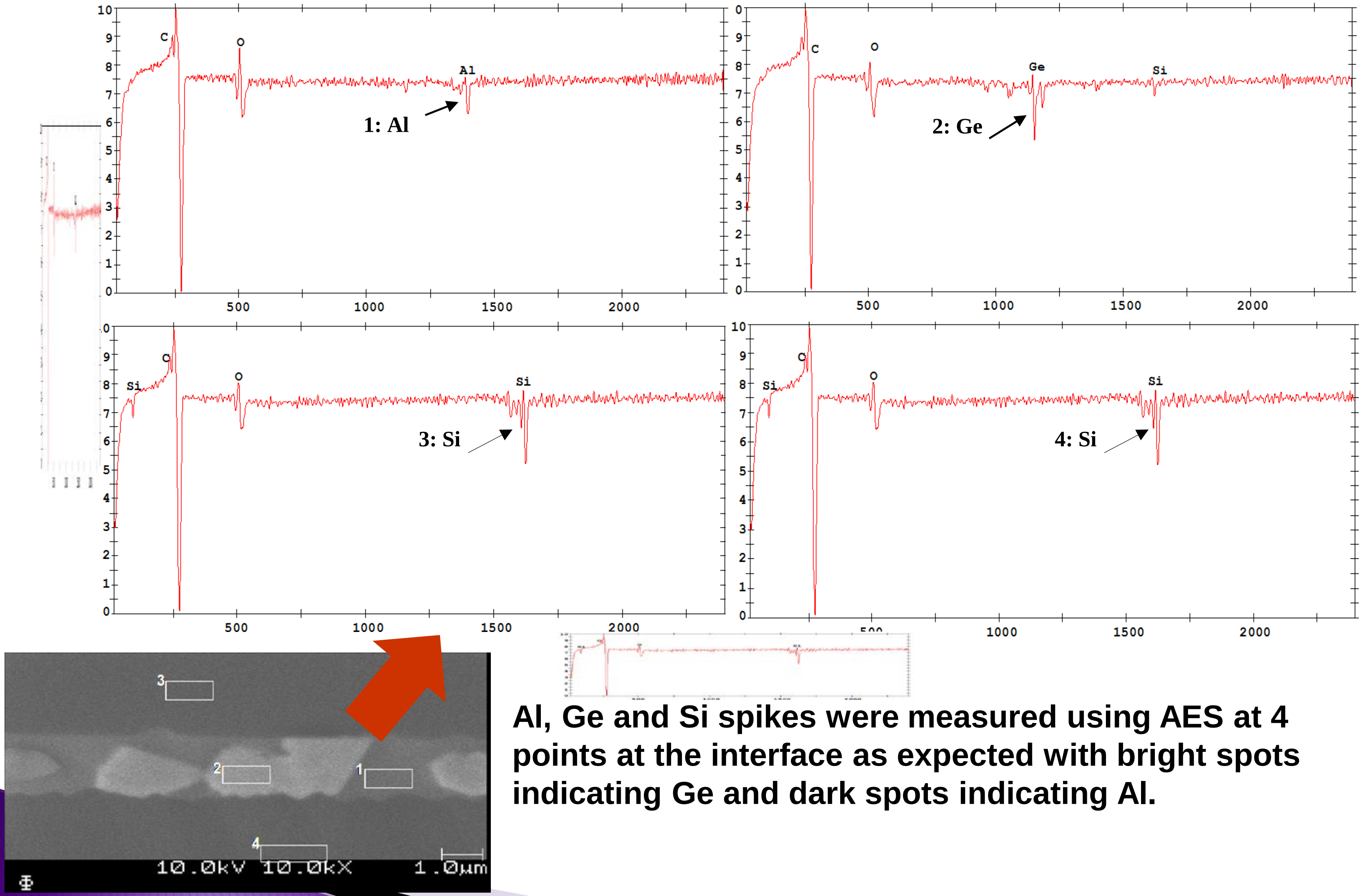


Plan SEM view of Al-Ge seal ring showing microstructure of Al-Ge eutectic bond at 450C. Germanium dendrites (light) within an Aluminum matrix



Cross-section SEM of the bonded pair section showing void-free eutectic AlGe alloy at the bond interface

AES Spectra for Al-Ge Bonded Pair

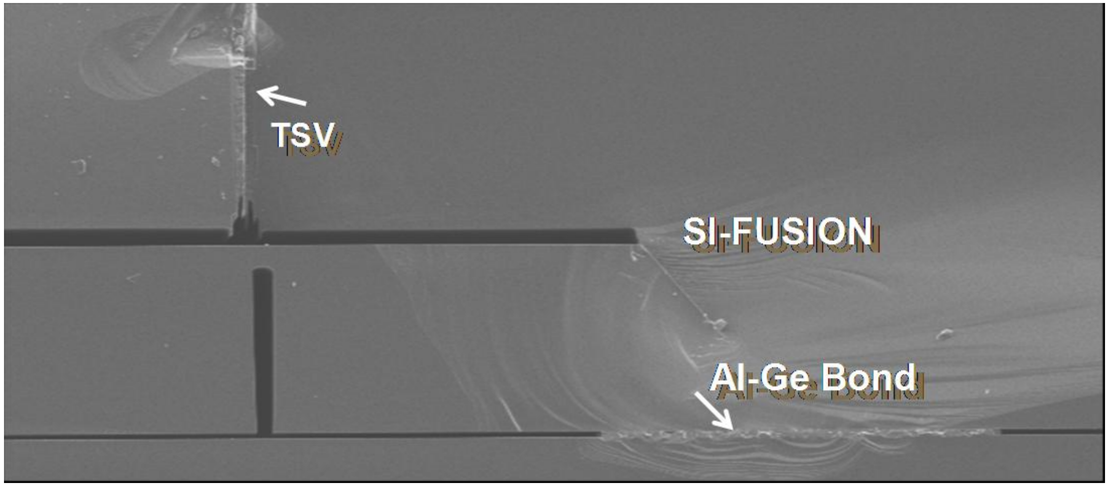


Al, Ge and Si spikes were measured using AES at 4 points at the interface as expected with bright spots indicating Ge and dark spots indicating Al.

Contents

Concluding Remarks

- Evolution from Frit to Metal-Eutectic Wafer Bonding
- Focus on Al-Ge eutectic and Sn based TLP Bonding
- Automated bond cluster optimized for Process proven in HVM (cap fly off < 2% , yield >95%, TPuT 5.5W/Hr)
- Ongoing Integration of Al-Ge bond process with TSV processes for wafer stacking
- Ongoing characterization of resonant structures to achieve better Q factor and higher cavity vacuum levels (for applications such as low frequency gyros etc)



SEM x-section of a triple stack bond showing a fusion bonded pair bonded to a third wafer using Al-Ge


Thank you!