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A Review of Eutectic Au-Ge Solder Joints

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Gold-germanium (Au-Ge) joints have been part of the electronics industry since the birth of the solid state transistor. Today they find their role as a reliable joining technology, especially for high-temperature applications. This article is a literature study reviewing Au-Ge joints: Their uses, properties, material compatibility, application techniques, and performance characteristics. The review concludes that it is possible to create high-quality and very strong Au-Ge joints with a shear strength up to 150 MPa. They are stable and reliable, showing limited degradation after thousands of hours at high temperature and thousands of thermal cycles. Joints may be used in low-stress applications up to 300 °C.

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I. INTRODUCTION

RESEARCH on semiconductor materials and devices in the 1940s was primarily made on the semiconducting materials germanium (Ge) and silicon (Si). Gold was deposited onto germanium to solve a contact issue with an early prototype amplifier device (point contact transistor) by a research team led by William Bradford Shockley Jr. and Stanley Morgan at Bell Labs in 1947.[1] This device led the research team to the discovery of the *transistor effect*. William Bradford Shockley, John Bardeen, and Walter Houser Brattain were awarded the *Nobel prize* in physics in 1956 for their work on the transistor and the discovery of the transistor effect.[2] Thus, the Au-Ge contact was a central part of the birth of modern electronics. The first types of semiconducting transistors that became commercially available in the 1950s were also made from germanium. The more stable silicon replaced germanium in the 1960s, which changed the role of Au-Ge from providing a contact surface for interconnects (wire bonds) to a die-attach material joining dies to substrates. Eutectic Au-Ge bonding as a die-attach method was patented already in the early 1960s.[3,4] In the 1970s and 1980s, research on Au-Ge bonding focused more towards ohmic contacts for gallium arsenide devices.[5–7] In the 1990s and especially post 2000, the high-temperature compatibility of Au-Ge joints has been thoroughly explored.[8–22] Environmental demands such as the RoHS directive have also lead to investigations on the Au-Ge system as a replacement for lead-based solders.[23,24] The high material cost has most likely limited its applicability into volume mainstream, low-end electronics devices.

The great majority of electronic devices and uses comprising Au-Ge joining technology has been explored with the utilization of a eutectic (or near eutectic) composition of the Au-Ge system. These alloys are today commonly used as a high-reliability, high-temperature compatible die-attach technology. The main motivation for this seems to be its high melting temperature at 361 °C[25] and the stable properties, corrosion, and thermal fatigue resistance, combined with excellent joint strength of the final joint. Typically, high-temperature applications with Au-Ge have aimed for use up to around 300 °C.[8,9,11,12,17,19,20,22,26–33] But, joints have also been explored for cryogenic temperatures down to around − 170 °C.[15,26,32,33] Au-Ge joints have been evaluated as materials for die-attach purposes in numerous devices and configurations and various other uses in recent years. Applications include silicon carbide (SiC) power devices,[10,19,28,34–36] SiC diodes,[10,18–20,26,29,32,33,35] SiC dummy dies,[15,30,31] Si dummy dies,[8,9,11,12,17,22] microwave circuit,[27] MEMS device,[37] for wafer bonding,[37] creating nanowires,[38] forming ohmic contacts,[6,39] and hermetic seals[40,41] to mention some. Ceramic substrates (circuit boards) have most commonly been the substrate of choice in the evaluated systems. In particular, substrates of silicon nitride (Si_3N_4)[12,15,17,20,30,31,34–36] or alumina (Al_2O_3)[10–12,18,27,28] have been used. Other ceramic substrates include AlN[15,19] and BeO.[26,33] Both

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Cu[16,22] and Kovar[27] have also been used as substrates (or lead frames).

II. MATERIAL PROPERTIES

Most materials properties of the Au-Ge system have been evaluated for the eutectic (or near eutectic) composition; 72 at. pct Au and 28 at. pct Ge, as shown in the phase diagram of Figure 1. All data presented in this review are based on this composition unless otherwise specified. The properties of pure Au and Ge have been thoroughly reported elsewhere and are not part of the scope for this report. As shown from the phase diagram of the Au-Ge system in Figure 1, only three stable condensed phases exist; the solids fcc_A1 (Au) and diamond_A4 (Ge), and a liquid (L).[42] However, it should be mentioned that Tasci *et al.* have reported the existence of a stable stoichiometric phase, Au_5Ge_2, at lower temperatures[43] and Maganin *et al.* identified a stable Au_3Ge phase after deposition of a Au film onto a Ge substrate.[44] These phases will not be discussed further in this review. The solubility of Ge in Au is up to 3.08 at. pct at the eutectic temperature, 361 °C, and less than 1 at. pct at room temperature.[25] The solubility of Au in Ge is negligible.[25] The chemical bonds between Au and Ge in eutectic $Au_{72}Ge_{28}$ have been identified to be covalent.[44–46] Eichhammer *et al.* illustrated the possibility to significantly reduce the solidus intersecting the eutectic point by using nanosized particles of 5 and 10 nm.[47] Kryshtal *et al.* showed that for a bilayer of Au/Ge, the Au film mass thickness needs to be larger than 0.2 nm for a eutectic compound to form on the surface.[48] Near eutectic compositions have an irregular lamellar type microstructure, see Figure 2(a).[8,9,12,15,16,19,20,23,27,49] Another common microstructure found in literature is colonies of Ge dispersed in a Au matrix,[8,9] see Figure 2(b). This second microstructure is especially common after thermal aging which typically coarsens the grain structure.[8,9,16,19,20] In contrast, Chidambaram *et al.* found that the microstructure of eutectic $Au_{72}Ge_{28}$ was refined after aging at 200 °C for three weeks.[23] No further explanation to this rather contradictory result was given. One explanation could be variations in cooling rates during fabrication which could cause different lamellar spacing.[50] Similarly, coarsened

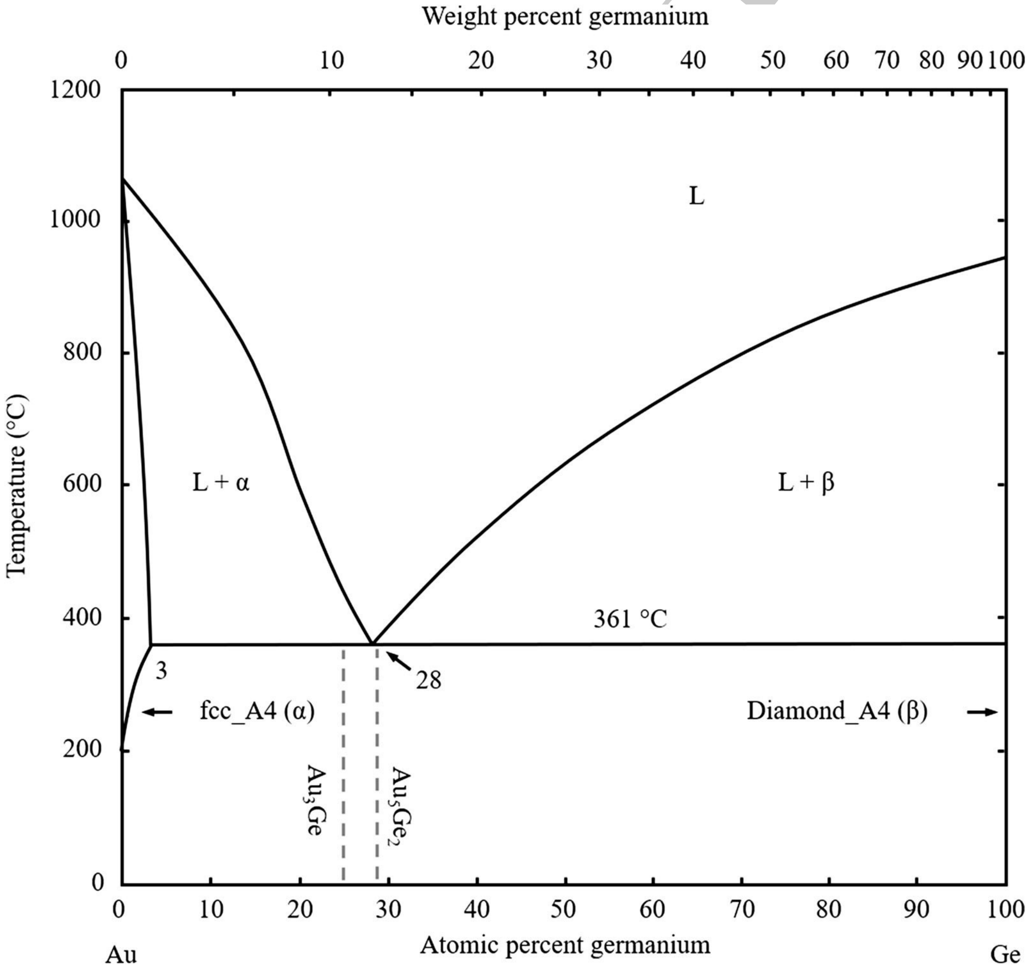

Fig. 1—The binary phase diagram of the Au-Ge system. The phase diagram was adapted from.[25,42–44] Note that the eutectic melting point varies slightly in the pertinent literature; 356 °C to 361 °C.[42,51]

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microstructures can also be found in samples with adjoining depletion layers, such as nickel (Ni).[9,16,19,20]

Typical static mechanical and thermal properties found in literature are compiled in Table I. Values vary somewhat between sources; thus, a range is provided when appropriate. Discrepancies between the references may originate from different setups during measurement, purity of the samples, the morphology of the different phases, heat treatment profiles, *etc.*

III. MATERIAL COMPATIBILITY

Material compatibility is crucial for any packaging system. Joining dissimilar materials creates new phases, *e.g.*, intermetallic compounds (IMC), and interfaces between these different phases. They have dissimilar properties, such as their coefficient of thermal expansion and Young's modulus, which may cause high-stress states in fabricated joints. Adjoined materials need to be chemically stable and provide suitable mechanical, thermal, and electrical performance for proper functionality and reliability. The final microstructure and composition may also depend on a wide variety of parameters such as how the fabrication process was carried out, *e.g.*, the deposition method used for the metallization on dies and substrates, and temperature profiles. Thus, care should be taken before concluding on apparently similar systems. Further comparison between different systems from different studies is even more troublesome. This section presents general trends and results extracted from the pertinent literature. Juxtaposed materials systems evaluated in literature are compiled below.

A. *Nickel/Gold (ENIG)*

Most commonly, eutectic Au-Ge have been used in systems with a metallization scheme based on the electroless nickel immersion gold (ENIG) system.[8,9,11,12,15,19,20,22,26–28,31,33,35,36,49] In such systems, Au-Ge typically reacts with Ni and forms Ge-Ni intermetallic compounds (IMC). Lang *et al.* and Egelkraut *et al.* reported the intermetallic phase to be near the stoichiometric phases NiGe and Ni_2Ge.[19,20] Chidambaram *et al.* reported a Ni_5Ge phase along with

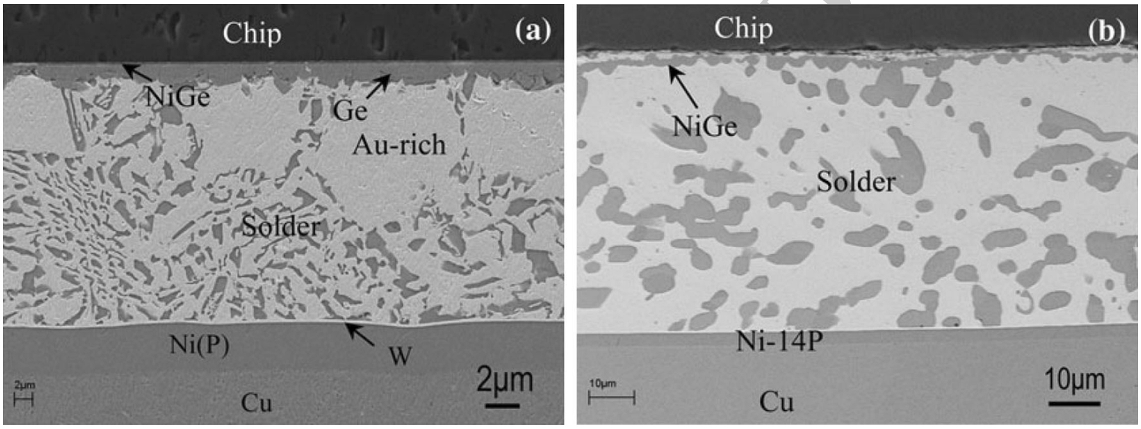

Fig. 2—Scanning electron microscope (SEM) image of cross-sections illustrating the microstructure of (*a*); a virgin joint and (*b*); a joint after heat treatment at 330 °C for 1000 h.[20] A coarsening of the microstructure is seen after thermal aging. Reprinted with permission.

Table I. Properties of Eutectic $Au_{72}Ge_{28}$

Property	Unit	Value	Source
Eutectic Composition	at. pct Ge	27.0 to 29.4	[25, 42]
Melting Point	°C	356 to 361[a]	[25, 42, 47]
Young's Modulus	GPa	50 to 75[b]	[18, 21, 52]
Poisson's Ratio		0.32	[21]
Yield Strength	MPa	100 to 240[b]	[18, 52]
Shear Strength	MPa	220	[53]
Ultimate Strength	MPa	175 to 185[b]	[52]
Elongation at Break	pct	10 to 50[b]	[18]
Hardness	GPa	3.6	[8]
Coefficient of Thermal Expansion (CTE)	ppm/K	10.2 to 16.5[b]	[52]
Thermal Conductivity	W/mK	44 to 44.4	[15, 52]
Electrical resistivity	$\mu\Omega$ cm	15 to 29	[32, 53]
Activation Energy—Creep	kJ/mol	11	[15]
Heat of Crystallization (a Ge)	J/mol	1.15	[54]

[a] Particle size dependent.
[b] Temperature dependent.

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the NiGe phase. The growth rate of Ni_2Ge was measured to be up to a few nanometers per hour at 200 °C to 250 °C.[16] Godignon *et al.* evaluated the electrical characteristics of a SiC diode joined with an ENIG-like system and found it to be stable at temperatures between − 170 °C and 270 °C.[26,33] They also found that the thermal resistance from junction to case increased as a function of ambient temperature with about 65 pct (0.6 K/W). The temperature dependence of the joint strength was reported to show a nearly linear decrease from about 115 MPa down to zero at the melting point of eutectic Au-Ge.[15] Stress tests may be found in References 8, 9, 19, 20, 26, 31, 33, 35, and 36. The phase diagram of eutectic Au-Ge with Ni can be found in Reference 27.

B. *Copper*

When Au-Ge is bonded directly to Cu, the components react and create new intermetallic compounds comprising Au-Cu-Ge.[8,9,16] Egelkraut *et al.* identified it to be $(Au,Cu)_5Ge$ (the ξ phase) with varying Au-Cu compositions.[16] They further measured the growth rate to be about 5 to 10 nm per hour at 200 °C to 250 °C. They also compared the results between Ni and Cu metallization and found that Cu could create stronger and more stable bonds than with the Ni metallization. Between the IMC and the Cu layer, they further observed a Au-Cu solid solution. The results indicate an interdiffusion process, or material transport, of Au and Cu through the joint, and that Ge does not interact significantly with the Cu. The bond seems to change its properties initially to finally stabilize at a new level when exposed to high temperatures.[8,9] The IMC formation likely causes the change. Related stress tests can be found in References 8, 9, 18, and 21.

C. *Silver*

Lang *et al.* studied asymmetric systems with Ni/Ag thin film on one side of the joint.[19,20] In one study, they identified the fracture surface to the side of the joint were Ni-Ge IMC were present. In another similar study, they later showed that the fracture surface could be moved to the device/joint interface by using tungsten (W) as a diffusion barrier between Ge and Ni. Tanimoto *et al.* showed that Ag in a thin film of Ni/Ag was completely dissolved by the adjacent Au-Ge material.[31] Both Egelkraut *et al.* and Drevin-Bazin *et al.* used devices with Ag films, but no joint/Ag film-related results were reported.[15,16] Related stress test may be found in References 8, 9, 18, and 21.

D. *Other Systems*

A variety of materials systems combined with Au-Ge have been evaluated in the pertinent literature, including Al,[34] Ti/Ti-W,[17] W,[20,32] and glass.[17] Lang *et al.* showed that it was possible to bond to an Al metalization creating strong joints, > 50 MPa, and with stable electrical performance results.[34] Long-term evaluation or other stress tests of that system was not performed, and one might suspect that the Al-Au-Ge system may form the well-known problematic Al-Au IMCs such as Al_2Au (purple plague) and Al_2Au_5 (white plague).[55]

IV. APPLICATION TECHNIQUES/PROCESS

Au-Ge joints have typically been created using various methods that are similar to common soldering techniques. Eutectic preforms have been used frequently.[11,12,15–18,27,28,31,35] Thin film techniques by deposition and patterning have also been evaluated,[37] along with solder balls[8,9] and pastes.[34] Bonding has been performed in a vacuum, inert atmospheres, reducing atmosphere, flux, and air.

Recent process parameters that have been used in literature are compiled in Table II. Avoiding atmospheric oxygen seems crucial to be able to create strong uniform joints. Cleanliness of bond surfaces also has a strong impact on the bond quality. Regarding the process peak temperature and time, it seems to be enough to generate a liquid phase (eutectic) that has enough time (seconds) to interdiffuse with the adjacent bond surfaces to create strong bonds. Longer times or higher temperatures affect the resulting microstructure somewhat, but do not seem to have a direct impact on the final bond quality. It has been demonstrated that it is possible to create uniform joints with excellent coverage and without significant voiding or microcracks inside the joint.[11,12]

V. PERFORMANCE

A. *Shear Strength*

Shear strength tests are one of the most widely used methods in literature for evaluating the bond quality. Mechanical strength is often a more revealing measure for bond quality than changes in electrical characteristics of devices. Tanimoto and Matsui illustrated this effect clearly in Reference 35. They measured a reduction in joint shear strength of several tens of percent while the leakage current remained unchanged when exposed to thermal cycling. A compilation of the shear strength for virgin joints is presented in Figure 3. Whenever possible, individual data points have been extracted from the references. Extracted test results have been assumed to have been carried out at 25 °C whenever no specific information has been reported. Shear test parameters are rarely disclosed in literature and are thusly not compiled here. It is clear that the final joint strength varies greatly, with a factor of more than ten times, between reported devices (see results at 25 °C). The variation may originate from sample preparation or simply from different system configurations of the final assembly. Nonetheless, it is clear that it is feasible to create very strong joints with eutectic Au-Ge. It is also interesting to notice that the shear strength at elevated temperatures, near the melting point of the Au-Ge compound, is still significant. It should be

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Table II. **Process Parameters Used to Fabricate Au-Ge Joints**

Peak Temperature (°C)	Preheat Temperature (°C)	Time at Peak Temperature (s)	Pressure	Atmosphere	Shear Strength (MPa)	Source
430	—	—	—	—	115	[15]
400	—	10	—	air	> 8	[28]
390	—	15	—	flux in air	22 to 34	[8,9]
—	—	—	—	N_2 AND VACUUM	—	[21]
> 363	—	300	2.1 MPa	vacuum or N_2	—	[37]
430	—	120	—	vacuum	50 to 116	[34]
385	—	120 to 180	—	vacuum	26 to 52	[17]
410	—	—	—	vacuum	64 to 72	[20]
400	200	quick	—	red/vacuum/N_2	128	[31]
—	—	—	> 0	red/vacuum	—	[26]
—	—	—	—	red/vacuum/N_2	25	[16]
450	300/330	1800	> 0	red	78	[12]
—	—	—	—	red	240	[18]

Red: Reducing atmosphere (formic acid or H_2).

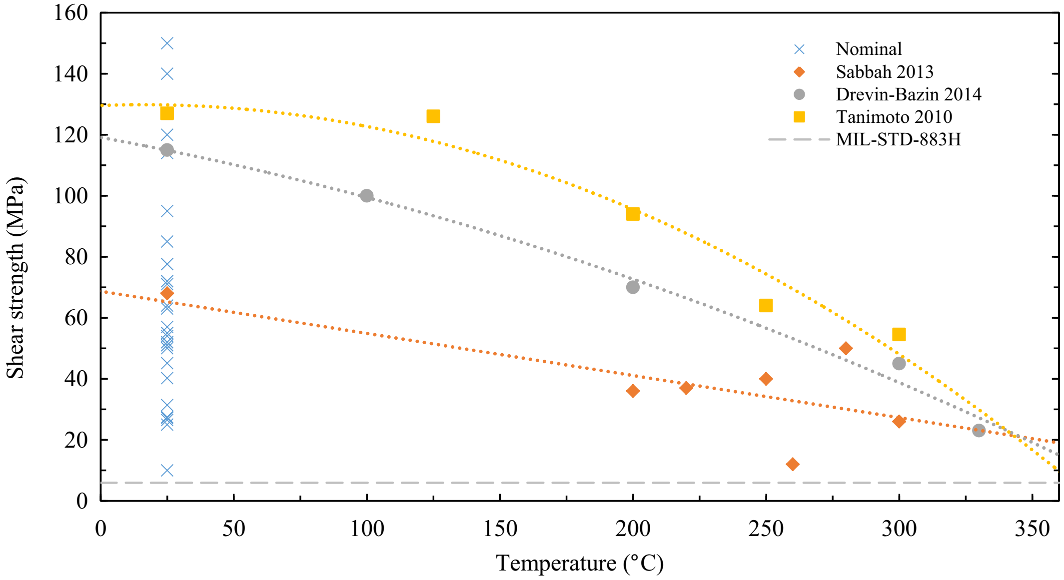

Fig. 3—Shear strength of virgin eutectic Au-Ge joints as a function of temperature for various devices.[8–12,15–17,19,20,22,28,31,34–36,49] Various samples tested at room temperature are compiled in the 'Nominal' series. Dashed lines are curve fits for each series. The strength requirement for solders, as stated in the US military standard (method 2019.8), is included here for Ref. [56].

pointed out that the reported strength results mirror the weakest link in the tested system, not necessarily the Au-Ge joint itself. Shear strength at cryogenic temperatures is yet to be evaluated.

B. *Electrical Evaluation*

Another way to characterize the bond quality is by electrical evaluation. Different devices have been electrically evaluated at temperatures from − 170 °C up to 330 °C.[10,19,29,32,35] The characteristics are typically evaluated on a system level where the entire assembly influences the results: the die, die-attach, wire bonds, *etc.* Waveforms, current, voltage, and characteristic drift have also been evaluated. The reported results typically showed a limited degradation of the electrical performance, and that this degradation could be directly accredited to the joint itself. The thermal performance has been evaluated at similar temperatures.[26] It was found that the thermal resistance from junction to case increased from 0.92 to 1.53 K/W.

C. *Stress Testing*

Stressing joints by exposing them to different loads is a common way to evaluate their performance and stability. Common techniques to stress devices include thermal storage at elevated temperatures, thermal cycling, and power loading. Different techniques stress different parameters or mechanisms, *e.g.*, thermal storage typically accelerates diffusion processes, thermal cycling stimulates material fatigue, and power loads excite migration mechanisms.

In general, literature demonstrates a joint that is very robust if given a proper design and applied within certain load conditions. It can withstand very high temperatures, near the melting point, as well as survive wide thermal cycles. Electrical characterization results also indicate a limited migration degradation when stressed.

One interesting observation from this review comes from an analysis of the combined results of Tanimoto *et al.*,[35] Drevin-Bazin *et al.*,[15] and Msolli *et al.*[21] Together, they point that the strength capacity of eutectic Au-Ge joints significantly depends on the mechanical load state. Drevin-Bazin *et al.* and Msolli *et al.* showed this by studying the creep behavior. Tanimoto *et al.* indirectly showed that fatigue failures were reduced by improving their system for CTE mismatch, thus reducing the stress state in the joint during cycling. Note that this change might have shifted the cycling characteristics, or failure mechanism, between low cycle fatigue (LCF) and high cycle fatigue (HCF). A detailed analysis of the joints would reveal this.

D. *Thermal Storage*

Figure 4 shows compiled thermal storage results. There is a widespread between reported results. A common denominator seems to be that proper diffusion barriers between adjoined materials are key for strong and stable joints. Results from Tanimoto *et al.* (250 °C series at the top) show very strong joints with no significant sign of degradation concerning high-temperature exposure.[35] In an earlier report on a similar system, they reported significant degradation of the joint strength which may be accredited to poor initial joint quality.[31] Other groups have shown similarly stable trends for temperatures near the melting point of eutectic Au-Ge.[11,17,20] Again, analyzing the results from devices stored at 250 °C (top and bottom series in Figure 4)[16,35] clearly illustrates how differently a joint can behave in two different systems. The shear strength differs by a factor of 10 between the two systems, even though utilizing the same bonding technology. The shear strength at 250 °C is reduced by about 30 pct after 500 hours at 300 °C.[9]

Among others, Godignon *et al.* have shown stable electrical properties in their assembled SiC diodes,[26,29,33] which indicate stable joint properties. Degradation of electrical properties may typically not be explicitly attributed to the joint. Note that joints evaluated in non-optimized systems, *e.g.*, with improper diffusion barriers,[29] show significant changes in electrical properties. Electrical properties in various evaluated systems may also be found in References 19 and 20.

E. *Thermal Cycling*

Au-Ge joints have been thermally cycled in a wide variety of temperature ranges, from cryogenic temperatures down to − 170 °C[26,29,32,33] and up to temperatures as high as 325 °C.[17] Cycling rates have varied between a few °C/min[10] and 40 °C/min[12,22,26,29,32,33] with varying dwell times.

Tanimoto *et al.* showed initially that performance degradation was significant due to thermal cycling by observing the joint strength evolution.[31,36] The degradation mechanism was coupled to an oxidation process in cavities inside the bond. They later showed that by optimizing the process with rigorous control of surface cleanliness and optimizing the system CTE mismatch, they could improve joint quality and both overall shear strength and cycling performance significantly.[35] Godignon *et al.* indicated excellent thermal cycling performance.[26,32,33] They inspected joints after exposure to

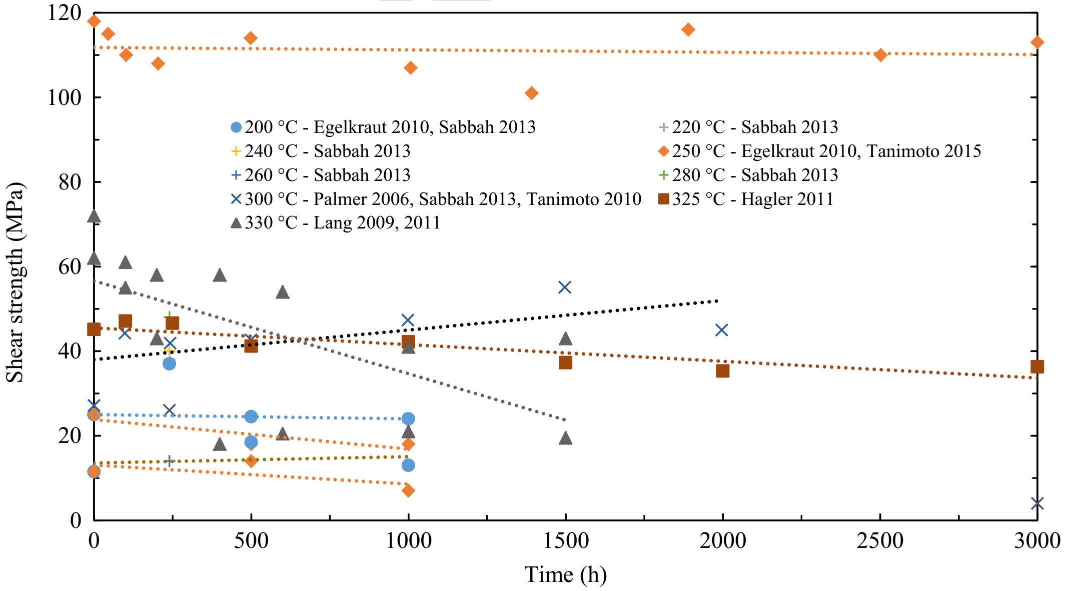

Fig. 4—Shear strength of eutectic Au-Ge joints in various devices after thermal storage between 200 °C and 330 °C.[8,9,11,12,16,17,19,20,28,31,35] Dashed lines are curve fits for each series.

thousands of extended thermal cycles with a scanning acoustic microscopy (SAM) technique, but no strength evaluation was performed. In another study, it was found that Au-Ge had limited thermal cycling capability which was ascribed partly due to the joint stiffness.[22] Zheng *et al.* tested a large joint (56.25 mm^2) and found that it has a shear strength of more than 17 MPa after 2000 cycles between 40 °C and 325 °C, at ± 10 °C/min with a 5-min dwell time.[14] Compiling these results, one may conclude that Au-Ge joints' thermal cycling capacity can be very good. This assumes that the temperature itself is not too close to the melting point, T_m, (at homologous temperatures exceeding 0.9 T_m) and that the mechanical stress state inside the joint is not very high. A compilation of thermal cycling results found in literature is presented in Figure 5.

Hutzler *et al.* used power cycles to thermally cycle devices. They applied 15 to 18 A in short cycles that created a temperature increase of the joint of 130 °C. The maximum temperature in the joint was between 155 °C and 250 °C depending on the test scheme.[18] Their system survived up to hundreds of thousands of such cycles before the die-attach failed. Tanimoto *et al.* power-cycled diodes between 35 °C and 200 °C and found no strength degradation after tens of thousands of cycles.[35] Thermally cycled devices (diodes), up to 4000 cycles between – 170 °C and 270 °C, have been characterized electrically without any significant degradation.[26,29,32,33]

F. *Electrical Load*

Various electrical loadings have been used to stress devices assembled with Au-Ge joints. In a series of reports, Godignon *et al.* have characterized SiC diodes under various electrical loads combined with temperature loads.[26,29,32,33] The diodes were biased at 5 A between 260 °C and 330 °C for up to 2000 hours and no electrical degradation were found. They further investigated their devices biased at – 300 V and at 270 °C and for 500 hours, again without any significant degradation. In the earlier reports, they observed drift behavior, but that was accredited to the Schottky barrier. Exchanging the barrier from Ni to W solved the issue.[29] The results indicate good-quality joints.

G. *Mechanical Load*

Shear-loaded samples were prepared and tested by Msolli *et al.* for strain rates in the order of magnitude μm/s, and mechanical loads of a few tens of MPa at temperatures up to 300 °C.[21] They found that the joints were fairly stable with limited dependence on displacement and load rates. The joints showed a secondary creep rate of about 3 μm/hour when a 16.7 MPa load was applied at 200 °C. At 300 °C and 16.7 MPa, measurements showed tertiary behavior after a few hours. Results also indicated a kinematic hardening of the material. Similar experiments were performed by Drevin-Bazin *et al.*[15] Unlike Msolli *et al.* they did not find a secondary stage. The joint showed a clear tertiary stage for high stress. In general, they found that the creep is thermally activated and stress-dependent.

VI. COMPARISON WITH OTHER TECHNOLOGIES

Egelkraut *et al.* showed that Au-Ge joints had better aging characteristics than lead-rich Pb-Sn joints.[16] Navarro *et al.* showed that Pb-Sn-Ag joints have a better thermal cycling capacity than Au-Ge joints.[22] Nevertheless, the quality of the produced Au-Ge joints varied greatly. Studies have compared Au-Ge joints with other binary Au-based alloys. It has been shown that Au-Sn alloys are more corrosion-resistant than Au-Ge

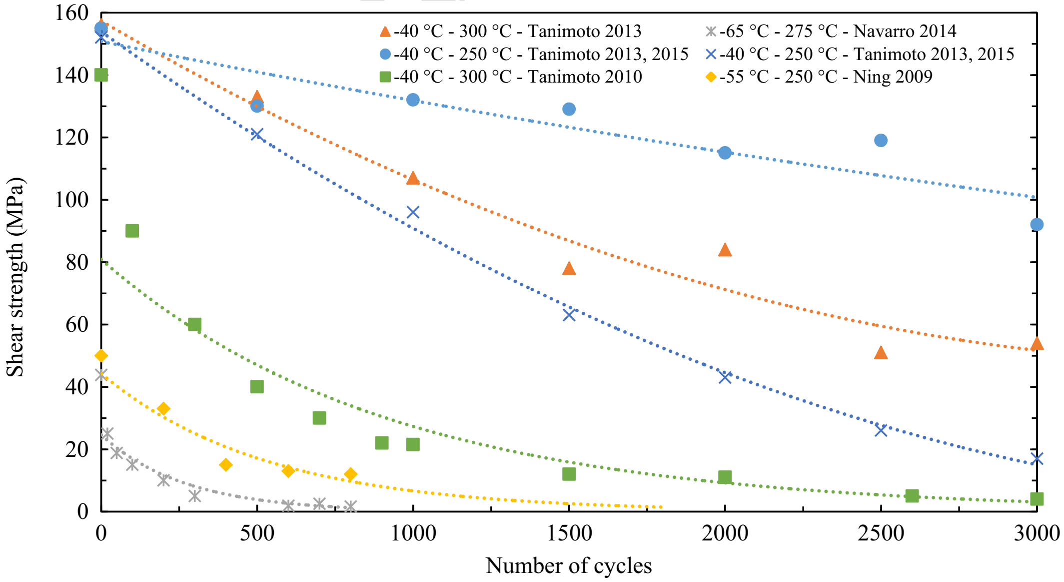

Fig. 5—Shear strength as a function of thermal cycles for various cycling regimes.[10,22,30,31,35,36] Dashed lines are curve fits for each series.

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Table III. Comparison Between Three High-Temperature Compatible Die-Attach Technologies; Eutectic Au-Ge, TLP/SLID, and Ag Sintering

Process	Advantages	Disadvantages
Eutectic Au-Ge Soldering	simple and fast soldering type process scheme low bond line pressure easily repaired by desoldering tolerates rough and irregular bond surfaces self-aligning fluxless thermally stable at very high homologous temperatures (0.9 T_H) excellent joint quality without significant voiding very strong joints (up to 150 MPa)	high process temperature operation temperature limited by eutectic melting point, $T_O < T_P$ oxygen-free atmosphere required during fabrication expensive materials no paste commercially available
TLP/SLID	high thermal joint stability ($T_O > T_P$) relatively low bond line pressure (0.2 to 5 MPa) tolerates some surface roughness tolerable to faying surface oxide fluxless similar material properties as the base material in bond surfaces good joint quality very strong joints (up to 150 to 200 MPa)	requires flat and well-aligned bond surfaces time consuming (hours to days) lack of reparability formation of thick IMCs which reduces strength and ductility expensive materials
Ag Sintering	monometallic joints thermally stable joints (typically, T_O = low T_H) excellent electrical and thermal material properties	high process temperature high bond line pressure (up to tens of MPa) somewhat time consuming (approx. 30 to 60 min) poor joint quality−porosity (approx. 20 pct) Ag migration relatively low joint strength (approx. 20 to 30 MPa)

T_P: process temperature, T_O: operation temperature, T_H: Homologous temperature, *IMC*: intermetallic compound.

alloys.[57] Lang *et al.* bonded Au-Ge and Au-Sn to Au stud bumps on Al pads and found mechanical and electrical characteristics of the produced joints to be similar.[34] Chidambaram *et al.* compared Au-Ge and Au-Si joints and found that the mechanical properties were similar.[8,9] Aging tests showed that the shear strength of the Au-Ge joints were about twice as strong as similar Au-Si joints at room temperature and at 250 °C. Au-Ge joints have also been compared with Au-In joints.[15] The Au-In joints showed better creep behavior and higher strength at elevated temperatures as they did not degrade as fast as Au-Ge. Nevertheless, at 300 °C, the two joints showed similar strength capacity since the initial strength of the Au-Ge joints was higher. Au-In (with roughly 30 to 67 at. pct In) and eutectic Au-Ge melt at between 450 °C and 500 °C and 360 °C, respectively. Thus, at 300 °C, the homologous temperature for the two tested joints are 0.75 and 0.90, respectively. The homologous temperature is the applied temperature divided by the melting temperature, measured in Kelvin. It should also be noted here that the Au-In preforms and Au-Ge preforms used in that study had different thicknesses.

A. *High-Temperature Die-Attach Technologies*

Since eutectic Au-Ge joints are commonly used in high-temperature high-reliability applications, it is interesting to compare it with other high-temperature compatible die-attach technologies such as transient liquid phase (TLP) or solid–liquid interdiffusion (SLID) bonding,[15,58–68] and silver sintering.[12,16,18,22,28,69,70] Table III shows a comparison between eutectic Au-Ge, TLP/SLID, and Ag sintering.

VII. RECOMMENDATIONS

Based on this literature study and the authors' experience, the following recommendations can be made for eutectic $Au_{72}Ge_{28}$ joints:

- It is important to have a suitable diffusion barrier between the joint and the adjoining layers to avoid changes in the composition and microstructure of the joint. Reaction with an adjoining Ni layer causes Ge-Ni IMCs to form. These IMCs are stable at high-temperature but seem to restrict the thermal cycling performance. Tungsten (W) is an effective barrier between Ni and the joint.
- The CTE mismatch between joined components should be minimized to avoid fatigue issues during thermal cycling. Alternatively, a mechanical absorption layer, *e.g.*, Au, could be used to reduce the stress state inside the joint.
- Fabrication should be performed in an oxygen-free atmosphere.
- Joints should not be used at temperatures above 300 °C as the shear strength of eutectic joints drops rapidly at very high homologous temperatures ($T_H \approx 0.9$).

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VIII. CONCLUSIONS

A compilation of literature shows that it is possible to form high-quality joints using eutectic $Au_{72}Ge_{28}$. The joints may have excellent thermomechanical properties and are very stable at temperatures as high as 300 °C. The shear strength may be up to 150 MPa at room temperature and around 50 MPa at 300 °C. This enables them for use in a wide variety of high-temperature applications. To create such high-quality joints, it is crucial to design the systems so that the stress state inside the joint is limited and that fabrication is done in an oxygen-free atmosphere. The main disadvantages are material cost and unavailability of a commercial eutectic paste. Thus, eutectic $Au_{72}Ge_{28}$ is a suitable technology for high-temperature, high-reliability, and high-end applications.

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