Monolithic 3D Integration via Al-Ge Bonding of Single Crystal Islands

F. Crnogorac[*1], R. Birringer[2], R. Dauskardt[2], R.F.W. Pease[1]

1) Department of Electrical Engineering, 2) Department of Materials Science and Engineering, Stanford University, Stanford, CA 94305

Key words: wafer bonding, monolithic integration, low-temperature processing, 3DIC.

Wafer bonding has been recognized as a flexible approach to material and device integration[1]. In case of monolithic 3D integration, where single-crystal device-quality semiconductor islands are needed for upper circuit layer fabrication, it is crucial to use low-temperature bonding methods (typically ≤400°C) to avoid degradation of metal/low-k dielectric interconnect structures, reduce thermal stress, defect generation and dopant redistribution in the circuits below.

The authors identified and investigated a variety of viable low-temperature (≤400°C) bonding methods for direct attachment of high quality islands: fusion bonding[2] (SiO_2-SiO_2, Si-SiO_2, Ge-SiO_2), thermo-compressive bonding (Cu-Cu, Ti-Ti), as well as Al-Ge eutectic bonding[3,4].

Here, we present successful Al-Ge eutectic (435°C) and sub-eutectic (400°C) bonding of both silicon and germanium single crystal islands onto amorphous SiO_2 substrates. Prime Si (100) wafers and Ge (100) epi wafers were first patterned into islands (2 μm – 3000 μm in size) and implanted with hydrogen (6×10^{16} cm^{-2}, 75 keV) to serve as donors. The mating SiO_2 wafers had Al and Ge films evaporated onto them sequentially such that the atomic composition of the bilayer matched that of the eutectic (30 *at*% Ge, 70 *at*% Al). Bonding took place at 435°C or 400°C, with 200 kPa down-pressure applied for 30 min to 2 hours, depending on the H^+ implant dose. During eutectic bonding at 435°C, the molten Al-Ge thin film undergoes dendritic segregation, separating into Al and Ge domains that span the thickness of the film (Figures 1,2). Next, with hydrogen induced splitting (SmartCut®) of the donor wafer, the transfer of crystalline islands onto SiO_2 substrate was complete (Figure 3). In the case of sub-eutectic bonding at 400°C, the cross-sectional SEM indicates that even though no melt occurred, AlGe binary alloy formed a bond between the two surfaces with visible Al and Ge rich domains (Figure 4).

While the strength of the eutectic Al-Ge bond at 435°C has already been measured to be extremely strong ($G_C = 50$ J/m^2)[4], we are in the process of determining the value for the sub-eutectic Al-Ge bond formed at 400°C.

[1] Q.-Y. Tong and U. Gosele, *Semiconductor Wafer Bonding,* John Wiley, New York (1999).
[2] Crnogorac F., Wong S., Pease R.F.W., *J. Vac. Sci. Tech. B.* 28(6), C6P53 (2010)
[3] B. Vu, P.M. Zavracky. *J. Vac. Sci. Tech. B.* 14(4), 2588 (1996).
[4] Crnogorac F., Birringer R., Dauskardt R., Pease R.F.W., *IEEE International Conference on 3D System Integration (3DIC)*, 5 pp. (2009)

[*] Electronic address: filip.crnogorac@gmail.com

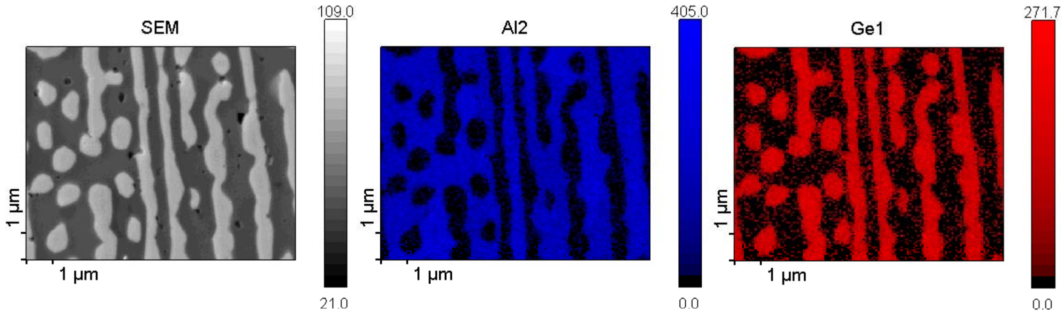


Figure 1. Auger Electron Spectroscopy (AES) elemental map (plan view) of the Al-Ge eutectic layer after a 435°C bond. The top wafer has been grinded and etched away to reveal the bond interface, where Al and Ge have segregated into distinct domains.

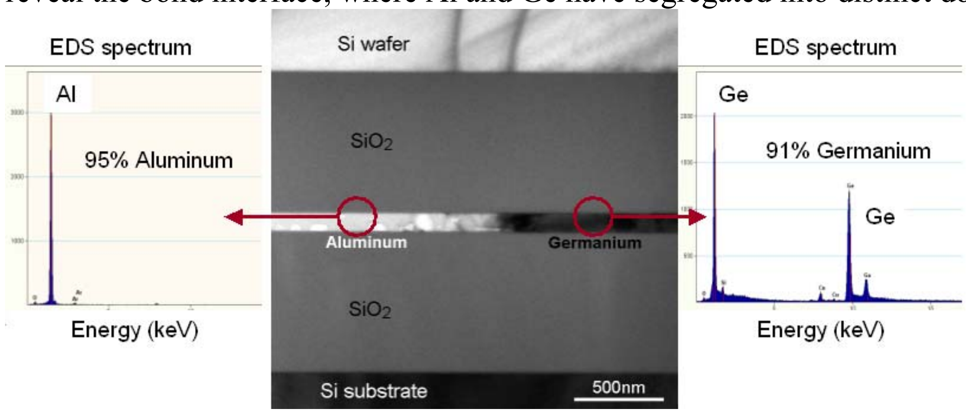


Figure 2. Cross-section TEM of Al-Ge eutectic bond formed at 435 °C.

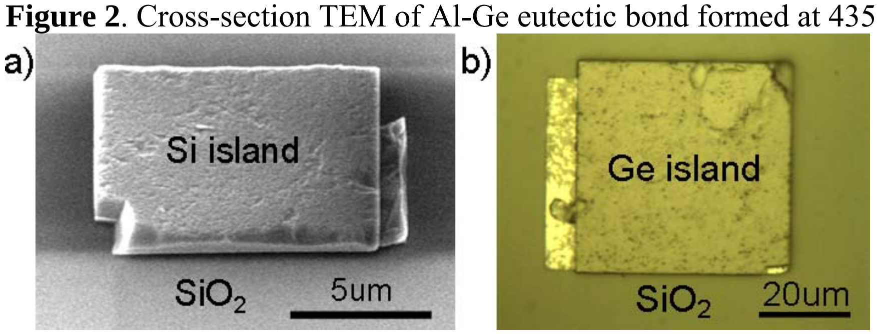
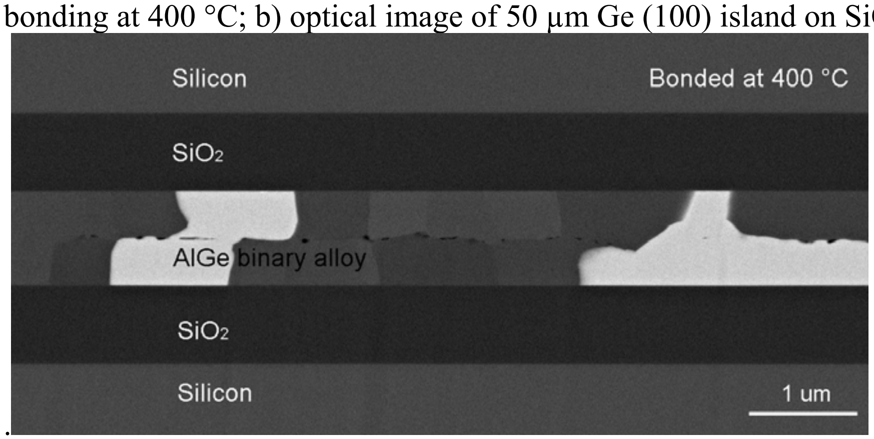


Figure 3. a) SEM image of 10 µm Si (100) crystal island bonded to SiO_2 via Al-Ge bonding at 400 °C; b) optical image of 50 µm Ge (100) island on SiO_2



.

Figure 4. Cross-sectional SEM image of Al-Ge bond at 400°C. Al and Ge segregated, and the bond has formed even though melt has not occurred.