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

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Wafer bonding has been recognized as a flexible approach to material and device integration1. 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 bonding2 (SiO2-SiO2, Si-SiO2, Ge-SiO2), thermo-compressive bonding (Cu-Cu, Ti-Ti), as well as Al-Ge eutectic bonding3,4.

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 SiO2 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 (6x1016 cm-2, 75 keV) to serve as donors. The mating SiO2 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 SiO2 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 (GC = 50 J/m2)4, we are in the process of determining the value for the sub-eutectic Al-Ge bond formed at 400°C.


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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 SiO₂ via Al-Ge bonding at 400 °C; b) optical image of 50 µm Ge (100) island on SiO₂.

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.