# Wafer Bonding Approach for Epitaxial Al/GaAs(001)/Al Tri-layers

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Superconductor-insulator-superconductor (Josephson) junctions utilizing amorphous oxide barriers have been studied extensively, however relatively little work has been done using single crystal semiconductors in place of amorphous oxide barriers. This is likely due to difficulty in fabrication of such structures including symmetry mismatch of the semiconductor to the superconductor and the reactions and roughening that may occur at the temperatures needed for semiconductor growth. This work focuses on a wafer bonding approach, subsequent substrate removal, and superconductor regrowth for fabrication of Al/GaAs(001)/Al Josephson junctions. AlGaAs/GaAs/Al structures are grown by molecular beam epitaxy on GaAs(001) substrates and wafer-bonded to Si. The substrate and sacrificial AlGaAs layers were removed by selective wet etching followed by surface cleaning in ultrahigh vacuum and aluminum regrowth. The wafer bond and Al/GaAs interfaces are studied by transmission electron microscopy (TEM). X-ray photoelectron microscopy (XPS) is used to determine GaAs surface cleaning conditions compatible with the wafer bonding process following substrate removal. X-ray diffraction (XRD) and reflection high energy electron diffraction (RHEED) is used to assess crystalline quality and orientation of the epitaxial aluminum.

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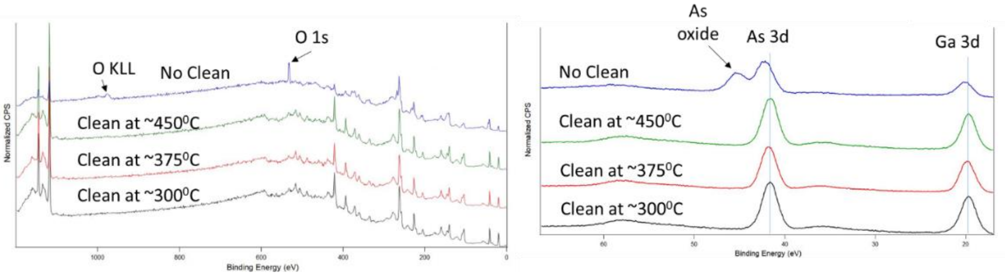


*Figure 1: XPS spectra of GaAs following selective wet etching for various hydrogen cleaning conditions showing oxide removal. The hydrogen flux and time were held constant, while the sample temperature was varied.*

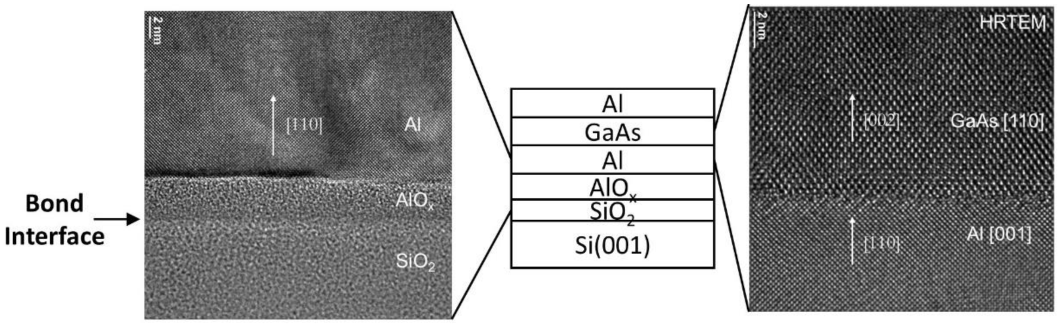


*Figure 2: TEM micrographs showing (a) the wafer bond interface and (b) the epitaxial Al/GaAs interface after the bonding procedure, substrate removal, and GaAs oxide removal using atomic hydrogen at a substrate temperature near 500ºC.*

# Supplemental

The goal of this work is to develop a new type of solid state quantum bit (qubit) that merges the capacitance and effective inductance of a superconducting transmon into a single trilayer junction structure with micrometer-scale area. Using Josephson junctions with high quality single crystal semiconductor barriers, we hope to achieve qubits with very low loss tangent at microwave frequency excitations at the single photon level, and hence increase qubit lifetime beyond the state of the art.

Growth of aluminum on III-V semiconductors such as GaAs is a well-developed technology. However, due to materials concerns including symmetry mismatch and high growth temperature, growth of high quality semiconductors on conventional metallic superconductors such as aluminum is likely not possible. In order to overcome this, we use a wafer bonding, substrate removal, and regrowth process as illustrated in Fig. S1 to fabricate semiconductor-based Josephson junctions,.

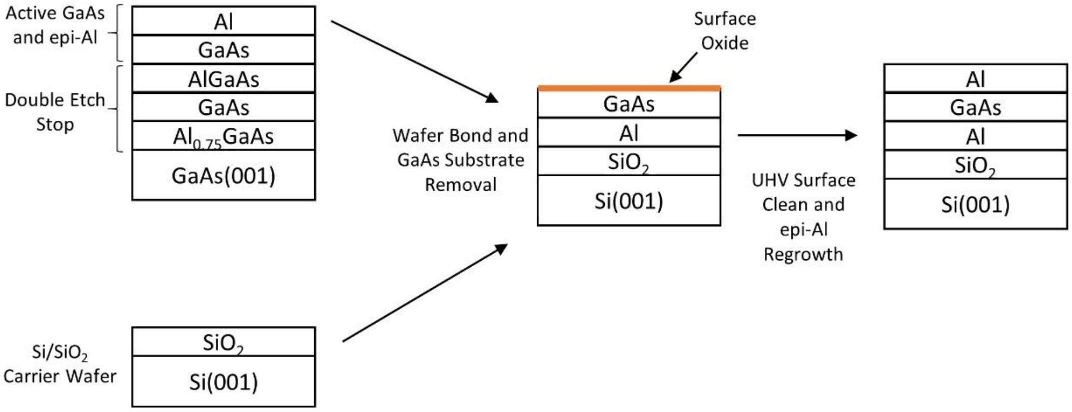
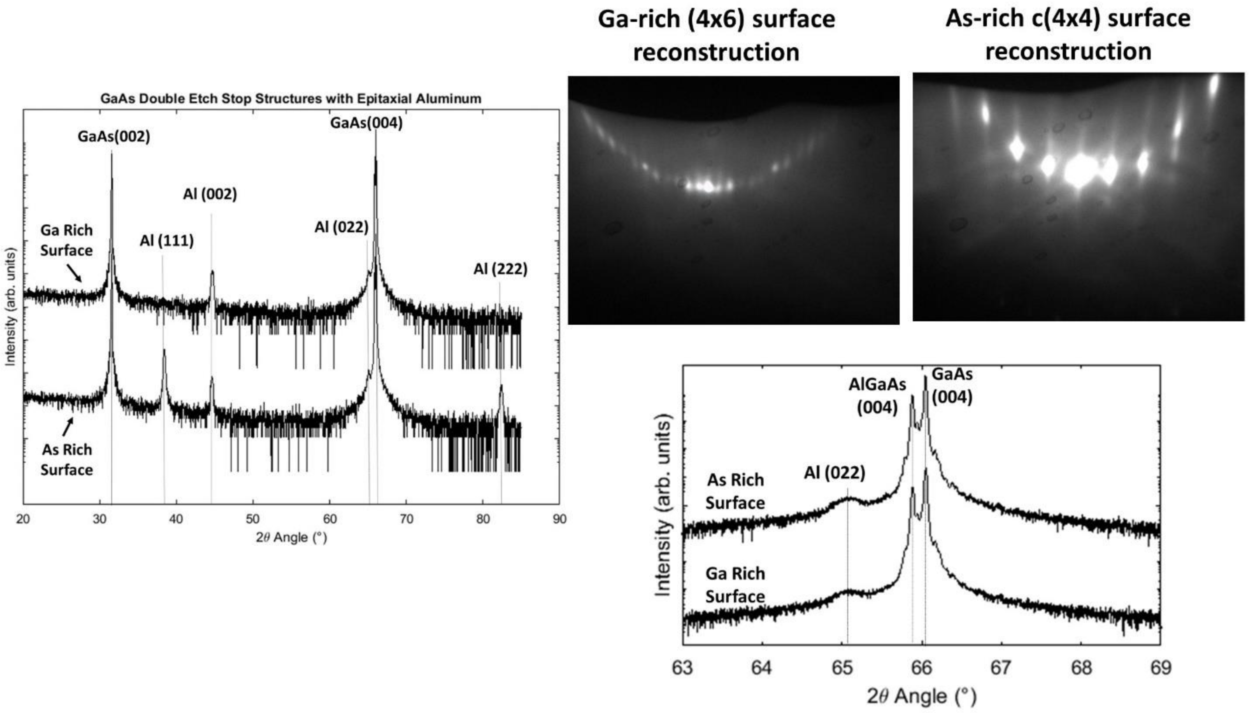


*Figure S1: Schematic illustrating wafer bonding, substrate removal, and regrowth process. III-V structure and aluminum layers are grown by molecular beam epitaxy.*

In order to be useful for the merged element transmon device, the thickness of the GaAs active layer must be precisely controlled. This is accomplished by use of molecular beam epitaxy (MBE) where layer thickness may be controlled with sub-monolayer precision. An inherent challenge is maintaining the original layer thickness following selective removal of GaAs substrate and AlGaAs layers, ultrahigh vacuum (UHV) surface cleaning and aluminum regrowth. We are actively studying the effects of selective layer removal and surface preparation techniques by electron diffraction, XPS, and TEM in order to attain the desired level of control of the GaAs surface and final layer thickness.

Another interesting avenue that has not been well studied in Joesphson junctions is the effect of the crystal orientation of the epitaxial superconductors on tunneling junction properties. For example, by tuning growth temperature and surface termination of (001) GaAs, aluminum may be grown epitaxial in (111), (011), and (001) orientations. A paramount concern for the wafer bonding process is that a very flat (peak-to-peak roughness on the order of ~2nm) surface is required. Our initial experiments have shown that growth of Al(111), (011), and (001) on GaAs/AlGaAs/GaAs(001) double etch stop structures is straightforward and the surface roughness is suitable for the wafer bonding process. Figure S2 shows how the aluminum crystal orientation may be controlled by changing the surface termination of the GaAs(001) layer it is grown on.


GaAs Double Etch Stop Structures with Epitaxial Aluminum

Ga-rich (4x6) surface reconstruction

As-rich c(4x4) surface reconstruction

*Fig. S2: ω-2ϑ x-ray diffraction (XRD) measurement showing out of plane lattice constant of two GaAs/AlGaAs double etch stop structures with epitaxial aluminum. The only difference between the two samples was the GaAs surface reconstruction before growth of the aluminum. Growth on a Ga-rich (4x6) surface results in mostly (001) oriented aluminum, while growth on the As-rich c(4x4) surface results in (111) and (001) oriented Al. Both films have some amount of (110) oriented Al. The RHEED images are of Ga-rich and As-rich surface reconstructions on GaAs(001). Both images show the diffraction pattern along the [1-10] direction.*