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Direct Bonding of GaAsSb to Silicon for High-Speed Avalanche Photodiodes

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Abstract: High-speed communications require photonic devices handling data rates greater than 200 Gbps. We present GaAsSb/Si heterojunction devices via direct bonding of GaAsSb to Si as a method to develop avalanche photodiodes for enhanced chip-to-chip connectivity. © 2023 The Author(s)

GaAsSb has several advantages as an absorption material in terms of its application to optoelectronic devices such as avalanche photodiodes (APDs) [1]. First, GaAsSb exhibits high quantum efficiency in the infrared wavelength range particularly at 1.55µm. This makes it well suited for APDs used in telecommunications and optical communication systems that operate in the optical C-band. Second the design of GaAsSb integrated with Si avalanche multipliers in APD structures results in low conduction band offset. Therefore, the integration of GaAsSb with Si multipliers allows for the realization of high-bandwidth, high-sensitivity and energy efficient SPDs for chip-to-chip communications in optical systems.

III-V semiconductors offer advantages, such as high electron mobility and wide bandgaps, making them ideal for high-speed electronics and optoelectronic devices. Typically, epitaxial growth is a commonly preferred method for combining III-V compounds with Si. However, when GaAsSb is epitaxially grown on silicon, crystal defects often arise due to the significant lattice mismatch (~8%) between GaAsSb and Si. This results in a high density of dislocations such as threading dislocation on the surface of the devices. In contrast, direct bonding can overcome these issues. Direct bonding is well-suited for wafer-level integration, allowing multiple devices or components to be bonded simultaneously. This is especially advantageous in the semiconductor industry for fabricating complex integrated circuits. In this paper, we present experimental results of the development of GaAsSb/Si heterojunctions using direct bonding.

Direct bonding is a technique used in semiconductor manufacturing to bond two separate dies or wafers together. The process involves bringing two sufficiently clean, flat, and smooth materials into contact and applying pressure to bond them together. Annealing at high temperatures is conducted to strengthen the bond and improve its reliability. Hydrophilicity of the surfaces is important for one approach to direct bonding as it enhances the surface reactivity and increases the number of functional hydroxyl groups (-OH) on the surfaces which can participate in hydrogen bonding or covalent bonding with other hydrophilic surfaces [2,3]. Our GaAsSb/Si bonding is shown in Fig.1 which illustrates the material stacks in our experiments before and after the bonding.

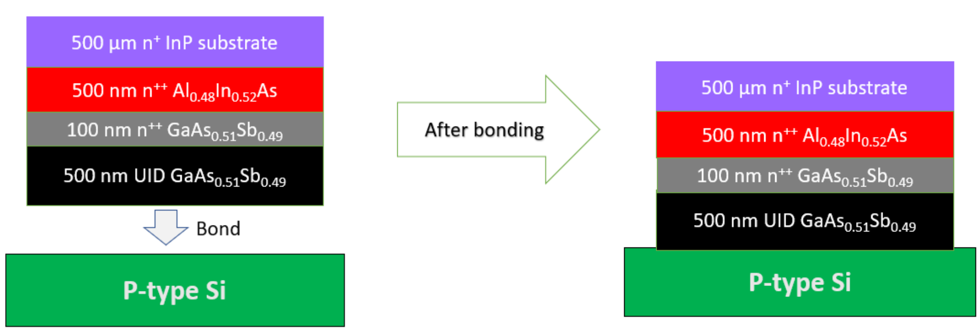

Fig. 1. Material stack used for direct bonding of GaAsSb to Silicon. The doping of the 500 nm thick $Al_{0.48}In_{0.52}As$ layer is greater than 1×10^{19} cm^{-3} and the doping of the 100 nm thick $GaAs_{0.51}Sb_{0.49}$ layer is 2×10^{18} cm^{-3}. The InP substrate thickness is 500 µm and the doping is greater than $1\text{x}10^{18}$ cm^{-3}. The silicon substrate thickness and doping is 2.75 µm and 1×10^{16} cm^{-3}, respectively. The GaAsSb die area is 1 cm^2 and the Si die area is 4 cm^2.

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Surface cleaning and preparation are essential for achieving high-quality direct bonding in both single and composite materials. These processes are tailored to each specific material to ensure optimal results. In most cases, conditioning steps yield hydrophilic surfaces that facilitate spontaneous adhesion at room temperature promoting successful bonding.Surfaces should be sufficiently cleaned to remove surface contamination which could hinder close contact and have the potential to impact electrical properties of the bonded materials [2].

In our experiments, before bonding, the Si substrate was cleaned with an ultrasonic bath of IPA for 5 min followed by ultrasonic bath of acetone for 5 min and then immersed in RCA solution (NH_4OH:H_2O_2: H2O 1:1:5) for 15 min, followed by a thorough deionized (DI) water rinse. Next, the Si substrates were immersed in Piranha solution (H_2SO_4:H_2O_2 5:1) for 15 minutes resulting in the formation of hydroxyl groups on the Si surface. These groups modify the surface chemistry of Si making it more wettable with improving adhesion properties to consequently promote direct bonding. The Si substrate is then temporarily stored in DI water until bonding is performed. Next, the GaAsSb/InP die is cleaned with an ultrasonic bath of IPA for 5 min followed by an ultrasonic bath of acetone for 5 min. The die is then rinsed in DI water and then dried with N_2. Since antimonide is sensitive to acids, argon plasma is used to activate the surface to improve hydrophilicity [4]. During plasma exposure for our chamber, the pressure was 5 mTorr, the Ar glass flow was 50 sccm, the ICP power was 900 W, and the RF power was 50 W. The plasma exposure time was 30 sec. The Si wafer was dried with N_2 and then immediately placed in contact with the GaAsSb die after retrieving the sample from the plasma chamber. Pressure was applied with a pair of tweezers establishing a successful bond between two wafers.

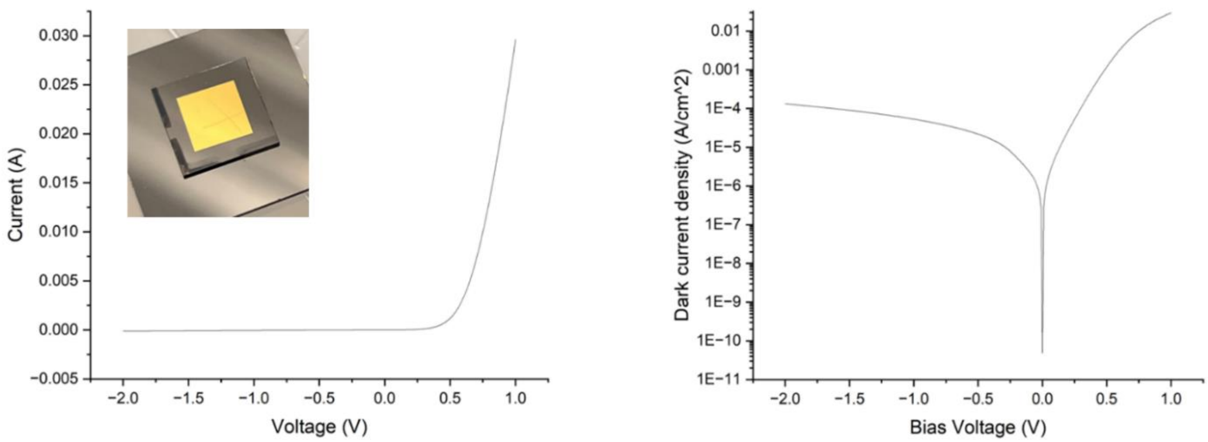

Figure 2. Current-voltage measurements of the GaAsSb/Si pair after direct bonding. Optical micrograph in inset shows bonded pair with top side Ti/Au contact.

After bonding, Ti/Au (30/90 nm) was evaporated on top of the InP substrate to implement an n-side ohmic contact. For the p-side contact, the Si die was mounted onto a gold-coated ceramic substrate using electrically conductive solder paste. Current-voltage (IV) measurements were then conducted for characterization. The IV characteristics of the bonded interface exhibited diode behavior, which indicates that direct bonding is a promising approach in terms of electrical properties. Future work involves optimizing surface preparation and bond quality through post-bond annealing treatments.

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