Transparent and electrically conductive GaSb/Si direct wafer bonding by argon-beam surface activation at low temperatures

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ABSTRACT

Novel n-GaSb/n-Si wafer bonds have been achieved by means of a low-temperature direct wafer bonding process, enabling an optical transparency of the bonds along with a high electrical conductivity of the boundary layer. In the used technique, the surfaces are activated by sputter-etching with an argon fast-atom-beam (FAB) and bonded in ultra-high vacuum. The bonds were annealed at temperatures between 300°C and 400°C, followed by an optical, mechanical and electrical characterization of the interface. Additionally, the influence of the sputtering on the surface topography of the GaSb was explicitly investigated. Fully bonded wafer pairs with high bonding strengths > 1 J/m^2 were found. The interfacial resistivities of the bonded wafers were significantly reduced by optimizing the process parameters, by which reproducible interfacial resistivities of less than 5 mΩcm^2 were reached. These promising results make the monolithic integration of GaSb on Si attractive for various applications.

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TEXT

The monolithic integration of III-V semiconductors on silicon offers a wide range of innovative applications, like in the fields of power electronics[1], photonics[2] and photovoltaics[3,4]. III-V layers on silicon allow combining favorable material characteristics of compound semiconductors with the low-cost, the mechanical stability and the advantages in the processing of silicon. Hence, direct wafer bonding between GaAs/Si[4,5] and InP/Si[5,6] was investigated extensively in the past years. Likewise, GaSb offers a wide choice of promising and unique characteristics such as small effective masses, high electron and hole mobilities and a band gap suitable for long-wavelength optical devices[7,8]. In this paper, we report about the development of a direct wafer bonding process for the formation of novel transparent and electrically conductive GaSb/Si heterojunctions with promise for the integration of antimonide layers on silicon. The low-temperature bonding process, which was used, is carried out mainly analog to the approach of Suga *et al.*, which was first published in 1992 for the formation of Al/Al and Al/Si_3N_4 wafer bonds[9].

An Ayumi SAB-100 wafer bonder was used to bond 4” monocrystalline Si wafers to 2” monocrystalline GaSb wafers. The 300 nm thick Si wafers received a thermal phosphorous diffusion, leading to an n-type doping of 1E20 cm^{-3} within the first 50 nm. A 500 nm thick GaSb epitaxial layer with an n-type (Te) doping of 1E18 cm^{-3} was grown onto the GaSb wafer. This is the highest active doping concentration which can be achieved for n-type GaSb[10]. A high surface carrier concentration is beneficial to overcome potential barriers at the interface and to achieve high conductivity of the bonded wafer pairs.

The activation of the semiconductor surfaces is achieved by removing of the oxides and contaminations by sputtering with an argon beam in a high vacuum environment of the reactor chamber (< 3E-6 Pa). At the same time, the crystal lattice is destroyed in the first few nanometers creating an amorphous layer.

The polished wafers are pressed together, bringing the activated surfaces in close contact. This enables dangling bonds on the surfaces to form covalent bonds, permanently joining the semiconductors[11]. Optical transparency is automatically achieved as there are no intermediate layers at the interface.

An essential condition for a successful process is, that the wafer surfaces have a RMS roughness < 1 nm[12]. This was accomplished by means of chemical-mechanical polishing, resulting in a RMS roughness of 0.2 ± 0.03 for the Si substrates and of about 0.5 ± 0.05 nm for the GaSb substrates. In addition, it is elementary that the roughness is not significantly increased by the FAB treatment.

Therefore the influence of the Ar bombardment on the GaSb surface was investigated. The RMS roughness of GaSb samples was measured before and after the sputter-etching at 5 random locations of the sample by means of atomic force microscopy (1x1 μm^2 scan fields with a resolution of 512x512 pixels). The duration of the sputter treatment and the argon energy was varied. The anode current, which correlates to the sputter dose[13], was kept constant at a value of 50 mA. Figure 1 shows the resulting RMS roughness after the sputter etching with varied process parameters as well as exemplary AFM images of the GaSb surface.

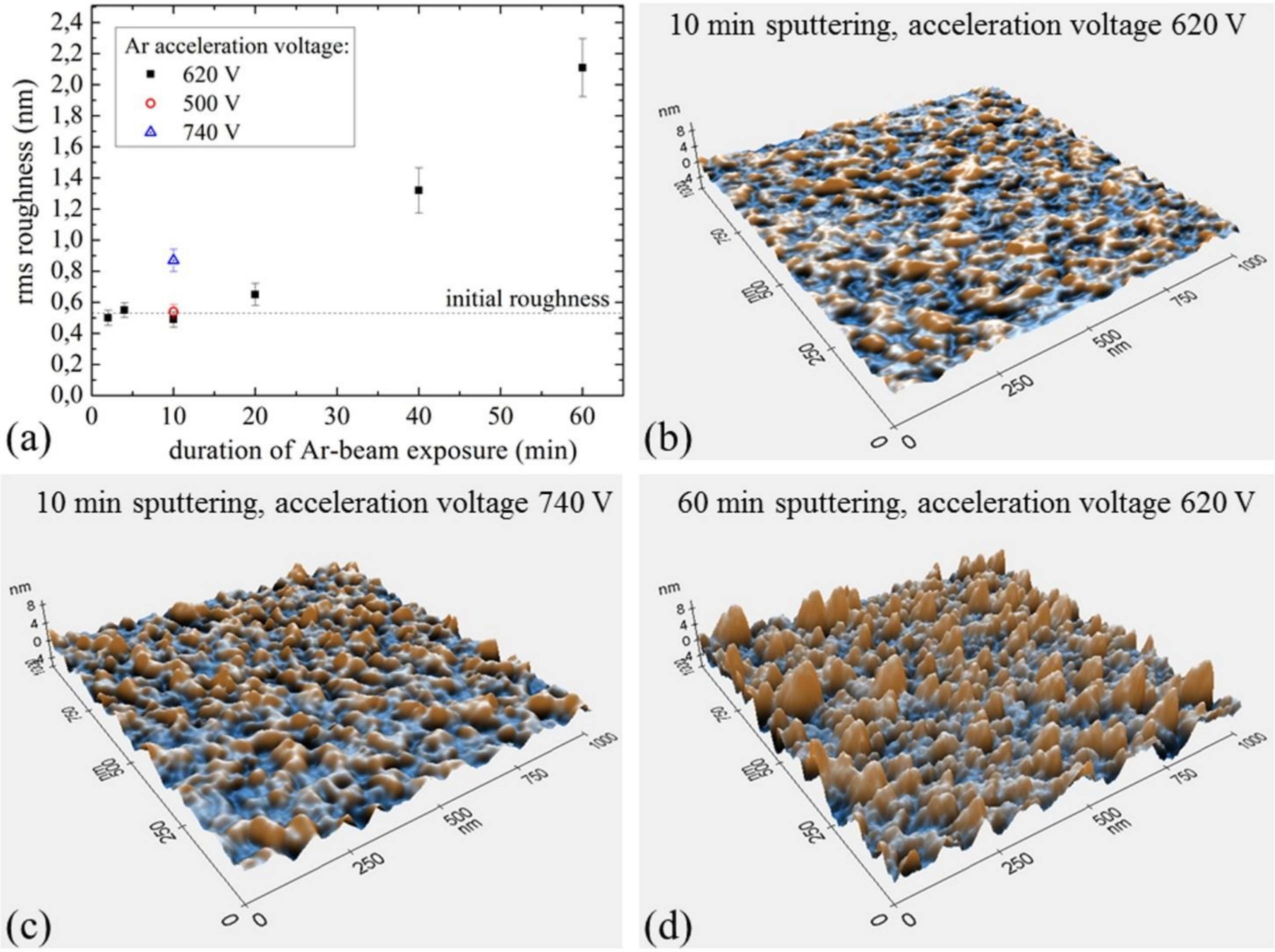

FIG. 1: Summary of the RMS roughness of the GaSb surfaces after sputtering with varying durations of the Ar-beam exposure and acceleration voltages (a). AFM images of the GaSb surface topography after: 10 min sputtering with an acceleration voltage of 620 V (b), 10 min sputtering with an acceleration voltage of 740 V (c), 60 min sputtering with an acceleration voltage of 620 V (d).

It was found that after the first 10 minutes sputtering, the roughness of the GaSb substrate is not increased due to the bombardment of the argon atoms accelerated at a voltage of 620 V and there is no change in the surface topography (Figure 1 (b)) in comparison to an polished GaSb surface (not shown owing to space constraints). After 20 min, 40 min and 60 min of sputtering, the RMS roughness increases to 0.7 nm, 1.3 nm and 2.1 nm, respectively. As GaSb exhibits different binding energies for Ga and Sb in its crystal structure (Ga: 18.6 eV, Sb: 31.7 eV[14]), this behavior can be explained by a selective sputtering of the GaSb surface, which becomes noticeable at longer sputtering durations after the oxide is removed. Thus it is likely, that the agglomerations in Figure 1 (d) consist of enriched Sb on the surface. At an increased acceleration voltage of 740 V, the roughening of the surface is already visible after 10 min of FAB treatment (Figure 1 (c)), as there is extended damage induced by the higher energy of the argon atoms. An even lower acceleration voltage of 500 V on the other hand, leads to no measurable change of the GaSb surface as it was the case for 620 V.

In the case of silicon, it was shown by Essig *et al*. and Howlader *et al*. that the RMS roughness is not altered by the Ar atom bombardment using comparable atom energies and doses[4,15].

Several bonds were processed, at which some essential process parameters were varied, including the temperature during bonding (20°C and 120°C), the Ar acceleration voltage (500 V, 620 V, 740 V) and the duration of the FAB bombardment on the GaSb wafers (4 min, 8 min and 12 min). The Si substrates were always sputtered for 8 min with an Ar acceleration voltage of 620 V.

The resulting bond interfaces between GaSb and Si were macroscopically investigated by means of scanning acoustic microscopy (SAM). In general, the wafer bonds reveal only small circular areas which were not bonded due to the presence of particles (see Figure 2). Otherwise, the bond was complete up to the rounded bevel edge of the GaSb wafer.

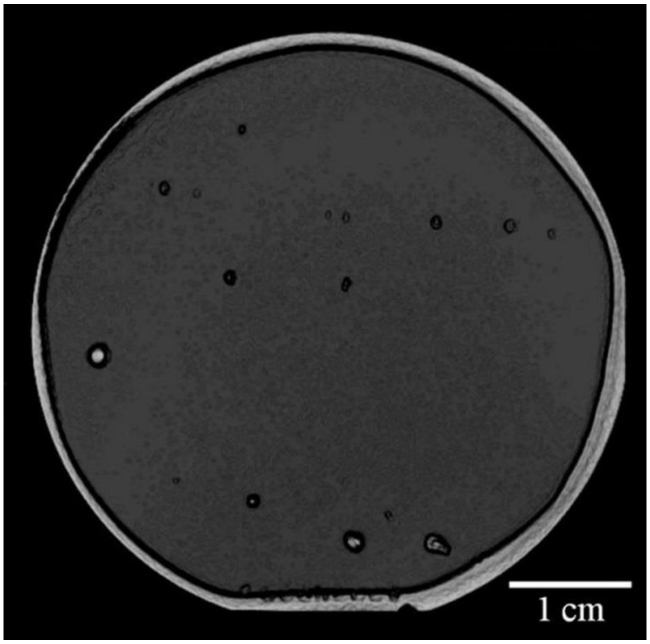

FIG. 2: SAM image of an exemplary GaSb/Si bond. The darker region indicates the bonded area, as the light spots indicate the not bonded areas, where a higher reflection of the acoustic wave at the boundary surface is prevalent.

It was not possible to determine the bond strength by the Maszara crack-opening method[16] as the blade could not be inserted at the bond interface without destroying the GaSb substrate. This speaks for a strong and mainly covalent bond at the interface, resulting in high bond energies > 1 J/m^2, which are comparable to the energies in the GaSb bulk crystal. This effect was also reported by Kopperschmidt *et al.* for hydrophobic GaAs/Si bonds, which were annealed at 850°C[17].

Stable interfaces with high bond energies were observed for all bonds except for the ones performed after FAB activation with an acceleration voltage of 740 V for the argon atoms. This bond was not stable, which can be explained by the surface roughening of the GaSb surface after bombardment by Ar atoms with a higher energy (see Figure 1 (c) above).

The electrical carrier transport over the GaSb/Si interface was investigated by dark IV-measurements. For this purpose, the bonded wafer pairs were metallized on both sides and diced into 3x3 mm^2 pieces, which were then annealed 1 min at either 300°C, 350°C or 400°C. In Figure 3, IV-curves of the resulting test samples are shown for a bonding temperature of 120°C and different annealing steps at 300°C, 350°C or 400°C for 1 min each. One further IV-curve is shown for a bonding temperature of 20°C with an annealing of 1 min at 350°C. The measured values have been corrected for influences caused by the metal contact and substrate resistances.

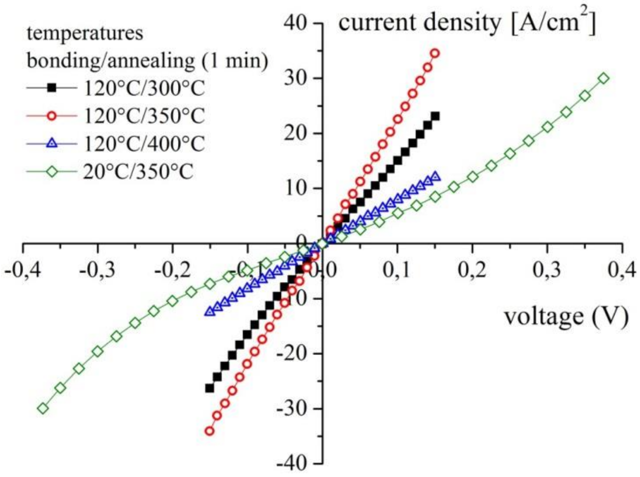

FIG. 3: IV-characteristics of n-GaSb/n-Si wafer bonds, which were processed at different bonding and annealing temperatures.

Despite the high bond strength, non-linear Schottky diode like IV-characteristics were found for all samples bonded at 20 °C room temperature. This can be correlated with the formation of a potential barrier exceeding ~ 3 k_BT prevalent at the boundary interface[18]. According to Bengtsson *et al.*, such a barrier in the conduction band may be formed by acceptor-like defects[19] and explained by the amorphous layer created during the FAB activation process. Carriers are trapped in the defect states, hindering them to contribute to the electrical conductivity. Differences in the electron affinities of GaSb and Si do not explain the diode like IV behavior as both material have similar electron affinities (4.06 eV for GaSb and 4.05 eV for Si[20]). It is plausible to assume, that with a higher bonding temperature, the defect density is reduced and in fact, we have observed higher conductivity and ohmic IV-characteristics for the GaSb/Si bonds at 120 °C (compare Figure 3).

Besides the influence of the temperature during bonding, also annealing of the samples after bonding has a strong effect on the conductivity. In Figure 3, it is shown, that the bond resistance decreases, when the samples are annealed for 1 min at 350°C instead of 300°C. It has been already observed for direct bonds between GaAs and Si, that the amorphous layer at the interface is partly recrystallized during annealing, resulting in lower resistances[4]. Surprisingly, all samples annealed at 400°C show a higher bond resistance. A possible negative effect of such a high temperature annealing could be induced thermal damage, resulting from the difference in the thermal expansion coefficient (7.756E-6K^{-1} for GaSb and 2.6E-6K^{-1} for Si[21]). Furthermore it is possible that gases, which are trapped at the bond interface, expand during the annealing step and break open established atomic bonds. This effect was described by Mitani *et al*. in the context of hydrophilic Si/Si bonds[22]. When an annealing temperature of 400°C is used, these negative effects seem to outbalance the positive influence of the higher annealing temperature.

Table I shows the interface resistivitiy after the bonding for different process parameters. The calculation of these values is based on the dark IV-curves, which were corrected for parasitic serial resistances caused by the metal contact and the substrate. The resistivitiy for the bond processed at 20°C was calculated in the mostly linear region of ± 0.1 V (compare with Figure 3). The standard parameters for the bonding were defined as a process temperature of 120°C, an acceleration voltage of 620 V, an Ar beam exposure duration of 8 min and an anode current of 50 mA. All variations from these parameters are listed in Table I. The stated error takes into account all presumable deviations from every contribution to the calculation of the interface resistance (resistance deviations of the metal contacts, the substrates and the bond interface itself).

TABLE I. Electrical interface resistances of GaSb/Si bonds, depending on the process parameters.

	bond resistances (mΩcm^2) after 1 min annealing at		
bonding temperature	300°C	350°C	400°C
20°C	35.6 ± 5.3	16.6 ± 3.5	24.9 ± 5,1
120°C	4.4 ± 2.2	2.2 ± 2.1	10.3 ± 3.5
argon atom energy			
500 eV	20.4 ± 3.7	8.6 ± 2.9	13.7 ± 3.8
620 eV	4.4 ± 2.2	2.2 ± 2.1	10.3 ± 3.5
740 eV	-	-	-
GaSb sputter duration			
4 min	5.7 ± 2.3	3.8 ± 2.5	28.7 ± 5.4
8 min	4.4 ± 2.2	2.2 ± 2.1	10.3 ± 3.5
12 min	1.5 ± 1.8	1.8 ± 2.3	7.6 ± 3.2

It is listed in Table I, that the bonds processed at 20°C exhibit a higher resistivity compared to the bonds processed at the elevated temperature of 120°C. This is explained by extended process-induced defects, which are also the origin for the non-linear behavior of the carrier transport (see above). With 120°C as the bonding temperature, it was possible to reach low interface resistivities of < 5 mΩcm^2 which speaks for a high amount of covalent bonds at the interface[23].

It was found, that with the use of an FAB energy of 500 eV the bond resistivity increases compared to the use of Ar atom energies of 620 eV. It is possible, that the oxide on the GaSb surface was not completely removed within 8 min sputter treatment with an acceleration voltage of 500 V. It was shown by Zhou *et al.* that remaining oxides at the bond interface hinders the carrier transport, thus increasing the surface resistivity[24]. The bonding at an elevated Ar acceleration voltage of 740 V was not successful, due to the roughening of the surface described above.

Table I shows, that low bond resistivities < 5 mΩcm^2 were found for all samples using the described standard process parameters and a 1 min annealing step at 350°C, independently of the sputtering duration of 4, 8 and 12 min.

In conclusion, we have demonstrated direct GaSb/Si wafer bonding after argon-beam surface activation. It was shown that surface roughening of the polished GaSb wafers can be avoided with an Ar acceleration voltage of 620 V and durations of the bombardment of up to 10 min. Fully bonded GaSb/Si wafer pairs with high bond energies of > 1 /m^2 were found. With the optimized process parameters of a bonding temperature of 120°C, an Ar acceleration voltage of 620 V and a 1 min annealing step at 350°C, it was possible to achieve a reproducible ohmic carrier transport over the boundary interface with low bond resistivities under 5 mΩcm^2. Together with the high bond energies, these low resistivities speak for a high amount of covalent bonds at the interface. With these characteristics of the bond, the presented wafer bonding process is suitable for various advanced applications in high speed electronics or long-wavelength optical devices like for multi-junction solar cells.

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