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Adhesive Wafer Bonding for Wafer-Level Fabrication of Microring Resonators

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Abstract. GaInAsP/InP passive microring resonator devices were successfully fabricated using a vertical integration concept with GaInAsP/InP-on-GaAs wafer bonding. BCB adhesive bonding has been identified as the preferred wafer bonding process. This paper reports results on the development of the wafer bonding and on the microring fabrication.

Keywords: microring resonators, adhesive wafer bonding, BCB.

1. Introduction

Wafer bonding is a very promising technology for fabrication of 3D structures, as well as for materials integration. With first medium-scale applications in the area of pressure sensors, different wafer bonding processes are today used in large scale production in Micro-Electro-Mechanical Systems (MEMS, e.g. for automotive applications – accelerometers, gyroscopes), Micro-Opto-Electro-Mechanical Systems (MOEMS), SOI substrate fabrication, development of advanced substrates (e.g. Germanium-on-Insulator: GOI, Strained Silicon-on-Insulator: SSOI, etc.), and more recent for fabrication of 3D electrical interconnections at wafer level by wafer stacking.

Under the generic name "Wafer Bonding" can be found different techniques of joining two substrates, each governed by different physical and chemical mechanism.

For this reason, the choice of the appropriate wafer bonding process is based mainly on the targeted application type and on the materials involved.

Adhesive wafer bonding is a process using an intermediate layer for bonding. Evaporated glass, polymers, spin-on glasses, resists and polyimides are some of the materials suitable for use as intermediate layers for bonding. The main advantage of using this approach is the low temperature processing (maximum temperatures up to 450°C). As it is well known, most of the wafer bonding processes consist in a room temperature pre-bonding step followed by a high temperature annealing (for silicon, ∼1 200°C) for a few hours [1]. Such high temperatures have to be avoided for many applications (e.g. when substrates contain metal layers, for compound semiconductors, etc.). So development of low temperature methods is a prerequisite for such applications. Some other advantages of adhesive bonding are: surface planarization prior to bonding, encapsulation of patterns on the wafer surface, particle compensation (intermediate layers can incorporate particles with diameter smaller than layer thickness) and decreasing of annealing temperature after bonding. Low temperature bonding has the major advantage of decreasing the thermal stress built in during thermal annealing when the bonding partners are thermally mismatched.

Adhesive wafer bonding process was applied for fabrication of optical microring resonator devices based on GaInAsP/InP.

Microring resonator devices are attractive for Wavelength Division Multiplexing (WDM) and optical sensor applications because of their inherent spectral characteristics. Such devices benefit of the high quality factor of the microring resonator. However, a crucial control of the physical dimensions as well of the structural parameters is a prerequisite for their fabrication. Especially e.g. for the development of microring laser devices and high performance optical add/drop multiplexers/demultiplexers (OADM) microring resonators based on active GaInAsP/InP material are required in which optical amplification for lasing or loss compensation is controlled via current injection, respectively. In terms of miniaturization, microrings with a diameter in the order of a few tens of micrometers are attractive candidates for compact devices with diverse functionalities (filters, lasers, wavelength converters, sensors). These active microrings are coupled to one or two transparent bus waveguides (acting as optical I/O ports). Such a combination of active and passive structures can only be realized in a vertical arrangement. The vertical integration concept encompasses major advantages such as the precise control of the critical coupling strength with epitaxial growth accuracy and hence the realisation of ultra short couplers. Wafer bonding implementation offers high flexibility in choosing the material composition and enables the growth of vertically coupled active and passive waveguide layers in a single epitaxial run.

III/V-wafer bonding and twin vertically aligned active/passive optical waveguides concept is identified as an ideal technology for the realization of such optical microcircuits. A wafer bonding approach using intermediate layers can provide the right process conditions for photonic microring devices fabrication.

This paper presents recent results obtained for adhesive wafer bonding using Benzocyclobutene (BCB) from Dow Chemicals [2] as intermediate layers for low temperature wafer bonding.

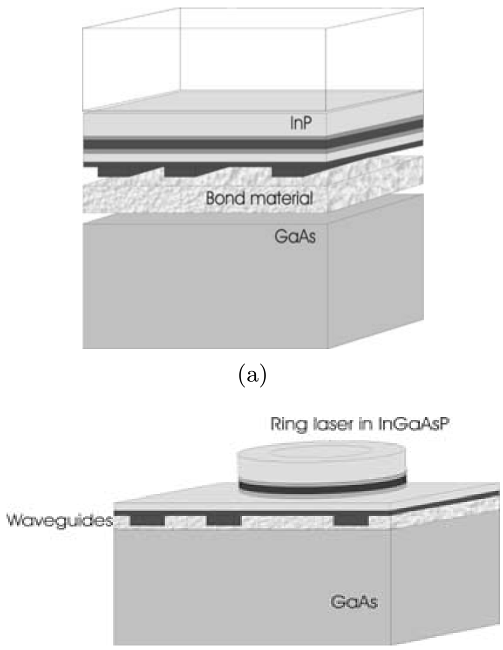
2. Experimental

A microring resonators fabrication process using a vertical integration concept consists practically of three major steps:

1. InP/GaInAsP epitaxial layers necessary for the fabrication of microring resonator devices are grown on InP substrates. Passive bus-waveguides are fabricated by photolithography and etching.

2. After bus waveguides definition the InP substrate is bonded to a transfer wafer, in our case a GaAs wafer. The use of GaAs assures both, a high selectivity during the wet chemical wafer thinning process and provides a good cleavability within the wafer dicing technology (Figure 1).

3. After the wafer bonding step, the InP substrate is removed by etching and microrings are fabricated by photolithography and etching. Different approaches were considered for the development of the microrings fabrication process: eutectic wafer bonding using $Au_{80}Sn_{20}$ system and adhesive wafer bonding using BCB intermediate layers. Low temperature processing is required by the difference in thermal expansion coefficients of GaAs and InP, which may result in warpage of the bonded material combination.



(b)

Fig. 1. Schematic of wafer bonding process (a) and final microring device structure (b).

2.1. Eutectic wafer bonding

Eutectic wafer bonding [3, 4] is a process in which adhesion between two surfaces occurs by forming an eutectic alloy at the interface. There are different approaches for placing the materials on the two surfaces in order to form the eutectic alloy:

– each eutectic component on one surface: this is the typical situation of Au-Si, Au-Ge or Al-Si eutectic bonds, where a metal surface is brought in contact with a semiconductor surface;

– metallization of eutectic mixture is on both surfaces: this is a typical situation for Au-Sn eutectic bonds, where on both surfaces are both metals in the form of multi-layer coating (alternating the two metals while keeping the ratio for forming the eutectic) or films sputtered from a target containing the two metals in the right ratio for forming the eutectic alloy.

The second approach allows a volume reaction of the eutectic components and for eutectic wafer bonding enables formation of very homogenous interface eutectic layers.

Eutectic alloy at the interface is formed in a liquid phase: for this reason, eutectic bonding is less sensitive to particles compared to the direct wafer bonding methods, being able to incorporate particles with dimensions lower than the eutectic layer.

$Au_{80}Sn_{20}$ eutectic system was chosen because of the low temperature: eutectic temperature is 280°C and maximum wafer bonding process is of about 300°C.

2.2. Adhesive wafer bonding using BCB intermediate layers

BCB is a heat curable solvent based thermosetting polymer compatible with IC technology. BCB is transparent in visible light ($> 90\%$) and has a low dielectric constant, which recommends it for optical or RF applications. BCB has also the advantage of being suitable for coating in a relatively wide range of thicknesses (from micrometer range to about 50 μm).

In order to use it for wafer bonding, BCB can be spin- or spray-coated onto one of the two wafers to be bonded. During bonding, BCB has the property to reach a viscous state and its ability to flow can be used for surface planarization and structures embedding. The planarization efficiency can be controlled by applying a very uniform contact force on the entire surface of the substrate and by heating the two substrates with very good temperature uniformity. The temperature profile of the bonding process is crucial for obtaining high quality bonds.

BCB was chosen as bonding layer for microrings resonators fabrication due to its specific characteristics: good planarization of patterned wafers, easy processing and reliable bonding processes in a temperature range 200°C–300°C.

3. Results

3.1. Au:Sn wafer bonding

Prime GaAs wafers, 2 inches diameter, were used for bonding with InP substrates.

The two wafers were coated with 1 μm thick $Au_{80}Sn_{20}$ metal layer by sputtering. The two wafers were then cleaned from particles using an EVG®301 single wafer cleaner with megasonic system. Megasonic cleaning is proved to be efficient in particles removal.

After cleaning, the two wafers were loaded in an EVG®520 semi-automated bond chamber. Wafers were mechanically fixed on a bond chuck, separated by three spacers. The two metalized surfaces of the substrates were put into contact under vacuum, to avoid trapping air between surfaces. Maximum process temperature was 300°C.

After bonding, wafers were investigated by Scanning Acoustic Microscopy (SAM) using a Sonoscan D-9000 system and bonded pairs warpage was measured using a VEECO-DEKTAK profilometer.

SAM images (Fig. 2) show good, voids-free quality bond with uniform interface. Dark gray contrast shows bonded areas and white contrast shows unbonded areas. The white ring at the wafer edge is unbonded because it was not deposited with Au:Sn metallization.

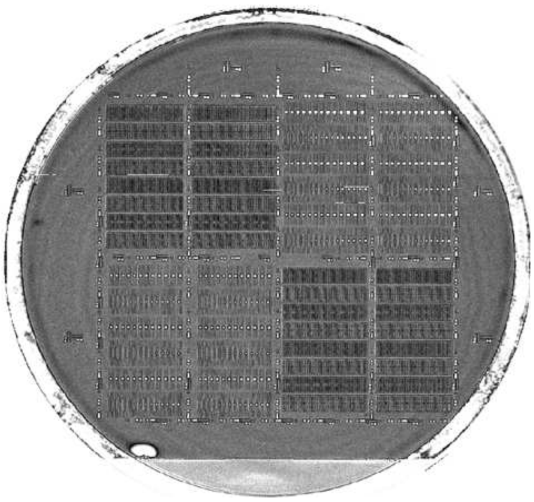


Fig. 2. SAM image of a InP/GaAs wafer pair after Au:Sn eutectic wafer bonding.

Despite the good results in terms of homogeneity and voids, the bonded pairs can not be used for further photolithography steps required by microrings manufacturing process flow due to the very high warpage measured after bonding (Fig. 3).

In Fig. 3 can be observed that warpage values are in the range of 100 μm, values to high to allow standard mask alignment for proximity exposure in a standard mask aligner.

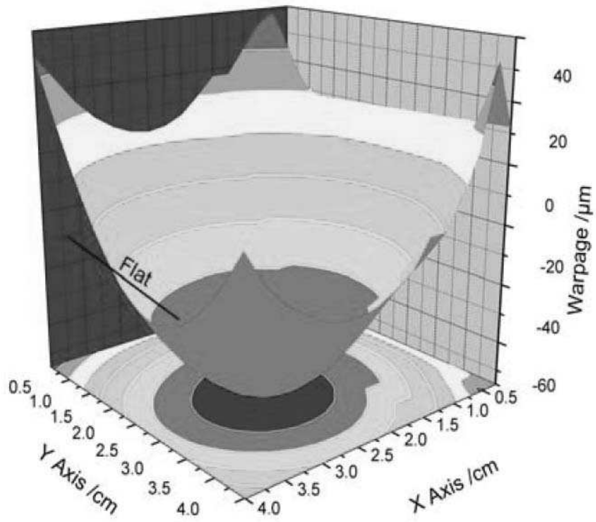


Fig. 3. Warpage measurement for a GaAs/InP wafer pair after Au:Sn eutectic wafer bonding.

3.2. BCB wafer bonding

The two wafers were cleaned from particles using EVG®301 single wafer cleaner with megasonic system.

After cleaning, different tests were performed in order to find the best coating method. The possibilities tested were:

a. Spin-coating of BCB onto the blank GaAs wafer;

b. Spin-coating of BCB onto the patterned InP substrate;

c. Spray coating of BCB onto patterned InP substrate.

Bonding of wafers coated with BCB as per process a. was successful. Due to BCB flow during the bond process the structures on the InP substrate were successfully enclosed into the BCB layer. Test b. was performed in order to evaluate structures planarization efficiency when BCB is spin-coated on top of the structures. Bond tests show no significant difference from test a.

Spray-coating is a method developed specifically for coating surfaces with topography. Among major advantages of spray-coating compared to spin-coating should be mentioned effective coating of surface topography and much lower liquid precursor consumption when coating flat surfaces [5].

Test structure dimensions used for the particular application described here allowed the same efficiency in surface planarization for both coating methods: no significant difference was observed when comparing bond results for wafers coated using processes a. and b. and process c.

After coating, the two wafers were loaded into the bond chamber separated by spacers. Prior to bonding the bond chuck was pre-heated to 65°C to enable solvent evaporation and avoid any void formation. Void formation can not be avoided in case of skipping the soft bake procedure due to the evaporated solvent, which can't diffuse outside the bonded interface.

A bonding force of 2 kN was necessary in order to ensure uniform contact of the entire wafer surface. Bond process was initially performed at 300°C, but due to the post-bond warpage observed also in this case (lower values than for eutectic bonding at same temperature, but still significant) process recipes were developed for the temperature range 200°C–300°C.

Figure 4a. shows an infrared (IR) transmission image of a bonded pair and Fig. 4b. represents the SAM image of the same bonded pair. For direct bonding of two substrates interference fringes like the ones visible in IR transmission image (Fig. 4a.) would suggest the presence of voids. It can be observed a correlation between the fringes on the IR transmission image and the dark areas on the SAM images.

After InP substrate removal by an etching process step it was found that these areas with fringes show same good quality bonding as the areas shown as fringes-free in IR image. The interference fringes are in this case generated by different compression of the BCB layer during bonding, due to the InP substrate surface topography and they do not represent voids at the bonded interface.

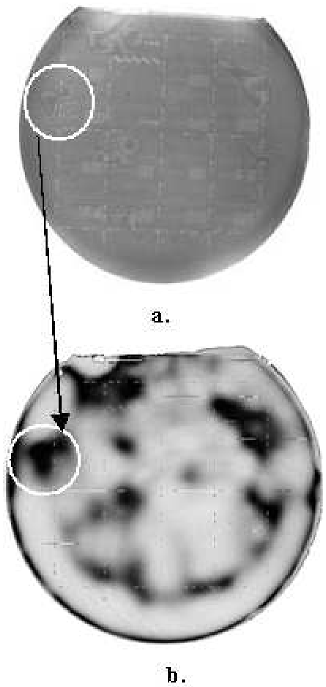
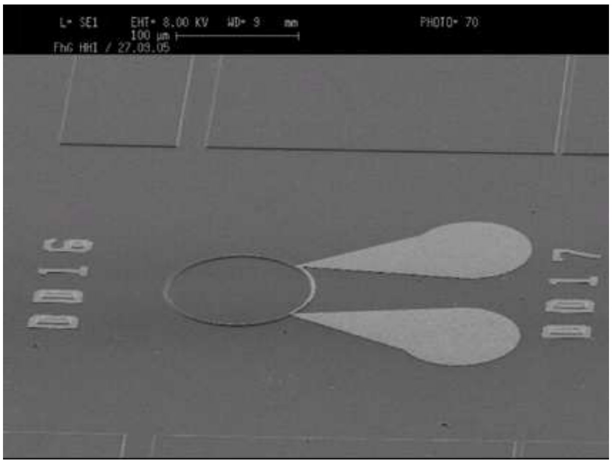
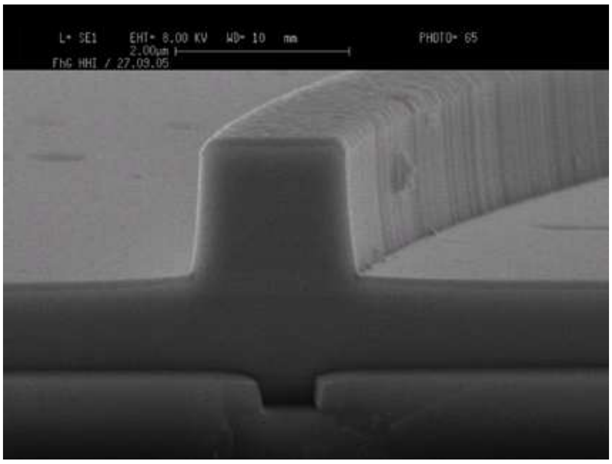


Fig. 4. IR transmission image (a) and SAM image (b) of a GaAs/InP wafer pair bonded with BCB layer.

After InP removal passive microring test devices were fabricated by patterning of the epitaxial multi-layers structures transferred onto GaAs wafer by wafer bonding (Fig. 5).



a.



b.

Fig. 5. SEM topographic image showing a microring resonator device with an integrated metallization layer for fine tuning via heating (a) and SEM cross-section of a cleaved microring/bus waveguide region showing the vertical coupler zone (b).

4. Conclusions

Passive microring resonator test devices were successfully fabricated using a vertical integration concept with wafer bonding.

The preferred wafer bonding process was BCB adhesive bonding due to the fact that Au:Sn eutectic bonding results in high warpage of the bonded wafer pair and an alignment of the optical layer structures to each other with submicrometer accuracy is not possible.

Adhesive bonding with BCB results also in a warpage of the bonded pair, but much lower than for eutectic bonding. This different behavior is given by the different properties of the two types of intermediate layers: while eutectic alloy becomes rigid during cooling down below eutectic temperature after bonding and remains rigid, BCB layers still shows some flexibility which gives elastic properties to the interface. As warpage occurs due to the thermal mismatch of the two substrates and the intermediate bonding layer, the process was optimized by decreasing the bonding temperature from 300°C (same as for eutectic bonding) to 200°C.

The samples investigated by IR transmission show interference fringes similar to voids (unbonded areas) in direct bonding. In this case the presence of fringes is not associated with voids at the bonded interface, but are most probably a result of the different compression of BCB layer during bonding as a result of InP surface topography.

The successful wafer bonding and substrate removal processes allowed microring devices fabrication by photolithography and etching. As shown in Fig. 5a., good alignment of the ring and the waveguide was possible, for obtaining high coupling efficiency.

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