Adhesive wafer bonding with Benzocyclobutene

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Abstract— **In this paper, we present and elaborate on a die to wafer bonding technology with benzocyclobutene (BCB). We will show that this technology allows to fabricate a variety of reliable waferbonded components in a fairly simple way using only standard cleanroom equipment. We have fabricated not only passive devices such as microring resonators, but also lasers and LEDs with good performance. These devices were subjected to damp-heat testing to demonstrate the quality of the BCB-bonding procedure. Due to the low thermal conductivity of BCB thermal management needs some attention. We will present an analysis of the thermal problem and a possible solution.**

Index Terms— **Bonding, benzocyclobutene, BCB, microring resonators, thin-film laser, thin-film LED, damp-heat testing, thermal analysis**

I. INTRODUCTION

WAFER bonding has over the years found very broad applications. The possibility to integrate opto-electronic III-V components with mature Si-circuitry is very promising and different methods have been studied to achieve this [1].

A large variety of wafer bonding methods exists, each with their own benefits and disadvantages. Wafer bonding procedures can roughly be divided into two categories: direct and indirect bonding. Direct bonding means joining two very smooth and clean semiconductor interfaces without using intermediate layers. To ensure the formation of a strong bond the two wafer surfaces normally have to be annealed at a high temperature. Work is being done on low temperature direct bonding procedures though ([2], [3]). The main disadvantages of the direct bonding process are the use of high temperature, the need for very flat surfaces, delicate and demanding process technology and the need for specialized equipment [3]. Indirect bonding covers a wide range of processes where an intermediate layer of some sort (polymers [4], [5], [6], spin-on-glasses ([7]) , metals [8], ...) is used to bond the two wafers.

While most papers in literature report on full wafer bonding (either directly or indirectly) we will focus on the die to wafer bonding process. The rationale to do this is twofold. An important application of bonding is the integration of CMOS and III-V material. As the size of the available III-V wafers (50-75mm) is much smaller than that of industrial CMOS wafers (300mm) the full wafer bonding of III-V wafers onto silicon wafers is not industrially viable. Even if the size of the wafers is the same the population density of opto-electronic devices will be much lower than that of VLSI CMOS, which implies that full wafer bonding would result in high cost systems due to the inefficient use of III-V material. Alternatively, one could bond opto-electronic devices on passive waveguide circuits that are typically much larger than the active devices. In these applications die to wafer bonding is the preferred technology.

We will focus on the indirect bonding of III-V dies using the polymer benzocyclobutene (BCB) as a bonding agent. The advantages of BCB bonding are excellent thermo-mechanical stability over time, no detectable outgassing at room temperature, low processing temperatures, lower than fusion bonding, and a fairly simple processing scheme that only requires basic cleanroom equipment. BCB is also a low-k dielectric which is chemically inert and resistant to chemical etching. It allows to bond different materials, structured wafers, full wafer bonding and die to wafer bonding. While die to wafer bonding using direct bonding technology can be problematic for small dies due to edge effects, in our opinion this is not the case using an adhesive like BCB. To our knowledge the first die to wafer bonded components fabricated with BCB were reported by Sakamoto [9]. The first microring resonators fabricated in this way were reported by Ma [10] and Absil [11]. Active devices have been reported by [12] and [13]. Full wafer adhesive bonding with BCB has been reported for instance for the fabrication of MEMS ([14], [15]).

In section II we will discuss in detail the processing procedure for die to wafer bonding from substrate preparation over bonding to substrate removal. In section III several kinds of devices that have been fabricated using this technology will be presented namely microring resonators, lasers and LEDs. This is followed by measurements on these devices in section IV. In section V results of reliability tests performed on the fabricated laser devices will be presented proving the quality of the BCB bonding procedure. Finally we shall comment on thermal management issues in section VI.

This paper will mainly focus on the bonding of InP-devices with a GaAs-transfer substrate but some tests of bonding InP onto Si or SOI have been carried out and there seems to be no problem extending this process to a large variety of materials and material combinations. Due to the low temperature of the process, the difference in thermal expansion is also not extremely important especially because we are focussing on die to wafer bonding.

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II. THE FABRICATION PROCESS

A. Substrate preparation

The substrate preparation required for indirect bonding is much less crucial than the preparation required for direct bonding. The wafers are cleaned with IPA, aceton and rinsed with DI water. Afterwards they are dried in an oven at 100 ^{o} C. Submicron sized particles at the surface can easily be tolerated and compensated for by the BCB-layer. Even structured wafers with for instance waveguides on them can be bonded. An adhesion promotor provided by DOW Chemical was then spun onto the sample but this is also not critical.

B. Benzocylobutene

Benzocylcobutene [16] (BCB) is available from DOW Chemical under the commercial name Cyclotene. It exists in two varieties: a photo-sensitive one and a dry-etch one. Wafer bonding has up to now only been demonstrated with the dry-etch variety. The dry-etch BCB can be bought in several varieties each differing in viscosity and therefore in achievable layer thickness. We have worked with the least viscous kind (3022-35) which allows to fabricate layers with a thickness ranging from 1 μm to 2.4 μm and the second least viscous (3022-46) with layer thicknesses from 2.4 to 5.8 μm.

C. The bonding procedure

The bonding itself is performed by spinning the BCB on the sample. We have performed experiments with BCB 3022-35 in order to work with thinner layers which would alleviate the thermal issues but the yield proved to be too low. Using BCB 3022-46 thicker layers were spun and processing yield was high. The reason for this is mainly the fact that we not only bond flat wafers but also patterned wafers. In order to tolerate these patterns the layer has to be thick enough.

The BCB is spun onto the sample to be bonded at 2000 rpm which leads to a layer thickness of 3.8 μm. The BCB is then placed onto a hot plate at 140 ^{o} C for a few minutes to allow some outgassing. An added advantage is the fact that the BCB becomes less viscous at this temperature and allows to move the sample around on the transfer substrate to position it accurately and remove trapped air bubbles. When the sample is in place it is left to cure in an oven under a nitrogen environment at 210 ^{o} C for an hour.

Bonding under a vacuum environment ([5]) might raise the yield of the process somewhat further, allowing to use thinner layers but it is not strictly necessary in our experience. This also would require the use of a specialized bonding chamber.

When bonding patterned wafers, the highest yield was obtained from spinning the BCB on the patterned sample. Bonding of two patterned samples has not yet been performed. Spinning BCB on both the patterned sample and the flat substrate lowered the yield.

The bonding is usually done onto a GaAs substrate, mainly because this substrate is chemically inert during the chemical etching for the InP substrate removal. Silicon could also be used however. We have fabricated structures bonded to silicon, but for waveguide based devices the cleaving of waveguide facets is particulary hard.

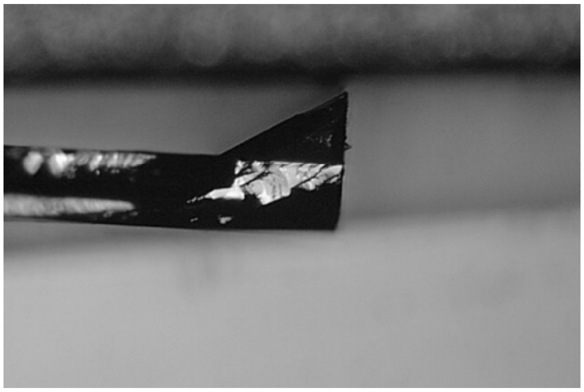

Fig. 1. Ridges are formed at the edge of the die when using chemical etching to remove the substrate

It is clear that this bonding procedure does not require anything but basic standard cleanroom equipment.

D. Alignment

Depending on the component being fabricated different kinds of alignment are important. We have currently only fabricated devices where the alignment to the possible structures on the transfer substrate was not very crucial. Angular alignment of the die with the transfer substrate on the other hand, is of extreme importance in waveguide-based components where the whole component has to be cleaved to achieve good facets. Of course other alignment issues exist when for instance one wants to fabricate ring resonators and process on both sides of the epi-layers. This is however not fundamentally different from aligning several lithography steps to each other.

E. Substrate removal

To remove the original substrate a combination of mechanical polishing and wet chemical etching is used. The substrate is mechanically thinned down to a thickness of about 50 μm. The remaining InP is removed in an HCl etching solution. This etching stops on the etch-stop layer. Complete chemical removal of the substrate would also be possible but this gives rise to slanted ridges at the edge of the sample as can be seen in Fig. 1. These ridges have the height of the original substrate (about 350 μm) and make subsequent lithography (especially with contact alignment) very difficult. Removing the ridges by cleaving is a possible solution. This seems to be an issue that only arises when dealing with die to wafer bonding and is assumed to be due to the anisotropic etching of InP by HCl. These edges only arise on two sides of the sample due to the undercut on the other sides.

III. FABRICATED DEVICES

Three kinds of devices have been fabricated using BCB wafer bonding: microring resonators, LEDs and lasers. We will discuss each of them in somewhat more detail.

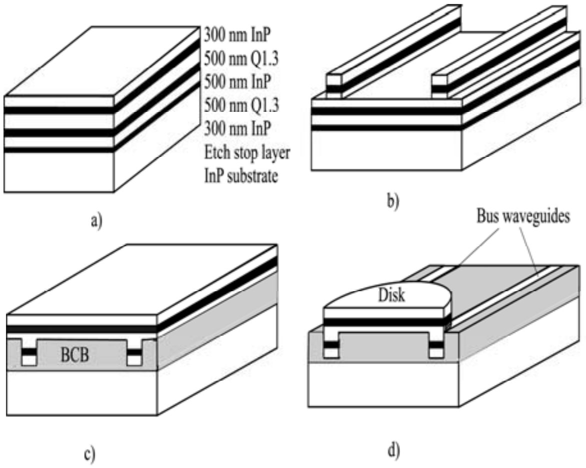

Fig. 2. Processing of vertically coupled microring resonators fabricated with polymer wafer bonding

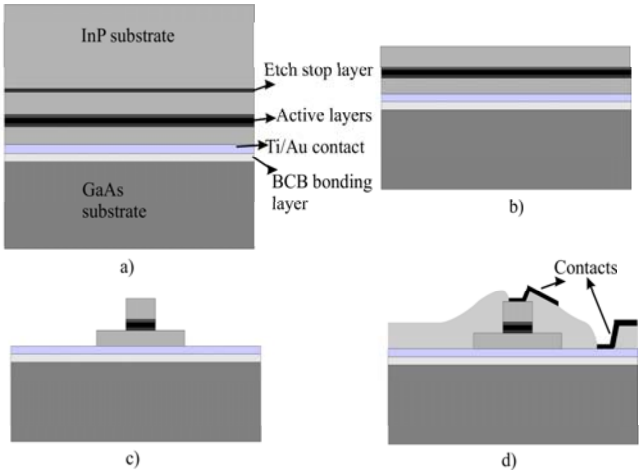

Fig. 3. Processing of thin film LED's fabricated with BCB wafer bonding

A. Microring resonators

Microring resonators consist of a circular waveguide and two straight waveguides which serve as input and output. The basic functionality is that of a wavelength filter.

Microring resonators can be fabricated in two ways: laterally coupled and vertically coupled. In the horizontally coupled approach the straight waveguides are in the same plane as the ring waveguide, in the vertically coupled approach they are underneath the ring. In the latter approach wafer bonding is required. This allows to access both sides of the epitaxial layer and perform double-sided processing. This was first introduced by Absil [11] for GaAs-based microrings and by Grover [17] for InP-based microrings. The fabrication process is illustrated in Fig. 2.

We start off (Fig. 2a) with an epitaxial layer-structure containing two waveguide core layers and an etchstop layer. Next the straight bus waveguides are defined (Fig 2b). This whole structure is flipped upside down and bonded onto a transfer substrate (usually GaAs) with the polymer benzocyclobutene (BCB). The original InP substrate is removed by a combination of mechanical polishing and chemical selective wet etching to the etch stop layer (Fig. 2c) as described in section II. This etch stop layer is also removed. The disk or ring resonator is then etched, the component is cleaved and AR-coated (Fig. 2d).

B. LEDs

The fabrication of the LEDs is illustrated schematically in Fig. 3. On the InP layer structure a Ti/Au contact was applied first. This was then bonded upside down onto the GaAs transfer substrate (Fig. 3a). Bonding with a Ti/Au contact deposited on one of the samples proved to be no problem either. Next the original InP substrate and the etch stop layer are removed (Fig 3b). In Fig. 3c we can see how the active device is etched in the InP membrane. Then a polymide layer is deposited through which contact openings are defined and contacts are deposited (Fig. 3d).The contacts in Fig. 3 are ring contacts to allow the LED to emit to the top.

C. Lasers

Two sets of lasers were fabricated. The processing sequence of the first batch of lasers was similar to the one of the LEDs. The second batch of lasers had electrical contacts through the BCB-layer to metal pads on the underlying substrate. This is interesting from an integration point of view because the III-V component could be connected to underlying Si-circuitry. The added contacts could also serve as a thermal heat sink allowing the laser to function in CW-operation. This will be discussed further in section VI.

The processing sequence is illustrated in Fig. 4. First both the InP-sample and the GaAs substrate are metallised. Then they are bonded with BCB (Fig. 4a). Next the InP substrate is removed (Fig. 4b). Then stripes are etched by a combination of dry etching and selective wet etching (Fig. 4c). Polyimide is spun on the sample, openings are defined on top of the ridges and n-contacts are deposited and plated (Fig. 2d). The metal patterns are then used as a mask in the next etching step that removes the polyimide and the remaining III-V semiconductor on both sides of the metal pattern. An opening is also defined next to the structure (Fig. 4e). This structure is then buried in a second polyimide layer and an opening is defined above the ridge, above the opening in the BCB and in the region where the p-contact is to be defined (Fig. 4f). Finally a metal bridging structure is defined that contacts the ridge metal with the Ti/Au layer on the GaAs substrate and also the p-contact is defined. These contacts are then deposited and further plated (Fig. 4g). The fabricated structure can be seen on Fig. 5 which shows an SEM picture with indication of the different regions and contacts.

IV. MEASUREMENTS

A. Microring resonators

Fig. 6 shows a typical measurement of the drop and pass port of a microring resonator. This particular microring resonator was a disk with a radius of 30 μm. The achieved Q-value was around 10000.

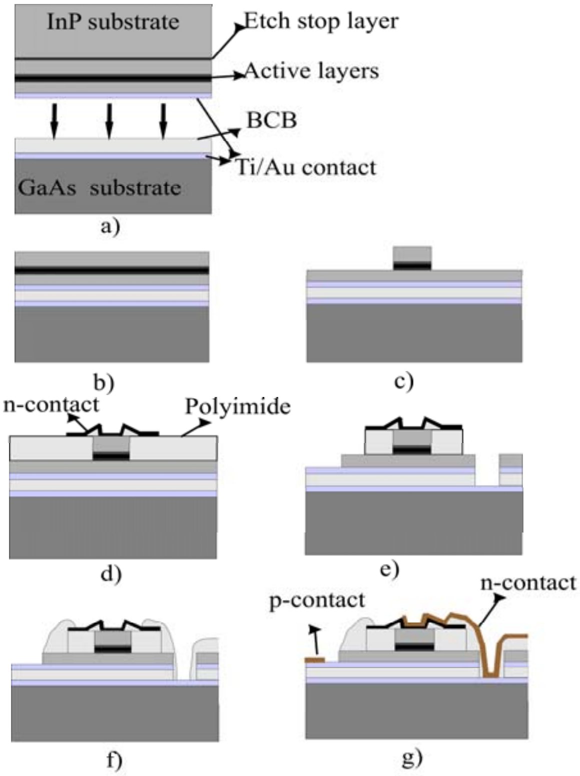

Fig. 4. Processing of a thin film laser fabricated with BCB wafer bonding. The electrical contact is led through the bonding layer

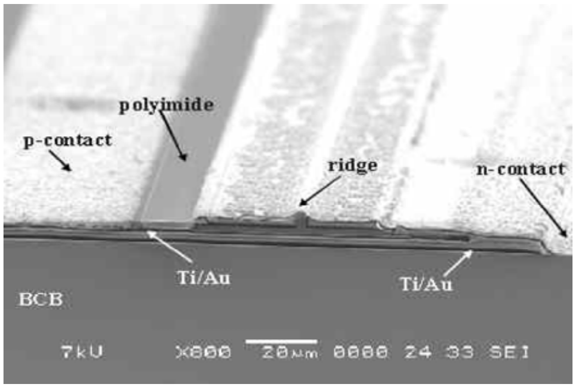

Fig. 5. SEM picture of a BCB bonded thin film laser with contacting through the bonding layer

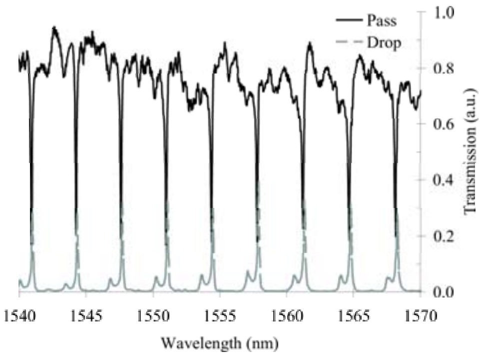

Fig. 6. The transmission (TE polarisation) at the drop and pass port of a 30 μm radius microdisk resonator

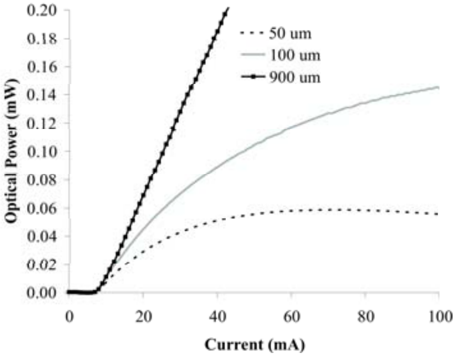

Fig. 7. Optical power versus current characteristic for III-V membrane LEDs (CW) with different diameters

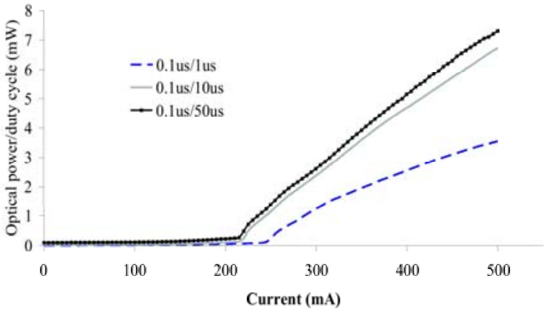

Fig. 8. Optical power versus current characteristic for III-V membrane lasers for different duty cycles

B. LEDs

Continuous wave operation was achieved for the bonded LEDs. This is illustrated in Fig. 7 which plots the measured optical power versus device current. LEDs with different sizes were measured showing the strong temperature dependence of the LEDs. Small area devices showed higher temperature sensitivity than large area devices due to the lower current density of the latter.

C. Lasers

Edge emitting lasers (length = 1mm, width = 7.5 μm) were demonstrated in pulsed regime with threshold current densities around 2.65 kA/cm^2 which is about double the threshold current density of standard lasers that were processed on the same wafer. Figure 8 plots the measured optical power versus current for different pulse duty cycles. High thermal resistance prohibited reaching continuous wave operation. These are measurements from the first laser design. Due to a processing error the second laser set had inferior characteristics.

V. DAMP HEAT TESTING

To assess the quality and reliability of the BCB-wafer bonding we have performed damp-heat tests on the lasers. The devices were subjected to tests at 85 ^{o} C and 85 % relative humidity (RH). The PI-curves and electrical characteristics of

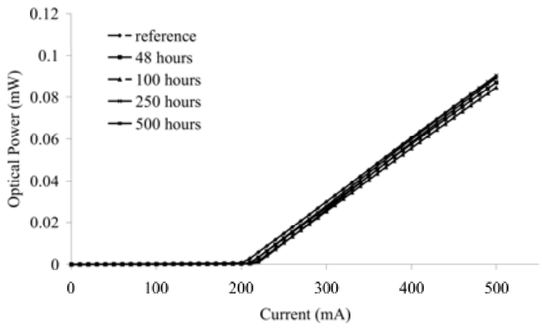

Fig. 9. Influence of the 85/85 degradation tests on the PI-characteristics of a laser (pulsed, 1μs/50μs).

the devices were measured before the tests and after 48, 100, 250 and 500 hours of degradation. Figure 9 show the results for a laser. The characteristics stay nearly constant and form a clear indication of the BCB-bonding quality.

VI. THERMAL ISSUES

BCB, as most polymers, has a low thermal conductivity (k=0.3 W/mK). Unless it can be used as an advantage such as for thermo-optic tuning [18], thermal management of active opto-electronic devices with BCB is necessary [19]. As was shown in section IV, measurements on LEDs clearly indicated the high thermal resistance of the bonded devices and the laser diodes operated only in pulsed regime. In some situations one could overcome this problem by mounting the devices upside down onto a heat sink. In most cases however this is not possible and other solutions are needed. In order to quantify the thermal resistance of bonded active devices and design structures that alleviate the self-heating problem, thermal simulations were carried out using the commercially available TCAD simulation package (Integrated Systems Engineering). The thermal resistivity of BCB bonded laser diodes was evaluated using a 2D model in which the maximum temperature rise due to a heat source placed in the active region was calculated. In these simulations we compared the thermal resistance of unbonded laser diodes and BCB bonded devices and investigated the possibility of heat sinking through the BCB layer by using the plated contact that contacts the laser ridge to the transfer substrate through the BCB. The structure under study is shown in Fig. 10. The 2.5 μm wide ridge laser is bonded onto a 500 μm thick Si wafer using 3 μm of BCB. All heat sinking is assumed to be through the substrate, so no convection or radiation is assumed. The thermal resistivity is a function of the InP undercladding thickness d due to the heat spreading function of this InP layer (k=68 W/mK). This dependence is shown in Fig. 12. In this case heat spreading by the thin contacts is neglected. As the thickness of the grown InP layers is limited, the thermal resistivity of the BCB bonded laser diode will be much larger than that of an unbonded laser diode. As a reference, the thermal resistivity of an unbonded laser diode on a 150 μm thick InP substrate is also shown.

In order to lower the thermal resistivity one could envision heat sinking by contacting the laser diode through the bonding layer as is shown in Fig.4g using thick plated Au-contacts (k=320W/mK). The structure simulated is shown in Fig. 11. The parameters of the laser diode are the same as in Fig. 10. The laser ridge is contacted through the BCB layer using a Au contact with thickness t. The thickness d is assumed to be 1μm. The thermal conductivity of the polyimide used for isolation is assumed to be the same as for BCB. Simulation results are shown in Fig. 13 in which the thermal resistivity of the bonded device relative to thermal resistivity of the unbonded laser diode is plotted. These results clearly show the strong influence of the thickness of the gold contact on thermal resistivity of the laser diode. For a gold contact thickness of 1μm a thermal resistivity equal to 1.5 times that of a standard diode is reached. This allows CW operation of the BCB bonded devices.

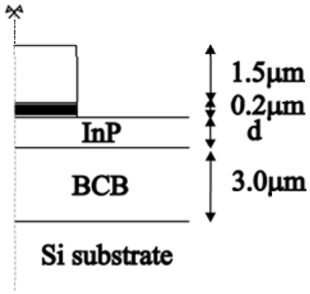

Fig. 10. Bonded laser diode structure under study - contacts are omitted for clarity

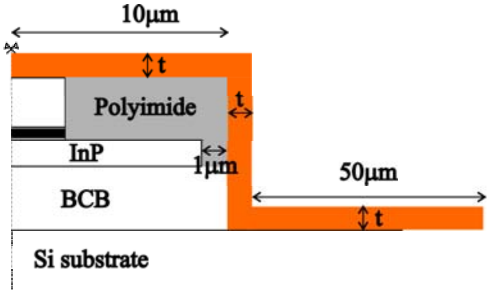

Fig. 11. Bonded laser diode structure with Au-contacts contacting through the bonding layer

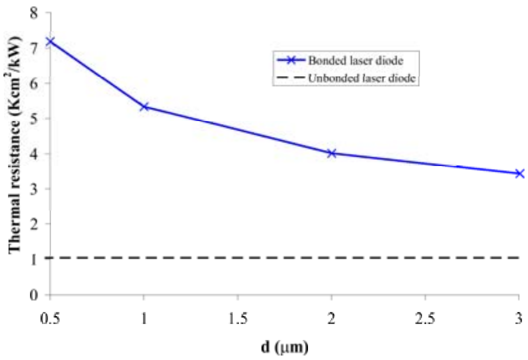

Fig. 12. Influence of InP thickness d on laser diode thermal resistance

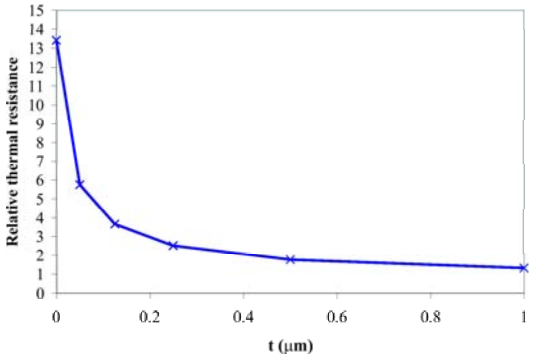

Fig. 13. Influence of Au thickness t on laser diode thermal resistance (divided by the thermal resistance of an unbonded laser diode as a reference)

VII. CONCLUSIONS

We have developed and described in detail the die to wafer bonding process with the polymer BCB. It is a very versatile, relatively easy and cheap technique. The process has been applied to the fabrication of passive devices (microring resonators) and active devices (lasers and LEDs). The reliability has been proven by means of damp heat testing of the fabricated lasers. The thermal issues, resulting from the low thermal conductivity of the BCB, have been analysed and possible routes for thermal management of active devices such as lasers have been suggested.

VIII. ACKNOWLEGDEMENTS

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REFERENCES

[1] D. L. Mathine, "The integration of III-V opto-electronics with silicon circuitry," *IEEE Journal of Selected topics in Quantum Electronics*, vol. 3, no. 3, June 1997.

[2] C. Seassal, P.Rojo-Romeo, X. Letartre, P. Viktorovitch, G. Hollinger, E. Jalaguier, S. Pocas, and B. Aspar, "InP microdisk lasers on silicon wafer: CW room temperature operation at 1.6 μ," *Electronics Letters*, vol. 37, no. 4, pp. 222–223, February 2001.

[3] D. Pasquariello and K. Hjort, "Plasma-assisted InP-to-Si low temperature wafer bonding," *IEEE Journal on selected topics in quantum electronics*, vol. 8, no. 1, pp. 118–131, January/February 2002.

[4] W. P. Eaton and S. H. Risbud, "Silicon wafer-to-wafer bonding at t lower then 200 ^{o}c with polymethylmethacrylate," *Applied Physics Letters*, vol. 65, no. 4, 1994.

[5] F. Niklaus, P. Enoksson, E. Kalvesten, and G. Stemme, "Low-temperature full wafer adhesive bonding," *Journal of Micromechanics and microengineering*, vol. 11, no. 2, 2001.

[6] B. Yacobi, S. Martin, K. Davis, A. Hudson, and M. Hubert, "Adhesive bonding in microelectronics and photonics," *Journal of Applied Physic: Applied Physics Reviews*, vol. 91, no. 10, May 2002.

[7] H. Lin, K. Chang, G. W. Pickrell, K. Hsieh, and K. Cheng, "Low temperature wafer bonding by spin on glass," *Journal of Vacuum Science and Technology B*, vol. 20, no. 2, April/May 2002.

[8] H. Lin, W. Wang, K. Hsieh, and K. Cheng, "Fabrication of 1.55 μm VCSELS on si using metallic bonding," *IEE Electronics Letters*, vol. 38, no. 11, May 2002.

[9] S. Sakamoto, A. Jackson, and N. Dagli, "Substrate removed GaAs-AlGaAs electro-optic modulators," *IEEE Photonics Technology Letters*, vol. 11, no. 10, October 1999.

[10] Y. Ma, G. Chang, S. Park, L. Wang, and S. T. Ho, "InGaAsP thin-film microdisk resonators fabricated by polymer wafer bonding for wavelength add-drop filters," *IEEE Photonics Technology Letters*, vol. 12, no. 11, November 2000.

[11] P. Absil, J. Hrynniewicz, B. Little, F. Johnson, K. Ritter, and P.-T. Ho, "Vertically coupled microring resonators using polymer wafer bonding," *IEEE Photonics Technology Letters*, vol. 13, no. 1, January 2001.

[12] A. Katsnelson, V. Tokranov, M. Yakimov, M. Lamberti, and S. Oktyabrsky, "Hybrid integration of III-V opto-electronic devices on si platform using BCB," in *MRS conference proceedings*, ser. Nano- and microelectromechanical systems and molecular machines, vol. 1. MRS, 2003.

[13] K. Ghawana, D. Delbeke, I. Christiaens, and S. V. ans R. Baets, "Grating-assisted resonant-cavity LEDs: towards thin film devices for heterogeneous integration," in *SPIE conference proceedings*, ser. Laser diodes, optoelectronic devices and heterogeneous integration, vol. 4947. SPIE, October 2002.

[14] F. Niklaus, H. Andersson, P. Enoksson, and G. Stemme, "Low temperature full wafer adhesive bonding of structured wafers," *Sensors and Actuators A*, vol. 92, pp. 235–241, 2001.

[15] V. Dragoi, T. Glinsner, G. Mittendorfer, B. Wieder, and P. Lindner, "Adhesive wafer bonding for MEMS applications," in *SPIE conference proceedings*, ser. First International Symposium Microtechnologies for the new millenium, vol. 5116. SPIE, May 2003.

[16] R. Kirchhoff, C. Carriere, K. Bruza, N. Rondan, and R. Sammler, "Benzocyclobutenes: a new class of high performance polymers," *Journal of Macromolecular science (Chemistry)*, vol. A28, no. 11 and 12, 1991.

[17] R. Grover, P. Absil, J. Hryniewicz, B. Little, O. King, L. Calhoun, F. Johnson, and P.T.-Ho, "Vertically coupled GaInAsP-InP microring resonators," *Optics Letters*, vol. 26, no. 8, April 2001.

[18] I. Christiaens, D. V. Thourhout, and R. Baets, "Low power thermo-optic tuning of vertically coupled microring resonators," *IEE Electronics Letters*, 2004.

[19] S. Pinel, A. Marty, J. Taselli, J.-P. Bailbe, E. Beyne, R. V. Hoof, S. Marco, J. R. Morante, O. Vendier, and M. Huan, "Thermal modeling and management in ultrathin chip stack technology," *IEEE Transactions on components and packaging technologies*, vol. 25, no. 2, June 2002.

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