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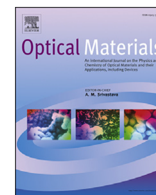

Reducing the thermal stress in a heterogeneous material stack for large-area hybrid optical silicon-lithium niobate waveguide micro-chips

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ABSTRACT

The bonding of silicon-on-insulator (SOI) to lithium niobate-on-insulator (LNOI) is becoming important for a new category of linear and nonlinear micro-photonic optical devices. In studying the bonding of SOI to LNOI through benzocyclobutene (BCB), a popular interlayer bonding dielectric used in hybrid silicon photonic devices, we use thermal stress calculations to suggest that BCB thickness does not affect thermal stress in this type of structure, and instead, thermal stress can be mitigated satisfactorily by matching the handles of the SOI and LNOI. We bond LNOI with a silicon handle to a silicon chip, remove the handle on the LNOI side, and thermally cycle the bonded stack repeatedly from room temperature up to 300°C and back down without incurring thermal stress cracks, which do appear when using LNOI with a lithium niobate handle, regardless of the BCB thickness. We show that this process can be used to create many hybrid silicon-lithium niobate waveguiding structures on a single patterned SOI chip bonded to a large-area (16 mm × 4.2 mm) lithium niobate film.

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1. Introduction

Despite advances in the last decade or so in silicon photonics, lithium niobate continues to find uses in advanced areas of integrated photonics due to its favorable nonlinear properties and low propagation loss [1–4]. Recently, researchers have been studying hybrid integrated photonic devices in which silicon-on-insulator (SOI) is bonded to lithium-niobate-on-insulator (LNOI), creating single-mode hybrid waveguides with sub-micron cross-sectional dimensions [5–10]. Bonded materials are sometimes subject to additional fabrication steps, for example, to pattern waveguides [11], and such processing generates stress in the layers due to a difference in coefficients of thermal expansion (CTEs) between the different materials and can cause irreversible damage. Similar to the work done earlier in bonding laser material to SOI [12,13], it is important to identify the parameters and properties of the interlayer bonding material, such as benzocylobutene (BCB), to mitigate the stresses [14–18].

2. Method

The approach to hybrid SOI-LNOI devices we study here is to bond an SOI chip (diced from SOI wafers from Soitec, Inc., and patterned using a standard silicon photonics foundry process) to an LNOI chip (LNOI from NanoLN Jinan Jingzheng Electronics Co. Ltd.) which has a thin layer of LN crystal, an SiO_2 buffer layer and a LN or Si handle [9]. A typical cross-section of a LNOI-SOI bonded chip is shown in Fig. 1. The chips are initially brought into contact at room temperature, and then the bond is strengthened by a thermal anneal. Compared to other approaches, such as those based on etched or deposited thin films [19–21], the advantage of this approach is that both the Si and LN thin film layers are crystalline and of high quality, which may benefit device performance and enable opto-electronic functionality.

However, if this stack is directly bonded and the LNOI has a LN handle, it can only be held together at room-temperature by weak hydrogen bonds. We have found that the stack debonds when the temperature is raised to about 70–80°C. Researchers who have studied direct bonding of bulk Si and LN under optimum conditions have found that the two materials either debond or crack by 150°C [22,23]. It may be hypothesized that debonding of Si and LN, two materials with substantially different properties (see Table 1), can

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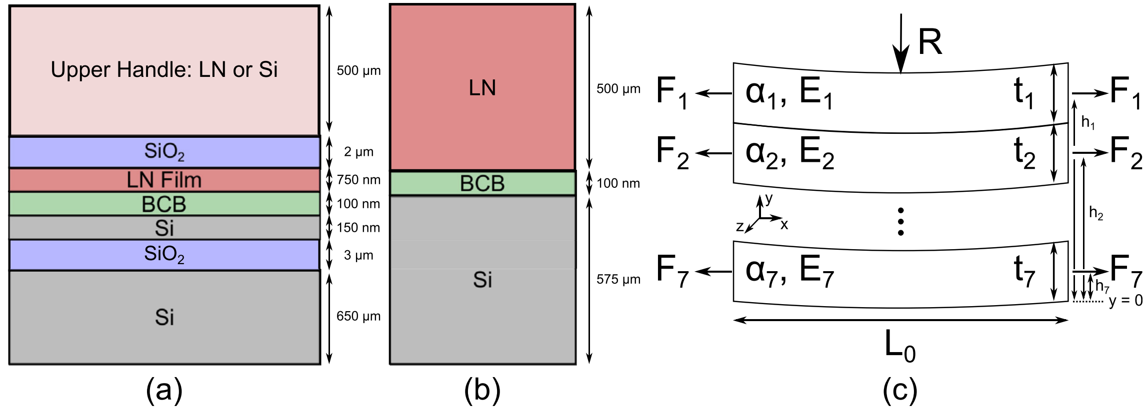

Fig. 1. (a) The thin-film stack used in hybrid photonic devices based on silicon-on-insulator (SOI) and lithium niobate-on-insulator (LNOI). (b) A simplified bulk LN-BCB-Si bonded structure used in the calculations shown in Fig. 2. (c) A schematic drawing of the bonded stack, labeling the dimensions and axial forces used in Eqs. (1)–(4).

Table 1
Material properties of all materials used in our numerical calculations of thermally-induced stress. All data is taken at room temperature. E is the modulus of elasticity, and α is the coefficient of thermal expansion (CTE). x, y, and z are used to denote the crystal axes of anisotropic LN.

Material	E (GPa)	α (10^{-6}-K^{-1})
Si	130 [25]	2.6 [26]
LN, z	199 [27,28]	3.4 [29]
LN, y	173 [27,28]	13.4 [29]
LN, x	173 [27,28]	13.4 [29]
SiO_2	75 [30]	1.0 [30]
BCB	2.9 [31]	52 [32]

be mitigated by using a layer of amorphous, low-optical-loss adhesive, such as benzocyclobutene (BCB, cyclotene 3022-35 resin from The DOW Chemical Company). BCB has a high bond strength and thermal stability, but has a high thermal resistance and a low refractive index that is substantially different from that of either Si or LN. A gap-filling, self-planarizing dielectric such as BCB simplifies the back-end process for LN integration with patterned SOI chips – which are likely to have different filling factors across the same chip and from one chip to another – without affecting the front-end processes for SOI device formation.

Calculations show that in order to maintain a hybrid optical mode similar to that of the directly-bonded case, the BCB layer must be no more than 100 nm thicker than the SOI patterned features; however, thin layers of BCB may not be sufficient to mitigate the built-up stresses. In studies of bonded III-V-to-SOI materials, BCB layer thicknesses of 50 nm have been used [16].

3. Experimental

Here, after thorough cleaning of a SOI chip and a LNOI chip, a layer of BCB was spun onto the Si chip; some of the chips used a BCB thickness of 300 nm (the summation of the height of the SOI features and the calculated 100 nm separation between SOI and LN), whereas other chips used a thickness of 1 µm. The chips were partially cured at 180°C for 45 min before being manually aligned, bonded and hard-baked for 14 h at 190°C. By placing a weight over the chips, a force of 9.8 N was applied over a bonded area of 1 cm × 1 cm during the hard-bake process.

Contrary to what may be initially believed, the thickness of the BCB layer did not play a role in managing thermal stress. We observed that LNOI with a LN handle cracked or debonded by the end of the hard bake, regardless of BCB thickness. However, if the LNOI stack was based on a Si handle, the bonded films did not crack or separate. This experimental observation is discussed using a simple computational model and supported by further test experiments on test (bulk Si) samples.

4. Theory

We use a strain model which accounts for self-induced thermal strain (since the materials will experience strain as temperature changes), stack-induced thermal strain (i.e., thermal strain due to a mismatch in CTEs of materials held together in the stack), and bending-induced thermal strain (a difference in CTEs causes a bonded stack to bend, resulting in an additional expansion or contraction of the layers in the stack) based on the seminal theory outlined in Ref. [24].

A schematic of the structure is shown in Fig. 1 (c), and consists of seven layers, each with a different axial force, and a common bending radius R. We require eight equations to solve for the total strain in each of the seven layers. The width of each cross-section is not shown, but it is assumed that they are all 1 cm, the nominal width of the test pieces used in this study. α_i is the CTE for the i-th layer, E_i is the modulus of elasticity for the i-th layer, and t_i is the thickness of the i-th layer, where $i = 1, 2, \ldots, 7$. The CTEs and moduli of elasticity at room temperature are provided in Table 1. The moduli of elasticity in anisotropic LN were recalculated from the stiffness tensor of [27]. Calculating a modulus of elasticity from a stiffness tensor is discussed in Ref. [28]. We assume all materials operate in the elastic regime, governed by Hooke's law: $\sigma = E\varepsilon$, and that there is no slip between bonded layers (i.e., two adjacent layers will stretch equally at their shared boundary). Additionally, we assume that the radius of curvature R is much larger than the sum of the thicknesses of all layers, and that the length L_0 of the stack is much smaller than R, so that the small-angle approximation [$\tan(\theta) \approx \theta$] is valid. Under these assumptions, the equation for the strain in the i-th layer is:

$$\varepsilon_i = \alpha_i \Delta T + \frac{F_i}{E_i A_i} + \frac{t_i}{2R}. \tag{1}$$

We solve the following equations for the eight variables F_i and R,

$$\sum_{i=1}^{i=7} F_i = 0, \tag{2}$$

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