Ultra-thin benzocyclobutene bonding of III-V dies onto SOI substrate

G. Roelkens, D. Van Thourhout and R. Baets

The bonding of InP/InGaAsP heterostructures dies onto an SOI substrate is reported. Bonding layer thicknesses down to 200 nm were reproducibly achieved. Bonding was achieved both on unprocessed SOI substrates as on processed SOI substrates containing high index contrast waveguides.

Introduction: In recent years, there has been much interest in using silicon-on-insulator substrates for optical waveguiding applications. The main advantages of this technology are the possible use of standard CMOS technology for the definition of the waveguides [1], which makes it mass manufacturable, and the high index contrast between the silicon core ($n=3.45$) and the oxide buffer layer ($n=1.45$), which makes ultracompact circuits possible and extends the degree of integration [2]. Although this is a very interesting technology for passive functions, up till now no highly efficient active optoelectronic devices fabricated in silicon have been reported despite significant research. If active functions need to be integrated with the passive silicon components for telecom wavelengths, InP/InGaAsP heterostructure dies need to be bonded on top of the silicon components and light needs to be coupled between both optical layers. As in these applications InP/InGaAsP active optoelectronic devices are bonded on top of the silicon waveguides, the bonding layer has to be very thin for efficient heatsinking of the active component through the bonding layer [3]. Optical coupling through this layer in an efficient way also requires ultra-thin bonding layers (~ 200 nm) [4] due to the high index contrast between InP/InGaAsP, benzocyclobutene ($n=1.55$) and silicon. Direct bonding of two semiconductor substrates requires ultra-flat surfaces [5]. Therefore, direct bonding of processed SOI substrates and InP/InGaAsP dies requires advanced chemical mechanical polishing (CMP) to obtain the required surface quality. Moreover, the influence of edge effects (due to roughness of the die edge) becomes important when directly bonding small dies (few mm^2). Also spin-on glass (SOG) can be used to obtain a thin bonding layer [6] when bonding two substrates. However, the required curing temperature is relatively high (400°C) and to our knowledge bonding on processed substrates using SOG has not been demonstrated.

Fig. 1 Bonding layer thickness (spun at 5000 rpm) against added fraction of mesitylene

Because of these drawbacks, benzocyclobutene (BCB), a spin-on polymer, was investigated as a bonding agent [7]. The planarising properties of the polymer make a CMP process redundant and owing to the physics of the bonding process edge effects are believed to be small. BCB bonding using layer thicknesses above 1 μm is well known [7, 8]. In this Letter we demonstrate for the first time submicron layer bonding layer thicknesses, thereby enabling good heatsinking and the possibility for optical coupling. Successful bonding with a layer thickness down to 200 nm was obtained, even on substrates showing a surface topography of the same order of magnitude.

Bonding method: The bonding of InP/InGaAsP heterostructures on both processed and unprocessed SOI was investigated. The SOI wafers consist of a 750 μm -thick silicon substrate, a 1 μm -thick buried SiO_2

Fig. 2 Bonding processing sequence

Fig. 3 InP film bonded to unprocessed SOI substrate and to processed SOI substrate using 200 nm-thick bonding layers

SOI substrate consisted of 220 nm Si layer on top of 1 μm -thick SiO_2 buffer layer. Si substrate 750 μm thick

buffer layer and a 220 nm-thick silicon waveguide layer. Optical waveguides were processed using standard CMOS deep UV lithography and by etching through the silicon waveguiding layer. The waveguides were defined using 4 μm -wide trenches with 30 μm separation. The waveguide width varied from 0.3 to 10 μm . Both SOI dies (few cm^2) and InP dies (0.25–1 cm^2) were thoroughly cleaned using acetone, isopropylalcohol (IPA) and deionised water. Samples are dried at 150°C on a hotplate. In a second step BCB is spun onto the SOI substrate. The achievable bonding layer thickness of commercially available BCB, supplied by Dow Chemicals, is limited to 1 μm (cyclotene 3022-35).

As this is too thick for most applications of optical coupling, cyclotene 3022-35 was diluted by adding mesitylene (C_9H_{12}). Measured bonding layer against thickness added mesitylene is shown in Fig. 1. This Figure shows that a BCB-mesitylene solution concentration of 2:3 spun at 5000 rpm results in a 200 nm bonding layer thickness. This is sufficiently thin to allow direct optical coupling between the silicon and InP waveguide layer [4] and to have efficient heatsinking of active optoelectronic devices. The thinned BCB needs to be ultrasonically agitated before application to allow reproducible bonding layer thicknesses. After the BCB is spun onto the substrate both samples are bonded at 150°C to drive out any residual solvents and to allow a maximum bonding strength. Bonded samples are cured at 250°C in nitrogen ambient for 1 h. After curing the InP substrate is mechanically thinned down to 50 µm. A final chemical etching step using HCl removes the rest of the substrate until an InGaAs etch stop layer is reached. The processing sequence is shown in Fig. 2.

Results: Different solution concentrations up to BCB-mesitylene 2:3 were successfully used to bond onto both processed and unprocessed SOI. SEM pictures of the interface of bonded samples are shown in Fig. 3. Figs. 3a and b show the bonding of an InP-die onto, respectively, an unprocessed and a processed SOI substrate, in both cases using a 200 nm thin bonding layer. Owing to the excellent planarising properties of BCB, these thin bonding layers can be applied on a substrate with 220 nm topography height without introducing voids.

Conclusions: InP/InGaAsP thin films were bonded to processed and unprocessed SOI substrates. Bonding layer thickness is sufficiently thin to allow direct optical coupling through the bonding layer and allow sufficient heatsinking of active optoelectronic components. This enables the integration of III-V sources, modulators, amplifiers, detectors and ultracompact SOI passive waveguide structures to fabricate complex photonic circuits.

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References

- 1 Bogaerts, W., Wiaux, V., Beckx, S., Luyssaert, B.F.J., Bienstman, P., and Baets, R.: 'Fabrication of photonic crystals in silicon-on-insulator using 248-nm deep UV lithography', *IEEE J. Sel. Top. Quantum Electron.*, 2002, 8, (4), pp. 928-934
- 2 Fukazawa, T., Sakai, A., and Baba, T.: 'H-tree-type optical clock signal distribution circuit using a Si photonic wire waveguide', *Jpn. J. Appl. Phys.*, 2002, 41, pp. 1461-1463
- 3 Katnelson, A., Tokranov, V., Yakimov, M., Lamberti, M., and Oktyabrsky, S.: 'Hybrid integration of III-V opto-electronic devices on Si platform using BCB', *Photonics packaging and integration III*, ser. *Proc. SPIE*, 4997, 2003
- 4 Roelkens, G., Van Thourhout, D., and Baets, R.: 'Heterogeneous integration of III-V membrane devices and ultracompact SOI waveguides', *IEEE LEOS Summer Topicals*, 2004, pp. 23-24
- 5 Miki, N., and Spearing, S.M.: 'Effect of nanoscale surface roughness on the bonding energy of direct-bonded silicon wafers', *J. Appl. Phys.*, 2003, 94, (10), pp. 6800-6806
- 6 Lin, H.C., Chang, K.L., Pickrell, G.W., Hsieh, K.C., and Cheng, K.Y.: 'Low temperature wafer bonding by spin on glass', *J. Vac. Sci. Technol. B*, 2002, 20, (2), pp. 752-754
- 7 Ma, Y., Chang, G., Park, S., Wang, L., and Tiong Ho, S.: 'InGaAsP thin-film microring resonators fabricated by polymer wafer bonding for wavelength add-drop filters', *IEEE Photonics Technol. Lett.*, 2000, 12, (11), pp. 1495-1497
- 8 Niklaus, F., Enoksson, P., Kalvesten, E., and Stemme, G.: 'Low temperature full wafer adhesive bonding', *J. Micromechan. Microeng.*, 2001, 11, (2), pp. 100-107

Using group delay function to assess glottal flows estimated by inverse filtering

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The estimation of the excitation of voiced speech, or the glottal flow, is usually carried out using inverse filtering, where vocal tract resonances are cancelled from the speech signal. The parameters of inverse filtering are typically adjusted using subjective evaluations of estimated flow signals. Proposed is a method to assess objectively the quality of inverse filtered glottal flows. The method computes the group delay function over a single cycle of the estimated flow. Incorrect settings of the inverse result in the distortion of the group delay function. This distortion is easily detectable and can be used in a straightforward manner to quantify how accurately the zeros of the inverse filter match the poles of the vocal tract.

Introduction: Inverse filtering (IF) is a non-invasive method to estimate the source of voiced speech, or the glottal flow, generated by fluctuating vocal folds [1]. The idea behind IF is first to form a computational model for the vocal tract transfer function. The effect of the vocal tract is then cancelled from the speech signal by filtering this through the inverse of the model.

Subjective criteria are typically used when inverse filter anti-resonances are adjusted. The optimal result is interpreted as a glottal waveform, which shows a maximally flat horizontal closed phase with minimal remaining formant ripple. Applying this kind of subjective criterion in adjusting inverse filtering parameters is problematic, because it causes the estimation outputs to be dependent on the experience and personal opinions of the experimenter. In addition, subjective adjustment of the filter parameters is time-consuming, which might limit utilising inverse filtering in applications that call for analysing extensive amounts of speech data.

There are only a few studies on objective assessment of inverse filtered waveforms. One such study (in [2]) was based on expressing the estimated glottal flow on a two-dimensional phase-plane plot. With this plot, optimal settings of the inverse filter were determined by searching for values that yielded a single closed-loop phase-plane plot. In this Letter, we propose a more straightforward method to objectively assess the quality of inverse filtered waveforms. The method proposed should be regarded as a general tool, which can be combined with any inverse filtering technique in order to assess objectively the quality of the glottal flow pulseform.

Preliminaries: Fourier analysis of speech yields a spectrum, which has two components: magnitude and phase. The phase spectrum can be transformed into the group delay function, i.e. the negative derivative of the phase spectrum [3]. In most cases, the main object of interest in spectral analysis of speech is the magnitude component; the phase spectrum is considered less important. There are, however, some studies where the phase spectrum has been used, e.g. in formant analysis of speech [4].

Fig. 1 Synthetic glottal flow waveforms (left panels) and their group delay functions (GD) (right panels)

Studies on the spectral analysis of the glottal flow are almost entirely based on the application of the magnitude component of the Fourier transform; there are only a few studies in which the phase spectrum has been analysed from the glottal flow [5, 6]. These studies, interestingly,

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