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DIFFUSION BONDING OF GaAs WAFERS FOR NONLINEAR OPTICS APPLICATIONS

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Diffusion-bonded stacked (DBS) periodic structures can create a new family of nonlinear optics crystals with spatially patterned nonlinear properties, while the bonding process preserves the optical and mechanical properties of the bulk materials. GaAs devices up to 20 layers were diffusion bonded and characterized. Optical loss was from interfacial voids and gaps at shorter wavelengths, and from processing induced p-type free carrier absorption at longer wavelengths.

INTRODUCTION

Laser sources in the spectral range between 1 μm and 10 μm have wide applications in spectroscopy, remote sensing and military countermeasures. However, currently available high-power lasers have output wavelengths around 1 μm (rare earth doped crystals) and at 10 μm (CO_2 laser). One way to generate laser radiation at mid-IR wavelengths is to extend present mature laser technology to these wavelengths by nonlinear optical frequency conversion. Unfortunately, existing infra-red nonlinear crystals are difficult to grow, have poor thermal properties, and are expensive.

GaAs has a large nonlinear coefficient, good optical transmission between 1 μm and 12 μm, and high optical damage threshold for high power applications. It has good chemical stability, good mechanical properties, and has a well developed growth technology. However, single crystal GaAs cannot be used directly for nonlinear frequency conversion because the interacting waves cannot be phasematched, i.e., there is no way to compensate for the wavelength dependence of the refractive indices (dispersion). In Figure 1(a), second harmonic generation (SHG) is shown as a function of length of crystal for a non-phasematched interaction. The fundamental wave has a different phase velocity from the second harmonic wave, due to dispersion. As the two interacting waves propagate through the crystal, the phase difference increases, and the conversion efficiency decreases. One coherence length into the crystal, the two waves are π out of phase, and the second harmonic wave starts converting back to the fundamental wave.

Changing sign of nonlinearity every coherence length allows growth of the second harmonic power (figure 1(b)). Sign of nonlinearity changes in $\bar{4}3m$ crystals with 180° rotation around $[1\bar{1}0]$. Stack of plates, each one coherence length thick, produces quasi-phasematching (QPM) structure. SHG using QPM interactions was first demonstrated in GaAs in 1976[1][2]. Plates were polished to one coherence length (106 μm for SHG of

10.6 μm [illegible]ation), and aligned at Brewster's angle. Enhanced conversion efficiency was measured; however, alignment was tedious and there were serious optical losses due to the many air-GaAs interfaces.

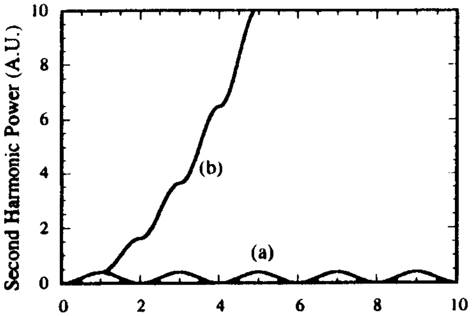

Figure 1. Theoretical second harmonic power as a function of crystal length
(a) Not phasematched interaction (b) Quasi-phasematched interaction

Direct material bonding of semiconductors has been used as an alternative to heteroepitaxy in electronic and optoelectronic devices[3-5]. While most work has been done with silicon, optoelectronic devices have been fabricated in the III-V semiconductors using various bonding techniques[6-8]. We have used direct material bonding to produce a DBS structure of GaAs plates for QPM interactions with reduced optical loss[9][10]. Figure 2 shows a schematic of a diffusion bonded crystal that can be used for frequency doubling a CO_2 laser radiation. Adjacent plates are rotated 180° to change the sign of the nonlinear coefficient. Commercial applications will require bonded stacks of 50 to 100 GaAs plates; therefore, loss introduced by bonding must be lower than 0.2% per layer for efficient frequency conversion. We report on our current work to understand and reduce processing-dependent losses.

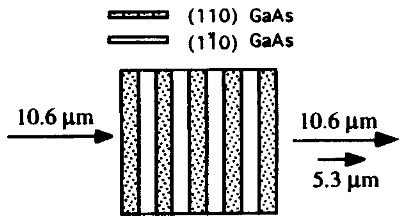

Figure 2. Diffusion-bonded stacked (DBS) GaAs for frequency doubling of 10.6 μm CO_2 radiation

PROCESSING

320 μm-thick {110} semi-insulating GaAs wafers were diced into 1 cm squares, which were cleaned and assembled in a cleanroom. The pieces were cleaned with hot detergent and de-ionized water, followed by degreasing baths of trichloroethane, acetone and methanol. The squares were then etched in NH_4OH for 15 min. After rinsing in flowing de-ionized water for 5 min, they were assembled by stacking alternating (110) and $(1\bar{1}0)$ GaAs plates under de-ionized water to reduce particle contamination at interfaces. The wafers were then placed into the bonding furnace shown in figure 3.

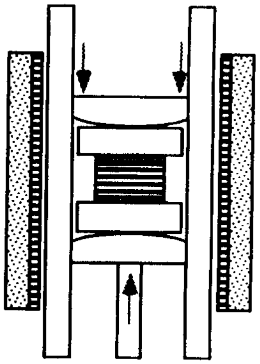

Figure 3. Schematic of the furnace used for bonding

The vertical furnace has two slightly radiused outer pressure plates to apply uniform pressure up to 10^7 N/m² (100 kg/cm²). Pressure is applied by a pneumatic piston from outside the furnace, permitting variation at any time during the process. The furnace can maintain sample temperatures of up to 1000°C.

The wafers were bonded at temperatures ranging from 700°C to 975°C under a pressure up to 20 kg/cm² in ~10% $H_2 + N_2$ atmosphere. The samples remained at high temperature for 2 to 9 hours.

CHARACTERIZATION

Usually during polishing, the two sides of the wafer will develop slightly different surface qualities, therefore, during the process development, three pieces were bonded together each run to test bonding of both sides. After bonding, the samples were cleaved and large sections of the interfaces observed under an optical microscope. Voids at interfaces were observed to be less than 0.5 μm in diameter. Interfacial gaps less than 0.2 μm wide millimeters long occurred occasionally. Optical transmission was measured with a Perkin-Elmer Lambda-9 spectrophotometer and a Bio-Rad FTS-40 FTIR. SEM and TEM were also use to characterize the interfaces. TEM indicates that bonding disrupts only a couple of atomic layers on each side of the interface.

RESULTS

The optical transmission spectrum of a 20 layer DBS GaAs is compared to that of an unprocessed single GaAs wafer in figure 4. Scattering from voids at interfaces can explain the loss at wavelengths between 1 μm and 2 μm, while gaps at interfaces may contribute to loss between 2 μm and 3 μm, however loss at wavelengths longer than 4 μm cannot be explained by either of these mechanisms.

Figure 5 shows transmission of a single wafer of GaAs annealed at 700°C to 975°C. Longer-wavelength-loss of single GaAs wafers increases as a function of annealing temperature. This loss at longer wavelengths is due to bulk absorption. Hall measurements show that semi-insulating wafers become p-type doped after annealing at 834°C, with a carrier concentration around $10^{16}/cm^3$. This is confirmed by the similarity of the loss spectrum to that of p-type free carrier absorption. The semi-insulating to p-type conversion has been reported previously[11-15] and is dependent on defect density as a function of temperature. It also depends on trace doping and the thermal history of the wafers. The annealing-induced loss is significantly reduced at 700°C.

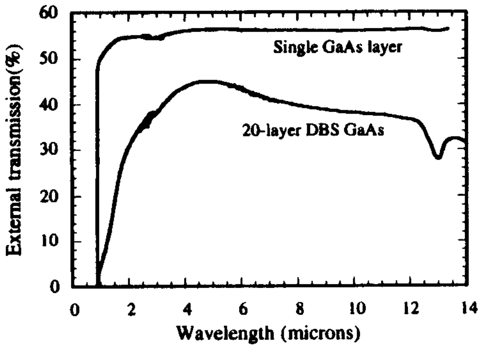

Figure 4. Transmission spectra of a 20-layer diffusion bonded stack (bonded at 834°C) and a single GaAs layer for reference

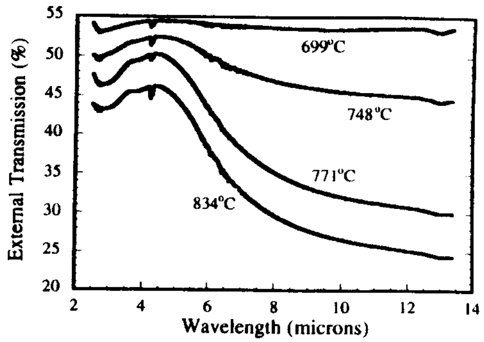

Figure 5. Transmission of a single GaAs wafer annealed at different temperatures

SUMMARY

In summary, we bonded multiple GaAs layers for nonlinear optics applications. Loss is from interfacial voids and gaps at shorter wavelengths, and processing induced p-type free carrier absorption at longer wavelengths. Induced loss is significantly lower for annealing at 700°C. To further reduce loss of DBS GaAs, we are currently using etching instead of dicing to cut wafers into small pieces for bonding so as to avoid contamination by the saw lubricant and debris, and lowering bonding temperature to avoid p-type conversion.

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