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Strain analysis of InP/InGaAsP wafer bonded on Si by X-ray double crystalline diffraction

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Abstract

Wafer bonding between p-Si and an n-InP-based InGaAsP multiple quantum well (MQW) wafer was achieved by a direct wafer bonding method. In order to investigate the strain at different annealing temperatures, four pre-bonded pairs were selected, and pair one was annealed at 150 °C, pair two at 250 °C, pair three at 350 °C, and pair four at 450 °C, respectively. The macroscopical strains on the bonded epitaxial layer include two parts, namely the internal strain and the strain caused by the mismatching of the crystalline orientation between InP (1 0 0) and Si (1 0 0). These strains were measured by the X-ray double crystalline diffraction, and theoretical calculations of the longitudinal and perpendicular thermal strains at different annealing temperatures were calculated using the bi-metal thermostats model, both the internal strain and the thermal strain increase with the annealing temperature. Normal thermal stress and the elastic biaxial thermal strain energy were also calculated using this model.

Keywords: InP; Si; X-ray double crystalline diffraction; Thermal strain; Wafer bonding

1. Introduction

Over the past 10 years, direct wafer bonding has received considerable attention for releasing the restrictions of lattice matching imposed by epitaxial growth and opening new degrees of freedom for the design of semiconductor devices [1–10]. During the wafer bonding process, thermal treatment is a very important step, which increases the surface energy and bonding strength of the bonded wafers [11]. However, if the bonded materials have different expansion coefficients, thermal strain will develop in the course of annealing and cooling. Furthermore, a big internal strain will severely affect the bonding quality and induce a high density of dislocations [12–14], even result in the failure to bond [15]. Therefore, it is important to study the strain of bonded wafers and the distribution of stresses, and to put forward an effective method to reduce these stresses.

2. Wafer bonding process

Single-facet polished silicon and InP wafers were used in this work. The 2-inch p-type silicon wafers were standard bare CZ-grown (1 0 0) orientation wafers, with a thickness of 280 μm, resistance of 1–50 Ωcm, and a surface root-mean-square (RMS) roughness ≤0.3 nm. A laser structured wafer with six InP/InGaAsP quantum wells, and with an epitaxial layer of about 4 μm was grown on a 380-μm-thick InP (1 0 0) substrate by MOCVD and used for wafer bonding.

The wafer bonding process is summarized as follows. The hydrophilic-treated InP and Si wafers were pre-bonded and baked at 70 °C for 5 h to drive the water out in order to prevent blisters in the subsequent annealing steps. The annealing process has three steps. First, the pairs bonded by the van der Waals force were put into a vacuum stove with a pressure of 40 N/cm^2 on the wafer pairs, and annealed in a vacuum at a slow temperature-rising rate (0.1 °C/min). When it reached 150 °C, 5 h of constant-temperature annealing was performed on the pairs. After that, the annealing temperature descended to 20 °C at a rate of −0.1 °C/min. Second, the InP substrate of the bonded pairs was mechanically thinned to about 150 μm. Third, the four bonded pairs were further annealed separately in a vacuum without any pressure on the pairs. Pair one was annealed at 150 °C again as the first step did. Pair two was annealed at a slow temperature rising rate of 0.1 °C/min when it reached 150 °C, 5 h of constant-temperature annealing was performed to the pair. Subsequently, the temperature continued to increase at a rate of 0.3 °C/min. As it reached 250 °C,

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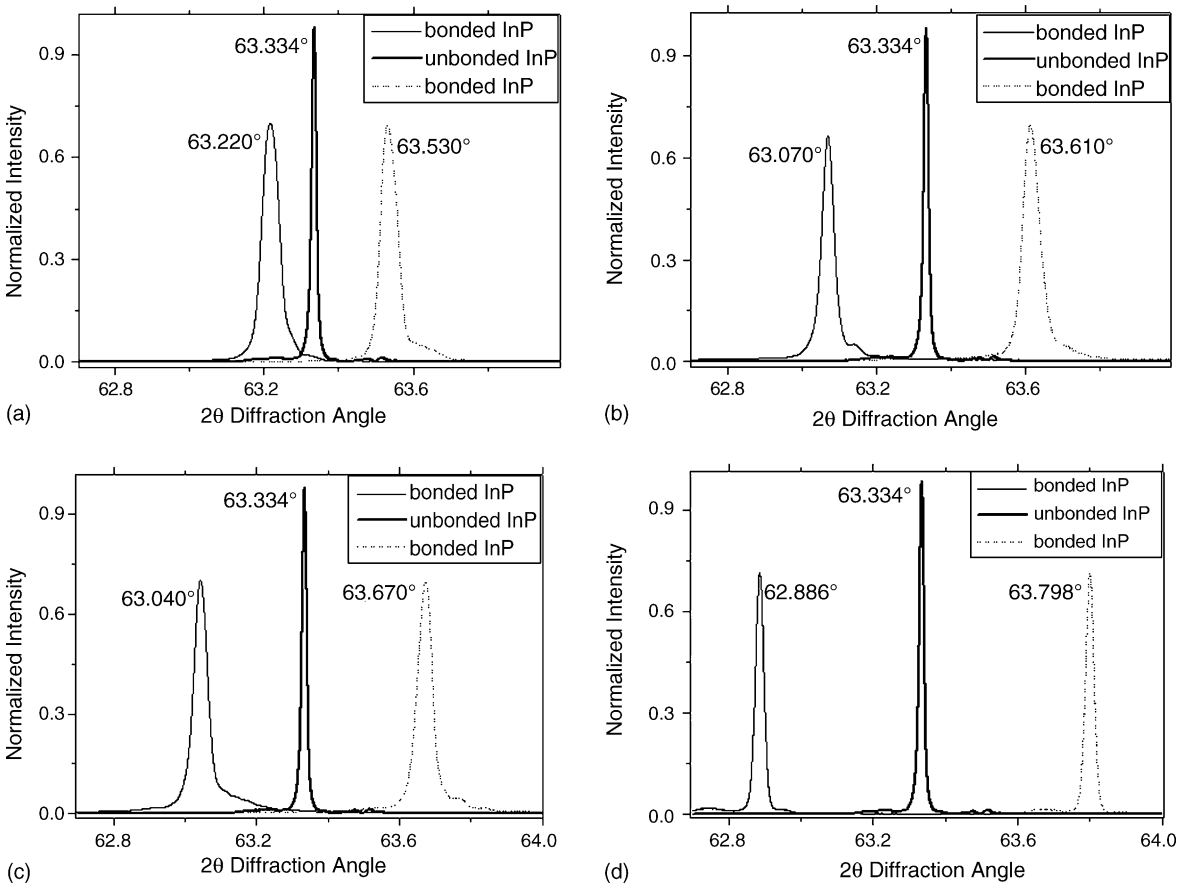

Fig. 1. The deflection of X-ray 2θ diffraction angle induced by internal strain and the strain caused by the mismatching of the crystalline orientation between InP (1 0 0) and Si (1 0 0). Samples were annealed at (a) 150 °C, (b) 250 °C, (c) 350 °C, (d) 450 °C. The dashed line labeled "bonded InP" indicates the measured diffraction angle with the X-ray incident angle of 31.667° irradiated on bonded InP transferred layer; the thin solid line labeled "bonded InP" indicates the measured diffraction angle with the X-ray incident angle of −31.667° irradiated on the bonded InP transferred layer; the thick solid line labeled "unbonded InP" indicates the Bragg diffraction angle 2θ of the stress-free InP.

5 h of constant-temperature annealing was performed to the pair. Finally the annealing temperature descended to 20 °C at a rate of −0.3 °C/min. Pair three was first annealed with a temperature-rising rate of 0.1 °C/min, and then be constant-temperature annealed at 150 °C for 5 h. After that, the annealing temperature continued to increase at a rate of 0.3 °C/min. As it reached 250 °C, the pair was constant-temperature annealed for 5 h. Then the annealing temperature continued to increase at a rate of 0.5 °C/min, as it reached 350 °C, constant-temperature annealing was performed to the wafer for 2 h. Finally, the temperature descended to 20 °C at a velocity of −0.5 °C/min. Pair four was first annealed as pair three did, when the pair was constant-temperature annealed at 350 °C for 2 h, the temperature continued to increase at a rate of 1 °C/min. As it reached 450 °C, the pair was annealed for 30 min. Finally, the annealing temperature descended to the room temperature at a rate of −1 °C/min. As the annealing temperature increases, the temperature rises or descends more quickly, and the time for constant-temperature annealing is also reduced. This is because the phosphor in the InP wafer surface is apt to volatilize and the indium separate out to the bonding interface as the temperature is high (generally above 400 °C) in a vacuum environment. As a result, defects and dislocations will engender around the bonding interface, this will increase the internal stress. The InP substrates on the bonded pairs were finally removed by selective wet chemical etching, leaving only the 4-μm-thick epitaxial layer on the Si substrate. The etching solution is hydrochloric acid: $H_2O = 4{:}1$ at 20 °C.

3. Strain measurement by X-ray double crystalline diffraction

The strains of the bonded pairs prepared by the method described above were then measured by a RIGAKU-SLX-1A X-ray double crystalline diffraction instrument. Since the Bragg diffraction angle θ of InP single crystal is 31.667°, we select ±31.667° as the two X-ray incident angles for investigating the strain. Most of the strain is loaded on the 4-μm-thick epitaxial layer since the InP substrate has been removed. The strain of the bonded wafer consist of two parts, namely the internal strain ε_i and the strain caused by the mismatching of the crystalline orientation between InP (1 0 0) and Si (1 0 0) ε_δ. Fig. 1(a)–(d) show the X-ray double crystalline diffraction spectra of the four bonded wafers. The Bragg diffraction angle 2θ of strain-free InP is 63.334°. When the 31.667° incident X-ray beam is irradiated on the bonded wafer, the diffraction angle is $2\theta + \Delta 2\theta + \delta$,