

Improvement of Wafer Bonding Processing for HB-LED with Low-Temperature-Grown Compound Semiconductors as Adhesive Materials

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Abstract

A wafer bonding process using low-temperature-grown (LTG) compound semiconductor as the bonding agent has been demonstrated. The optical and electrical properties of bonded samples have been characterized. This method provides several advantages, including high optical transparent, orientation-free, and low bonding temperature, which are desirable for high-brightness LED applications.

INTRODUCTION

The wafer bonding technology has been extensively used for orange and red color high-brightness LED application. [1-5] In an LED structure, spontaneous emission is assumed isotropic and approximately half of the light goes toward substrate. Those photons would easily be absorbed if the substrate has a smaller bandgap than the active region. In order to achieve high-brightness LED, bottom distributed Bragg reflectors [6] or metal layers [4-5] can be incorporated in the LED structure to reflect the light back to the surface and prevent it from entering the absorbing substrate. Alternatively, a transparent-substrate LED structure, achieved by direct wafer bonding, also enhances the light extraction because of the transparent substrate, which has a higher bandgap energy and does not absorb the light emitted from the active region. [1-3] To date, using metal layer as a bottom reflector and using transparent substrate are the two most common approaches to fabricating high-brightness LEDs in high-volume manufacturing.

Having a high bandgap energy of 2.2 eV, GaP is an excellent material to be used as a transparent substrate material for orange and red LEDs. [1-3] However, it is relatively difficult to integrate materials such as GaAs with GaP by using the direct wafer bonding technique,

because GaP has a high melting point. It usually requires high temperatures over 750°C for atoms to interchange through the interface and hence to bond the two wafers. Consequently, this high bonding temperature process may affect the doping profile and the emission wavelength of the active region. [7] There are additional concerns with the direct wafer bonding. For example, it has been found that electrical conduction through the interface depends on the orientation and/or misalignment between bonded wafers. Non-ohmic characteristics were observed across the bonded interface with two misaligned n-type substrates (InGaP and GaP layers). [8] On the other hand, perfect alignment of two n-type wafers results in an ohmic I-V dependence through the bonded interface.

EXPERIMENTS AND DISCUSSION

In this study, we focus on developing a new bonding agent which can be used for fabricating high-brightness transparent-substrate LEDs. This potential bonding agent is low-temperature-grown (LTG) compound semiconductors. By applying this new LTG material as an adhesive layer, it provides several advantages over the current direct wafer bonding technology for high-brightness LED, such as low bonding temperatures, and high optical transmission through the bonding interface. Additional advantage includes the recrystallization in the bonding layer. It is found that the recrystallized polycrystalline structure does not have a specific or preferred crystal orientation. This lack of specific orientation in the recrystallized bonding layer completely disrupts the crystal orientation and direction relationship between the two bonded substrates or wafers. As a result, the misorientation/misalignment dependence of non-ohmic current conduction encountered in the conventional direct wafer bonding can be reduced or even eliminated. [8]

Two main material systems: (Ga,As) and (Ga,P) were investigated in this study. The

microstructure and V/III incorporation ratio of the LTG materials were studied with TEM and Auger electron spectroscopy. The crystallinity of the as-grown LTG materials, amorphous or polycrystalline, is controlled by the group V overpressure during growth. Figure 1 shows the dependence between V/III atomic ratio and phosphorous overpressure of the LTG (Ga,P).

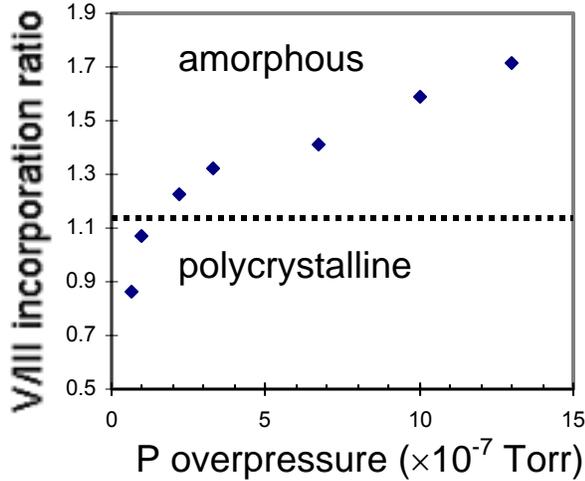


Figure 1. V/III incorporation ratio in low-temperature-grown (Ga,P) materials as a function of phosphorous overpressure during growth. With a decreasing phosphorous overpressure, less phosphorous atoms were incorporated in the film and the microstructures of (Ga,P) materials changed from amorphous to polycrystalline (dash line indicates the border between amorphous and polycrystalline).

The LTG materials are used as adhesive materials to bond two GaP wafers. Before bonding, the wafers coated with LTG material were cleaved in 1cm \times 1cm pieces and the surfaces were cleaned by standard degreasing solvents and a short HCl dip to remove organic contamination and surface oxides. Two clean LTG material-coated surfaces were then brought together and placed in a stainless steel jig. Pressure is applied and the whole fixture is then placed in an open-tube furnace. Bonding is performed by heating the wafers in N₂ ambient at different temperatures for different times.

The results show that two n-type GaP substrates, each with a LTG (Ga,P) material on top were strongly bonded face-to-face at 600 °C for several hours. When using LTG (Ga,As) as the bonding agent, either amorphous or polycrystalline, two GaP substrates could be bonded at even lower temperature at 400 °C for 1hr. This annealing condition for amorphous LTG (Ga,As) bonding agents can yield sufficient bonding strength for further processing. The

further decrease from 600 °C to 400 °C in bonding temperature and reduction in annealing time from several hours to one hour are significant. TEM shows that along the bonded interface recrystallization of the LTG layer has taken place during high-temperature annealing and hence helped two wafers bond together, as shown in Figure 2.

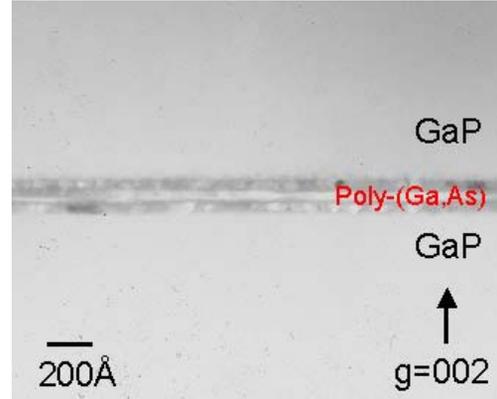


Figure 2. The dark field TEM image shows that two GaP substrates were bonded with the polycrystalline LTG (Ga,As) grown at As overpressure of 3.3×10^{-7} torr.

The optical light transmission and current-voltage (I-V) characteristics of the bonded samples were also characterized. Polycrystalline LTG (Ga,As) material grown at 3.3×10^{-7} torr shows the highest light transmission ratio, compared with other LTG (Ga,As) materials. In addition, the sample bonded with such LTG (Ga,As) material of as thin as 60 Å shows light transmission of 99%, as shown in Figure 3

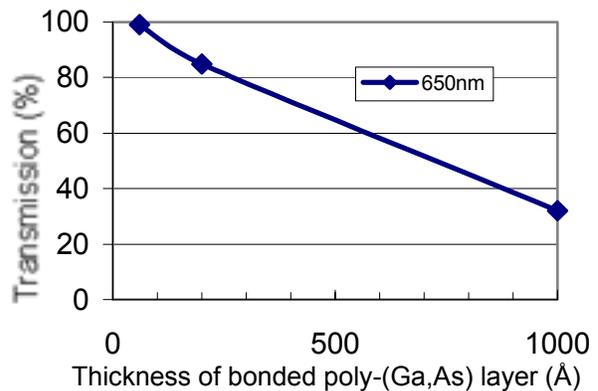


Figure 3. The light transmission ratio of bonded samples with different thickness of the LTG polycrystalline (Ga,As) layers (As: 3.3×10^{-7} torr) as the bonding agents. With a decreasing thickness of the bonding agent to 30 Å, more light (~99%) can transmit through the bonding interface (60Å).

For the I-V characteristic, samples bonded with Ga-rich polycrystalline LTG (Ga,P) layer exhibit linear I-V dependence across the bonded interface. In contrast, samples bonded with group V-rich LTG materials, either (Ga,As) or (Ga,P), show back-to-back Schottky I-V characteristics. The two bonded interfaces show great similarity in microstructure except that there exists gallium clusters only at the interface of the sample bonded with Ga-rich polycrystalline LTG layer. Figure 4 shows the bonding interface of two GaP wafers bonded with polycrystalline (Ga,P) materials (Ga-rich). EDS shows that the intensity of gallium atoms is 17 times more than that of phosphorous atoms, indicating that excess gallium atoms in the initial Ga-rich polycrystalline (Ga,P) film diffused and segregated in the middle of the bonded interface. Further evidence in the compositional x-ray mappings of Fig. 4(b) and 4(c) indicates that the dark region in Fig. 4(a) is chemically uniform and is Ga-rich and P-deficient. We attribute the linear ohmic I-V dependence to the presence of Ga-clusters.

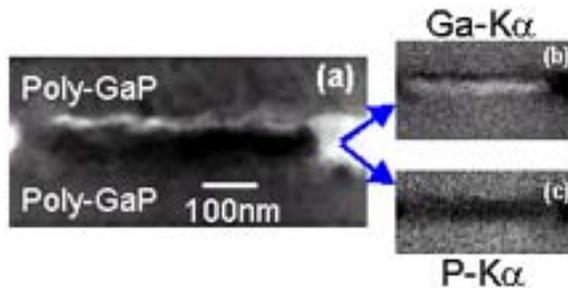


Figure 4. (a) The microstructure in the middle of the bonded interface of polycrystalline (Ga,P) bonding sample, which consists of dark particles. EDS shows the dark region in (a) indicates that the gallium concentration is 17 times more than that of phosphorous atoms after bonding. Compositional x-ray mappings, corresponding to (b) Ga map and (c) P map, show that the black region in Fig. 5(a) is uniform in composition and indeed Ga-rich.

Two processing approaches are used to evaluate the device after bonding and the practicality of such bonding technique. The first approach includes transferring device layers (~650 nm) onto a GaP substrate via wafer bonding using polycrystalline (Ga,As) material as the bonding agent, as shown in Figure 5. PL measurements are used to determine the quality of the materials and the intensity of light out of the samples. The bonded sample went through a series of polishing with alumina powder and etching to remove GaAs substrate and etch stop layer. PL measurements at 300K were performed on as-grown sample (absorbing GaAs

substrate) and bonded sample (transparent GaP substrate) to investigate the material quality. The bonded sample actually shows a slightly higher intensity than the as-grown sample. This indicates that the bonding medium and bonding process did not affect the active region and degrade device performance. It appears that the bonding with a thin low-temperature grown semiconductor layer is a promising wafer bonding technology for optoelectronic device integration.

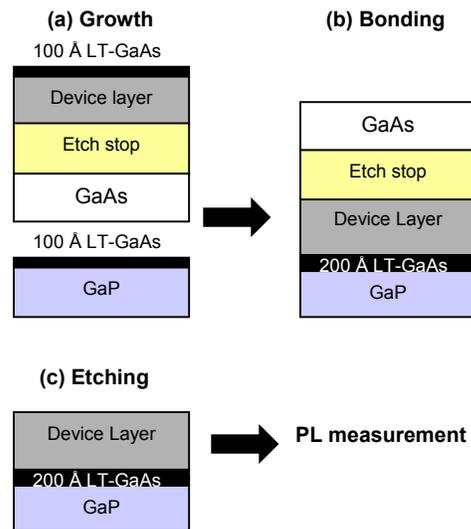


Figure 5. Illustration of bonding and etching process to transfer a GaAs-based device layer to a GaP substrate with LTG (Ga,As) material as the bonding agent.

Another approach includes a similar bonding technique, but emphasizes on the transfer and regrowth techniques. The process involves transferring a thin epi-layer (GaAs-based) onto a GaP substrate and using this thin layer as a template to regrow the device layers. Figure 6 shows the PL spectra of a device grown on a template which is made on GaP substrate through such a bonding process and a control sample which is grown directly on GaAs substrate. The control and regrowth samples have the identical layer structures. It clearly shows the regrowth sample has higher PL intensity because it does not suffer from the absorbing substrate.

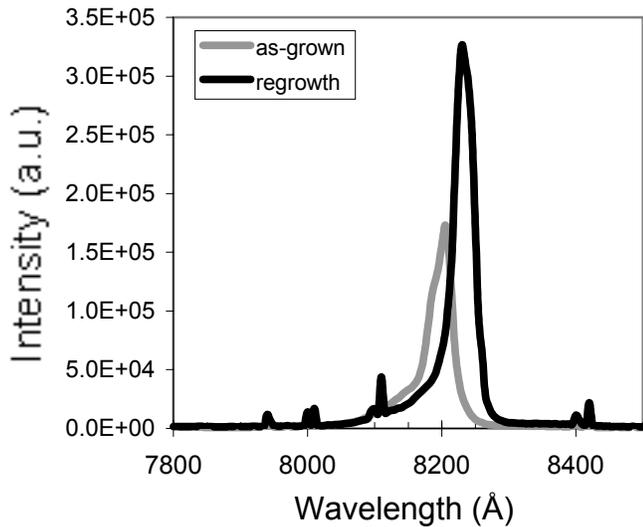


Figure 6. The PL measurements on an as-grown sample (on a GaAs substrate) and a regrowth sample (on a GaP substrate with AlGaAs template). Results show that the regrowth sample has higher PL intensity than the as-grown sample.

CONCLUSION

In summary, using amorphous or polycrystalline LTG material as a bonding agent have realized a new approach of wafer bonding. The bonding mechanism and bonding strength are closely related to the recrystallization of LTG material during annealing. This bonding method has the advantages of good bonding strength and low bonding temperatures for high bandgap materials, such as GaP. It also provides high optical transparent through the bonding interface which is crucial for transparent substrate high-brightness LED applications. It is also

demonstrated that almost twice as much of light can be emitted with a wafer-bonded transparent substrate as compared to the otherwise absorbing substrate.

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ACRONYMS

LED: Light Emitting Diode
 LTG: Low-Temperature-Grown
 TEM: Transmission Electron Microscopy
 EDS: Energy Dispersive X-ray Spectroscopy
 PL: Photoluminescence