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Heterogeneous Integration Based on Low-Temperature Bonding for Advanced Optoelectronic Devices

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Abstract

Heterogeneous integration is an attractive approach for manufacturing advanced microelectronic, MEMS (microelectromechanical systems) and optoelectronic devices. Recently, many low-temperature bonding methods such as plasma activation bonding and surface activated bonding have been studied to create unique device structures for a wide range of photonics applications. This paper focuses on low temperature bonding technologies and reviews the state-of-the-art applications in optoelectronic devices.

1. Introduction

For the last several decades the progresses of semiconductors are powered by Moore's law and the direction for further miniaturization of integrated circuits (ICs) by scaling down the transistor is called 'More Moore'. The concept of 'More than Moore' characterized by functional diversification was introduced in the 2005 edition of the International Technology Roadmap for Semiconductors (ITRS). For future success of semiconductors, it is essential to combine 'More Moore' and 'More than Moore' via heterogeneous integration complimentary. One of the key challenges of heterogeneous integration is bonding technologies to combine different materials.

In this paper, we focus on low temperature bonding technologies and reviews the state-of-the-art applications in optoelectronic devices.

2. Low Temperature Bonding Technologies

Although traditional bonding technologies such as fusion bonding, thermocompression bonding, and eutectic bonding are widely used, they typically require high-temperature treatment (> 300 ºC), which generates serious problems such as defect diffusion, dopant diffusion, and the introduction of large thermal stresses caused by a mismatch in the coefficients of thermal expansion between dissimilar materials. Therefore, in recent years, low-temperature bonding technologies have become very important integration methods to create unique device structures for a wide range of photonic applications [1].

Among the various low-temperature bonding technologies, a surface-activated bonding (SAB) method is a promising candidate for achieving room-temperature bonding.

Figure 1 shows the schematic process flow of the SAB and plasma activation bonding (PAB) processes. The SAB method starts with activating wafer surfaces by Ar fast atom beam (FAB) bombardment. Immediately after surface activation, the two wafers are brought into direct contact at room temperature in vacuum without exposing them to ambient pressure. In the PAB process, the wafers are treated by an oxygen plasma to obtain a hydrophilic surface. Then, the wafers are brought into contact at room temperature in ambi-

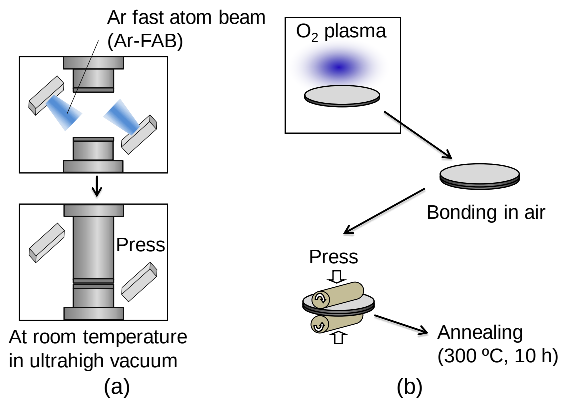

Fig. 1 Schematic process flow of low-temperature wafer bonding. (a) Surface activated bonding (SAB) and (b) Plasma activation bonding (PAB).

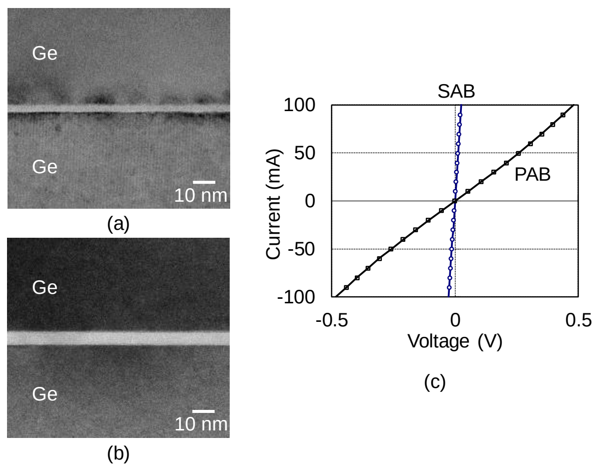

Fig. 2 Cross-sectional TEM images and I-V characteristics of p-Ge/p-Ge bonded interface. (a) SAB, (b) PAB, (c) I-V characteristics.

ent air. Then, the wafers in contact are annealed at 300ºC for 10 h to obtain a high bonding strength.

The microstructures and current-voltage characteristics of Ge/Ge bonded interfaces formed by SAB and PAB were compared (Fig. 2) [2]. It was found that the Ge/Ge interface had a disordered amorphous interlayer, which might have been formed by the Ar-FAB irradiation. EDX analysis of the interface prepared by the PAB method indicated that the interlayer was mainly composed of Ge and small amounts of O. The existence of a thin oxide layer (GeO_2) increases the junction resistance, as shown in Fig. 2(c), and is not appropriate for applications where low junction resistance is important.

3. Heterogeneously Integrated Optoelectronic Devices

3.1 Optical Micro Sensors

Hybrid integration of multiple optical chips such as laser diode (LD) and photodiode (PD) chips in three dimensions is an important technology for realizing highly functional, compact optoelectronic microsystems with wafer-level chip-scale packaging. Integration of multiple optical chips and hermetic sealing were performed using Au-Au SAB in ambient air at a bonding temperature of 150 ºC. Using this technology, various microsensors, including a high-resolution encoder that can measure the displacement or revolution angle (Fig. 3) [3], an optical polarization sensor (Fig. 4), and a blood flow sensor that can monitor blood flow in human skin, have been developed.

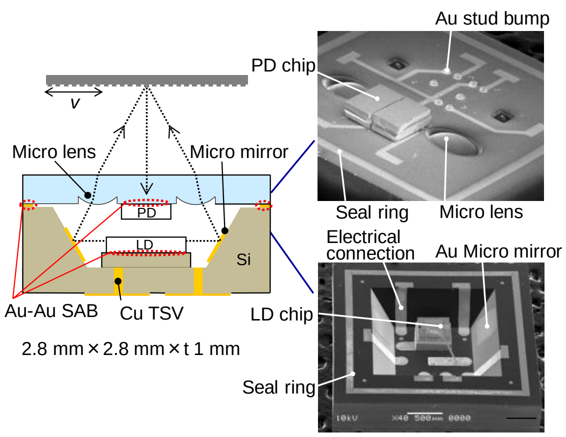

Fig. 3 Optical micro encoder fabricated by low-temperature bonding.

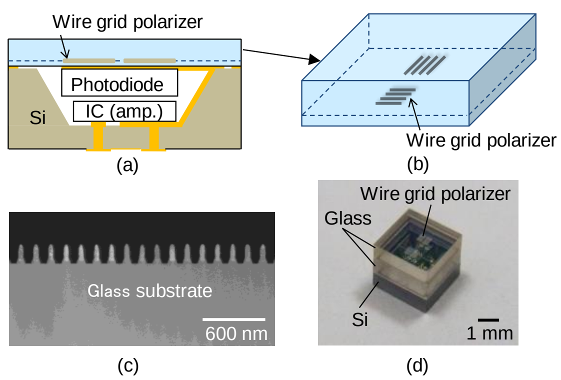

Fig. 4 Optical polarization sensor fabricated by low-temperature bonding.

3.2 $LiNbO_3$ Optical Modulators on Si

To realize a high-speed electro-optic phase modulation function on a Si substrate, $LiNbO_3$ high-speed electro-optical modulator chips were integrated on Si platforms by low-temperature flip-chip bonding using Au microbumps (Fig. 5). Air-gap structures between the $LiNbO_3$ modulator chips and micromachined Si substrates were fabricated to prevent the influence by the high permittivity of the Si substrate [4].

3.3 High-Power Semiconductor Lasers

Thermal management of high-power semiconductor lasers is of great importance since the output power and beam quality are affected by the temperature rise of the gain region. To realize thin-film semiconductor lasers bonded on a high-thermal conductivity substrate, SAB was applied to the bonding of GaAs and SiC wafers [5]. Room-temperature bonding in air ambient was also demonstrated using smooth Au thin films.

4. Conclusions

Heterogeneous integration of materially different components made with wide ranges of processes enables us to construct highly functional and small optoelectronic devices. Low-temperature bonding technologies are becoming increasing important to create various sensors in Internet of Things (IoT) applications.

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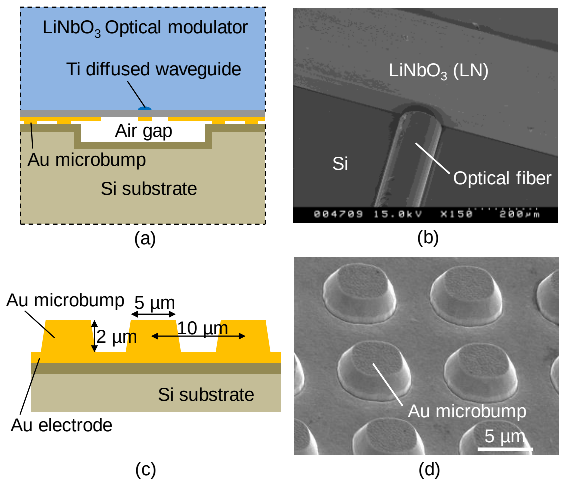

Fig. 5 Integration of $LiNbO_3$ optical modulator chip on micromachined Si substrate by low-temperature flip-chip bonding using Au microbumps.