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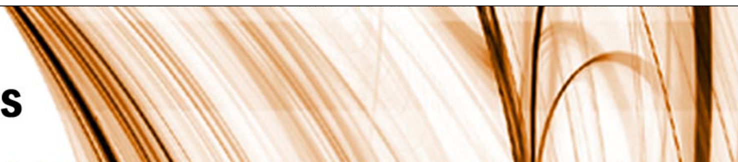

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Metallic wafer bonding for the fabrication of long-wavelength vertical-cavity surface-emitting lasers

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A novel metallic bonding method using AuGeNiCr as the bonding medium was developed for the fabrication of long-wavelength vertical-cavity surface-emitting lasers (VCSELs). The metallic bonding process can be performed at a low temperature of 320 °C within 1 h and it does not require chemical-mechanical polishing or etching treatments on the bonding surfaces. As determined by atomic force microscopy, the process can tolerate a surface roughness of ~10 nm on the surface of bonding samples. Cross-sectional transmission electron microscopy shows that the bonding interface is smooth and damage-free. Using this bonding technique, a 1.55 μm GaInAsP/InP VCSEL structure with Al-oxide/Si distributed Bragg reflectors was demonstrated on a Si substrate. No degradation was found on the bonded VCSEL structure after annealing at 420 °C. The reflectivity and resonance measured from the bonded VCSEL cavity confirmed the high optical quality provided by this bonding process for device fabrication. © *2002 American Institute of Physics.*
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Wafer bonding techniques have been developed to integrate two lattice mismatched materials for better device performance such as high brightness red light-emitting diodes (LEDs) and long-wavelength vertical-cavity surface-emitting lasers (VCSELs).[1,2] For high brightness 650 nm red LEDs, an $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ active region grown on an absorptive GaAs substrate is fused with transparent GaP substrates to increase the light extraction efficiency.[3] In the production of 1.3 and 1.55 μm VCSELs, the lattice-matched InP-based distributed Bragg reflectors (DBRs) have inherent disadvantages such as a small refractive index difference and low thermal conductivity. Wafer bonding has been used to solve this problem by bonding the GaInAsP/InP active region directly with GaAs/AlGaAs DBRs grown on GaAs substrates at a relatively high temperature of around 650 °C.[4,5] However, the bonding takes place inside the VCSEL cavity and near the active region. Consequently, the quality of the bonding interface can significantly influence the device performance. In order to achieve high bonding quality, special treatments such as chemical-mechanical polishing and wet etching are required to ensure flat, clean, and oxide-free surfaces of the wafers are bonded together.[1] The crystallographic alignment between two bonding wafers also influences the bonding quality.[6] These stringent requirements impose further processing limitations on the fabrication of long-wavelength VCSELs.

In this article we present a new metallic bonding method for the fabrication of long-wavelength VCSELs. This bonding method employs AuGeNiCr metal alloy as the bonding medium. The eutectic point of AuGe alloy is 280 °C which enables a low-temperature bonding process.[7,8] The use of NiCr is to enhance the adhesion and the strength of bonding with respect to both semiconductor and dielectric surfaces. The metallic bonding process does not require chemical-mechanical polishing or etching treatments on the bonding surfaces. Atomic force microscopy (AFM) and cross-sectional transmission electron microscopy (XTEM) were used to characterize the surface roughness of the bonding medium and the bonding interface, respectively. The thermal stability and optical quality of the bonded VCSEL structure were evaluated by thermal annealing and reflectivity measurements. Using this bonding technique, 1.55 μm GaInAsP/InP VCSEL structures with Al-oxide/Si DBRs have been fabricated on a Si substrate with the bonding interface formed outside the VCSEL cavity and away from the active region.

Prior to bonding, samples 1×1 cm^2 in size were first cleaned sequentially by acetone, methanol, isopropyl alcohol, and deionized water with ultrasonic agitation. After cleaning, the bonding metals were evaporated on the two samples to be bonded together using electron-beam evaporation. No additional heating was applied to the samples during the evaporation. After evaporation, two samples were brought to contact with the bonding metals facing each other. A pressure apparatus was used to press the composite samples tight as they were then heated in an open tube quartz furnace set at 320 °C in a N_2 ambient for an hour to complete the bonding process.

Prior to the bonding process, AFM was used to determine the surface roughness on the bonding samples. The root-mean-square surface roughness (R_{rms}) was measured by scanning a 5×5 μm^2 surface area on bonding samples. The

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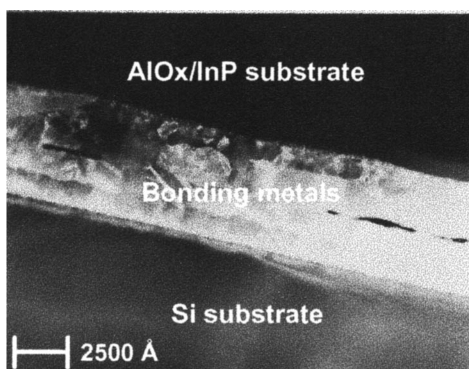

FIG. 1. The XTEM micrograph of a Si substrate bonded with Al-oxide deposited on an InP substrate. The metallic bonding medium on each sample fused together after the 320 °C bonding process. Some unbonded area was found at the bonding interface.

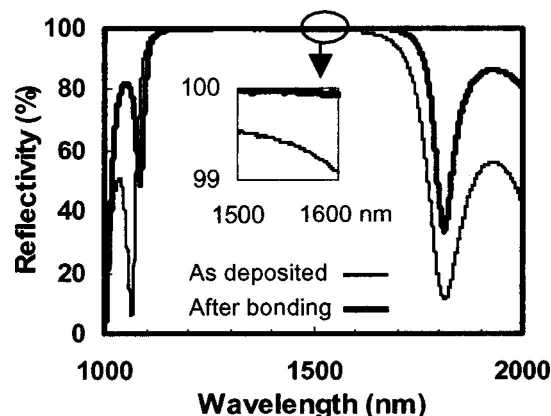

FIG. 2. The reflectivity spectra of a 6.5 period Al-oxide/Si DBR measured as-deposited and after the bonding process. The inset is the spectra compared above 99% around 1.55 μm wavelength. The DBR reflectivity measured after bonding is better than that of as-deposited DBR.

R_{rms} measured on a bare Si substrate was about 0.4 nm. The R_{rms} increased with increasing thickness of the bonding metals deposited on the substrate. Under the deposition condition described above, R_{rms} was 1.7 nm on a sample coated with 500 Å bonding medium and it increased to 9.8 nm for a bonding medium with a thickness of 3500 Å. The quality of the bonding interface was inspected by XTEM. During the XTEM sample preparation, the bonding interface experienced a series of strong mechanical stress due mostly to the sample dicing, lapping, and milling processes. Only strongly bonded samples can survive through the complete sample preparation process without falling apart. Successful bonding of GaAs to InP, GaAs to Si, and InP to Si have been obtained using this metallic bonding process. In addition, this bonding method was also found useful to bond semiconductors with dielectric materials such as Si-oxide or Al-oxide. These bonding results showed a similar bonding interface under the XTEM analysis as demonstrated in Fig. 1 where a Si substrate and an InP substrate deposited with Al-oxide on its surface were joined together by the fusion of the bonding metals. The thickness of the bonding metals was $\sim$2500 Å on the surface of each sample. Due to the low bonding temperature used, the bonding metals did not penetrate into the semiconductors after the bonding process. The bonding interface remained smooth without generating damages into the bonded wafers. Nevertheless, some unbonded regions were found at the interface, which was due to the rough metal surface on the bonding samples. By reducing the metal layer thickness for a smaller surface roughness, the unbonded region can be reduced. Successful bonding results were obtained using these samples in spite of their variation on the metal thickness and surface roughness, which indicates that the metallic bonding process has a large tolerance on these process conditions.

The effect of the metallic bonding to the optical quality of a VCSEL cavity was evaluated by measuring the reflectivity spectra of bonded DBRs including the resonance of a bonded VCSEL structure. Highly reflective DBRs used as cavity mirrors are essential for the operation of VCSELs. To determine if there was any adverse effect generated by the bonding process to the reflectivity of a DBR, a 6.5 period Al-oxide/Si DBR deposited on a bulk InP wafer was bonded to a Si substrate by the metallic bonding process. The Al-oxide/Si DBR was deposited using an electron-beam evaporator equipped with an *in situ* optical reflection monitor. After bonding, the InP substrate was completely removed by chemical etching in HCl solution leaving only the Al-oxide/Si DBR on the Si substrate. Using a spectrophotometer, the reflectivity spectra of the DBR measured before and after bonding were compared. As seen in Fig. 2 and the inset, the as-deposited Al-oxide/Si DBR on InP substrate reaches a reflectivity of 99.4% with a wide stop band in merely 6.5 periods because of the very large refractive index difference ($\sim$1.7) between these two materials. Nevertheless, the reflectivity of the same DBR bonded to Si substrate measured after bonding is above 99.9% at wavelengths around 1.55 μm, which is better than that of the as-deposited. The improvement of the DBR reflectivity is caused by the metallic bonding medium and its inherently higher reflectance in the range of measured wavelengths. Hence the remaining light transmitted through the bonded DBR will be reflected by the bonding metals and contribute to the overall reflectivity of the bonded DBR. In addition, the shape of the high-reflectivity stop band and its bandwidth are not distorted. Thus the bonding metals as well as the bonding process does not degrade the quality of the bonded DBR. Instead, the metallic bonding layer serves as an end mirror which can enhance the reflectivity of the bonded DBR. This can been seen more easily by comparing the reflectivity level of side lobes in the two spectra shown in Fig. 2.

Using this bonding technique, a 2λ GaInAsP/InP VCSEL cavity sandwiched by two Al-oxide/Si DBRs designed for a wavelength of 1.55 μm was fabricated on a Si substrate to evaluate the cavity resonance property. The 2λ thick GaInAsP/InP cavity was grown on a (100) InP substrate. On top of the as-grown wafer, the bottom 6.5 period Al-oxide/Si DBR was deposited by electron-beam evaporation followed by the deposition of the bonding medium. Then, the 1×1 cm^2 sample was bonded to a Si substrate where the bonding interface was formed between the bottom DBR and the Si substrate. After the bonding process, the InP

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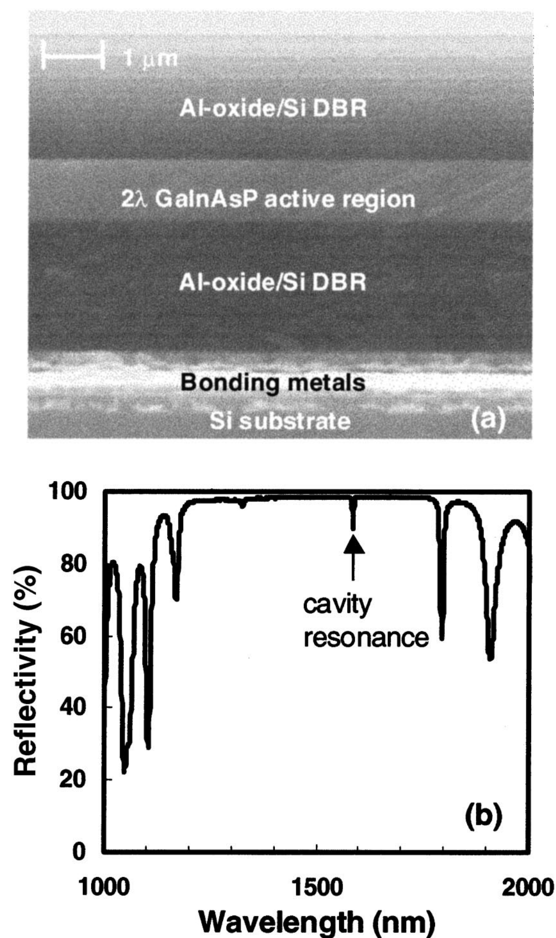

FIG. 3. (a) A 2λ thick GaInAsP/InP VCSEL cavity with Al-oxide/Si DBRs fabricated on a Si substrate using metallic wafer bonding. (b) The reflectivity spectrum measured from the bonded VCSEL structure. A cavity resonance at 1.55 μm was observed as indicated by the dip in the stop band.

substrate was removed by HCl solution to expose the GaInAsP active region. Finally, the top 6 period Al-oxide/Si DBR was deposited on the exposed active region to complete the structure as shown in Fig. 3(a). To mimic the thermal process used during device fabrication and to evaluate the thermal stability of the bonding, the bonded VCSEL structure was tested by thermal annealing. The sample was directly placed on a ceramic hot plate and annealed to 420 °C in a hydrogen ambient. The temperature of the sample was ramped up from room temperature with a rate of 5 °C/s and it was kept at 420 °C for 5 min before cooling down to room temperature. This annealing condition is typically used during device fabrication such as forming ohmic contacts. No degradation was found on the bonded films after the thermal process. The bonded VCSEL structure maintains a mirror-like surface after the thermal cycle as inspected under a Normaski optical microscope. After thermal annealing, the reflectivity spectrum of the bonded VCSEL structure was measured and shown in Fig. 3(b). The reflectivity spectrum of the bonded VCSEL structure shows a high-reflectivity stop band with a clear resonance at a wavelength of 1.55 μm. These results show that a functional VCSEL cavity can be obtained by using this metallic bonding process and the bonding interface is thermally stable for device fabrication. In addition, this demonstration also indicates that highly efficient Al-oxide/Si DBRs can be incorporated into the fabrication of long-wavelength VCSELs and thereby eliminate the need to grow thick epitaxial DBRs. With the bonding interface being located outside the DBR mirror and away from the VCSEL cavity, the impact of wafer bonding to the active region as well as the device performance can be minimized.

In summary, we have developed and characterized a wafer bonding method that utilizes AuGeNiCr as the bonding medium for the fabrication of long-wavelength VCSELs. This metallic bonding method can bond various combinations of materials including semiconductors and dielectrics at a low temperatures of 320 °C within 1 h. Process requirements are less stringent for the metallic bonding since it does not require polishing, etching, and orientation alignment for the bonding samples. Moreover, the process has a large acceptable range on the thickness and surface roughness of the bonding medium. Using metallic bonding, 1.55 μm GaInAsP/InP VCSEL structures were fabricated on Si substrates with the bonding interface formed outside the VCSEL cavity and away from the active region. The bonded samples exhibit excellent thermal stability when undergoing 420 °C annealing cycles. The bonding process does not degrade the reflectivity of DBR as well as the resonance of the VCSEL cavity. In fact, the metallic bonding medium can enhance the reflectivity of the bonded DBR. Thus this metallic wafer bonding method demonstrates a great potential for the fabrication of long-wavelength VCSELs and it would be also very useful for other integration applications.

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