Orientation-mismatched wafer bonding for polarization control of 1.3 μm-wavelength vertical cavity surface emitting lasers (VCSEL)

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Abstract. We propose and demonstrate a new type of long-wavelength (LW) VCSEL which consists of a (311)B InP-based active region and (100) GaAs-based distributed Bragg reflectors (DBRs), with an aim to control the in-plane polarization of output power. Crystal growth on (311)B InP substrates was performed under low-migration conditions to achieve good crystalline quality. The VCSEL was fabricated by wafer bonding, which enables us to combine different materials regardless of their lattice- and orientation-mismatch without degrading their quality. The VCSEL showed polarization dependent performance with a maximum power extinction ratio of 37 dB.

1. Introduction

LW VCSELs have been extensively studied as low-cost, high-performance light sources for telecommunications. However, compared to edge-emitting lasers, VCSELs have the disadvantage of not having fundamental selection rules for the polarization axis of output power due to its crystal symmetry when fabricated on the conventional (100) plane. To make polarization fixed to one axis of the VCSEL, there has to be some asymmetry introduced in its structure. For example, it has been shown theoretically [1] and experimentally [2] that multi-quantum wells (MQWs) grown on an asymmetric crystal plane have asymmetric in-plane gain, which leads to a fixed in-plane polarization axis. Such polarization control research has been mainly done for short-wavelength VCSELs, but relatively little has been done on LW VCSELs.

To fabricate LW VCSELs, various techniques have been investigated [3-8]. Among them, wafer bonding is a technique that has enabled LW VCSELs to operate continuously up to 115^{o}C [6-8]. With this technique we can combine two dissimilar materials without degrading their quality. Therefore, it is possible for a wafer-bonded VCSEL to have an InP-based active region and GaAs-based DBRs. Also, with wafer bonding, we have the freedom to choose the crystal planes of active region and DBRs independently [9]. Here we present the fabrication of a wafer-bonded LW VCSEL which utilizes (311)B InP-based active region and (100) GaAs-based DBRs and investigate its polarization properties.

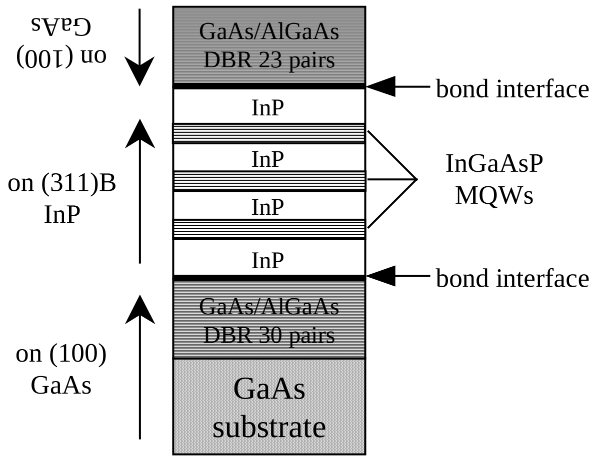


Figure 1. Structure of VCSEL

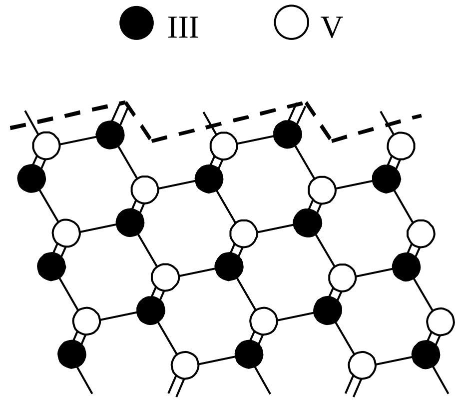


Figure 2. Schematic of atomic structure of (311)B

2. VCSEL structure and its fabrication procedure

Figure 1 is a schematic of our VCSEL structure. By changing the crystallographic orientation of the active region to (311), we can expect to have not only an asymmetric in-plane gain, but also an asymmetric stress provided from two bonded interfaces of (311)B InP and (100) GaAs. That is, at the lattice- and orientation-mismatched interface, effective lattice mismatch would be very different between two orthogonal in-plane axes [9]. We expect this asymmetric stress to have an effect on controlling the polarization axis. To focus on this effect, the MQWs were designed to have a small lattice mismatch so that the asymmetry of in-plane gain prior to bonding would be small.

The 2.5 λ-cavity active region consisted of three identical sets of InGaAsP MQWs and each set consisted of five 50Å thick wells and six 100Å thick barriers. It was grown by metalorganic chemical vapor deposition (MOCVD) using trimethylindium, trimethylgallium, tertiarybutylarsine, and tertiarybutylphosphine as the source materials. DBRs consisted of GaAs and $Al_{0.9}Ga_{0.1}As$, and were grown by conventional solid-source molecular beam epitaxy. The VCSEL was intended to be optically pumped, hence, all structures were grown undoped.

After the material growth, wafer bonding was performed to fabricate the VCSEL. First, the surfaces of the active region and one DBR were chemically cleaned and then they were placed face-to-face and annealed at 650°C with an applied pressure of about 3MPa. The InP substrate was selectively etched by a mixture of HCl and H_2O from its back side, i.e., (311)A plane. Then another DBR was wafer-bonded in the same way. A more detailed procedure about wafer bonding can be found elsewhere [8].

3. Growth on (311)B InP substrate

Figure 2 is a schematic drawing of the (311)B atomic structure, showing the step-like features of this surface. Phenomena such as In atom accumulation at steps during growth have been reported on this surface [2]. Therefore, it is important to perform growth under low-migration conditions such as low temperature and high V/III ratio. Figure 3 compares photoluminescence (PL) spectra from MQWs grown under two different conditions. As can be seen, when grown under high-migration conditions, PL intensity degraded to half of that from MQWs grown on (100) substrate at the same time.

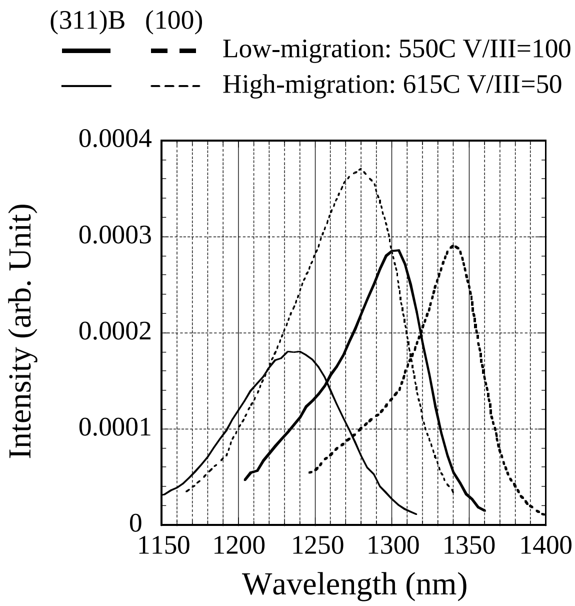


Figure 3. PL spectra from MQWs grown under different conditions.

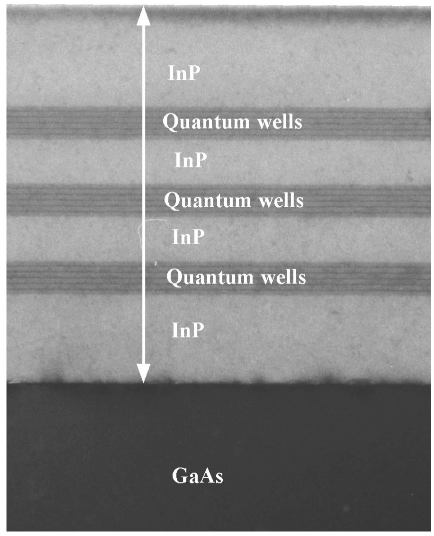


Figure 4. Cross-section TEM of VCSEL active region bonded to GaAs substrate.

The PL intensity and shape is comparable to that of (100) when grown under low-migration condition, but a notable fact is a blue-shift of the emission peak by about 40nm. By comparing bulk InGaAsP materials grown on (311)B and (100), it was found that this blue-shift is due to a large reduction in In incorporation and a small reduction in As incorporation on the (311)B surface. It is believed that In tends to desorb from step corners on the (311) surface [10]. Since the strain in the MQWs was small, little piezoelectric effect was expected. A low temperature PL experiment showed no peak shift by changing excitation power, confirming this expectation.

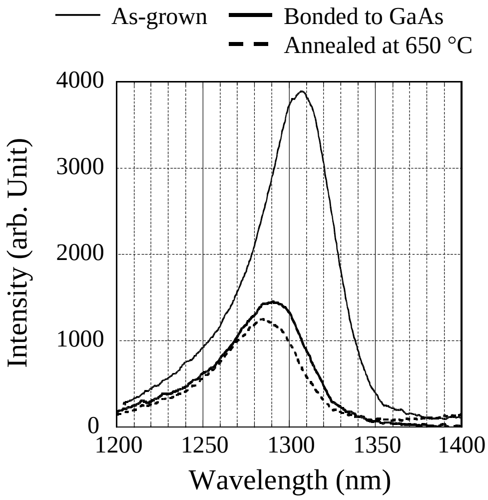
4. Wafer bonding of (311)B InP and (100) GaAs

Figure 4 shows a cross-section image of the active region bonded onto a plain GaAs substrate taken by transmission electron microscope (TEM). No dislocations can be observed in the structure. A high-resolution TEM observation was also performed, and atomic bonding between these two materials was confirmed.

Figure 5 compares PL spectra from the active region grown on (311)B InP. After the bonding, the PL intensity decreased to less than half of that of the as-grown active region, and the emission peak blue-shifted by about 20 nm. Since these changes are also visible on the annealed active region, they are due to annealing during the bonding at a temperature 100°C higher than the growth temperature. It is assumed that there was interface mixing occurring at well/barrier interfaces during the annealing process [11]. These PL changes can be suppressed by changing barrier material to InP.

5. VCSEL performance

Figure 6 shows the polarization-dependent lasing characteristics of the VCSEL measured by an optical spectrum analyser. The VCSEL was optically pumped by a 980nm edge-emitting laser via free-space optics. Since the pump laser was TE polarized, the VCSEL polarization behavior was examined by aligning the pump laser polarization axis to one of the two orthogonal crystal axes of the VCSEL.



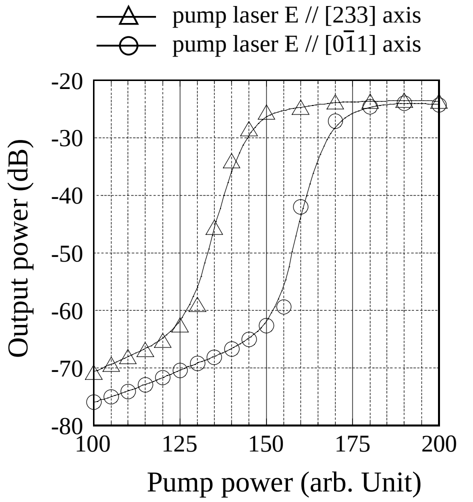


Figure 5. PL spectra from active region Figure 6. Output power of VCSEL

The power extinction ratio between the two axes was 37 dB at the largest point. The VCSEL had no index guiding structure, and showed a single mode spectrum at 1273 nm with side-mode suppression ratio of 41 dB.

6. Conclusion

We have fabricated a LW VCSEL which utilized a (311)B InP-based active region instead of a conventional (100) InP-based active region, in order to achieve polarization control. MOCVD growth on (311)B InP showed distinctive properties due to the step-like feature of this surface. TEM observations showed no signs of defects in the active region wafer-bonded to (100) GaAs, while PL showed its intensity degradation due to annealing during the bonding process. The active region was double-bonded to (100) GaAs-based DBRs to form a VCSEL. A power extinction ratio between the two orthogonal axes of the VCSEL was 37 dB at its maximum point, showing polarization dependent behavior.

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