1.3 μm wavelength vertical cavity surface emitting laser fabricated by orientation-mismatched wafer bonding: A prospect for polarization control

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We propose and demonstrate a long-wavelength vertical cavity surface emitting laser (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 was polarized with a power extinction ratio of 31 dB. [DOI: 10.1063/1.1568162]

Long-wavelength vertical cavity surface emitting lasers (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. This leads to random polarization switching,[1] which causes problems such as an increased relative intensity noise.[2,3] To make polarization fixed to one axis of the VCSEL, there has to be some asymmetry introduced in its structure. Previous approaches include techniques such as fabricating in asymmetric shape[4–6] and providing asymmetric mechanical force.[7–9] Also, it has been shown theoretically[10,11] and experimentally[12,13] that strained multiquantum wells (MQWs) grown on an asymmetric crystal plane have an asymmetric in-plane gain, which leads to a fixed in-plane polarization axis. These polarization control schemes have been mainly studied on short-wavelength VCSELs, but relatively little has been done on long-wavelength VCSELs.

To fabricate long-wavelength VCSELs, various techniques have been investigated.[14–16] Among them, wafer bonding is a technique that has enabled long-wavelength VCSELs to operate continuously up to 115 °C.[17,18] With this technique, we can combine two dissimilar materials without degrading their quality.[19] Therefore, it is possible for a wafer-bonded VCSEL to have an InP-based active region and GaAs-based distributed Bragg reflectors (DBRs). Also, with wafer bonding, we have the freedom to choose the crystal planes of active region and DBRs independently. Here, we present the fabrication of a wafer-bonded long-wavelength VCSEL which utilizes a (311)B InP-based active region and (100) GaAs-based DBRs and investigate its polarization properties.

Figure 1 is a schematic drawing of the epitaxial layer structure of our VCSEL. 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, since (311)B InP and (100) GaAs have different symmetries, effective lattice mismatch at the interface would be different between two orthogonal in-plane axes.[19] 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 (311)B InP was chosen due to its feasibility of growth and wafer-bonding processing.

The 2.5 λ-cavity active region was grown by metalorganic chemical vapor deposition (MOCVD) using trimethylindium, trimethylgallium, tertiarybutylarsine, and tertiarybutylphosphine as the source materials. It consisted of three identical sets of MQWs and each set consisted of five 50 Å thick InGaAsP wells with 0.15% compressive strain and four 100 Å thick InP barriers. DBRs consisted of pairs of GaAs and $Al_{0.9}Ga_{0.1}As$, and were grown by conventional solid-source molecular beam epitaxy. The top DBR consisted of 23.5 pairs, while the bottom DBR had 30 pairs. The VCSEL was designed to be optically pumped,[17] hence, all structures were grown undoped.

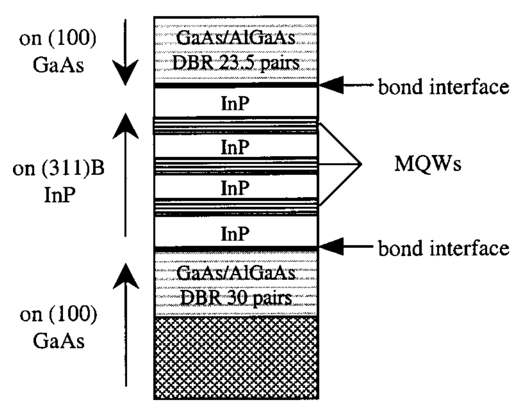

FIG. 1. Cross-sectional schematic drawing of the VCSEL epitaxial structure.

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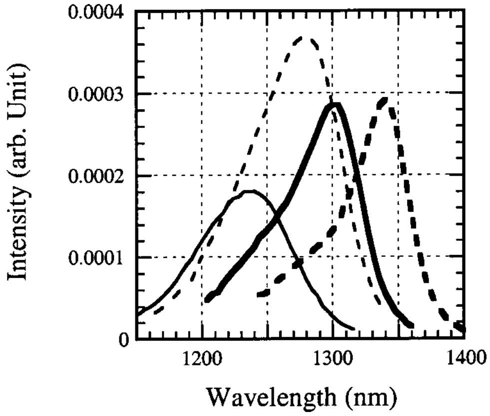

FIG. 2. PL spectra from MQWs grown on (311)B (solid lines) and (100) (broken lines) substrates, under low-migration (thick lines) and high-migration (thin lines) conditions.

The (311)B surface has the steplike feature, and phenomena such as In atom accumulation at those steps during growth have been reported.[13] Therefore, it is important to perform growth under low-migration conditions such as low temperature and high V/III ratio. Figure 2 compares photoluminescence (PL) spectra from MQWs grown under different conditions. As can be seen, when grown under high-migration conditions at which the growth temperature (*Tg*) is 615 °C and the V/III ratio is 50, the PL intensity degraded to half of that from MQWs grown on (100) substrate at the same time.

The PL intensity and shape is comparable to that of (100) when grown under low-migration conditions at which *Tg* is 550 °C and V/III ratio is 100. However, a notable fact is a blueshift of the emission peak by about 40 nm. By comparing compositions of bulk InGaAsP materials grown on (311)B and (100), it was found that this blueshift 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.[12] 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.

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 with their $[0\bar{1}1]$ cleaved facets aligned, and annealed at 650 °C with an applied pressure of about 1 MPa. 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. To avoid having any unintentional geometric asymmetry, there was no patterning etching performed after bonding, hence, the VCSEL was tested as bonded.

Figure 3 shows a cross section image of the active region bonded onto a plain GaAs substrate taken by transmission electron microscope. No dislocations can be observed in the structure. An atomic bonding between these two materials was observed in a high-resolution image.

Figure 4 compares PL spectra from the active region as grown on (311)B InP and bonded onto GaAs substrate. PL intensity after the bonding is as good as that of as grown,

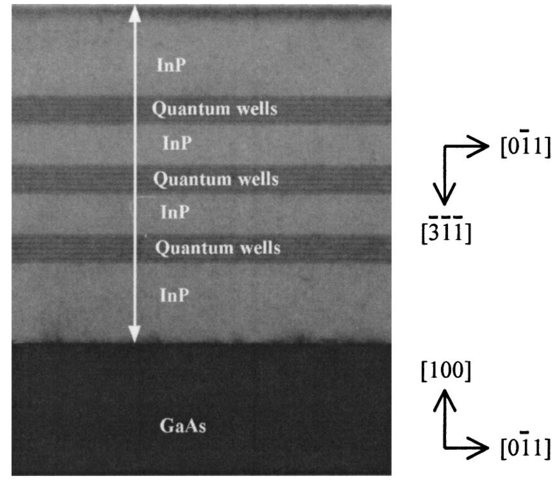

FIG. 3. Cross-sectional transmission electron micrograph of the active region bonded onto the GaAs substrate. Total thickness of the active region (indicated by an arrow) is about 1 μm.

even though bonding was performed at a temperature 100 °C higher than *Tg*. In an experiment with InGaAsP as the barrier material, the PL property degraded after the bonding, presumably due to interface mixing occurring at the well/barrier interfaces during the annealing process.[20] This problem was solved by employing the InP barriers.

The VCSEL was optically pumped by a 980 nm edge-emitting laser which was linearly transverse electric (TE) polarized. From an absorption measurement, it was predicted that the VCSEL would have maximum and minimum gain axes at $[\bar{2}33]$ and $[0\bar{1}1]$, respectively.[20] Therefore, the VCSEL was positioned in a way that its $[\bar{2}33]$ and $[0\bar{1}1]$ axes are both 45° off from the TE axis of the pump laser, so that there was no pumping preference between them. Measurements were also done by positioning the VCSEL differently to confirm that $[\bar{2}33]$ was the maximum gain axis.

Figure 5 shows the polarization-resolved output power plot of the VCSEL. As shown in the inset, it lased single mode up to 2 P_{th}, where P_{th} is a threshold pump power. The power plotted in Fig. 5 is that of the strongest mode measured by an optical spectrum analyzer at 0.1 nm resolution. The VCSEL showed polarization-controlled behavior with an extinction ratio of 31 dB. However, in some regions, polarization switching or decrease of extinction ratio was ob-

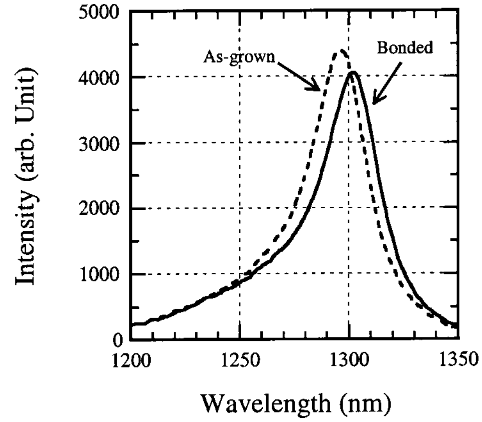

FIG. 4. PL spectra from the active region. Broken line: As grown on (311)B InP, solid line: Bonded onto GaAs substrate.

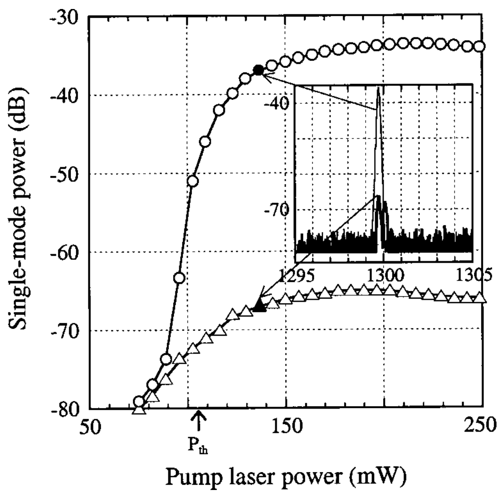

FIG. 5. Polarization-resolved single-mode output power of the VCSEL vs pump laser power. The polarizer was at $[\bar{2}33]$ axis (circle) or at $[0\bar{1}\bar{1}]$ axis (triangle) of the VCSEL. Inset is spectra at 137 mW pump power (filled marks).

served when pumped at high power past the rollover point. Therefore, it can be said that the stress from asymmetric interfaces is effective in controlling polarization in a practical range, but not strong enough for perfect control. Since the maximum gain axis is the same as that by crystallographic asymmetry of (311)B,[11–13] we can expect to improve the polarization behavior by adding large strain in the MQWs.

In conclusion, we have fabricated a long-wavelength 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 steplike feature of this surface. The active region maintained good PL properties after it was wafer bonded to (100) GaAs. A VCSEL was formed by double bonding the active region to (100) GaAs-based DBRs. It showed polarization-controlled behavior with maximum/minimum power extinction ratio of 31 dB between its two orthogonal axes. This behavior, however, deteriorated at high power operation in some measurement points. These results suggest that the bonded interfaces between (311)B InP and (100) GaAs provide asymmetric stress effective to control in-plane polarization, but the stress is not large enough. We can add strain in MQWs so that more complete polarization control can be expected using this technique.

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[1] C. J. Chang-Hasnain, J. P. Harbison, G. Hasnain, A. C. Von Lehmen, L. T. Florez, and N. G. Stoffel, IEEE J. Quantum Electron. **27**, 1402 (1991).
[2] F. Koyama, K. Morito, and K. Iga, IEEE J. Quantum Electron. **27**, 1410 (1991).
[3] T. Mukaihara, N. Ohnoki, Y. Hayashi, N. Hatori, F. Koyama, and K. Iga, IEEE Photonics Technol. Lett. **7**, 1113 (1995).
[4] T. Mukaihara, F. Koyama, and K. Iga, IEEE Photonics Technol. Lett. **5**, 133 (1993).
[5] K. D. Choquette and R. E. Leibenguth, IEEE Photonics Technol. Lett. **6**, 40 (1994).
[6] T. Yoshikawa, T. Kawakami, H. Saito, H. Kosaka, M. Kajita, K. Kurihara, Y. Sugimoto, and K. Kasahara, IEEE J. Quantum Electron. **34**, 1009 (1998).
[7] A. K. Jansen van Doorn, M. P. van Exter, and J. P. Woerdman, Appl. Phys. Lett. **69**, 1041 (1996).
[8] A. K. Dutta and K. Kasahara, Solid-State Electron. **42**, 907 (1998).
[9] F. M. di Sopra, M. Brunner, and R. Hovel, IEEE Photonics Technol. Lett. **14**, 1304 (2002).
[10] D. Sun and E. Towe, Jpn. J. Appl. Phys., Part 1 **33**, 702 (1994).
[11] T. Ohtoshi, T. Kuroda, A. Niwa, and S. Tsuji, Appl. Phys. Lett. **65**, 1886 (1994).
[12] M. Takahashi, P. O. Vaccaro, T. Watanabe, T. Mukaihara, F. Koyama, and K. Iga, Jpn. J. Appl. Phys., Part 1 **35**, 6102 (1996).
[13] N. Nishiyama, M. Arai, S. Shinada, M. Azuchi, T. Miyamoto, F. Koyama, and K. Iga, IEEE J. Sel. Top. Quantum Electron. **7**, 242 (2001).
[14] E. Hall, G. Almuneau, J. K. Kim, O. Sjolund, H. Kroemer, and L. A. Coldren, Electron. Lett. **35**, 1337 (1999).
[15] W. Yuen, G. S. Li, R. F. Nabiev, J. Boucart, P. Kner, R. J. Stone, D. Zhang, M. Beaudoin, T. Zheng, C. He, K. Yu, M. Jansen, D. P. Worland, and C. J. Chang-Hasnain, Electron. Lett. **36**, 1121 (2000).
[16] M. Fischer, M. Reinhardt, and A. Forchel, IEEE Photonics Technol. Lett. **12**, 1313 (2000).
[17] V. Jayaraman, T. J. Goodnough, T. L. Beam, F. M. Ahedo, and R. A. Maurice, IEEE Photonics Technol. Lett. **12**, 1595 (2000).
[18] A. Karim, P. Abraham, D. Lofgreen, Y.-J. Chiu, J. Piprek, and J. E. Bowers, Appl. Phys. Lett. **78**, 2632 (2001).
[19] Y. Okuno, K. Uomi, M. Aoki, and T. Tsuchiya, IEEE J. Quantum Electron. **33**, 959 (1997).
[20] Y. L. Okuno, J. Geske, Y.-J. Chiu, S. P. DenBaars, and J. E. Bowers, *Proc. IEEE 18th Int. Semiconductor Laser Conf., Garmishch, Germany* (IEEE, Piscataway, NJ, 2002), p. 17.