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1.1 mW Single-Mode Output Power of All-Monolithic 1.3 μm InAlGaAs/InP Vertical Cavity Surface Emitting Lasers Grown by Metal Organic Chemical Vapor Deposition

Mi-Ran PARK*, O-Kyun KWON, Byueng-Su YOO¹, Ki-Hwang LEE¹, Hyun-Woo SONG, Won-Seok HAN, Sang-Hee Ko PARK, Jong-Hee KIM and Seong-Joo PARK¹

Basic Research Laboratory, Electronics and Telecommunications Research Institute,
161 Gajeong-dong, Yuseong-gu, Daejeon, 305-350 Korea

¹RayCan Co., Ltd., 52 Oun-dong, Yuseong-gu, Daejeon, 305-333 Korea

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We present all-monolithic InAlGaAs/InP vertical cavity surface emitting lasers (VCSELs) emitting wavelength of 1.3 μm grown by metal organic chemical vapor deposition (MOCVD). The devices with tunnel junction (TJ) and the air-gap aperture showed the performances as high as output power of 1.1 mW and as low as threshold current of 1.9 mA operating in single-mode at room temperature. We obtained the emitting transverse wavelength of 1333.1 nm with side mode suppression ratio (SMSR) of 40 dB, the continuous wave (CW) operation of temperature over 80°C, and modulation bandwidth exceeding 2.5 Gbit/s. [DOI: 10.1143/JJAP.44.L101]

KEYWORDS: vertical cavity surface emitting laser (VCSEL), InP, InAlGaAs, metal organic chemical vapor deposition (MOCVD), monolithic, long wavelength

Vertical cavity surface emitting lasers (VCSELs) have been of great interests as alternatives of edge emitting lasers because of their inherent advantages such as low manufacturing cost, on-wafer testing, and ease of coupling a circular beam to a fibre. All these features hold for 1.3 μm VCSELs and make them useful for the applications of optical fibre communication systems including coarse wavelength division multiplexing and the metro and access networks. Accordingly, many research groups have proposed GaAs-based,^{1,2)} InP-based,^{3–5)} and hybrid-type structures^{6,7)} for the development of 1.3 μm VCSELs. Among these approaches, the hybrid-type structures^{6,7)} involving InP-based active materials combined with binary distributed Bragg reflectors (DBRs) or dielectric-based DBR mirrors of the large thermal conductivity and high reflectivity have provided high light output power and high temperature operation. However, these approaches need two or more complicated processes and lead to an increase in the manufacturing cost and a decrease in the reliability. On the other hand, monolithically grown GaInNAs-based material schemes^{1,2)} offer good lasing performance as well as the simplicity of single epitaxial growth without any additional processes, while they have the reliability problems of metastable materials and the limit of wavelength below 1.3 μm . Recently, we first demonstrated all monolithic InAlGaAs/InP VCSELs by using metal organic chemical vapor deposition (MOCVD).^{3,4)} These approaches, utilizing not only InAlGaAs quantum wells (QWs) with lattice matched DBRs but also monolithically epitaxial growth by MOCVD technology, have shown the potential for mass-production, high reliability, and low cost wafer-scale fabrication in 1.3–1.5 μm waveband VCSELs. The performance, however, still need to be much more improved since it requires stable uncooled continuous wave (CW) operation over a wide range of temperature providing high enough power to overcome all system loss through data transmission.

In this work, we have designed, fabricated, and charac-

terized all-monolithic 1.3 μm VCSELs based on tunnel junction (TJ) and the air-gap aperture. The whole structure in the thickness of about 20 μm epitaxial layers was successfully monolithically grown by MOCVD. Our investigations showed that the devices revealed high performances with high single-mode output power, low threshold current, and CW operations of temperature over 80°C, and also operated with perfectly open eye diagrams at the modulation speed of 2.5 Gbit/s.

The structure of a 1.3 μm VCSEL is shown in Fig. 1. All layers of 1.3 μm VCSELs were monolithically grown by one-step and vertical-flow low-pressure MOCVD technique on InP substrate. The 0.5- λ thick active region consisted of 7 pairs of strain compensated (SC) InAlGaAs QWs with a photoluminescence peak at 1300 nm. The C-doped InAlAs TJ was positioned at a standing-wave node of the cavity mode between the top n-InP layer and active region for reducing a absorption loss. The top DBRs and the bottom DBRs were grown as 33 pairs and 50 pairs of InAlAs/InAlGaAs scheme, respectively. The undoped-InAlGaAs/InAlAs DBRs resulted in the reduced free carrier absorption loss.

The intra-cavity structure with two-step mesa was formed by reactive ion etching with Ar-Cl₂ and CH₄-H₂ mixed gases. The structure of a double intra-cavity contact with the 2.0- λ thick n-InP cladding layers allows the high efficient heat spreading and a low series resistance to overcome inherent low thermal conductivity and high voltage drop in quaternary DBRs. Current confinement was provided by an air-gap aperture formed in the selective wet etched 0.5- λ thick InAlGaAs active layer. For the measurement of electrical and optical characteristics of VCSELs, the devices were die-bonded, and then mounted on TO-can. The temperature dependence of the light–current–voltage (L–I–V) was conducted inside the temperature-controlled chamber. The fibre-pigtailed devices were used for the measurement of eye diagrams.

Figure 2 shows CW L–I–V characteristic of a monolithic InAlGaAs VCSEL with 12 μm in aperture diameter at room

*E-mail address: miranp@etri.re.kr

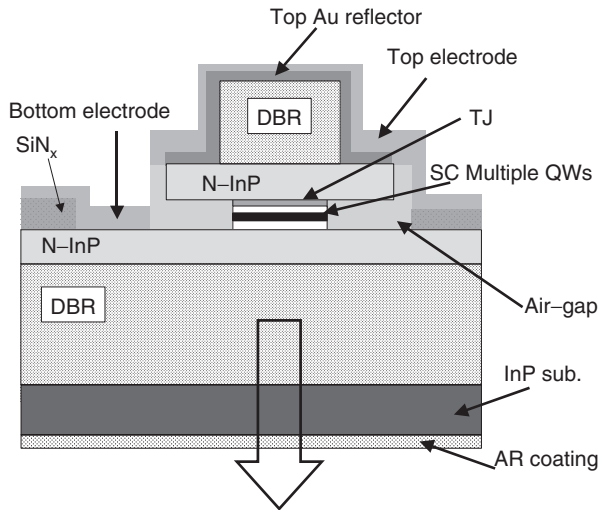


Fig. 1. Schematic diagram of all-monolithic VCSELs emitting in 1.3 μm wavelength.

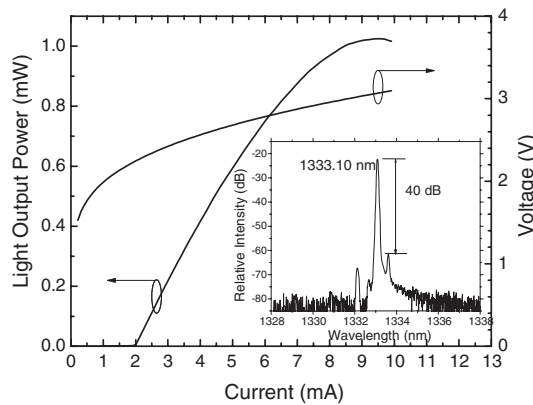


Fig. 2. Continuous wave L-I-V characteristics of a 1.3 μm monolithic VCSEL with aperture diameter of 12 μm at room temperature. Inset shows an emission spectrum at 8 mA.

temperature. The threshold current (I_{th}), threshold voltage (V_{th}), and differential resistance at V_{th} were 1.9 mA, 2.2 V, and $\sim 150 \Omega$, respectively. The maximum output power was 1.1 mW at 9 mA. The high slope efficiency of 0.21 W/A was achieved near I_{th} . We observed an emission wavelength of 1333.1 nm at a bias current of 8 mA at room temperature, as shown in the inset of Fig. 2. Its lasing transverse-mode was in single-mode operation with the side mode suppression ratio (SMSR) of more than 40 dB, which maintained in the full operating current range. The temperature dependence of the threshold current and output power for VCSELs was shown in Fig. 3. We obtained CW operation of the devices with temperature ranging from -10°C to 80°C . The maximum CW output power was 1.1 mW at 20°C and 0.2 mW at 70°C , respectively. Figure 4 shows the far-field profile of the single-mode device at a current of 8 mA in x - and y -axes. We could clearly see circularly symmetric operation of fundamental transverse mode with a full-width half-maximum (FWHM) divergence angle of 9° . It is very small as compared to that of edge emitting lasers and results in ease coupling to a fibre. A FWHM divergence angle remained under 9° up to a bias current at the peak output

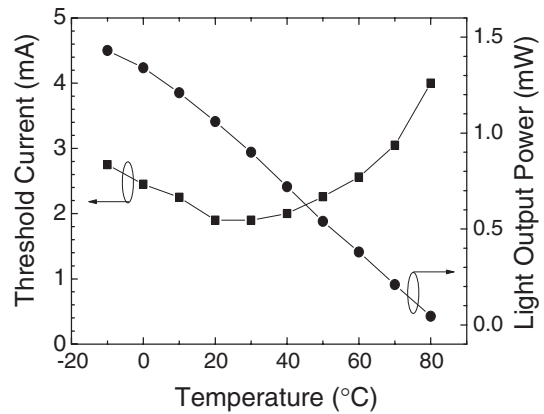


Fig. 3. Threshold current and optical power versus temperature.

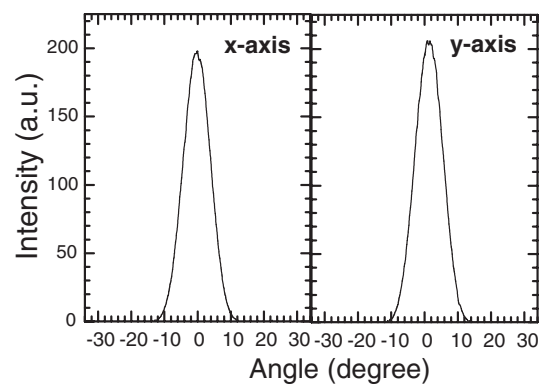


Fig. 4. Beam divergence angle at 8 mA.

power.

The fibre-coupled single mode VCSEL module was directly modulated at a speed of 1.25 Gbit/s and 2.5 Gbit/s. The back-to-back signal shows opening in the eye diagrams as shown in Figs. 5(a) and 5(b). Pseudorandom-bit sequence with $2^{23} - 1$ word lengths were imposed by using a bias tee. The driving current and the peak-to-peak voltage were 7.0 mA and 0.8 V, respectively. The extinction ratios were measured by 9.1 dB at a speed of 1.25 Gbit/s and 8.8 dB at 2.5 Gbit/s. We obtained clearly opened eye pattern passing the standard device mask test in the modulation speed of both 1.25 Gbit/s and 2.5 Gbit/s, as shown in Figs. 5(a) and 5(b). We believed that these high performances were attributed to the high gain SC InAlGaAs QWs, low absorption loss in undoped DBRs and efficient heat spreading through 2.0λ thick n-InP cladding layers. Consequently, we expect to considerably improve properties of the device by steering a thickness and optical position of aperture, and high temperature characteristics by the gain offset optimization.

We successfully demonstrated all-monolithic single mode 1.3 μm VCSELs with output power of 1.1 mW, a SMSR of 40 dB, a FWHM divergence angle of 9° , CW operation over 80°C , and open 2.5 Gbit/s eye diagram passing the standard device mask. To the best of our knowledge, our results represent the best performance published in the literature so far for all monolithic 1.3 μm InAlGaAs/InP VCSELs with InAlGaAs DBRs grown by MOCVD. These results indicated

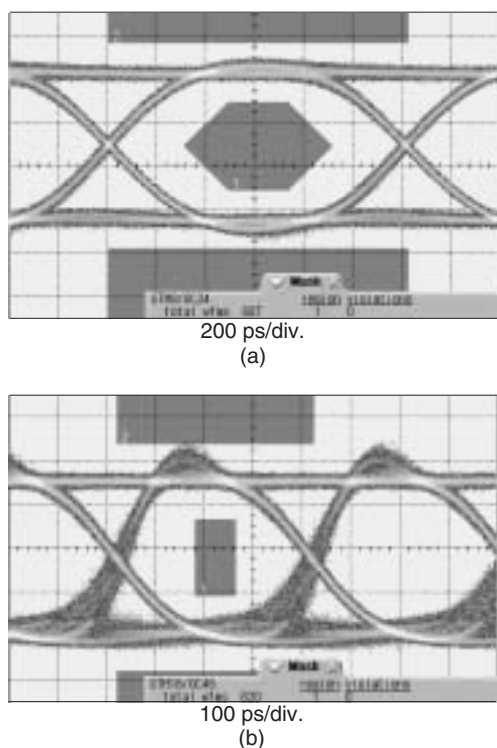


Fig. 5. (a) 1.25 Gbit/s and (b) 2.5 Gbit/s eye diagrams of a VCSEL connected back-to-back with a mask.

that allmonolithic InAlGaAs/InP VCSELs were good candidates in 1.3 μm wavelength for the applications of optical fibre communication systems including the metro and access networks.

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