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1.5-μm Long-Wavelengh MQW Laser on a Si Substrate

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Room-temperature cw-operation of an InGaAs/InGaAsP multiple-quantum-well (MQW) laser diode on a Si substrate is reported. The MQW laser emits at 1.54 μm wavelength and exhibits no degradation after over 1,000 hours of operation. Employing a hybrid organometallic vapor phase epitaxy/vapor mixing epitaxy method and a layer structure for improving crystalline quality, high-quality MQW layers were obtained. Stable longitudinal mode spectrum demonstrates the effectiveness of the MQW active layer and results in a low measured intensity noise.

1. INTRODUCTION

A particularly attractive application of the III-V/Si structure is optoelectronics integrated circuits (OEICs) of III-V optical devices and Si-LSI. A laser diode (LD) on a Si substrate is a key device for developing viable III-V/Si OEICs.

Most of the previous work on LDs employing the III-V/Si system has focused on GaAs LDs on Si. High-performance LDs have been developed despite a high lattice mismatch of about 4%.[1,2] However, rapid degradation has been observed in GaAs LDs on Si.[3] This problem results from high dislocation density > 10^7 cm^{-2} and high residual stress > 10^9 dyn/cm^2 due to large lattice mismatch and different thermal expansion coefficients between GaAs films and Si substrates. Recently, Razeghi et al. have reported the room-temperature operation of InP-based LDs emitting at 1.3 μm on a Si substrate.[4] Rapid degradation does not occur in these LDs, despite a higher lattice mismatch of about 8%, but gradual degradation sets in after several hours of operation. The authors have been studying ways to improve the performance and lifetime of InP-based LDs on Si.[5] InP-based lasers are particularly important for optical fiber communications and generally offer high resistance to degradation compared with GaAs-based lasers.

In this paper, we describe a multiple-quantum-well (MQW) LD on a Si substrate that emits at 1.54 μm wavelength and exhibits no degradation during over 1,000 hours of room-temperature cw-operation. Employing a hybrid organometallic vapor phase epitaxy (OMVPE)/vapor mixing epitaxy (VME) method and a specific layer structure, high-quality InGaAs/InGaAsP MQW layers were obtained. A threshold current as low as 55 mA has been measured for a ridge waveguide LD with 6-μm stripe width and 300-μm cavity length. Stable longitudinal mode spectrum demonstrates the effectiveness of the MQW active layer and results in a low measured intensity noise.

2. HIGH QUALITY InP GROWTH ON Si

The layer structure for providing InP quality enhanced consists of a 13-μm layer of n-InP, a strained-layer superlattice (SLS) consisting of five alternating layers of InP (20 nm) and strained InGaAsP (40 nm), and a 2–μm GaAs buffer layer on a Si(001) substrate. First, the GaAs buffer layer and InGaAsP/InP SLS were grown by OMVPE. Then the 13-μm Se-doped InP layer is grown by VME using thermal cycle growth.[6] Employing VME, a high-quality InP layer can be grown with a higher growth rate of about 20 μm/h than by using conventional OMVPE methods.[7] Employing this hybrid method and this layer structure, a high-quality InP layer with a full width at half maximum (FWHM) of X-ray rocking curve of 110 arcsec, a dislocation density lower than 10^7 cm^{-2}, and a low residual stress of $2x10^8$ dyn/cm^2 was obtained. This 13-μm-thick InP exhibited no cracks, as sometimes appear in thick GaAs on Si. This is attributed to the lower residual stress of this structure compared with GaAs on Si,

which is over 10^9 dyn/cm^2.[8] Details of growth procedure and layer structure have been reported in References 5 and 9.

3. MQW LASERS ON Si

The separated confinement heterostructure was grown by OMVPE, and consists of (i) a 100-nm InGaAsP (λ=1.3 μm) confinement layer, (ii) six pairs of 7.5-nm InGaAs (λ=1.65 μm) well and 10-nm InGaAsP (λ=1.3 μm) barrier layer, (iii) a 100-nm InGaAsP (λ=1.3μm) confinement layer, (iv) a 1.2-μm zinc-doped InP cladding layer, and (v) a 0.2-μm zinc-doped InGaAs (λ=1.65 μm) cap layer.

Ridge waveguide LDs were fabricated by wet etching. A schematic diagram of an InGaAs/InGaAsP MQW ridge waveguide LD on a Si substrate is shown in Fig.1. The stripe width and cavity length are 6 μm and 300 μm, respectively. SiO_2 was deposited to a thickness of 0.2 μm for the insulating layer. Both n and p contacts were formed on the epitaxial layer side, a requirement for application to planar OEICs. The ohmic contacts for p and n electrodes are alloyed Au-Zn-Ni and Au-Ge-Ni, respectively. The Si substrate is lapped down to 60 μm and then cleaved into LD-sized chips (300 μm x 300μm). The LDs were mounted junction up on heat sinks with Au-Sn solder.

Figure 2(a) shows light-current characteristics of an MQW LD on Si. The threshold current was as low as 55 mA and differential quantum efficiency was 0.1 W/A per facet in cw-operation at room temperature. As shown in Fig. 2(b), a stable single mode spectrum around 1.54-μm wavelength with a high mode suppression ratio of about 20 dB is obtained. It can be attributed to the effect of the MQW active layer. Narrow spontaneous emission spectra of MQW LDs should result in the single longitudinal mode with high mode suppression ratio. To our knowledge, this is the first successful fabrication of an MQW laser operating in the 1.5-μm wavelength region on a Si substrate.

The MQW LDs on Si also exhibit low measured intensity noise. Figure 3 shows a relative intensity noise (RIN) of an MQW LD on Si as a function of the injection current. A RIN of -137 dB/Hz at 400 MHz bears comparison with conventional LDs on InP. This low measured intensity noise is due to the stability of the longitudinal mode spectrum for MQW LD on Si, as shown in Fig. 2(b).

Results of a preliminary cw aging test at room temperature are shown in Fig. 4. The aging test was performed under cw-operation at room temperature with a constant output power of 2 mW per facet. An MQW LD on Si showed no increase in driving current, that is, no degradation after over 1,000 hours of operation. We think this phenomena of decreasing driving current is probably due to annealing by the operation of the laser as is observed in conventional LDs,[10] but the details will be investigated. We believe that this is the first stable operation of a III-V LD on Si substrate. The new MQW LDs on Si have two advantages over other III-V LDs on Si that has

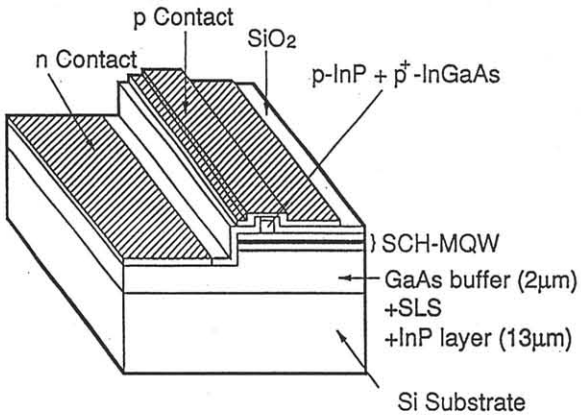

Fig.1 Schematic diagram of an InGaAs/ InGaAsP MQW ridge waveguide LD on a Si substrate.

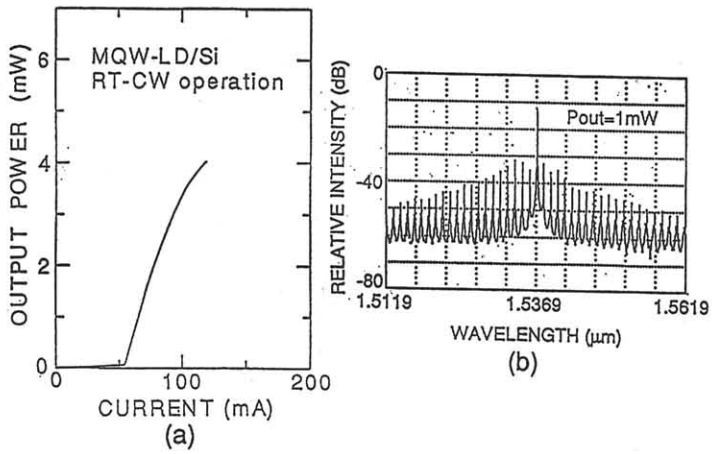

Fig.2 (a)Light-current characteristics and (b) spectrum of an MQW LD on Si.

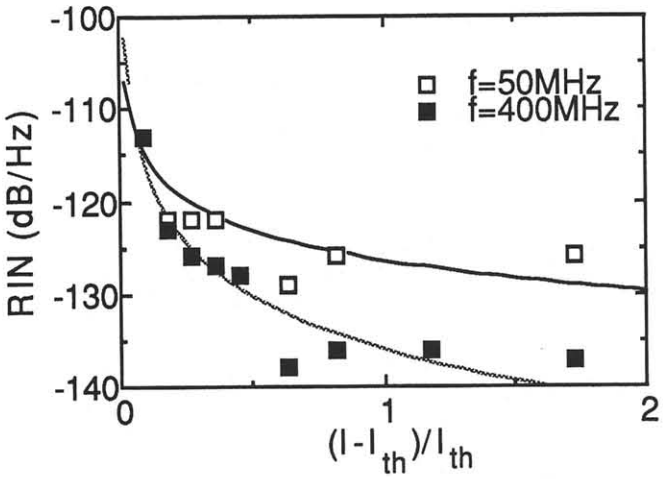

Fig.3 Relative intensity noise of an MQW LD on Si as a function of the injection current.

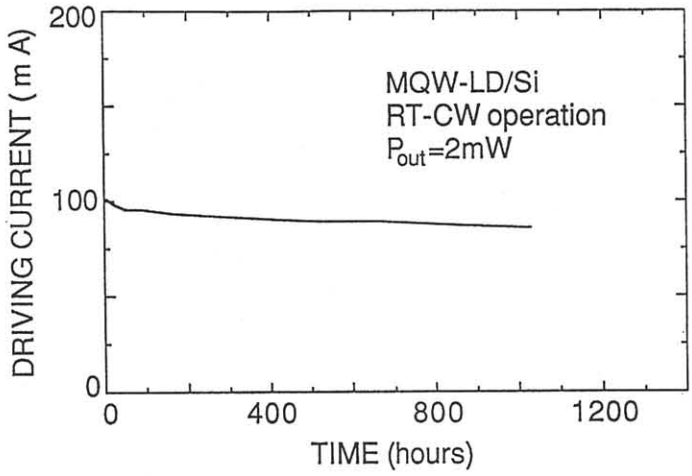

Fig. 4 Results of a preliminary aging test of an MQW LD on Si at room temperature with a constant light output power of 2 mW per facet.

been reported. First is that the crystalline quality is higher than those of other LDs on Si; this means, lower dislocation density, narrower FWHM of X-ray rocking curve, and lower residual stress. Second, our device exhibits longer lasing wavelength than other LDs on Si; that is, lower energy of recombination. These features should work against the multiplication of dark line defects and prolong the laser life. These advantages make the long-wavelength InP-based LD on Si the most promising device available for use as a light source in III-V/Si OEICs.

4. CONCLUSION

An MQW LD on Si that emits at 1.54 μm wavelength and exhibits no degradation after over 1,000 hours of room-temperature cw-operation has been reported. Employing a hybrid OMVPE/VME method and a specific layer structure, high-quality InGaAs/InGaAsP MQW layers were obtained. A threshold current as low as 55 mA has been measured for a ridge waveguide LD with 6-μm stripe width and 300-μm cavity length. Stable longitudinal mode spectrum with a high mode suppression ratio of 20 dB demonstrates the effectiveness of the MQW active layer and results in a low RIN of -137 dB/Hz. These results demonstrate the high quality of the new MQW laser structure on Si and suggest the potential of OEICs using InP-based optical devices and Si-LSI.

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