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Invited

InP-Based Optical Devices on Si Substrates

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High-quality InGaAs/InGaAsP multiple quantum well (MQW) layers on Si. are obtained by employing a hybrid organometallic vapor phase epitaxy/vapor mixing epitaxy method and a layer structure for improving crystalline quality. The laser active layers on Si have an excellent optical property comparable to the active layers on InP despite a high dislocation density of $10^7 cm^{-2}$. The MQW laser emits at a 1.54 μm wavelength and exhibited no degradation after over 8,000 hours of room-temperature cw operation.

Introduction

A particularly attractive application of the III-V/Si structure is the optoelectronic integrated circuit (OEIC) of III-V optical devices and Si-LSIs. 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 the high lattice mismatch and different thermal expansion coefficients between GaAs films and Si substrates. On the other hand, Razeghi, et al., reported room-temperature operation of InP-based LDs emitting at 1.3 μm on 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. InP-based lasers at 1.5 μm wavelengths are particularly important for optical fiber communications and generally offer high resistance to degradation compared with GaAs-based lasers. It is difficult to grow InP on Si than to grow GaAs or GaP because of the larger lattice mismatch of about 8%. The most important point of this study is how to grow high-quality InP on Si substrates.

In this paper, we demonstrate a multiple quantum well (MQW) LD on a Si substrate that emits at a 1.54 μm wavelength and exhibited no degradation during over 8,000 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 are obtained. Laser active layers on Si have an excellent optical property comparable to active layers on InP despite a high dislocation density of 10^7 cm^{-2}.

High quality InP growth on Si

The layer structure for providing enhanced InP quality 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 are grown by OMVPE. The thickness of GaAs buffer layer is chosen for reduction of residual stress in InP layer.[5)] Then the 13-μm Se-doped InP layer is grown by VME using thermal cycle growth.[6)] This thick InP layer greatly improves the InP crystalline quality.[7)] A high-quality InP layer can be grown by VME with a growth rate that is about 20 μm/hs higher than the growth rate with conventional OMVPE methods.[8)] Employing this hybrid method and this layer structure, we obtained a high-quality InP layer with a full width at half maximum (FWHM) of the 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. 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.[9)] Details of the growth procedure and layer structure were reported in References 7 and 10.

The same layer structure grown by only the OMVPE method (OMVPE InP/Si) shows the same residual stress and dislocation density, but a higher FWHM (200 arcsec) than that of InP grown by the OMVPE/VME hybrid method (OMVPE/VME InP/Si). Figure 1 shows a comparison of the correlation between

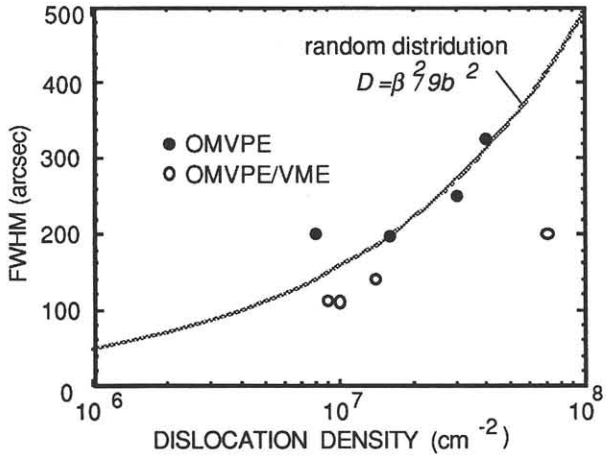

Fig.1. Comparison of correlation between dislocation density and full width at half maximum of the X-ray rocking curve of OMVPE InP/Si and OMVPE/VME InP/Si.

the dislocation density and FWHM of OMVPE InP/Si and OMVPE/VME InP/Si. The solid line in this figure shows calculated data when the distribution of dislocations is supposed to be random.[11] FWHM of OMVPE/VME InP/Si is lower than that of OMVPE InP/Si at the same dislocation density. Data for OMVPE InP/Si nearly coincides with the calculated data. This means that the dislocations in OMVPE InP/Si distribute randomly and that the dislocations in OMVPE/VME InP/Si do somewhat regularly. The regularity of dislocation distribution should form in thick InP growth by VME with the higher degree of equilibrium.

The optical properties of an InGaAsP DH on Si substrate depend largely on its dislocation density. A correlation between the dislocation density and relative photoluminescence (PL) peak intensity at room temperature of InGaAsP (λ=1.55μm) DHs on OMVPE/VME InP/Si and OMVPE InP/Si is shown in Fig. 2. The relative intensity is defined by normalizing the PL intensity of the DH on Si by that grown on InP substrate simultaneously. The solid line in this figure shows calculated data according to the reference 12. The PL intensity for OMVPE InP/Si nearly coincides with calculated data but the PL intensity for OMVPE/VME InP/Si is higher than that for OMVPE InP/Si and reaches

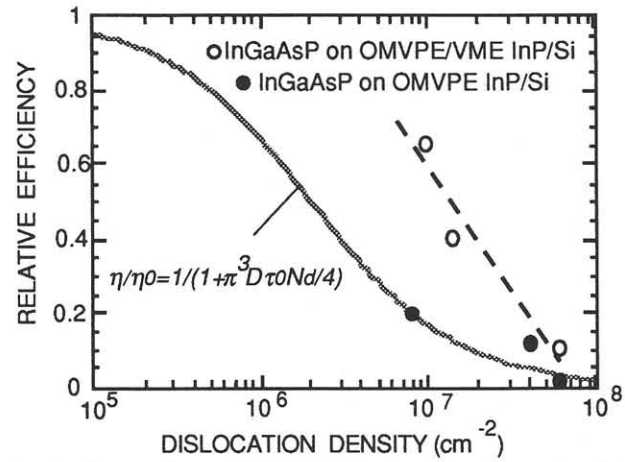

Fig.2. Correlation between dislocation density and relative photoluminescence intensity of InGaAsP DHs on Si substrates.

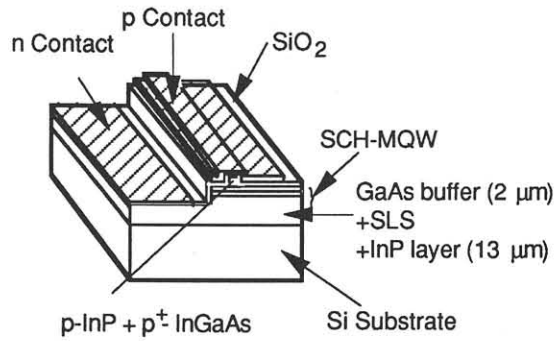

Fig.3. Schematic diagram of an InGaAs/InGaAsP MQW ridge waveguide LD on a Si substrate.

a value of 70%. This result indicates that the regularity of dislocation distribution observed in OMVPE/VME InP/Si has the effect of improving the optical property for DH on it. Therefore, DHs on Si with high PL intensity comparable to the PL intensity of DHs on InP can be obtained despite a high dislocation density of $10^7 cm^{-2}$.

MQW lasers on Si

Figure 3 shows a schematic diagram of an InGaAs/InGaAsP MQW ridge waveguide LD on a Si substrate. The separated confinement heterostructure MQW is 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) wells and 10-nm InGaAsP (λ=1.3 μm) barrier layers, (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) contact layer.

Ridge waveguide LDs are fabricated by wet etching. The stripe width and cavity length are 6 and 300 μm, respectively. Both n and p contacts are formed on the epitaxial layer side, a requirement for application to planar OEICs.

Figure 4(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. 4(b), a stable single mode spectrum

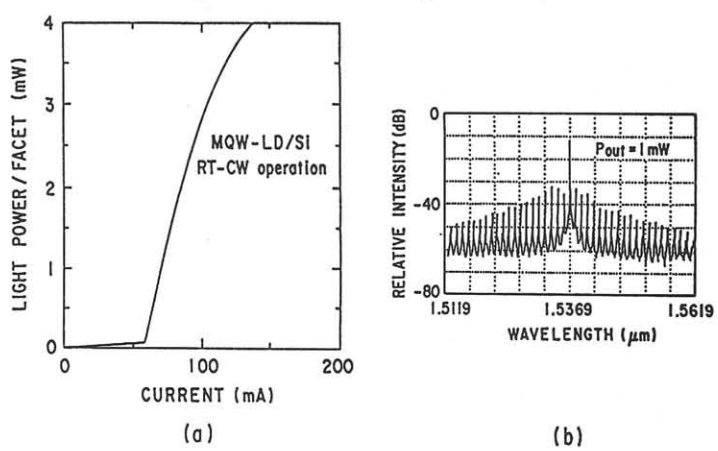

Fig.4. (a) Light-current characteristics and (b) the spectrum of an MQW LD on Si.

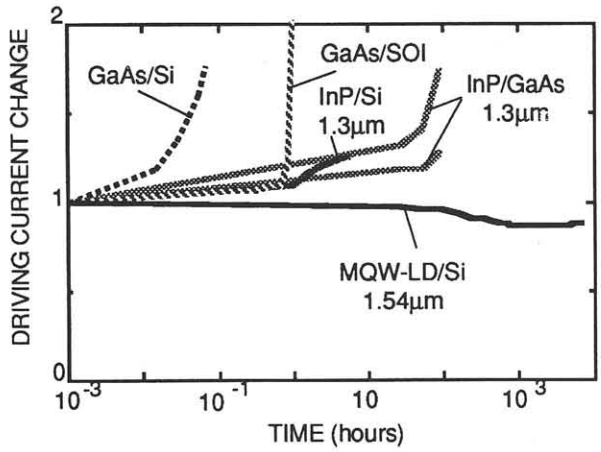

Fig.5. Results of aging test on the new MQW LD on Si and the other LDs on heteroepitaxial substrates that have been reported.

around a 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 a single longitudinal mode with a high mode suppression ratio.

Results of a preliminary cw aging test at room temperature are shown in Fig. 5. The aging test was performed at 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 8,000 hours of operation. Figure 5 also shows the comparison of the results of aging test for the new MQW LDs and the other LDs on heteroepitaxial substrates that have been reported.[4),13)-15)] It should be pointed out that the new MQW LD has no increase in driving current different from the others. The new MQW LDs on Si have two advantages over the other III-V LDs on Si. First, the crystalline quality is higher than those of other LDs on Si, this means lower dislocation density, narrower FWHM of the X-ray rocking curve, and lower residual stress. Second, our device exhibits a longer lasing wavelength than other LDs on Si; that is, lower recombination energy. These features should work against the multiplication of dark line defects and prolong laser life. These advantages make the long-wavelength InP-based LD on Si the most promising device for the light source in III-V/Si OEICs.

Conclusion

We have described an MQW LD on Si that emits at a 1.54 μm wavelength and exhibits no degradation after over 8,000 hours of room-temperature cw operation. We employed a hybrid OMVPE/VME method and a specific layer structure to obtain high-quality InGaAs/InGaAsP MQW layers. Laser active layers on Si have an excellent optical property comparable to the active layers on InP despite a high dislocation density of $10^7 cm^{-2}$. This results from the regularity of dislocation distribution that forms in InP growth by VME. These results demonstrate the high quality of the new MQW laser structure on Si and suggest the potential for OEICs using InP-based optical devices and Si-LSIs.

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