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Room temperature lasing of GaAs quantum wire vertical-cavity surface-emitting lasers grown on (775)*B* GaAs substrates by molecular beam epitaxy

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Abstract

Self-organized GaAs/$(GaAs)_4(AlAs)_2$ quantum wires (QWRs) grown on (775)*B*-oriented GaAs substrates by molecular beam epitaxy have been applied to an active region of vertical-cavity surface-emitting lasers (VCSELs). The (775)*B* GaAs QWR-VCSEL with an aperture diameter of 3 μm lased at a wavelength of 765 nm with a threshold current of 0.38 mA at room temperature. This is the first demonstration of laser operation of the QWR-VCSEL by current injection. The light output was linearly polarized in the direction parallel to the QWRs due to the optical anisotropy of the self-organized (775)*B* GaAs QWRs.

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1. Introduction

Recently, quantum wire (QWR) structures have been attracting much interest in device applications. QWR lasers are expected to have superior characteristics compared with conventional quantum well (QW) lasers, such as lower threshold current (I_{th}), higher differential gain, reduced temperature sensitivity of I_{th}, because of their large optical gain [1,2]. So far, we have reported high-density and highly uniform GaAs QWRs can be self-organized in a thin GaAs/$(GaAs)_m(AlAs)_n$ QW grown on (775)*B*-oriented GaAs substrates by molecular beam epitaxy (MBE) [3,4]. (Strictly speaking, the (775)*B* plane should be written as the $(57\bar{7})B$-oriented plane, which is 8.5°-off from $(11\bar{1})$ toward $(01\bar{1})$, but we call this plane as the (775)*B* plane for convenience.) GaAs layers grown on a (775)*B*-oriented GaAs substrate are regularly corrugated with a lateral period of a few 10 nm and a vertical amplitude of about 1.0 nm, while the AlAs surface is flat [5]. Hence, a GaAs/AlAs QW grown on the (775)*B* GaAs substrate has a regularly corrugated AlAs-on-GaAs upper interface and a flat GaAs-on-AlAs lower interface. These two different interfaces lead to lateral modulation of the QW thickness, and electrons and holes tend to accumulate in the thick part of the QW, resulting in formation of (775)*B* GaAs/AlAs QWR in a thin GaAs/AlAs QW when the thickness of the GaAs QW layer is less than 4 nm [3,4]. The (775)*B* QWRs show high-density ($2–8\times10^5$ QWRs/cm), good

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uniformity (full width at half maximum (FWHM) values of photoluminescence (PL) smaller than 20 meV at 12 K), and good one dimensionality (PL with strong polarization in the wire direction). Stripe-contact self-organized (775)*B* GaAs QWR lasers showed room temperature laser operation with the threshold current density of 2–3 kA/cm^2 under a pulsed current condition [6,7], indicating device-quality of the GaAs QWRs. In this case, however, Fabry–Pérot mirrors are only perpendicular to the QWRs direction, and QWR lasers cannot take advantage of their one-dimensional characteristics [8]. VCSELs can be considered as one of the most suitable laser application of the (775)*B* QWRs.

VCSELs have excellent characteristics such as low threshold current, single longitudinal mode operation, circular spot profile of light output and two-dimensional array capability. However, the direction of polarization of light output of VCSELs grown on (100) GaAs substrates often changes with increasing injection current due to their isotropic material gain and symmetric cavity structure [9–11]. In the case of high-speed data transmission with the use of VCSELs, polarization switching of light output may cause excess noise and increase bit-error rates [12,13]. In order to resolve this problem, many methods such as formation of rectangular mesa [14], birefringence in top mirrors [15] and using non-(100) substrates [16,17] have been attempted. Use of the (775)*B* QWRs in the active region of VCSELs is believed to be one of the best candidates to resolve the polarization instability problem because of their optical anisotropic gain. Recently, we demonstrated room temperature lasing of (775)*B* InGaAs QWR-VCSEL by optical pumping [18,19]. The light output was linearly polarized in the direction parallel to the QWRs direction and the polarization switching was not observed. In this study, we fabricated (775)*B* GaAs QWR-VCSELs and demonstrated room temperature laser operation of the QWR-VCSELs by current injection for the first time.

2. Device fabrication

Typical surface image, observed by atomic force microscopy (AFM), of a 3.2-nm-thick GaAs layer grown on the (775)*B* GaAs substrate at 660 °C by MBE is shown in Fig. 1. High substrate temperature (>640 °C) for growing a GaAs layer was necessary to form regular surface corrugation of a (775)*B* GaAs layer. Straight step edges along [011] direction and regular corrugation with a lateral period of about 20 nm and a vertical amplitude of 1.0 nm can be seen.

PL measurements were carried out at room temperature and 14 K for the (775)*B* GaAs/$(GaAs)_4(AlAs)_2$ QWRs by using an Ar-ion laser (514.5 nm) with an excitation power of 1.0 mW and a beam diameter of about 200 μm. PL spectra from the sample were observed by a monochromator and a photomultiplier. Fig. 2 shows room temperature PL spectra of the (775)*B* GaAs/$(GaAs)_4(AlAs)_2$ QWRs for the polarization parallel to QWRs ($I_{\|}$) and perpendicular to the QWRs ($I_{\perp}$). The FWHM value of the PL peak was 50 meV at room temperature (25 meV at 14 K). The polarization degree, P $[\equiv(I_{\|} - I_{\perp})/(I_{\|} + I_{\perp})]$, of the PL peaks from the QWRs was 0.11 at room temperature ($P = 0.11$ at 14 K, also).

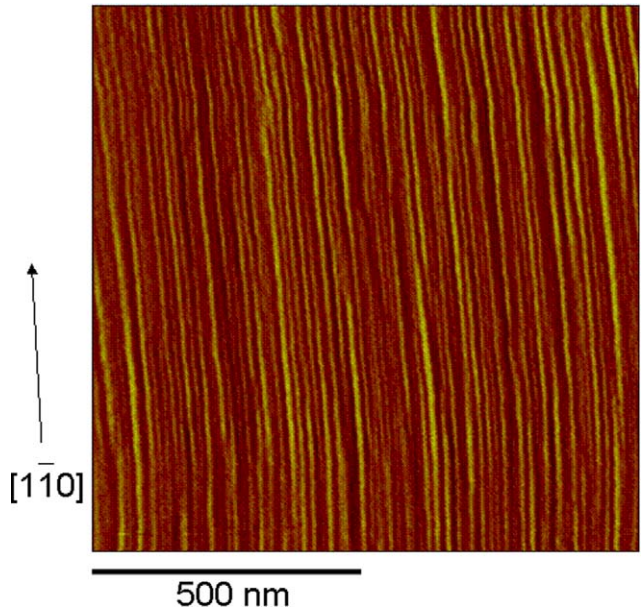

Fig. 1. AFM surface image of a 3.2-nm-thick GaAs layer grown on a (775)*B* GaAs substrate by MBE.

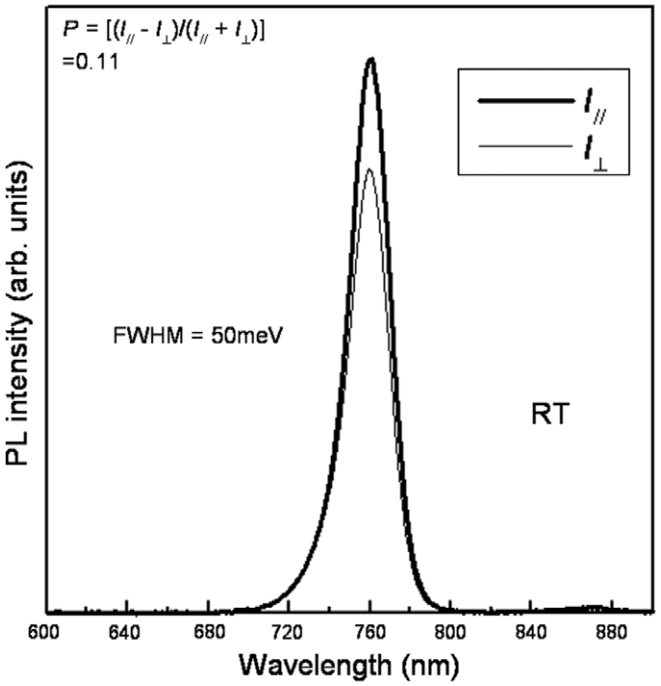

Fig. 2. Polarization resolved photoluminescence spectra of the (775)*B* GaAs/$(GaAs)_4(AlAs)_2$ QWRs grown by MBE. Photoluminescence intensity with polarization parallel to the QWRs ($I_{\|}$) which is 20% larger than that ($I_{\perp}$) of polarization perpendicular to the QWRs.