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# Extremely Low Threshold Current Density in (111)-Oriented GaAs/AlGaAs Quantum Well Lasers

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High quality (111)-oriented GaAs/AlGaAs quantum wells (QWs) with the smooth heterointerface comparable to conventional (100)-QWs have been grown by molecular beam epitaxy on (111)B-GaAs substrates by adapting the misorientation of 0.5°. Near-ideal low threshold current density $J_{th}$ has been attained for (111)-oriented graded-index separate-confinement-heterostructure single QW lasers in which $J_{th}$ almost unchanges for well widths of 30-100 Å. The lowest $J_{th}$ of 145 A/cm$^2$ achieved for 490-μm long device is lowest ever reported for semiconductor lasers.

## 1. Introduction

Quantum wells (QWs) and superlattices are very important for novel device applications and for basic physics studies. These modulated semiconductor structures are based on the one-dimensional modulation of electronic band structure along the growth axis. Thus fundamental properties of these structures are believed to change with their crystal orientation. However, most of modulated semiconductor structures have been grown on (100)-oriented substrates until recently. There are a few reports on the growth of GaAs/AlGaAs heterostructures on (N11)- and (110)-oriented substrates ($N \geqq 1$).[1),2)] No dependence of quantum effects on the orientation is reported except the effect of the strain-induced polarization field theoretically calculated for (111)-oriented strained-layer superlattices.[3)]

Recently we have succeeded in the molecular beam epitaxial growth of high quality GaAs/AlGaAs Qws on (111)B-oriented substrates by very slightly (0.5°) misorienting the substrate orientation.[4)] As a result, we found that the photoluminescence (PL) efficiency of (111)-oriented QWs is higher than (100)-QWs by more than one order of magnitude, and the threshold current density $J_{th}$ of (111)-QW lasers is reduced compared with (100)-oriented ones. In this paper, near-ideal low $J_{th}$ in (111)-QW lasers are presented.

## 2. Why (111) ?

In order to test the orientation dependence of quantum size effect, we selected the (111) orientation because the effect of the largest anisotropy in the atomic configuration was expected for (111)-oriented QWs. In Fig.1 are shown crystal models of GaAs/AlAs QWs for (100) and (111) orientations. In (100)-QWs, [010] and [001] axes equivalent to the [100]-growth-axis lie in the QW plane, and thus the atomic configuration is isotropic. By contrast, in (111)-Qws, the atomic configuration is extremely anisotropic with respect to the growth axis and directions parallel to the heterointerface; there are no axes equivalent to the [111]-growth-axis in the QW plane. Therefore we can expect different properties based on the one-dimensional quantization for (100)- and (111)-oriented

QWs.

3. Photoluminescence Study

Samples were grown by MBE (RIBER 2300) on Si-doped GaAs substrates with the orientations of (100) and (111)B misoriented by 0.5° toward (100). Details for crystal growth are reported elsewhere.[4),5)]

To assess the smoothness of heterointerface, four GaAs QWs with different well width $L_z$ separated by 500-Å thick $Al_{0.3}Ga_{0.7}As$ barriers were successively grown. PL spectra were measured at 10 K by excitation with 514.5-nm light from an $Ar^+$ ion laser with the excitation density of 0.05 $W/cm^2$. PL spectra shown in Fig.2 demonstrate that the heterointerface of (111)-QWs is as smooth as that of (100)-QWs. For 50-Å wide wells, the line width of 5 meV in (111)-QW is only slightly larger than that of 4.2 meV in (100)-QW. Detailed study on the interface disorder in (111)-QWs will be reported elsewhere.[6)] Even at 10 K, where the carrier recombination processes competing with the radiative recombination in QW is lower than those at room temperature, the PL intensity of (111)-QWs is at least several times higher than that in (100)-QWs. This indicates the enhancement of optical transition rate in (111)-QWs compared with that of (100)-QWs.[4)]

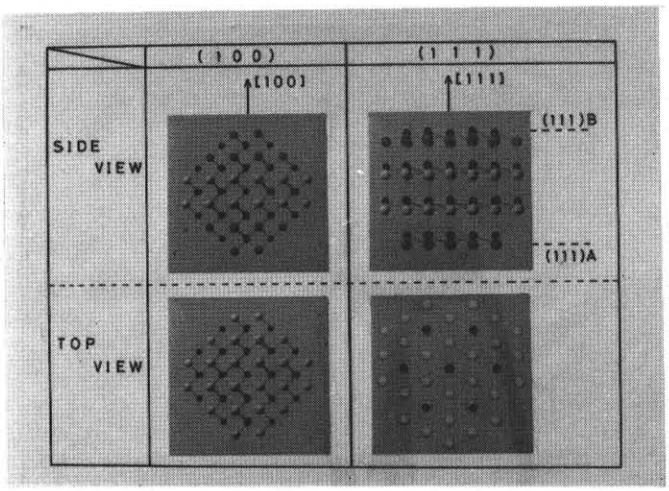


Fig.1, Crystal models of GaAs/AlAs quantum well for growth axes of [100](left) and [111] (right). Large white spheres represent Ga, and large and small black ones represent Al and As respectively. Two monolayer thick GaAs is sandwiched by AlAs.

4. Quantum Well Lasers

Graded-index separate-confinement-heterostructure (GRIN-SCH) GaAs single quantum well(SQW) lasers with different $L_z$ in the range of 15-300 Å were grown on (100)- and 0.5°-misoriented (111)B-substrates. A GaAs SQW was sandwiched by 0.15-μm thick $Al_xGa_{1-x}As$ GRIN layers in which x was varied from 0.2 to 0.7. A compositionally graded buffer layer (CGBL) was inserted under the first cladding layer to improve the quality of $Al_{0.7}Ga_{0.3}As$ cladding layer.[7)] Broad-area Fabry-Perot lasers with a cavity length of 490 μm and a width of 120-200 μm were fabricated. For randomly selected devices from one or two bars, the light output-current curves were measured and the $J_{th}$ was calculated by mea-

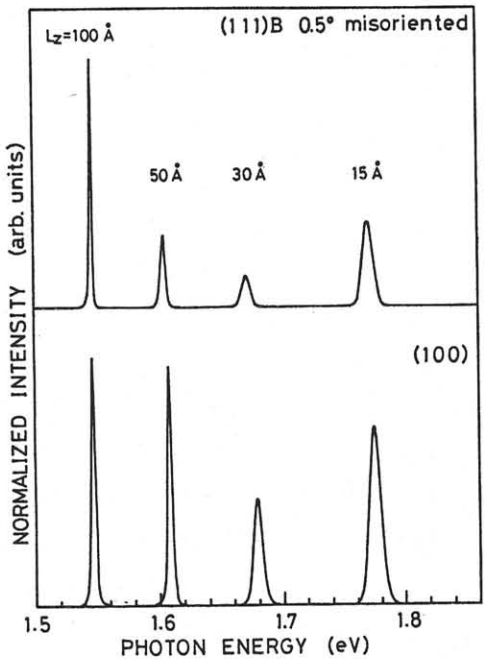


Fig.2, Photoluminescence spectra at 10 K of samples with four GaAs quantum wells grown on 0.5°-misoriented (111)B- and (100)-GaAs substrates at 720 °C.

suring the actual area of each device using an optical microscope.

Figure 3 shows $J_{th}$ as a function of $L_z$ for (100)-oriented devices. Compared with previously reported results,[8)-11)] $J_{th}$ in the present study is lowest in the whole range of $L_z$, which demonstrates the highest quality of material grown under our optimized conditions by using a CGBL.[5),7)] Distributions of $J_{th}$ in devices with $L_z$=70 Å for (111)- and (100)-orientations are shown in Fig.4. The average $J_{th}$ of 176 A/cm$^2$ for the (111) orientation is about 20 A/cm$^2$ lower than that of 196 A/cm$^2$ for the (100) orientation. For $L_z \geq 100$ Å, it was found that there is no difference in $J_{th}$ for both (111) and (100) orientations. By contrast, for $L_z$<100 Å, the $J_{th}$ of (111)-oriented lasers is lower than that of (100)-oriented ones as shown in Fig.5. It should be noted that the $J_{th}$ of (111)-devices is almost constant within 160±5 A/cm$^2$ in the range of $L_z$=30-100 Å. This dependence of $J_{th}$ on $L_z$ is consistent with the theoretical calculation

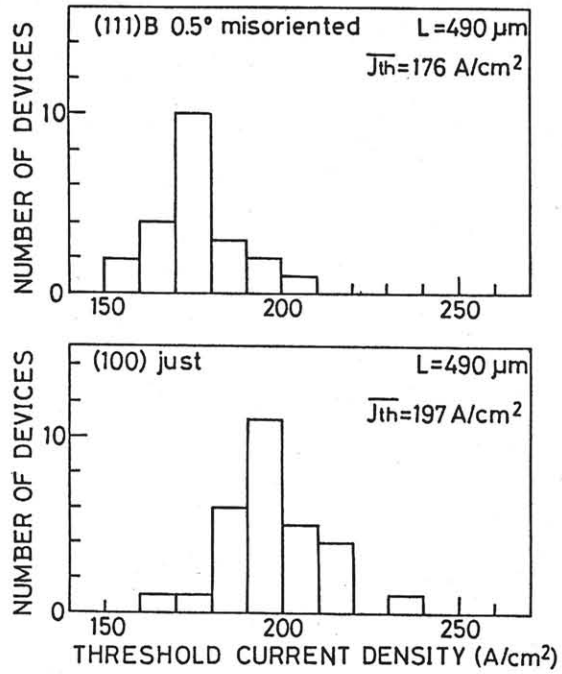


Fig.4, Distribution of threshold current density of GRIN-SCH SQW lasers with $L_z$=70 Å grown on substrates oriented: 0.5°-misoriented (111)B (upper) and and (100) (lower).

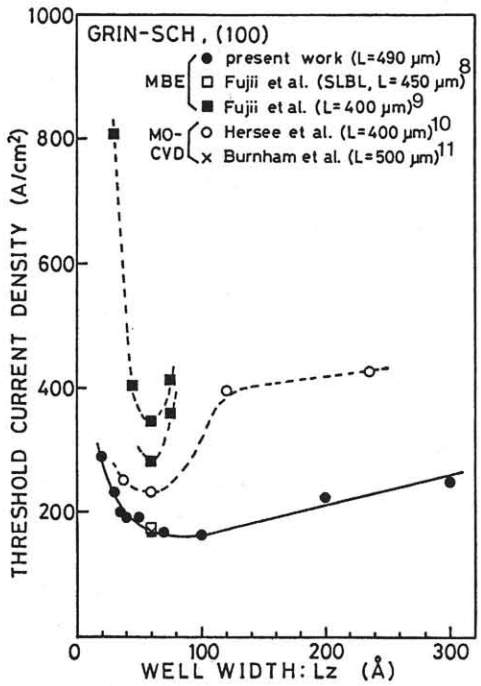


Fig.3, Threshold current density of (100)-oriented (GRIN-)SCH SQW lasers as a function of well width.

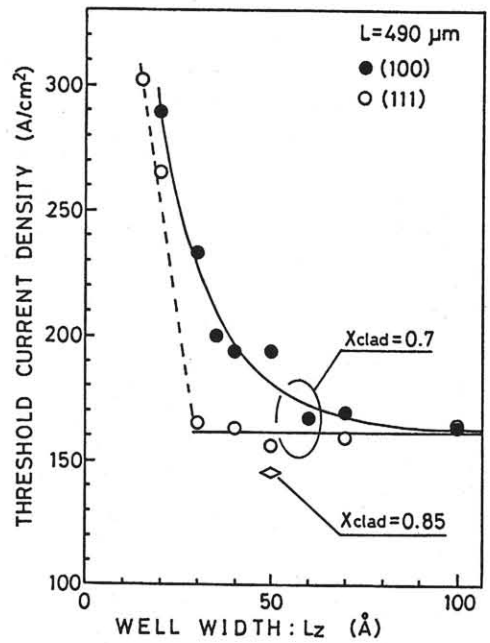


Fig.5, Threshold current density of GRIN-SCH SQW lasers as a function of well width ($L_z \leq 100$ Å) for (100) and (111) orientations.

by Sugimura[12] for the case that all carriers injected into the QW region contribute to the stimulated recombination between ground states of electrons and hevy-holes; thus the ideal extreme. The abrupt increase in $J_{th}$ for $L_z$<30 Å is considered to result from the loss of quantum confinement of carriers. By increasing the AlAs mole fraction in the cladding layers from 0.7 to 0.85, the $J_{th}$ is further reduced to 145 A/cm$^2$ in a (111)-oriented devices with $L_z$=50 Å as plotted in Fig. 5. This is the lowest $J_{th}$ ever reported for semiconductor lasers with a similar cavity length.

## 5. Conclusion

It is shown that high quality GaAs/AlGaAs QWs with the smooth heterointerface comparable to those on conventional (100)-substrates can be grown on (111)B-GaAs substrates by adapting the misorientation of 0.5°. The $J_{th}$ of (111)-oriented GRIN-SCH SQW lasers is reduced for $L_z$<100 Å compared with that of (100)-oriented ones, and it almost unchanges for $L_z$=30-100 Å, which corresponds to the ideal extreme. The lowest $J_{th}$ of 145 A/cm$^2$ achieved for a 490-μm long device is lowest ever reported for semiconductor lasers. We are convinced that these improvements arise from the enhancement of optical transition in (111)-oriented QWs compared with (100)-QWs. The one-dimensional quantization along the [111] axis will improve performances in all kinds of optical devices based on the quantum size effect, such as modulators, switches, and bistable devices with the QW region. The detailed study on basic properties of (111)-oriented QWs is now underway.

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