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Cathodoluminescence of GaAs/AlAs Quantum Wells Grown on Stripe and Square Patterns by Molecular Beam Epitaxy

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We present the results of the cathodoluminescence (CL) spectroscopy of wire- and box-like GaAs/AlAs quantum wells (QWs) grown by molecular beam epitaxy on stripe- and square-shaped mesa structures oriented along the <001> directions. The wire- and box-like structures defined by {110} facets on the top of these mesas were confirmed by CL imaging. In addition, we found considerably large variations in the QW thickness, i.e., a 110% increase on the top of the mesa-stripe region compared to the (100) plane, and a 240% increase on the top of the mesa-square region, indicating a very low growth rate of {110} facets. These results show that the use of <001>-mesa structures is very advantageous for fabricating low-dimensionally confined heterostructures.

Introduction

Much effort to realize low-dimensional heterostructures, such as quantum wires or quantum boxes, has been exerted using various fabrication techniques, being motivated by their promising properties to improve the performance of optoelectronic devices.[1,2] For fabricating quantum wires by molecular beam epitaxy (MBE), it has been common to use patterned substrates with either mesa stripes or V-shaped grooves aligned along the [011] and [01̄1] directions.[3-6] We have proposed the use of patterned substrates with mesa-stripes[7] or -squares[8] with sides along the <001> directions. Under certain growth conditions, the GaAs growth on <001> mesa-stripes or -squares allows the formation of {110} facets as sidewalls. The GaAs growth rate on these facets is extremely low compared with that on the (100) plane, making it easy to fabricate wire- or box-like structures on the mesa-top. In this paper we describe the cathodoluminescence (CL) characterization of the wire-[9] and box-like structures fabricated on the <001>-mesas by MBE. By CL spectroscopy, the spacial variations in a GaAs/AlAs quantum well (QW)-thickness and the composition of AlGaAs alloy were determined.

Experimental

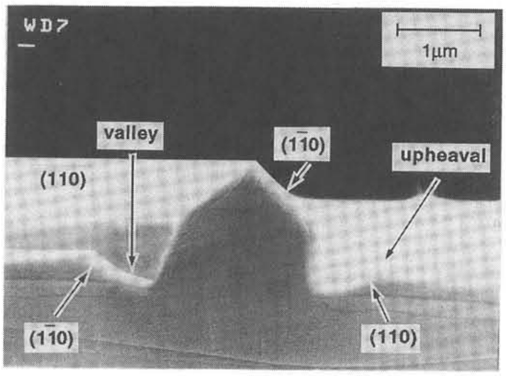
Stripe- and square-shaped mesa patterns aligned along the <001> directions were formed by conventional photolithography and wet chemical etching in NH_4OH:H_2O_2:H_2O (4:1:20 by volume) on (100) GaAs substrates. The width of the mesa stripes and the dimension of the mesa squares were 1~2 μm with 1-μm depth. For growth on the mesa stripe, a growth rate of 1 μm/h for both GaAs and AlAs, an As_4 pressure of 2×10^{-5} Torr, and a growth temperature of about 600 °C were used. First, we fabricated wire-like structures. By growing a GaAs buffer layer, the width of the (100) plane on the top of the [001]-mesa-stripe was reduced. In succession, a GaAs/AlAs QW structure (well width of 7 nm) and an $Al_{0.5}Ga_{0.5}As$ alloy layer were grown.

Next, growth was carried out to fabricate a box-like QW structure in a pyramidal structure.[8] A mesa square with sides along the [010] and [001] directions was patterned on the substrate. The MBE growth condition for the pyramidal structure was slightly different: a growth rate of 0.5 μm/h and an As_4 pressure of 1.8×10^{-5} Torr were used. One sample having a pyaramidal structure was fabricated in which only the GaAs buffer layer was grown on the mesa-square for scanning electron microscope (SEM) observations. The other was for CL investigations; in this case the GaAs/AlAs QW structure (well width of 5 nm) was grown before the pyramidal structure pintched-off.

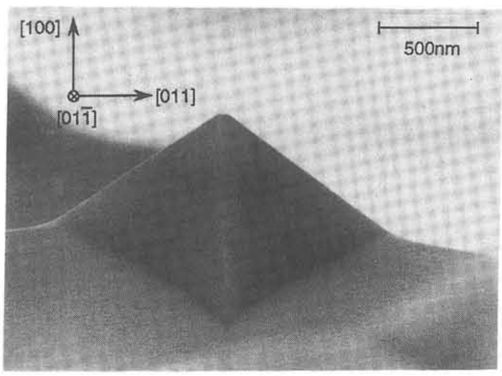
CL measurements at 75 K were performed on a cooling stage equipped in an ultrahigh vacuum chamber of an SEM machine, which makes it possible to detect weak luminescence. A 10-keV electron beam with 1 nA current was used as an excitation source; it was estimated that the focused beam-diameter was about 0.1 μm. Even when taking into account the diffusion of excited carriers, our CL system has sufficiently high spacial-resolution compared to conventional photoluminescence spectroscopy-systems.

Results and discussion

Figure 1(a) is a cross-sectional SEM photograph of a wire-like structure after MBE growth on a substrate patterned with [001]-mesa stripes. In our proposed fabrication method, wire-like structures have smooth {110} facets as sidewalls. The feature of {110} facets is that the growth rate of GaAs is considerably lower than that on the (100) surface, because the Ga atoms on {110} surfaces have a long diffusion length.[10] We can, therefore, fabricate a wire-like structure on the top of mesa-stripes. From this SEM photograph, the lateral width of a QW grown on the top of a mesa-stripe is found to be reduced to about 300 nm. Valleys and upheavals were formed at both sides of the mesa-stripe in the bottom region as shown in the figure, which were caused by shadowing of the molecular beam.



(a)



(b)

Fig. 1. (a) (0$\bar{1}$1) Cross-sectional SEM photograph of an MBE grown [001] mesa stripe. (b) SEM photograph of a pyramidal structure formed on a mesa square by MBE growth.

The SEM photograph of the pyramidal structure, which was formed by the growth of a GaAs buffer layer on the mesa-square, is presented in Fig. 1(b). The {110} facets are also observed in this case. It is interesting to note that the dimensions of the top plane of the mesa-square are reduced by GaAs growth; finally, the four {110} facets converge and pinch-off at a center of mesa-square.[8]

For wire-like structures, the characteristic CL spectra (A, B, and C, as shown in Fig. 2) were obtained by probing the top of the mesa (A), the bottom area (upheaval) near to the mesa edge (B), and the bottom area at a distance of about 2 μm from the mesa edge (C), respectively. While the intentional growth on the unpatterned substrate consisted of a 7-nm-thick QW (CL peak at 772 nm, as shown by the arrow in spectrum C), CL spectrum A shows 3 peaks at 807, 740, and 705 nm, in addition to the GaAs peak. Because of the diffusion of Ga atoms from the sidewalls to the mesa-top, a thicker QW and a thinner QW are expected to be formed on the mesa-top and on the sidewall, respectively. We, therefore, assigned the peaks of spectrum A to be from a 15-nm-thick QW on the mesa-top (CL peak at 807 nm) and from a 4-nm-thick QW at the {110} sidewalls (CL peak at 740 nm). The growth of the intentional 7-nm QW resulted in a change in the QW thickness depending on the grown plane: an increase of ~110% for a mesa-top, and a decrease of ~40% for sidewalls. These assignments have been confirmed by CL imaging, which is explained later. Moreover, CL spectrum A reveals that the Al-content of the intentionally grown $Al_{0.5}Ga_{0.5}As$ alloy on the planar area considerably changed to 0.18 (CL peak at 705 nm) on the mesa-top. From CL spectrum B by excitation at the

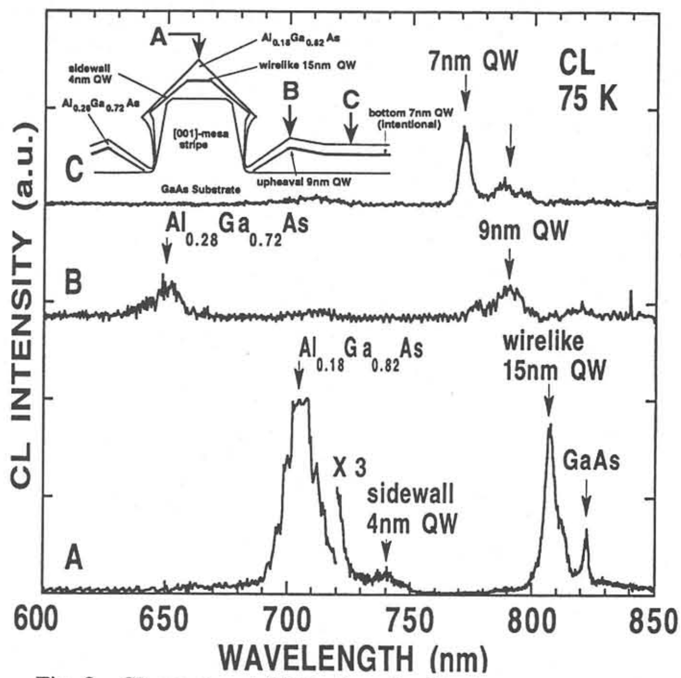
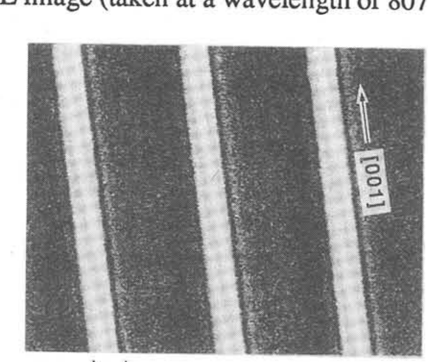


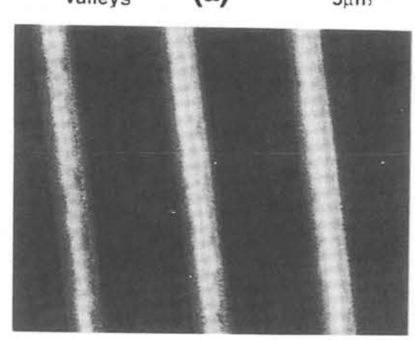
Fig. 2. CL spectra at 75 K of a wire-like heterostructure. The notations A, B, and C indicate the CL probing positions on the sample as schematically illustrated in the inset, corresponding to spectra A, B, and C, respectively.

upheaval, the thickness of the QW and the Al-content also changed to 9 nm (CL peak at 790 nm) and 0.28 (CL peak at 650 nm), respectively. The broadening of the CL peak at 790 nm indicates that QW structures at the upheaval with a thickness fluctuation of several nanometers were formed.

Figures 3(a) and (b) show the top-view SEM image and a CL image (taken at a wavelength of 807 nm) of the



valleys (a) 5μm



(b)

Fig. 3 (a) Top-view SEM image of [001]-mesa stripes after growth. (b) CL image at 75 K of the structure of (a). The selected wavelength at 807 nm was the CL peak of a QW on the top of the mesa stripe.

mesa-stripes after growth, respectively. It is directly found by comparing these images that a 15-nm QW with 807-nm CL peak formed the wire-like structure. The emitting area at 807 nm is wider than the width estimated from the cross-sectional SEM photograph (300 nm), because the carriers excited by the electron-beam irradiation diffuse from the 4-nm sidewall QW with higher band-gap energy to the 15-nm mesa-top QW with lower one.

We next discuss the CL spectrum of a QW grown on the mesa square. The sample used in the CL measurements is not the same sample as exhibited in Fig.1(b) (only growth of a GaAs buffer). A 5-nm-thick GaAs/AlAs QW was grown on an unpitched-off pyramidal structure after the GaAs-buffer growth. Similar to the case of the wire-like structure on a [001]-mesa stripe, the shape of the CL spectrum showed a drastic change, depending on the probing position. Figure 4 shows the CL spectrum at 75 K by excitation at the top of the pyramidal structure. While the peak of the intentionally grown 5-nm QW is around 760 nm (not shown here), that of the QW grown on the top of pyramidal structure is greatly shifted to 810 nm, corresponding to a 17-nm-thick QW (240% increase in the QW thickness). Considering the result of CL imaging (not shown), the broad peak around 780 nm was attributed to a QW formed in the surroundings of the pyramidal structure (shown in Fig. 5(a) as "S").

Figures 5(a) and (b) show top-view SEM and CL images of a grown pyramidal structure with the same magnification at 75 K, respectively. The CL image at a wavelength of 810 nm shows a box-like luminescent-pattern with a dimension of ~ 1 µm. Taking into account the carrier diffusion effect, the real size of a box-like structure is thought to be much smaller.[9] These results indicate the possibility of fabricating three-dimensionally confined structures using this method.

Conclusion

We performed CL measurements at 75 K for wire- and box-like QW structures with {110} sidewalls grown by MBE. The fabrications of wire- and box-like structures were confirmed. Large variations in the QW thicknesses of 110% increase for a wire-like structure and of 240% increase for a box-like structure were determined. This technique was, therefore, proven to be very promising for fabricating high-quality low-dimensional structures.

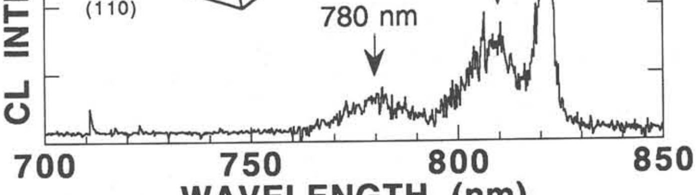


Fig. 4. CL spectrum at 75 K of a QW grown on the top of a pyramidal structure. The probing position of the electron beam was at the very top of the pyramid, as schematically illustrated in the inset.

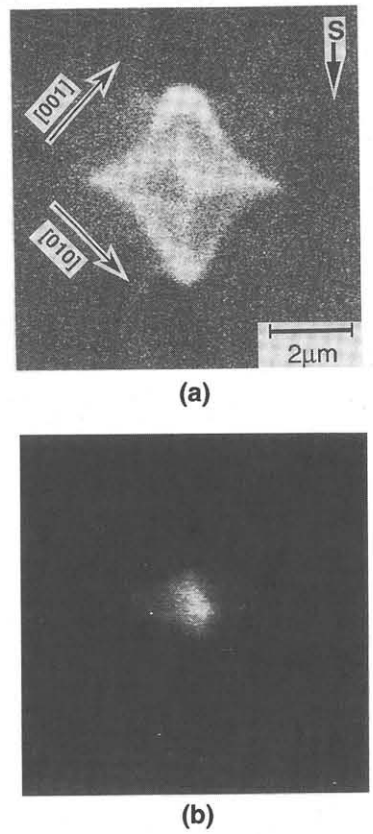


Fig. 5 (a) Top-view SEM image of an MBE-grown pyramidal structure. (b) CL image at 75 K of the structure of (a). The luminescent pattern at 810 nm was observed at the center of the pyramid.

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