Solid-immersion photoluminescence microscopy of carrier diffusion and drift in facet-growth GaAs quantum wells

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Carrier diffusion and drift in facet-growth quantum wells (QWs) on mesa-patterned substrates by molecular beam epitaxy was studied by high-resolution microscopic photoluminescence spectroscopy and imaging using a solid immersion lens at low temperatures. Under point excitation, excitation-position-dependent anisotropic carrier migration was observed, which was explained by carrier diffusion and drift due to spatial change in the quantization energy in QWs. © 1998 American Institute of Physics.

Facet epitaxial growth on patterned substrates is a promising method to fabricate self-formed damage-free modulated semiconductor structures, such as quantum wires, quantum dots, micro-optical waveguides including lasers, and electron transport devices. To establish facet growth techniques and to optimize growth conditions, characterization of spatial variation or uniformity of electronic or optical properties in the formed structures is important. Moreover, carrier distribution, diffusion, and drift in low-dimensional structures are essential subjects both in fundamental physics and in device performance.

To characterize such properties in facet structures, microscopy with high-spatial resolution and high efficiency is required because of their small size. Recently, we developed a low-temperature microscopic photoluminescence (micro-PL) imaging technique using a solid immersion lens (SIL). The SIL is an aberration-free solid lens made from high-refractive-index material with a truncated-sphere shape. Combining the SIL with conventional micro-PL imaging, we observed PL images with high-spatial resolution beyond the diffraction limit and high collection efficiency. In our previous study, we demonstrated low-temperature PL imaging of GaAs quantum wells (QWs) formed by facet growth on patterned substrates with molecular beam epitaxy (MBE). Under uniform excitation, the spatial distribution of photocarriers in the QW structures was monitored at various temperatures.

In this work, micro-PL spectroscopy as well as imaging has been performed with the SIL, particularly under point excitation. Point-excited PL spectra have shown the local electronic structures of a GaAs QW grown on a patterned substrate. The PL images under point excitation enabled us to directly reveal carrier diffusion and drift in QW structures with high resolution. In addition, these results gave us detailed understanding on the PL images obtained in our previous study.

The experimental setup of SIL micro-PL spectroscopy and imaging was simply composed of a Weierstrass-sphere-shaped SIL with a refractive index \( n = 1.8 \) placed on the sample and the standard micro-PL setup. For point excitation, light from a He–Ne laser was focused on the sample surface with a spot size of 0.4 \( \mu m \) via an objective lens and the SIL.

Figure 1(a) shows a cross-sectional scanning electron microscope (SEM) image of the GaAs QW sample. A GaAs QW with a nominal vertical thickness of 5 nm sandwiched by AlAs barriers was grown on a patterned GaAs (001) substrate with 10-\( \mu m \)-wide mesa stripes along the [110] direction by MBE following the growth of a 1.5-\( \mu m \)-thick GaAs buffer layer.

It has been known that the facet structure was caused by the atom migration process. When the GaAs buffer layer was grown on the mesa-patterned substrate, (111)B facets were formed on both sides of the (001) top surface. The migration of Ga atoms from the (111)B to the (001) facets and their deposition near the edges made the deposition rate faster near the edges than at the center of the (001) facet. Since the following GaAs QW layer was deposited in a similar way, the QWs denoted as the top-QW and the side-QW were formed on the (001) and (111)B facets. Due to the difference of the deposition rate, we expected that the top-QW on the top curved surface should get thicker, and hence, have lower quantization energy, near both edges than at the center on the mesa stripe, as schematically shown in Fig. 1(b).

First, to confirm the well thickness variation in the top QW, we measured spatially-resolved PL spectra under point excitation. Figure 2 shows the PL spectra under point excita-

![FIG. 1. (a) A cross-sectional scanning electron microscope image of the GaAs QW sample grown on a patterned GaAs (001) substrate with 10-\( \mu m \)-wide mesa stripes along the [110] direction and (b) a schematic drawing of QW thickness variation. Dashed line indicates the original mesa-patterned substrate.](image-url)
tation at five different positions on the top-QW, which are indicated as A–E in the SEM image in Fig. 1. The PL peak shifted to the lower energy side as the excitation position was moved from the center to the edges of the mesa, which indicates the well thickness variation in the top-QW across the mesa. The well thicknesses estimated from the PL peak energy at the center and at the edge were 5.2 and 5.8 nm, respectively, and the thickness variation was 12%.

If such well thickness variation exists in the top-QW, it is expected that photocarriers generated at the center of the top-QW tend to drift toward the lower energy region at both sides. To directly reveal this carrier migration in the top-QW, we observed PL images under point excitation.

Figure 3(a) shows the PL images observed from the top of the mesa under point excitation at three different temperatures. The upper images were obtained with the point excitation at the center (position C in Fig. 1) and the lower ones were obtained at the edge (position A in Fig. 1).

At 20 K, the PL images are small circular spots. At higher temperatures, however, PL images become broader and anisotropic. At the edge, the PL image spread only along the mesa stripe direction, whereas at the center it dominantly spread across the mesa stripe direction.

To examine the observed PL images, we estimated full widths at half maximum (FWHM) of the cross-sectional intensity profiles of the PL images along and across the mesa-stripe direction.

At the center of the mesa, the migration length of the carriers was smaller than 0.5 μm at low temperatures from 4 to 20 K. However, as the temperature increased, the migration length increased in both directions and became anisotropic. The FWHM predominantly spread across the mesa-stripe direction, which indicates carriers preferably migrated from the center to the edge sides, that is, to the lower quantization energy sides due to drift of carriers in addition to diffusion.

At the edge, on the other hand, only the increase of the FWHM along the mesa-stripe direction was observed. Since the quantization energy is the lowest near the edge sides, carriers can only diffuse within the energetically same states along the mesa-stripe direction and not across the mesa direction. Then, such anisotropic carrier migration was observed.

On the basis of the above confirmation of position-dependent and anisotropic carrier migration in the top-QW, the PL images under uniform excitation at various temperatures observed in our previous work are now fully interpreted.

Figure 4(a) shows the PL image under uniform excitation for the same GaAs QW sample at 50 K. Strong PL was observed along two positions near both edges of the top-QW. Similar PL images were measured at temperatures from 5 to 200 K.  

To explain the observed PL images, we consider the position-dependent and anisotropic carrier migration in the top-QW described above. At the center of the top-QW, carriers diffuse and drift to the lower energy states at both sides, whereas, at the edges, carriers only diffuse along the mesa-stripe direction. This carrier migration in the QW should result in decrease of carrier density at the center and increase at the edge sides in the steady state under uniform excitation. Thus, the weak PL at the center and the strong PL at the thick QW region at both edge sides were observed.
corresponding position. Each profile was normalized by its peak intensity. Mesa direction at 20, 50, and 100 K and the SEM image for indicating the ~ at 50 K.

FIG. 4. Cross-sectional PL intensity profiles along A–B in (a) across the mesa direction at 20, 50, and 100 K and the SEM image for indicating the corresponding position. Each profile was normalized by its peak intensity.

It is interesting to investigate the temperature-dependent PL intensity ratio or contrast between the strong PL regions near the edge sides and the weak region at the center of the top-QW. Figure 4(b) shows the cross-sectional PL intensity profiles along A–B in Fig. 4(a) at three different temperatures. The profiles are normalized by the peak PL intensity near the edges, so that the ratio or contrast is read from the normalized intensity at the center region.

Note first that the PL intensity contrast became stronger when the temperature was raised from 20 to 50 K. This was due to the enhanced carrier migration from the center region to the edges at higher temperatures.

Second, however, over 80 K, the PL intensity contrast became weak, in spite of the increase of the migration length of the carriers. This was most likely caused by the thermal population effect of the carriers. As the temperature increases and the thermal energy becomes close to the difference of the quantization energy in the top-QW, the carriers are thermally activated and occupy higher energy states at the center region.

In summary, we performed high-resolution SIL micro-PL spectroscopy and imaging under point excitation for the facet-growth GaAs QWs on a patterned substrate and revealed carrier diffusion, drift, and distribution in the formed top-QW. We observed anisotropic carrier migration both at the center and at the edge sides of the top-QW with orthogonal direction from each other, which was caused by the spatial change in the quantization energy according to the well thickness variation in the top-QW. This anisotropic carrier migration and its temperature dependence well explained the PL images under uniform excitation observed in our previous study.

We finally emphasize the advantages of SIL in the high-resolution PL microscopy of epitaxially grown quantum structures. The first important advantage is the high-spatial resolution to resolve the structural feature and carrier migration of 1 μm scale, which can be achieved easily on the basis of the standard micro-PL system. The other advantage is the real-time two-dimensional imaging with high detection efficiency, which enabled us to observe anisotropic carrier migration and distribution directly with collection efficiency 6–10 times higher than that obtained without SIL.

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