2.8 Molecular-beam-epitaxial growth window for long-wavelength-emitting (Ga,In)(N,As,Sb) multiple quantum wells

Quaternary (Ga,In)(N,As) or quinary (Ga,In)(N,As,Sb) quantum wells (QWs) on GaAs are materials of interest due to their band gap tunability, which is promising for the realization of low-cost and high-performance 1.3-μm and 1.55-μm telecommunication lasers. The incorporation of large amounts of In ($\geq$ 30%) and N ($\geq$ 3%) into the QWs is required for the emission above 1.5 μm. This, however, enhances the phase separation tendency related to the inherent large miscibility gap and complicates the growth of high-quality epitaxial layers. A surfactant-mediated growth using Sb has been suggested as a possible solution. However, several groups have recently reported emission beyond 1.5 μm from (Ga,In)(N,As) QWs without Sb, using specific growth conditions. These conditions are characterized by a lower substrate temperature T_s and a lower As beam equivalent pressure (BEP), compared to the commonly used T_s of 400–450 °C and V/III BEP ratio, $R_{\mathrm{BEP}} = (\mathrm{BEP}_{\mathrm{As}})/(\mathrm{BEP}_{\mathrm{Ga}} + \mathrm{BEP}_{\mathrm{In}})$, of 15–20. In general, the growth processes for this growth window are not yet well understood. Hence, we investigated the molecular-beam-epitaxial (MBE) growth of long-wavelength-emitting (Ga,In)(N,As,Sb) multiple quantum wells (MQWs) focusing on the impact of T_s, R_{BEP}, and the supply of Sb.

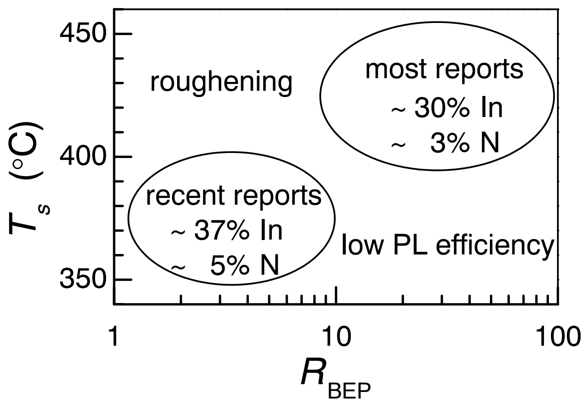

Fig. 20. MBE growth window for (Ga,In)(N,As) QWs. High-quality QWs can be grown within the elliptical areas. Recent experiments carried out at low T_s and R_{BEP} condition result in QWs containing large amounts of In and N.

Figure 20 summarizes the MBE growth window for (Ga,In)(N,As) QWs. First, we focused on the growth conditions of low T_s and low R_{BEP}. The prospects are the following: (i) the low growth temperature prevents composition modulations, leading to abrupt heterointerfaces; (ii) the low As pressure allows for the introduction of a large amount of N in the layers due to the reduced competition for the incorporation of group-V elements; and (iii) reducing the As pressure reduces the excess group-V atoms, which will reduce the point defects such as antisites and interstitials, thus improving the photoluminescence (PL) intensity.

To examine the above assumptions, we grew (Ga,In)(N,As)/Ga(N,As) MQWs at a T_s of 375 °C and a R_{BEP} of 5, namely four 10-period MQW samples, each one containing QW widths of 4, 6, 7, or 8 nm, separated by 14 nm barriers. Figure 21 (a) displays a cross-sectional transmission-electron-microscopy (TEM) micrograph of the sample with 8-nm-wide QWs. The image shows the regularly stacked 10 QW layers, which remain homogeneous with smooth interfaces throughout the structure. X-ray diffraction scans showed that these samples are composed of 36% In and 4.5% N for the (Ga,In)(N,As) wells and 0.8% N for the Ga(N,As) barriers. Figure 21 (b) shows room temperature (RT) cathodoluminescence (CL) spectra for the series

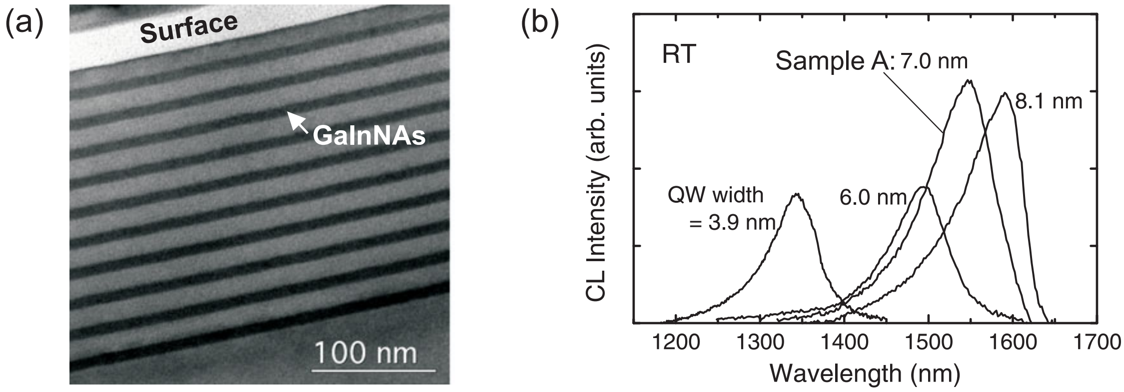

Fig. 21. (a) Cross-sectional TEM image of the 10-period MQW with 8 nm (Ga,In)(N,As) and 14 nm Ga(N,As). (b) CL spectra for the 10-period MQWs having different QW widths. The QW width obtained from the XRD fit is indicated for each spectrum.

of the MQWs with different QW widths, which were annealed at 720 °C for 60 s prior to the measurements to enhance the luminescence yield. We observed emission in the range from 1.34 to 1.6 μm, showing a clear redshift of the spectral peak position with increasing QW width. The full width at half maximum of these peaks amounts to less than 50 meV. These results verify the feasibility of the low-T_s and low-R_{BEP} growth concept for the fabrication of high-quality (Ga,In)(N,As) QWs for long wavelength emission.

Next, we grew 6.5-nm-wide QWs designed to emit at 1.55 μm which contain Sb in the (Ga,In)(N,As) layer. The indium and nitrogen content was 34% and 3.1%, respectively. We employed the standard growth conditions, namely a T_s of 420 °C and a R_{BEP} of 20. Figure 22 shows PL spectra at 300 K of a series of 3-period MQWs grown for different Sb fluxes, which were measured after post-growth annealing at 730 °C for 60 s. For comparison, the spectrum of the 10-period MQW with 7-nm-wide (Ga,In)(N,As) QWs (sample A in Fig. 21) is also plotted. As a result, the addition of Sb improved the PL intensity and led to a redshift of the peak positions. We could consequently achieve the desired 1.55 μm emission by use of Sb, which showed an intensity and a linewidth comparable to the one of sample A as shown in Fig. 22. In summary, we investigated the growth of long-wavelength-emitting (Ga,In)(N,As,Sb) QWs. Two efficient approaches to achieve 1.55 μm emission were demonstrated, both of which shows comparable PL characteristics at 300 K.

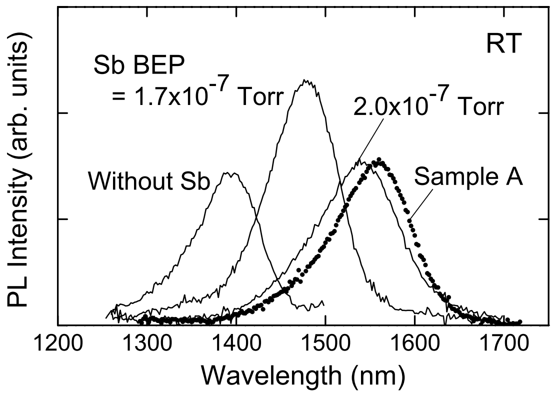

Fig. 22. PL spectra of (Ga,In)(N,As,Sb) QWs grown with different Sb BEPs as indicated. For comparison, a spectrum from sample A (shown in Fig. 21) is also plotted with dotted curve.

(F. Ishikawa, Á. Guzmán, E. Luna, A. Trampert, U. Jahn, K. H. Ploog)