Fabrication of Quantum Well Wires and Vertical Quantum Wells on Submicron Gratings by MOVPE

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Fabrication of quantum well wires and vertical quantum wells on submicron gratings by MOVPE

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The fabrication of quantum well wires (QWWS) by overgrowing submicron gratings is reviewed. The advantages of one-dimensional semiconductor structures have already been understood for some time and are expected to alter laser performances, such as extremely low threshold currents, very high modulation bandwidths, very low temperature dependence. The realization of the nanostructures, however, has set some major demands on crystal growth. The MOVPE growth on submicron gratings (etched in a GaAs substrate) has become one of the most successful techniques and is studied in this paper. Vertical 'quantum wells' (VQWS) (formed during growth of bulk $Al_xGa_{1-x}As$ on gratings) are also studied and a new fabrication technique for QWW lasers is proposed. Finally the application of QWWS and VQWS is discussed for the realization of Fabry–Perot and distributed feedback laser diodes.

1. Introduction

(*a*) *Impact of low-dimensionality*

The last two decades there has been enormous research activities on III–V quantum confined semiconductor structures. Due to the constant improvement of the epitaxial growth techniques (such as MOVPE and MBE), very thin (typically smaller than 20 nm) epitaxial layers can nowadays be easily realized. Introducing quantum confinement in semiconductor structures, revealed numerous interesting physical effects and resulted in a strong improvement of several electronic and optoelectronic devices. Extending the quantization to two (quantum well wires or QWWS) or three (quantum well boxes or QWBS) dimensions is expected to offer some very interesting perspectives and bring along new physical phenomena. The idea of the so-called low-dimensional semiconductor structures was published in 1980 by Sasaki, who calculated that 10 nm thin GaAs quantum wells (QWS) should allow extremely high electron mobilities (up to 10^8 cm^2 V^{-1} s^{-1}), if the width of the QW is smaller than 10 nm.

Quantization in more than one dimension will significantly modify the bandstructure of the semiconductor system, which has a strong impact on the density of states (DOS). Figure 1 illustrates the changes of the electron density of states as the dimensionality of the heterostructure is decreased (Asada 1986). Compared to the parabolic shape for bulk material, the DOS becomes more peaked as it transforms into a step-like, reciprocal square root and delta-function as the dimensionality of quantum confinement is increased. If we ignore the higher subbands of the zero-dimensional structures, QWBS are similar to two-level atomic systems and QWB lasers are for instance comparable to gas lasers.

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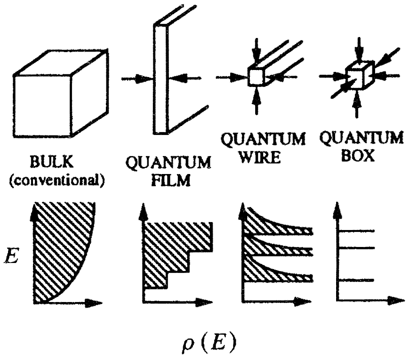

Figure 1. Density-of-states of low-dimensional semiconductor structures (Asada 1986).

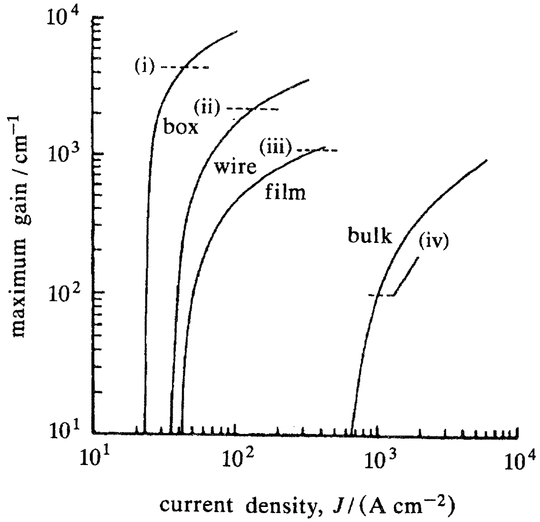

Figure 2. Calculated gain/current curves for low-dimensional GaAs–AlGaAs semiconductor lasers (Asada 1986). (i) $J_{\text{th}} = 45$ A cm^{-2}; (ii) $J_{\text{th}} = 140$ A cm^{-2}; (iii) $J_{\text{th}} = 380$ A cm^{-2}; (iv) threshold level, $J_{\text{th}} = 1050$ A cm^{-2}. $T = 300$ K.

(b) *Low-dimensional semiconductor lasers*

Due to the modified DOS the carriers in QWW and QWB semiconductor lasers are more concentrated in energy levels useful for laser action. As a result a much narrower gain profile is obtained and the same amount of carriers above inversion will lead to higher volume gain as the dimensionality of the semiconductor is decreased (Weisbuch 1990). Besides the higher gain, the differential gain of QWW and QWB lasers is also much higher compared with bulk or QW lasers (see figure 2 (Asada 1986)). Higher differential gain is one of the most important characteristics of low-dimensional structures and affects for instance significantly the modulation bandwidth and the linewidth enhancement factor α. The relaxation oscillation frequency f_{r} should be three times higher for QWB lasers compared to QW lasers, while α becomes smaller for QWW lasers and theoretically equals 0 for QWB lasers (Arakawa 1984). In practice, size fluctuations of the QWWs and QWBs result in inhomogenous broadening of the gain spectrum and can completely overrule all the advantages related to two- and three-dimensional quantum confinement. This condition of very uniform QWWS or QWBS puts some major challenges on the fabrication and explains the remaining difficulties in confirming clearly the predicted characteristics of QWWS and QWBS. Due to the peaked DOS, QWW and QWB lasers should also exhibit far less temperature sensitive threshold currents (Arakawa 1982) and show enhanced nonlinear gain effects (Arakawa 1990).

During the design of QWW or QWB lasers, one will first have to deal with one of the major problems concerning these kind of lasers, namely the very small optical filling factor Γ. Due to the dramatic decrease of Γ, the increased volume gain will after all end up in a much smaller modal gain compared to QW lasers. The threshold condition for lasing action is

$$\Gamma g = \Gamma \alpha_{\mathrm{fc,act}} + (1-\Gamma)\,\alpha_{\mathrm{fc,pas}} + \alpha_{\mathrm{scat}} + \alpha_{\mathrm{mir}},$$

where g is the volume gain, $\alpha_{\mathrm{fc,act}}$ and $\alpha_{\mathrm{fc,pas}}$ represent the losses due to free carrier absorption in the active QWWS or QWBS and the surrounding passive layers respectively, α_{scat} are the scattering losses and α_{mir} account for the photons leaving the cavity through the facets. In order to reach this threshold condition, great care should be taken of the following points:

(1) optimization of the waveguide structure of the laser in order to increase Γ;

(2) reduction of the free carrier absorption around the QWWS or QWBS because they contribute almost entirely (factor $(1-\Gamma)$) to the cavity losses;

(3) avoid damaged and defectful interfaces to minimize α_{scat};

(4) apply high reflection coatings to decrease the mirror losses.

Because Γ is so small, the carrier density at threshold in the QWWS or QWBS will be high and will probably lead to bandfilling effects. To avoid thermal bandfilling into higher energy subbands, large (surely higher than $kT = 25$ meV for room temperature laser operation at the lowest subband) intersubband spacing will be needed.

Referring to the low modal gain of one- and zero-dimensional semiconductor structures, it could be possible that the balance between increased volume gain and decreased filling factor is optimal for QW lasers and one could wonder if QWW and QWB lasers will actually decrease the threshold current. Threshold currents are calculated to be a few μA (Yariv 1988) and thus two orders of magnitude lower than the minimum (to our knowledge) of 0.36 mA for QW lasers (Kapon 1990). As indicated by Weisbuch (1990), probably the most important motive to investigate low-dimensional semiconductor lasers is the high differential gain resulting in high modulation bandwidths and small spectral enhancement factors. Finally one can also wonder if extrapolation from one-dimensional to two- and three-dimensional quantum confinement is always correct and in addition new physical effects concerning low-dimensional structures can surely be expected.

(*c*) *Fabrication techniques*

The very strong restrictions on the QWW and QWB sizes, invokes severe requirements on the nanostructure fabrication techniques. Compared to QW structures, the reduction of the active layer dimensions in the directions perpendicular to the growth direction is far more difficult to obtain and nowadays a huge variety of different approaches are investigated. Most interesting for the study of optical properties of QWWS and QWBS are the single-step growth techniques where the wires and dots are defined *in situ* during epitaxial growth. Hence there is no need for fine-line lithography, there are no exposed facets and good quality interfaces can be obtained. Some of the more successful techniques are the growth on off-oriented substrates for the realization of tilted superlattices, fractional layer superlattices or serpentine superlattices (Fukui 1987; Petroff 1984), self-organized growth on high-index surfaces (Ploog 1992), macrosteps during non-planar growth on off-oriented substrates (Colas 1989), selective MOVPE growth on GaAs (Fukui 1989) and InP (Galeuchet 1990).

Probably one of the most successful techniques, especially for investigating optical properties and for the realization of QWW lasers, is the non-planar growth on V-grooved substrates (Kapon 1992) and submicron gratings (Kojima 1990; Marti 1991; Karam 1991; Tsukamoto 1992; Vermeire 1992). Due to surface diffusion of group III species, crescent-shaped QWWS are formed at the bottom of the V-grooves. The diffusion process during MOVPE growth is very well controlled as will be shown later on and integration in a laser structure can be rather easily obtained. Laser operation for a QWW FP laser on a V-grooved substrate has been demonstrated, showing a threshold current of 0.6 mA (Simhony 1991).

3. Non-planar MOVPE growth

The growth runs at atmospheric pressure have been carried out in a small, horizontal MOVPE reactor using trimethylgallium (TMG), trimethylaluminum (TMA) and arsine (AsH_3, 5% diluted in H_2) as group III and group V sources, respectively. The typical growth velocity for GaAs was 8.6 Å s^{-1} with a V/III ratio of 42. A low pressure MOVPE system was used for the growths at 76 Torr. The same precursors of group III and V elements has been used except that undiluted arsine was applied. The GaAs growth velocity in the LPMOVPE system was 12.1 Å s^{-1} with a V/III ratio of 92. Both systems are provided with lamp heating to reach temperatures up to 850 °C. Submicron gratings, with periods between 600 and 800 nm, were realized by holographic lithography and wet chemical etching in citric acid. The corrugations are oriented along the [011] direction and were defined in both (100) exact and 2° off-oriented GaAs substrates. A very interesting alternative for the grating fabrication has been recently proposed (Tsukamoto 1992). 100 nm wide SiO_2 stripes were defined on a GaAs substrate with a 200 nm period. During the selective growth of GaAs triangular prisms are formed and a 200 nm pitch grating is defined during the epitaxial growth, resulting in very uniform gratings with smooth sidewalls.

Non-planar MOVPE growth was the first time studied by Hersee (1986) and received in the mean time a lot of interest (Demeester 1988; Bhat 1988). The appearing and disappearing of different crystallographic planes during non-planar MOVPE growth is determined by the nucleation and incorporation properties for group III and group V atoms at these facets. The submicron gratings, used during our experiments, expose quasi-{111}A facets and the crystallographic planes developed during further MOVPE growth are mainly (100), {111}A and {311}A planes. If we use the dangling bond model proposed by Sangster (1962) we can qualitatively analyse the nucleation and incorporation properties of these facets. Due to a better incorporation on the (100) planes compared to the {111}A planes, a concentration gradient of group III atoms exists (the 'growth limiting' species are group III species because a group V overpressure is commonly established during MOVPE growth). This results in surface diffusion of group III elements (reactant products or probably the atoms themselves) to more favourable incorporation planes to minimize the total surface energy (see figure 3). As a result, besides the incorporation and nucleation properties, surface diffusion effects also determine the relative growth velocities on the different

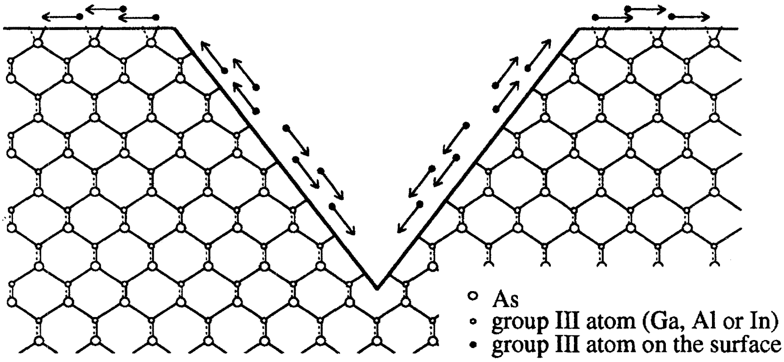

Figure 3. Schematic representation of surface diffusion effects on (100) and {111}A planes during non-planar MOVPE growth.

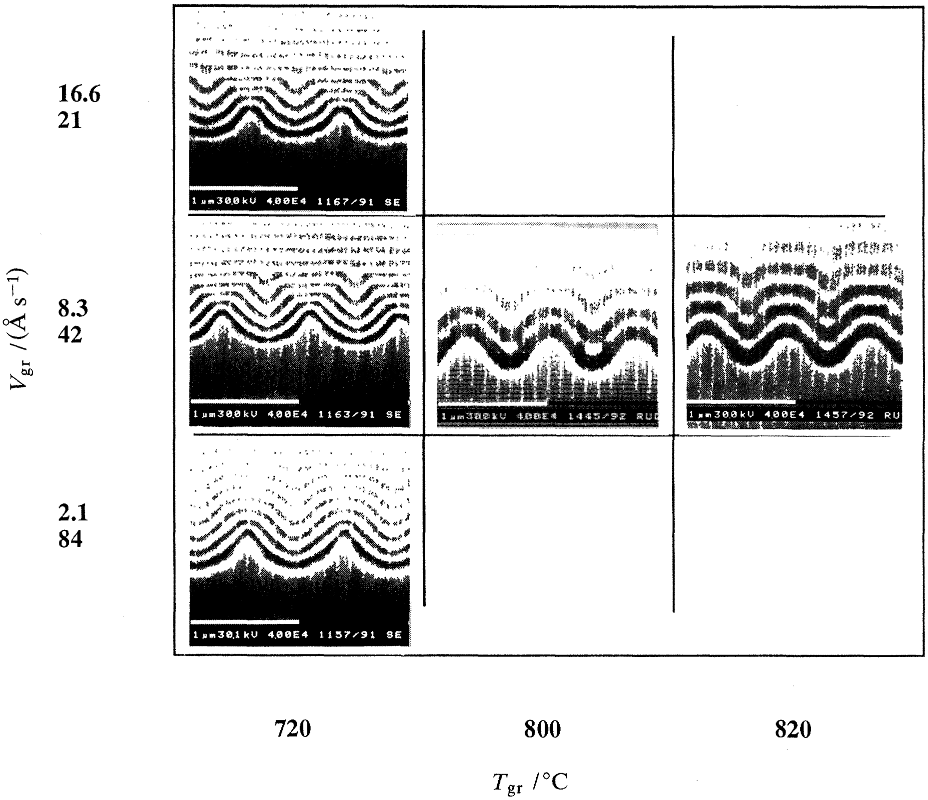

Figure 4. GaAs–AlGaAs multilayer grown on submicron gratings using different growth parameters. SEM pictures of stain etched cross sections.

crystallographic planes. From literature (Galeuchet 1990) we know that surface diffusion of group III species depends on the group III element, growth temperature T_{gr}, reactor pressure, growth velocity V_{gr}, V/III ratio. These parameters give us several possibilities to optimize the growth conditions for realizing high quality crescent shaped QWWs during the overgrowth of gratings.

Figure 4 shows stain etched cross sections of overgrown gratings at different growth temperatures and for several V_{gr} and V/III ratios. At 720 °C multilayers of

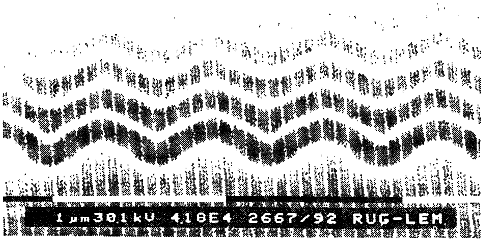

Figure 5. GaAs–AlGaAs multilayer grown at low pressure on a submicron grating. SEM picture of a stain etched cross section.

GaAs–$Al_{0.35}Ga_{0.65}As$ were deposited, while at the other T_{gr} GaAs–$Al_{0.60}Ga_{0.40}As$ multilayers were grown. Hersee (1986) found that the V_{gr} on the (100) planes increases compared to the one on inclined facets ({111}A planes in our case) as the growth temperature is increased. The same effect can be seen in figure 4 as T_{gr} is raised from 720 to 820 °C. At 820 °C {311}A-planes emerge at the intersection of (100) and {111}A-planes. The enhanced growth velocity on (100) planes can be explained by the increased surface diffusion at higher temperatures and thus more Ga and Al atoms reach the (100) planes where they can easily incorporate. When the surface diffusion becomes too high, enhanced incorporation occurs at the intersection of the (100) and the {111}A facets, hence resulting in the formation of {311}A-planes. Also due to the improved surface diffusion of Ga at high temperatures, isolated crescent shaped GaAs layers occur at the bottom of the grooves. It seems that GaAs crescents are formed rather easily, but that pinching off only occurs at high T_{gr}. Lowering the growth velocity and accordingly raising the V/III ratio also alters surface mobilities as can be seen in figure 4.

Out of the pressure dependence of the surface diffusion, one can also expect that the reactor pressure will affect the non-planar growth behaviour. Figure 5 illustrates the growth of $Al_{0.60}Ga_{0.40}As$ (with GaAs marking layers) at 76 Torr and for three different temperatures, respectively 800, 760 and 720 °C changed every three periods. At high temperatures it seems that a stabilized corrugation is formed by {311}A planes. By lowering the temperature (100) planes emerge, finally planarizing the grating structure. It is also interesting to remark that there is no filling up of the grooves by GaAs, probably because the {311}A planes have better incorporation properties than the {111}A planes (during atmospheric growth) what reduces the need for surface diffusion. The possibility to preserve the corrugation, independently of grating period or layer thickness, offers some very interesting perspectives, for instance for the growth of DFB lasers only needing one growth step.

4. Realization of vertical ‘quantum wells’

As mentioned in the previous paragraph the group III atom itself determines surface diffusion properties. The reactant species containing aluminum and the Al atom itself are very reactive hence resulting in a minor surface mobility compared to Ga (Karam 1991). As a result of the different surface diffusion properties of Al and Ga, vertical layers of Ga-rich AlGaAs are formed along the grooves of the grating

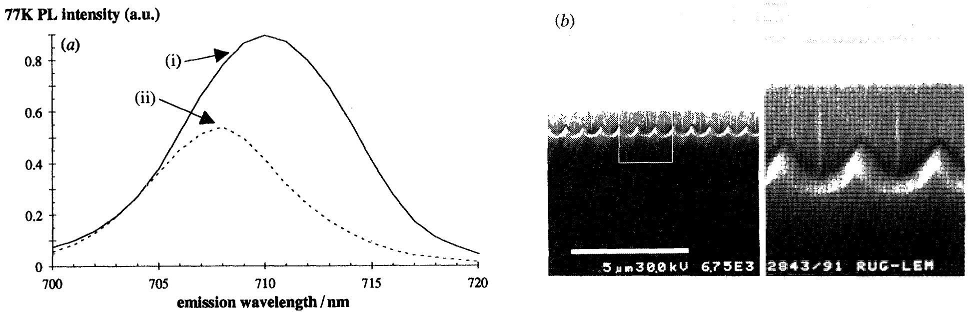

Figure 6. (*a*) 77 K PL emission spectra (two polarizations) of vertical AlGaAs layers; (i) parallel and (ii) perpendicular polarization. (*b*) SEM picture of a stain etched cross section of vertical AlGaAs layers realized during MOVPE growth of 1 μm $Al_{0.35}Ga_{0.65}As$ on a grating.

during the growth of bulk AlGaAs on gratings (Vermeire 1992). A SEM picture of a stain etched cross section of 1 μm $Al_{0.35}Ga_{0.65}As$ grown on a grating is shown in figure 6*b*. Narrow stripes of lower bandgap AlGaAs are sandwiched between AlGaAs layers with a higher Al content resulting in vertical double heterostructures. Low temperature (77 K) PL measurements reveal rather intense light emission from the vertical layers and a different behaviour as we look at the emitted light with polarization parallel and perpendicular to the grating direction (see figure 6*a*). By changing the polarization direction from parallel to perpendicular the intensity of the emitted light drops by a factor 1.7 and the wavelength shifts approximately 5 meV to the high-energy side. The same polarization dependence has been seen by Fukui *et al.* during PL measurements on fractional layer superlattices (FLS) (Fukui 1991) and analogous behaviour was also found during photoluminescence excitation (PLE) measurements on QWWS (Tsuchiya 1989). These effects are explained by the polarization selection rules for the interband (e–hh and e–lh) transitions in QWS (Bastard 1988).

The polarization anisotropy in the PL spectra is not an indisputable evidence of lateral quantum confinement, although it strongly points that way. From now on we will use the word vertical quantum well (VQWS) although we know that further measurements are needed (such as polarized PLE) to evidence lateral quantum confinement. It is also very important to remark that one should be very careful with polarization experiments if a grating structure is involved, because the electromagnetic influence of the corrugation can be polarization dependent. During our experiments we have found that the polarization anisotropy is very reproducible and consistent with the theoretical expectations, as long as the surface is fully planarized. If a corrugation is still present at the surface after growth, great care should be taken and one should check if the PL spectra of bulk material or (100) QWS doesn't show any polarisation anisotropy. The most reliable effect to check lateral confinement, is a shift of the emission wavelength as the grating can influence the intensity but not the emission wavelength when the polarization direction is changed.

(*a*) *Influence of aluminium content*

By changing the Al content of the bulk AlGaAs layer, the composition of the VQW and the resultant emission wavelength are expected to change. Figure 7 shows some experimental results. The *x*-scale is the Al content, determined by X-ray diffraction, the layer grown on planar substrate under corresponding growth conditions. The

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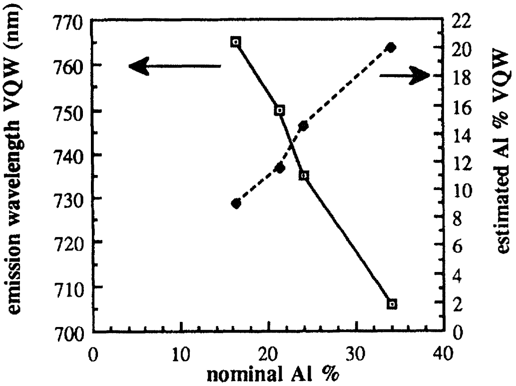

Figure 7. 77 K PL emission wavelength of VQWs obtained during growth of $Al_xGa_{1-x}As$ on gratings for different x values. Also the Al content corresponding to the emission wavelength without considering quantum confinement has been set out.

left-side ordinate is scaled by the 77 K emission wavelength of the VQWs. The right-side ordinate is the Al content y in a planar $Al_yGa_{1-y}As$ layer showing the same emission wavelength at 77 K as the VQW. With these suppositions we find a proportional variation of the Al content y, except for the higher Al contents x. The bandgap difference between the $Al_xGa_{1-x}As$ layer and the related VQW increases as x is increased and hence a stronger quantum confinement can occur, what could explain the deviation of the linear relation between x and y at higher values of x. This possible change in quantum confinement is also confirmed by a stronger degree of polarization anisotropy in the PL spectra of the vertical layers as x is increased.

(*b*) *Influence of growth temperature*

Increasing the growth temperature results in higher surface mobilities and hence a slower planarization of the grating structure (see previous paragraph). Consequently the VQWs become 'shorter' as the growth temperature is decreased, because the grating is planarized faster. To investigate the influence of T_{gr} on the VQWs we have plotted the 77 K PL emission wavelength of VQWs, grown at different temperatures (see figure 8). Also the shift in transition energy and the intensity drop due to polarization anisotropy, has been set out as a function of T_{gr}. An increased anisotropic behaviour is clear as T_{gr} is decreased which could imply that the lateral quantum confinement becomes stronger as T_{gr} is lowered. A reasonable explanation for the wavelength shift is a higher Al content of the VQWs as T_{gr} is increased and hence resulting in a weaker quantum confinement, consistent with the polarization measurements. Bhat suggests that the increase of the surface mobility of Al (or related reactants) as T_{gr} is raised is higher compared to Ga (Bhat 1988). Hence the amount of Al atoms reaching the bottom of the grooves will increase more compared to Ga atoms as T_{gr} is raised and consequently the Al content of the VQWs will rise.

(*c*) *Applications*

Due to the good luminescence properties of the VQWs, it should be interesting to realize gain coupled DFB lasers, with VQWs as active material. Regrowth of $Al_xGa_{1-x}As$ on a grating etched in $Al_xGa_{1-x}As$ can strongly diminish index coupling effects and provide periodic gain through the *in situ* formed VQWs. From a physical point of view it is also interesting to look at a VQW Fabry–Perot laser and study the polarization of the emitted light (TM polarized light is expected).

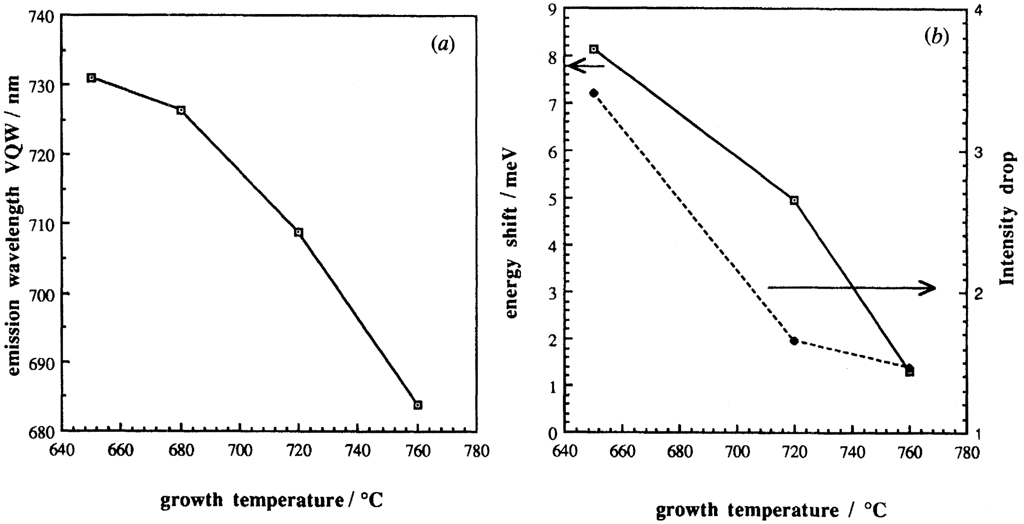

Figure 8. (*a*) 77 K PL emission wavelength of VQWs grown at different T_{gr} (*b*) polarization anisotropy of the 77 K PL emission spectra of VQWs grown at different temperatures. The shift in transition energy and the relative change of the intensity due to a change in polarization orientation from parallel to perpendicular to the wire direction.

5. Realization of quantum well wires

Based on the previous results on surface diffusion, VQWs and polarisation effects, we have grown the layer structure, schematically drawn in figure 9, on a 765 nm period grating etched in an off-oriented substrate and a 650 nm grating etched in an exact substrate. Submicron gratings have some additional advantages because the distance between the QWWs is smaller than the surface diffusion lengths of the group III atoms and smaller than the carrier diffusion lengths allowing efficient thermalization of carriers into the wires. The growth temperature was 760 °C and V_{gr} was 8.6 Å s^{-1} for GaAs (V/III = 42). Surface diffusion of Ga and Al results in VQWs and crescent shaped QWWs. The VQWs will operate as efficient collection channels for carriers as they can guide carriers to QWWs as has been recently demonstrated by researchers at Bellcore (Walther 1992).

The PL spectra (both polarizations) are also given in figure 9 for the planar sample and the two overgrown grating samples. For both grating samples three peaks can be resolved: light emitted by the VQWs centred around 695 nm, emission at 727 nm from the QWs on (100) planes between the grating grooves and a very intense PL signal from the thicker QWWs in the grooves of the gratings. The emission wavelength of the QWWs is respectively 790 and 794 nm for the off-oriented and exact sample, corresponding to a confinement energy of 63 and 53 meV. The polarization anisotropy is very strong for the VQWs, almost nothing for the QWs (as expected) and gives an idea of the degree of lateral confinement for the QWWs. The QWWs on the off-oriented substrate show the strongest polarization anisotropy (intensity drop with a factor 1.17 and an energy shift of 3 meV) what indicates a stronger lateral confinement and agrees with the larger confinement energy compared with the QWWs on the exact substrate. Increasing the temperature to 300 K results in an increase of the QWW PL intensity related to the QWs and VQWs PL intensities, providing that thermalization of carriers out of the surrounding QWs and VQWs into the QWWs takes place.

The layer structure in figure 9 still has to be optimized before it can be applied to

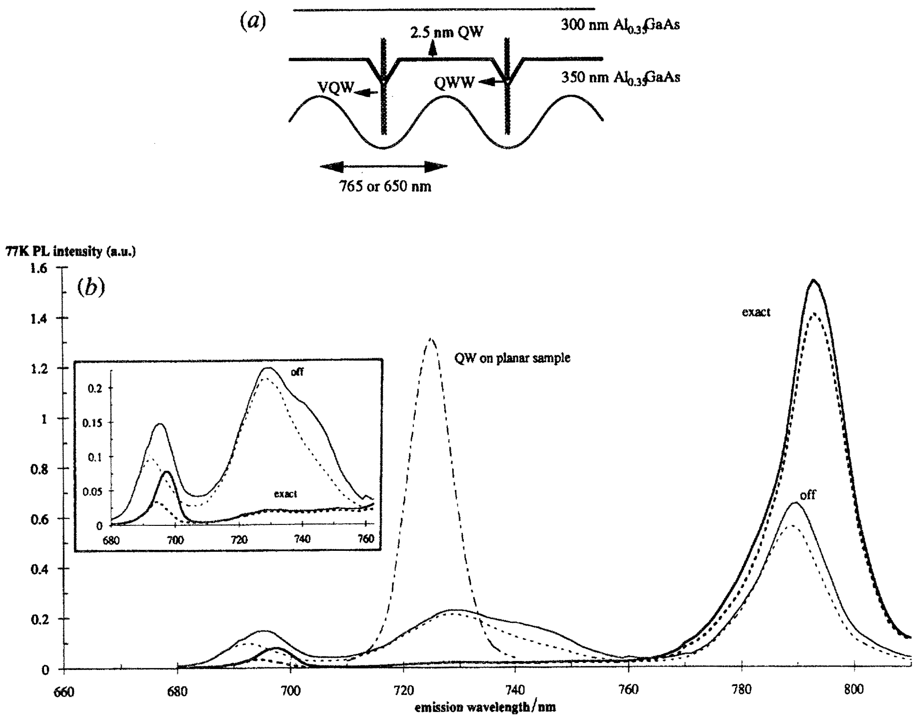

Figure 9. Schematic representation of QWWs grown on a submicron grating and the corresponding 77 K PL emission spectra for both polarization directions: ----, perpendicular; ——, parallel.

a QWW laser structure. First of all vertically stacking of QWWs, with uniform dimensions will be necessary to deal with the low filling factor Γ in QWW lasers. Also the growth parameters need to be further optimized for instance to achieve very sharp V-grooves. The intersection of the {111}A planes becomes sharper as the surface diffusion is diminished. The growth of the GaAs QWWs on the other hand requires high surface mobilities to obtain a strong filling up of the grooves and a pinching off of the surrounding QWs. One possibility to maintain the same growth conditions for the growth of the GaAs QWWs and the surrounding AlGaAs layers, is increasing the Al content and thus reducing surface diffusion effects to obtain sharp V-grooves. The disadvantage of this technique will be a decrease in refractive index difference between the cladding and waveguiding layers in the laser structure, resulting in a smaller Γ. Also the design of the waveguide structure has to be investigated and the VQWs need to operate as collection channels for carriers into the wires, allowing laser action on the QWW subbands and not on the surrounding QW-levels. Finally the possibility to preserve the grating structure as mentioned in Richter (this volume), can open some interesting perspectives for the growth of DFB and QWW Fabry Perot and DFB lasers, only needing one growth step. Figure 10 shows a preliminary experiment on the growth of a QW DFB laser starting from a corrugated GaAs substrate. As the corrugation is maintained by the {311}A planes, we do not expect problems in reducing the grating period to the exact period for a second-order DFB laser.

Finally we propose the following technique for the realization of QWWs. If it is possible to achieve lateral confinement during the growth of AlGaAs layers on gratings, it should also be possible to realize QWWs by growing an AlGaAs QW on a

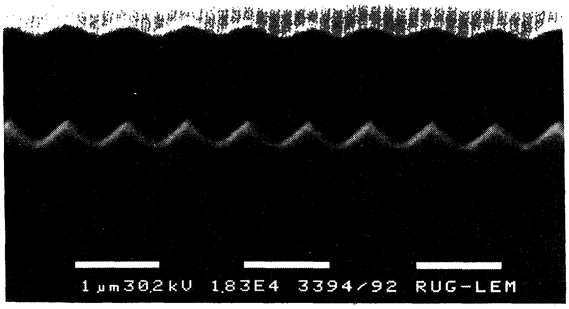

Figure 10. InGaAs QW between two $Al_{0.20}Ga_{0.80}As$ barrier layers on top of a 1.5 µm $Al_{0.60}Ga_{0.40}As$ undercladding layer grown on a submicron grating. SEM picture of a stain etched cross section.

grating. By growing a thin $Al_{0.25}Ga_{0.75}As$ QW between $Al_{0.50}Ga_{0.50}As$ barrier layers on a grating it should be possible to isolate QWWS in the grooves of the gratings due to a concentration variation of the Al in the QW. Also InGaAs QWWS could give interesting perspectives. As it has been demonstrated by Galeuchet (1990) that the diffusion length of In containing species, on a SiO_2 mask and on {111} planes in InP substrates, is larger compared to Ga. If In has the same enhanced diffusion on {111}A planes in GaAs, it should be possible to realize InGaAs QWWS with a higher In concentration (lower bandgap) compared to the adjacent QWS. An additional effect is that the amount of strain in the QWWS will also increase, enhancing the bandgap lowering due to concentration variation. One can even think at InAlGaAs strained QWWS probably containing less Al and more In compared to the surrounding InAlGaAs QWS on the {111}A facets. In conclusion strained QWWS on GaAs gratings can offer a great potential for the realisation of QWW lasers, although interpretation of the obtained results will be very difficult, due to a mixing of strain and two-dimensional quantum confinement effects.

6. Conclusion

A brief review has been given on the advantages and disadvantages of low-dimensional semiconductor lasers. Non-planar MOVPE growth on submicron gratings has been studied to understand the surface diffusion effects and their dependence on growth conditions. Due to the different surface mobilities of Ga and Al, VQWS are formed during the growth of bulk AlGaAs on gratings. These VQWS play an important role as carrier collection channels for QWWS grown on gratings in between the VQWS. Finally some remarks on future QWW laser design have been made and some techniques for the realization of AlGaAs and strained QWWS have been proposed.

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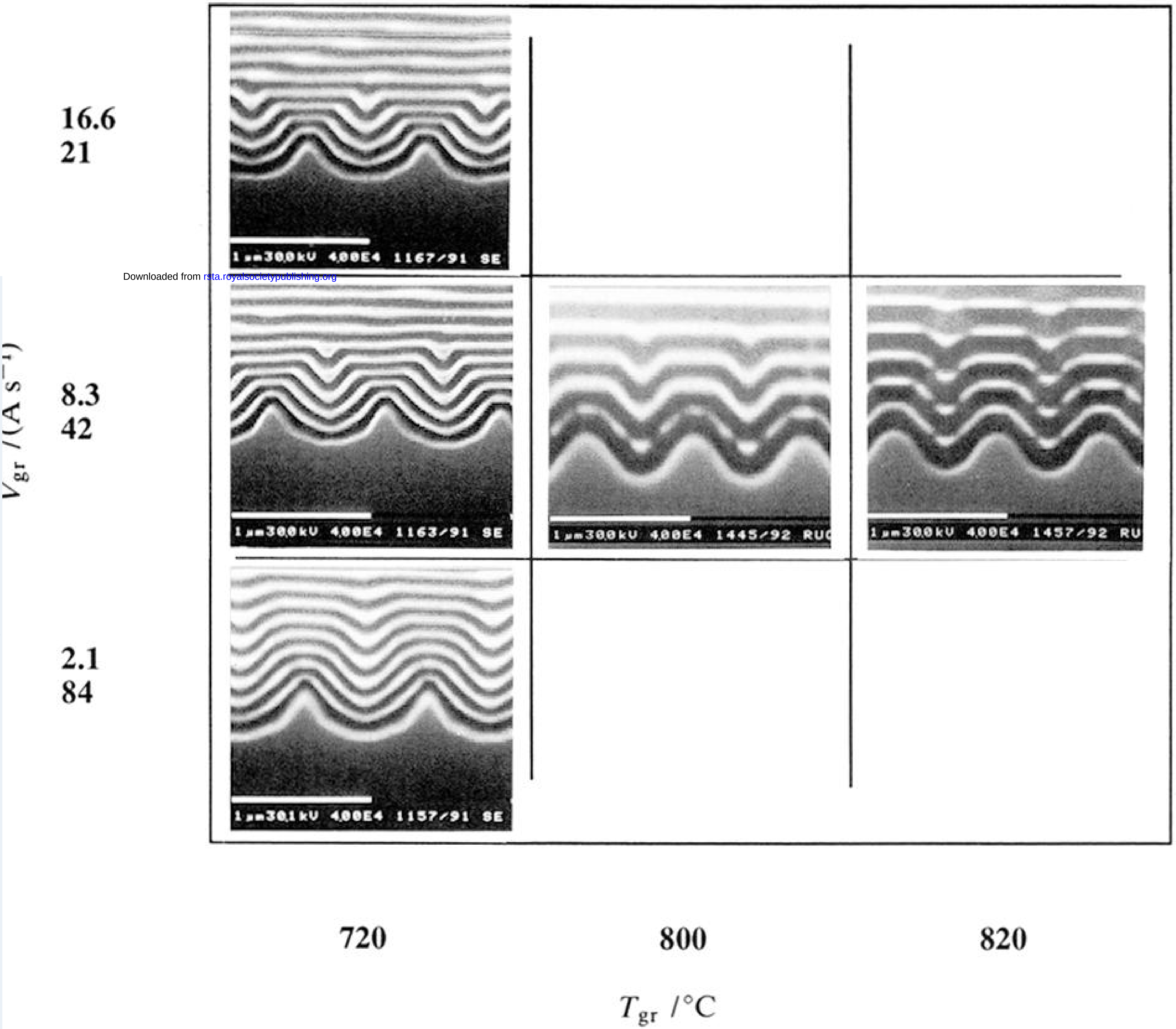


igure 4. GaAs–AlGaAs multilayer grown on submicron gratings using different growth parameters. SEM pictures of stain etched cross sections.

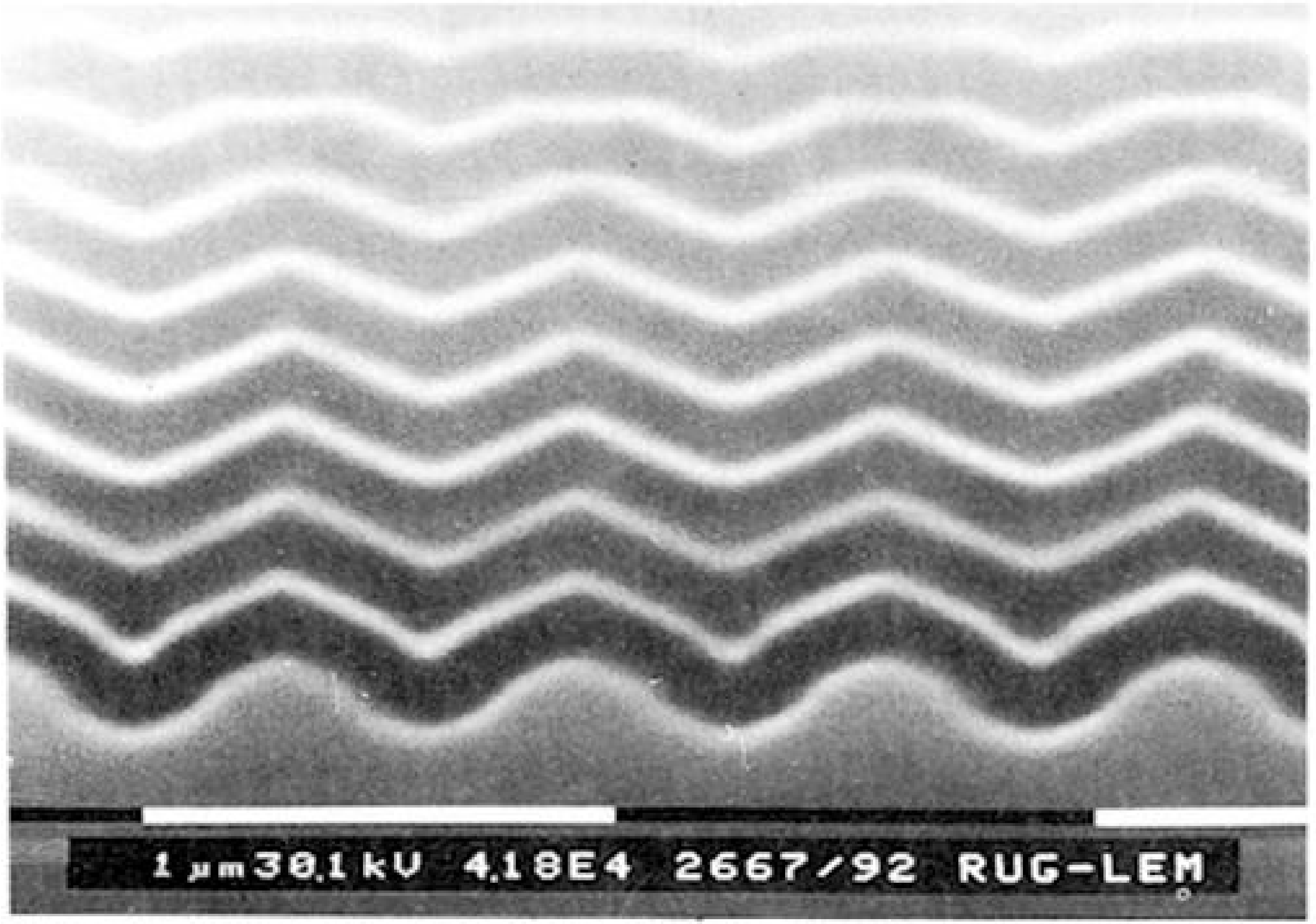


Figure 5. GaAs–AlGaAs multilayer grown at low pressure on a submicron grating. SEM picture of a stain etched cross section.

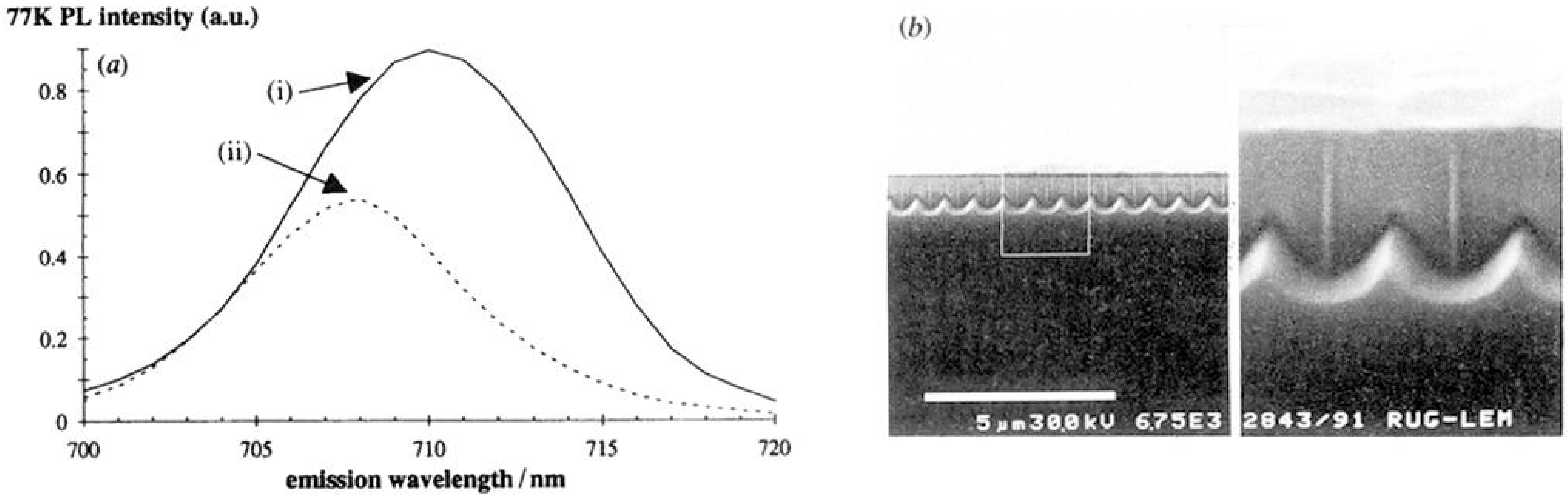
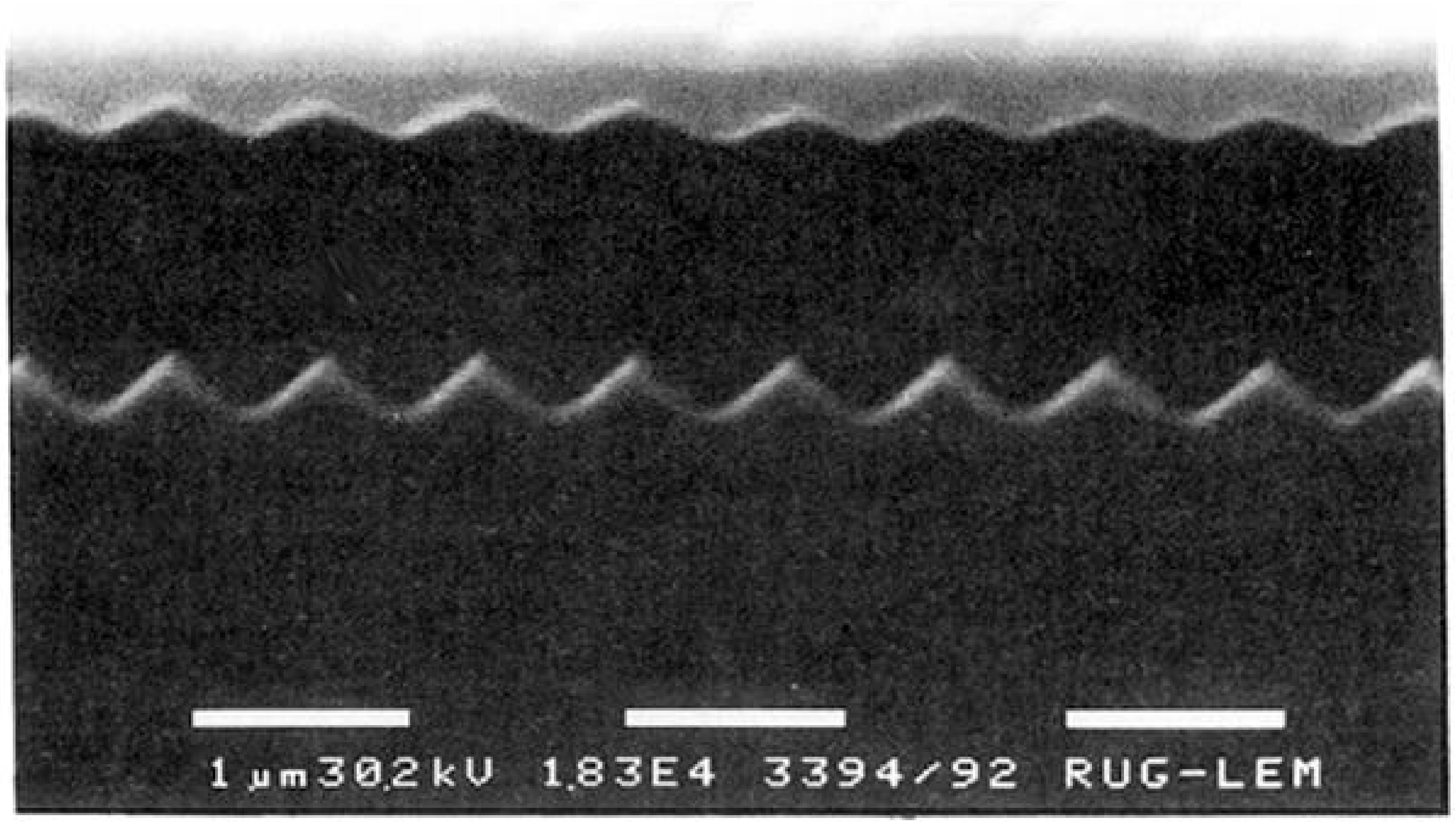


Figure 6. (*a*) 77 K PL emission spectra (two polarizations) of vertical AlGaAs layers; (i) parallel and ii) perpendicular polarization. (*b*) SEM picture of a stain etched cross section of vertical AlGaAs ayers realized during MOVPE growth of 1 μm $Al_{0.35}Ga_{0.65}As$ on a grating.



igure 10. InGaAs QW between two $Al_{0.20}Ga_{0.80}As$ barrier layers on top of a 1.5 μm $Al_{0.60}Ga_{0.40}As$ undercladding layer grown on a submicron grating. SEM picture of a stain etched cross section.