Gas-Source MBE Growth of a Long-Wavelength Material and Its Application to Semiconductor Lasers

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ABSTRACT Work is under way on the development of Group III-V optical and electronic devices using gas-source molecular-beam epitaxy (GSMBE), an extension of molecular-beam epitaxy in which the Group V are gas-source (AsH_3, PH_3). High uniformity of composition and thickness has been achieved by optimizing the position and conditions of growth. In considering the application of GSMBE to 1.3μm MQW lasers, n-type modulation-doped MQW lasers using InAsP multi-quantum wells were studied, since GSMBE is suited to the doping of extremely restricted regions. Using a laser selectively n-doped to $1 \times 10^{18} cm^{-3}$ at optimized growth temperature, with a cavity length of 1200μm, the extremely low threshold current density J_{th} of 250 A/cm^2 was achieved. This has for the first time confirmed the superiority of GSMBE for selective n-doping with respect to threshold current density.

1. INTRODUCTION

Studies on gas-source molecular-beam epitaxy, or GSMBE, in which one or more of the sources for MBE is a gas, are being actively carried out in Europe and the United States. The main advantages of MBE are the abruptness of heterojunctions and impurity distributions, uniformity of layer thickness and composition, safety, since it is an ultra-high vacuum process, and the fact that growth can be monitored *in situ*. GSMBE, while retaining these advantages, makes possible simultaneous handling of As and P, which is a problem in conventional MBE, and improved duty factors since sources are supplied from outside. The use of gases means that safety is slightly compromised relative to MBE, but since it consumes only about 1/20th as much AsH_3 and PH_3 as MOCVD, it offers an excellent trade-off between safety and environmental friendliness.

At present only Group V materials are used in gas form, but this will eventually be possible for Group III too, making possible selective growth, lateral growth[1)], etc., rendering GSMBE technology indispensable to the future realization of optoelectronic ICs.

In introducing this GSMBE technique in which Group III elements are supplied in metallic form, but Group V in the form of AsH_3 and PH_3 gas, we have confirmed the basic performance of the Group V cracking cell, and studied the fundamental aspects of GaInAsP uniformity on 2-inch wafers and MQW laser growth conditions. In terms of laser applications, we have also studied 1.3-μm n-type modulation-doped InAsP MQW lasers, which show great promise as an optical source for access networks and in laser arrays. This paper describes GSMBE growth of GaInAsP --a long-wavelength material--and discusses InAsP MQW lasers.

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2. UNIFORMITY OF THICKNESS

2.1 Wafer Position (θ) Dependence of Thickness Distribution in AlAs/GaAs

First the wafer position θ at which uniformity is maximized was determined using GaAs and AlAs, which as binary compounds are the most fundamental.

When crystals are grown with the center of the wafer rotated to the peak position of the molecular beam of each of the sources (center of the chamber), the growth rate at the center of the wafer increases, creating a convex profile in which the layer is thicker at the center and thinner toward the edges. It is therefore necessary that growth be carried out with the center of the manipulator offset from the peak position. Accordingly in these experiments, the position of the angle of wafer retention (θ) was adjusted equivalently to find the point of maximum uniformity.

The experiments were conducted by growing alternate layers of AlAs and GaAs on 2-inch GaAs wafers, moving the position of θ to 80 through 95° (where 95° is the point at which the wafer is oriented directly underneath), and observing changes in thickness distribution by scanning electron microscopy (SEM).

As Figure 1 shows, thickness distribution was poorest when θ was 90-95°, whereas at 84-87°, a relatively good result of ±2% or less was obtained for both AlAs and GaAs. Since wafer thickness was measured by SEM, accuracies better than ±2% could not be effectively measured, but this method is used to find trends relating to the point of optimum uniformity. Thickness distribution was calculated as being ±1/2 {(maximum value - minimum value) / average value}. If, on the other hand, θ is decreased, the growth rate for AlAs was reduced, and that for GaAs tended to increase slightly. This is because moving the θ of the wafer resulted in a decrease in the angle of incidence of the Al cell molecular beam to the wafer.

Thus from the standpoint of both thickness distribution and growth rate, the growth position of θ = 86° gave a good thickness distribution for both AlAs and GaAs, with values of ±1.9% and ±1.3% respectively.

2.2 Distributions of Thickness, Composition and Photoluminescence Wavelength for InP, Ternary Lattice- Matched $In_{1-x}Ga_xAs$ and 1.3 μm Quaternary $In_{1-x}Ga_xAs_yP_{1-y}$ (1.3Q)

Experiments for growth uniformity were carried out at growth rates (GR) of 0.3 μm/h for InP, 0.5 μm/h for $In_{1-x}Ga_xAs$ and 0.4 μm/h for 1.3Q. In all cases the growth temperature was 515°C and the chamber pressure in the order of 4-5 x 10^{-5} torr. Thickness distribution was measured by the α step difference due to selective etching. Table 1 summarizes the results obtained.

Comments regarding the main properties are as follows:

1) The thickness distribution for InGaAs was ±1.1% and the photoluminescence wavelength distribution (except for 5 mm at the edge) was ±0.5 nm, which were satisfactory.
2) The thickness distribution for 1.3 μm bulk InGaAsP was ±1.6% and the photoluminescence wavelength distribution (except for 5 mm at the edge) was ±1 through ±3 nm, which were satisfactory.

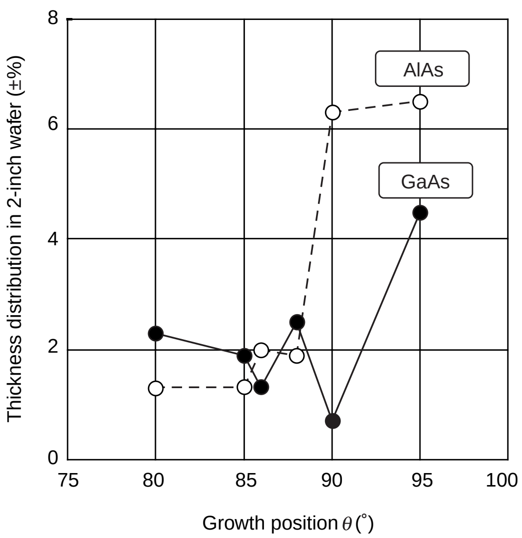

Figure 1 Thickness distribution vs. growth position in 2-inch wafers

Table 1 Uniformity in 2-inch wafers grown by GSMBE

InP thickness distribution	±2.5%
InGaAs bulk thickness distribution	±1.1%
InGaAs bulk wavelength distribution	±0.5nm
1.3Q bulk thickness distribution	±1.6%
1.3Q bulk wavelength distribution	±2nm

3. TEMPERATURE DEPENDENCE OF MQW LASER GROWTH

The growth temperature dependency was investigated for 1.3-μm compressively-strained InAsP/GaInAsP MQW lasers (nondoped barriers). InAsP MQW lasers have a large conduction band offset ΔE_c, have attracted attention as a material for high-temperature operation lasers, and are being actively developed outside. GSMBE, being a low-temperature growth technique, is considered suitable for the growth of InAsP MQW lasers which have high-strain (1.4 to 1.6%).

Using GSMBE, we grew a quantum well layer of compressively strained $InAs_yP_{1-y}$ 7-8 nm thick, a barrier layer of lattice-matched GaInAsP 9-10 nm thick (having a wavelength of 1.1 μm, abbreviated 1.1Q), an optical confinement (SCH) layer of 1.1Q 120 nm thick, a lower clad layer of n-InP 0.3 μm thick doped with 5 x $10^{17}cm^{-3}$ Si, and an upper clad layer of p-InP 0.1 μm thick doped with 5 x $10^{17}cm^{-3}$ Be. Growth temperature for the InP clad layers was 515°C constant, but was varied to several points between 415 and 515°C for the SCH-MQW layer to investigate the influence of growth temperature.

The photoluminescence (PL) wavelength from both the MQW and SCH layers was lengthened by a decrease in growth temperature. To investigate the reason for this lengthening, composition and thickness were calculated for each of the layers. The composition of the 1.1Q optical confinement and barrier layers was determined by X-ray and PL wavelength, and the composition and thickness of the MQW by X-ray analysis and quantum level, after carrying out PL and X-ray analysis, and TEM measurements.

Figure 2a) shows the growth temperature dependence of composition (x, y) in InAsP/GaInAsP MQW layers. The Group III constituent does not vary greatly, but the amount of As in the Group V constituent increased at lower growth temperature.

Figure 2b) shows the growth temperature dependence of thickness in InAsP/GaInAsP MQW layers. The rate of change of the barrier layer is small, but that of the well layer is great, so that growth at lower temperature results in greater thickness. This is attributed to increased growth rate due to an increase in the rate of capture of As and P at lower temperatures. The smaller change in barrier layer growth rate is due to the fact that it includes Ga, and since the bonding strength of Ga to P and Ga to As is greater than that of In to P or In to As, there is less chance of the re-desorption of impinging molecules[2].

Figure 3a) shows the growth temperature T_g dependence

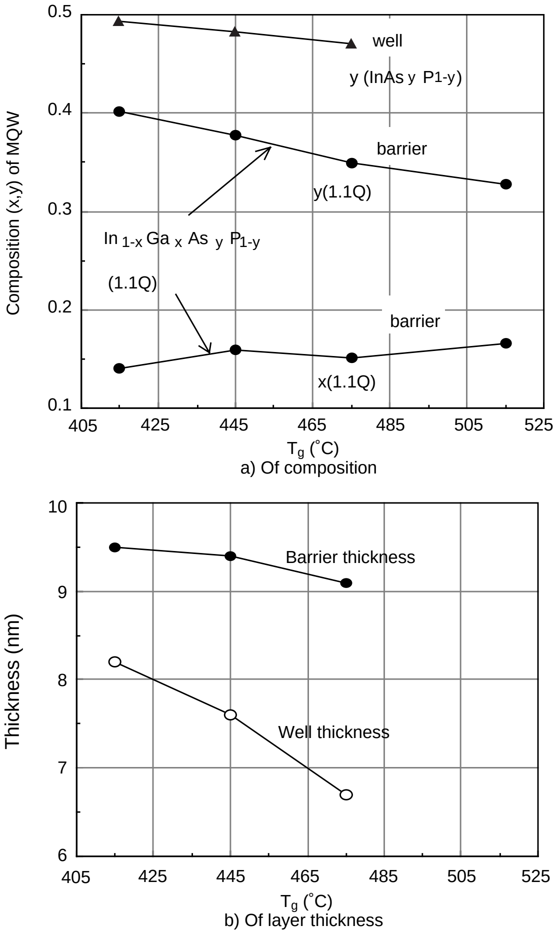

Figure 2 Growth temperature T_g dependence in InAsP/GaInAsP MQW layers

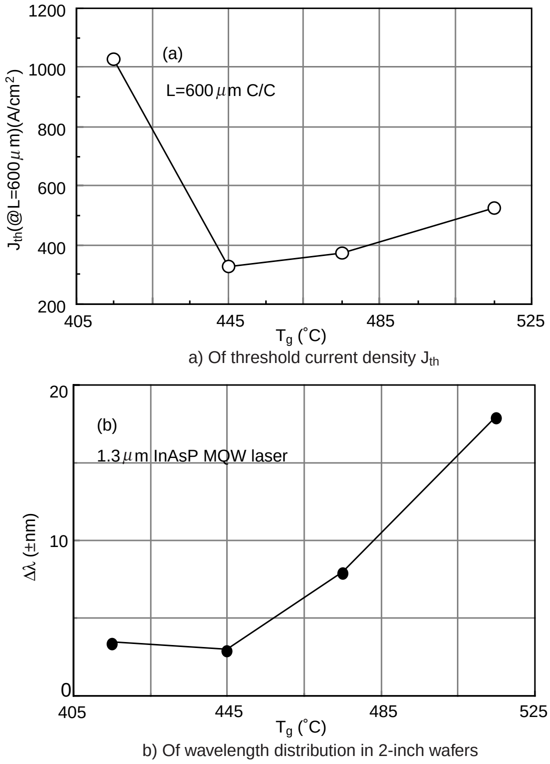

Figure 3 Growth temperature T_g dependence in InAsP MQW lasers

of threshold current density J_{th} in InAsP MQW lasers, at a fixed cavity length L of 600 μm. The rise in J_{th} at the high-temperature side is due to deterioration in crystal properties due to the decrease in critical thickness as growth temperature increases. The rise in J_{th} at the low-temperature side is due to the fact that the atoms lack in migration, resulting in the proliferation of nonradiative recombination centers. Thus the threshold current density is at the minimum around 445°C, and as a result of this it was possible to reduce J_{th} from 450 to 325 A/cm^2 (at L = 600 μm) by growing the clad layers at 515°C and growing the optical confinement and MQW layers at around 445°C. These results are an improvement over the J_{th} of 1.3-μm lasers made by MOCVD[3]. Figure 3b) shows the growth temperature T_g dependence of wavelength distribution in 2-inch InAsP MQW laser wafers (except for 5 mm at the wafer edge). At a growth temperature of 515°C, there was a large distribution of ±18 nm, but at 445°C or below, the distribution was ±3 nm or less, a comparatively good value. Here too, a growth temperature of around 445°C proves suitable.

4. LOW-THRESHOLD 1.3μm InAsP n-TYPE MD-MQW LASERS

4.1 The Need for Low-Threshold Lasers and the Principle of the MD-MQW

The crucial component of high-density parallel optical interconnection systems is a semiconductor laser with an emitting wavelength of 1.3 μm. The need to reduce discrepancies in delay time (skew) and reduce power consumption make it essential that a lower threshold current be achieved. One attractive method for reducing threshold current density is the n-type modulation doped MQW structure, which has an undoped quantum well layer and an n-doped barrier layer. This is because it has been theoretically demonstrated that the use of this MD-MQW structure will greatly reduce the transparent carrier density[4]. There have already been several reports of n-type MD 1.3μm GaInAsP MQW lasers using MOCVD technology[5)–6)], but none for that wavelength band using MBE or GSMBE. Since GSMBE makes it possible to achieve an abrupt doping profile, it is considered suited to the growing of MD-MQWs, and a study has accordingly been conducted on the use of GSMBE in growing n-type modulation doped 1.3μm InAsP MQW lasers.

4.2 Fabrication and Evaluation of MD-MQW Lasers

A 1.3μm InAsP/GaInAsP n-type MD-MQW laser (see Figure 4) was grown on an n-InP substrate. The laser was composed of n-InP and p-InP clad layers, a compressively strained MQW layer, and SCH layers of GaInAsP (1.1Q) 120 nm thick on both sides of the MQW. The MQW active layer was composed of a 1.45% compressively strained

$InAs_{0.45}P_{0.55}$ quantum well layer 8 nm thick and a barrier layer of lattice-matched GaInAsP on InP having the same composition as the SCH layer and measuring 10 nm. There were 3 wells. The center 7 nm of the barrier layers were n-doped, with doping density N_D varied from 1 to 5 x $10^{18}cm^{-3}$. The dopant used was silicon.

Figure 5 shows the silicon doping profile near the MQW layer measured by secondary ion mass spectroscopy (SIMS). The doping density of the barrier layers was 1 x $10^{18}cm^{-3}$. As can be seen, the doping profile is extremely abrupt, with most of the silicon atoms remaining within the barrier layer. To evaluate optical properties, measurements of room-temperature photoluminescence were made for all the types of lasers grown at varying doping concentrations. For lasers with undoped barrier layers, it was possible to obtain higher photoluminescence intensities with a full-width half-maximum value of only 32 meV, but as the doping concentration of the barrier layer increases, the peak intensity drops abruptly and the FWHM value increases, even to 130 meV in lasers doped to 5 x $10^{18}cm^{-3}$.

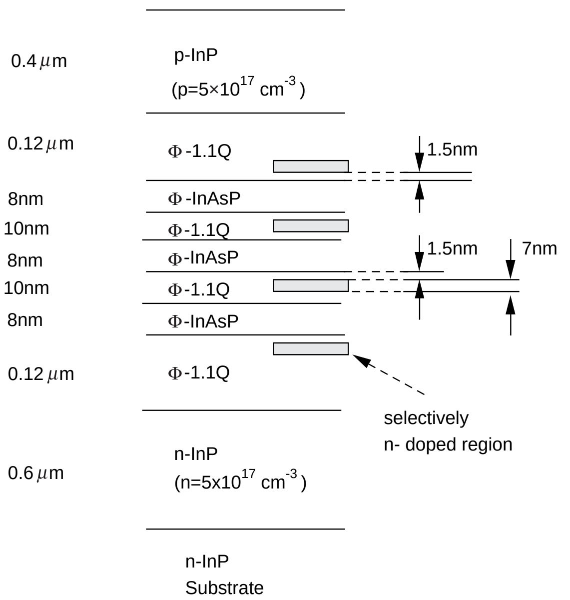

Figure 4 Schematic structure of 1.3μm InAsP/GaInAsP n- type MD-MQW lasers grown by GSMBE

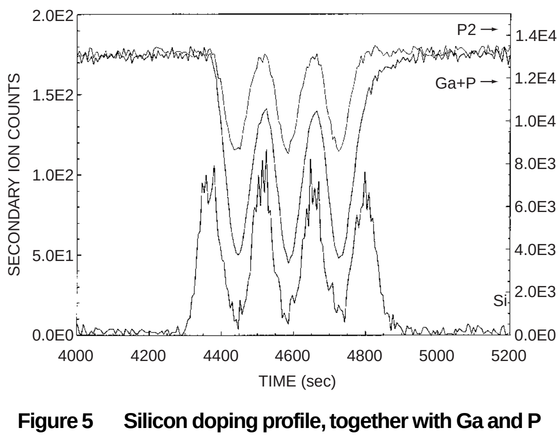

Figure 5 Silicon doping profile, together with Ga and P element profiles near the quantum well active layer, measured by SIMS; doping density of the barrier layers was 1 x $10^{18}cm^{-3}$

Figure 6 shows the dependence of threshold current density on inverse cavity length during growth at a constant temperature of 515°C with N_D as a parameter. In devices with cleaved facets and a cavity length of 1000μm or more, a decrease in threshold current density was observed in 1 x $10^{18}cm^{-3}$ doped MD lasers compared to nondoped barrier lasers. The minimum threshold current density was in lasers doped to 1 x $10^{18}cm^{-3}$, with 330 A/cm^2 obtained at a cavity length of 1200 μm.

Further, optimization of the growth temperature of MD-MQW lasers was then carried out with N_D constant at 1 x $10^{18}cm^{-3}$, as shown in Figure 7. The growth mode at which minimum threshold current density was achieved consisted of growing the clad layer at 515°C, the SCH-MQW layer at 455°C, with a threshold current density of only 250 A/cm^2 --a world-class value--achieved at a cavity length of 1200μm. An estimate was also made of the threshold current density at infinite cavity length $J_{th}\infty$.

Figure 8 shows the relationship $J_{th}\infty$ per well and N_D for two kinds of growth temperature. The broken line shows extrapolation from results obtained from lasers grown at a constant temperature of 515°C. The minimum $J_{th}\infty$ per well, for lasers doped to 1 x $10^{18}cm^{-3}$, was 57 A/cm^2/well, a result that is just as good as that reported for an n-type MD laser made by MOCVD[8].

In addition, with respect to nondoped barrier lasers and 1 x $10^{18}cm^{-3}$ doped MD-MQW lasers, stripe lasers having a width of 20μm were fabricated and their properties were evaluated. The differential quantum efficiency of devices with cleaved facets having a cavity length of 300μm was good, at 42%/facet for nondoped barrier lasers and 44% for MD-MQW lasers. Based on the cavity length dependence of efficiency, internal loss was estimated to be 6.0 cm^{-1} for nondoped barrier lasers and 4.6 cm^{-1} for MD lasers, and quantum well efficiency to be 100% for both. The lower internal loss for MD lasers is attributed to a reduction in intervalence band absorprion caused by a

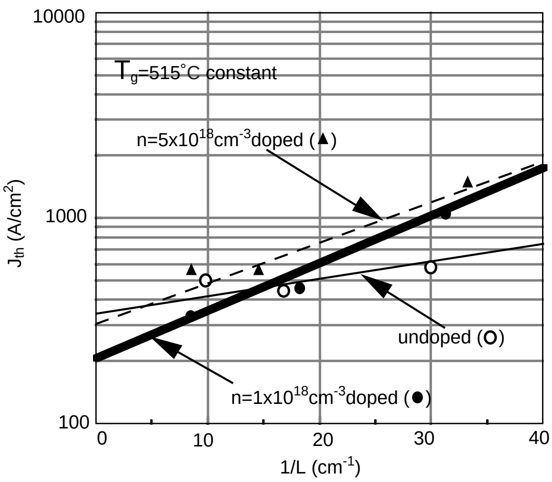

Figure 6 Dependence of threshold current density J_{th} on inverse cavity length 1/L in 1.3μm MD-MQW lasers (N_D = 1 x $10^{18}cm^{-3}$)

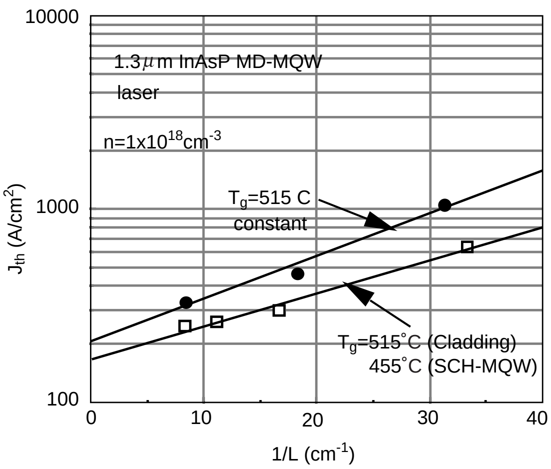

Figure 7 **Dependence of threshold current density J_{th} on inverse cavity length 1/L in 1.3μm MD-MQW lasers (N_D= 1 x $10^{18}cm^{-3}$) at selected growth temperatures T_g**

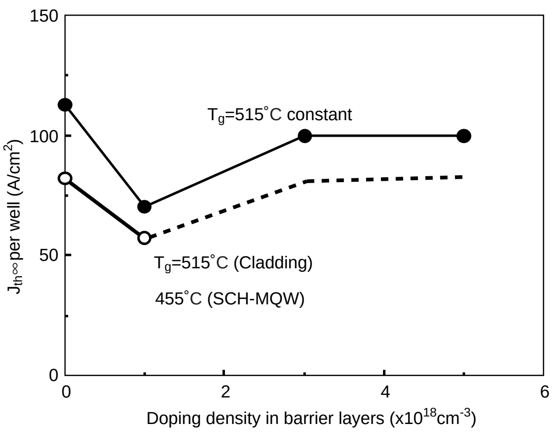

Figure 8 **Dependence of threshold current density J_{th} at infinite cavity length on doping density in barrier layers of 1.3μm MD-MQW; broken line is extrapolated from data for 515°C constant growth lasers**

decrease in threshold carrier density. The characteristic temperature T_0 in the range of 20 to 70°C in devices with cleaved facets and a cavity length of 1200μm were 75 K for both types of lasers.

Further, with respect to stripe lasers with a width of 20μm, devices were fabricated with a cavity length of 200μm and with highly reflective coatings on both facets (90%/96%) (see Figure 9), and comparisons with nondoped barrier lasers were carried out. In MD-MQW lasers, low-threshold operation (at a threshold current of 11.5 mA) was confirmed. This suggests that if an ideal buried heterostructure laser with a width of 1μm can be fabricated, we may expect to achieve threshold currents of as low as 0.6 mA, opening the way for applications in laser array devices.

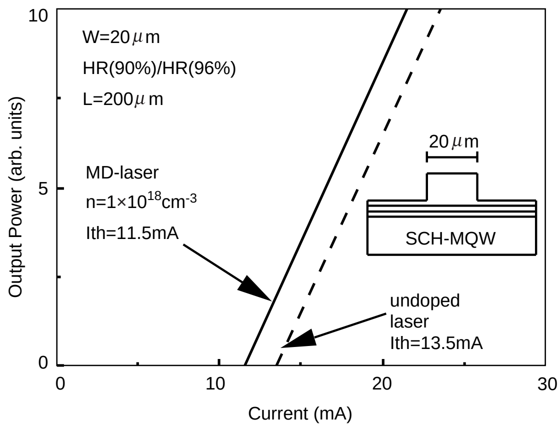

Figure 9 **Light output power vs. current in 1.3μm MD-MQW lasers (N_D= 1 x $10^{18}cm^{-3}$) and undoped MQW lasers**

5. CONCLUSION

Work is proceeding on the development of Group III-V optical devices and electronic devices by means of gas-source molecular beam epitaxy (GSMBE), a variant of MBE technology in which the Group V sources are in the form of the gases AsH_3 and PH_3. A major advantage of GSMBE is high uniformity, and by optimizing the growth position and growth conditions it was possible to achieve excellent uniformity in composition and thickness. With a view to using the advantages of GSMBE technology in the growing of 1.3μm MQW lasers, which show promise as optical sources for access networks and laser array devices, work is going forward on n-type modulation-doped MQW lasers in which the quantum well layer is nondoped, and only the barrier layer is n-doped. With a 1 x $10^{18}cm^{-3}$ selectively n-doped laser grown under optimized temperature, extremely low threshold current density J_{th}--250 A/cm^2 at a cavity length of 1200μm--were achieved. It was possible to confirm the superiority of n-type modulation doping by GSMBE in terms of threshold current density.

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