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SIMS depth profiling of InGaAsN/InAlAs quantum wells on InP

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Abstract

Quaternary $In_xGa_{1-x}As_yN_{1-y}$ ($x > 0.53$, $1 - y < 0.03$) QWs grown between $In_{0.52}Al_{0.48}As$ barriers on InP substrate were analyzed by SIMS depth profiling. For the determination of the indium and nitrogen calibration curves, $In_xGa_{1-x}As$ ($0 \leq x \leq 1$) standards were used which were partly implanted with nitrogen at an energy of 75 keV and a dose of 5×10^{15} N_2 molecules/cm^2. The QW structures were grown by molecular beam epitaxy with a nitrogen plasma source. MCs^+ secondary ions (M = Al, Ga, In, As and N) were used for depth profiling. Nitrogen is found incorporated in $In_xGa_{1-x}As$ layers in concentrations needed for the intended laser applications. The nitrogen concentration can be reliably assessed by SIMS. Thickness and compositional data agree with the nominal data and the data determined by high resolution X-ray diffraction. The In-content is apparently not influenced by the incorporation of nitrogen and vice versa.

Keywords: SIMS; Depth profiling; Laser diode; Quantum well; InGaAsN/InAlAs

1. Introduction

Semiconductor diode lasers emitting at around 2 μm ($E = 0.62$ eV) are of significant interest for absorption spectroscopy of atmospheric gases. H_2O, N_2O and CO_2 for example are absorbing in this spectral region. Due to its technological maturity, $In_xGa_{1-x}As$ on InP substrate is a promising material system. Fig. 1 shows the bandgap energy versus lattice constant of the binaries GaAs, InAs and InP and of the ternary $In_xGa_{1-x}As$. Lattice matching of the ternary layer to the InP substrate is obtained with $x = 0.53$. The corresponding bandgap energy of about 0.76 eV is too high for the intended applications. Further increase of the In concentration is limited by compressive strain generated by lattice mismatch. A new approach to increase the emission wavelength is to incorporate nitrogen in the $In_xGa_{1-x}As$ QWs. The bandgap energy versus lattice constant curves of $GaAs_yN_{1-y}$ based on calculations of Kondow et al. [1] and also of $In_{0.53}Ga_{0.47}As_yN_{1-y}$ are shown in Fig. 1. The behaviour of the quaternary compound is assumed to be similar to the corresponding curve for $GaAs_yN_{1-y}$. Thus, the incorporation of nitrogen into $In_{0.53}Ga_{0.47}As$ at a concentration of a few percent only is expected to decrease the bandgap energy to the desired lower value. In addition, the In-content must be increased beyond $x = 0.53$ to achieve lattice matching (dashed line through $In_{0.53}Ga_{0.47}As$ in Fig. 1). In this paper, SIMS is applied for the depth profiling of structures containing $In_xGa_{1-x}As_yN_{1-y}$ QWs between lattice matched $In_{0.52}Al_{0.48}As$ barriers on InP substrate.

2. Experimental

For the determination of both the depth and the In calibration curves, $In_xGa_{1-x}As$ layers with the

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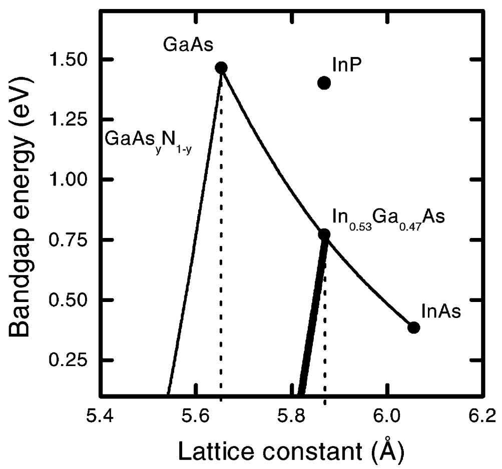

Fig. 1. Bandgap energy vs. lattice constant of GaAs, InP, InAs, $In_xGa_{1-x}As$, calculated bandgap energy of $GaAs_yN_{1-y}$ on GaAs, assumed curve for $In_{0.53}Ga_{0.47}As_yN_{1-y}$ on InP (bold line) and lattice matched GaInAsN on GaAs and InP (dashed lines).

composition varying between GaAs and InAs were grown by molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD). The In-content was determined by both energy dispersive X-ray analysis (EDX) and high resolution X-ray diffractometry (HRXRD). The N calibration curve was established by implantation of nitrogen into some of the above $In_xGa_{1-x}As$ layers at an energy of 75 keV and a dose of 5×10^{15} N_2 molecules/cm^2. Single and double QW structures of $In_xGa_{1-x}As_yN_{1-y}$ QWs were grown between $In_{0.52}Al_{0.48}As$ barriers on InP substrate by MBE with an rf plasma nitrogen source. The schematics of the nominal structures with approximate layer thicknesses are shown in Table 1. The list of selected samples is given in Table 3. Depth profiles were measured in an ATOMIKA spectrometer. Cs primary ions at an energy of 1.5 and 5 keV impinging at an angle of 45° were used for sputtering. The ion current was 11 and 47 nA, respectively. The width of the quadratic crater was 250 and 350 μm, respectively. MCs^+ secondary ions (M = Al, Ga, In, As and N) were used for depth profiling.

Table 1
Schematic of single and double QW structures

Function	Composition	*d* (nm)
Single QW structure		
Cap	$In_xGa_{1-x}As$	5
Barrier	$In_{0.52}Al_{0.48}As$	50
QW	$In_xGa_{1-x}As_yN_{1-y}$ [a]	12
Barrier + buffer	$In_{0.52}Al_{0.48}As$	200
Substrate	InP	
Double QW structure		
Cap	$In_xGa_{1-x}As$	5
Barrier	$In_{0.52}Al_{0.48}As$	200
QW	$In_xGa_{1-x}As_yN_{1-y}$ [a]	10
Barrier	$In_{0.52}Al_{0.48}As$	30
QW	$In_xGa_{1-x}As_yN_{1-y}$ [a]	10
Barrier + buffer	$In_{0.52}Al_{0.48}As$	100
Substrate	InP	

[a] For composition, see Table 3.

3. Results and discussion

Table 2 shows the sputtering rates used for depth calibration. The sputtering rates of $In_xGa_{1-x}As$ can be described by a linear fit between GaAs and InAs. Relative sensitivity factors (RSFs) were used for quantitative calibration of secondary ion intensities. The definition used here is $RSF = C_M/(I_M/I_{ref})$. C_M and I_M are concentration and secondary ion intensity of element M, respectively, and I_{ref} is the secondary ion intensity of a reference element, here As. Fig. 2 shows the RSF of $InCs^+$ normalized to $AsCs^+$ ion intensity versus the In-content x derived from the $In_xGa_{1-x}As$ standards at a primary ion energy of 5 keV. The RSF depends linearly on the In-content. The RSF of NCs^+ normalized to $AsCs^+$ ion intensity and derived from the implanted $In_xGa_{1-x}As$ standards at a primary ion energy of 5 keV is 3.1, without significant dependence on the matrix composition. This value is larger by more than one order of magnitude as compared with the RSF of $InCs^+$ (see Fig. 2) reflecting the smaller ion yield of NCs^+.

Fig. 3 shows the dependence of the normalized $AlCs^+/AsCs^+$ ion intensity on sputtering time of a

Table 2
Sputtering rates

E (keV)	Sputtering rate *r* (nm/min)		
	$In_xGa_{1-x}As$ ($0 \leq x \leq 1$)	$In_{0.52}Al_{0.48}As$	InP
1.5	$7.4 \leq r \leq 11.9$	8.3	
5	$34 \leq r \leq 57$	33	60

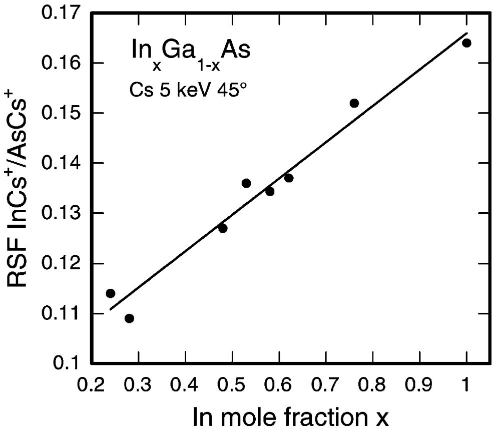

Fig. 2. RSF of $InCs^+$ normalized to $AsCs^+$ ions vs. the In concentration for $In_xGa_{1-x}As$.

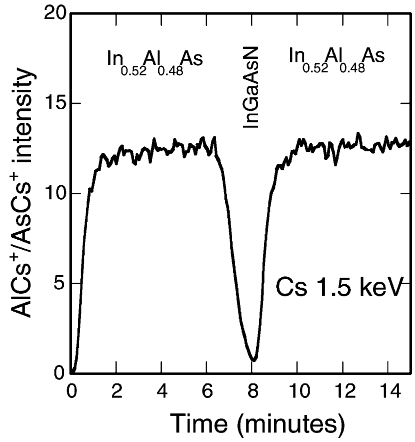

Fig. 3. Normalized $AlCs^+/AsCs^+$ intensity vs. time of a single QW structure.

single QW structure, determined at an energy of 1.5 keV for optimum depth resolution. The QW thickness is obtained in time units by approximation of the measured $AlCs^+/AsCs^+$ profile by a step function profile with the same plateau $AlCs^+/AsCs^+$ intensity and the same area under the profile [2]. The time interval corresponding to the QW is then converted into thickness using the sputtering rates of $In_xGa_{1-x}As$ in Table 2. The small amount of nitrogen in the quaternary QW is assumed to have no significant influence on the sputtering rate of $In_xGa_{1-x}As$. The obtained QW thicknesses are listed in Table 3. Fig. 4 shows the depth profiles of a single QW structure with an In- and N-content in the QW of $x = 0.8$ and $1 - y = 0.02$, respectively, measured at an energy of 5 keV. The profiles appear to be significantly smeared by ion beam induced mixing. The Ga profile of the QW exhibits the typical asymmetric broadening of the leading and trailing edges. The resulting In-contents are summarized in Table 3. The N profile in Fig. 4 is broadened in the same way as the Ga profile. For the determination of the N concentration of the QW, the N profile is therefore approximated by a step function profile with equal area and a step width given by the QW thickness in Table 3. The plateau concentration of the step function represents the N-content of the QW. The resulting N concentrations are also given in Table 3.

The evaluation of the measured HRXRD profiles of the quaternary QW structures is based on the knowledge of the In/Ga concentration ratio obtained from ternary reference samples grown under the same conditions and on the validity of Vegard's rule. Table 3 shows the HRXRD thickness and N concentration data for the single QW structures. The double QW structures are optimized for optical investigations

Table 3
Thickness and concentration data

No.	Nominal			SIMS			HRXRD	
	d (nm)	x_{In}	$(1-y)_N$	d (nm)	x_{In}	$(1-y)_N$	d (nm)	$(1-y)_N$
3207	~12	0.75	0	15.9	0.78	0		
3208			0.01	16.6	0.79	0.008	15.5 ± 2.0	0.009 ± 0.003
3211			0.02	15.9	0.82	0.015	13 ± 2	0.012 ± 0.003
3313[a]	~10	0.53	0	11.5	0.56	0		
3314[a]			0.007	11.8	0.60	0.006		
3315[a]			0.014	12.0	0.60	0.017		

[a] Double QW structure, SIMS data of d, x and $1 - y$ are averages of both QWs, no HRXRD.

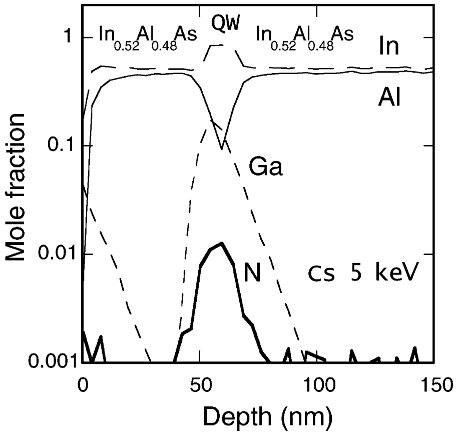

Fig. 4. Depth profiles of a single QW structure (QW = In0.8Ga0.2As0.98N0.02).

and are not suited for HRXRD. The nominal, SIMS and HRXRD data show good agreement. It is seen that nitrogen can be incorporated in $In_xGa_{1-x}As$ on InP by MBE deposition. The data in Fig. 3 further show that the In-content is not significantly influenced by the nitrogen incorporation.

4. Summary

Quaternary $In_xGa_{1-x}As_yN_{1-y}$ QWs grown between $In_{0.52}Al_{0.48}As$ barriers on InP substrate were analyzed by SIMS depth profiling. Thickness and compositional data agree with the nominal data and the data determined by HRXRD. Nitrogen is incorporated in $In_xGa_{1-x}As$ layers in concentrations needed for the intended laser applications and can be reliably assessed by SIMS and HRXRD. The In-content is apparently not influenced by the incorporation of nitrogen.

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