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Surface Recombination Reduction by $(NH_4)_2S_x$-Passivation in MOCVD Regrowth for AlGaAs/GaAs BH Lasers

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We have introduced an ammonium sulfide [$(NH_4)_2S_x$] treatment to reduce the non-radiative surface recombination into the MOCVD regrowth process of an AlGaAs/GaAs buried heterostructure (BH) laser. By Sulfur-treatement in regrowth process the AlGaAs growth on AlGaAs become reproducible and the surface recombination velocity on the side wall of active region was noticeably reduced isotropically. This fabrication technology is expected to be very effective for the realization of ultra low threshold micro-cavity lasers with a few-micron or submicron cavity structure.

1. Introduction

Micro-cavity surface emitting (SE) lasers[1] are becoming attractive for applications to optoelectronics as well as lightwave communication. In order to realize such micron- or submicron-order cavity devices, the development of fine micro-fabrication process is inevitable. Recently, J. Jewell et al.[2] and R.S. Geels et al.[3] demonstrated a device with the threshold of less than 1 mA. But, this value is still much larger than a theoretical one[4], that can be attributed to the nonradiative surface recombination at the side wall exposed to air during the process.

Recently, we have reported that the $(NH_4)_2S_x$-treated BH lasers showed much lower threshold current than BH lasers without this sulfur passivation[5]. The effect of this treatment is mainly due to the reduction of the oxide layer on the GaAs and/or AlGaAs surface[6]. The passivation can decrease the surface carrier recombination velocity.

In this study, we have fabricated BH lasers with different stripe widths and different stripe directions. We estimated the surface recombination velocity from the threshold current density. We have found that it can be reduced by one order of magnitude compared with no-passivated samples. Additionally, we discuss the active region size dependence of the threshold current in micro-cavity SE lasers by taking the surface recombination into account.

2. Experiments

Figure 1 shows the schematic diagram of the fabricated BH stripe laser. This device was fabricated by a two step MOCVD. First, we grew a standard DH structure with four layers: i.e., n-type $Al_{0.3}Ga_{0.7}As$ cladding layer (2 μm), p-type GaAs active layer (0.5 μm), p-type $Al_{0.3}Ga_{0.7}As$ cladding layer (1 μm) and p^+-type $Al_{0.1}Ga_{0.9}As$ cap layer (0.2 μm) on the n-type GaAs substrate. This active layer thickness (0.5 μm) is chosen to apply the wafer to surface emitting lasers afterwards. After forming a 10 μm or 15 μm wide SiO_2 stripe mask with stripe direction of $<01\bar{1}>$ or $<011>$, we chemically etched the sample to reach the n-AlGaAs cladding layer with a $H_2O:H_2O_2:H_2SO_4$ (8:8:1) solution at 20℃ to form mesas, and rinsed in deionized

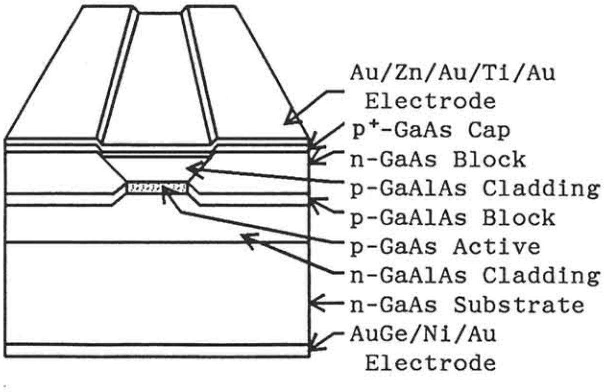

Fig.1 Schematic diagram of the BH stripe laser.

Table I Accumulated data on the AlGaAs/GaAs stripe laser. Surface recombination velocity v_s is $I_s/2eN_{th}Ld$. The threshold carrier density N_{th} is estimated to be 1.8×10^{18} cm^{-3} corresponding to the threshold current density of sample "St-15". We assume that this value does not include nonradiative leakage current.

Sample name	Stripe width W (μ m)	Stripe direction	Threshold current I_{th}(mA)	Threshold current density J_{th}(kA/cm^2)	Leakage current I_s(mA)	Surface recombination velocity v_s(cm/s)
St-15	15		120	2.5	0	0
O-10a	10	<01$\bar{1}$>	333	9.8	248	2.6×10^5
O-10b	10	<011>	681	21.9	604	6.9×10^5
O-15b	15	<011>	690	14.3	570	6.3×10^5
S-10a	10	<01$\bar{1}$>	103	3.8	36	4.6×10^4
S-15a	15	<01$\bar{1}$>	140	3.0	24	2.7×10^4
S-10b	10	<011>	170	4.7	80	7.8×10^4
S-15b	15	<011>	210	4.0	78	7.9×10^4

Active Layer Thickness d=0.5 μ m

(DI) water. These samples were soaked in an $(NH_3)_2S_x$ solution (sample "S-10a", "S-10b, "S-15a" and "S-15b") for about 8 hours, rinsed with DI water and were blown dry with a N_2 gas. The excess sulfur, except one monolayer, on the surface may be removed by this process[6]. The passivated samples were loaded into the MOCVD reactor and heated for 20 min at 630 ℃ in in the AsH_3 atmosphere before the regrowth. By this heat treatment the sulfur layer is believed to be completely removed, since the evaporation temperature of sulfur is 520 ℃ [7]. Then the current blocking layers consisting of 0.5 μ m thick p-type $Al_{0.1}Ga_{0.9}As$ blocking layer, 1 μ m thick n-type GaAs blocking layer and 0.2 μ m thick p^+-type GaAs cap layer were successively regrown. We obtained an almost flat surface after the regrowth. After removing the SiO_2 mask, we formed the electrodes for the n-side and p-side, respectively. The samples without ammonium sulfide treatment (sample "O-10a", "O-10b" and "O-15b") were also fabricated for comparison.

Tested samples were cleaved into ~ 300 μ m cavity length. We measured light output/current characteristics under pulsed oscillation at room temperature. In Table I, we summarize the accumulative data on the threshold current density and leakage current due to surface recombination. The stripe contact laser with the stripe width of 15 μ m was fabricated using the same DH wafer. This does not have a BH structure which is denoted by sample "St-15".

3. Evaluation of Surface Recombination Velocity

In Table I, I_s and v_s denote the surface leakage current and surfacerecombination velocity on the side walls of the GaAs active region. These values were obtained by the following procedure. Figure 2 shows the analytical model for this estimation. The injection current is divided into emission current I_{eff} and non-radiative leakage current I_s originated from the surface recombination. At the threshold condition, I_s is expressed by the following equation;

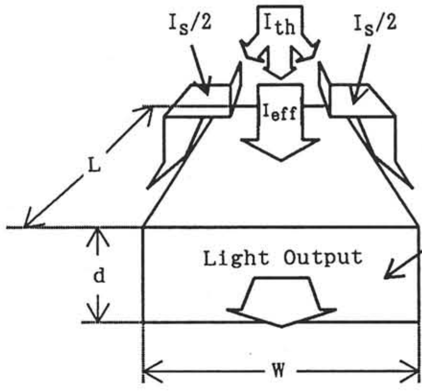

Fig.2 Analytical model of surface recombination.

$$I_s = I_{th} - I_{eff} = WL(J_{th} - J_0) \quad (1)$$

where W is the stripe width, L is the cavity length and J_0 is the threshold current density of the stripe contact laser. J_0 obtained is 2.5 kA/cm^2. We considered that this value did not include non-radiative leakage current. Therefore, the surface recombination velocity v_s is expressed by the following equation.

$$v_s = \frac{I_s}{2eN_{th}Ld} \quad (2)$$

where e is the electron charge, d is the active layer thickness, and N_{th} is the threshold carrier density. This value is estimated to be 1.8×10^{18} cm^{-3} corresponding to the threshold current density J_0=2.5 kA/cm^2 of the stripe contact laser.

From Table I, the surface recombination velocity v_s is estimated to be 2.6× 10^5 cm/s for "O-10a" and to be 6.3~ 6.9× 10^5 cm/s for "O-10b" and "O-15b", which correspond to non-passivated samples. On the other hand, passivated samples "S-10a", "S-15a" and "S-10b", "S-15b" show v_s=2.7~ 4.6× 10^4 cm/s and 7.8~ 7.9× 10^4 cm/s, respectively. As a result, v_s of the $(NH_4)_2S_x$-passivated surfaces were reduced by one order in comparison with the non-passivated samples. It was found that the surface recombination velocity of the samples with stripe direction of <01$\bar{1}$> was about half of that for <011> direction samples.

4. Threshold of Micro-cavity Surface Emitting Laser

Using these values, we can estimate the threshold current of micro-cavity SE lasers. Figure 3 shows the dependence of the threshold on active region diameter with the surface recombination velocity as a parameter. For this estimation, we take the average of the both values, those were 4.5(=(6.3+2.6)/2)× 10^5 and 5.3 (=(7.8+2.7)/2)× 10^4 cm/s for no passivated and passivated surfaces, respectively. In case of v_s=0, an ultra-low threshold current as low as 1 μA is expected when the active region can be D~ 1 μm as shown by the curve A[4]. However, the ultimate threshold is limited to be 180 μA without the surface passivation (curve C). The threshold can be reduced by one order of magnitude as indicated by the curve B by using this passivation technique compared with no passivation case.

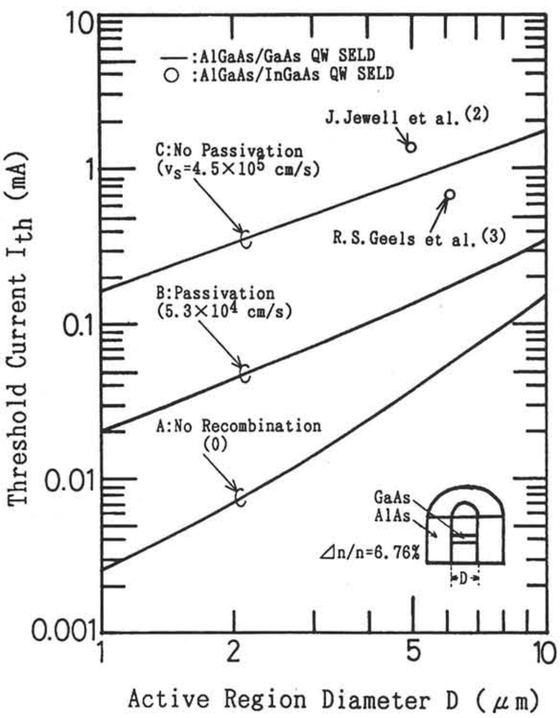

Fig.3 The estimated threshold current of micro-cavity SE lasers vs. active region diameter.

5. Conclusions

In conclusion, the passivation by sulfur atoms using ammonium sulfide $(NH_4)_2S_x$ was introduced and found to be very effective for surface protection in the process between etching and the regrowth of GaAs/AlGaAs buried structure formation. This technique can be applied to an MOCVD regrowth of AlGaAs to prepare BH lasers with a truncated active layer. We found that on the $(NH_4)_2S_x$-passivated BH lasers, the surface recombination velocity on the side wall of the GaAs active region can be reduced isotropically by one order in comparison with non-passivated ones. We are now applying this technique to AlGaAs/GaAs surface emitting lasers.

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