Surface Recombination Reduction by (NH₄)₂Sₓ-Passivation in MOCVD Regrowth for AlGaAs/GaAs BH Lasers

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We have introduced an ammonium sulfide [(NH₄)₂Sₓ] 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 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 (NH₄)₂Sₓ-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 Al₀.₃Ga₀.₇As cladding layer (2 μm), p-type GaAs active layer (0.5 μm), p-type Al₀.₃Ga₀.₇As cladding layer (1 μm) and p⁺-type Al₀.₁Ga₀.₉As 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 SiO₂ stripe mask with stripe direction of <011> or <011>, we chemically etched the sample to reach the n-AlGaAs cladding layer with a H₂O:H₂O₂:H₂SO₄ (8:8:1) solution at 20°C to form mesas, and rinsed in deionized Au/Zn/Au/Ti/Au Electrode p⁺-GaAs Cap n-GaAs Block p-GaAlAs Cladding p-GaAlAs Block p-GaAs Active n-GaAs Cladding n-GaAs Substrate AuGe/Ni/Au Electrode

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 x $10^{18}$ cm$^{-3}$ corresponding to the threshold current density of sample "St-15". We assume that this value does not include nonradiative leakage current.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Stripe width W (μm)</th>
<th>Stripe direction</th>
<th>Threshold current $I_{th}$ (mA)</th>
<th>Threshold current density $J_{th}$ (kA/cm$^2$)</th>
<th>Leakage current $I_s$ (mA)</th>
<th>Surface recombination velocity $v_s$ (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>St-15</td>
<td>15</td>
<td>&lt;011&gt;</td>
<td>120</td>
<td>2.5</td>
<td>248</td>
<td>2.6 x $10^5$</td>
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<td>0-10a</td>
<td>10</td>
<td>&lt;011&gt;</td>
<td>353</td>
<td>6.8</td>
<td>248</td>
<td>6.9 x $10^2$</td>
</tr>
<tr>
<td>0-10b</td>
<td>10</td>
<td>&lt;011&gt;</td>
<td>681</td>
<td>21.9</td>
<td>604</td>
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<tr>
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<td>&lt;011&gt;</td>
<td>890</td>
<td>14.3</td>
<td>570</td>
<td>6.3 x $10^2$</td>
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<td>&lt;011&gt;</td>
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<td>3.8</td>
<td>36</td>
<td>4.8 x $10^2$</td>
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<tr>
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<td>&lt;011&gt;</td>
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<td>3.0</td>
<td>24</td>
<td>2.7 x $10^4$</td>
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<tr>
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<td>15</td>
<td>&lt;011&gt;</td>
<td>170</td>
<td>4.7</td>
<td>80</td>
<td>7.8 x $10^4$</td>
</tr>
</tbody>
</table>

Active Layer Thickness $d=0.5$ μm

(DI) water. These samples were soaked in an (NH$_4$)$_2$SO$_4$ 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 650 °C 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 °C$^7$. Then the current blocking layers consisting of 0.5 μm thick p-type Al$_0.3$Ga$_0.7$As blocking layer, 1 μm thick n-type GaAs blocking layer and 0.2 μm 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 "0-10a", "0-10b" and "0-15b") were also fabricated for comparison.

Tested samples were cleaved into 300 μm cavity length. We measured light output/current characteristics under pulsed oscillation at room temperature. In Table I, we summarize the accumulated data on the threshold current density and leakage current due to surface recombination. The stripe contact laser with the stripe width of 15 μm 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 surface recombination 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 nonradiative leakage current $I_s$ originated from the surface recombination. At the threshold condition, $I_s$ is expressed by the following equation:

$$I_s = I_{th} - I_{eff} = W L (J_{th} - J_0)$$ (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.

$$v_s = \frac{I_s}{2eN_{th}Ld}$$ (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 x $10^{18}$ cm$^{-3}$ corresponding to the threshold.
current density \( J_0 = 2.5 \text{ kA/cm}^2 \) of the stripe contact laser.

From Table I, the surface recombination velocity \( v_s \) is estimated to be \( 2.6 \times 10^5 \text{ cm/s} \) for "0-10a" and to be \( 6.3 \sim 6.9 \times 10^5 \text{ cm/s} \) for "0-10b" and "0-15b", which correspond to non-passivated samples. On the other hand, passivated samples "S-10a", "S-15a" and "S-10b", "S-15b" show \( v_s = 2.7 \sim 4.6 \times 10^4 \text{ cm/s} \) and \( 7.8 \sim 7.9 \times 10^4 \text{ cm/s} \), respectively. As a result, \( v_s \) of the (NH\(_4\))\(_2\)S\(_x\)-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 \(<011>\) 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 \( 4.5 = (6.3 + 2.6) / 2 \times 10^5 \) and \( 5.3 = (7.8 + 2.7) / 2 \times 10^4 \text{ cm/s} \) for no passivated and passivated surfaces, respectively. In case of \( v_s = 0 \), an ultra-low threshold current as low as 1 \( \mu \text{A} \) is expected when the active region can be \( 0 \sim 1 \mu \text{m} \) as shown by the curve A

However, the ultimate threshold is limited to be 180 \( \mu \text{A} \) 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.

5. Conclusions

In conclusion, the passivation by sulfur atoms using ammonium sulfide (NH\(_4\))\(_2\)S\(_x\) 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\(_4\))\(_2\)S\(_x\)-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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References