Annealing effect on effective mass of two-dimensional electrons in InGaAsN/GaAsSb type II quantum well

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Annealing effect on effective mass of two-dimensional electrons in InGaAsN/GaAsSb type II quantum well

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Abstract. The InP-based InGaAs/GaAsSb type II multiple quantum well is the system for developing optical devices for 2 – 3 μm wavelength regions. By doping nitrogen into InGaAs layers, the system becomes effective to fabricate the optical devices with longer wavelength. The epitaxial layers of InGaAsN/GaAsSb on InP substrates are grown by the molecular beam epitaxy. The electrical resistance has been measured as a function of the magnetic field up to 9 Tesla at several temperatures between 2 and 8 K. The effective mass is obtained from the temperature dependence of the amplitude of the Shubnikov-de Haas oscillations. We have reported the nitrogen concentration dependence of the effective mass on the InGaAsN/GaAsSb type II system. The effective mass increases as the nitrogen concentration increases from 0.0 to 1.5 %. In this report, the annealing effect on the effective mass is investigated. The effective mass decreases by the annealing. This result suggests that some amount of nitrogen atoms of the InGaAsN layers are considered to diffuse to the GaAsSb layers by the annealing.

1. Introduction

The mid-infrared laser technology by compound semiconductors grown on the InP substrate has been well developed [1-4]. Therefore, the InP-based compounds have been extensively studied in order to develop optical devices. Since mid-infrared light has absorption bands for several molecules such as NO$_x$, SO$_x$, CO$_2$, a lot of potential applications are expected for pollution monitoring, chemical gas analysis, and medical diagnostics. The InP-based InGaAs/GaAsSb type II multiple quantum well system has been investigated in order to develop the optical devices for 2 - 3 μm wavelength regions [5-7]. According to measurements of photoluminescence and photoreflectance for the InGaAsN monolayer on the InP substrate, the band gap energy becomes smaller by doping nitrogen into InGaAs layers [5]. Therefore, the InGaAsN/GaAsSb system becomes more effective in fabricating the optical devices for a longer wavelength by doping nitrogen into the InGaAs layers. In fact, the light emitting diodes have been developed by using the InGaAsN/GaAsSb type II quantum well on the InP substrate. The wave length corresponding to the peak energy of the electro-luminescence increases from 2.34 μm for N = 0.0 % to 2.86 μm for N = 1.0 % [8]. On the other hand, terahertz quantum cascade lasers based on type II InGaAs/GaAsSb/InP [9] have been developed in addition to the mid-infrared lasers [10].
Substituting nitrogen for arsenic in the InGaAs layers introduces carriers of electrons in the layers. We have reported the nitrogen concentration dependence of the effective mass on two-dimensional electrons of the InGaAsN/GaAsSb type II system. The effective masses of the epitaxial layers with several nitrogen concentrations $N = 0.0, 0.6, 1.2$ and $1.5 \%$ are obtained from the temperature dependence of the amplitude of the Shubnikov-de Haas (SdH) oscillations. The effective mass increases as the nitrogen concentration increases from $N = 0.0$ to $1.2 \%$ then saturates from $N = 1.2$ to $1.5 \%$ [11]. On the other hand, the nitrogen concentration dependence of the bandgap energy, $E_g$ has been investigated by optical absorption measurements for the InGaAsN epitaxial layers with nitrogen concentrations $N = 0.0, 0.5, 1.1, 1.6, 1.8$ and $1.9 \%$. $E_g$ decreases as the nitrogen concentration increases from $N = 0.0$ to $1.1 \%$ then saturates from $N = 1.1$ to $1.9 \%$ [11]. These results are consistent with the band anticrossing model [12,13]. The mass enhancement corresponding to the reduction of the bandgap energy with increasing the nitrogen concentration is explained in the following way: The hybridization of the original conduction band and the narrow resonant band by nitrogen causes splitting into two subbands. As a result, the bottom energy of the conduction band decreases to reduce the bandgap energy. Simultaneously, flattening of the dispersion relation curve, $E(k)$ occurs to make the effective mass heavier.

In this report, the effective mass of two-dimensional electrons are reported on the annealed InGaAsN/GaAsSb type II system. The effective mass is obtained from the temperature dependence of the amplitude of the SdH oscillations observed in the magnetic field dependence of the electrical resistance. Annealing effect on the effective mass is discussed.

2. Experimental

The multiple quantum well (MQW) InGaAsN/GaAsSb epitaxial layers on semi-insulating Fe-doped (100) InP substrates were grown by molecular beam epitaxy (MBE) method at 480 degrees Celsius. The InAlAs buffer layer with the thickness of $0.10 \mu m$ was grown on the InP substrate first. Then, the InGaAsN and GaAsSb layers were grown with 50 periods. The thickness of each layer was 7 nm for both of the InGaAsN and GaAsSb layers. This thickness of 7 nm was determined in order to obtain the light emission with the relatively longer wave length. The growth rates of the InGaAsN layers were $1.45 \mu m/h$ and those of GaAsSb layers were $0.70 \mu m/h$. Arsenic was supplied by needle-valve cracking cells, where the cracking temperature is set to be 600 degrees Celsius, so that tetramer As$_4$ was used. The tetramer Sb$_4$ was supplied by a conventional effusion cell. Indium and gallium were supplied by conventional effusion cells. Nitrogen was supplied by using an RF plasma cell. The composition ratio of the epitaxial layer is In$_{0.53}$Ga$_{0.47}$As$_{1-N_N}$/GaAs$_{0.5}$Sb$_{0.5}$. The composition ratio of In$_{0.53}$Ga$_{0.47}$ was established in order to achieve lattice matching to the InP substrate. There is no compensation doping in the epitaxial layers.

The X-ray diffraction measurements show that lattice mismatching is less than 0.1 \% by introducing nitrogen into the InGaAs layers. Post-growth thermal annealing was carried out for 30 sec in nitrogen cover-gas environments. The InGaAsN/GaAsSb MQW with nitrogen concentration $N = 1.2 \%$ were annealed at 550 degrees Celsius and 600 degrees Celsius, and that with $N = 1.5 \%$ were annealed at 600 degrees Celsius. No difference between before and after the annealing was observed in the X-ray diffraction measurements.

The longitudinal electrical resistance was measured by an AC four probe method with a current of 0.1 mA and frequency of 23 Hz. The measurements have been carried out as a function of the magnetic field, $B$ up to 9 Tesla at several temperatures, $T$ between 2 and 8 K. In order to remove the inference on the longitudinal resistance by the transverse component due to the Hall effect, the longitudinal electrical resistance at magnetic field $B$, $R(B)$ was obtained as the average of the resistance at $+B$ and that at $-B$, $(R(B)+R(-B))/2$. 


3. Results and discussion

The magnetic field dependencies of the electrical resistance at 2 K for the InGaAsN/GaAsSb with N = 1.2 % are shown in figure 1. Those for the InGaAsN/GaAsSb with N = 1.5 % are shown in figure 2. The dotted, broken and solid lines indicate data for the epitaxial layers of as-grown at 480 degrees Celsius, annealed at 550 degrees Celsius and annealed at 600 degrees Celsius, respectively. The SdH oscillations are observed for all five data. The SdH oscillations also appear at all temperatures between 2 and 8 K for all epitaxial layers.

At each temperature, the amplitude of the SdH oscillation is obtained by the fast Fourier transform of the invers magnetic field dependence of the resistance, $R(1/B)$ in the magnetic fields between 2 and 9 Tesla. The temperature dependence of the amplitude of the SdH oscillation, $A$ is described by the Lifshitz-Kosevich formula [14]:

$$A \propto \frac{T \exp\left(-\frac{\lambda m^* T_D}{B}\right)}{\sinh\left(\frac{\lambda m^* T}{B}\right)},$$

where $m^*$ is the effective mass, $T_D$ is the Dingle temperature and $\lambda = \frac{2\pi^2 k_B^2}{e\hbar}$. The detail of fitting to the temperature dependence of the SdH oscillation amplitude by using equation (1) is described elsewhere [11]. Each data is well fitted and the value of $m^*$ is obtained as the fitting parameter. The annealing effect of $m^*$ normalized by the free electron mass, $m_0$ is summarized in table 1. The value of $m^*/m_0$ decreases by the annealing for the epitaxial layers with both nitrogen concentrations of N = 1.2 and 1.5 %. The sheet carrier densities, $n$ obtained from the period of the SdH oscillations are listed in table 2. They also decrease by the annealing for both nitrogen concentrations of N = 1.2 and 1.5 %.

Since the effective mass increases with increasing the nitrogen concentration as reported previously [11], these results suggest that some amount of nitrogen atoms of the InGaAsN layers are considered to diffuse to the GaAsSb layers by the annealing. The results are not due to the compositional variations during the annealing because the X-ray diffraction measurements shows no difference between before and after the annealing.

| $N$ concentration (%) | As grown at 480°C | Annealed at 550°C | Annealed at 600°C |
|-----------------------|-------------------|-------------------|-------------------|
| 1.2                   | $m^*/m_0 = 0.062$ | $m^*/m_0 = 0.056$ | $m^*/m_0 = 0.051$ |
| 1.5                   | $m^*/m_0 = 0.062$ | $m^*/m_0 = 0.046$ |

| $N$ concentration (%) | As grown at 480°C | Annealed at 550°C | Annealed at 600°C |
|-----------------------|-------------------|-------------------|-------------------|
| 1.2                   | $n = 8.7$         | $n = 8.3$         | $n = 6.5$         |
| 1.5                   | $n = 6.2$         | $n = 6.1$         |                   |

Table 1. Effective mass $m^*$ normalized by the free electron mass $m_0$.

Table 2. Sheet carrier density, $n\left(\times 10^{11} \text{cm}^{-2}\right)$. 
Figure 1. Magnetic field dependencies of electrical resistance at 2 K for InGaAsN/GaAsSb with N = 1.2 %. The dotted, broken and solid lines indicate data for the epitaxial layers of as-grown at 480 °C, annealed at 550 °C and annealed at 600 °C, respectively.

Figure 2. Magnetic field dependencies of electrical resistance at 2 K for InGaAsN/GaAsSb with N = 1.5 %. The dotted and solid lines indicate data for the epitaxial layers of as-grown at 480 °C and annealed at 600 °C, respectively.
4. Conclusion
In summary, the annealing effect has been investigated for the InGaAsN/GaAsSb epitaxial layers with the nitrogen concentrations of N = 1.2 and 1.5 %. The electrical resistance has been measured as a function of the magnetic field up to 9 Tesla at several temperatures between 2 and 8 K. The oscillation of the resistance due to the SdH effect is observed at each temperature. The effective mass is obtained from the temperature dependence of the amplitude of the SdH oscillations. The value of the effective mass decreases by the annealing. The sheet carrier densities obtained from the period of the SdH oscillations also decrease by the annealing. These results suggest that some amount of nitrogen atoms of the InGaAsN layers are considered to diffuse to the GaAsSb layers by the annealing.

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