Study on annealing experiment of AlGaInP - based LED wafer by electron beam irradiation

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ABSTRACT. Electron beam irradiation AlGaInP-based LED epitaxial wafers can change their internal structure to improve their luminous performance. Annealing can repair a part of damages induced by irradiation and affect the luminous performance of LED. In this paper, the optical properties and electrical properties of AlGaInP-based LED epitaxial wafers irradiated by different energy and dose electron beam are investigated. The annealing experiment condition are 900 ℃ with 1s and 460 ℃ with 15min. In the comparative test, it is shown that the epitaxial wafer failure at 900 ℃, the luminescence intensity of the epitaxial wafer after annealing is higher than before, and still higher than that before irradiation at the annealing condition of 460 ℃, While the forward voltage is lower. The results of the experiments are analyzed.

1. Introduction

With the development of LED lighting industry, how to improve its luminous efficiency has become the focus of attention. In recent years, it has been found that irradiating the semiconductor materials with appropriate amount of neutron, electron or γ-ray can damage the internal structure of the material and form defects, which promotes the combination of minority-carriers and improves the luminous intensity[1,2]. However, appropriate annealing process can eliminate the stress and dislocation in the material, which will repair the crystal structure and eliminate defects. Therefore, annealing can affect the effect of irradiation. Previous studies have shown that[3,4] when the multi-quantum well structure of AlGaInP material is rapidly annealed at 600-875° C for 1 second, the deep level defects in the multiple quantum well will be reduced and the complex or defect associated with the phosphorus element due to the annealing may affect the device performance.

In addition, Jalonen et al. anneals a multi-quantum well structure of an AlGaNp semiconductor laser rapidly at a temperature of 800-900°C for 1 second[5]. The studies by Tukiainen et al.[6] show that rapid annealing for 1 second increased the carrier concentration of p-type AlGaNp at an annealing temperature of 700-925°C. At present, the research about the effect of annealing on the AlGaNp system materials is generally based on the rapid annealing method, the annealing time is short, and the study shows that at the appropriate annealing temperature P-type GaP and P-type AlGaInP carrier concentration significantly increased. The appropriate annealing temperature (such as 460°C), can significantly improve the AlGaInP layer carrier concentration[7]. This is likely due to the destruction of
the Mg-H complex by annealing, which repair the activity of the Mg atoms, and then the Mg atoms diffuse into the multiple quantum wells. When the annealing temperature is at 460°C, the hole concentration of P-type GaP and p-type AlGaInP layers will be significantly changed, this annealing temperature is much lower than the results reported in the literature[1-6], which may be due to the conventional annealing method and the longer annealing time. Lower annealing temperature has little effect on the crystallization performance of the LED epitaxial wafers, which is very beneficial for improving the overall performance of the epitaxial wafers. Epitaxial wafer structure is generally composed with double heterostructure or multiple quantum well structure. After the electron beam irradiation, the internal structure of the epitaxial wafer changes, resulting in a lot of instability defects, which improves the luminous intensity of the device, while annealing can repair the damage to the internal structure of the epitaxial wafer, so annealing has a significant impact on AlGaInP-based material performance[7]. In this paper, the annealing effect of AlGaInP-based LED epitaxial wafers irradiated by different energy and dose of electron beam are studied, and the effects of annealing on the radiation effects of the epitaxial wafers are investigated.

2. Experiment
The samples used in this experiment are AlGaInP-based LED epitaxial wafers with three different energies of 1.5 MeV, 3 MeV and 7.5 MeV, and three different doses of 5kGy, 10kGy and 15kGy. The luminescence intensity of the irradiated epitaxial wafers was measured by a phosphorim一一ence (PL) spectrometry system and then annealed with a RTP-500 rapid annealing furnace. Annealing experiments are divided into two groups. The first group of annealed epitaxial wafers were 9 samples of the epitaxial wafers No.1 after irradiation, the annealing temperature was 900°C with 1s. The second group of annealed wafers were 9 samples of epitaxial wafer No.2 after irradiation, the annealing temperature was chosen to be 460°C with 15 min. When the two groups of epitaxial wafers were annealed, using nitrogen atmosphere as the protect flow, after the annealing, samples were taken out after the samples naturally cooled to below 120°C, and then testing their PL spectra and electrical properties.

3. Results and analysis

3.1 Electron beam irradiation LED epitaxial wafers
The PL spectra of the epitaxial wafers irradiated by electron beams with different energies and doses are shown in Fig. 1. Three different bar charts in each figure respectively represent PL peak of post-irradiation epitaxial wafers with the electronic energies of 1.5 MeV, 3 MeV and 7.5 MeV.

![PL peak value of 5kGy dose](image1)

![PL peak value of 10kGy dose](image2)

![PL peak value of 15kGy dose](image3)

(a)PL peak value of 5kGy dose   (b)PL peak value of 10kGy dose   (c) PL peak value of 15kGy dose

Fig.1 Different energies and doses electron beam irradiation epitaxial wafer PL peak.

It can be concluded from the results that with the increase of the irradiation electron beam energies and doses, the luminescence intensity of the epitaxial wafer increases accordingly. However, when the energy and dose is too large, it will produce permanent damage to the internal structure of the epitaxial wafer, resulting in its luminous intensity decreased. So with the appropriate energy and dose of electron beam irradiation LED epitaxial wafer can increase its luminous intensity.
3.2 Optical properties of LED epitaxial wafers before and after annealing

3.2.1 LED epitaxial wafers after annealing at 900°C.
The first set of epitaxial wafers PL spectra before and after annealing shown in Fig. 2, solid line Before in the figure represents before annealing, and broken line After represents the PL spectrum after annealing. It is clear that almost all samples in this group have very low luminous intensities after annealing. From the literature analysis we can see that this is mainly due to the 900°C annealing temperature is too high for the AlGaInP epitaxial wafer, resulting in failure of the epitaxial wafer.

![PL spectra before and after annealing](image)

Fig. 2 The PL of 9 samples of Epitaxial wafers No.1 before and after annealing.

3.2.2 LED epitaxial wafers after annealing at 460°C.
The PL values of the second epitaxial wafer before and after annealing are shown in Fig. 3. In this figure, the solid bars represent the unirradiated PL peaks, the diagonal bars represent the post-annealing PL peaks, and we can see that in the second group of epitaxial wafers, 2-A-1 No luminous intensity measured after annealing; The luminous intensity of the epitaxial wafers irradiated by electron beam with A, B, D three kinds of energy but different doses after annealing are higher than those before annealing, however the luminous intensity of the epitaxial wafers irradiated by electron beam with C energy but different doses after annealing are lower than those before annealing. The luminous intensity of the sample after irradiation with relatively high energy electron beam of 7.5 MeV in each group of epitaxial wafers is lower than the other two energy-irradiated epitaxial wafers luminous intensity. This is because the high-energy electron beam irradiation will cause greater damage to the epitaxial crystal lattice, resulting in permanent failure of the epitaxial wafer, so even after a suitable temperature annealing, the epitaxial wafers is still in failure after irradiation with that energy. Therefore, the luminous intensity decreases compared to that before irradiation.

![PL spectra before and after annealing](image)
3.3 Comparison of electrical properties of LED epitaxial wafers before and after annealing

General diode turn-on voltage refers to the forward voltage of P-N junction when the positive current starts to increase (more than 1mA). For LEDs, the forward voltage refers to the voltage drop between the positive and negative poles of the LED under forward current conditions, which is an important parameter that reflects the electrical performance of the LED. The forward voltage of the LED is related to the internal chip material. When a current is generated, there is a certain height barrier between the P-N junction in the chip. For different semiconductors, the barrier height is different, so the turn-on voltage is also different. For example, a binary series GaN material has a forward voltage of about 3.4V and a quaternary series has a forward voltage of typically 2V and 2.5V. Such as AlGaInP, when the forward current is 20mA, the forward voltage of the AlGaInP material is about 2V. Another important factor affecting the forward voltage is the doping concentration of the material, the higher the impurity concentration, the greater the forward voltage. Secondly, the external temperature will also affect the forward voltage, but in the AlGaInP material LED, the equivalent series resistance is not so large, the temperature coefficient of variation in the experiment had little effect on the LED forward voltage, can be ignored.

In this experiment, only the second group of epitaxial wafers did not fail after annealing. Therefore, we compare the forward voltage of the epitaxial wafer No.2 before and after annealing as shown in Fig. 4. Annealed epitaxial wafer use the I-V testermade of ST-103A four-probe station and YB4810A/ YB4811-type transistor characteristics of the icon to measure the electrical properties and draw the forward voltage. The results obtained after the two correspond one by one as shown in Figure 4. In the figure, we can see that most of the irradiated and annealed epitaxial wafers have a lower forward voltage than the epitaxial wafers that have not been irradiated by the electron beam. With low-energy electron beam irradiation, the forward voltage of the epitaxial wafer is reduced. This is because part of the irradiated electron beam energy is converted to heat, which causes the material temperature to rise[8], part of the irradiated electron beam energy transfer to the outermost atom of the electron. So that the electrons get enough energy to break away atomic bondage, generating electron-hole carrier pairs. The electron-hole pairs generated by electron beam irradiation increase the minority carrier concentration near the P-N junction, and the increased holes and electrons are diffused to the N and P regions respectively, and minority injection occurs. According to the typical PN junction current voltage equation [9]

$$J = q\left(\frac{D_{p}n_{i}}{L_{n}} + \frac{D_{n}p_{i}}{L_{p}}\right) \tag{1}$$

$$J = J_{s}\left[\exp\left(\frac{qV}{kT}\right) - 1\right] \tag{2}$$
We can get that the saturation current density flowing through the P-N junction is increased by $\Delta J_s$ and the forward current remains constant. There is a logical correlation between the increased saturation current density and the voltage change across the PN junction as shown in equation (3), where C is a constant.

$$\left(J_s + \Delta J_s\right) \left[\exp\left(\frac{qV}{kT}\right) - 1\right] = C$$

(3)

From the formula (3) we know that the minority carriers of the P-N junction increase, the saturation current density increases, but the forward current does not change, so the forward voltage drop has changed. The annealing process can eliminate the stress and dislocation in the material, but can not eliminate the increase of minority carriers, so the forward voltage after annealing is lower than before irradiation, it shows that the electron beam irradiation has an impact on LED forward voltage.

4. Conclusion
This paper mainly studied the effect of annealing process on the effect of electron beam irradiation on LED epitaxial wafers. Because the electron beam irradiation will induce some damage to the internal structure of the epitaxial wafer, and annealing can repair some of the damage, so the annealed epitaxial wafer performance more stable. The experimental results show that the appropriate electron beam irradiation can improve the luminous intensity of the LED epitaxial wafers. And by comparing the PL emission intensity and the forward voltage before and after annealing, it is shown that the epitaxial wafer failure at 900℃, and the luminescence intensity of the epitaxial wafer after annealing is higher than before, and still higher than that before irradiation at the annealing condition of 460℃, While the forward voltage is lower. When the annealing temperature is 460℃, the hole density of the p-type AlGaInP layer can be significantly changed. This makes it easier for us to improve LED luminous intensity, and at the same time the crystallization performance of LED epitaxial wafers is less affected at the lower annealing temperature. These provide us some reference value and theoretical significance in improving the LED luminous intensity and the performance of other light-emitting devices, and at the same time, contributing to the research and improvement of the performance of the AlGaInP epitaxial wafer material.

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