Effect of temperature on resistance of LEDs based on AlGaAs heterostructures to $^{60}\text{Co}$ gamma radiation

A V Gradoboev, P V Rubanov and V V Sednev

National Research Tomsk Polytechnic University

Abstract. The paper presents the results obtained in the study of the change in the parameters of IR LEDs based on AlGaAs double heterostructures under $^{60}\text{Co}$ gamma irradiation with regard to irradiation temperature. The study indicated several consecutive stages of LED emissive power lowering under ionizing radiation. Increased temperature during gamma irradiation enhances radiation resistance at the first stage due to radiation-stimulated defect annealing, which reduces relative contribution of the first stage to the overall emissive power lowering. It was found that in exposure at temperature more than 380 K, the first stage of LED emissive power lowering is completely eliminated. At the second stage, increase in resistance is caused by the decreased relative contribution of the less stable first stage to the overall emissive power lowering. The maximum resistance of LEDs to gamma radiation depends on radiation resistance of metal–semiconductor contacts.

1. Introduction

Light-emitting diodes (hereinafter LEDs) are the basis for manufacturing various electronic devices and systems that operate under various conditions, including elevated temperature during exposure to ionizing radiation. A simultaneous (complex) and staggered (combined) effect of ionizing radiation and long operating time may significantly affect both the process of emissive power lowering and reliability of LEDs. Based on general information on radiation defect accumulation and annealing, it can be unambiguously assumed that increased temperature during exposure to ionizing radiation is supposed to decrease the rate of LED parameter degradation due to thermal annealing [1,2]. At present, no information is available on the studies of the effect of irradiation temperature on LED resistance to ionizing radiation.

On the other hand, ionizing radiation can stimulate radiation-enhanced diffusion and accelerate LED degradation [3]. In the first place, the occurrence of radiation-enhanced diffusion effects can be one of the main causes of the accelerated degradation of metal-semiconductor contacts under simultaneous and/or combined action of long-term operation and ionizing radiation. Virtually no information on the effect of ionizing radiation on the performance reliability of semiconductor devices and devices based on them is currently available.

The paper aims to investigate the change in the parameters of IR LEDs based on AlGaAs double heterostructures exposed to $^{60}\text{Co}$ gamma radiation depending on irradiation temperature.

2. Research objects and methods

The objects to study were commercial IR LEDs based on double AlGaAs heterostructures. The heterostructures were produced through liquid-phase epitaxy, and an n-GaAs single crystal was used as a substrate. The thickness of the active layer was about 5 µm.
The emissive power of each of the LEDs was measured in the ball at an operating current of 50 mA before and after irradiation under normal climatic conditions. The obtained measurement results were processed by mathematical statistics. An average value of the measured parameters was calculated for each of the batches of the test LEDs. Each batch contained 20 LEDs. Since the error of the emissive power measurement did not exceed ±2.5%, the spread of the LED emissive power in the batch did not exceed ±10% and it insignificantly increased under irradiation, we do not provide the relations with confidence intervals.

The temperature in the active region of LEDs during gamma irradiation was raised by means of the forward operating current (increased forward current during irradiation results in temperature growth in the active region). The thermal resistance of the LED being known, the active region of the temperature was calculated by the formula

\[ T = T_p + R_T \cdot I_{op} \cdot U_{op} \]  

(1)

where \( T \) is the temperature in the LED active region during irradiation; \( T_p \) is the temperature of the LED housing measured during irradiation; \( R_T \) is thermal resistance of LED; \( I_{op}, U_{op} \) are operating current and operating voltage, respectively.

Irradiation was performed in different power supply modes under normal conditions, and the gamma irradiation level was characterized by the absorbed dose \( D_\gamma \). The temperature of the housing during irradiation was controlled. When estimating the temperature in the active region of LED by relation (1), it was assumed that the thermal resistance of LED did not depend on the temperature and gamma radiation absorbed dose. Thus, the temperature in the LED active region varied in the range of (320 –350) K.

The required irradiation level was provided by a consequent set of the absorbed dose for each of the chosen irradiation temperatures (i.e., for chosen operating current values). Multiple measurements of the tested parameters under intermediate levels of gamma irradiation showed high repeatability of measurement results, which indicated the absence of radiation defect annealing in intermediate measurements.

After irradiation and cooling, LEDs were removed from the irradiation box and the required parameters were measured.

3. Results and discussion

Consider the experimental results. Figure 1 shows the data on emissive power lowering for several LED batches. Each LED batch has its own temperature value in the active region.

The results indicate several consecutive stages of emissive power lowering under ionizing radiation, each of which has its own pattern of LED emissive power lowering. It should be noted that as the irradiation temperature grows, the differences between the identified stages of emissive power lowering become more distinct (in figure 1, the solid arrow shows a shift of the boundary between the first and the second stages of emissive power lowering at increased irradiation temperature).

The studies conducted previously [4] suggest that emissive power lowering at the first stage is caused by radiation reorganization of the defect structure (growth of defects, technological defects, etc.). In other words, this stage of emissive power lowering is finite and limited by the initial defect content. At the second stage, emissive power lowering is caused by introduction of radiation-induced defects. At the third stage, LED turns to the mode of low electron injection into the active LED layer and catastrophic failure occurs (ohmic contact degradation, breakdown and/or burnout of the active layer). This is a physical limit of LED resistance to ionizing radiation. The third stage is not shown in figure 1. The above-described radiation model is fully consistent with the study results published earlier [4, 5]. Consider the first stage of emissive power lowering in more detail. At this stage, LED emissive power lowering can be described by the relation

\[ \frac{P_{\gamma}}{P_{0}} = \left( k_1 \cdot D_\gamma \right)^\alpha \]  

(2)
where \( P_0, P_\gamma \) are LED emissive power at a forward current of 50 mA before and after gamma irradiation, respectively; \( k_1 \) is the damage coefficient at the first stage, the amount of which does not depend on irradiation temperature and characterizes the resistance of the double AlGaAs heterostructure to gamma radiation at the first stage of emissive power lowering; \( \alpha \) is the exponent and its value determines the irradiation temperature contribution to LED emissive power lowering at the first stage.

The results presented in figure 1 show that when temperature grows, the proportionality factor \( \alpha \) decreases. This indicates that during LED emissive power lowering caused by radiation-enhanced reorganization of the initial defect structure (the first stage of emissive power lowering), the emissive power is observed to restore as a result of annealing of the defects involved in reorganization of the initial defect structure, i.e. relative contribution of the first stage to the overall process of LED emissive power lowering decreases due to gamma irradiation.

In previous studies conducted to test the performance reliability of these LEDs through step-by-step tests, no facts of emissive power restoration as a result of LED operation at increased temperatures were found [6]. Therefore, it can be argued that the observed annealing of the defects involved in the reorganization of the initial defect structure at the first stage is enhanced by gamma irradiation.

The obtained results were used to determine the dependencies for emissive power lowering at the first stage under gamma irradiation at different temperatures which are well described by relation (2). Some of them are shown in figure 1.

\[
\frac{P_\gamma}{P_0}, \text{ related units}
\]

![Figure 1](image-url)

**Figure 1.** Change in the LED emissive power under gamma irradiation at different temperatures of the active region: 1, 2 are the stages of emissive power lowering; the solid arrow indicates the boundary between stages 1 and 2; vertical arrows show the change in relative contribution of the 1st stage to the overall LED emissive power lowering at different irradiation temperatures.

The experimental data can be used to plot the dependence of \( \alpha \) coefficient on irradiation temperature shown in figure 2.
Figure 2. The $\alpha$ coefficient versus the irradiation temperature under gamma irradiation

The determined dependence allows estimation of the temperature which indicates zero contribution of the first stage to emissive power lowering, at $T_{\text{min}1} \geq 400$ K.

Consider other possible ways to determine the temperature characteristic of the first stage $T_{\text{min}1}$. If we make sections in the region where only the first stage of emissive power lowering occurs, as shown in figure 1 in dotted downward directed vertical arrows, the dependence of the $(1-P_\gamma/P_0)$ value on the irradiation temperature for each of the sections will indicate the change in the contribution of the first stage of $A_{1i}$ emissive power lowering for the given level of exposure to $D_\gamma$ against irradiation temperature.

Thus, we obtain the results shown in figure 3, which give a similar value of the limit temperature $T_{\text{min}1} \geq 400$ K.

Figure 3. The contribution of the first stage of LED emissive power lowering under gamma irradiation to the overall power lowering versus radiation temperature
4. Conclusion
In conclusion, summarize the main results of the studies of emissive power lowering of LEDs based on double AlGaAs heterostructures exposed to $^{60}$Co gamma radiation at different temperatures.

1. The observed emissive power lowering of the studied LEDs irradiated with increased gamma doses occurs through three stages:
   - at the first stage, LED emissive power lowering is caused by radiation-stimulated reorganization of the initial defect structure;
   - at the second stage, LED emissive power lowering is caused by introduction of purely radiation defects;
   - for the limit case, the second stage is followed by the third stage, when LED turns to the mode of low electron injection into its active layer.
2. The third stage determines terminal radiation resistance of LEDs. At this stage, catastrophic failures of LEDs caused by mechanical rupture of the metal-semiconductor boundary can be observed.
3. At the first stage of LED emissive power lowering under gamma irradiation at increased temperatures, two different simultaneous radiation-stimulated processes can be observed: radiation-stimulated emissive power lowering due to reorganization of the initial defect structure and radiation-stimulated annealing of defects that cause decrease in LED emissive power lowering.
4. As the irradiation temperature increases, the differences between the first and the second stages of emissive power lowering become increasingly distinct. This demonstrates the validity of the proposed radiation LED model.
5. As the irradiation temperature grows, relative contribution of the first stage to the overall LED emissive power lowering decreases, and at irradiation temperature $\geq$380 K, the first stage of LED emissive power lowering disappears due to full radiation-stimulated annealing of the defects responsible for LED emissive power lowering at this stage.
6. At the second stage of LED emissive power lowering, the rate of radiation defect introduction does not depend on the irradiation temperature within the studied temperature range of (300–350) K. Increased LED resistance to gamma radiation observed in practice is caused by decreased contribution of the first stage to the overall LED emissive power lowering.
7. For certification testing of LEDs based on AlGaAs heterostructures, a passive mode of power supply is recommended since this mode provides minimal resistance of LEDs to ionizing radiation.

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