

Research on the radiation exposure “memory effects” in AlGaAs heterostructures

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Abstract. Radiation exposure and long running time cause degradation of semiconductors' structures as well as semiconductors based on these structures. Besides, long running time can be the reason of partial radiation defects annealing. The purpose of the research work is to study the “memory effect” that happens during fast neutron radiation in AlGaAs heterostructures. Objects of the research are Infrared Light Emitting Electrodes (IRED) based on doubled AlGaAs heterostructures. During the experimental research LEDs were preliminarily radiated with fast neutrons, and radiation defects were annealed within the condition of current training with high temperatures, then emission power was measured. The research proved the existence of the “memory effect” that results in radiation stability enhancement with subsequent radiation. Possible mechanisms of the “memory effect” occurrence are under review.

1. Introduction

It is necessary to give a brief observance of microelectronic articles utilization. Microelectronic articles are utilized in different environments. More specifically, they serve in outer space, in upper atmosphere and at nuclear energy centers [1, 2] being subjected to different kinds of ionizing radiation. As ionizing radiation takes place, active layers of microelectronic articles get different radiation defects, which change articles specifications and finally cause their break-down.

Similar effect occurs as a result of a longtime service when electric and thermal fields cause defects of articles' active layers.

Consequently, ionizing radiation and longtime exploitation lead to defects in microelectronic articles' active layers and to degradation of their output characteristics. It is worth noticing that defects caused by ionizing radiation can differ in their structure and properties from defects caused by long operation time.

However, it is well known that longtime service factors might result in full or partial annealing of defects that occur as a consequence of ionizing radiation (e.g., [3]). In this case if we preliminarily subject microelectronic articles to ionizing radiation and then to longtime service, we shall obtain full or partial recovery of articles specifications, which can be observed in actual practice.

Behavior of prepared articles newly subjected to radiation is expected to be different from that of primary ones. Whence, if ionizing radiation and/or annealing provoke defect migration to the stock region, where it might interact with other defects, there is a little hope it will move back.

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Consequently, difference in primary and prepared articles behavior being newly radiated can be called the “memory effect”. Similar effects were observed previously in metal alloys [4].

The purpose of this research work is to study the “memory effect” in AlGaAs doubled heterostructures meant to be used to produce infrared light emitting diodes (LED) radiated with fast neutrons.

In the first instance it is necessary to prove the existence of this effect. The “memory effect” investigations (conditions that cause its occurrence, its impact on radiated articles criteria parameters changes, its stability over time, etc.) will hereafter allow us to forecast microelectronic articles behavior when subjected to complex (simultaneous) or combined (spread out over a period of time) ionizing radiated emission or to longtime service factors.

2. Research objects and methods

Commercial LEDs based on doubled AlGaAs heterostructures with $1\mu\text{m}$ thickness of an active layer, obtained through liquid-phase epitaxi with monocrystall n-GaAs as a base-member, were taken as research objects.

LEDs were fabricated through the standard sandwich technology where deposition techniques and layer metallization to form ohmic contacts are applied; photolithography and chemical etching to form crystals (chips) as well as scribing to divide wafers into separate chips were used. LEDs had corpses and lens elements to form necessary diagram of light flux directivity from optical compound. According to the preliminary research data optical compound used to fabricate lenses does not change its optical properties even at $F_n = 2 \cdot 10^{14} \text{ cm}^{-2}$ fast neutron radiation. From there all changes of LEDs' optical properties resulted from radiation within the mentioned above fast neutrons transfer might be considered as conditioned by changes of diodes active region optical properties.

When battery mode is continuous the intensity of forward operating current of LEDs under review makes $I_{op} = 100 \text{ mA}$, for this purpose voltage supply does not exceed $U_{op} = 3 \text{ V}$. Maximum wave mode is within $0,82 \dots 0,90 \mu\text{m}$ range.

Watt – ampere specification of each LED before and after radiation were evaluated in a blob. Data obtained were analyzed by mathematical statistics technique. Each lot of LEDs was classified by average measured values. Dispersion in the radiation power in primary LEDs did not exceed $\pm 10\%$, but it increased after fast neutron radiation up to $\pm 15\%$.

It is worth noticing that equipment used to measure vat-ampere specification in a blob provided each individual LED with radiation measurement repeatability with less than $\pm 2,5\%$ deflection for (1-200) mA operating current range.

Fast neutron radiation was delivered in passive battery mode without operating current, while fast neutron impact level was characterized by $F_n (\text{cm}^{-2})$ particle transfer.

Each lot of LEDs was provided with a sequential number of fast neutron transfers with each definite pitch. Results from the analysis of different lots of LEDs and vat-ampere specification measurements make it possible to prevent any radiation defects annealing during measurement. Therefore an observable change of radiant power is determined by fast neutrons impact only.

Three lots of LEDs were investigated during the research work. Each lot specifications are shown in table 1. Experiments allowed obtaining and describing corresponding relations between radiation power decrease and fast neutrons transfer.

Table 1 shows that the “memory effect” research was carried out by means of comparative study of relation between LEDs' radiant power decrease when radiated with fast neutrons (for primary LED-0) and LEDs' radiation power decrease when radiated with fast neutron (other two lots of LED-1 and LED-2) which were obtain under following conditions:

LEDs were preliminarily subjected to radiation at different fast neutrons transfer rates that resulted in radiant power decrease (ground for neutron transfer rate choice will be given in the following chapter);

Then LEDs were subjected to current training with $I_{op} = 75 \text{ mA}$ operating current during 24 hours with $+ 65 \text{ }^\circ\text{C}$ environment temperature, which led to radiant power recovery;

Further LEDs' radiant power decrease when radiated with fast neutrons was investigated. During the experiments a sequential increase in effect level was applied.

Table 1. Investigated lots of LEDs specifications

LED-0	Preconditioning	Primary LED	Radiation: non	Annealing: non
	Radiant power P , mW	34,82	-	-
	Forward voltage U_{op} , V	1,63	-	-
LED-1	Preconditioning	Primary LED	Radiation: $F_n = 6,08 \cdot 10^{11} \text{ cm}^{-2}$	Annealing: $t = 24 \text{ h}, T = +65 \text{ }^\circ\text{C}, I_{op} = 75 \text{ mA}$
	Radiant power P , mW	36,00	27,18	36,02
	Forward voltage U_{op} , V	1,55	1,54	1,56
LED-2	Preconditioning	Primary LED	Radiation: $F_n = 3,57 \cdot 10^{13} \text{ cm}^{-2}$	Annealing: $t = 24 \text{ h}, T = +65 \text{ }^\circ\text{C}, I_{op} = 75 \text{ mA}$
	Radiant power P , mW	32,67	10,08	24,89
	Forward voltage U_{op} , V	1,45	1,45	1,48

Practically observable LEDs' specification changes (radiant power and forward voltage at predetermined operating current) for each lot subjected to different types of preconditioning are presented in table 1. The table contains half-values for each lot of LEDs.

3. Experimental findings and discussion

In the first instance it is necessary to study the findings obtained during the investigation of LED-0 lot's radiant power decrease when radiated with fast neutrons, presented in table 1. Radiant power measured after radiation P_F was normalized to P_0 in case with primary LEDs, thereby power level measured when applying $I_{op} = 100 \text{ mA}$ operating current was used. Similar normalization of LEDs' radiant power will be employed further on using for starting value its value before it obtained these relations.

Radiation model [5] for LEDs based on AlGaInP heterostructures with multiple quantum wells is the most relevant to describe experimental findings. Data presented in figure 1 show that process of power decrease can be described through three periods.

During the first period radiant power decrease occurs as a result of radiation-stimulated

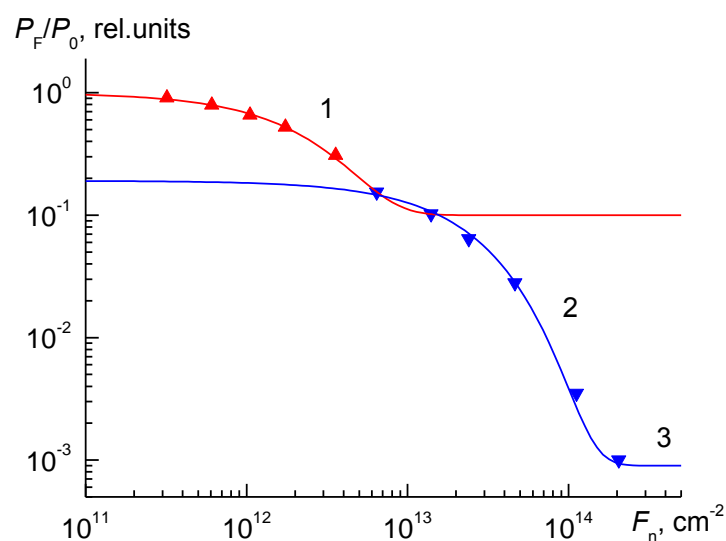


Figure 1. LED emissive power lowering in passive power mode under fast neutron irradiation.

reconfiguration of present defect structure what allows explaining the period finiteness (radiant power decrease process saturation). In this case radiant power decrease is described with the following equation:

$$\frac{P_F}{P_0} = 1 - A \cdot [1 - \exp(-C_1 \cdot F_n)] \quad (1)$$

where P_F , P_0 – radiant power with $I_{op} = 100$ mA, measured before and after radiation consequently; A – coefficient of proportionality that characterizes the first period input into the overall radiant power decrease when radiated with fast neutrons; C_1 – damage coefficient that specifies the speed of radiant power decrease during the first period at neutron transfer growth [cm^2].

The second period is characterized by LED's radiant power change with neutrons transfer growth that occurs due to the radiation defects and is described with the equation

$$\frac{P_F}{P_0} = \frac{P_{min}}{P_0} + B \cdot \exp(-C_2 \cdot F_n) \quad (2)$$

where P_{min} – LED radiant power with low injection of electrons into its active region without any dependence from current flow; B – coefficient of proportionality that characterizes the second period input into the overall radiant power decrease when radiated with fast neutrons; C_2 – damage coefficient that specifies the speed of radiant power decrease during the second period at neutron transfer growth [cm^2].

The third period corresponds to LED fast neutron radiation limiting value. LED occurs in a mode of low injection of electrons into its active region. Radiant power is described in the equation

$$P_F = P_{min} \quad (3)$$

During the third period of radiant power decrease, the majority of LEDs catastrophically break down. More precise comparison of 1-3 formulae and results, presented in table 1, makes some discordance observable. The second period starts with some higher level of LED's radiant power, than it comes from formula (1).

In particular, from formulae (1,2) goes the following formula

$$A + B = 1 \quad (4)$$

Actually, results from table 1 and equations we have

$$\delta\left(\frac{P_F}{P_0}\right) = (A + B) - 1 \geq 0 \quad (5)$$

Earlier investigations [6] in AlGaInP heterostructured LEDs' radiant power decrease when radiated with gamma-ray quantum proved that at the edge of the first and the second periods of power decrease some relaxation processes occur. These processes result in partial recovery of radiant power. At this LEDs' radiant power at the edge of the first and the second periods were observable in an explicit form.

In this research radiant power growth $\delta\left(\frac{P_F}{P_0}\right)$ on the edge of the first and the second periods can also be explained by alike relaxation processes with partial recovery of radiant power which are not observable in an explicit form.

Summing up, LEDs under consideration being subjected to fast neutron radiation get through the period when radiant power conditioned by radiation-stimulated reconfiguration of present defect structure decreases. This fact ground the decision to take these LEDs as “memory effect” research objects. This is a serious possibility to assume the “memory effect” at this period.

Research findings submitted in the paper allow explaining the choice of fast neutrons transfer for preliminary radiation (figure 1). The first transfer of neutrons (LED-1) is chosen to the effect that radiant power decrease occurs within the first period and the second transfer of neutrons (LED-2) corresponds to the second period of radiant power while radiated.

Further the influence of a preliminary fast neutron radiation mode in the identical conditions of annealing on radiant power decrease with further fast neutron radiation (LFD-1, LED-2) is described.

Figure 2 shows relative changes of radiant power for given LEDs with further fast neutron radiation. In this case LED s' radiant power normalization was up to its value after annealing (see table 1). Here are the experimental findings obtained for lot LED-0 to make comparison possible.

Results in figure 2 prove that radiant power changes after radiation are explained by earlier presented equations (1-3). Table 2 contains proportionality and damage coefficients for 1-3 equations, which were obtained during experimental findings analysis, presented in figure 2.

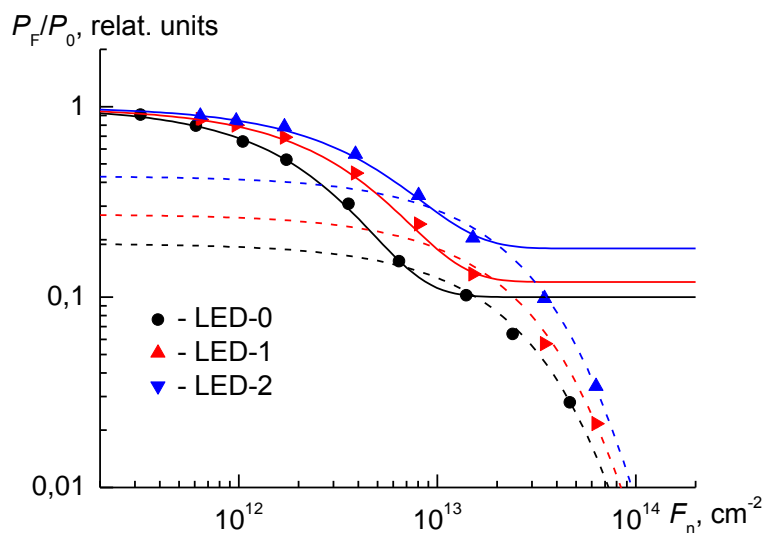


Figure 2. LED-0, LED-1, LED-2 radiant power change when radiated with neutrons: symbols – experimental data; lines – determined relations

Table 2. Proportionality and damage coefficients for different lots of LEDs

LED lot	A	$C_{1,2}$ cm ²	$\delta\left(\frac{P_F}{P_0}\right)$	B	$C_{2,}$ cm ²
	First period			Second period	
LED-0	0.90	$4,35 \cdot 10^{-13}$	0,09	0,19	$4,17 \cdot 10^{-14}$
LED-1	0.88	$2,70 \cdot 10^{-13}$	0,15	0,27	$4,17 \cdot 10^{-14}$
LED-2	0.82	$2,12 \cdot 10^{-13}$	0,25	0,43	$4,17 \cdot 10^{-14}$

Obtained data show that the “memory effect” brings into change A , B , C_1 , proportionality coefficients value of which depends on the LED's history, whereas in contrast C_2 coefficient is identical to all presented lots of LED. The fact that C_2 coefficient does not depend on the history of LED additionally proves that during the second period fast neutron radiated LED s' radiant power decrease is the result of radiating defects, at that, defect structure of LED s' primary active layer is absolutely prevented. Besides, the “memory effect” exceeds recovery degree of radiant power at the edge of the first and the second periods of LED radiant power decrease when radiated with fast neutrons.

Thereby, “memory effect” occurrence when AlGaAs heterostructures are radiated with fast neutrons has been proved. Experiment findings presented in figure 2 demonstrate a possibility to increase LED s' stability to fast neutron radiation by means of the “memory effect”. Of course, it is possible to object that preconditioning result in radiant power decrease in some cases, in spite of its partial (sometimes full) recovery during annealing. It is worth pointing out that any microelectronic article with high ionizing radiation resistance does not possess peak specifications as its basic property is parameter permanence. If parameters change, they change in some limited boundaries being subjected to maximal value of ionizing radiation.

Moreover, taking into consideration that the purpose of the research work is to prove experimentally the anticipation that the ionizing radiation “memory effect” exists; chosen conditions cannot be admitted as optimum. In future radiation and annealing modes optimization might make it possible to develop some practical techniques of the “memory effect” application in order to improve exploitation specifications of different microelectronic articles. At this, ionizing radiation stability might grow without any significant decrease of primary microelectronic articles’ parameters.

Fast neutrons radiation stability growth can be demonstrated with the help relations presented in figure 3. Here are relations of the maximum allowable transfer of fast neutrons that allows to keep radiant power decrease at the maximum permissible value $(P_F/P_0)_{\text{limit}}$ for the lots of LEDs under consideration.

It is obvious that the “memory effect” causes fast neutron influence stability growth not only within the first period but also within the second period. At this the maximum LED s’ stability growth occurs within the first period as a consequence of a relative contribution of this period into the general radiant power decrease when radiated, and owing to damage coefficient decrease. Stability during the second period of radiant power decrease grows as well, but damage coefficient remains unchanged.

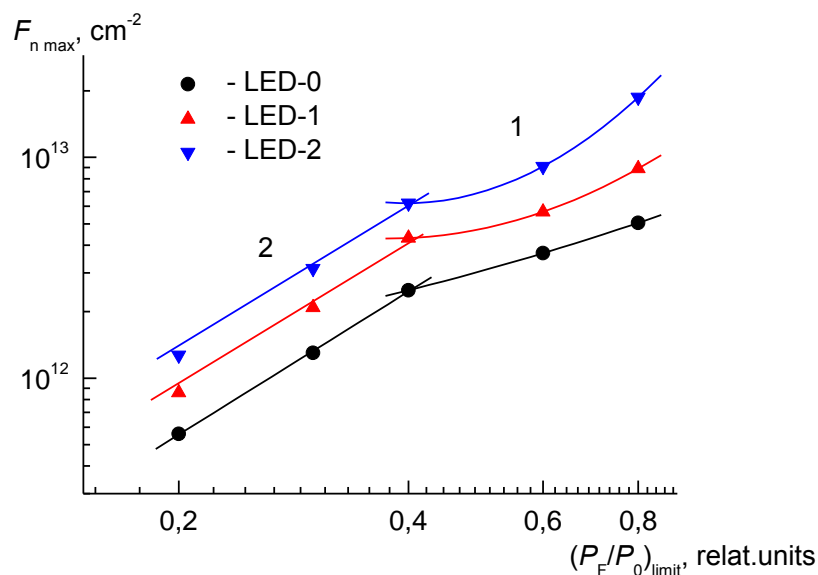


Figure 3. Relations of neutron bearable transfer and maximum permissible radiant power decrease for different LED lots: symbols – experimental data; lines - determined relations; 1 – radiant power change during the first period; 2 – radiant power change during the second period

4. Conclusion

1. For the first time a hypothesis of the “memory effect” of radiation exposure in semiconductor materials and instruments was formulated.
2. For the first time the “memory effect” existence during fast neutron radiation in doubled AlGaAs heterostructures, aimed to be used for IRED production, was experimentally proved.
3. The “memory effect” causes fast neutron influence stability growth. At this LED’s fast neutron radiation stability growth within the first period of radiant power decrease is preconditioned by relative contribution reduction of this period into the general radiant power decrease during radiation and damage coefficient depletion. Stability during the second period of radiant power decrease grows as well, but damage coefficient remains unchanged.
4. The “memory effect consideration” allows increasing a prognostication quality of LEDs’ operation in the conditions of complex (simultaneous) and combined (spread out over a period of time)

factors of long running time and fast neutrons transfer.

5. The “memory effect” application allows increasing the quality of AlGaAs heterostructured LEDs’ running properties.

References

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