IOP Conf. Series: Materials Science and Engineering **363** (2018) 012025 doi:10.1088/1757-899X/363/1/012025

Main principles of developing exploitation models of semiconductor devices

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Abstract. The paper represents primary tasks, solutions of which allow to develop the exploitation modes of semiconductor devices taking into account complex and combined influence of ionizing irradiation and operation factors. The structure of the exploitation model of the semiconductor device is presented, which is based on radiation and reliability models. Furthermore, it was shown that the exploitation model should take into account complex and combine influence of various ionizing irradiation types and operation factors. The algorithm of developing the exploitation model of the semiconductor devices is proposed. The possibility of creating the radiation model of Schottky barrier diode, Schottky field-effect transistor and Gunn diode is shown based on the available experimental data. The basic exploitation model of IR-LEDs based upon double AlGaAs heterostructures is represented. The practical application of the exploitation models will allow to output the electronic products with guaranteed operational properties.

1. Introduction

Robotic centers, or more precisely control systems of the robotic centers, are broadly used at nuclear power plants, on different space vehicles etc. That is, they used in the instances that do not allow a working man to provide the define work. In addition, the control systems of the robotic centers are exposed to impact of combined and complex influence of various types of ionizing irradiation and long-term operation factors (electrical fields, temperature gradient, mechanical stress etc.) [1–7]. In this case, we interpret that complex influence is the simultaneous impact of two or more radiation factors. Accordingly, the combined influence is the impact of two or more radiation factors spread out over a period of time [8]. We note, that interest in combined influence of ionizing irradiation on various semiconductor devices increases [9–16].

Nowadays, there is practically absent the possibility to guarantee the useful quality of the control systems of the robotic centers under the complex and combined influence of damaging factors.

The reliability and radiation resistance problems take on particular importance to ensure the guaranteed security of nuclear power facilities, radiation technology objects, repositories for radioactive substance etc.

Moreover, the electronic products (EP) are the main components for control systems of various robotic centers. Therefore, the performance characteristics of the EP can be represented as a set of following main properties: set of parameters and characteristics; radiation resistance; reliability (failure-free operation, durability and storability).

Therefore, the operation of the EP under these conditions can be characterized by exploitation model (EM) which should include: radiation model (RadM) and reliability model (RelM).

RadM (RelM) of the EP is a system of theoretical, empirical or/and semi-empirical laws, outlining correlations of basic material characteristics and/or parameters and characteristics of the EP with radiation resistance (reliability) indexes.

Before working out the EM of the EP it is necessary to develop the EM of basic components of the EP, which are discrete semiconductor devices. A list of basic discrete semiconductor devices used in the various EP is sufficiently small. In particular, this list can be limited to the following devices: Gunn diode; Schottky barrier diode; p-n-junction diode; light-emitting diode (LED); photodiode; Schottky field-effect transistor; p-n-p (n-p-n)-junction transistor and Hall-effect transducer.

Furthermore, the list of used semiconductor materials is also small enough. In addition, silicon and gallium arsenide are used as basic semiconductor materials. We note, that the heterostructures are abundantly used recently, for instance, AlGaAs, AlGaInP, InGaN, AlGaN [17].

The main methods of manufacture of device structures are vapor phase, liquid-phase and molecular beam epitaxy, ion implantation and various diffusion technology. As is evident, there are also few methods of devices structures formation, because all the rest are particular causes of listed methods.

Therefore, the purpose of this work is to develop the main principles of exploitation models of semiconductor devices (EM-SD), which allow to predict the change of criterion parameters under the influence of ionizing irradiation and factors of long-term operation with their combine and complex influence. Furthermore, the purpose of the work is to present the practical realization of the basic principles through the exploitation model of LED (EM-LED).

In this case, criterion parameter of the device is a parameter which determines its durability, at which point, it is the most sensitive to the influence.

2. Exploitation model of semiconductor devices

This section describes the basic principles of EM-SD development, which can be define in the following way:

- based on the theory;
- based on the semi-empirical laws, which establish relation between parameters of basic materials (parameters and characteristics of the devices) and radiation resistance (reliability) indexes;
- based on the experimental laws, which describe the change of criterion parameters of the device under the influence of ionizing irradiation (during long-term operation).

We note that it is required to ensure the following problem solving in the making of EM-SD:

- to determine the requirements to parameters and characteristics of basic semiconductor material;
- to establish the criterion parameters and characteristics of the device and basic device structures, which define radiation resistance (reliability) of the device;
- to detect the requirements to parameters and operational conditions used in the manufacture of the devices, which can influence over rate of defect introduction under influence of ionizing irradiation and during long-term operation factors;
- to take into account the influence of design factors on radiation resistance and reliability of the devices.

At present time there is sufficiently large number of computer models, which allow to calculate the formation of various radiation defects in condensed matter [18–21]. The obtained results correlate with experimental research results. However, the discrepancies do not allow to use these models as a basis for development of the RadM.

The RadM can be create on the basis of semi-empirical laws established relations between changes in the criterion parameters of the device under ionizing irradiation and electrophysical with geometrical characteristics of the device structures. The RadM allows to get the quantitative estimation of radiation resistance of the device in establishing the sufficient correction relations.

Furthermore, the RadM can be developed from experimental laws outlining the change in criterion parameters of the semiconductor device under influence of various types of ionizing irradiation. In this case, it is necessary to establish the ratio between damage coefficients for a given type of semiconductor device and its initial characteristics. Therefore, the algorithm of the RadM creation for general case, when there are not the theoretical laws that determine relation between parameters of the semiconductor device and electrophysical with geometrical characteristics of the given semiconductor structures.

These approaches for creating the RadM are fully applicable to develop the RelM of the semiconductor device.

3. Stages of practical implementation of radiation (reliability) model of the semiconductor device creation

The foregoing approach to create the RadM of semiconductor device can be represented as a set of the stages, whose solution of specific problem is characterized. We note that the problem solution of each several stage can already provide practical usefulness.

Subsequently, the RadM will be used as a basis for consideration, because the available experimental data allow to proceed with its development now as it will be show in the following.

On the first stage of RadM development it is necessary to research the change in parameters and characteristics of the semiconductor device under influence of ionizing irradiation.

Such research makes possible to estimate the relations that describe the changing in different parameters and characteristics of the semiconductor device depending on irradiation level. In addition, the damage constants will be determined for various types of ionizing irradiation.

On the next stage of the RadM development it is necessary to relate damage constants of the semiconductor device with its initial parameters. Obtained data in such way have practical importance, because based on them the additional radiation resistance sorting of the manufactured semiconductor devices can be introduced.

At present moment, for instance, the relations have been established that describe the change in majority charge carrier density and charge carrier mobility under ionizing irradiation for device structures based on silicon and gallium arsenide which were manufactured by various technique [8, 22–24]. The initials semiconductor devices can be sorted by radiation resistance following these relations.

The experimental date obtained in this way can be put to the purpose to develop the RadM of Gunn diode, Schottky barrier diode; and Schottky field-effect transistor as is shown in [4, 23, 25].

Next, it is necessary to research the influence of technology and design factors on radiation resistance of the semiconductor device. This can be provided by analysis of manufacturing technology of the semiconductor device for the purpose of detection of the most critical manufacturing process as illustrated in [26] for Gunn diode.

The presented algorithm of development of the RadM of the semiconductor device shows complexity of the model and its development. It is a reminder that during development of the model it is necessary to take into account complex and combined influence of ionizing irradiation and long-term operation factors, which are characteristic of field operating conditions.

This algorithm of development of the RadM of the semiconductor device are fully applicable to develop the RelM of the device with account for specificity of operation factors.

4. Practical implementation of radiation and reliability model of the semiconductor device

Let us take a closer look at practical implementation of RadM and RelM of semiconductor device by the example of the LEDs. In this work we selected industrial IR-LEDs based upon double AlGaAs heteroctructures. Their manufacturing technology, measuring methods of main parameters and using equipment for determination of reliability indexes and for irradiation by fast neutrons and gamma-quanta were described in more detail in [27].

In this paper we confined to the most distinctive types of ionizing irradiation, which were fast neutrons and gamma-quanta. The decision depends on the following motivation. There are two main mechanisms of defect formation under influence of ionizing irradiation on condensed matter. Firstly, it is ionization mechanism of defect formation, which is typical for gamma-quanta, low-energy electrons and protons in fore part of path [21, 28–32]. Secondly, displacement effect of defect formation is typical for fast neutrons, low-energy protons (at the close of particle path) and heavy ions [18, 19, 33, 34].

Therefore, the use of gamma-quanta and fast neutrons makes possible to research the change in parameters and characteristics of the semiconductor device under developing process of two typical mechanisms of defect formation.

We established [35, 36] that the decrease of emissive power of the LEDs under irradiation by fast neutrons and gamma-quanta includes three stages as illustrated in Figure 1.

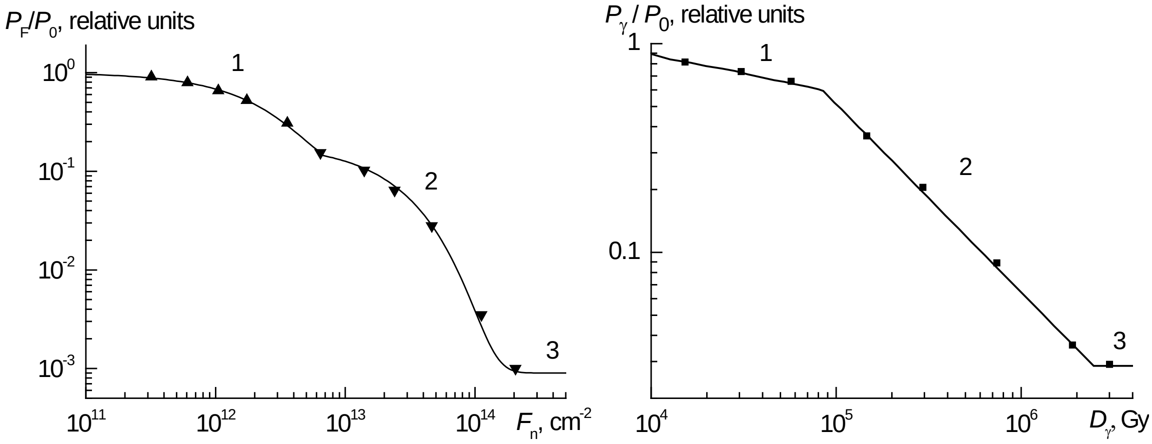

Figure 1. Relative change in the emissive power depending on fast neutron fluence (left) and gamma-quanta dose (right), where 1, 2, 3 are stages of the emissive power decrease.

The above presented research results allow to present the following RadM of the LEDs, which describes changing in emissive power under irradiation by fast neutrons and gamma-quanta.

- On the first stage the decrease of emissive power of the LEDs is attributed to the radiation-stimulated reconstruction of the initial defect structure of the LED crystal as evidenced by saturation of this stage as the level of exposure increases (field 1 in Figure 1).
- On the second stage the decrease of emissive power of the LEDs is attributed to the introduction of new radiation defects (field 2 in Figure 1).
- On the third stage the LED transits into the field of low electron injection in its active region (field 3 in Figure 1). The field is characterized by the fact that the emissive power does not depend on operating current. It should be noted that the boundaries between these stages are rather sharp.

Likewise, the emissive power decrease of the LEDs was researched during their long-term operation. We have been established [37] that there are three distinctive stages of the emissive power decrease of the LEDs during long-term operation referring to Figure 2.

Previously we have been observed the similar behavior of decreasing the emissive power of the identical LEDs under irradiation by fast neutrons and gamma-quanta [35, 36].

Therefore, our results (see Figure 2) can assume the following model for decreasing the emissive power of the LEDs during operation (RelM of the LEDs).

- On the first stage the emissive power decreases due to rearrangement of original defect structure exposed to operation factors in the same way that it was observed under irradiation previously (field 1 in Figure 2).
- On the second stage the emissive power decreases due to introduction of new defects by aging (field 2 in Figure 2).
- On third stage we observe a transition of the LEDs into the mode of low electron injection with further origination of catastrophic failure like the previously observed effect of ionizing irradiation. Moreover, the degradation of ohmic contacts “metal – semiconductor” takes priority of the catastrophic failure (field 3 in Figure 2).

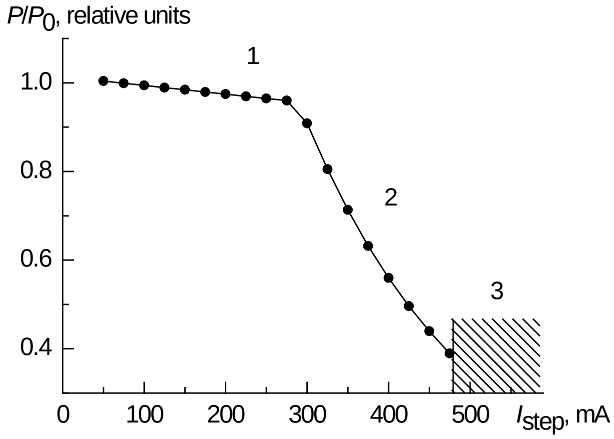

Figure 2. Relative change in the emissive power of the LEDs depending on step number, where 1, 2, 3 are stages of the emissive power decrease.

Crucially, the eigenvalue ratio between established stages are observed for each of influencing factors. For instance, the contribution of the first stage of decreasing emissive power of the LEDs can be estimate at 85% (Figure 1) for fast neutrons. Moreover, it is about 40% from initial value (Figure 1) for gamma-quanta, while the contribution of the first stage is about 5% during operation (Figure 2).

The presented results prove the identity of degradation processes in the LEDs under influence of ionizing irradiation and long-term operation factors. In other words, in this case we can discuss about unify model of the emissive power degradation of the LEDs under ionizing irradiation and during log-term operation. Therefore, the described model is substantially the template for EM-LED.

We note that for creating fully-featured EM-LED it is necessary to provide the research for complex and combined influence of various types of ionizing irradiation and factors of long-term operation.

5. Conclusion

1. The structure of the exploitation model of the semiconductor device is presented, which is based on radiation and reliability models. Furthermore, it was shown that the exploitation model should take into account complex and combine influence of various ionizing irradiation types and operation factors.
2. The algorithm of developing the exploitation model of the semiconductor devices is proposed.
3. The possibility of creating the radiation model of Schottky barrier diode, Schottky field-effect transistor and Gunn diode is shown based on the available experimental data.
4. The basic exploitation model of IR-LEDs based upon double AlGaAs heterostructures is represented.
5. The practical application of the exploitation models will allow to output the electronic products with guaranteed operational properties.

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