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Local mechanical stress relaxation of Gunn diodes irradiated by protons

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Abstract. The aim of the work is studying the impact of Gunn diodes thermocompression bonding conditions upon their resistance to being radiated with protons of various energies. It was established that the tough conditions of Gunn diodes thermocompression bonding results in local mechanic stresses introduced into the active layer of the device, reduction of electron mobility because of the faults introduction and, subsequently, to reduction of operating current, power of UHF generation, percentage of qualitative units production and general reduction of production efficiency of the devices with required characteristics. Irradiation of Gunn diodes produced under the tough conditions of thermocompression bonding with protons which energy is (40–60) MeV with an absorbed dose of $(1–6)\cdot10^{2}$ Gy does not practically reduce the radiation resistance of Gunn diodes produced with application of the given technique. This technique can be recommended for all semiconductor devices on the base of GaAs, which parameters depend significantly upon the mobility of the electrons, to increase the efficiency of production.

1. Introduction

Semiconductor devices are actively applied as the main component base for various electronic devices operating in the upper layers of the Earth atmosphere, near and far space, at various objects with increased radiation background including nuclear power objects [1-3]. In this case, they are exposed to complex (simultaneous) and combined (distributed in time) impact of various kinds of ionizing radiation as well as to various factors of long-time operation. Thus, the given conditions of operation set especially firm requirements for reliability and radiation resistance of semiconductor devices.

In the process of semiconductor and semiconductor based devices production, various technologic defects may be introduced into the active layers of the devices which results in deterioration of the output parameters of the devices, reduction of the percentage of good device output during production as well as in deterioration of their operational characteristics such as radiation resistance and reliability [4].

Currently the works aimed at studying the impact of technological parameters upon the radiation resistance of semiconductor devices are very scarce.

On the other hand, it is known that radiation technologies can be efficiently applied right in the technology of semiconductor devices production [4-6].

Thus, the analysis of available reference data brings us to the conclusion that the research on the impact of technological factors upon the resistance of semiconductor devices to ionizing radiation is relevant.

The aim of the given paper is to study the impact of thermocompression bonding of Gunn diodes upon their resistance to exposure to protons of various energies.

2. Research objects and methods

2.1. Objects of research

We chose industrial Gunn diodes 3A728 [7] as the objects of research. Choosing Gunn diodes as the objects of research is based on their rather high sensitivity to technology factors exposure [8-10].

Gunn diodes under study were produced on the base of one multilevel epitaxial structure of gallium arsenide of n^+-n-n_b^+-n^{++}-type according to standard sandwich technology [11] where n^+ is the below contact heavily doped epitaxial layer; n is working layer; n_b^+ is buffer heavily doped epitaxial layer and n^{++} is heavily doped bulk substrate from volume monocrystalline GaAs. The multilayer epitaxial structure was grown according to the method of gaseous-phase epitaxy within a single technologic process.

When manufacturing Gunn diodes, the following basic technologic methods were applied:

- lost wafer process with the methods of abrasive and chemical polishing;
- ohmic contacts deposition on the base of Au-Ge-Ni with their further formation by thermal treatment;
- formation of active elements with the methods of photolithography and chemical etching;
- dividing the plates into separate crystals with laser scribing.

As a result of completing of the mentioned above operations, we obtained a separate chip (crystal) of Gunn diode containing an active element in the form of a mesostructure with round cross-section on the crystalline underplate with square cross-section.

Then structurally complete Gunn diode was manufactured applying reattachment of the crystal onto the copper chip-carrier (heat removal) with golden coating with implementation of thermocompression bonding. With such construction of Gunn diode the contact was on the side of the heat removal.

Two sets of Gunn diodes were produced: the first set (DG-1) – the optimal conditions of thermocompression bonding; the second set (DG-2) – the tough conditions of thermocompression bonding (increased temperature and pressure). The diodes manufactured this way were put to in-process testing (current training under the increased temperature, thermocycling, etc.) and presorting. The optimal conditions of the thermocompression bonding were selected according to the criteria of minimum process scrap revealed during the in-process testing. It should be noted that for the tough conditions of bonding the increased amount of the process scrap was observed.

Thus, under the tough conditions of thermocompression bonding we observe introduction of local mechanic stresses which result in development of additional faults and deterioration of the electrophysical characteristics of the active layer of the Gunn diode [4,8-10].

From the manufactured sets of Gunn diodes, random series were formed (each including 20 diodes) to be used for the research.

2.2. The methods of Gunn diodes parameters monitoring

Each Gunn diode was characterized in terms of operating current I_{op}, transit-time frequency which corresponds to the maximum value of SHF generation P_{HF} within the frequency range 33.0 – 37.5 GHz and, accordingly, in terms of maximum power of SHF generation P_{HF}. All measurements of Gunn diodes parameters were conducted under the input voltage of 4.0 V.

The listed above SHF characteristics were measured in a corresponding waveguide cell with the power supply used for supplying the required input voltage, rated detector head used for measuring energy and the frequency meter. The waveguide cell was adjusted so that to ensure the maximum possible value of SHF generation power.

The studied series of diodes from the described above sets were characterized by the measured parameters distribution histogram, mean values of parameters and their range. The characteristics of the formed research series for each of the diode sets did not practically differ which definitely allows relating the differences in diode parameter changes during testing to the differences in the technology of their production.

2.3. Methods of research

We measured the described above parameters for each series of the devices before and after the irradiation with protons of various energies. To study the regularities of Gunn diode parameters changing in their relation to exposure increase we applied both single irradiation and successive accumulation of the required exposure level. In this case, the identity of the data obtained for different series allows concluding that measurements of the SHF characteristics of diodes do not result in annealing of radiation defects introduced by irradiation. Then all the observed changes can be undoubtedly related to the differences in the technology of Gunn diodes production. The growth of exposure level was limited to complete diode failure, i.e. extinction of SHF generation.

Further we shall provide only mean values of parameters for all the dependences characterizing changes of the parameters of Gunn diodes from various series related to exposure growth. Besides, in all cases, we are going to analyze the changes of diodes parameters distribution histograms. We applied Isochronous Cyclotron U-240 as the source of proton irradiation as it allows obtaining proton beams with the energy of 8–80 MeV [12]. The level of exposure to protons of different energies was characterized by energy E_p [MeV] and fluence of particles F_p [cm^{-2}]. Energy of protons E_p was calculated with consideration to its losses at the passive elements of the package and the crystal of the Gunn diode. In all cases, the path of protons significantly exceeded the thickness of the active layer of the studied Gunn diode.

As previously [4] it was established that irradiation with protons with the applied energies under the particle fluence over $3\cdot10^{10}$cm^{-2}s^{-1} results in annealing of the part of introduced radiation defects and increase of the temperature of irradiated samples, in the given work we applied particle fluence below $1\cdot10^{10}$cm^{-2}s^{-1}.

Thus, irradiation of all the studied series of diodes was conducted under normal climatic conditions and constant control of diode temperature which allows elimination of annealing radiation defects in the process of irradiation.

3. Results and discussion

3.1 The original characteristics of Gunn diodes

First of all, let us consider the original characteristics of Gunn diodes for two studied sets of devices. In figure 1, we present typical distribution histograms of Gunn diodes from the two sets considered above in the series formed for the research according to the SHF generation power. From the presented results we can see significant difference between the studied sets of Gunn diodes in terms of generation power. For the series of Gunn diodes from set DG-1, a typical mean value of power is (144±4) mW and its change range is (120 – 170) mW, while for the typical series of Gunn diodes from set DG-2, the mean value of generation power is (132±5) mW and its change range is (100–160) mW. Similar results are observed for operating currents.

The analysis of the results presented in figure 1 brings us to the conclusion that tough conditions of thermocompression bonding lead to noticeable reduction of the operating current and power of SHF generation of the produced diodes. We also observe a clearly marked left shift of diode distribution histogram in terms of SHF generation – to the region of lower power. In this case, the group of diodes with higher generation power practically disappears and there appears the group of diodes with lower power. The same is obviously demonstrated by the observed differences of the measured power ranges which were presented above. The same difference is also observed for the operating current. It should be also noted that for the diodes from DG-2 set higher frequency of generation is observed corresponding to the maximum of SHF power which value characterizes the transit-time frequency, i.e. the velocity of high-field domain propagation in the active layer of the Gunn diode. Growth of generation transit-time frequency can be explained by the growing resistance of ohmic contacts for Gunn diodes from DG-2 set [4].

It should be noted that during the in-process testing of Gunn diodes from DG-2 set partial restoration of operating current corresponding growth of SHF generation power growth were observed. Similar results were observed when storing diodes from DG-2 set without in-process testing under normal climatic conditions as it is shown in figure 2.

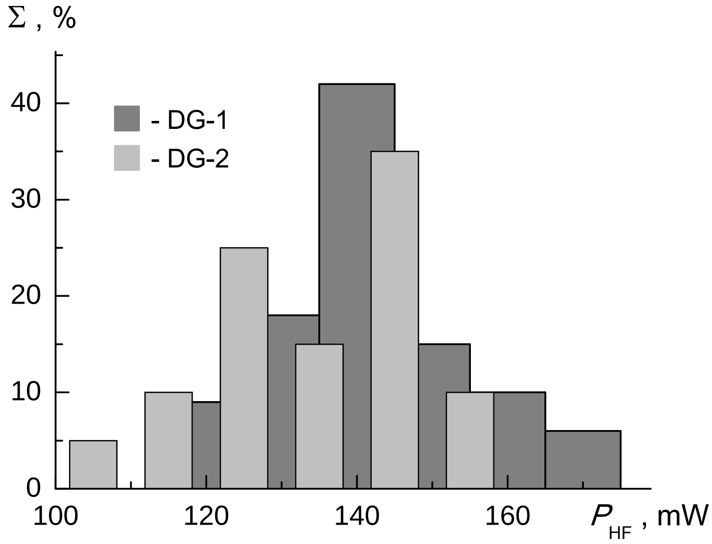

Figure 1. Typical histograms of Gunn diode distribution by power of SHF oscillation in the two batches of Gunn diode.

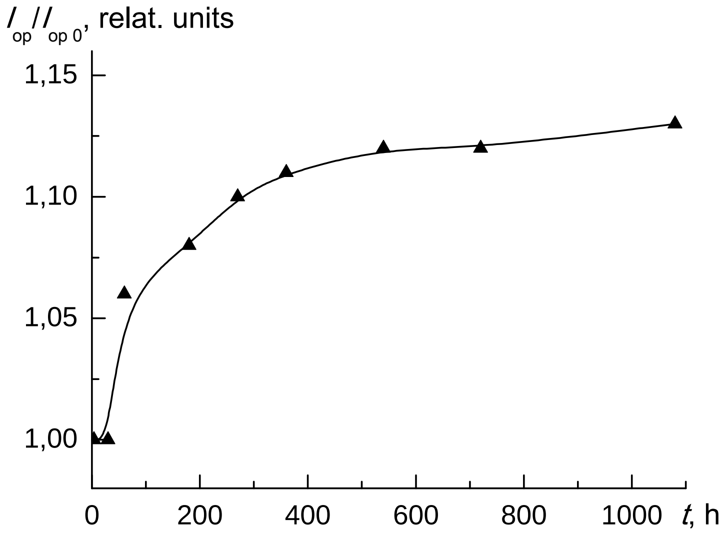

Figure 2. Recovery of operation current of GD-2 without technological tests during storage.

In-process testing and storing Gunn diodes DG-1 without in-process testing under normal climatic conditions did not lead to traceable change of the operating current and, accordingly, to the change of SHF parameters.

On the other hand, storing Gunn diodes of the studied sets undergone the whole complex of in-process testing also did not lead to the traceable change of their parameters and characteristics.

The presented above results of the Gunn diodes analysis allow concluding that the tough conditions of thermocompression bonding lead to deterioration of electrophysical characteristics of their active layer, increase of process scrap and reduction of SHF parameters due to introduction of local mechanic stresses and development of additional defects. The given conclusion agrees with the previously presented results [4, 8-10].

The question about the deterioration of electrophysical characteristics of the active layer of Gunn diodes under the tough conditions of thermocompression bonding still remains open. To answer this question diodes with Schottky barrier were produced according to the same sandwich technology on the base of the epitaxial structure of gallium arsenide of $n\text{-}n_b^{+}\text{-}n^{++}$-type with close characteristics of the active layer. The given structure was grown during single technologic process according to the same technology that was used for growing the epitaxial structure applied in Gunn diodes production. Two sets of diodes with Schottky barrier were produced under identical conditions of thermocompression bonding of diodes into the metal-ceramic package.

Analysis of capacitance-voltage curves of the diodes with Schottky barrier showed that the thermocompression bonding conditions do not influence the concentration and the electron distribution profile in their active layer.

The given results allow concluding that the observed changes of the electrophysical characteristics of the active layer of Gunn diodes depending upon the conditions of the thermocompression bonding are determined by the changes of electron mobility.

3.2. Changes of Gunn diodes parameters under irradiation with protons of various energies

Let us consider the results of the study of proton irradiation influence upon the characteristics of the studied sets of Gunn diodes. Figure 3 shows the changes of the mean value of the operating current under proton irradiation with energy 14.3 MeV and 63 MeV.

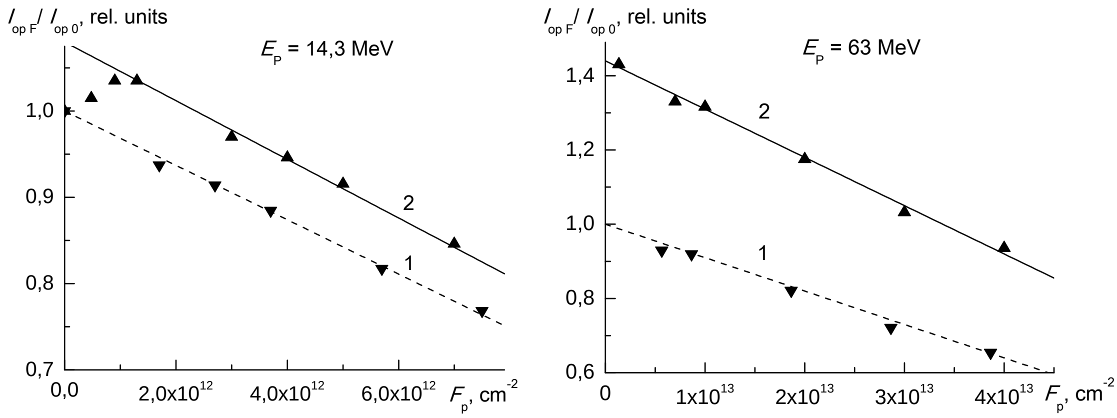

Figure 3. Change of operation current of Gunn diode DG-1 (1) and DG-2 (2) under irradiation by protons with energy of 14.3 MeV и 63 MeV.

For other proton energies, similar results were obtained. From the presented results we can see that for Gunn diodes DG-2 in the region of low levels of exposure restoration of the operating current and, accordingly, growth of SHF generation power are observed as it is shown in figure 4.

At the same time, for Gunn diodes DG-1 irradiated with protons in the region of low exposure levels noticeable changes of the operating current are not observed and for SHF generation power its insignificant growth is observed as it is shown in figure 5.

From figure 4 and figure 5 we see that in both cases irradiation with protons in the region of low exposure levels results in disappearing of diodes with low values of SHF generation power. The observed effect of SHF generation power increase is most significant for the diodes from DG-2 set.

From the results presented in figure 5 we can see that the degree of operating current restoration under irradiation in the region of low exposure levels significantly depends on proton energy which is additionally proved by the results presented in figure 6.

It should be noted that long-time storing of Gunn diodes from DG-2 set leads to noticeable reduction of the degree of operating current restoration under proton irradiation as it is shown in figure 7. In the given case we understand the time of storing under standard climatic conditions as the time between the bonding of the devices and proton irradiation.

On the base of the study results for the original Gunn diodes we can state that the observed operating current restoration of Gunn diodes is determined by restoration of mobility in the region of low levels of proton irradiation.

For different diode sets, different proton energies, the optimal value of proton fluence under which maximum restoration of electron mobility was achieved corresponded to the absorbed dose within (1-6)$\cdot 10^2$ Gy.

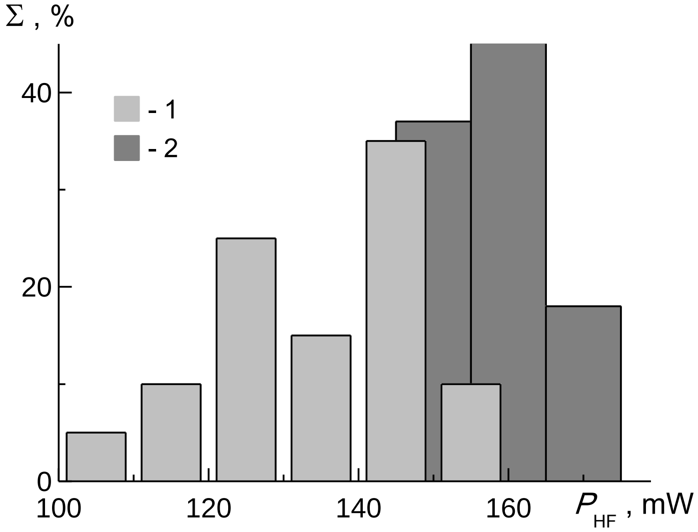

Figure 4. Histograms of Gunn diode DG-2 distribution by power of SHF oscillation before (1) and after (2) irradiation by protons with energy of 63 MeV at low levels of exposure.

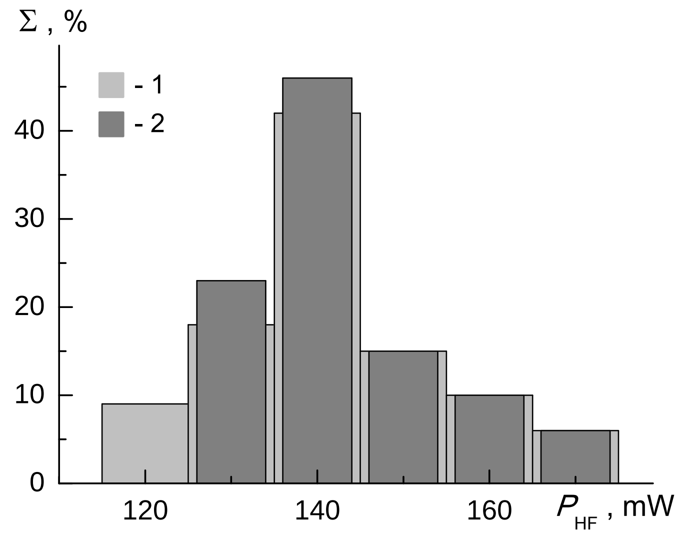

Figure 5. Histograms of Gunn diode DG-1 distribution by power of SHF oscillation before (1) and after (2) irradiation by protons with energy of 63 MeV at low levels of exposure.

Let us sum up the considered above results on proton irradiation of the studied sets of Gunn diodes in the region of low exposure levels.

For Gunn diodes DG-2 produced under tough conditions of thermocompression bonding being irradiated with protons with absorbed dose within (1–6)$\cdot 10^2$ Gy, restoration of electron mobility is observed, which results in growth of the operating current and power of SHF generation.

Thus, irradiation of Gunn diodes with protons with the energy within (40–60) MeV range allows relaxing the local mechanic stresses introduced into the active layers of Gunn diodes under the tough conditions of thermocompression bonding and restore electron mobility in the active layer. Besides, the given exposure can be recommended for treating Gunn diodes with low level of SHF generation power which were discarded after the in-process testing as it allows increasing their SHF generation power and, thus, reduce the amount of process scrap and increase the efficiency of Gunn diodes production.

We should note that relaxation of local mechanic stresses in the semi-conductor devices have been also observed before under other kinds of energy deposition [4,5,13].

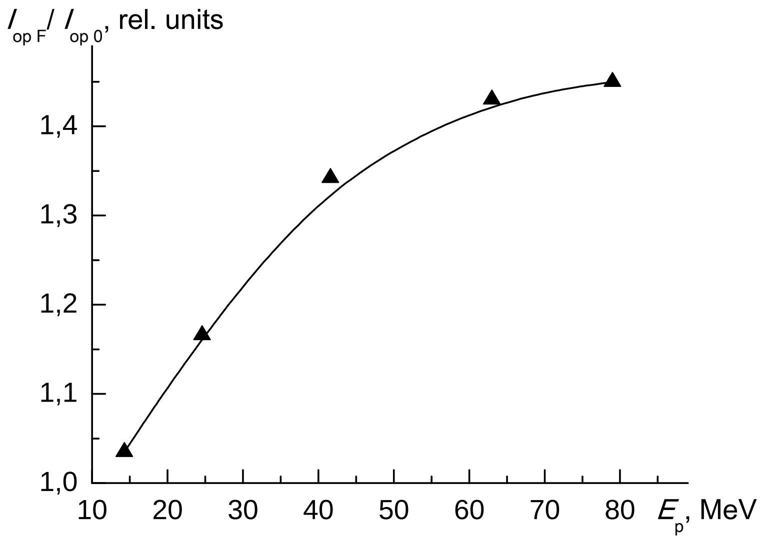

Figure 6. The dependence of average value of reduction degree of operating current of Gunn diode DG-2 on the proton energy.

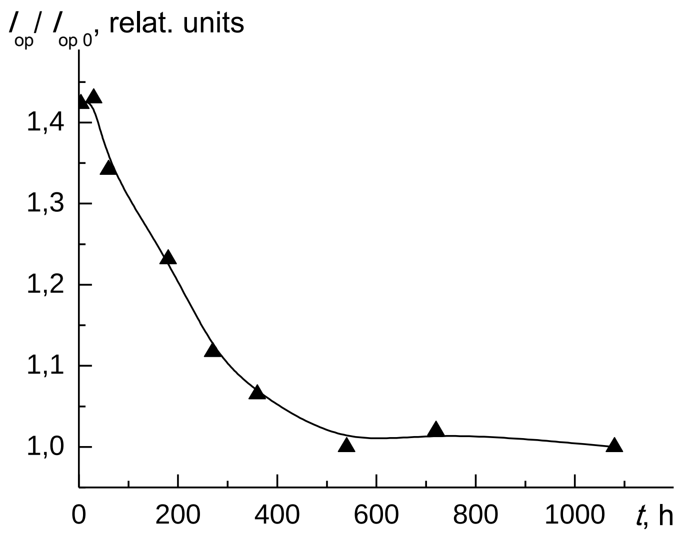

Figure 7. The reduction degree of operating current of Gunn diode DG-2 under irradiation by protons with energy of 63 MeV depending on storage time.

3.3. Resistance of Gunn diodes to irradiation with protons of various energies

Further we shall consider the resistance of the studied sets of Gunn diodes to irradiation with protons of different energies in the range of exposure which leads to their degradation up to complete failure. Here standardization was completed according to the value of the operating current measured after

Gunn diodes bonding.
As irradiation with protons in the region of low exposure can be considered as a technologic operation, then to study the resistance of Gunn diodes to proton irradiation standardization should be done for the values of parameters after the complete production cycle. Figure 8 shows the change of the operating current under irradiation with protons with the energy of 63 MeV for the studies sets of Gunn diodes. Standardization for DG-2 diodes was done for the value of the operating current after preliminary irradiation, and the fluence of protons was taken excluding the fluence of preliminary irradiation.
Similar dependences were obtained for protons of other energies and also for changes of SHF generation power. Results presented in figure 8 show that the Gunn diodes from the sets under study have practically identical resistance to proton irradiation.

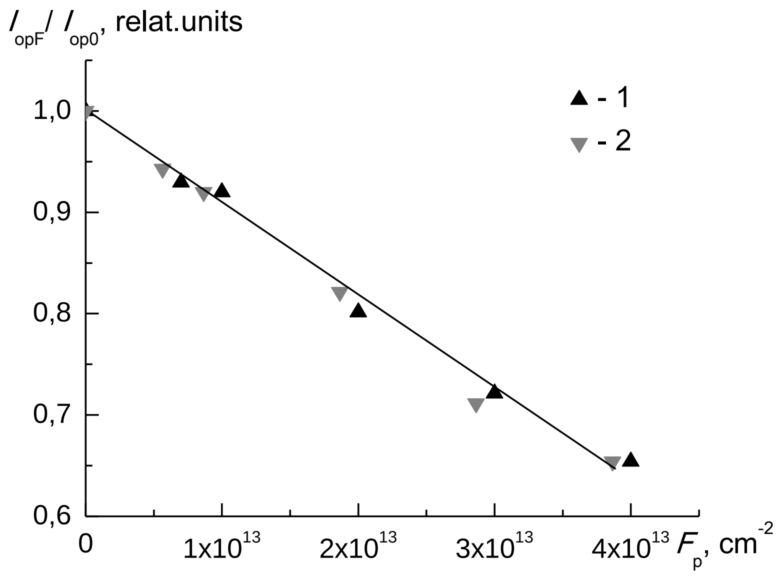

Figure 8. Operating current of Gunn diode DG-1 (1) and DG-2 (2) under irradiation by protons with energy of 63 MeV: symbols are experimental data; lines are results of the calculation of established correlations [4].

In [4], the authors present regularities of electron concentration and their mobility for epitaxial GaAs under irradiation with protons of different energies which can be applied for calculation of Gunn diodes operating current changes. The results of the calculations are presented in figure 8 in the form of a line. It is obvious that there is good correlation between the calculated and the experimental values.

Thus, the obtained experimental data allow concluding that preliminary irradiation with protons in the region of $(1–6)\cdot 10^2$ Gy does not practically reduce the radiation resistance of Gunn diodes produced under the tough conditions of thermocompression bonding. The observed insignificant resistance reduction is explained by insignificant reduction of electron concentration and mobility under preliminary irradiation.

4. Conclusion
In the conclusion, let us sum up the main results obtained in the given work.

1. The technologic factors may lead to significant deterioration of the output parameters and reduction of production efficiency of semi-conductor devices with the required characteristics.
2. Tough conditions of thermocompression bonding of Gunn diodes lead to introduction of local mechanic stresses into the active layer of the device, reduction of electron mobility in the active layer due to introduction of defects and, as a result, to reduction of the operating current level, SSHF

generation power, percentage of quality devices production and general reduction of production efficiency of devices with required characteristics.

3. Irradiation of Gunn diodes produced under the tough conditions of thermocompression bonding with protons with energy of (40–60) MeV and absorbed dose of $(1–6)\cdot10^2$ Gy allows relaxing the local mechanic stresses without formation of additional defects, restoring electron mobility, level of the operating current and SHF generation power.

4. Preliminary irradiation with protons with the energy of (40–60) MeV and absorbed dose of $(1–6)\cdot10^2$ Gy does not practically reduce the radiation resistance of Gunn diodes produced with application of the given technique.

5. Preliminary irradiation with protons with the energy of (40–60) MeV and absorbed dose of $(1–6)\cdot10^2$ Gy may be recommended for treating Gunn diodes which were discarded for the purpose of improving their output parameters and, accordingly, for increasing the percentage of quality devices production.

6. The given technique may be recommended for all semiconductor devices based on GaAs if their parameters depend upon the electron mobility to increase the efficiency of their production.

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