Stability of the GaAs based Hall sensors irradiated by gamma quanta

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Abstract. The present work is aimed at investigation of the stability of the GaAs based Hall sensors (pickups) to irradiation by gamma quanta. The examined objects are the gallium arsenide based Hall sensors manufactured on thin active layers by the methods of vapor phase epitaxy (VPE), molecular beam epitaxy, and ion implantation. Our research methodology involves measurements of the volt-ampere characteristics (VACs) of all sensors for different values of the supply voltage polarity and electron concentration and mobility by the Van-der-Pau method as well as investigations of the noise properties of the sensors before and after irradiation. The sensors are irradiated by gamma quanta of Co^{60} at room temperature in the passive mode, that is, without imposition of an electrical bias. As a result of investigations, it is established that a part of the active layer of finite thickness adjoining the substrate plays an important role in the charge carrier transmission process depending on the concentration of deep-level centers in the substrate. Irradiation by high doses leads to degradation of VACs and increase in the spectral density of the sensor noise. Low gamma radiation doses have a stabilization effect on the sensors. Periodic relaxation processes are observed for a part of the structures manufactured by the VPE method. The assumption is made that they can be caused by the deep-level centers in GaAs.

1. Introduction

Progress of methods of data processing, especially with application of microprocessors, has increased the role of sensors being a primary chain in perception of information from the object being measured. Nowadays to provide safe operation of transport systems, robotics devices, dual application navigation systems, and space technology, new sensors are required to measure magnetic fields with increased sensitivity, accuracy, and radiation stability. The Hall sensors of magnetic field possess sufficient degree of reliability and can operate under extremely adverse conditions, including irradiation. However, their radiation properties are studied insufficiently. Planar high-sensitivity gallium arsenide based sensors of magnetic field have been developed at the Tomsk Joint-Stock Company "Research Institute of Semiconductor Devices" [1]. Since the Hall voltage is inversely proportional to the sensor thickness ($1/d$), the main condition of implementation of the high-sensitivity Hall pickups is manufacture of semiconductor films with small thickness that have some specific features.

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This work presents results of experimental investigation of the influence of irradiation by gamma quanta on the electrophysical characteristics of the magnetic field sensors based on the Hall effect (the Hall pickups or sensors) arranged on thin active gallium arsenide layers and produced by different methods.

2. Objects of research and experimental procedure

Sensors manufactured from gallium arsenide layers arranged on a semi-insulating substrate were used as objects of research. The employed epitaxial structures of n^+-n-n_{bi}-n_i type were manufactured by the methods of vapor-phase (VPE) and molecular beam epitaxy (MBE). In this case, the thickness of the n^+ layer changed from 0.2 to 2 μm. A specially grown LT-layer characterized by very high resistance and small lifetime was used as a buffer n_{bi} layer. In addition, the n^+-n-n_i type structures manufactured by the ion implantation method (IIM) were used to manufacture sensors; the thickness of the n^+ layer was about 0.1 μm.

The parameters of the epitaxial structures were measured with an electrolytic profilometer. The application of the electrolyte-barrier having a mobile barrier and zero or close to zero bias moving through the film depth due to chemical etching allows us to exclude the restrictions characteristic for the metal-semiconductor barrier caused by a breakdown and to measure structures with complicated implantation profile.

The etcher based on H_2SO_4 and H_2O_2 was used as an electrolyte. The typical profile of the electron concentration distribution over the epitaxial structure used for manufacture of the Hall pickups was registered with the profilometer having a probe diameter of 3 mm at a measuring signal frequency of 10^4 Hz [2].

It was established that the profile of concentration of charge carriers providing low residual stress of the Hall pickup (HP) should be sharp on the film-substrate interface.

The concentration of charge carriers and their mobility were measured for the manufactured n^+-n-n_i type structures (here n is the concentration of charge carriers in the active layer, n^+ is the concentration of charge carriers in the contact layer, and n_i is the concentration of charge carriers in the substrate). The influence of the structure of the deep-level centers on the film-substrate interface on the conductivity was also investigated using a microwave resonator of reflection type operating at a frequency of 38 GHz [3]. The change in the conductivity of the structure irradiated by light-emitting diodes of the visible range from the side of the film (or substrate) with bias applied to the n^+-n or n-n_i transition was determined from the proportional change of the microwave power reflected from the resonator. The structures were rejected by the photoresponse shape. Its typical shape is shown in figure 1.

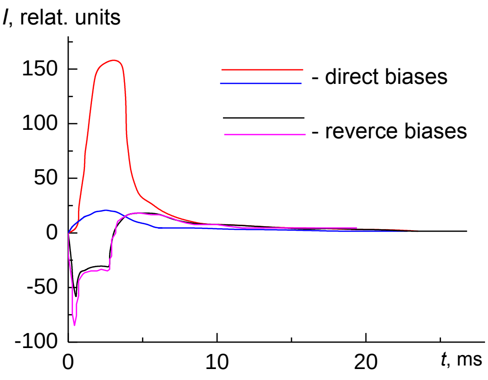

Figure 1. Photoresponce of the structure for different voltage of direct and reverse biases

From figure 1 it can be seen that the longterm relaxation of the photoconductivity depends on the recharge of the deep level (DL) localized in the n-i transition. Irradiation (injection of holes into the n-n_i transition) causes its recharge.

Crystals of sensors were prepared using traditional technology for GaAs field effect transistors. Ohmic contacts were formed by deposition of the Au–Ge–Ni alloy with subsequent alloying. The active regions for ion-implanted structures were insulated using the methods of ion implantation; for other structures, chemical etching was used. Laser scribing was used to separate the plates into individual crystals. Crystals were arranged on the ceramic metalized substrate and sealed with a compound after unwelding of the terminals.

For all sensors, the static volt-ampere characteristics (VACs) were measured for different values of the supply voltage polarity and electron concentration and mobility by the Van-der-Pau method; the noise properties of sensors before and after irradiation were also investigated. The sensors were irradiated by gamma quanta of Co^{60} at room temperature in the passive mode, that is, without imposing electrical bias. In this case, the irradiation dose was successively accumulated. The modes of VAC measurements used in our investigations did not lead to annealing of the incorporated radiation defects, which was confirmed by the identity of experimental data obtained under single irradiation of samples by preset doses and by subsequent accumulation of the dose with intermediate VAC measurements.

Let us consider the main characteristics of the manufactured Hall pickups. The VACs of sensors were in most cases symmetric (figure 2). Several characteristic regions can be identified on the forward and reverse VAC branches: region I with a linear dependence of the current on the voltage ($I \sim U$), region II with a sublinear dependence $I \sim U^k$ ($k < 1$), and region III of current saturation. Moreover, the saturation region started the earlier, the smaller is the quantity ($n{\cdot}d$). This can be explained by the effect of reverse control through the substrate as well as by the effect of traps on the active layer surface [4]. The layer of finite thickness depleted of the charge carriers was formed on the interface between the active layer and the substrate. The thickness of this layer depended on the concentration of deep-level centers in the substrate.

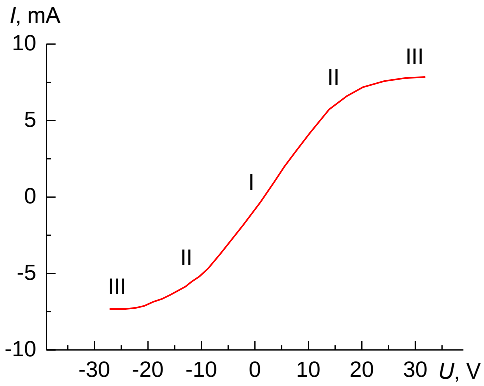

Figure 2. Volt-ampere characterisric of the Hall picup

We consider the MDS structure to be a model of this system [5]. When voltage is applied to the current contacts, some of the electrons diffuse from the active layer through the substrate into the metal, which is charged negatively. The negative charge of the metal is compensated by positive ions in the semiconductor that forms a depletion region extending deep into the semiconductor. In this case, the higher the input voltage, the larger is the depletion region and the higher is the sample resistance. The maximum width of the depletion region, disregarding the electron current through the reverse-biased Schottky barrier, can be estimated from the formula [4]

$$d_{\max} = \left[4kT\varepsilon\varepsilon_0 \ln\left(N_d / n_i\right) / qN_d \right]^{1/2} \quad (1)$$

where N_d is the impurity concentration for homogeneous implantation, ε is the dielectric constant of GaAs, ε_0 is the absolute dielectric constant, k is the Boltzmann constant, and n_i is the concentration of charge carriers. For $N_d = 6{\cdot}10^{15}$ cm^{-3} and $T = 300$ K, $d_{max} = 0.5$ μm.

The saturation current in this case is

$$I_{sat} = N_d q A_{act} U_{sat} \quad (2)$$

where A_{act} is the thickness of the active part of the channel. From Eqs. (1) and (2) it follows that d_{max} increases and the saturation current decreases with decreasing impurity concentration in the active region, as was observed experimentally. For samples with impurity concentration of the order of $6{\cdot}10^{15}$ cm^{-3} and $(n{\cdot}d) < 6{\cdot}10^{11}$ cm^{-2}, $I_{sat} = 2$ mA, and for samples with $(n{\cdot}d) > 6{\cdot}10^{11}$ cm^{-2}, $I_{sat} > 5$ mA in agreement with our experimental results.

3. Experimental results and discussion

For irradiation doses in the range ($1.4{\cdot}10^2$–$7{\cdot}10^5$) Gy, the sensors behaved ambiguously [6]. An analysis of the results obtained allowed us to identify some characteristic groups of sensors.

In the first group of sensors manufactured by the MBE and some sensors manufactured by the VPE, the VACs remained unchanged for irradiation doses in the range ($1.4{\cdot}10^2$–$4.2{\cdot}10^5$) Gy. For higher irradiation doses, a decrease in the current was observed that was described sufficiently well by the relationship established in [7] for the change of the electron concentration upon exposure to gamma quanta, which was the quite expected typical behavior of the sensors under irradiation.

After irradiation by small doses ($1.4\cdot10^2$ Gy) in the second group comprising a part of structures manufactured by the VPE, the current increased up to 40% of its initial value and remained unchanged when the irradiation dose subsequently increased up to $4.2\cdot10^5$ Gy; in this case, the direct measurements also demonstrated the corresponding increase in the electron mobility. For higher irradiation doses, a decrease in the current was observed, which was completely described by the change of the electron concentration under irradiation by gamma quanta. That is, the main peculiarity of the second group was the restoration of the electron mobility under irradiation by small doses of gamma quanta due to the relaxation of mechanical stresses (the effect of small doses) [7, 8].

In the third group of ion-implanted structures (as well as for some VPE structures), the current after irradiation by small doses ($1.4\cdot10^2$ Gy) decreased down to 40%. Our measurements demonstrated that the electron concentration in the active layer of the sensor decreased. With further increase in the irradiation dose, the current remained unchanged up to a dose of $4.2\cdot10^5$ Gy. For higher irradiation doses, a decrease in the current was observed that was completely described by the change of the electron concentration under irradiation by gamma quanta. From the foregoing we can conclude that under irradiation of ion-implanted structures (as well as of some VPE structures) by small doses, the local mechanical stresses on the implanted layer - semi-insulating substrate interface are relaxed, which is accompanied by radiation-stimulated diffusion of defects from the substrate into the active layer, thereby decreasing the electron concentration. For low doses, the absence of the radiation effect on the structures with the LT layer in which the substrate was separated from the active layer testified in favor of this assumption.

In addition, the change of the contact resistance of the samples upon exposure to small doses can contribute to VAC changes [8]. The technology of electrode material deposition and its further annealing form an inhomogeneous electrode layer on the plate surface, thereby leading to chaotic Ge and Ni distributions over the surface area. It seems likely that the effect of small doses leads to accelerated diffusion of these elements, whereupon the resistance of the contact changes. The resistance of the contact can also be caused by the increased inhomogeneity of the *n*-layer because of the penetration of defects from outside into this layer in the process of radiation exposure. Among them are dislocations generated by thermoelastic stresses in the crystal.

And finally, the fourth group of sensors. Under irradiation by sufficiently small doses ($1.4\cdot10^2$–$7\cdot10^5$) Gy, periodic relaxation processes were observed for a number of structures manufactured by the VPE method: the first irradiation with a dose of $1.4\cdot10^2$ Gy led to the increase of the current by 50% of its initial value, and the subsequent irradiation by a dose of $1.4\cdot10^2$ Gy led to the restoration of the initial current. Under subsequent irradiation by a dose of $1.4\cdot10^2$ Gy, the current increased, and then the process repeated once again. A change of the irradiation dose during intermediate exposures in a sufficiently wide range did not change the amplitude of current oscillations.

In [9] the mechanism of their origin was discussed. As a result of investigation of deep-level centers of growth in GaAs [10] it was revealed that some deep-level centers can have several quasi-stationary states. In one of the states, this center captures the current carriers, and in the other state, it donates the captured carriers. That is, in this case we can say that each of the quasi-stationary states is characterized by its own energy level, and these states are separated by an energy barrier. Then the first radiation exposure leads to the activation of the quasi-stationary state either with the capture of a charge carrier or with its liberation depending on the initial state of the examined defect thereby leading to the observed sharp change of the current (either its increase or decrease). The subsequent exposure activates the second quasi-stationary state of the examined defect leading to a decrease (increase) of the current. This process is periodically repeated. In this case, we should note especially that the amplitude of changes of the working current is independent of the dose of intermediate exposures to gamma quanta. This has been proved experimentally by changing the intermediate irradiation doses in a wide range from $1.4\cdot10^2$ to $7\cdot10^5$ Gy.

The foregoing results allowed us to state that under irradiation with a dose of $1.4\cdot10^2$ Gy (low doses), the stabilization effect of gamma radiation on the sensors was observed.

The noise properties of the sensors were measured at frequencies in the range 5–100 kHz [11]. The band width Δf corresponded to 3 %. The bias was applied to the samples that provided the preset current. The noise was estimated from the noise temperature T_n given by the formula [12]

$$T_n = u_n / \Delta f / u_{nR} / \Delta f \tag{3}$$

where u_n is the noise voltage measured at the output from the Hall pickup, u_{nR} is the noise voltage measured with the same ohmic resistance as for the alternating signal, and Δf is the frequency band of the noise meter. The dependences of the noise temperature on the frequency measured for the epitaxial sample and current equal to 1, 1.5, and 2.0 mA [11] demonstrated that T_n and hence, the noise voltage increased with increasing current running through the sample. The dependences measured for I = 1, 1.5, and 2 mA were qualitatively similar. They were similar to the curves presented in [13].

To analyze the results obtained, we note that the main components of the intrinsic noise for the Hall pickups are thermal, shot (current), and $1/f$ (flicker) noise components. In the initial segment of the curve, a linear dependence of T_n on the reciprocal frequency characteristic for the flicker noise was observed. The $1/f$ noise was manifested through fluctuations of the concentration of charge carriers when current ran through the sample. We now present quantitative estimates of the thermal and shot (current) noise components for the concrete sample with sizes 0.4 × 0.25 × 0.0011 mm^3, charge carrier concentration of $1.5 \cdot 10^{16}$ cm^{-3}, and resistance of 1 kΩ.

For the thermal noise, the average squared noise voltage u^2 is determined by the Nyquist formula [12]:

$$u^2 = 4kT \cdot R \cdot \Delta f \, , \tag{4}$$

where R is the active resistance of the measured source of noise. The thermal noise estimated from formula (4) yields $u^2 = 1.6 \cdot 10^{-17} \Delta f$ [V^2·s]. The shot noise is determined by the mechanisms responsible for the concentration of current carriers (largely by the lifetime of the minority current carriers) and is independent of the frequency [9].

To estimate the shot noise i, we take advantage of the formula for the shot current presented in [13]:

$$i^2 = 4I^2 \tau_1^2 \tau_2^2 \Delta f / N_{av} (\tau_1 + \tau_2)^2 (1 + \omega^2 T^2) \, , \tag{5}$$

where τ_1 is the average lifetime of charge carriers, τ_2 is the average lifetime of charge carriers captured in traps, N_{av} is the average number of carriers participating in charge transfer (it is determined by the product of N and the volume of the active region), and $1/T = 1/\tau_1 + 1/\tau_2$.

The average squared shot current i^2 is equal to $2 \cdot 10^{-27} \Delta f$ [A^2·s], and the average squared voltage is $2 \cdot 10^{-21} \Delta f$ [V^2·s], which is much less than the average squared voltage of the thermal noise. The flicker noise is manifested only at low frequencies. The main role is played by the thermal noise.

The spectral noise density increased approximately by one and a half orders of magnitude in comparison with S_u of the unirradiated sample. The increase in S_u can be caused by the following reasons: the decrease of the lifetime (τ) of charge carriers caused by radiation defects and liberation of charge carriers from trapping centers causing additional recombination of charge carriers. To elucidate a reason for increase in S_u, we measured the lifetime of charge carriers for unirradiated and irradiated samples by the method of injection of minority charge carriers. The measurements demonstrated that τ of an irradiated sample was 0.3 ns, and that of an irradiated sample was 0.5 ns. Since according to Eq. (5), the shot noise changed insignificantly with increasing τ, this implies that the active resistance should change.

Conclusions

1. The gallium arsenide based Hall sensors possess sufficiently high radiation stability.
2. The technology of manufacture of device structures affects significantly the behavior of sensors irradiated by gamma quanta.
3. Significant role in the processes of current transport is played by the part of the active layer of finite thickness adjoining the substrate that is depleted of the main charge carriers. The layer thickness depends on the concentration of the deep-level centers in the substrate.

4. Irradiation leads to the VAC degradation. Changes of the VACs of the sensors after irradiation with a dose of $1.5 \cdot 10^2$ Gy are caused either by decreased or increased thickness of the depletion layer near the active layer - substrate interface that changes due to reorganization of the defect structure upon exposure to radiation.
5. For irradiation dose of $1.4 \cdot 10^2$ Gy (for small doses), the stabilizing effect of gamma irradiation on the sensors was detected.
6. For some samples grown by the VPE method periodic relaxation processes were observed. It was demonstrated that they could be caused by the deep-level centers in GaAs and manifestation of 2 quasi-stationary states of the electron traps.
7. The investigation of the noise properties of the irradiated samples demonstrated that the spectral noise density (S_u) for the irradiated samples increased approximately by one and a half orders of magnitude in comparison with S_u of the unirradiated samples. The change of the spectral noise density of sensors before and after irradiation is in agreement with explanations of relaxation oscillations in the samples manufactured by the VPE method.

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