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SURFACE CURRENT IN GaAs P-N JUNCTIONS, PASSIVATED BY SULPHUR ATOMS

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Influence of the storage (low-temperature annealing) of sulphur-passivated GaAs p-n structures in a neutral (helium) atmosphere at room temperature on *I-V* characteristics of forward and reverse currents was studied. The storage strongly reduces the excess forward current and the reverse current in p-n junctions. The ideality coefficient of *I-V* characteristics decreases with the storage. This effect has two stages. It is showed that all these phenomena can be explained by lowering of the surface recombination centers density and reduction of the electrically active centers concentration in the surface depletion layer.

1. INTRODUCTION

P-n junctions on wide-band III–V semiconductors can be used as gas sensors [1, 2]. Such sensors have low background currents, are sensitive at room temperature, have a response time of 100 s [3]. The gas sensitivity of these sensors is due to forming of a surface conducting channel in the electric field induced by the ions adsorbed on the surface of the natural oxide layer [`1, 2].

The threshold gas partial pressure of a sensor on p-n junction depends on the surface states density in the semiconductor [3]. The results of calculations [3] predict rise of the sensitivity to low concentrations of a donor gas when the surface states density in the p-n junction is diminished.

The surface states density in GaAs can be lowered by sulphur atoms deposition from some solutions [4]. The sulphur-passivation reduces the excess forward current and reverse current in GaAs p-n junctions, enhances the photosensitivity in the spectral region of strong absorption, substantially increases the sensitivity to ammonia vapors [5]. However the stability of the characteristics of sulphur-passivated p-n junctions was not investigated.

The aim of this work is a study of the influence of the storage in a neutral gas on the surface currents in sulphur-passivated GaAs p-n junctions. Effect of the storage in helium atmosphere at room temperature on I-V characteristics of forward and reverse currents in sulphur-passivated GaAs p-n structures was studied.

2. EXPERIMENT

I-V characteristics were measured on GaAs p-n junctions with the structure described in previous works [1, 2]. The sulphur atoms deposition (passivation) was carried out by a treatment of different durations in 30% water solutions of $Na_2S \cdot H_2O$ [5].

I-V characteristics of the forward current in a typical p-n structure are presented in Fig. 1.

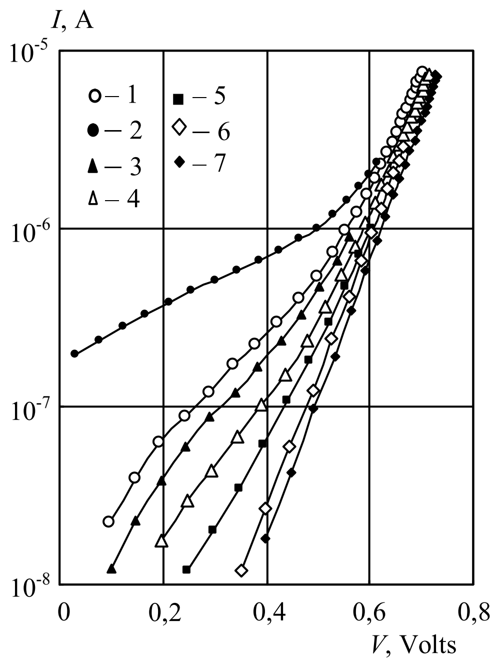

Fig. 1. I–V characteristics of the forward current of a p-n structure: initial (1) and after S-treatment and subsequent storage in helium: 2 – $2.4 \cdot 10^3$ s; 3 – $7.2 \cdot 10^3$ s; 4 – $1.7 \cdot 10^5$ s; 5 – $5.2 \cdot 10^5$ s; 6 – $2.6 \cdot 10^6$ s; 7 – $7.8 \cdot 10^6$ s;

Curve 1 was measured before the treatment. Over the current range between 1μA and 1mA the *I–V* curve can be described with the expression

$$I(V) = I_0 \exp(qV / n_t kT), \quad (1)$$

where I_0 is a constant; q is the electron charge; V denotes bias voltage; k is the Boltzmann constant; T is temperature; $n_t \approx 2$ is the ideality constant. Such *I-V* curves can be ascribed to recombination on deep levels in p-n junction and (or) at the surface [6]. And the corresponding current is known as a recombination current.

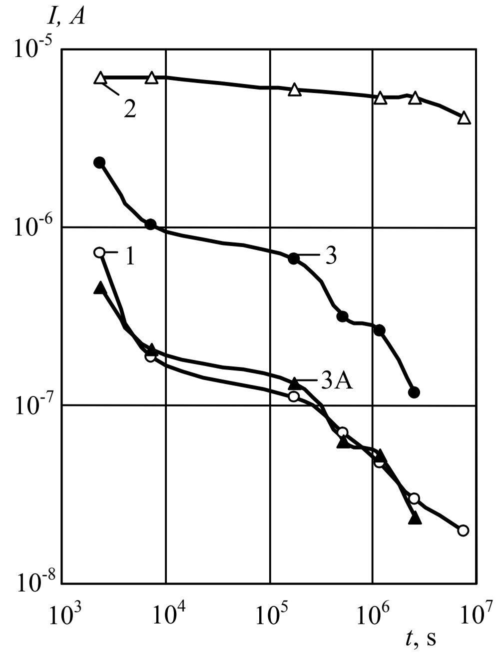

Fig. 2. Effect of the storage duration on the forward current at V=0.4 V (1) and at V=0.7 V (2) and on the reverse current at V=-4 V (3, 3A). Curve 3A is shifted down by 0.7.

At lower biases curve 1 has a section of an excess current, which has an ideality constant n_t>2 and corresponds to the phonon-assisted tunnel recombination at deep centers [6]. This recombination is located at the p-n junction non-homogeneities, which cause local increase of the electric field [6].

Curves 2 to 7 in Fig. 1 were obtained after passivation of 40 s duration. Curve 2, measured after subsequent 40 min storage, exhibits an increase of the excess current. And the further storage leads to a substantial decrease of the excess current, as illustrated by curves 3 to 7. After the storage during one month the excess current disappears, and the I–V characteristic corresponds to (1) over the current range from 10^{-8} A to 10^{-3} A with ideality constant $n_t \approx 2$.

Curve 1 in Fig. 2 represents the dependence of the excess current (at the voltage of 0.4 V) on the storage duration. Curve 2 illustrates such dependence for the recombination current (at the voltage of 0.7 V). A comparison between curves 1 and 2 shows that the influence of passivation and the subsequent storage on the recombination current is much weaker than on the excess current.

The effect of the passivation and the subsequent storage on the I–V characteristic of reverse current in the same p-n junction is illustrated by Fig. 3. Curve 1 was obtained before passivation. Curve 2, measured after subsequent storage during 40 min, exhibits an increase of the reverse current. And further storage decreases the reverse current, as is seen from curves 3 to 6. Curve 3 in Fig. 2 presents the dependence of the reverse current, measured at a voltage of –4 V, on the storage duration. Curve 3A is obtained from curve 3 by a shift down by 0.7. This curve practically coincides with curve 1. It means that the time-dependences of the excess forward current and the reverse current are identical.

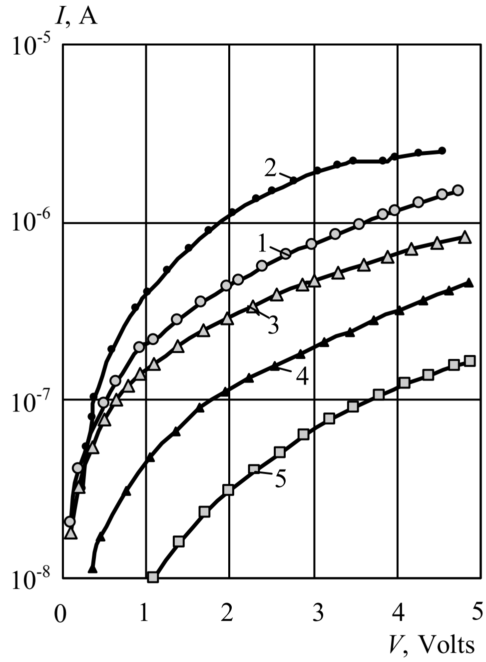

Fig. 3. I–V characteristics of the reverse current of a p-n structure: initial (1) and after S-treatment and subsequent storage in helium: 2 – $2.4 \cdot 10^{3}$ s; 3 – $1.7 \cdot 10^{5}$ s; 4 – $1.2 \cdot 10^{6}$ s; 5 – $2.6 \cdot 10^{6}$ s; 6 – $7.8 \cdot 10^{6}$ s.

3. DISCUSSION

The presented experimental results show that storage in helium atmosphere at room temperature substantial reduces recombination and excess forward currents, as well as reverse current in sulphur-passivated GaAs p-n junctions. The storage time dependence of the excess forward current and the reverse current are identical. It suggests that decrease of these currents has the same nature. It is known [6] that the excess current in GaAs p-n structures is localized in non-homogeneities of the p-n unction. A strong influence of the passivation and the subsequent storage on the excess current suggests that these non-homogeneities are placed on the surface of our structures. And the same can be concluded about the localization of the reverse current in our samples.

Curve 2 in Fig. 2 illustrates the time dependence of the recombination current during the storage. The surface component of this current can be expressed [6] as

$$I_s = q l_p n(0)(C_s N_s / 2)^{\frac{1}{2}} (D_{ns}^{\frac{1}{2}} + D_{ps}^{\frac{1}{2}}). \quad (2)$$

Here l_p is the perimeter of the p-n junction; n(0) is the surface electron concentration at the point, where the surface recombination centers are half-occupied; N_s and C_s are the density of surface recombination centers and their electron capture coefficient, correspondingly; D_{ns} and D_{ps} are the diffusion coefficients for electrons and holes at the surface, respectively.

Sulphur-passivation of GaAs reduces the density of surface recombination centers [4]. Therefore the decrease in the recombination current, illustrated by curve 2 in Fig. 2, can be ascribed to the lowering of the density N_s of surface recombination centers in (2).

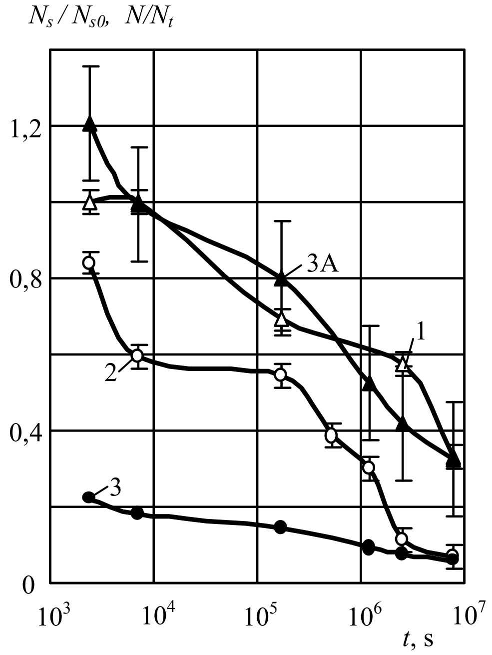

Fig. 4. Effect of the storage duration on the concentrations: 1 – $N_s/N_s(0)$; 2 – N/N_t in surface non-homogeneities; 3, 3A – average of N/N_t in surface. Ordinates of curve 3A are normalized at t=7.2·10^3 s.

An analysis of curve 2 in Fig. 2 with the help of relation (2) gives the time-dependence $N_s/N_s(0)$, where $N_s(0)$ is the concentration of surface recombination centers before storage. This dependence is represented by curve 1 in Fig. 4.

Some information about the concentration N of electrically active centers at the surface of a p-n structure gives an analysis of ideality coefficient n_t of I–V characteristics [6]. This coefficient is related to N by expression [6]

$$N = N_t(1 - 2/n_t), \quad (3)$$

where

$$N_t = 12\varepsilon m_t (kT)^2/(q\hbar)^2, \quad (4)$$

ε is the permittivity; m_t denotes the tunnel effective mass of charge carriers.

Curves 1 and 2 in Fig. 5 present the time-dependences of the ideality coefficients at low and high injection levels, respectively. An analysis of curve 1 by using formula (3) gives the change of electrically active centers concentration N in the surface depletion layer of non-homogeneities, which are responsible for the excess current. *N(t)* dependence during the storage for these centers is depicted as curve 2 in Fig. 4. The dependence *N(t)* for the homogeneous region of the surface, obtained from analogous analysis of curve 2 in Fig. 5, is represented by curve 3 in Fig. 4.

A comparison between curves 2 and 3 in Fig. 4 shows that the storage much stronger reduces the concentration of electrically active centers (non-compensated acceptors) in surface non-homogeneities, than in average at the surface of p-n structure. After a storage for one month curve 2 in Fig. 4 trends to curve 2. It means that the non-homogeneities at the surface, which are responsible for the excess current, disappear. The main defects that increase the excess current in p-n junctions on III–V semiconductors are dislocations [6]. And sulphur atoms are donors in GaAs. It permits to conclude that during the storage S atoms at the surface diffuse to dislocations and compensate their charge.

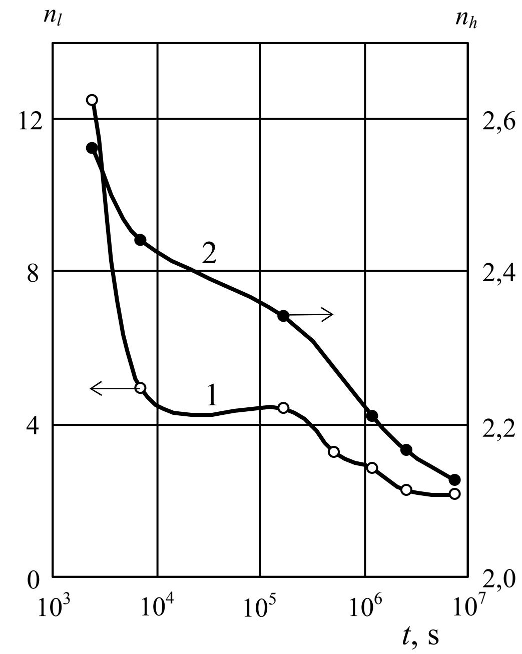

Fig. 5. Effect of the storage duration on the ideality coefficient n_t at low (1) and high (2) injection levels.

As mentioned, curves 1 and 3 in Fig. 4 represent the time-dependences of the surface recombination centers concentration N_s (normalized to initial its value $N_s(0)$) and the electrically active centers at the surface N (normalized to the quantity N_t , defined by Eq. (4)). Curve 3A was obtained from curve 3 by normalization to its value at t=2h. The courses of curves 1 and 3A at t.>10^4 s are similar. It means that the density of surface recombination centers and the concentration of electrically active centers vary identically during the storage. However, at the beginning, at t<10^4 s, the density of recombination centers N_s is practically constant, while the concentration of electrically active centers N substantially (by 20%) drops. It suggests that these both kinds of centers are of different nature. We can only assume that both these centers are acceptors and are compensated by penetration of sulphur atoms into the crystal during the storage.

The course of curve 2 in Fig. 4 suggests that the quantity N_t in surface non-homogeneities has two stages. In the first stage, at t<10^4 s, N_t drops by 40%, and then its decrease is slower. Probably, the two-stage relaxation of N_t at the surface and in its non-homogeneities is due to two different processes, leading to compensation of acceptors.

4. CONCLUSIONS

The storage of GaAs p-n structures in a neutral (helium) atmosphere at room temperature after sulphur atoms deposition (sulphur passivation) substantially reduces forward and reverse currents.

The excess current, caused by phonon-assisted tunnel recombination in non-homogeneities, where the depletion layer is thinned, especially strong decreases with the storage. This effect is due to reduction of the concentration of electrically active centers in the surface depletion layer.

The enhanced reverse current in GaAs p-n structures passes through the same non-homogeneities, as the excess forward current, and similarly decreases with the storage after sulphur-passivation.

The forward current at high injection level (at *I*>1μA) also decreases with the storage, due to lowering of both the density of surface recombination centers and the concentration of electrically active centers in the surface depletion layer.

All these effects can be ascribed to compensation of acceptors (perhaps, related to dislocations) by sulphur atoms in the surface depletion layer and to destroying of surface states, acting as recombination centers.

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ПОВЕРХНЕВИЙ СТРУМ У P-N ПЕРЕХОДАХ НА ОСНОВІ GaAs, ПАСИВОВАНИХ АТОМАМИ СІРКИ

Досліджено вплив зберігання (низькотемпературного відпалу) пасивованих атомами сірки p-n переходів на основі GaAs у нейтральній атмосфері (в гелії) при кімнатній температурі на ВАХ прямого і зворотного струмів. При зберіганні значно зменшуються надлишковий прямий струм та зворотний струм у p-n переходах. Коефіцієнт ідеальності ВАХ зменшується в процесі зберігання. Даний процес є двостадійний. Показано, що всі ці явища можна пояснити зменшенням щільності поверхневих центрів рекомбінації та зменшенням концентрації електрично-активних центрів у поверхневому збідненому шарі.

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ПОВЕРХНОСТНЫЙ ТОК В P-N ПЕРЕХОДАХ НА ОСНОВЕ GaAs, ПАССИВИРОВАННЫХ АТОМАМИ СЕРЫ

Исследовано влияние хранения (низкотемпературного отжига) пассивированных атомами серы p-n переходов на основе GaAs в нейтральной атмосфере (в гелии) при комнатной температуре на ВАХ прямого и обратного токов. При хранении существенно уменьшаются прямой избыточный ток и обратный ток в p-n переходах. Коэффициент идеальности ВАХ уменьшается в процессе хранения. Этот процесс двухстадийный. Показано, что все эти явления можно объяснить уменьшением плотности поверхностных центров рекомбинации и уменьшением концентрации электрически активных центров в поверхностном обедненном слое.