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Forward voltage drop of the electron irradiated silicon p-n–junctions at low temperatures

ABSTRACT

Electron (E = 4 MeV) irradiation influence on the temperature dependence of forward voltage drop U_F of silicon gradual p-n–junctions manufactured on the basis of floating-zone growth n-*Si* with ρ = 0.06–0.5 $\Omega\cdot$cm in temperature range 4.2–80 K have been investigated.

U_F value abruptly increases more than 6 times at the unirradiated samples cooling below 40–30 K. U_F increase occurs at two temperature regions 20–30 and 4.2–20 K that is associated with charge carriers freezing-out on doping (*Al*, *P*) impurities levels in p and n regions respectively.

The p-n–junction electron irradiation results in monotone increase of the U_F value in all investigated temperature ranges. These changes at 4.2–40 K are 5–6 times bigger

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than at 40–80 K. Such essential differences are the result of the U_F temperature dependence behavior enhancement caused by electron irradiation.

At the identical electron fluences the U_F change is higher for p-n–junctions with higher base resistivity.

The strong U_F electron fluence dependence at temperatures lower than 40 K is explained by the influence of compensation degree on the *Si* conductivity at low-temperatures.

1. INTRODUCTION

The experimental data on investigation of penetrating irradiation influence on forward current-voltage characteristics of silicon p-n–junctions that are available in scientific literature are obtained mainly at 78–400 K [1]. At the same time the high sensitivity of low-temperature electrical conductivity of silicon to a different kind of structural disruptions and also the development of cryoelectronics testify scientific and practical significance of such investigations at lower temperatures. The objective of the work is to investigate the influence of electron irradiation on forward voltage drop U_F of silicon p-n–junctions in the temperature range of 4.2–80 K.

2. EXPERIMENTAL

Diffusively-alloyed gradual p-n–junctions manufactured on floating-zone growth phosphorous doped silicon with resistivity $\rho = 0.06–0.5\ \Omega\cdot\text{cm}$ (p-emitter region is boron-doped *Si* with $\rho = 0.015\ \Omega\cdot\text{cm}$). The alloying of wafers was carried out in vacuum ($1.3\cdot10^{-3}$ Pa) with the utilization of silumin, then the stratum of eutectic was conducted away in p-region by the floating-zone melting method with the simultaneous spreading of aluminium in n-region. All investigated p-n–junctions had a linear profile of impurity concentration distribution. The irradiation was carried out by electrons (E = 4 MeV) at room temperature by different electron fluences F. The $U_F(T)$ dependence (T = 4.2–80 K) was measured for each F value at forward current density of 50 mA/cm^2.

3. RESULTS AND DISCUSSION

The typical dependencies of $U_F(T)$ for samples with (ρ = 0.2 Ω·cm) irradiated with different electron fluences are shown in Figure 1. An unirradiated sample cooling in temperature range 80–30 K results in forward voltage drop monotonical increase of 0.9 V and in temperature range 30–4.2 K U_F increases by the factor of more than 6. The abrupt U_F value increase at low temperatures occurs on two ranges 30–20 and 20–4.2 K. The investigated samples electron irradiation results in forward voltage drop value monotonic increase in all investigated temperature range (Fig. 1). The magnitude of these changes at 4.2–40 K is 5 to 6 times greater than at 40–80 K. Such essential differences in the U_F value changes precedes from the change of the investigated parameter temperature dependence behavior caused by electron irradiation.

With F increasing the enhancement of $U_F(T)$ dependence is observed at temperatures below 40 K. For samples manufactured on silicon with other resistivity values the behavior of $U_F(T)$ dependence change qualitatively was the same as for that shown in Figure 1. To some extent it is confirmed by the results introduced in Figure 2. For example, with F increasing the relative change U_F at 4.2–40 K (Fig. 2, a) for all samples is much greater than at 40–80 K (Fig. 2, b). It also can be seen that at the identical electron fluence the U_F change is greater for p-n–junctions with greater value of base resistivity. So at $F = 5.1 \cdot 10^{16}$ cm^{-2} the forward voltage drop value of a sample with ρ = 0.5 Ω·cm was increased by the factor of 4 in comparison with a sample with ρ = 0.06 Ω·cm (Fig. 2, a). This feature is exhibited at higher temperature of measurement as well

(Fig. 2, b). However, in this temperature range, as it was already mentioned, U_F changes for all samples were much smaller than at $T < 40$ K.

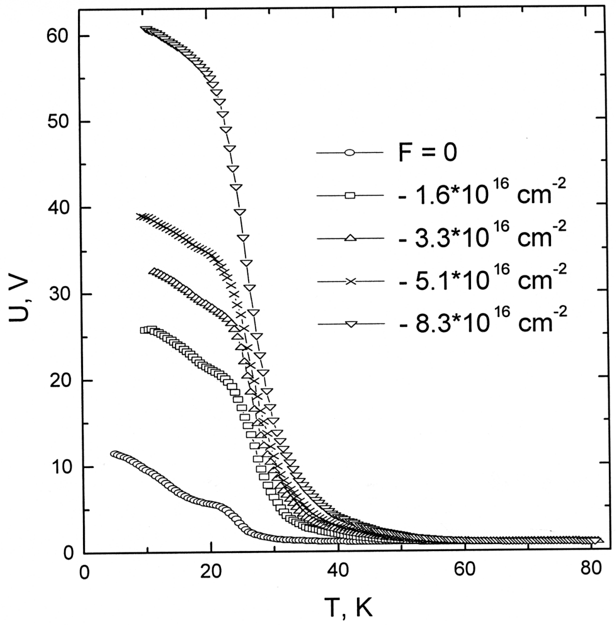

Fig. 1. Temperature dependencies of the forward voltage drop (j = 50 mA/cm^{-2}) of one of the investigated samples (ρ = 0.2 Ω·nm) measured after different fluences of electron irradiation

In general U_F is determined by the voltage drop across p-n–junction U_{pn} and on lightly doped base n-region U_n [2]. The p-region, as a rule, is heavily doped and the voltage drop on it is usually neglected. This assumption is reasonable only at measurement temperatures high enough. In the range of cryogenic ($T < 120$ K) temperatures in the presence of charge carriers freezing-out on shallow levels of doping impurities it is necessary to take into account the voltage drop on p-region U_p. The temperature being decreased the p-n–junction voltage drop increases [1]. However, its changes for diodes with the high resistivity base cannot exceed changes of the Si potential barrier height, which is always less than Si band gap. Therefore, it is worthwhile to consider the negligible contribution of this component to U_F change together with U_p and U_n at 30–80 K only. At $T < 30$ K the value of U_F is completely determined by the voltage drop across quasi-neutral p-n–junction regions.

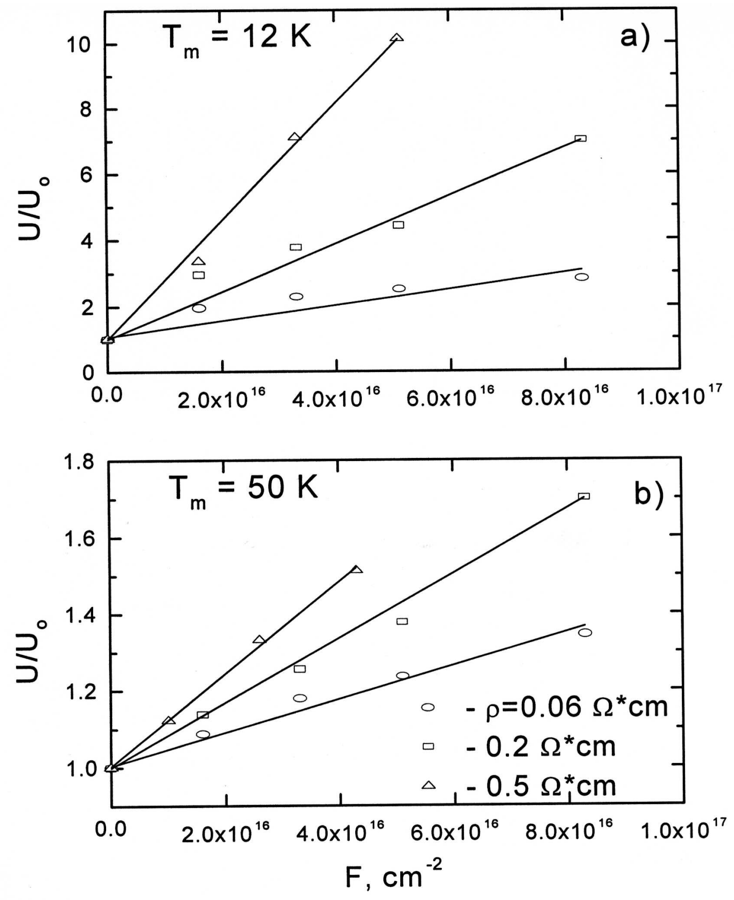

Fig. 2. Relative changes of the forward voltage drop (measured at 12 K and 50 K) of the samples manufactured on silicon with different resistivity after irradiating with different electron fluences

In the absence of conductance modulation the U_p and U_n can be considered as the voltage drop across simple ohmic resisters, the magnitude of which depends on mobility and concentration of free charge carriers. In the low temperature region the mobility is determined by the scattering processes on impurity centers [3]. The radiation defects concentration in our experiment did not exceed the basic doping impurities concentrations. It confirms by the negligible U_F changes at 40–80 K and also by linear character of $U_F(F)$ dependencies shown in Figure 2 [1, 4]. Therefore it is possible to assume that the U_F behavior at irradiation and temperature variation basically depends on free holes and electrons concentration changes in quasi-neutral p-n–junction regions.

The concentration of conduction electrons n in a semiconductor doped by the single-charge donors only with the concentration N_d and the ionization energy E_d is determined by the following expression [3]:

$$n = \sqrt{\frac{N_d N_c}{2}} \cdot \exp\left(-\frac{E_d}{2kT}\right), \qquad (1)$$

where N_c is the effective density of states in the conduction band, k is the Boltzmann constant, T is the temperature.

As it follows from the expression (1), the temperature being decreased the n value exponentially decreases. The same speculations are valid for holes in the p-region. That is the cause of n- and p-regions resistance increase and the samples forward voltage drop abrupt increase at temperatures lower than 40 K (Fig. 1) respectively. The thermal ionization energy of aluminum (60.69 MeV) is higher than that for phosphorus (45.59 MeV) [5]. Therefore the freezing-out for holes in p-region will happen at higher temperatures than those for electrons in n-region. This explains the complicated character of the initial samples U_F dependencies at 4.2–30 K. Besides, the increase of U_p and U_n will last as long as an electric field intensity does not reach the value at which the process of the impurity levels impact ionization begins [6]. If the relevant field intensity is not reached, the mechanism of conductance through the conduction band will be replaced by conductance via impurity states [7]. All this will result in $U_F(T)$ dependencies behavior change also at $T < 20$ K.

At samples irradiation the introduction of radiation defects (RD) with concentration N_r in p- and n-regions results in their compensation degree increase [8]. For a compensated n-type semiconductor the temperature dependence of free charge carriers concentration is [3]:

$$n = \frac{N_c\left(N_d - N_r\right)}{2N_r} \cdot \exp\left(-\frac{E_d}{kT}\right), \tag{2}$$

where $N_r/N_d < 1$ is the ratio of radiation defects (acceptors) and doping impurities (donors).

It follows from the expression (2) that the N_r increase results in n decrease and therefore to n-region resistance and U_F increase at all temperatures of measuring. All these speculations are valid for p-region of samples as well. However, it is initially compensated by doping donor impurity. Therefore, introduction of RD with concentrations smaller than phosphorous atoms concentration will hardly result in its essential resistance changes.

It is seen from the preexponential factor in the expression (2) that at the identical concentration of the irradiation induced defects the change in the electron concentration is smaller for samples with lower N_d values in the whole investigated temperature range. It explains the apparent differences in $U_F(F)$ dependencies for samples manufactured on silicon with different resistivity values (Fig. 2). The strong difference in the change in the forward voltage drop value at 4.2–40 and 40–80 K caused by irradiation from our point of view is associated with two reasons. One of them, as it was already mentioned, is the enhancement of the U_F temperature dependence behavior at 4.2–40 K. It is caused by the respective change of the $n(T)$ dependence that resulted from the absence of the factor 2 in the exponent denominator of the expression (2). Alongside with it, with increasing of the material compensation degree the increase of an activation energy of shallow impurity centers is also possible [9]. The increase in the material compensation degree leads to increase in the electric field intensity which is relevant to an impurity breakdown in semiconductors represents another reason mentioned above [6]. All this will cause with F increase the considerably greater U_F changes at 4.2–40 K than at 40–80 K (see Fig. 1, 2).

4. CONCLUSION

Thus, for initial and electron irradiated (E = 4 MeV) silicon p-n–junctions the region with strong forward voltage drop temperature dependence caused by charge carriers freezing-out on shallow impurity centers in quasi-neutral p-n-junction regions was detected. It was established that RD introduction results in forward voltage drop increase at 4.2–40 K is 5–6 times greater than at 40–80 K which is caused by the material compensation degree influence on the low-temperature silicon conductance.

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