ANNALES
UNIVERSITATIS MARIAE CURIE-SKŁODOWSKA
LUBLIN – POLONIA
VOL. LV/LVI, 4 SECTIO AAA 2000/2001

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Minsk (Belarus)

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Avalanche breakdown in electron irradiated silicon p-n–junctions at low temperatures

ABSTRACT

The influence of electron (E = 4 MeV) irradiation on the temperature dependence of avalanche breakdown voltage U_b of silicon diffused-alloyed gradual p-n–junctions manufactured on the basis of floating-zone growth Si (n-region – ρ = 0.2 Ω·cm, p-region – ρ = 0.015 Ω·cm) in temperature range 4.2–80 K has been investigated.

The greatest U_b increase of the initial and irradiated p-n–junctions occurred in temperature range 17–30 K. The introduction of radiation defects results in sharper temperature dependence of the avalanche breakdown voltage in the given area. Capacity and conductivity temperature dependencies analysis of the initial and irradiated samples has shown that such U_b behavior is caused by the charge carriers freezing-out on the shallow doping centers in the quasi-neutral region of the structure. The introduction of radiation defects results in n-region material compensation degree and an ionization thermal energy of donor centers increase, which increases the temperature dependence of the breakdown voltage at 17–30 K.

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1. INTRODUCTION

It is known [1, 2], that the recharge of radiation defects (RD's) deep levels in a space charge region of silicon p-n–junctions changes the sign of the avalanche breakdown voltage temperature coefficient TKU_b. There are some works [1] dealing with the influence of electron irradiation on the temperature dependence of an avalanche breakdown voltage U_b. But these dependencies were investigated only at 78–300 K. At the same time the high sensitivity of a silicon low-temperature electrical conductivity to the presence of compensating impurities, and also the development of cryoelectronics testify to a scientific and practical significance of such investigations at lower temperatures. The objective of the given work is to experimentally investigate the influence of electron irradiation on an avalanche breakdown voltage of silicon diffusively–alloyed p-n–junctions at 4.2–80 K

2. EXPERIMENTAL

Diffusively–alloyed p-n–junctions manufactured on floating-zone growth phosphorous doped silicon with resistivity ρ = 0.06–0.5 Ω·cm (p-emitter region – CZ-growth, boron-doped *Si* with ρ = 0.015 Ω·cm). The alloying of wafers was carried out in vacuum ($1.3 \cdot 10^{-3}$ Pa) with the utilization of silumin, then the layer of eutectic was conducted away in p-region by the floating-zone melting method with the simultaneous spreading of aluminum in the n-region. All investigated p-n–junctions had a linear profile of impurity concentration distribution. Irradiation was carried out by electrons with energy E = 4 MeV at room temperature with different electron fluences F. The temperature dependence of an avalanche breakdown voltage was measured after each F value. The voltage drop across a sample at breakdown current density $j = 50\cdot10^{-3}$ A/cm^2 was considered as U_b value. Alongside with a breakdown voltage the reverse current-voltage characteristic, the barrier capacitance C and the conductance G of p-n–junctions were measured ($f = 1\cdot10^6$ Hz). The temperature variation was executed by heating of previously cooled samples from the liquid helium temperature.

3. RESULTS AND DISCUSSION

The representative breakdown voltage temperature dependencies for one of the investigated samples irradiated with different electron fluences are shown in Figure 1. The initial sample cooling in the temperature range 80–40 K results in breakdown voltage monotonically increases by to 5–6 V. The dependence of $U_b(T)$ in temperature range 40–4.2 K is expressed much stronger. The measured change of U_b value in this temperature range is 4–5 times greater than in temperature range 80–40 K. The increase of U_b value happens in two temperature regions: 40–30 and 30–17 K. The electron irradiation results in the breakdown voltage value monotone increase throughout the investigated temperature range (Fig. 1).

The magnitude of these changes at 4.2–30 K is much greater than at 40–80 K. For example, at $F = 8.3\cdot10^{16}$ cm^{-2} the U_b value at 50 K had increased at approximately 20 V and at 10 K its increase ranges up to 70 V. Such essential variations in the U_b value changes proceed from the change of the investigated parameter temperature dependence behavior caused by electron irradiation. With F increasing the abrupt increase of the absolute magnitude of U_b temperature coefficient was observed at temperatures lower than 30 K.

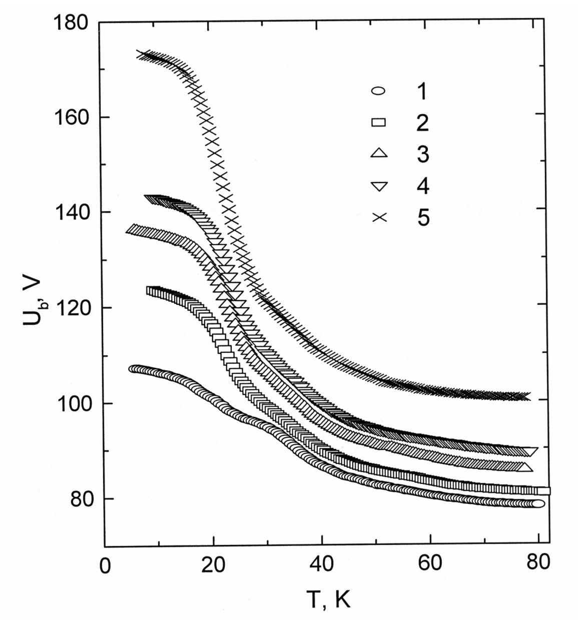

Fig. 1. Temperature dependencies of the avalanche breakdown voltage of one of the investigated samples measured after different fluences of electron irradiation: 1 – F = 0; 2 – $1.6\cdot10^{16}$ cm^{-2}; 3 – $3.3\cdot10^{16}$ cm^{-2}; 4 – $5.1\cdot10^{16}$ cm^{-2}; 5 – $8.3\cdot10^{16}$ cm^{-2}

To explain the U_b behavior resulting from temperature variations and electron irradiation, the measurement of barrier capacity and conductance of the investigated p-n–junctions have been performed. The dependencies of $C(T)$ (a) and $G(T)$ (b) of the same sample as shown in Figure 1 are submitted in Figure 2. In the temperature range 65–22 K an unirradiated p-n–junction capacity value decreases up to several picofarads (a sample geometrical capacity) and this one is kept constant up to 4.2 K. With samples cooling the C value abruptly decreases in two temperature regions 43–65 and 22–35 K which is accompanied by the origin of two maximums: E_1 and E_2 on $G(T)$ dependencies.

When electron fluence increases the capacity and conductance are monotonically decreased throughout the investigated temperature range (Fig. 2). It can also be seen that the samples irradiation shifts the second region (22–35 K) of the abrupt capacity decrease and conductance maximum E_2 in the higher temperature region. $C(T)$ and $G(T)$ dependencies behavior in the temperature region 35–80 K practically does not depend on electron fluence.

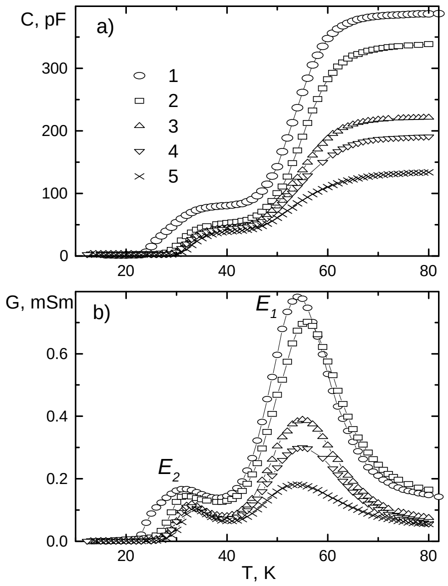

Fig. 2. P-n–junction $C(T)$ and $G(T)$ dependencies measured with the applied reverse bias 1 V, after different fluences of electron irradiation: 1–5 the same, as in the Figure 1

The non-monotone changes of Si step p-n–junctions capacity and conductance were observed in [3, 4] at cryogenic temperatures as a result of charge carriers freezing-out on the basic doping impurity levels in a base n-region. The base resistance increase results in adding to a p-n–junction depletion layer capacitance of a small quantity of a base region capacity connected to it in series. It causes the abrupt decreasing of the measured capacity and the origin of the relevant maximum on a conductance spectrum is observed. We have investigated the p-n–junctions with the gradual impurity distribution profile. Therefore, as opposed to [3] in our case it is necessary to allow for charge carriers freezing-out on impurity levels both in n- and in p-type quasi-neutral p-n–junctions regions, and thus into the investigated device dual circuit the relevant to p-region capacity and resistance connected to each other in parallel should be added.

The maximum position on $G(T)$ curves is determined mainly by the temperature dependencies of the n- and p-regions resistance which mainly depend on electron and hole concentrations changes accordingly that are caused by the temperature variations. The mobile electrons concentration n in a semiconductor doped by the single-charged donors with a concentration N_d and an ionization energy E_d, is determined by the following expression [5]:

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

where N_d is the states density in the conduction band, k – the Boltzmann constant, T – a temperature. The same expression can be used for a hole concentration in p-region. The basic doping impurity in n-region is the phosphorous and in p-region – aluminum. The essential difference in phosphorous (45.59 MeV) and aluminum (69.03 MeV) ionization energy values gives a good enough resolution of the relevant peaks in conductance spectra and the regions of abrupt decrease of the measured capacity [6]. In this case the peak E_1 corresponds to the holes freezing-out on *Al* atoms in the p-region and E_2 – to electrons freezing-out on *P* atoms in n-region.

The breakdown voltage value is determined by a space charge density [2, 7]. The higher the latter the smaller value of the applied to a p-n–junction voltage will be required to attain the critical electric field strength needed for the avalanche breakdown to occur. The change in the charge state of the shallow donor and acceptor levels resulting from the charge carriers freezing-out will cause decreasing in space charge density. Therefore, to maintain the critical electric field strength it is required to increase the applied to a p-n–junction bias which equals the breakdown voltage. The filling degree of shallow donor center levels resulting from the temperature variation will correlate with the mobile electrons concentration in the conduction band given by the expression (1). And the same is valid for shallow level acceptors. In this case, as it was already stated above, the holes freezing-out in the p-region will occur at higher temperatures. And it is also the origin of the two characteristic regions of the U_b temperature dependence at 17–30 and 30–40 K.

The change of investigated parameters during electron irradiation of p-n–junctions takes place as a result of radiation defects (RD's) introduction into the n- and p-regions. All RD's give either deep acceptor levels in the upper half of the Si forbidden gap or donor levels in the lower one [8], which leads to the reduction of the p-n–junction space charge density and to the observed increase of a breakdown voltage at 4.2–80 K and also to decreasing a depletion-layer capacitance and conductance values (Fig. 1, 2). The change of the temperature dependencies behavior of a breakdown voltage at 4.2–30 K and also a capacity and a conductance at 22–35 K as a result of electron irradiation is related to the change of the mobile electron concentration temperature dependence in the n-region of a p-n–junction. It is necessary to allow for two factors here. The first is related to the influence of the material compensation on the $n(T)$ dependence form itself. With the availability of the compensating centers the preexponential multiplier in expression (1) varies and the exponent of an exponential curve is doubled [5]. The other factor is the increase the donor centers thermal ionization energy with the increase in the material compensation degree [9]. For that reason the RD's concentration increase at p-n–junctions irradiation also results in breakdown voltage temperature dependence enhancement at 17–30 K and also to the shift of the conductance maximum E_2 and the region of the capacity abrupt decrease into the higher temperatures field. The same speculations are also valid for p-region. However, this region was initially compensated by the doping donor impurity. Therefore, the RD’s introduction in quantities smaller than the phosphorus atoms concentration will hardly result in the essential changes of the hole concentration temperature dependence.

4. CONCLUSIONS

Thus, for the initial and electron irradiated (E = 4 MeV) silicon diffusively-alloyed p-n–junctions the regions with non-monotone temperature dependence of a breakdown voltage at 4.2–40 K and also a barrier capacity and conductance at 4.2–40 K caused by charge carriers freezing-out on shallow impurity centers in quasi-neutral p-n-junction regions have been detected. It is determined that RD's introduction results in breakdown voltage temperature coefficient increase at 17–35 K and also leads to the conductance maximum and abrupt capacity decrease region at 22–35 K shifting into the higher temperatures region which is caused by the n-base compensation degree influence on the low-temperature silicon conductance.

ACKNOWLEDGEMENT

This work was carried out thanks to the Belorussian Fund of Fundamental Investigations financial support.

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