THE EFFECT OF AN ANISOTROPIC PRESSURE ON THE REVERSE CURRENTS AND THE LIFETIME OF MINORITY CARRIERS IN GERMANIUM DIODES

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The effect of pressure on the reverse currents, the lifetime of minority carriers and the charging capacitance of fused germanium diodes is considered. The p-n junctions are arranged in the (111) crystallographic plane. It is established that the reverse current increases rapidly with increased pressure. The lifetime of minority carriers falls by a factor of 1.5 to 2 up to a pressure of $3 \cdot 10^9$ dyne/cm^2 and the charging capacitance increases. Starting from a pressure of $3 \cdot 10^9$ dyne/cm^2 the lifetime of minority carriers increases and the charging capacitance is reduced to a particular constant value. A qualitative explanation of the dependence of τ_e, C_j and I_{rev} is given.

At the present time there are a number of papers [1–5] dealing with the effect of mechanical pressure on the current-voltage characteristics of semiconductor devices. In [1, 2] the effect of anisotropic pressure on the resistance of shallow surface p-n junctions was considered. It was established that the reverse currents are changed by a whole order of magnitude, while the forward currents are affected to a lesser extent. A uniaxial pressure leads to an increase in the forward and reverse currents and to a reduction in the breakdown voltage [3, 4]. Matsuo [5] obtained results which indicate that with an anisotropic pressure of the order of $1.1 \cdot 10^4$ kg/cm^2 the lifetime of the minority carrier current in Si transistors is reduced. The precise reason for these changes in reverse current and lifetime has still not been established. However, suggestions have been made that in this case we have the simultaneous action of several mechanisms associated with a) a change in the width of the forbidden zone, b) the appearance in the space-charge region of generative-recombination centers due to an increase in the concentration of defects, and c) surface effects.

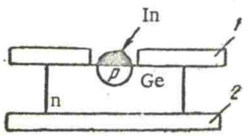

Fig. 1

In this paper we shall consider the effect of an anisotropic pressure on the current-voltage characteristic, the lifetime of minority carriers and the charging capacitance of alloyed germanium diodes. The diodes were made of n-type germanium having a specific resistance of 2–3 ohm · cm, and the p-n junction was formed in the (111) crystallographic plane at a temperature of 550° C. The thickness of the base of the diodes was 2 mm. The pressure was applied by means of a lever in a direction perpendicular to the (111) plane, i.e., along the direction of current flow. For this the diode was squeezed between two plates of plexiglass in one of which there was a circular hole. A pellet of indium projected into this hole, the diameter of which was somewhat greater than the indium pellet. Thus the edge of the plate was close to the spacecharge region of the p-n junction (Fig. 1). With this form of upper plate the minimum mechanical stress developed in the base of the diode will be distributed at the center of the p-n junction, and the stress will increase as we move from the center to the edge of the hole. The pressure is considered as the applied force divided by the area of the boundary of the diode base. It can be seen from Fig. 2 that as the pressure is increased the reverse current increases, and the greater the reverse bias the greater the increase in current due to the pressure. With a bias of 5 V and a pressure of $3 \cdot 10^9$ dyne/cm^2 the current increases by a factor of approximately three, and with a bias of 50 V by almost two orders: when the pressure is removed the reverse current returns to its initial value. The behavior of the reverse current-voltage characteristics can be explained in accordance with Rindner [1]. With an increase in the reverse voltage the space-charge of the p-n junction broadens out and falls within the region of greater mechanical stress, which in turn leads to a sharper change in current. The increase in current, starting from a pressure of the order of $(2–3) \cdot 10^9$ dyne/cm^2, causes a rise in the concentration of minority charge carriers in the diode base because of the deformation of the energy bands [3]. At lower pressures it seems that the change in reverse current can be explained by a change in the lifetime. In order to clarify this problem simultaneous measurements were made of the relaxation time τ_r of the transient on switching the diode from a neutral to a conducting state [6] at different pressures. This relaxation time τ_r for a diode with a thick base ($d \gg L_p$) should be the same as the volume lifetime of the carriers τ_p, but since the areas

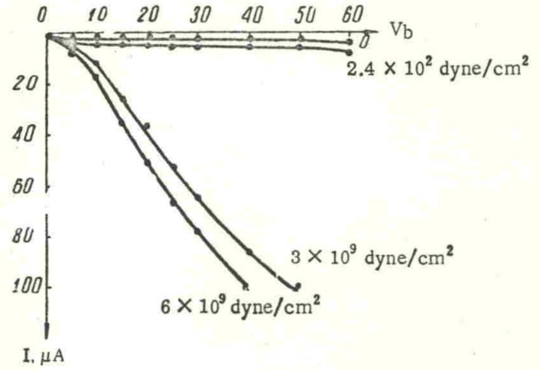

Fig. 2

Dependence of τ_r on Pressure

No. of specimen / dyne/cm²	τ_r, μsec						
	0	$1\cdot10^9$	$2.4\cdot10^9$	$4\cdot10^9$	$4.5\cdot10^9$	$6\cdot10^9$	0
1	1.35	—	0.75	1.23	—	—	1.35
2	2.38	—	1.90	2.30	—	2.68	2.32
3	6.85	—	4.65	6.65	—	—	6.85
4	8.30	6.10	5.30	6.73	8.10	—	8.30
5	4.35	3.20	3.08	4.80	—	—	4.35
6	2.00	1.75	1.18	3.30	—	—	2.00

of the p-n junctions in our diodes were small, and therefore recombination of the minority carriers at the surface of the germanium round the injection contact played a significant part, a certain effective lifetime was measured. Taking into account the effect of the space-charge on the relaxation of a transient [7]

$$\tau_r = \tau_e + R_j C_j, \tag{1}$$

where C_j is the charging capacitance of the p-n junction, and R_j is the resistance of a p-n junction with a small bias of $(2-3)\cdot10^{-3}$ V. Results of measuring τ_r are given in the table.

It can be seen from the table that τ_r falls by a factor of 1.5 to 2 for a pressure of about $(2-3)\cdot10^9$ dyne/ /cm², and with a further rise in pressure it increases. The quantity τ_r only approximately reflects the change in τ_e with increased pressure since the value of C_j also depends on the pressure. The capacitance of the p-n junction was measured at different pressures by the resonance method, and the dependence of C_j on pressure obtained in this way is given in Fig. 3. This dependence of C_j on pressure can be explained qualitatively as follows. With zero bias

$$C_j = A\left(\frac{\varepsilon\varepsilon_0 qN_d}{2\varphi_k}\right)^{1/2}, \tag{2}$$

where ε and ε_0 are the dielectric constants of the semiconductor and of free space respectively and N_d is the concentration of donor impurity atoms,

$$\varphi_k = \frac{kT}{q}\ln\frac{p_p\cdot n_n}{n_i^2}. \tag{3}$$

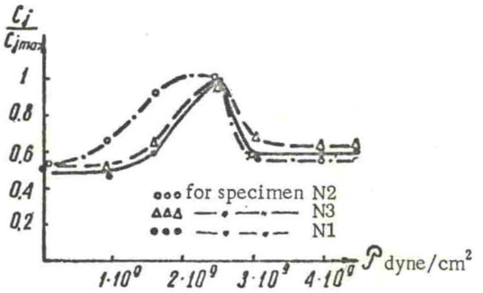

Fig. 3

Because of the compression of the semiconductor in the region of the p-n junction N_d may increase and therefore C_j also. On the other hand with an increase in pressure the deformation of the energy band of n-germanium becomes all the more marked directly in the region of the space-charge of the p-n junction.

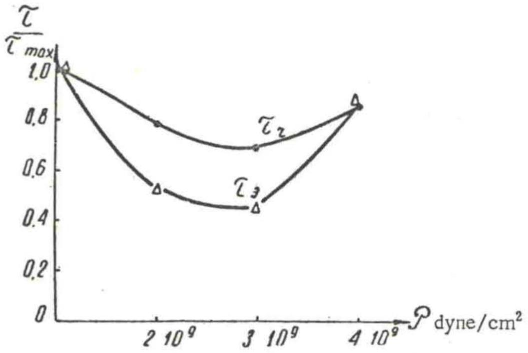

Fig. 4

This should lead to an increase in φ_k and a reduction in C_j, since in the presence of the contact there are two semiconductors (p- and n- regions of the p-n junction) with different widths of forbidden zone, and the width of the forbidden zone of the n-semiconductor falls with increase in the pressure (the mechanical stress in the p-region is practically zero). Apparently the interaction of these factors also leads to a complicated dependence of C_j on the pressure, which has been found experimentally. The resistance of the p-n junction R_j changes very little with increase in pressure. Knowing R_jC_j for different pressures we can calculate τ_e from (1).

The dependence of τ_r and τ_e on pressure is given in Fig. 4 for one of the specimens. It can be seen from the graph that τ_e changes more sharply than τ_r with increased pressure. The reduction in τ_e with a rise in pressure is due, apparently, to an increase in the number of defects, which act as recombination centers [5]. The subsequent increase in τ_e may be caused by a rise in the level of injection at which τ_e is measured. The measurement of τ_e at all pressures was carried out with the same dc bias, and as a result the excess concentration of holes at the boundary of the space-charge region and the base

$$\Delta p = p_n\left(e^{\frac{qV}{kT}} - 1\right) \tag{4}$$

will rise with increased pressure because of the rise in p_n. In the case of low ohmic germanium τ_e increases with an increase in the injection level [8].

In conclusion it should be noted that at low reverse voltages and comparatively low pressures (up to $3 \cdot 10^9$ dyne/cm^2) there is a correlation between the change in the diode reverse current with low bias and the change in τ_e, which is expressed by the formula

$$j_s = \frac{qp_n \sqrt{D_p}}{\sqrt{\tau_p}}. \qquad (5)$$

The change in D_p with increasing pressure can be ignored since it is very small [3].

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