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ELECTRIC SIGNALS IN SHOCK COMPRESSION OF DOPED SILICON

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Electric signals during shock compression are investigated in p- and n-type silicon single crystals containing various amounts of impurities. It is shown that the nature of the observed phenomenon is connected with volume redistribution of the ionized atoms of the impurities during the course of the shock compression of the crystals. The surface density of the bound charges in the investigated materials is estimated within the framework of the phenomenological theory of shock polarization.

WE have established earlier[1] that shock compression of single crystals of silicon and germanium is accompanied by occurrence of an emf, which was registered in an external circuit of the experimental setup, see Fig. 1a. Since the sign of the emf in the silicon samples did not depend on the sign of the charge carriers, and its values were much higher than the expected thermal emf (temf), the observed effect was attributed to volume polarization of the single crystals due to the passage of the shock wave (SW). In our paper[2] we advanced the hypothesis that shock polarization of these substances, which consist of electrically neutral atoms of the main lattice and impurity ions, consists in a directed displacement of the latter during the passage of the SW. It was noted that the concentration of the impurities contained in the sample suffices to explain the value of the observed emf. On the other hand, Dremin, Rozanov, and Yakushev[3] proposed that the observed effect can be due to a considerable degree to surface phenomena—temf or electrochemical effects on the interface between the shock-compressed phases of the metal and the investigated substance.

The present paper is devoted to a further investigation of the phenomenon and to an explanation of its nature. The investigations were performed on single-crystal p- and n-type silicon, in which the impurity content was varied in a range of several orders of magnitude.

EXPERIMENT

1. The experimental setup is shown in Fig. 1a. The samples were compressed by a plane SW perpendicular to the (111) plane. The geometry of the explosive devices and the dimensions of the samples were such that the attenuation of the SW and the influence of the lateral relaxation in the sample could be neglected. The measuring electrode (see 1 of Fig. 1a) was a cadmium disc, whose acoustic stiffness was close to that of silicon. This prevented reflection of the SW from the electrode. The parameters of the SW in the samples were calculated from the known state of the screen (aluminum, copper) and the dynamic adiabat of silicon[4]. The experiments were performed at pressures (p) of 20, 40, and 200 kbar. It is known that the Hugoniot elastic limit of silicon along the (111) axis is 40 kbar, and that at $p = 112$ kbar silicon experiences a phase transition connected with the transition from a semiconducting state into the metallic state. Therefore at $p = 20$ or 40 kbar there propagates through the sample a single elastic wave with velocity $D = 8.5$ km/sec, and at $p = 200$ kbar there propagates a configuration of three compression waves (elastic wave, first plastic SW, second plastic SW), the amplitudes of which amount to 40, 72, and 128 kbar, respectively.

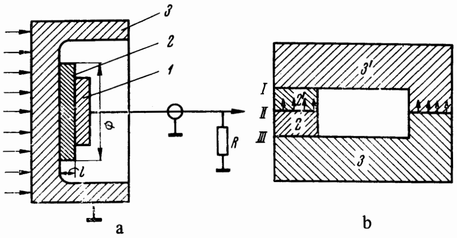

FIG. 1. a—Diagram of experimental setup: 1—measuring electrode; 2—sample; 3—screen; R = 100 ohm—input resistance of OK-33 oscilloscope. The arrows show the direction of propagation of the SW front. b—equivalent circuit for the estimate of the thermal emf: 2) 2′)—compressed (uncompressed) part of the sample; 3) 3′)—compressed (uncompressed) part of the screen—cable—electrode system. I, III—sections of the sample, II—section formed by the SW front.

We subjected to shock loading samples of silicon doped with boron (Si of p-type) and phosphorous (n-type). Data on the specific volume resistance of the sample ρ_0 and the impurity contents in them N are given in Table 1. According to Pearson and Bardeen[5], N corresponds approximately to the number of carriers. The sample length was $l \sim 0.1–1$ cm and the diameter ~2–3 cm. A layer of aluminum 2–3 μ thick was deposited on the end surfaces. The sample surface adjacent to the screen 3 was completely coated with aluminum. The opposite end of the sample was covered with aluminum only under the measuring electrode (area $S = 1$ cm^2).

In the experiments we registered the time-varying voltage drop U(t) across the input resistor R of the oscilloscope. Since $R \gg \rho_0 l/S$, it follows that U(t) is equal to the emf produced in shock-compressed samples. Typical U(t) oscillograms are shown in Fig. 2.

The experimental results have shown that the voltage across R is produced at the instant when the SW enters the sample ($t = 0$). The instant of emergence of the elastic wave from the sample ($T = l/D$) corresponds in all cases to a drop in the voltage U(t). In comparing the experimental results it is best to use the

Table I. Volume resistivity and number of impurity atoms in the initial samples. Experimental (P_0) and calculated (P) values of the polarization, electric field intensity, and thickness of double layer in shock-compressed samples at 40 kbar pressure

Si	ρ_0, cm-cm	N, cm^{-3}	P, C-cm^{-2}	P_0, C-cm^{-2}	Δ, cm	E, V-cm^{-1}
p-type	$2\cdot10^{-2}$	$6\cdot10^{18}$	$5\cdot10^{-7}$	$2\cdot10^{-7}$	$2\cdot10^{-8}$	$2\cdot10^{7}$
	4,5	$1\cdot10^{16}$ *	$7\cdot10^{-9}$	$4\cdot10^{-8}$	$4\cdot10^{-6}$	$4\cdot10^{4}$
	7,5	$7\cdot10^{15}$	$6\cdot10^{-9}$	$-3\cdot10^{-8}$	$6\cdot10^{-6}$	$3\cdot10^{4}$
	$3{,}5\cdot10^{4}$	$5\cdot10^{11}$	$1\cdot10^{-11}$	$-(2\cdot10^{-12}\div2\cdot10^{-10})$ **	$3\cdot10^{-2}$	2
n-type	4,5	$2\cdot10^{15}$	$2\cdot10^{-9}$	$-5\cdot10^{-8}$	$4\cdot10^{-6}$	$5\cdot10^{4}$
	7,5	$9\cdot10^{14}$	$3\cdot10^{-9}$	$-5\cdot10^{-8}$	$6\cdot10^{-6}$	$5\cdot10^{4}$
	45	$1\cdot10^{14}$	$4\cdot10^{-10}$	$-1\cdot10^{-9}$	$4\cdot10^{-5}$	$3\cdot10^{3}$

*In accordance with [5], the value of N given in [1] should be regarded as too low by about one order of magnitude.

**The first value corresponds to the condition $\Theta_0 \ll t_0$, the second to $\Theta_0 \gg t_0$. The actual value of P_0 therefore lies in the indicated range.

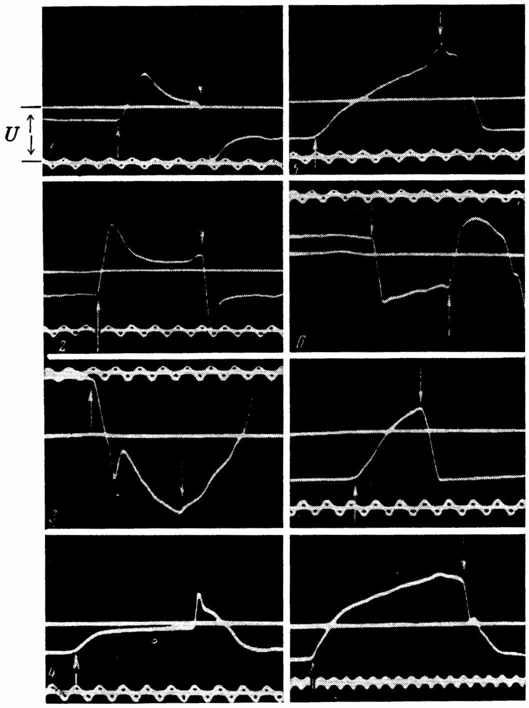

FIG. 2. Characteristic oscillograms of the voltages U(t) for Si: 1–5–p-type, 6–8–n-type, 1–3 and 6–U = 0.15 V; 4, 5, and 7, 8–U = 1.5 V. The oscillograms were obtained in experiments with p equal to 20 kbar (1), 40 kbar (2, 3, and 6), and 200 kbar (4, 5, and 7, 8). ρ_0 (in ohm-cm) and l (in cm) are respectively: 1–0.02 and 0.28; 2–4.5, 0.38; 3–7.5; 0.3; 4–4.5; 0.49; 5–3.5 X 10^4, 0.48; 6–4.5, 0.29; 7–4.5, 0.26; 8–7.5, 0.98. The arrows show the instants of entrance and emergence of SW from the samples. The sweep is from left to right. Time markers–0.1 μsec.

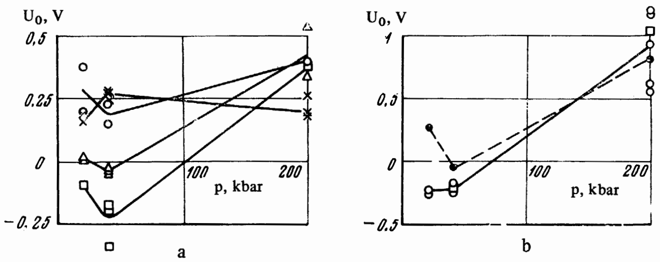

FIG. 3. Dependence of U_0 on the pressure at the SW front for p-Si (a) and n-Si (b) at the following values of ρ: X–0.02; ○–4.5; □–7.5; Δ–$3.5\cdot10^4$; ●–45 ohm-cm.

quantity U_0 (the value of U(t) extrapolated to $t = 0$[1)] inasmuch as the initial part of the U(t) plot (the region of the transients with characteristic time $t_0 \sim 10^{-9}$ sec) could not be resolved by the apparatus, and was possibly distorted also by the fact that the SW did not enter the sample all at once. In a number of experiments, the front of the signal U(t) extended over a time on the order of T and the plot of U(t) is a curve with saturation (Fig. 2, 8). In this case U_0 is taken to be the value of U(t) in the saturation region. This case will be discussed separately below.

2. The results of experiments on p-Si are shown in Fig. 3a (see oscillograms 1 and 5 of Fig. 2), where plots of U_0 against p are given for samples with different ρ_0. Each point on the plot is a result of a separate explosion experiment. An analysis of the experimental data has shown that, unlike the polarization of signals obtained with dielectrics[2,3], the character of the U(t) plots and the value of U_0 do not depend on l (0.2–1 cm), S (1–7 cm^2), or R (93–1053 ohm).

3. The results of the experiments on n-Si are shown in Fig. 3b (see also oscillograms 6 and 8 of Fig. 2). The data in Fig. 3 demonstrate the complicated character of the dependence of U_0 on the type of the carriers, the number of impurity atoms, and the pressure on the SW front in the investigated samples.

Let us note the following peculiarities in the plots of U(t) for both types of silicon:

a) All the plots of U(t) can be approximated either by the formula $U \sim \exp(-t/\tau)$ or by $U \sim 1 - \exp(-t/\eta)^{2})$ (where τ and η are certain time constants), or else U = const. The dependence of the form of the registered signal on the parameters of shock-compressed samples is illustrated by Table II.

[1)] For most plots of U(t), the value of U_0 obtained by extrapolation does not exceed 30% of the experimentally registered values. However, in cases similar to those shown, for example, in oscillograms 2 and 3 of Fig. 2, the extrapolated value may differ from the experimental one by a factor of 2.

[2)] An exponential growth of U(t) was first observed by Novitskiĭ et al. in an investigation of polystyrene [6].

Table II. Dependence of the registered signal on the parameters of shock-compressed samples

Formula for U (t)	Si n-Si		Si p-Si		τ, μsec	η, μsec
	ρ_0, ohm-cm	p, kbar	ρ_0, ohm-cm	p, kbar		
$U \sim e^{-t/\tau}$	4.5	20; 40	4.5	20; 40	0.2—0.4	$\ll 0.1$
	7.5	40	$2 \cdot 10^{-2}$	20; 40; 200		
	45	20	—	—		
$U \sim 1 - e^{-t/\eta}$	4.5; 7.5; 45	200	7.5	40; 200		0.1—1
	—	—	$3.5 \cdot 10^4$	200		
$U = \text{const}$	—	—	4.5	40; 200		

b) Not only U_0 but also U(t) is independent of T when p = const. For example, for n-Si ($\rho_0 = 4.5$ ohm-cm, p = 200 kbar) at values of T equal to 0.19, 0.3, 0.61, and 1.1 μsec, each succeeding plot of U(t) duplicates the corresponding parts of the preceding plots.

c) At p = 200 kbar, U(t) decreases when $t > T$ to the resolution limit of the measuring apparatus within times on the order of 0.05—0.2 μsec. At all other pressures, when $t > T$, the current in the measuring circuit decreases to zero within a time ~0.2—0.5 μsec.

d) For plots in the form $U \sim \exp(-t/\tau)$ with $t > T$, the current in the circuit is opposite in direction to the current at $t < T$. In all other cases the directions of the currents in the measuring circuit at $t > T$ and $t < T$ coincide (see Fig. 2).

DISCUSSION

1. It is clear from general physical considerations that the nature of the considered effect is connected either with volume or with surface phenomena occurring upon shock compression of semiconductors. We shall show that the latter group of phenomena cannot lead to the experimentally observed values of the emf. To this end we turn to Fig. 1b and estimate the temperatures in the characteristic cross sections of the sample.

A feature of the sections III (at $t > 0$) and I (at $t > T$) is that in these sections there is produced a contact between two shock-compressed substances heated to different temperatures[7]. In the course of time, there is established in these sections a temperature

$$T^0 = \frac{T_2^0 + kT_1^0}{k+1}, \quad k = \left(\frac{\lambda_1 c_1 \delta_1}{\lambda_2 c_2 \delta_2}\right)^{1/2}$$

(λ, c, and δ are the thermal conductivity, the specific heat per unit volume, and the density of the substances in contact; the parameters with index 2 pertain to the hotter substance). The dimension of the region ν with stationary temperature increases like $\nu = \sqrt{4\chi t}$, where χ is the thermal-conductivity coefficient, equal to ~1 cm^2/sec (copper) and 10^{-2} cm^2/sec (silicon) under normal conditions. Within times $t_0 \sim 10^{-9}$ sec (the resolution time of the apparatus), $\nu \sim 10^{-4}$—10^{-5} cm. An estimate shows that at p = 40 kbar we have $T_{\text{III}}^0 = 318$ and $T_{\text{I}}^0 = 326$°K. The calculation was carried out under the assumption that the ratio of the values of c and λ of shock-compressed silicon and copper (Sec. III), and also of silicon and cadmium (Sec. I) is the same as under normal conditions. The temperature of the shock-compressed silicon was determined from the relation $T_{\text{H}}^0 = T_0^0(\delta/\delta_0)$, where δ and δ_0 are the densities of the silicon ahead of and behind the elastic-wave front and γ is the Gruneisen constant, equal to 0.43[8]. At p = 40 kbar we have $T_{\text{H}}^0 = 275$°K ($T_0^0 = 273$°K).

The calculated value of the temf at $\Delta T^0 = 35°$, with allowance for the static dependence of the Seebeck effect on the pressure (assumed to be the same as for GaAs[9], a semiconductor similar in its thermoelectric properties to silicon) was 35 mV, which is smaller by one order of magnitude than the experimentally registered emf values. Another experimental fact that cannot be attributed to the influence of surface effects is that a current flows in the measuring circuit at $t > T$, when $\Delta T^0 = 8°$. One more fact confirming the volume character of the observed emf is the independence of the sign of the emf in the investigated range of p of the sign of the carriers (for example n-Si and p-Si with $N = 9 \times 10^{14}$ and $N = 7 \times 10^{15}$ cm^{-3}, respectively). This fact cannot be attributed to the reversal of the sign of the carriers in the silicon upon shock compression, as was the case in Kennedy's experiments[10], where it was shown that the reversal of the sign of the carriers in n-Si (p = 35 kbar) takes place only at $N \leq 7.5 \times 10^{13}$ cm^{-3}. Finally, the assumption that the effect has a thermoelectric nature is contradicted also by the following estimate. If the data of the plots of Figs. 3a and 3b are represented in the form of the functions $\alpha \equiv U_0/\Delta T^0 = f(\ln N)$ at constant p, then the linear sections of these relations have slopes from 86 to 1300 μV/deg. According to semiconductor theory[11], on the other hand, the maximum slope of the $\alpha = f(\ln N)$ curves does not depend on the scattering mechanism, the degree of degeneracy, or the electronic effective mass, and cannot exceed 86 μV/deg.

Thus, the presented facts indicate that the nature of the observed emf is not connected with surface phenomena and consequently is due to a volume redistribution of the charges, occurring following the shock compression of the investigated semiconductors (shock polarization).

2. Let us calculate the volume density of the bound charges P(t). In differential form, the connection between the shock polarization P(t) and the parameters of the measuring circuit and of the investigated substance, for an active load R, is written in the form[12]

$$P(t) = \varkappa T t_0 F''(t) + \left[\varkappa T\left(\frac{t_0}{\Theta_0} + \frac{t_0}{\Theta} + 1\right) - (\varkappa - 1)t\right]F'(t)$$
$$+ \left[\frac{\varkappa T}{\Theta}\left(\frac{t_0}{\Theta_0} + 1 + \left(\frac{1}{\Theta_0} - \frac{\varkappa}{\Theta}\right)t - (\varkappa - 1)\right]F(t), \qquad (1)$$

where $\kappa = \epsilon\sigma/\epsilon_0$; ϵ_0 and ϵ are the dielectric constants of the substance in front of and behind the shock wave; $\sigma = \delta/\delta_0$; $t_0 = RC_0$ is the relaxation time of the measuring circuit, $C_0 = \epsilon_0/4\pi l$ ($S = 1$ cm^2), $\Theta_0 = \rho_0\epsilon_0/4\pi$, $\Theta = \rho\epsilon/4\pi$, ρ_0, ρ—volume resistivities of the matter in front of and behind the SW;

$$F(t) = \exp\left(-\frac{t}{\Theta_0}\right)\int_0^t j(t')\exp\left(\frac{t'}{\Theta}\right)dt'$$

is the density of the charges on the measuring electrode and $j(t) = U(t)/R$ is the density of the polarization current.

In our experiments $T \sim 10^{-6}$ sec, $t_0 \sim 10^{-9}$ sec, and $\Theta_0 \sim 10^{-8}$—10^{-14} sec. For semiconductors compressed by weak SW we have $\rho \sim \rho_0$[13]. Let us assume that in the range of pressures under consideration we have $\epsilon \sim \epsilon_0$. In this case $H \sim 1$ and $\Theta \sim \Theta_0$.

Let us consider the case when

$$\Theta \sim \Theta_0, \quad \varkappa \sim 1; \Theta_0 \ll t_0 \ll T. \tag{2}$$

These conditions are satisfied for all the investigated samples with the exception of p-Si with $\rho_0 = 3.5 \times 10^4$ ohm-cm. Taking (2) into account, Eq. (1) takes the form

$$F''(t) + \left(\frac{1}{\Theta_0} + \frac{1}{\Theta}\right)F'(t) + \frac{1}{\Theta_0\Theta}F(t) = \frac{P(t)}{\varkappa T t_0}. \tag{3}$$

Let us compare the terms in the left side of the obtained equation. Assuming that the function $F(t)$ increases in such a way that after a time $t \sim T$ the increment of F is of the order of F itself, we obtain

$$F''(t) \sim F/T^2, \quad F'(t) \sim F/T. \tag{4}$$

Then, taking (2) into account, Eq. (3) at $t \gg \Theta_0$ takes the form

$$\frac{\varkappa T t_0}{\Theta_0} j(t) = P(t). \tag{5}$$

This means that for substances with good conductivity on both sides of the SW front, unlike dielectrics, $P(t)$ can be readily obtained from $j(t)$. Thus, in spite of the fact that the thickness of the double layer is small ($\Delta \sim \Theta_0 D$, see Table I), nonetheless $j(t)$ contains information concerning the processes of mechanical depolarization behind the SW front[14]. In the particular case when the polarization is established jumpwise and a double layer propagates behind the shock-wave front ($\tau \ll T$ or $\Theta \ll T$), formula (5) coincides with that previously obtained in[1].

Although the solution (5) is valid only for $t \gg \Theta_0$, nonetheless it makes it possible to estimate the value of $P(t)$ close to $t = 0$, since $\Theta_0 \ll T$. If it is assumed that there is a polarization jump on the SW front, then, unlike in dielectrics, where $P_0 = j_0\kappa T$, in substances with good conductivity, other conditions being equal, the value of j_0 turns out to be smaller by a factor t_0/Θ_0. In terms of the equivalent electric circuit, the appearance of the factor $t_0/\Theta_0 = R/\rho_0 l$ can be interpreted as the shunting influence of the resistance of the investigated sample.

For $t > T$ we assume in analogy with (2) that $\Theta_0 \ll t_0 \ll t - T$. Then, taking (4) into account, we obtain from (29) of[12]

$$\frac{\varkappa T t_0}{\Theta_0} j_{\text{p}}(t) = P(t) - P(t - T), \tag{6}$$

where $j_r(t)$ is the relaxation current[14,15]. Subtracting (5) from (6), we find that after a time $t - T \sim t_0$ we have

$$\frac{\varkappa T t_0}{\Theta_0}\Delta j = -P(t_0), \tag{7}$$

where $\Delta j = j_r(T) - j(T)$. Thus, if the polarization on the SW front reaches its maximum value within a time $t < t_0$, then a jump of the current will be observed at $t = T$, in accordance with (7).

Inasmuch as the coefficient in (5) $\kappa T t_0/\Theta_0 = \kappa R/\rho_0 D$, it follows that $j(t)$ is independent of the sample thickness. This conclusion is confirmed by experiment.

We shall show that the current $i(t)$ in the circuit does not depend on S. Indeed, since the emf in the circuit of the polarization pickup does not depend on the load, and the circuit resistance consists of R and the sample resistance, we get

$$\left(R + \frac{\rho l}{S_1}\right)i_1(t) = \left(R + \frac{\rho l}{S_2}\right)i_2(t),$$

where $i_1(t)$ and $i_2(t)$ are the polarization currents in samples with areas S_1 and S_2. At $\Theta_0 \ll t_0$ or $\rho l/S_1 \ll R$ and $\rho l/S_2 \ll R$ we have $i_1(t) = i_2(t)$. In the case of dielectrics, when $\rho l/S \gg R$, we get $i_1(t)/S_1 = i_2(t)/S_2$, i.e., $i(t) = j(t)S$[16].

The greater part of the obtained experimental data, with account taken of (5), can be described by a single formula

$$P(t) = P_0 e^{-t/\tau}[1 - e^{-t/\eta}]. \tag{8}$$

The physical meaning of (8) is that it represents in the general case the process of establishment of polarization and mechanical depolarization in a shock-compressed substance. The term with $\exp(-t/\tau)$ is the consequence of the physically plausible assumption that the process of mechanical depolarization per unit volume of the medium is determined by the time that this volume remains behind the SW front[17]. The second term represents the polarization-establishment process connected, for example, with the finite region of the real shock transition. As a first approximation, the time dependence of this process is taken in the form of an exponentially growing function, which describes qualitatively the experimentally obtained plot of $U(t)$ with a stretched out signal-establishment front. We note that whereas at $p = 200$ kbar the value ηD is comparable with the region of the phase transformation, at $p = 40$ kbar the quantity ηD is apparently much larger than the width of the shock transition.

The function (8) has a maximum at

$$t_r = \eta \ln(1 + \tau/\eta), \tag{9}$$

$$P(t_r) = P_0\left(1 + \frac{\tau}{\eta}\right)^{-(1+\eta/\tau)}\frac{\tau}{\eta}. \tag{10}$$

differentiating (5) and taking (8) into account, we obtain

$$\eta = P_0\frac{\rho_0 D}{\varkappa R}\left(\frac{dj}{dt}\right)^{-1}_{t\sim t_0}. \tag{11}$$

If $t_M < T$, then expressions (9)—(11) make it possible to find P_0, τ, and η. In the particular case when $\tau \gg T$ or $\eta \to 0$, Eq. (8) simplifies to

$$P = P_0[1 - e^{-t/\eta}] \tag{12}$$

or

$$P = P_0 e^{-t/\tau}. \tag{13}$$

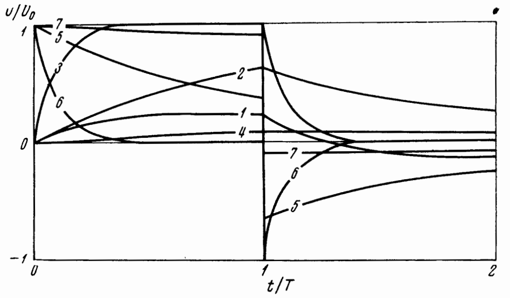

FIG. 4. Values of (T/η) and (T/τ) for the theoretical curves: 1–1(1); 2–1(0); 3–10(0); 4–0.1(0); 5–∞(1); 6–∞(10); 7–∞(0.1).

Table III

	Si n-si			Si p-si
ρ_0, ohm-cm	4,5	7,5	45	7,5
P_0, C-cm^{-2}	$1,6\cdot10^{-6}$	$1,1\cdot10^{-6}$	$8\cdot10^{-8}$	10^{-7}
η, μsec	0,97	0,75	0,55	0,1

The values of P_0 and η can be determined from (11) and (12), and P_0 and τ can be found from (13) at $t = t_0$ and $t = T$. The value of τ can also be obtained from the polarization jump at $t = T$:

$$\tau = T\{\ln[1 - j_p(T)/j(T)]\}^{-1}.$$

The curves of the polarization current $(0 < t < T)$ and of the relaxation current $(T < t < 2T)$ calculated from (5) and (6), with account taken of (8), for different values of τ and η, are shown in Fig. 4. A comparison of the calculated and the experimental $U(t)$ curves shows a qualitative agreement between experiment and calculation. The values of $P_0 = f(N)$ calculated from (5) at $p = 40$ kbar are given in Table I. The values of P_0 and η at $p = 200$ kbar, for different values of ρ_0, determined from (11) and (12), are listed in Table III.

3. The mechanism of the shock polarization of silicon is not clear in many respects. However, the large values of τ and η obtained from the reduction of the experimental data, and also the fact that P_0 increases with N, offer evidence in favor of the hypothesis advanced by us earlier[1,2], namely the volume redistribution of the ionized impurity atoms during the course of the passage of the shock wave through the silicon. It can be assumed further that as a result of the smaller dimensions of the impurity ions (the radius of the boron anion is 0.89 Å and that of the phosphorus cation is 1.1 Å), compared with the silicon atoms (1.17 A[5]) and the low binding energy of the impurities with the main lattice (0.044 eV[18]), the mechanism of volume polarization consists in the following: 1) formation of bound or separated Frenkel pairs possessing an electric moment by the impurities under the influence of the shock wave, and 2) orientation of these pairs in the direction of motion of the shock wave. This assumption is confirmed by the data of[19], where it is shown that with increasing degree of doping of the silicon the number of point defects produced after shock loading increases.

The electric field produced upon polarization becomes cancelled out after a time $\odot$ by the field of the carriers. This state of matter is analogous to the state of the "short circuited" electret, in which the total field is equal to zero at nonzero polarization[20]. However, whereas the electret can remain in such a state for a sufficiently long time, in the case of a shock-compressed semiconductor this time may be comparable with the characteristic time of the experiment (T). The process of establishment of the thermodynamic equilibrium will be characterized by a time τ and can consist in the fact that during the time $\sim\tau$ the ions of the impurities occupy the vacancies. This depolarization process will cause a change in the electric field of the carriers. If $\tau \approx \odot$, then the law governing the variation of this field with time will coincide with the law governing the change of polarization.

Let us estimate the order of magnitude of the polarization of silicon within the framework of the hypothesis under consideration. We assume that all the ionized atoms of the impurity are displaced by one lattice period along the direction of propagation of the shock wave relative to the lattice of the host material. Then the polarization of 1 cm^3 of matter is $P = qN^{2/3}$, where N is the number of ionized impurity atoms with charge q equal to the electron charge. The results of the calculation are listed in Table 1. Comparisons of the values of P obtained from the foregoing estimate and from the reduction of the experimental data with the aid of the phenomenological theory (see Table I) show these quantities to be in qualitative agreement.

From the fact that P_0 depends on N and p it follows that the direction of the displacement of the impurity ions in the SW front relative to the lattice of the silicon itself is a function of N and p. Thus, for example, it must be assumed that at $p = 200$ kbar the phosphorus cations move against the direction of propagation of the shock wave, and the boron anions in its direction (independently of the number N). At $p = 40$ kbar and $\rho_0 = 4.5$ ohm-cm, the displacement of the phosphorus and boron ions in the SW front is in the direction of the SW propagation.

The presence of shock polarization in a substance with good conductivity ahead of and behind the SW front means that a double electric layer of thickness $\Delta = \odot D$ propagates in such a medium together with the front (at $\eta = 0$). Assuming that the potential difference across this layer is equal to the value of U_0 observed in the experiment, let us estimate the field intensity E in this layer: $E \geq U_0/\Delta$. The obtained values of Δ and E for the investigated samples at $p = 40$ kbar are listed in Table I.

We note that the conclusions of the phenomenological theory of shock polarization, drawn in the present paper, can apparently be extended also to substances with better conductivity than the investigated semiconductors. We note in this connection that an emf of the order of 10–100 mV was observed by the authors in shock compression of a number of metals (bismuth[21], beryllium, zinc, magnesium, ytterbium) at $p = 100$–1000 kbar. It is possible that it is precisely the shock polarization of the metals which explains the results of a number of authors[22,23,7] who investigated the emf of the shock-compressed pair nickel-copper. In the cited papers, the observed emf (~10–30 mV) turned out to be 2–4 times larger than the expected emf.

In the case of $U(t) = \text{const}$, one cannot exclude the possibility that the observed emf is due to volume processes with short transient times, for example with electronic polarization. Let us estimate the maximum value of the emf behind the SW front due to electronic polarization of the medium, from the condition that the field intensity E in the double layer does not exceed the breakdown values. Putting $E \sim 10^6$ V, we find $U \sim E\xi D \sim 5$ mV, where $\xi \sim 10^{-14}$ sec is the relaxation time of the electronic polarization. An emf of this order of magnitude cannot be discerned in shock compression of dielectrics (in view of the tremendous internal resistance possessed by the dielectric when regarded as the source of the emf), but can be measured in the case of motion of a shock wave through semiconductors or metals.

We note that we found no acceptable explanation for the following facts:

a) The emergence of the elastic wave at the measuring electrode ($t = T$) is accompanied in all cases by a decrease of $U(t)$. This means that $P(t)$ should also be determined only by the parameters of the elastic wave, i.e., $U(t)$ should be independent of the pressure in the pressure interval from 40 to 200 kbar. This, however, is not confirmed by the experiment.

b) As indicated above, the change of p from 40 to 200 kbar leads to a radical difference in the structure of the SW front. However, in view of the insufficiency of the experimental data, it is impossible to estimate the contribution made to $P(t)$ by each of the three waves at $p = 200$ kbar.

CONCLUSIONS

1. The emf observed following shock compression of silicon is due principally to volume processes behind the SW front, i.e., to shock polarization. The dependence of the surface density of the bound charges on the SW front on the number of impurity atoms, and also the large times of establishment and destruction of the polarization, indicate that the mechanism of the phenomenon is apparently connected with the ionized impurity atoms.

2. Unlike in dielectrics, the polarization current recorded in the external circuit following shock compression of semiconductors is determined only by the time-varying polarization.

3. The thermodynamic equilibrium in the electric phenomena under consideration is characterized by the relaxation times $\tau \sim 0.1-1$ μsec. Times of the same order are characteristic of shock-polarization processes in ionic crystals[14] and in organic substances consisting of polar molecules (see, for example,[15]). This indicates the absence of a strictly thermodynamic equilibrium behind the SW front in the substances under consideration3). However, the noted effect is small, since the change of the external energy of these substances due to the shock polarization amounts to $10^{-7}-10^{-3}\%$ of its total increment on the SW front ($\sim 10^{10}$ erg/cm^3).

A further study of the mechanism of shock polarization of semiconductors is expected to be connected with investigations of the phenomenon of the growth of polarization behind the shock front, with clarification of the roles of elastic and plastic waves in the polarization of silicon, and also with physical interpretation of the reversal of the sign of the polarization with changing pressure on the SW front.

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3) A similar conclusion was drawn by Luzin [24] on the basis of a theoretical analysis of the motion of shock waves in an ideal crystal lattice.

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