termined by formula (1).

[4)]The authors are grateful to S. Dzh. Tsakadze for the opportunity of becoming acquainted with new as yet unpublished experimental curves that contain a large number of successive self-accelerations, as well as data used in Sec. 11.

[5)]In our computer experiments, r_j^2/r_{j0}^2 is initially the same for all j, but as the outer vortices approach the wall it becomes more strongly dependent on j. The relation $L_s=I_s\omega_0/\theta(t)$ is obtained by replacing in (17) the upper limit of the integral by R, i.e., when $\theta(t)$ loses its meaning of the universal ratio r_j^2/r_{j0}^2.

[1]J. S. Tsakadze and S. J. Tsakadze, Zh. Eksp. Teor. Fiz. **64**, 1816 (1973) [Sov. Phys. JETP **37**, 918 (1973)].

[2]E. L. Andronikashvili and Yu. G. Mamaladze, Prog. in Low Temp. Phys., Amsterdam, 1967, vol. 5, Chap. 3, § 2.

[3]O. B. Hess, Phys. Rev. **161**, 189 (1967).

[4]E. L. Andronikashvili and Yu. G. Mamaladze, Rev. Mod. Phys. **38**, 567 (1966).

[5]R. E. Packard, Phys. Rev. Lett. **28**, 1080 (1972).

[6]Dzh. S. Tsakadze and S. Dzh. Tsakadze, Usp. Fiz. Nauk **115**, 503 (1975) [Sov. Phys. Usp. **18**, 242 (1975)].

[7]I. M. Khalatnikov, Teoriya sverkhtekuchesti (Theory of Superconductivity), Nauka, 1971, p. 107.

[8]D. Staufer and A. L. Fetter, Phys. Rev. **168**, 156 (1968).

[9]W. F. Vinen, Progr. in Low Temp. Phys., Amsterdam, 1961, vol. 3, p. 21.

[10]L. V. Kiknadze and Yu. G. Mamaladze, Fiz. Nizk. Temp. **2**, 1501 (1976) [Sov. J. Low Temp. Phys. **2**, 731 (1976)].

[11]Yu. K. Krasnov, Zh. Eksp. Teor. Fiz. **73**, 348 (1977) [Sov. Phys. JETP **46**, 181 (1977)].

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Effect of shock wave on the conductivity of *n*-type germanium

A. V. Polyaninov, K. P. Gurov, and V. A. Yanushkevich

A. A. Baĭkov Metallurgy Institute, USSR Academy of Sciences

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We investigate the relaxation of the electric conductivity of *n*-Ge after the passage of shock waves generated by laser pulses. The initial concentration of the structure point defects and the probability of electron capture by donor impurity center are determined. Two models are considered in the discussion of the experimental results: narrowing of the forbidden band under uniaxial compression, and ionization of Shockley-Read traps. Residual effects are also considered.

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1. INTRODUCTION

Investigations of the influence of a shock wave (SW) on the electrophysical properties of germanium and silicon are of considerable interest to modern microelectronics. The most convenient and easily controlled method of producing SW in materials is to act on them by a laser pulse. A laser can be used to generate SW of small amplitude without damaging the material.

The action of SW excited by ruby-laser radiation of pulse duration 50 nsec and energy flux density 10^8–10^9 W/cm^2 on the electric conductivity of germanium and silicon whisker crystals is described in Ref. 1. At a SW pressure in the front 1.2–4.8 kbar ($(1.2–4.8)\times10^8$ Pa), the resistance of *n*- and *p*-type silicon decreased by a factor of 2; the corresponding decrease in germanium was by a factor of 2 for *n*-type and by more than an order of magnitude for *p*-type. Similarly, the relaxation times of the excess conductivity in silicon of both types were comparable in magnitude, whereas in *n*-Ge the relaxation time was smaller by approximately one order of magnitude than in *n*-Ge. Thus, from the scientific point of view, particular interest attaches to a detailed study of the electrophysical properties of germanium.

We report here a detailed investigation of the influence of SW on the conductivity of *n*-Ge, as well as of the relaxation and residual effects. In addition, the following particular question was posed: are the observed effects properties peculiar to whiskers?

2. EXPERIMENTAL PROCEDURE

The bombardment procedure is described in Ref. 1. The laser pulse duration was 30 or 50 nsec, and the flux density range from 1.8 to 4.4×10^8 W/cm^2.

In contrast to Ref. 1, the samples were prepared by the traditional procedure, in the form of parallelepipeds of area 1.2×3.6 mm and with variable thickness from 0.25 to 1.4 mm. The material used was commercial *n*-type germanium with resistivity 40 Ω-cm. Electric contacts of tin with antimony admixture were deposited on the end faces and checked for linearity of the current-voltage characteristic. The samples were glued to a quartz substrate and a copper foil was glued on their top surface to protect them from the direct action of the laser radiation. An estimate of the depth of SW formation, using the formulas of Refs. 2 and 3, has shown that in our experiments copper foil 55 μm thick was sufficient. The germanium single-crystal samples were so oriented that the SW propagated in the [111] direction, which was perpendicular to the di-

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rection of the current (0.3 mA). The change of the sample conductivity was registered with a memory oscilloscope S8-2 or with an S-1-15 oscilloscope. The residual resistance of the sample was measured approximately 3 min after each shot with an R37-1 potentiometer. Particular attention was paid to shielding the measurement circuit against electromagnetic static.

Altogether, more than 60 samples were bombarded. To study the residual effects, all the samples were repeatedly bombarded by the laser until they were damaged. Depending on the sample thickness and on the laser pulse energy flux density, the samples withstood from one to 100 shots. The shots were both single-spike and multispike. The relaxation times were calculated by least squares and had a variance 4%.

The shock-wave amplitudes corresponding to the chosen bombardment regimes were calculated by the formulas proposed in Ref. 1. Estimates have shown that the pressure in the SW front ranged from 2.7 to 7.3 kbar.

3. EXPERIMENTAL RESULTS

A sharp increase of the conductivity is observed initially (for about 1 μsec) in all bombardment regimes. The largest increase of the conductivity σ is observed for thin samples (up to 0.25 mm thick) and ranges from 90 to 170%. The increase is much smaller for thick samples and does not exceed 25%. A typical oscillogram for a single-spike shot is shown in Fig. 1.

The curve corresponding to the relaxation process in single-spike laser operation was approximated on the major part of the oscillogram by an exponential function with a time constant $\tau_1 \approx 10$ μsec.

Under multispike bombardment, the conductivity increase was produced by each individual spike, and managed to relax completely between the individual spikes. Figure 2 shows a typical oscillogram of a three-spike pulse.

Particular interest was attached to the results of a multiple bombardment of the same sample, at both single-spike and multispike laser operation. The results have shown that the effects of multiple bombardment manifest themselves significantly in thin samples, while in thick samples they are qualitatively similar but are strongly attenuated.

Forty shots applied to a thin sample revealed the following: The relaxation time τ_1 changes slowly after each shot from 10 to 4 μsec, and this change is linear (Fig. 3). The amplitude of $\Delta\sigma/\sigma$ remains almost constant.

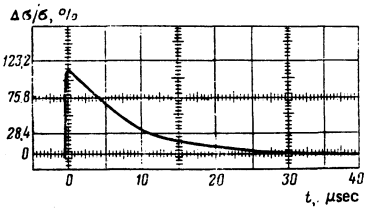

FIG. 1. Oscillogram of the change of the conductivity of n-Ge after passage of a shock wave with maximum pressure amplitude 3.8 kbar. The conductivity at maximum increased by 112%; the relaxation time $\tau_1 = 8.3$ μsec.

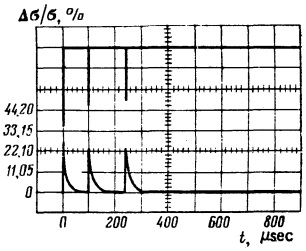

FIG. 2. Oscillogram showing the action of multispike pulse on the conductivity of n-Ge. Upper trace—photocell signal, lower —change of sample conductivity.

Thin samples exhibited one peculiarity not observed in thick ones. For about thirty shots, the picture described above, that of brief growth and subsequent relaxation of the conductivity, repeated itself. In the subsequent shots (i.e., shortly before disintegration of the sample), however, the picture became more complicated and took the form shown in Fig. 4. As seen from this figure, following the increase, the excess-conductivity relaxation curve passes through zero after approximately 15 μsec, and then $\Delta\sigma$ becomes negative, reaches a minimum, and finally tends to zero with a relaxation time $\tau_2 = 20$ μsec.

As already indicated, the residual resistance of the sample was measured after each shot and it was established that the resistance increases (see Fig. 3) with increasing number of shots.

In the case of thick samples that withstood a much larger dose of absorbed laser energy, the linear growth of the residual resistivity R_{res}, similar to that of Fig. 3, is followed by a maximum of R_{res} and by a subsequent decrease—Fig. 5—after which the sample disintegrated. The sample exhibited rectifying action in section BC,

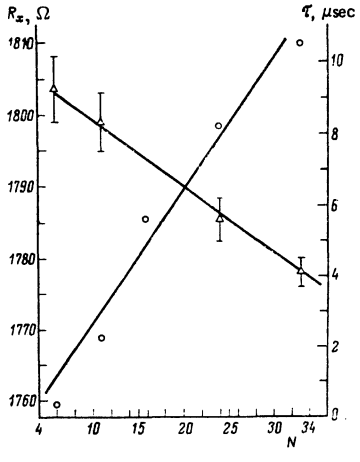

FIG. 3. Change of residual resistance R_{res} (○) and of relaxation time τ_1 (△) in repeated bombardment of n-Ge sample 1.36 mm thick by laser pulses with energy flux density 6.5×10^7 W/cm^2. The pressure in the SW in each shot is 2.1 kbar.

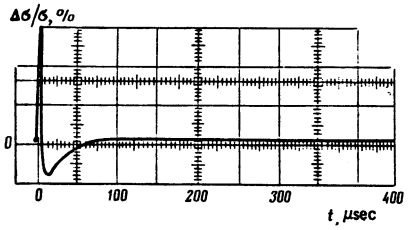

FIG. 4. Typical oscillogram of the conductivity of samples 0.25 mm thick after passage of a shock wave. Pressure in shock wave 3.5 kbar. Ordinate scale 1.67% per division.

wherein the voltage drop across the sample changed by three orders of magnitude when the current direction was reversed. Depending on the sample thickness and the bombardment conditions, the maximum increase of R_{res} fluctuates between 2.5 and 35%.

4. DISCUSSION OF RESULTS

In Fig. 1, the conductivity increases in a time of the order of 1 μsec. This agrees with the assumption that the production of the additional carriers continues during the entire time of passage of the shock wave through the sample. A detailed analysis of the leading fronts of the SW generated by laser pulses is given in Ref. 4 and is confirmed by our experiments.

We discuss now the possible causes of the abrupt increase of conductivity in the SW front. It was noted in Ref. 1 that the increase of the conductivity of germanium and silicun under the influence of a laser pulse can-

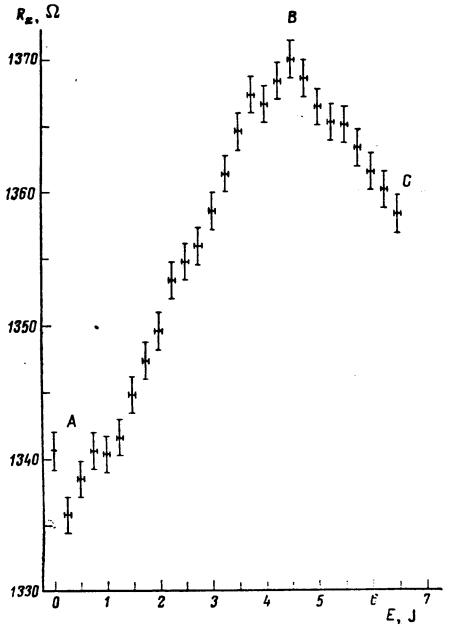

FIG. 5. Dependence of residual resistance of n-Ge on the total absorbed laser energy. The resistance increases linearly in section AB; section BC corresponds to overcompensation of the sample with formation of a p–n junction; point C marks the disintegration of the sample. Average energy flux density per pulse 4.4×10^8 W/cm^2, average pressure 5.6 kbar.

not be attributed to either heating of the sample in the interaction region or to the stain effect. Metallization by impact is also impossible, since this called for a pressure[5,6] of 120 kbar for silicon and 143 kbar for germanium.

The change of the resistivity of n-Ge ($\rho_0=50$ Ω-cm) under shock loading within the limits of elastic strain was investigated in Ref. 6. It was noted that the resistivity decreased exponentially with increasing relative strain ε and amounted to $0.18\rho_0$ at $\varepsilon=0.023$. The authors of Ref. 6 attributed their results to narrowing of the forbidden band E_g of the semiconductor under uniaxial compression in the [111] direction, which leads to an exponential growth of the carrier density. According to the estimates made in Ref. 6, the change δE_g of the forbidden bandwidth was 5.3 eV per unit of ε.

Let us examine the possibility of applying this model to our results. From the electroneutrality conditions and the effective-mass law (which are valid for nondegenerate semiconductors) it is easy to obtain the change $\Delta n\approx\Delta p$ of the carrier density due to a change δE_g of the forbidden band, assuming the change of the carrier effective masses to be negligibly small[7,8]:

$$\frac{\Delta n}{n+p}=\frac{1}{2}\left\{\left[1+\frac{n_i^2}{(n+p)^2}\left(\exp\left(-\frac{\delta E_g}{kT}\right)-1\right)\right]^{1/2}-1\right\}, \tag{1}$$

where n and p are the equilibrium concentrations, in the absence of strain, of the electrons and holes in an impurity semiconductor, n_i is the same for an intrinsic semiconductor, T is the temperature, and k is the Boltzmann constant. It is obvious that the contribution of the holes to the equilibrium conductivity of n-Ge can be neglected (in our material the ratio $p\mu_p/n\mu_n=5\times10^{-2}$), but the nonequilibrium holes make a noticeable contribution to $\Delta\sigma$, proportional to the mobility ratio $b=\mu_p/\mu_n$:

$$\frac{\Delta\sigma}{\sigma}=(1+b)\frac{\Delta n}{n}, \tag{2}$$

where σ is the equilibrium conductivity. We shall henceforth neglect p compared with n, the ensuring error in our case being not larger than 10%. Substituting (2) in (1) and solving the equation for $\exp(-\delta E_g/kT)$, we get the connection between σE_g and $\Delta\sigma$:

$$\delta E_g=-kT\ln\left\{1+\left(\frac{n}{n_i}\right)^2\left[\left(\frac{2\Delta\sigma}{\sigma(1+b)}+1\right)^2-1\right]\right\}. \tag{3}$$

In the derivation of (3) we did not use the condition $\Delta n \ll n$, so that this solution, unlike the analogous calculations in Ref. 7, remains valid also at large $\Delta\sigma/\sigma$.

An estimate using (3) shows that our result $\Delta\sigma/\sigma=1.12$ (see Fig. 1) corresponds to $\delta E_g=-0.104$ eV (we used in the calculations the data of Ref. 9 for n_i, μ_n, and μ_p and the value of $n=7.2\times10^{13}$ cm^{-3} calculated by us from our measurements of the Hall constant). Thus, the pressure coefficient that gives the ratio of the change of the forbidden band δE_g to the applied pressure is in our experiments equal to -2.74×10^{-5} eV/bar.

We have also estimated the value of δE_g from the experimental data of Ref. 6: $\delta E_g=-0.122$ eV under shock compression to 40 kbar in the [111] direction. This yields for the pressure coefficient a value -3.05×10^{-6}

eV/bar, smaller than our experimental results by 8.8 times in absolute value.

Thus, the phonon mechanism of generation of nonequilibrium electron-hole pairs when the forbidden band of germanium is narrowed down in the SW front can hardly account for the observed anomalous increase of the conductivity. A more realistic cause of carrier generation can be ionization of point defects (impurities, vacancies, and others), which form energy levels in the interior of the forbidden band of the sample. The latter can be explained by the fact that the narrowing of the forbidden band under the influence of the SW decreases the ionization energy of the defects. This is attested also by the available experimental data on the influence of high static pressure[8] on the position of the local levels of the impurities. There are no grounds for assuming that the SW does not produce a similar effect. Moreover, the SW causes a spatial displacement of the atoms, i.e., is itself the cause of defect formation, so that the appearance of the indicated effect under dynamic conditions is even more probable than under static compression.

The formation of ionization defects, which are apparently of the same type, under the influence of laser radiation has been noted in a number of papers.[10-13] To attribute the observed experimental data to deep-level traps it must be assumed that in our case the concentration of the ionized defects is not less than 8.4×10^{13} cm^{-3}.

It will be shown below that the concentration of the structural point defects (vacancies, interstices, and their complexes with impurities) did not exceed 2×10^{12} during the entire bombardment process, and consequently their ionization in the SW front can be neglected.

It remains to assume that the SW ionized principally the impurity atoms or their compounds with germanium, which are electrically neutral under equilibrium conditions (e.g., the oxygen concentration in commercial germanium reaches 5×10^{17} cm^{-3}, and it forms three donor levels at distances 0.015, 0.037, and 0.22 eV from the bottom of the conduction band[14]). To be electrically neutral, the impurity atoms (traps) must have an energy level E_t inside the forbidden band of the sample (if there are several such levels, only one of them can be effectively ionized in the SW front; this is the level that will be considered). These traps should be predominantly of the donor type. In fact, acceptor levels in n-type material are negatively charged. When the SW passes, the conductivity approximately doubles (see Fig. 1), and consequently the concentration of the nonequilibrium electrons generated from the traps is commensurate with the equilibrium concentration. It is clear that the relatively weak perturbation of the SW ($|\delta E_g| \lesssim 4kT$) can not ionize all the traps, and therefore, even in compensated material, the deep-level acceptors are not in a position to enable the conductivity to double when the SW passes.

We examine now the behavior of donor traps in n-Ge in the course of passage of a SW. To simplify the calculation we neglect their interaction with the valence band. Since the traps exchange electrons with the conduction band at all instants of time, the electroneutrality condition takes the form

$$n = N_d + fN_t, \tag{4}$$

where N_d is the concentration of the doping impurity ("shallow" donors), N_t is the concentration of the traps ("deep" donors), $f = N_t^+/N_t$ is the fraction of ionized traps, and N_t^+ is the concentration of the charged traps. Under equilibrium conditions, which will henceforth be labeled by a zero index, it follows from Eq. (4) and from the Fermi distribution for f_0 that the position of the energy level E_t of the traps is given by

$$E_{t0} = E_{F0} - kT \ln\left[\frac{N_t}{n_0 - N_d} - 1\right] \tag{5}$$

where E_{F0} is the equilibrium Fermi level.

We consider now the process of the increase of the conductivity of n-Ge in "instantaneous" (at $t = 0$) deformation of the band structure.[1)] We assume that the concentration $n(t)$ of the conduction electrons changes only because of the shift of the equilibrium between the donor traps and the electrons with changing ionization energy of the traps behind the SW. In this appraction, the Shockley-Read[15] expression for $n(t)$ takes the form

$$\partial n/\partial t = \gamma N_t [n_1'(1-f) - nf], \tag{6}$$

where γ is the probability of electron capture (per unit time) by the donor trap, $n_1' = N_c \exp[(E_t' - E_c')/kT]$, N_c is the effective state density in the conduction band, and E_t' and E_c' are the positions of the trap level and of the bottom of the conduction band; the primed symbols pertain to the SW-compressed state of the material.

Solving Eq. (6) jointly with the electroneutrality condition (4) under the initial condition $n(t=0) = n_0$ we get

$$n(t) = \frac{A(n_0 - B)\exp(t/\tau_{gen}) - B(n_0 - A)}{(n_0 - B)\exp(t/\tau_{gen}) - (n_0 - A)}, \tag{7}$$

where

$$2A = N_d - n_1' + D, \quad 2B = N_d - n_1' - D,$$
$$\tau_{gen} = (\gamma D)^{-1}, \quad D^2 = (n_1' + N_d)^2 + 4n_1' N_t. \tag{8}$$

From the character of the observed oscillogram (absence of "plateau" on the crest, magnitude of the signal) we can obtain a rough (order-of-magnitude) estimate. At 5×10^{-8} sec $< \tau_{gen} < 10^{-6}$ sec (the lower limit is determined by the duration of the laser pulse, and the upper by the magnitude of the observed signal) the electron density at the maximum of the curve is $n_{max} \approx A$. At $\tau_{gen} > 10^{-6}$ sec, obviously, $\tau_{gen}/A \approx \tau_3/n_{max} \approx 10^{-19}$ sec-cm^3, where τ_3 is the experimentally observed duration of the conductivity growth. On the other hand, τ_{gen} is connected with A, N_d, and N_t by relation (8), where $N_d \ll n_1 \approx N_t$. These relations are compatible only at $\tau_{gen} \approx 10^{-6}$ sec. It will be shown below that $\gamma \approx 10^{-9}$ cm^3/sec, which corresponds in order of magnitude to $D \sim 10^{15}$ cm^{-3}. In our material $n_0 = 7.2 \times 10^{13}$ cm^{-3} and, taking into account the estimates above as well as the obvious relations

$$N_d < n_0, \quad A + B = N_d - n_1', \quad n_1' < D, \quad -B > A$$

we can obtain

$$N_t \sim n_1' \sim 10^{15} \text{cm}^{-3}.$$

It follows from (5), from the definition of n_1', and from the obtained estimates that the trap level E_t, which lies in the initial material some $(2-5)kT$ below the Fermi level, is capable to become equalized with latter when the SW acts on the crystal, and may even rise to $2kT$ above E_F. This means that all the traps in the SW front can become ionized.

We consider now the relaxation of the nonequilibrium electrons after the passage of the shock wave. Assume that their concentration at the instant $t=0$ is maximal and is connected with the experimentally measured conductivity growth $(\Delta\sigma/\sigma_0)_{max}$ by the relation

$$n(t=0)=n_0[1+(\Delta\sigma/\sigma_0)_{max}]. \tag{9}$$

The recombination process for the nonequilibrium electrons after the passage of the SW is described by an equation similar to (6), in which the quantities in the right-hand side are determined by the band structure of the unperturbed crystal (unprimed). The solution of this equation, with account taken of the electroneutrality (4) and of the initial condition (9), is of the form

$$\frac{\Delta n(t)}{n_0}=\frac{\Delta\sigma(t)}{\sigma_0}=\left[\left(\frac{\sigma_0}{\Delta\sigma_{max}}+\xi\right)\exp\left(\frac{t}{\tau_\gamma}\right)-\xi\right]^{-1}, \tag{10}$$

where $\tau_\gamma=(\gamma N_d)^{-1}$ and $\xi=(2-N_d/n_0)^{-1}$. Since $\sigma_0/\Delta\sigma_{max}\approx 1$ (see Fig. 1) and $N_d/n_0<1$, the value of ξ lies between 1/2 and 1.

It was already mentioned that the experimentally observed plot of the relaxation process is well approximated by an exponential relation of the type

$$\Delta\sigma/\sigma_0=\text{const}\cdot\exp(-t/\tau_1),$$

with a time constant $\tau_1=10\pm1$ μsec. Assuming this approximation, we readily obtain the connection between τ_γ and τ_1:

$$\tau_1=\tau_\gamma\ln\frac{\xi+e(\sigma_0/\Delta\sigma)_{max}}{\xi+(\sigma_0/\Delta\sigma)_{max}}.$$

Knowing τ_γ, we can estimate the probability γ of electron capture by the traps:

$$\gamma\approx(0.85-1.4)\cdot10^{-9}\,\text{cm}^3/\text{sec}. \tag{11}$$

It follows thus from all the foregoing that the anomalous growth of the electric conductivity of germanium due to passage of the SW cannot be attributed merely to a narrowing of its forbidden band under uniaxial compression and to subsequent (phonon) generation of electron-hole pairs. A likely mechanism capable of explaining the observed effects is ionization of deep-level impurity centers (traps). It can be due in principle to ionization of the traps by either the phonons or the shock wave itself. The latter mechanism, however, has not been sufficiently studied so far.

We discuss in conclusion the "residual" effects observed in our experiments following multiple bombardment of a single sample. The carrier recombination after the first few pulses takes place on traps present in the material in the initial state. After this, as seen from Fig. 2, the lifetime begins to decrease noticeably, as evidenced by the growth of the resistivity of the sample. This character of variation of the electric properties under repeated bombardment is not unexpected. It as shown in Ref. 16 that bombardment of semiconductors by single laser pulses is characterized by four qualitatively different intensity ranges. In the first one observes only short-duration photoelectric changes. In the second, the residual resistance changes irreversibly and is fully restored only by heating to 400°C. An appreciable and partially irreversible change takes place in the third, and finally the sample is destroyed in the fourth range. The boundaries between the ranges exhibit a clearly pronounced threshold character, but repeated bombardment at energy below threshold also leads to a transition to the next range, a fact apparently observed in our case.

It is quite probable that the crystal-lattice defects act as SW scattering centers and this may cause formation of new defects. Repeated bombardment results therefore in an exponential change of the electrophysical characteristics. If the increment ΔC of the defect concentration for a successive N-th laser pulse is proportional C then, obviously,

$$C=C_0e^{\alpha N}, \tag{12}$$

where α is the probability of defect formation per pulse, and C_9 is the initial defect concentration. A relation of this kind was observed in Ref. 16.

The experimental dependences of R_{res} and τ_1 on N (Fig. 3) show that in our case $\alpha N\ll 1$ during the entire bombardment. Since the defects introduced in germanium by laser radiation are acceptors,[16] it is obvious that at room temperature the concentration of the captured electrons can be equated to the concentration of the residual (non-annealed) defects C_{res}. In this case it is easy to estimate the dependence of R_{res} on the number of pulses N:

$$R_{res}\approx\frac{1}{e\mu_n(n_0-C_{res})}\approx R_0\left[1+\frac{C_0}{n_0}(1+\alpha N)\right], \tag{13}$$

where n_0 and R_0 are the concentrations of the electrons and the resistance in the initial material. From (13) and from the experimental results (Fig. 2) we obtain an estimate for C_0:

$$C_0\approx 8.2\cdot10^{11}\,\text{cm}^{-3}. \tag{14}$$

It must be emphasized that the behavior of the structure defects introduced in the germanium by laser radiation differs substantially from the deep-level trap considered above. The SW-generated structure defects are acceptors and are capable of overcompensating the high-resistance n-Ge (see Sec. *BC* of Fig. 5). In addition, despite their small number, they alter substantially the lifetime of the free carriers (electrons). It is this that can explain, apparently, the experimentally observed (Fig. 3) decrease of the relaxation time of the nonequilibrium conductivity when one sample is repeatedly bombarded.

In the third irradiation-intensity range, a qualitative change is observed in the character of the oscillograms (see Fig. 4). This change can be interpreted in the following manner. When the conductivity decrease due to the introduced defects becomes commensurate with its initial growth, a change in the sign of $\Delta\sigma$ sets in after

some time interval (approximately after 15 μsec in Fig. 4) because of the difference between the relaxation time of the nonequilibrium carriers and the defect-annealing time. After the nonequilibrium carriers have relaxed, annealing of the introduced defects is observed (the growth of $\Delta\sigma$ after the 20-th microsecond in Fig. 4).

Further repeated bombardment in this intensity range leads to an appreciable growth of the resistance. The latter, after passing through a maximum, then begins to decrease (see Fig. 5). This sample state, observed also in Ref. 16, can be attributed to overcompensation and formation of a section with p-type conductivity in the irradiation interaction region. In view of the difference between the current-voltage characteristics of the produced p-n junctions, the sample as a whole begins to exhibit rectifying properties. This bombardment state precedes the sample disintegration. An important role in the magnitude and character of the observed effect is played by the sample thickness. The size effect can be the result of two causes. First, the short duration of the laser pulse can cause the thickness of the compressed layer (between the compression-wave front and the relaxation wave), which is approximately equal to the produce of the laser-pulse duration by the speed of sound in the sample, to be much less than the sample thickness. Second, in thick samples, the damping of the SW and the shunting action of the unperturbed part of the sample come into play. This is precisely why oscillograms of the type shown in Fig. 4 were not observed in our experiments on thick samples bombarded until they disintegrated.

5. CONCLUSION

Our experiments have shown that the SW generated by a laser pulse in n-Ge causes a radical change in the carrier density, followed by their relaxation, as well as residual effects due to defect formation. The results of the experiments can be satisfactorily explained as being due to phonon ionization of the impurity atoms that have a deep level in the forbidden band of the semiconductor; this is possible when the electron structure is deformed as a result of uniaxial compression of the crystal in the SW.

The residual effects can also be satisfactorily explained as being due to peculiarities of the formation and annealing of the structure effects.

The procedure developed can be used also for other elemental semiconductors, such as n-Si, whose band structure is similar to that of germanium, or for semiconductor compounds, if the concentration of the intrinsic defects in them (violation of stoichiometry etc.) is small. Lifting of the degeneracy of the valence band in germanium and silicon of p-type on passage of a shock wave[7] leads to substantial singularities in the conductivity change that is observed in them.

In conclusion, the authors thank L. I. Ivanov and R. A. Sirus for a useful discussion.

[1)] When the SW propagates, the sample is in a deformed state for approximately 10^{-7} sec. It is known that the band structure "adjusts itself" to the change of the distance between atoms in the crystal lattice within $\sim 10^{-11}$ sec. It can therefore be assumed that the forbidden band has changed jumpwise by an amount δE_g.

[1]L. I. Ivanov, Yu. N. Nikiforov, and V. A. Yanushkevich, Zh. Eksp. Teor. Fiz. **67**, 147 (1974) [Sov. Phys. JETP **40**, 75 (1975)].
[2]V. A. Yanushkevich, Fiz. Khim. Obrab. Mater. **5**, 9 (1975).
[3]L. I. Ivanov, N. A. Litvinova, and V. A. Yanushkevich, Kvantovaya Elektron. (Moscow) **4**, 204 (1977) [Sov. J. Quantum Electron. **7**, 121 (1977)].
[4]R. M. Zaĭdel', Zh. Eksp. Teor. Fiz. **54**, 1253 (1968) [Sov. Phys. JETP **27**, 670 (1968)].
[5]M. N. Pavlovskiĭ, Fiz. Tverd. Tela (Leningrad) **9**, 3192 (1967) [Sov. Phys. Solid State **9**, 2514 (1968)].
[6]R. A. Graham, O. E. Jones, and J. R. Holland, J. Phys. Chem. Solids **27**, 1519 (1966).
[7]G. L. Bir and G. E. Pikus, Simmetriya i deformatsionnye effekty v poluprovodnikakh (Symmetry and Deformation Effects in Semiconductors), Nauka, 1972, ch. 5, 6.
[8]Solids under Pressure, W. Paul and D. M. Warschauer, eds., McGraw, 1963, Chap. 8.
[9]S. M. Sze and J. C. Irvin, Solid State Electron. **11**, 599 (1968).
[10]A. A. Zolotukhin, L. I. Ivanov, L. S. Milevskiĭ, E. G. Prutskov, and V. A. Yanushkevich, Kvantovaya Elektron. (Moscow) **2**, 417 (1975) [Sov. J. Quantum Electron. **5**, 240 (1975)].
[11]Yu. N. Nikiforov, V. A. Yanushkevich, and A. V. Sandulova, Fiz. Khim. Obrab. Mater. **3**, 132 (1972).
[12]M. M. Zaripov, I. B. Khaĭbullin, and E. I. Shtyrkov, Usp. Fiz. Nauk **120**, 706 (1976) [Sov. Phys. Usp. **19**, 1032 (1976)].
[13]I. S. Koehler, Radiat. Eff. **30**, 183 (1976).
[14]L. A. Goncharov, P. A. Leonov, and A. M. Khorvat, Fiz. Tekh. Poluprovodn. **10**, 981 (1976) [Sov. Phys. Semicond. **10**, 580 (1976)].
[15]W. Shockley and W. T. Read, Phys. Rev. **87**, 853 (1953).
[16]Z. I. Mezokh, L. I. Ivanov, V. A. Yanushkevich, and L. D. Dobychina, Fiz. Khim. Obrab. Mater. **5**, 10 (1973).

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