A study of the photoconductivity of silicon in the region $\lambda = 0.248 - 0.082$ A. The effect of X-rays on the conductivity of silicon has been insufficiently studied. The number of works on this topic is not large. The present study partially eliminates the resultant gap.

The photoconductivity was measured by means of a bridge circuit with a symmetry of the form $R_I = R_3$, $R_2 = R_4$. The specimens were inserted in the arm $R_I$. As we know, the current strength $I_r$ in the meter and the resistance $R_r$ of the diagonally wired bridge, when the voltage of the power supply is $U$, are related as follows:

$$I_r = \frac{(R_I R_r - R_2 R_3) U \times [R_I (R_3 + R_2) (R_3 + R_1) + R_2 R_3 (R_3 + R_1) + R_1 R_2 (R_3 + R_1) - R_3 R_1 (R_3 + R_2)]^{-1}}{R_3 (R_3 + R_1)}$$

(1)

By balancing the bridge before irradiation and noting the current $I_r$ in the irradiation process, it is possible to find the new resistance of the branch $R_I$ and to calculate the change in the resistance of the silicon specimens.

The use of this circuit is explained by the fact that the changes $\Delta R_I$ during the irradiation of silicon are very small. The bridge circuit is a highly sensitive electrical device which can register relative changes in the resistance of specimens with an accuracy of 0.001%; this is confirmed by the following short calculation.

The power $P_r$ developed along the diagonal of the bridge, with the chosen symmetry, is [1]

$$P_r = I_r^2 R_r = \frac{U^2 z}{8} \frac{R_I R_1}{(R_3 + R_2)}$$

(2)

where $\varepsilon = \Delta R_I / R_I$ is the relative change in the resistance of the branch $R_I$.

Solving Eq. (2) for $I_r$ and substituting the values of the elements in the circuit:

$U = 1.25$ V; $R_1 = 543$ ohm; $z = 10^{-2}$;
$R_4 = 400$ ohm; $R_1 = 480$ ohm (0.001%),

we obtain $I_r \approx 3.3 \times 10^{-9}$ A.

This current exceeds the current constant $c_I (0.6 - 1.7) \times 10^{-8}$ A/m of the M-21 galvanometer which served as the meter, and makes it possible to find $\varepsilon$ with the accuracy mentioned. The actual deviations of the instrument were found to be within the limits of 50–250 divisions and guaranteed a reliable observation of the effect which was being studied. The bridge circuit is more sensitive than the standard two-probe circuit (such as the one which employs the PPTV-1 potentiometer).

The physical processes which take place in silicon can be explained from Evans's diagram, given in Fig. 1. The field of this diagram is divided into three parts A, B, C; along the x-axis are the energies of the quanta, and along the y-axis the atomic number of the element being irradiated. The part A indicates the region where the photoeffect predominates, the part B the region where pairs are formed, and the part C distinguishes the region where the Compton effect is most probable. The lines dividing these regions are drawn in such a way that on them the probabilities of adjacent processes are the same. From the diagram it is evident that the change in the resistance of silicon during irradiation by quanta with energies $h \nu_{eff}$ equal to 50, 75 and 100 keV, is a consequence of two processes—the photoelectric and the Compton.

**Fig. 1.** Diagram of the main processes during the interaction of γ-rays with matter (after Evans).

**Fig. 2.** Technique for determining the effective coefficients of attenuation of X-rays, $\mu_{eff}$: 1) X-ray beam; 2) phototograph index; 3) silicon laminae; 4) photometric measurement sections (illustration not original); 5) X-ray film.

The coefficients $\mu$ of linear attenuation of the X-rays for silicon should be represented in the form

$$\mu = \sigma + \tau,$$

(3)

where $\sigma$ is the coefficient of attenuation caused by the Compton scattering; $\tau$ is the absorption coefficient due to the photoeffect.
Theoretically \( \sigma \) can be calculated from the relationship [2]

\[
\sigma = \frac{NZ\rho}{A}\sigma_c, \tag{4}
\]

where \( N \) is Avogadro’s number; \( Z \) is the atomic number of silicon; \( A \) is the atomic weight; \( \rho \) is the density; \( \sigma_c \) is the Compton scattering coefficient per electron, given by the Klein-Nishina-Tamm formula:

\[
\sigma_c = 2\pi r_0^2 \left\{ \frac{1}{2} \frac{1 + \alpha_0}{\alpha_0^2} \ln(1 + 2\alpha_0) \right\} + \frac{2(1 + \alpha_0)}{1 + 2\alpha_0} \ln(1 + 2\alpha_0) \ln(1 + 2\alpha_0)^{1}\left(1 + 3\alpha_0\right)
\]

where \( r_0 = 2.82 \times 10^{-13} \) cm; \( \alpha_0 \) is the energy of an incident photon in \( \text{m}^2 \text{e}^2 \) units.

For the second coefficient \( \tau \) it is possible to use the relationship [3]

\[
\tau = \frac{N\rho}{A}\tau_a, \tag{5}
\]

where \( \tau_a \) is the atomic absorption coefficient given by the empirical formula

\[
\tau_a = 2.64 \times 10^{-2} Z^{1.94} \lambda^3;
\]

here \( \lambda \) is the wavelength of the X-rays (cm).

Theoretically the calculated coefficients of attenuation in the semiconductors can differ markedly from the actual ones, as was shown by B. I. Boltaks and his colleagues [5, 4] for \( \beta \)- and \( \gamma \)-rays. It is logical to expect the same sort of difference also in the X-ray region of the spectrum. In order to verify this an experimental determination was made of the coefficients of attenuation \( \mu_{\text{eff}} \). Plane-parallel laminae of monocrystalline silicon, differing little in thickness, were placed on an X-ray film, and were irradiated with X-rays in such a way that blackenings of the film under the laminae took place on the linear section of the sensitometric curve of the X-ray film.

By measuring photometrically a sufficiently large number of these sections (Fig. 2), it is possible to calculate the required coefficient from the formula

\[
\mu_{\text{eff}} = \frac{\ln I_1 - \ln I_2}{d_2 - d_1}, \tag{6}
\]

where \( I_1, I_2 \) are the intensities of the X-rays which have passed through the silicon laminae and which are proportional to the readings of the microphotometer.

<table>
<thead>
<tr>
<th>Wave-length ( \lambda )</th>
<th>Theoretical</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma )</td>
<td>( \tau )</td>
<td>( \mu )</td>
</tr>
<tr>
<td>0.248</td>
<td>0.4440</td>
<td>0.6620</td>
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<td>0.092</td>
<td>0.3503</td>
<td>0.0830</td>
</tr>
</tbody>
</table>

The coefficients obtained are given in the table.

From the table it follows that:

1. The calculated coefficients \( \sigma \) and \( \tau \) agree qualitatively with Evans’s diagram: the value of \( \sigma \) for the first process is less than \( \tau \), but in the two succeeding irradiation processes \( \sigma \) makes an important contribution to the attenuation of the X-rays, reaching 65.8 and 81% of \( \mu \).

2. The experimental coefficients \( \mu_{\text{eff}} \) differ from the theoretical, but not by more than a factor of 1.5.

In order to determine the absorbed X-ray energy in the specimens the experimental coefficients were used.

Figure 3 gives the changes in the resistivity of the specimens \( \{\Delta \rho\} \) (circles) due to the X-ray dose-rate \( \rho \) absorbed by the crystals (dots). The duration of the irradiation was determined by the reaction of the meter, including 20–30 sec of stable readings, which amounted to about 100 sec. Longer irradiation was liable to cause heating in the specimens on account of energy from the power supply of the bridge circuit. Formula (2) gives

\[
\rho_t = \frac{8(1 + k)}{k^2\rho^2} P_1, \tag{7}
\]

where \( k = R_4/R_1; P_1 \) is the power obtained by the arm \( R_1 \) from the power supply when the bridge is working.

Calculation shows that the thermal ionization in the crystals in the first hundredths of a second may be ignored, since the heating in them is insignificant. In what follows this neglect is inadmissible, the more so that the power \( P_1 \) exceeds the power obtained by the specimens from the apparatus.

The long-term effect of X-rays on silicon was studied by workers at the Siberian Physico-Technical Institute: the change in the resistance takes a complex form [6].

For X-rays of one spectral composition the value of \( \{\Delta \rho\} \) slowly increases during the transition to higher