INTRODUCTION

The specific feature in the action of a pulsed electron beam (PEB) on a target is the high rate of simultaneous input of energy and charge, which results in dynamic mechanical stresses of various origin appearing in the sample exposed to radiation and leading to the formation of an acoustic pulse (AP). Analysis of the modes of AP formation under the action of accelerated electrons was carried out in [1]. It was assumed that the main reason for the formation of dynamic mechanical stresses under the action of electrons beams with an energy up to ~1 MeV and a fluence up to ~10^{13} electron/cm^2 is the pulsed heating of the material due to thermalization of nonequilibrium electrons and holes produced as a result of ionization and energy loss by beam electrons. Relaxation of dynamic stresses is manifested, apart from the generation of acoustic waves, in the excitation of flexural oscillations and plastic deformation [2, 3].

The second (in efficiency) energy dissipation channel for a PEB in high-resistivity material is the release of energy stored in the electric field of the injected charge. At low PEB current densities, for which the Maxwellian relaxation time is substantially shorter than the pulse duration, this energy is released in the form of the Joule loss due to electric conduction. With increasing current density, strongly nonuniform PEB energy release in insulators and semiconductors can take place during the evolution of multichannel electrical breakdown [4, 5], which can also be responsible for the emergence of dynamic mechanical stresses.

This study aims at analysis of the formation of acoustic waves in high-resistivity materials under the action of a PEB with a complex energy spectrum and its dependence on the current density and irradiation geometry.

1. EXPERIMENTAL TECHNIQUE

The emission of AP in alkali-halide crystals (AHCs) was studied experimentally using the polarization–optical method [6, 7]. In experiments, the transverse probing of the sample exposed He–Ne laser radiation was employed. To eliminate transverse gradients of stresses, the free surface of the sample prepared in the form of a right parallelepiped was irradiated by a diaphragmatic beam with a cross section approximately equal to the sample cross section. These conditions ensure the formation of a nearly plane stress wave in the 1D geometry, which we used in model calculations of the AP shape. The acoustic pulse was recorded during laser radiation probing of the region located at a distance exceeding the extrapolated depth of penetration of electrons with the maximal energy. The morphology of failure was studied using the D11N11 microscope after single or multiple action of the PEB.

Alkali-halide crystals were irradiated in a pulsed electron accelerator with the following parameters: maximal energy ~0.28 MeV, half-amplitude current pulse duration ~12 ns, and current density J_{max} at the pulse maximum up to 500 A/cm^2. The energy spectrum of beam electrons was determined using the technique described in [8] and is given in the table. Incident beam current J_0 and current J that passed through a foil of a preset thickness were measured using the Faraday cylinder, and partial transmission factors h = J/J_0 were determined for selected instants. The PEB energy spectrum was determined using the family of J/J_0 curves calculated for a number of discrete values of energy W_i and the measured values of h. The application of this method implies instantaneous energy homogeneity of beam electrons.

Analysis of the results of measurement of the PEB energy spectrum performed in [8] shows good coinci-
Spectral and temporal parameters of an electron beam

<table>
<thead>
<tr>
<th>$t_i$, ns</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_i$, keV</td>
<td>14.0</td>
<td>26.0</td>
<td>48.4</td>
<td>80.0</td>
<td>114.2</td>
<td>154.3</td>
<td>194.3</td>
<td>237.2</td>
</tr>
<tr>
<td>$J_i$, rel. units</td>
<td>0.25</td>
<td>0.35</td>
<td>0.46</td>
<td>0.57</td>
<td>0.67</td>
<td>0.76</td>
<td>0.83</td>
<td>0.90</td>
</tr>
<tr>
<td>$t_i$, ns</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>$U_i$, keV</td>
<td>265.7</td>
<td>280.0</td>
<td>280.0</td>
<td>265.7</td>
<td>242.8</td>
<td>214.2</td>
<td>182.8</td>
<td>151.5</td>
</tr>
<tr>
<td>$J_i$, rel. units</td>
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<td>1.00</td>
<td>1.00</td>
<td>0.96</td>
<td>0.90</td>
<td>0.83</td>
<td>0.76</td>
<td>0.67</td>
</tr>
<tr>
<td>$t_i$, ns</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td>20</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td>$U_i$, keV</td>
<td>128.5</td>
<td>105.7</td>
<td>85.7</td>
<td>71.4</td>
<td>57.1</td>
<td>42.8</td>
<td>28.6</td>
<td>17.4</td>
</tr>
<tr>
<td>$J_i$, rel. units</td>
<td>0.57</td>
<td>0.49</td>
<td>0.40</td>
<td>0.33</td>
<td>0.26</td>
<td>0.20</td>
<td>0.13</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Note: $U_i$ is the electron energy, $J_i$ is the current pulse shape normalized to unity at the peak, and $t_i$ is the time.

dence of the results obtained on a magnetic spectrometer and using the partial absorption method to within the errors of measurements (~15%).

The high energy input rate under the action of the PEB as a result of dissipative processes leads to an increase in the temperature of the ion subsystem of the crystal. If the irradiation pulse duration is smaller than acoustic relaxation time $t_{AR}$ (defined as the ratio of the characteristic size of the irradiated region to the longitudinal velocity of sound), the volume in which the energy has been absorbed has no time to expand, which leads to the formation and propagation of an acoustic light pulse. The 1D model for the thermoelastic response in the absence of stresses at free surfaces of the irradiated sample was considered in [9, 10]. The relation between the absorbed energy distribution profile and velocity field $dV(z, t)/dt$ is given by the equation

$$
\frac{dV(z, t)}{dt} = \gamma (2 \rho \nu)^{-1} \left[ W_1(z - \nu t) - W_2(z + \nu t) \right],
$$

where $\gamma$ is the Grüneisen parameter, $\rho$ is the density of the substance, $\nu$ is the longitudinal velocity of sound, and $z$ is the coordinate in the direction of incidence of the electron beam. With allowance for the wave impedance, the absorbed energy distribution profile and field of stresses $I_{AP}(z, t)$ are connected by the relation

$$
I(z, t) = \frac{-\gamma}{2} \left[ W_1(z - \nu t) - W_2(z + \nu t) \right].
$$

The compression region formed as a result of heating of the substance propagates in the positive (direction of incidence of electrons) and negative directions. The compression pulse propagating in the negative direction is reflected from the solid—vacuum interface. Since the irradiated surface ($z = 0$) is free, the boundary conditions are defined as the equality to zero of the sum of pressures produced by the incident and reflected pulses [11]. Consequently, the amplitude and shape of the pulse remain unchanged upon reflection, and only the stresses reverse their sign. This means that after reflection, an extension pulse propagated in the positive direction. Thus, a bipolar extension—compression pulse propagates in the positive direction, and the AP shape is determined by the absorbed energy profile.

We calculated the AP contour for the spectral and kinetic parameters of the PEB used in experiments and for computing the absorbed energy profiles.

The computational algorithm for distribution of thermalized electrons in the sample and for the absorbed energy density profile in the region of beam deceleration included one of the versions of the “coarsened” collisions in the Monte Carlo method using the Moliere—Bethe angular distribution and was described in detail in [12]. Since the decelerating action of the field in the sample in the case of short-circuited irradiation scheme is much weaker that the slowing-down power of the substance [13], the effect of electron deceleration in the field of a space charge was taken into account only in the geometry with a vacuum gap in front of the irradiated surface of the target.

In our case, the duration $b = 24$ ns of the electron pulse is of the same order of magnitude as the acoustic relaxation time (e.g., $t_{AR} \approx 75$ ns for KCl); for this reason, the calculations were carried out as follows. The entire current pulse of the PEB was split into a continuous sequence of monoenergetic pulses with a duration less than 0.1 ns, for which the absorbed density profile was calculated, and then the AP profile was determined using formula (2). The overall AP contour at the end of the irradiation pulse was determined using the principle of superposition of acoustic waves. The velocity of sound used in our calculations was determined experimentally and compared with the available reference data. The values of the Grüneisen parameter were borrowed from [14].

2. RESULTS OF CALCULATIONS OF THE ABSORBED ENERGY PROFILE AND THE DYNAMICS OF ACOUSTIC PULSE FORMATION

The regularities of the formation of the AP and the absorbed energy density profile upon a change in the