MEASUREMENT OF HIGH ELECTRICAL CONDUCTIVITY IN SHOCK-COMPRESSED DIELECTRICS

L. A. Gatilov and L. V. Kuleshova

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The absence of a satisfactory solution of the problem of measuring high electrical conductivity $\sigma > 10^2 \ \Omega^{-1} \cdot m^{-1}$ in shock-compressed dielectrics, in particular for detecting the dielectric—metal transition in a shock wave, has been repeatedly pointed out [1-4].

In the present work, we examine the two-probe method for measuring electrical conductivity using coaxial cylindrical current electrodes. In this case, it turns out to be possible to set up and solve the corresponding problem of determining the distribution of high conductivity behind the shock wave front (SWF).

The scheme for the experiment is illustrated in Fig. 1. The difference in the potentials U(t) between thin wire probes 1 is recorded, as is the pulsed current I(t) flowing through the specimen 2 and coaxial electrodes 3, with the help of the noninductive shunt R_1. It is assumed that the conductivity of the specimen behind the SWF is sufficiently high that it is possible to neglect the shunting of the specimen by the dielectric screen 4 and the asymmetry of the electromagnetic field introduced by the detection circuit. The arrows indicate the direction of the SWF. The screens of the oscillographic cables are grounded at the instrument complex.

We will assume that the conductivity in the specimen begins to differ noticeably from zero immediately behind the SWF, which has a neglibly small thickness. Let a plane stationary shock wave propagate along the specimen from the time t = 0. The specific conductivity in this case depends only on the time the substance is in the compressed state:

$$\sigma = \sigma\left(t - \frac{z}{D}\right), \quad ut \leqslant z \leqslant Dt, \tag{1}$$

where D and u are the wave and mass velocities in the specimen.

In the quasistationary approximation, in a cylindrical system of coordinates r, φ, x = z − ut moving together with the substance, the electromagnetic field and current behind the SWF, appearing as a result of the aperiodic discharge of the capacitance C, are described in the form

$$\beta'_x = -\mu j; \tag{2}$$

$$e'_x = -\beta'_t; \tag{3}$$

$$j = \sigma e, \quad \frac{\beta(x, t)}{B_\varphi} = \frac{e(x, t)}{E_r} = \frac{j(x, t)}{J_r} = r, \tag{4}$$

where E_r and J_r are the radial components of the electric field intensity and current density; B_φ, azimuthal component of the magnetic induction; $\mu \approx 4\pi \cdot 10^{-7}$ G/m, magnetic permeability. The one-dimensional equation for the magnetic induction follows from (2)-(4):

$$\beta''_{xx} - \mu\sigma\beta'_t - \frac{\sigma'_x}{\sigma}\beta'_x = 0. \tag{5}$$

Taking into account the axial symmetry of the field, we obtain

$$\beta[(D-u)t < x < (z_k - ut); t] = -\frac{\mu I(t)}{2\pi}, \quad \beta(x < 0; t) = 0. \tag{6}$$

As a result of the finiteness of the conductivity, the magnetic field must be continuous at the dielectric—conductor boundary x = 0:

$$\beta(0; t) = 0. \tag{7}$$

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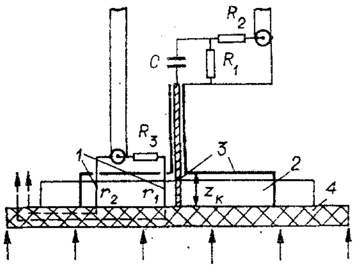

Fig. 1

Integrating (2), we obtain

$$\beta\,[(D-u)\,t;\,t] = -\mu \int\limits_0^{(D-u)t} j dx = -\mu\,\frac{I\,(t)}{2\pi}. \tag{8}$$

Therefore, in the model being examined, neglecting the width of the SWF, the magnetic field is continuous at the boundary $x = (D - u)t$, i.e., the field is frozen into the moving conductor [5].

Solving the parabolic equation (5) with boundary conditions (7) and (8) and the initial condition $\beta(x;\,0) = 0$ permits determining $\beta(x;\,t)$ from the known functions $\sigma(x;\,t)$ and $I(t)$ and, thus, permits determining $e(x;\,t)$ and $j(x;\,t)$ taking into account (2) and (4).

The potential difference $U(t)$ measured in the experiments is made up of the emf, acting between the probes along the boundary of the conducting region behind the SWF $e_f \ln(r_2/r_1)$, where $e_f(t) = e[(D - u)t;\,t]$, and the emf of the electromagnetic induction in the measuring circuit. Taking into account (6) and (8), we have

$$e_{\mathrm{f}}\,(t) = \frac{U\,(t)}{\ln\frac{r_2}{r_1}} + \frac{\mu u I(t)}{2\pi} - \frac{\mu\,(z_{\mathrm{k}} - Dt)}{2\pi}\,I'_t.$$

Assuming that in the conducting region it is possible to neglect the electromagnetic induction, i.e., the distribution of the electric field is close to uniform, $e'_x \approx 0$, we obtain

$$e_{\mathrm{f}}\,(t) \approx \frac{\int\limits_0^{(D-u)t} \sigma e dx}{\int\limits_0^{(D-u)t} \sigma dx} = \varepsilon\,(t).$$

Taking into account (1) and (4), we have

$$\sigma\,(0;\,t) = \frac{1}{2\pi\,(D-u)}\left[\frac{I\,(t)}{\varepsilon\,(t)}\right]'_t \approx \frac{1}{2\pi\,(D-u)}\left[\frac{I\,(t)}{e_{\mathrm{f}}\,(t)}\right]'_t. \tag{9}$$

In order to take into account the electromagnetic induction, we used the method of successive approximations. The iteration formula is

$$\sigma_n\,(0;\,t) = \frac{1}{2\pi\,(D-u)}\left\{\frac{I\,(t)}{(n+1)\,e_{\mathrm{f}}\,(t) - \sum\limits_{i=0}^{n-1} e_i\,[(D-u)\,t;\,t]}\right\}'_t, \tag{10}$$

where $e_i[(D - u)t;\,t]$ are determined from a numerical solution of (5) with $\sigma_i(x;\,t)$, $I(t)$, while $\sigma_0(0;\,t)$ is determined from (9).

In this case, the sequence $e_i[(D - u)t;\,t]$ converges to $e_f(t)$, while the sequence $\sigma_i(0;\,t)$ converges to some distribution of the conductivity, which agrees with the experimentally determined current $I(t)$ and the potential difference $U(t)$. The region of applicability of the method of successive approximations can be determined by modeling the experiment on a computer. By giving different $I(t)$ and $\sigma(x;\,t)$, we find $e_f(t)$. Knowing $e_f(t)$ and $I(t)$, we can reproduce the starting function $\sigma(x;\,t)$ with the help of (10).

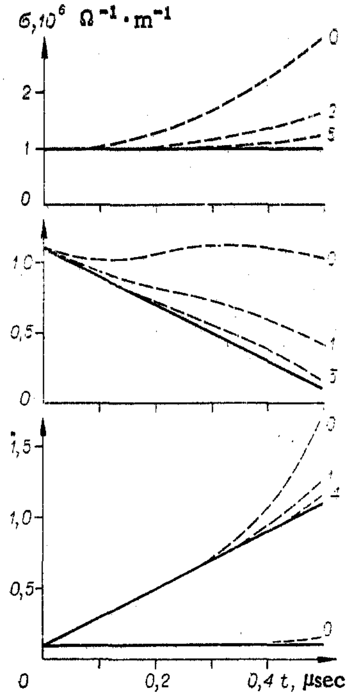

Fig. 2

Reconstruction of the conductivity distribution with acceptable accuracy indicates the applicability of the technique for measuring the chosen $\sigma(x; t)$ for corresponding $I(t)$. Then, $\sigma_n(0; t)$ converges to $\sigma(0; t)$, and the expression $(n+1)e_f(t) - \sum_{i=0}^{n-1} e_i[(D-u)t; t]$, as can be seen by comparing (9) and (10), converges to $\varepsilon(t)$.

We carried out calculations for a linearly increasing, linearly decreasing, and constant conductivity behind the SWF $\sigma(x; t) = K(t - x/(D - u)) + C$. The current was given in the form $I(t) = A\,[\exp(-\alpha t) - \exp(-\gamma t)]$, characteristic of an aperiodic discharge, where $\alpha = 2\cdot10^5$ sec^{-1} and $\gamma = 4\cdot10^6$ sec^{-1}. We used an implicit difference scheme for solving (5) numerically [6].

The results of the calculations are presented in Fig. 2. The continuous lines show the given $\sigma(0; t)$ and the dashed lines show the corresponding $\sigma_i(0; t)$.

If the law governing the variation of the conductivity behind the SWF is known, then it is possible to determine the form of the current pulse for which the nonuniformity of the electric field will be relatively low, and we can try to realize it experimentally. Thus, if the conductivity behind the SWF was constant, while the current is increasing linearly $I(t) = At$, the solution of (5) will be $\beta(x; t) = -A\mu x/2\pi(D - u)$ and (9) will be satisfied exactly. In this case, the linearly increasing conducting region is filled up uniformly by a linearly increasing current and there is no skin effect!

For $\sigma \geqslant 10^5$ $\Omega^{-1}\cdot m^{-1}$, the emf of the electromagnetic induction in the measuring circuit becomes comparable with $e_f(t)$, which considerably decreases the precision of the measurements. For this reason, it is of interest to measure instead of $e_f(t)$ the emf acting between probes on the other boundary $x = 0$. Then, the induction emf in the measurement circuit, partially situated in the screen (the circuit is shown in Fig. 1 by the dashed line), will be negligibly small.

In arranging the experiments shown in Fig. 1, we measured the conductivity of cesium iodide with a ~0.1% admixture of thallium with a pressure p = 65 GPa behind the SWF.

CsI crystals with a thickness of 3-4 mm and a starting density of $\rho_0 = 4.51$ g/cm³ were pressed onto a Teflon screen.

The diameters of the specimen, the outer current electrode made of copper foil with a thickness of 0.1 mm, and the inner electrode constituted 38, 28, and 1 mm, respectively.

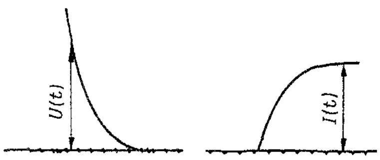

Fig. 3

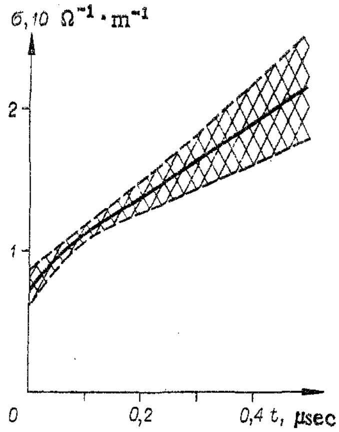

Fig. 4

The probes made of copper wire with a diameter of 0.35 mm were placed at distances $r_1 \approx 2$ mm and $r_2 \approx 12$ mm. Figure 3 shows oscillograms of one of the experiments. The maximum values of the current and potential differences here are $I_* \approx 1200$ A and $U_* \approx 10$ V and the frequency of the time markings is 10 MHz.

The current I(t) and the potential difference U(t) were taken from the oscillogram at ~10 points, and in doing so, we took into account the nonlinearity of the electron beam tube.

In order to introduce the experimental data into a computer, the recorded current was described by a difference of two exponentials with an error ≈1%. The quantity $I(t)/e_f(t)$ was described with the help of the least-squares method using a polynomial of degree 4 with an error ≈1-3%. We took into account the fact that $I(0)/e_f(0) = 0$.

Figure 4 shows the function σ(t) behind the SWF determined with the help of iteration (10). The data were obtained as a result of averaging four experiments and are presented with a confidence probability of 0.5.

The error in the measurements is determined mainly by the fact that the shock wave parameters in the specimen were not identical in different experiments. Probably, the increase in the error at the beginning of the measurements is related to the asymmetry in the shock wave entering the specimen. In addition, the asymmetry leads to underestimated values of the conductivity for $t \lesssim 0.1$ μsec. The noticeable increase in conductivity during the time of the measurements, apparently, indicates the nonequilibrium nature of the thermodynamic state in the substance behind the shock front.

The results of the measurements and computer modeling show that the two-probe method using cylindrical coaxial current electrodes taking into account the electromagnetic induction with the help of successive approximations permits measuring the conductivity close to metallic conductivity, i.e., it permits detecting the dielectric–metal transition in a shock wave.

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