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S. I. Shkuratov

Jason Baird
Missouri University of Science and Technology, jbaird@mst.edu

E. F. Talantsev

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Note: Utilizing $Pb(Zr_{0.95}Ti_{0.05})O_3$ ferroelectric ceramics to scale down autonomous explosive-driven shock-wave ferroelectric generators

Sergey I. Shkuratov,[1,a)] Jason Baird,[1,2] and Evgueni F. Talantsev[3]
[1]*Loki Incorporated, Rolla, Missouri 65409, USA*
[2]*Department of Mining and Nuclear Engineering, Missouri University of Science and Technology, Rolla, Missouri 65409-0450, USA*
[3]*Pulsed Power LLC, Lubbock, Texas 79416, USA*

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Further miniaturization of recently designed autonomous ferroelectric generators (FEGs) [S. I. Shkuratov, J. Baird, and E. F. Talantsev, Rev. Sci. Instrum. **82**, 086107 (2011)], which are based on the effect of explosive-shock-wave depolarization of poled ferroelectrics is achieved. The key miniaturization factor was the utilization of high-energy density $Pb(Zr_{0.95}Ti_{0.05})O_3$ (PZT 95/5) ferroelectric ceramics as energy-carrying elements of FEGs instead of the previously used $Pb(Zr_{0.52}Ti_{0.48})O_3$ (PZT 52/48). A series of experiments demonstrated that FEGs based on smaller PZT 95/5 ferroelectric elements are capable of producing the same output voltage as those based on PZT 52/48 elements twice as large. It follows from the experimental results that the FEG output voltage is directly proportional to the thickness of PZT 95/5 samples. A comparison of the operation of FEGs based on PZT 95/5 and on PZT 52/48 ferroelectrics is presented. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4733294]

From the end of the 1950s, the idea to use shocked ferroelectrics for generation of pulsed high voltages and currents[1] was widely discussed in the literature (see Ref. 2 and references therein). This idea initiated systematic studies of ferroelectrics compressed by planar shock waves generated by projectile impacts from light gas guns a few decades ago at the U.S. Department of Energy's Sandia National Laboratories. These studies continue all over the world (Ref. 2 and references herein); however, the size and complexity of gas guns make it impossible to use them to create practical systems based on shock-wave depolarization effect. Recently,[3,4] we reported on the successful utilization of the shock depolarization effect for first practical autonomous ultrahigh-voltage ferroelectric generator (FEG), in which the ferroelectric element was shocked directly by the detonation of a high-explosive (HE) charge. This FEG (Refs. 3 and 4) was based on PZT 52/48 ceramics as energy-carrying elements. There are two main reasons to use PZT 52/48: it possesses excellent ferroelectric and piezoelectric properties, and this material is in mass production and commercially available in a variety of shapes, sizes, and trademarks (it is widely used in modern electromechanical technology).

Since publishing Ref. 4, we further miniaturized the explosive-driven FEG, but the miniaturization of explosive-driven devices creates several challenges.[5] As such, we focused on two approaches, which we describe herein. The first approach addresses a challenge related to decreasing the geometrical dimensions of the HE charge. Recently,[6] we reported on one of the limitations to reducing the HE charge—scaling down the charge size results in distortion of the shock wave front. We experimentally demonstrated in Ref. 6 that shock front geometry has a significant effect on the shock depolarization of poled PZT 52/48 ferroelectrics.

Our second approach is to scale down the size of the ferroelectric energy-carrying element of the FEG. In this note, we report on successful two-fold reduction of the size of high-voltage FEG ferroelectric elements through the utilization of poled PZT 95/5 ceramics that possess physical properties under shock compression different from those of PZT 52/48.

In contrast to PZT 52/48, PZT 95/5 is not a good piezoelectric material and it is not used in electromechanical devices. PZT 95/5 was originally developed[7] at the U.S. Department of Energy's Sandia National Laboratories. This ferroelectric ceramic was not commercially available until recent time because of the absence of industry demand. For the past few years, production technology for PZT 95/5 ferroelectric ceramics has been under development by several research groups, including TRS Technologies Inc.[8]

The FEG design we developed earlier for PZT 52/48 ferroelectrics[3,4] was used as a basis for this work. A schematic diagram of the FEG is in Fig. 1. The FEG consisted of two parts: a detonation chamber and a ferroelectric element incorporated in a plastic body. The shock wave in the ferroelectric element was generated by detonating the HE charge, which was in direct contact with the top of the plastic body. For the HE charge, we used desensitized cyclotrimethylene trinitramine (RDX) high explosives and a RISI RP-501 detonator.[9] The diameter of the FEGs was 38 mm, and the mass of RDX was 10.4 ± 0.7 g.

We conducted experiments requiring explosive charges in the smaller blast chamber of the Energetic Materials Research Laboratory at the Missouri University of Science and Technology, Rolla, Missouri. We placed the FEGs within the blast chamber, and connected their output terminals to a North Star PVM-5 high voltage probe located outside the chamber. Other experimental details are described in Refs. 4, 6, and 10.

a)Author to whom correspondence should be addressed. Electronic mail: shkuratov@lokiconsult.com.

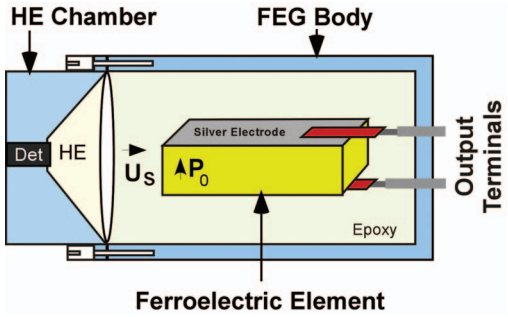

FIG. 1. Schematic diagram of a ferroelectric generator with a ferroelectric element that is shocked directly by the detonation of high explosives. P_0 is the polarization vector. U_S is the shock vector.

The FEGs (Fig. 1) operated as follows. After ignition of the detonator, the detonation wave (detonation velocity 8.04 km/s and theoretical dynamic pressure at the shock front 36.7 GPa) propagated in the HE charge toward the top of the plastic body. The hemispherical shock wave front reached main body of the generator and propagated through it. Because of shock depolarization, a surface electric charge was released at the electrodes of the ferroelectric element and voltage was generated at the output terminals of the FEG.

In this note, we investigated the generation of high voltage with PZT 95/5 and PZT 52/48 ferroelectric elements. Our primary goal in this work was to obtain dependences between the peak output voltage, U_g, produced by the FEGs, and the thickness, d, of the ferroelectric elements. As such, we studied high voltage generation using a single ferroelectric element within each FEG.

We purchased custom-made PZT 95/5 ceramic samples for these tests from TRS Technologies Inc.[8] Table I shows the sizes of PZT 95/5 samples (thickness (d), width (w), and length (l)) that we investigated. TRS poled each PZT 95/5 sample across its thickness to its remnant polarization.

The parameters of the PZT 95/5 ferroelectrics were: theoretical density (TD) 8.00 g/cm^3, typical density 95%–97%TD, the dielectric constant and loss (unpoled) 410%/2.00%, the dielectric constant and loss (poled) 350%/1.97%, remnant polarization 0.32 C/m^2, piezoelectric coefficients d_{33} and d_{31} were 68 pC/N and −16 pC/N, respectively, voltage coefficients g_{33} and g_{31} were 26.28 and -5.99×10^{-3} Vm/N, respectively, electromechanical coupling coefficients k_p, k_{31}, and k_t were 18.2%, 11.1%, and 46.0%, respectively, elastic compliances S_{11E} and S_{12E} were 7.68 and -1.97×10^{-12} m^2/N, respectively, acoustic velocity = 4194 m/s, Poissons' ratio = 0.2572.

TABLE I. Sizes of PZT 95/5 ferroelectric elements and peak output voltages, U_g, produced by the FEGs.

FEG designation	PZT 95/5 element size (mm)	FEG output voltage (kV)
Case 1	3.0(d) × 16.0(w) × 28.0(l)	22.1 ± 1.9
Case 2	6.0(d) × 16.3(w) × 38.0(l)	41.2 ± 2.8
Case 3	9.0(d) × 14.2(w) × 44.2(l)	59.2 ± 2.7
Case 4	11.5(d) × 13.0(w) × 46.0(l)	78.9 ± 2.6

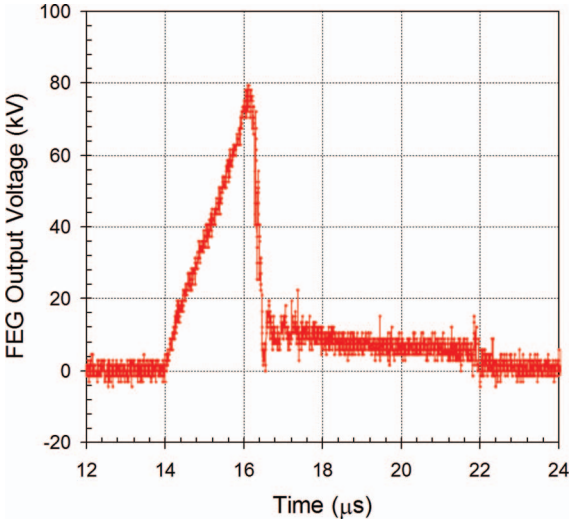

FIG. 2. Typical waveform of the output voltage, $U(t)$, produced by FEGs containing a 11.5(d) mm × 13.0(w) mm × 46.0(l) mm PZT 95/5 element (Case 4).

We purchased PZT 52/48 standard commercial samples from ITT Corp. for these tests; the properties of these samples can be found in Ref. 10. ITT poled each PZT 52/48 sample across its thickness to its remnant polarization.

A typical waveform of the output voltage, $U(t)$, produced by a FEG containing a PZT 95/5 element for Case 4 is shown in Fig. 2. The voltage increased during 2.1 μs to its peak value $U_g = 79.8$ kV at $t = 16.1$ μs.

The generation of the high voltage by the FEG is direct experimental evidence of the depolarization of a PZT 95/5 element by a hemispherical shock wave propagating across the polarization vector of the ferroelectric material. After reaching its maximum, $U(t)$ decreased to 10 kV (Fig. 2) and lasted for 5.5 μs.

Peak output voltages, U_g, produced by FEGs containing PZT 95/5 elements of four types are summarized in Table I. It follows from our experimental results that increasing the thickness of PZT 95/5 elements from 3.0 to 11.5 mm leads to an increase in the FEG output voltage from 22.1 to 78.9 kV.

Peak output voltages produced by FEGs containing PZT 52/48 elements are summarized in Fig. 3. Typical waveforms, $U(t)$, of the output voltage produced by FEGs containing PZT 52/48 ceramic elements can be found in Refs. 4 and 10.

Figure 3 shows dependence of the FEG peak output voltage, U_g, on the thickness, d, of PZT 95/5 and PZT 52/48 elements. It follows from our experimental results that U_g is directly proportional to the thickness, d, of the elements for PZT 95/5 and PZT 52/48. Comparison of the d vs U_g graphs in Fig. 3 allows one to conclude that the use of PZT 95/5 ferroelectric materials allows a two-fold miniaturization of the FEG energy-carrying element in comparison with the PZT 52/48.

The shock pressure at the HE charge-plastic body interface was the same in all experiments with PZT 95/5 and PZT 52/48 samples described above. Apparently, the main reason of a two-fold increase of output voltage produced by the FEGs containing PZT 95/5 elements is that at this level of pressure

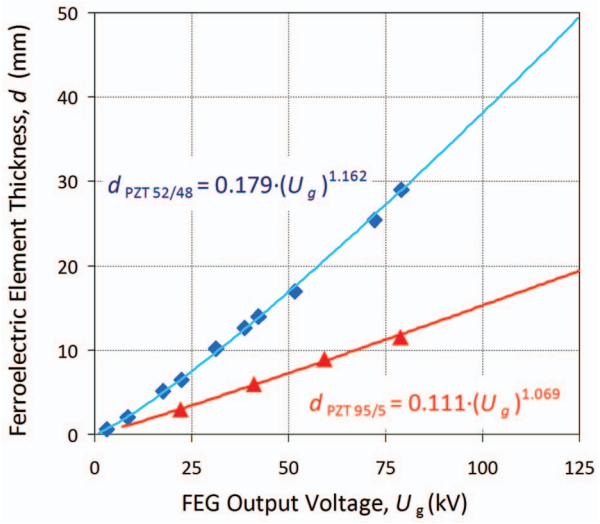

FIG. 3. Experimentally obtained output voltages produced by FEGs containing PZT 95/5 elements (triangles) and PZT 52/48 elements (diamonds) vs ferroelectric element thickness, and fitting curves for experimental data in a presumption that shocked ferroelectrics obey the $U_g(d) = \text{const} \cdot d^{1-\xi}$ law.

(36.7 GPa) the PZT ceramics having the formulation lying very close to a boundary between ferroelectric and antiferroelectric phases (PZT 95/5) has a higher energy density compared with that around morphotropic phase boundary (PZT 52/48).

Note that the d vs U_g dependence for PZT 52/48 (Fig. 3) shows non-linear behaviour when the element thickness is greater than 10 mm. Therefore, thick PZT 52/48 elements are less effective in producing high voltage in comparison with thinner ones. Apparently, this effect is related to breakdown within PZT 52/48 compressed by a transverse shock wave (shock front propagates across the polarization vector $\boldsymbol{P}_0$). It was demonstrated in Ref. 10 that the U_g in longitudinally shock compressed (shock front propagates along the polarization vector $\boldsymbol{P}_0$) PZT 52/48 is described by the $U_g(d) = \text{const} \cdot d^{1-\xi}$ law (where d is the thickness of a ferroelectric element, and ξ is a coefficient that is justified by the mechanisms of electric breakdown[11–15]). Studies of the breakdown in PZT 52/48 compressed by transverse shock are in progress now.

In Fig. 3, we fitted our experimental data for PZT 52/48 and PZT 95/5 under the presumption that both ferroelectrics shocked by transverse shocks obey the $U_g(d) = \text{const} \cdot d^{1-\xi}$ law. It follows from the simulated curve in Fig. 3 that a 49-mm-thick PZT 52/48 sample would be capable of generating $U_g = 125$ kV. This result is close to our recently reported experimental data[4] for transverse shock-wave FEG utilizing ferroelectric module containing four PZT 52/48 elements connected in series (total thickness of 50.8 mm), that was capable of producing output voltages, U_g, of 123.3 $\pm$ 3.2 kV. In accordance with our simulation results (Fig. 3), the thickness for a PZT 95/5 ferroelectric element that would be capable of producing $U_g = 125$ kV is 19.3 mm, which is 2.5 times thinner than PZT 52/48 for the same voltage.

In conclusion, we experimentally demonstrated that a two-fold miniaturization of a high-voltage FEG can be achieved by utilization of $Pb(Zr_{0.95}Ti_{0.05})O_3$ ferroelectric ceramics as energy-carrying elements. It follows from our experimental results that FEGs based on 95/5 ferroelectric elements of 6.9 cm^3 volume are capable of producing output voltages up to 80 kV. We developed FEGs of this type that provided reliable and reproducible operation.

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