where D_0 is the initial electric displacement $E\varepsilon^+$ and α is the ratio of strained-to-unstrained permittivity.

Experimental studies within the elastic range have been performed on monocrystalline Al_2O_3 (sapphire) and the nonpiezoelectric Z-cut of quartz. Experiments are performed with a circuit devised by Ingram [68G5] in which a low-loss coaxial cable is used for both application of the potential and monitoring the current. For an applied potential difference of a few kilovolts, a current of about 1 mA is produced at a compression of several percent.

Constants determined from data reported in ref. [68G5] and from the piezoelectric studies of X-cut quartz are shown in table 4.4. The coefficients are found to be constant over the range of strain indicated.

Table 4.4
Electrostrictive constants

Material and orientation	Experiments	Strain range %	f_{iii}[(a)] 10^{-12} F/m
Z-cut Al_2O_3	5	0.3 to 1	$+58 \pm 2$
60° cut Al_2O_3	7	0.3 to 2	$+86 \pm 4$
Z-cut quartz	4	2.4 to 6.5	$+6.0 \pm 0.2$
X-cut quartz[(b)]	—	—	-4 ± 0.1

[(a)] f_{iii} is the electrostrictive constant for the orientation indicated, ± indicates standard deviation.

[(b)] as determined from piezoelectric current pulse studies (see section 4.2).

Similar studies can be performed above the elastic range if the hydrodynamic model is a suitable approximation to the response of the material. Such studies have provided permittivity data on polyethylene to 25 GPa [70H2], although these studies were complicated by a shock-induced polarization effect. In materials which exhibit shock-induced polarization, a unique phenomenon discussed briefly in section 4.5, permittivities can be determined in a manner analogous to that used for piezoelectric solids [65H1, 70H2]. Hauver [70H2] has used a resonant *LC* circuit to determine permittivities for an organic material, o-nitroanisole. Permittivities observed in shock-compression experiments on ferroelectrics are documented in section 4.3. Lysne [78L5] has recently measured the permittivity change on a “slim loop” ferroelectric ceramic which shows a linear reversible permittivity change with stress from 0.24 to 0.88 GPa.

4.5. *Shock-induced polarization*

When dielectric or semiconductor samples which are unbiased electrically are subjected to shock loading, it is commonly observed that the loading will cause currents to flow in circuits connecting electrodes on the samples. The maximum polarizations responsible for these currents range from about 0.1 per cent to about 30 per cent of those achieved due to the piezoelectric effect in shock-loaded quartz. If the sample is not piezoelectric, ferroelectric, or an electret, the observed shock-induced polarizations are anomalous when considered in terms of equilibrium thermodynamic processes. The term “shock-induced polarization” is used to describe those anomalous polarizations unique to samples subjected to shock loading. Studies of shock-induced polarization provide basic insight into the non-equilibrium behavior of shock-induced defects.

Work in this area has recently been given comprehensive and critical reviews by Murri et al. [74M3], and Mineev and Ivanov [76M4], and with these reviews available, it is only necessary to briefly consider the principal results. Unfortunately, the review of Mineev and Ivanov is flawed by its dependence on references not available outside the Soviet Union. Graham [79G5] has recently summarized shock-induced polarization work in polymers. Anomalous emf observed at metal and semiconductor thermocouple junctions are considered separately in section 4.11.

Shock-induced polarizations were first observed in the polymeric materials, PMMA, Teflon, C-7 Epoxy and polystyrene by Eichelberger and Hauver [62E1]. Following that work, Allison [65A1] derived an expression for current pulses from shock-loaded materials with polarization relaxation. A number of authors have now derived related or more general relationships for such current pulses and a summary of the characteristics of the various theories is given in table 4.5. This table follows that compiled by Mineev and Ivanov [76M4] with the addition of piezoelectric polarization and dielectric relaxation. Treatments of ferroelectrics are given separately in section 4.3.

Table 4.5
Theories of polarization currents (after Mineev and Ivanov [76M4])

Authors	Polarization relaxation time	Conductivity behind shock	Permittivity	Conductivity ahead of shock	Electrical load	Dielectric relaxation time
Graham et al. [65G1], Graham [72G3]	∞	0	Arbitrary	0	0	∞
Lawrence and Davison [77L1] (fully coupled)	∞	0	Arbitrary	0	Arbitrary	∞
Lysne (see section 4.7)	∞	0	Arbitrary	0	Arbitrary	Arbitrary
Zel'dovich [68Z2]	∞	Arbitrary	Constant	0	0	∞
Graham and Halpin [68G1]	∞	Arbitrary	Constant	0	0	∞
Allison [65A1]	Arbitrary	0	Arbitrary	0	0	∞
Ivanov et al. [68I2]	Arbitrary	Arbitrary	Arbitrary	0	0	∞
Zaidel [68Z1]	Arbitrary	Arbitrary	Arbitrary	Arbitrary	Arbitrary	∞

In general, current pulses due to shock-induced polarization will be affected by polarization relaxation time, electrical conduction, electrical load and dielectric relaxation. For short-circuited conditions in which volume polarization processes are fast compared to the loading time, the initial current jump in all theories is the same and is given by eq. (4.6) in section 4.2. The influence of "tilt" in loading systems on current pulses has been analyzed by Antinenko et al. [75A1].

Very recent work by Lysne [78L6] on dielectric relaxation in shock-damaged dielectrics will necessitate reexamination of work in which shock-induced conduction has been inferred in shock-polarized dielectrics, since dielectric relaxation can be easily confused with conduction (see section 4.7).

Shock-induced polarization has been observed in ionic crystals, polymeric materials, and semiconductors. The most thorough work, and that leading to the development of physical models, is that carried out since 1965 on ionic crystals, principally alkali halides, by Mineev, Ivanov, Novitskii, Tyunyaev and Lisitsyn [76M4]. Early work was reported by Linde et al. [66L3], Ahrens [66A1], and Wong et al. [69W2]. Ionic materials studied include LiF, NaCl, KBr, RbCl, KI, RbI, MgO, CsI, $\mathrm{Li}^7\mathrm{H}$ and $\mathrm{Li}^6\mathrm{D}$. In addition to work on relatively pure crystals of various