significant limitation. Although large lithium niobate and lithium tantalate crystals are available, no domain alignment or irreversible changes in remanent polarization are observed at room temperature and their electrical responses are piezoelectric, not ferroelectric, in character. (It is interesting to note, however, that lithium tantalate, whose Curie temperature is about 900 K, should exhibit typical ferroelectric behavior at reasonably modest elevated temperatures.)

Important distinctions that can be made for the experimental investigations shown in table 4.3 include whether both electrical and mechanical observations were undertaken and the level of resolution with which mechanical and electrical measurements were accomplished. For mechanical effects, the direct measurement of particle velocity or stress reveals important detail not observed in recorded displacement histories. For electrical effects, investigations in which time-resolved waveforms are measured and interpreted are far more revealing than those in which only peak voltage or charge are measured. Some investigations have been more concerned with analysis of the shocked ferroelectric as a circuit element than with analysis of the physical processes. Investigations have been performed in both the axial mode, in which propagation direction is along the remanent polarization direction, and the normal mode, in which the propagation direction is normal to the polarization direction.

Most of recent work has been accomplished by Lysne and coworkers in the United States, Bauer and coworkers in France, and Novitskii and coworkers in the Soviet Union. Lysne's work has been the most extensive and has ranged from fundamental studies to those which treat the sample as a circuit element. His work in analysis of waveforms has revealed evidence for kinetic effects and dielectric breakdown, and his work with partially poled samples has provided the first data on dielectric hysteresis loops under shock loading [77L4]. Lysne has also provided first evidence and analysis for dielectric relaxation in shock-loaded ferroelectrics [79L1] and has introduced wave reverberation as a tool of experimental investigation.

Bauer and coworkers [76B3, 77B1] have examined the effects of varying composition more thoroughly than other investigators. Their work on lead zirconate/lead titanate (PZT) compositions in the vicinity of the ferroelectric-antiferroelectric phase boundary includes both shock loading and pulsed hydrostatic loading with risetimes of tens of miliseconds. Bauer [77B1] has also identified a well-defined first-order phase transition at 0.2 GPa for shock-loaded PZT 96.5/3.5 with a 1% Nb_2O_5 additive.

Novitskii and coworkers in the Soviet Union have developed considerable capability for modeling rate-dependent electrical effects. They also point out the importance of careful circuit design [73N2] but their interpretation of Halpin's [66H1] results is based on erroneous inductance values. Their recent review emphasizes the importance of shock-induced conduction [79N3].

Many investigations show the presence of a maximum in observed charge versus stress followed by a minimum after which charge again increases. This apparently is the result of shock-induced conduction which is probably associated with dielectric breakdown. If the sample goes through a phase transition, such behavior can result from the larger fields resulting from a reduced permittivity.

Chen and coworkers [76C3, 76C4, 78B7, 78A1, 78A2] have developed theories of plane-wave propagation in ferroelectrics but detailed comparison between theory and experiment has not yet been attempted. It seems likely that it will be necessary to develop a fully-coupled computer code such as has been developed for piezoelectrics [77L1], but also incorporating kinetic and hysteretic properties, before reasonable progress can be made.

Experimental progress requires consistent, persistent, and systematic efforts which incorporate

Table 4.3
Studies of ferroelectrics under shock loading*

	Density, kg/m^3 Polarization, C/m^2	Stress GPa	Measurements[a)] Mech.	Elect.	Conduction	Permit-tivity	Switching kinetics	Mode[b)]	Remarks
Barium titanate									
Reynolds and Seay [61R1]	____; ____	2.4 to 18	Yes, $d(t)$	No	—	—	—	Axial	Two-wave structure
Reynolds and Seay [62R1]	5710; 0.__	2 to 100	Yes, $d(t)$	No	—	—	—	Axial	Room and elevated temperature
Novitskii et al. [73N2]	6050; 0.26	12 to 19	No	Yes, Q	—	—	—	Axial	Crystal
95% $BaTiO_3$ 5% $CaTiO_3$									
Reynolds and Seay [61R1]	____; ____	2.8 to 18	Yes, $d(t)$	No	—	—	—	Axial	Two-wave structure
Doran [68D3]	____; ____	0.5 to 30	Yes, $d(t)$	No	—	—	—	Axial	Room and elevated temperature
Linde [67L1]	5540; 0.10	0.35 to 1.9	No	No	—	—	—	Axial	Polarization on shocked and recovered samples
Lead titanate									
Novitskii et al. [73N2]	7950; 0.6 to 0.7	2 to 19	No	Yes, Q	—	—	—	Axial	Crystal
PZT 52/48 + 1% Nb_2O_5									
Reynolds and Seay [61R1]	____; ____	1.9 to > 25	Yes, $d(t)$	No	—	—	—	Axial	Two-wave structure
Reynolds and Seay [62R1]	7580; 0.32	1.9 to 39	Yes, $d(t)$	Yes, Q	?	—	—	Axial	Two-wave structure
Linde [67L1]	7680; 0.34	0.55 to 0.95	No	Yes, Q	—	—	—	Axial	Polarization on shocked and recovered samples
PZT 54/46 + 1% Nb_2O_5									
Bauer and Vollrath [76B2]	____; 0.35	0.2 to 0.7	No	Yes, Q	No	—	—	Axial	Maximum charge at 0.45 GPa
PZT 53/47 + 1% Nb_2O_5									
Zubarev [71Z3]	7300–7400; 0.35	10 to 47	Yes, $d(t)$	Yes, I	Yes, above 2 GPa	—	—	Axial	No residual polarization
Novitskii et al. [72N2]	7160–7370; 0.36	0.5 to 15	Yes, $d(t)$	Yes, Q	Yes	Yes	Yes	Axial	
Novitskii et al. [73N2]	____; ____	0.5 to 2	No	Yes, Q	Yes, 0.5 to 2 GPa	Yes	No	Axial	Principally theory
Novitskii et al. [77N2]	8000; ~ 0.4	1 to 170	Yes, $V(t)$	Yes, I	—	—	—	Axial	Hot pressed, poss. phase trans.
Novitskii et al. [77N2]	7160–7370; 0.36	0.2 to 160	Yes, $V(t)$	Yes, I	—	—	—	Axial	Possible phase transition
Bauer [77B1]	____; 0.33	0.9 to 2	No	Yes, Q	—	—	—	Axial	—
PZT 56/44									
Mock and Holt [78M5]	7550–7580; 0.33	4.4 to 11.8	No	Yes, I	Yes, at 11.8 GPa	—	—	Normal	Capacitor loads
Mock and Holt [78M5]	7500; 0.31	1.5 to 8.8	No	Yes, I	Yes, at 6.8 GPa	—	—	Axial	Polarity effect
PZT 65/35 + 1% Nb_2O_5									
Cutchen [66C1]	____; ____		No	Yes, Q	Yes	No	No	Axial	Polarity effect
Lysne [73L3]	7870; 0.1, 0.2, 0.3	0.3 to 2.3	Yes	Yes, I	Yes	No	No	Axial	Dielectric breakdown
Lysne and Bartel [75L4]	7870; 0.025 to 0.05	0.5 to 8.0	Yes	Yes, I	Yes	No	Yes	Axial	Multiple reverbation
Lysne [75L2]	____; ____	—	No	No	Yes	No	No	Axial	Data from [73L3]
Lysne [77L4]	____; ____	0.3 to 2.4	No	Yes, I	Yes	No	No	Axial	Residual polarization
Bauer [77B1]	____; 0.34	0.9 to 2.2	No	Yes, Q	—	—	—	Axial	Polarity effect