Electrical measurements in silicon under shock-wave compression*

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The electrical behavior of p-type silicon in the (111) orientation was studied under shock stresses from 8 to 160 kbar. Positive electrical signals are induced in the crystals during passage of elastic shock waves. Maximum signal amplitude was detected below the Hugoniot elastic limit (55 kbar). Resistance-vs-stress measurements were made when the polarization signal was zero, i.e., no elastic waves were in the crystals. The resistance becomes very small near the elastic limit, indicating that a metallic state is reached. The relative resistance, R/R_o, then increases significantly at 133 kbar where a phase transition is indicated.

INTRODUCTION

The major purpose of this study was to measure the electrical resistance of p-type silicon as a function of temperature and pressure under shock conditions. The data could be used to obtain the energy gap between the impurity level and the conduction band or, combined with the thermal effect on the static pressure—energy-gap data, the temperature in the shock specimen could be determined. Also, resistance measurements during planar shock loading of Si in a known crystallographic direction could give an understanding of silicon's transition states. The resistance data should provide a test of Pavlovskii's[1] interpretation of the discontinuity in his dynamic compressibility (Hugoniot) measurements. Pavlovskii interpreted the discontinuity as a metallic transition state at ~100 kbar. This value is 100 kbar lower than the static pressure transition state speculated as metallic by Minomura and Drickamer[2] from static resistance-pressure measurements. Wentorf and Kaspar,[3] using static resistance-pressure measurements also, detect transition states in silicon and cite two regions of ~thousandfold reduction in resistivity, within 110—120 kbar and 150—160 kbar.

Electrical measurements in solids during the microsecond intervals of shock compression are complicated by anisotropic compression by elastic shocks, by creation of structure defects by plastic shocks, and often by large electrical polarization signals. There have been a number of recent studies of electrical signals generated in dielectrics[4,5] and nonpiezoelectric ionic solids[6] during compression by shock waves. The existence of shock-induced polarization in doped Si was reported recently by Mineev *et al.*[7] We also reported measurements of polarization in silicon.[8] We have continued polarization measurements to explain the origin of the signals and their magnitude. The shock-resistance data of this paper also help identify the transition states of silicon.

The electrical measurements were made in silicon single crystals of (111) orientation with a p-type carrier concentration of ~10^{14} cm^{-3} and a resistivity of ~50 Ω cm. The duration of shock compression was ~1 μsec. Pressures were in the 8—160-kbar range. The polarization results indicate that only positive charges were generated during passage of the shock wave. The maximum signal amplitude occurred when the stress was below the Hugoniot elastic limit (HEL) of 55 kbar. We discuss a model of polarization based on a double charge layer across the elastic shock. The order of magnitude of the signal can be explained by such a model. The shock-resistance measurements imply that doped silicon is converted from a semiconductor to a metallic state at stresses near the HEL. The resistance, however, increases significantly at higher shock stresses. The analysis correlating the electrical measurements with the shock-compression results leads us to believe that silicon acts as an elastic-plastic solid.

EXPERIMENTAL

In the electrical and Hugoniot measurements, the crystals were oriented with their faces perpendicular to the (111) plane. Shock compression was accomplished by a plane shock wave which propagated perpendicularly to the crystal face. By explosively producing plane shock waves in systems consisting of materials of different shock impedance, a wide range of stresses was transmitted to the Si crystals. The stress pulses were essentially square steps, i.e., not changing in stress amplitude during the shock transit. Measurements of the shock waves in the crystals and the driver plate were made by light-reflection techniques described previously,[9,10] and were used to derive Hugoniot equation-of-state data for silicon. These measurements and those of Gust and Royce[11] provide the calibrated stress points that are given in this paper. Table I gives the shock driving systems used to obtain different stress amplitudes in the crystal specimens. The induced polarization signals were used to study the shock-wave structure and to establish shock-wave transit times from which shock-wave velocities were calculated.

The geometry for observing the electrical signals, Fig. 1, was similar to that of a parallel-plate capacitor with the Si crystal mounted between the electrically grounded shock driver and the aluminum back-up electrode. Since no voltage was applied in the polarization experiments, the back-up electrode was also initially at ground potential. The end faces of the crystals (2.2 cm in diameter and 0.32 cm high) were coated with a vapor-deposited aluminum layer, ~3 μ thick. To assume Ohmic contact surfaces, the coated crystals were heated in an oven for 30 min at ~550 °C. Charges generated within the p-type Si during the shock transit were measured by a recording oscilloscope as a voltage drop across a 50-Ω load resistor which shunted the back-up electrode to ground. In the resistance measurements, a voltage, usually 1.3 V negative, was applied across the crystal faces through a constant current power supply. To minimize resistance heating, the timing of the current pulse was controlled so that the pulse was imposed ~5 μsec prior to the shock-wave compression of the crystal. Silicon-controlled rectifiers were used to switch

TABLE I. Shock driving systems.

System No.	Explosive and thickness (cm)	Shock attenuator and thickness (cm)	Specimen plate and thickness (cm)	Stress[a] (kbar) Specimen plate	Silicon
1	2.54 DATB		2.54 steel	129	82
2	2.54 Pentolite	0.32 A./0.32 Plexiglas 2.54 steel	0.32 Al	87	(90)
3	2.54 Pentolite		2.54 steel	129	82
4	2.22 Nitromethane	1.27 brass/2.54 Plexiglas	0.64 Al	50	59
5	2.54 Pentolite	1.27 Al/1.27 phenolic resin	1.27 Al	130	133
6	1.27 Comp B		1.27 brass	298	162
7	2.54 DATB/Nylon	0.64 Plexiglas	0.64 Al	(177)	(162)

[a]Stresses are known to ± 10% except for values in parentheses which are known to ± 15%.

the current on when probe switches imbedded in the driver plate were contacted by the shock-wave front.

WAVE PROPAGATION

The x-t diagram, Fig. 2, gives some insight into the shock-wave structure and its effects on the electrical characteristics of silicon. The diagram describes shock propagation measurements in (111) Si crystals at a stress level of 162 kbar (e.g., system 6, Table I). The numbers in the diagram denote certain times of wave arrival or wave interactions corresponding to the events marked with the same numerals[12] in the electrical records (see Fig. 3). Stress levels identified with these events were obtained using impedance matching and a simple elastic-plastic model.

We observe that three forward-facing waves originate at the specimen-plate—Si boundary when plane shock compression of the crystal begins with stress levels behind the waves of 55, 133, and 162 kbar, respectively. At the time marked (2) in Fig. 2, the 55-kbar elastic precursor traveling at 9.6 mm/μsec in (111) Si reaches the Si—aluminum-electrode interface, and a backward-facing relief wave with a stress gradient of 9 kbar is reflected from the aluminum electrode. This wave continues backward, relieving the stress in the states behind the two advancing plastic shocks. It interacts at (3) with the first plastic shock. The state just ahead of this shock, however, is now at a stress of 46 kbar but can withstand 55 kbar (HEL). Therefore, the first plastic shock after the interaction separates into two new forward-facing shock waves, an elastic shock with a stress gradient of 9 kbar and a plastic shock. The second elastic shock arrives at the electrode at (5). Again a shock wave is transmitted to the aluminum electrode and a relief wave is reflected into the crystal but now with a stress gradient of only 1 kbar.

Similar interactions recur producing splitting of the plastic shocks as described above. However, no further relief waves are shown reflected from the aluminum-electrode—crystal boundary, since the elastic shocks now are very weak and the shock impedances of Si and Al in their elastic compression states now are essentially the same. The first plastic wave front reaches the electrode at (6) where a 10-kbar shock is reflected back into the silicon. [The stress—particle-velocity (P-u) curve of aluminum crosses and goes above the silicon P-u curve at ~115 kbar, which is the reason a shock wave is reflected at (6).] The second plastic wave reaches the electrode at (7) where an 8-kbar shock is reflected back into the silicon. The stresses behind the various waves in the crystals are all within the range 155—175 kbar for at least 0.25 μsec after time (7) if the relief from the edges can be ignored.

The above description of the shock- wave structure in (111) Si is based on optical measurements of the free-surface motion, wave transit times obtained from oscillograph records of the electrical response of the crystals to shock loading, and shock-resistance measurements. These measurements show that Si stressed to 162 kbar in the (111) direction has just two phase transitions, the elastic-plastic transition at ~55 kbar and a polymorphic transition at ~133 kbar. This result differs from the interpretation of Gust and Royce based on free-surface motion measurements. Their interpretation would have the second wave arriving at (5) in Fig. 2 be a plastic shock centered at the x-t origin and due to another polymorphic transition at ~110 kbar. Our free-surface velocity values agree with Gust and Royce's[11] values but our interpretation, supported by electrical measurements, disagrees as to the origin and type of wave arriving at (5). Both of the above interpretations of silicon's Hugoniot could explain the measured free-surface motions but Gust and Royce's

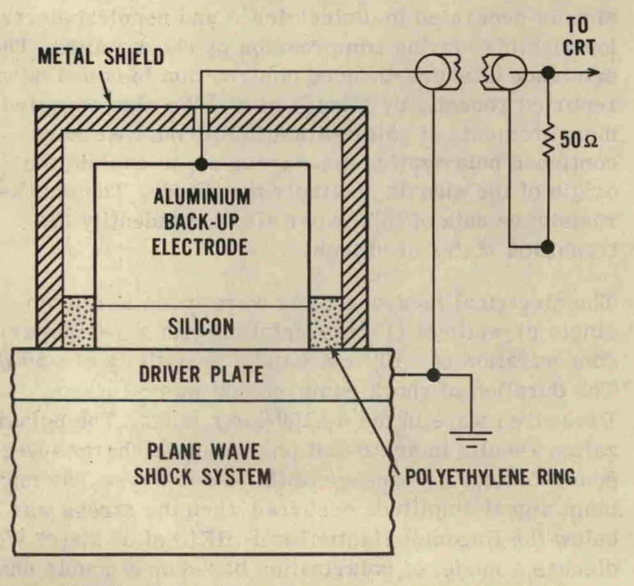

FIG. 1. Experimental arrangement for observing shock-induced electrical signals.