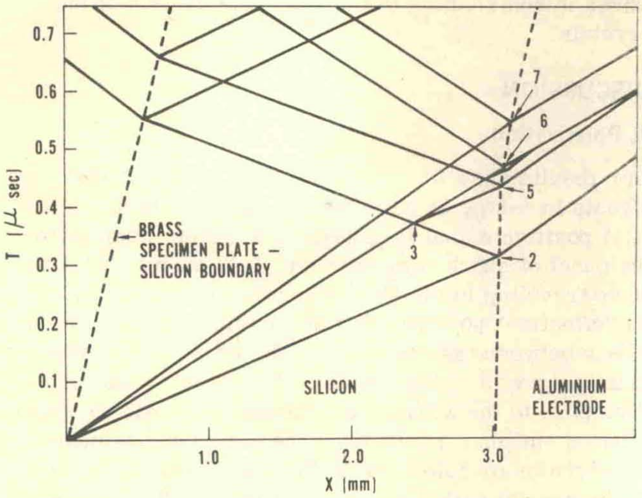


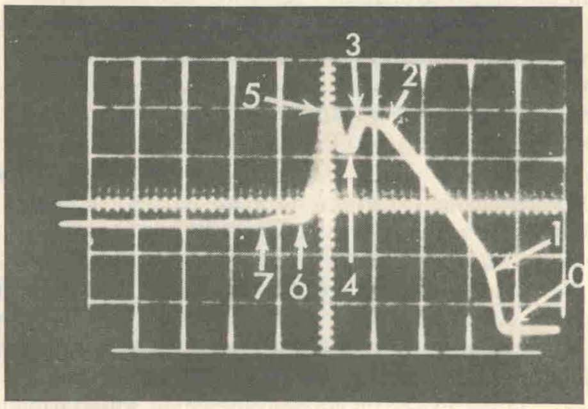
FIG. 2. x-t diagram of shock-wave propagation in silicon for the experimental arrangement of Fig. 1. The stresses behind the three forward-facing shock waves are 55, 133, and 162 kbar, respectively.

interpretation appears inconsistent with events noticed on our electrical records.

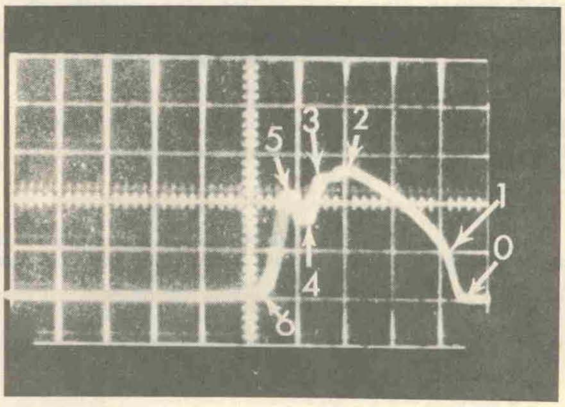
ELECTRICAL RECORDS

Figure 3(a) shows the voltage-time profile for a dynamic electrical resistance measurement at the 162-kbar loading pressure. In Fig. 3(a) the plane stress pulse enters the crystal specimen ~0.1 μsec after the oscilloscope was triggered at the time designated (0). The first inflection in the voltage-time profile occurring at (1) is at a voltage of 0.75 V. The significance of this inflection will be discussed later. The following inflection noted at (2) signals the arrival of the first elastic shock of 55 kbar at the Si–Al-electrode interface. [The inflection noted at (3) and (4) also will be discussed below using Fig. 3(b).] The second elastic shock makes its exit at (5). The voltage decreases to a new value at (6) when the first plastic shock arrives at the electrode. Then at the time (7) a small inflection again occurs in the waveform. This inflection denotes the arrival of the second plastic shock wave at the electrode. At that time the relative resistance change is 0.17 in response to an average stress of ~162 kbar in the crystal. Figure 3(b) is a waveform of the polarization voltage induced in a crystal by the calibrated 162-kbar stress from system No. 6 of Table I. The characteristics of the signal profile are nearly identical to Fig. 3(a) except that no voltage was imposed on the crystal. However, a positive voltage was generated at the shock front simultaneous with its impact and entry into the crystal at the time (0). The initial inflection in voltage was 0.55 V at (1), but the induced signal had its maximum value, 1.35 V, when the first elastic shock wave had completed its transit of the crystal at (2). At (3) the front of a backward-facing relief wave, which was reflected from the Si–Al-electrode interface, interacts with the first plastic wave front as was shown in Fig. 2. The total polarization begins to decrease. This decrease however is interrupted at (4), because of an increasing positive signal due to the second elastic wave which advances from the plane of interaction ahead of the plastic wave. At the time (5) this second elastic wave has left the crystal and the induced voltage again immediately begins to decrease. Zero potential is not recorded immediately on the exit of the second elastic wave because of relaxation effects, mechanical effects, and electronics response time. However, a state of zero potential is regained by the time (6) when the first plastic shock wave reaches the electrode and only the second plastic shock wave is still in the crystal.

Figure 4 gives the waveform of polarization signals generated in Si crystals by input stresses below the HEL. Si has a high shock impedance and when explosive-induced shocks are used, it is difficult to avoid exceeding its HEL. Therefore, an elastic-plastic wave separation method was used to obtain elastic input stresses. The crystals were impacted by the 21-kbar elastic precursor followed by the 130-kbar plastic I wave in the triple shock structure[13] of a steel driver plate. The precursor wave provided polarization signals at 12 kbar, the measured input stress for the Si crystal in Fig. 4. Several features are noted here which differ



(a)



(b)

FIG. 3. (a) Oscilloscope record of a shock-wave resistance measurement of a silicon crystal. The crystal was stressed to 162 kbar. A voltage of −1.3 V was applied to the crystal. Time increases from right to left. The vertical scale is 0.5 V/div and the horizontal scale is 0.12 μsec/div. (b) Oscilloscope record of the induced positive voltage in a silicon crystal when stressed to 162 kbar. No voltage was applied to the crystal. Time increases from right to left. The vertical scale is 0.5 V/div and the horizontal scale is 0.12 μsec/div.

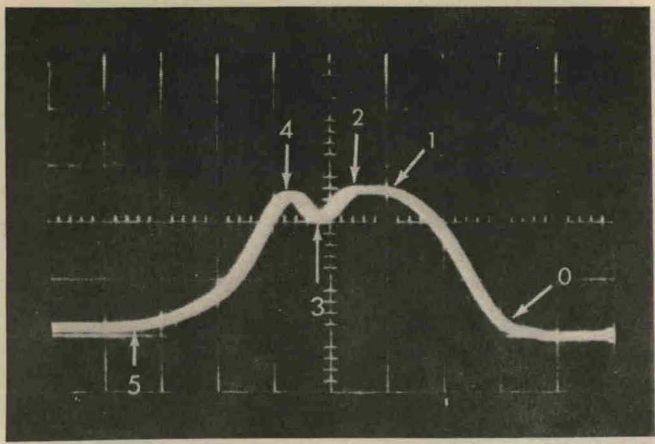


FIG. 4. Oscilloscope record of the induced positive voltage in a silicon crystal when stressed initially to 12 kbar. A second shock enters the crystal from the shock-driving system at ~0.4 μsec after the 12-kbar shock entered. This second shock takes the crystal to a stress of ~90 kbar. No voltage was applied to the crystal. Time increases from right to left. The vertical scale is 1.0 V/div and the horizontal scale is 0.11 μsec/div.

from the signal profile in Fig. 3(b). The waveform in Fig. 4 has no inflections prior to the arrival (2) of the 12-kbar elastic shock wave at the aluminum back-up electrode. The maximum signal (1) is 2.6 V as compared to 1.35 V in Fig. 3(b). After the 12-kbar wave leaves the crystal at (2) the signal amplitude begins to decrease until the time (3). A second elastic wave which enters near time (3) with a 33-kbar stress gradient (transmitted to the crystal by the 130-kbar plastic I shock in the steel driver) produces an increase again to the maximum polarization potential of 2.6 V at (4). The times at which the events (3) and (4) occur result from the separation in time, ~0.50 μsec between the elastic precursor front and the plastic I wave in the steel driver. In the experimental arrangement which produced Fig. 4, a number of elastic shocks reverberate between the steel-driver-plate—silicon interface and the oncoming plastic I shock in the steel. The effects of these reverberations should occur at times greater than ~0.4 μsec after the initial elastic shock enters the sample. Since few inflections occur in these electrical records, it is difficult to identify the roles of these waves in contributing to the total polarization of the crystals.

DISCUSSION

A. Polarization

Our results show that the shock-induced electrical signals in *p*-type Si have the following characteristics: (i) A positive signal is generated simultaneously with the onset of shock compression. This means that a shock wave traveling in the (111) direction in *p*-type Si carries an "effective" positive charge. (ii) An electric current exists between the end faces of the crystal only when an elastic wave is in the crystal. This result could imply, analogous to the acoustoelectric effect,[14] that the shock-induced emf may result from the simultaneous bunching of electrons or holes during the elastic wave's transit of the crystal with the majority carriers (holes in *p*-type Si) polarized by the wave in the direction of propagation. This effect of carrier dragging by the shock was proposed by Coleburn *et al.*[15] to explain the luminescence detected when a shock wave exits from chemically abraded aluminum oxide surfaces. More recently, similar luminescence and voltages produced during shock compression of europium[16] and other lanthanides were attributed to this effect. Harris[17] also offers a theoretical justification of shock-induced emf in semiconductors based on the acoustoelectric effect. (iii) For compressions in the plastic regime, an early inflection occurs in the induced emf signal. The inflection is labeled (1) in the electrical records, Figs. 3(a) and 3(b). Since it does not appear in the signal profile induced by shock compressions below the HEL, we speculate that it signals the onset of crystal yielding.[18] (iv) The maximum signal amplitude is obtained in response to stresses below the HEL. This result for *p*-type Si differs from the measurements of Graham *et al.*[19] who made resistivity measurements using *n*-type germanium with 10^{14} carrier concentration. They do not report polarization for elastic compressions.

Table II shows that the largest peak polarization signals are observed for stresses below the HEL, and that the peak amplitude of the signals decreases with increasing stress above the HEL. The peak polarization signal appears to be constant (2.6 V) for stresses below the HEL for initial temperatures of ~20 °C. The peak signal

TABLE II. Shock-induced electrical signals in *p*-type silicon (111).

System No.	Crystal[a] thickness (mm)	Initial resistance (Ω)	Stress amplitude[b] (kbar) First wave	Second wave	Third wave	Maximum signal (V)
1	3.50	9.0[c]	14			3.02
2	3.00	5.0	12			2.60
3	3.50	4.1	(8)			2.60
4	3.00	4.3	59			2.60
5	3.00	75.0	55	133		1.50
5	3.00	1300	55	133		1.48
6	3.02	4.4	55	133	162	1.35
7	3.02	4.1	55	133	(162)	1.20

[a] Crystal cross-sectional area 3.20 cm^2.
[b] Observed stress values behind the forward-facing shocks before wave interactions occur. Stresses are known to ± 10% except for values in parentheses which are known to ± 15%.
[c] Preheated sample at 139 °C (R_0 = 4.3 Ω at 20 °C). The other experiments were conducted at ~20 °C.