TABLE III. Relative resistance measurements.

System No.	Initial resistance, R_0 (Ω)	Stress[a] (kbar)	R/R_0[b]
2	4.00	(90)[c]	≤0.02
2	4.23	(90)	≤0.02
4	4.30	59	≤0.02
5	22.5	133	0.18
5	22.2	133	0.10
5	20.3	133	0.23
5	4.30	133	0.17
6	3.84	162	0.17
7	4.86	(162)	0.09

[a] Stress behind wave incident at Si-Al boundary at the time that the relative resistance measurement was made.
[b] The relative resistance was measured after the polarization had disappeared, e.g., near point (7) in Fig. 3(a). The smallest relative resistance measurable was 0.02.
[c] Stresses are known to ± 10% except for values in parentheses which are known to ± 15%.

increases to 3.02 V when a p-type Si single crystal is preheated to 139 °C, and then shocked elastically to 14 kbar. The peak polarization voltage for stresses above the HEL is not appreciably affected by the sample's initial resistance as seen in Table II. Two crystals with initial resistances of 1300 and 75 Ω each gave peak signals of about 1.5 V. This result when compared to the other signals' values may be attributed to a decrease in the transient resistance at the Si-Al interface on the shock-wave arrival. The characteristics of these records were affected by the initial resistances of the crystals and relatively low voltages occurred until the elastic shock wave reached the electrode. Then the maximum signal resulted and was in the form of a spike for the 1300-Ω crystal.

Zel'dovich[20] has offered an explanation of the shock-induced polarization based on the propagation of the double layer. If we assume, similarly to Mineev *et al.*,[21] that the electrical signals are primarily a response of the charged impurity particle to shock compression, the thickness r of the double layer is

$$r=\rho\epsilon U/\eta. \tag{1}$$

When the crystal is stressed by the 12-kbar shock in Table II, the resistivity behind the shock front is $\rho \simeq 1.0\ \Omega\,\text{cm}$, which corresponds to the resolution capability for our measurements. With the compressibility $\eta=0.926$ and the shock velocity $U=0.96$ cm/μsec, the dielectric constant $\epsilon=1.03\times10^{-10}$ C/N cm², we obtain $r=1.1\times10^{-6}$ cm. The measured potential difference $V_{max}=2.6$ V is related to the surface charge density,

$$\sigma=\eta V_{max}/AUR_L, \tag{2}$$

where the load resistor, $R_L=50\ \Omega$, and A, the crystal cross-section area is 3.2 cm². We obtain $\sigma=7.4\times10^{-9}$ C/cm². This value of σ corresponds to 7×10^{15} electrons/cm³ of the double layer, as compared to 10^{14} boron atoms/cm³ in our crystal specimens. This order-of-magnitude calculation suggests that the polarization is related to the impurity concentration, since each boron atom in p-type Si contributes a "hole" for ionization and conduction[22] with the same amount of charge as an electron but with a positive sign.

The growth of the induced emf signal can be described by

$$V(t)\propto[1-\exp(-t/\tau)], \tag{3}$$

where $V(t)$ is the voltage as a function of time t and τ is the relaxation time. A general argument for the use of an exponential expression to describe the growth in signal can be made, since it is a fundamental result from theories of rate processes. Other arguments also justify use of Eq. (3) in explaining the growth of the polarization signal. For example, a shock polarization model for dielectrics is used by Allison[23] to describe a mechanical contribution to the signal. He proposes that the shock front initiates a mechanical disturbance of the molecular dipoles, thereby creating in each element of the dielectric a net dipole moment per unit volume which decays with a characteristic relaxation time. A more fundamental model[24] for the shock polarization of semiconductors has been proposed which is based on the shifting of the energy levels behind the shock front. The voltage drop due to conduction across the shock front would also be represented by Eq. (3) for this theory if the sample's resistivity is small.

The recent work of Mineev *et al.*[7] on the polarization of silicon under shock conditions shows records similar to our results above the HEL for similar doping concentrations. However, they were unable to explain the roles of elastic and plastic waves in the polarization of Si. Their records of polarization of Si in the elastic region of stress are quite different from ours for corresponding doping levels. The three major differences are (i) the small magnitude of their signals in the elastic region, (ii) the emf decays behind an initial peak value, and (iii) the signals go negative when the elastic wave reaches the electrode. We have no satisfactory explanation for these different results. However, it is evident that at least a mechanical property difference exists in silicon crystals available in the USA and USSR. For example, Pavlovskii finds a value of 40 kbar for the HEL (dynamic yield) of (111) Si while our value is ~55 kbar, in agreement with the value reported by Gust and Royce. Also the Russian's value for the velocity of the elastic shock precursor is 8500 m/sec as compared with the USA value of 9600 m/sec measured in (111) Si at the HEL.

Earlier work on shocked copper-germanium junctions[25] gave electrical signals which were attributed to a thermoelectric effect, and inflections occurring in the records were identified with multiple shock waves in germanium. A second inflection occurring soon after the elastic shock left the crystal was interpreted as a possible new phase transition in germanium. It was pointed out that this inflection occurred at the time a backward-facing elastic relief wave interacts with the forward-facing plastic shock front. The wave interaction was not believed to be the cause of the inflection. We find, however, that the association of the inflection with the interacting waves agrees with our interpretation of the observed inflections occurring in the polarization records of p-type Si.

B. Shock resistance

There are certain limitations in our shock-resistance data of Table III which should be noted. We cannot ascertain all changes that occurred in the crystal structure during passage of the shock waves and what effect these changes had on the final resistance values. The polarization effect, however, was eliminated since the final values were measured when the polarization voltage was zero, e.g., corresponding to the times denoted (7) in Fig. 3(a).

The measurements show that the resistance becomes very small ($R/R_0 < 0.02$) for stresses near the HEL, indicating that a metallic state is reached. The resistance then increases, and for a stress of 133 kbar the relative resistance is ~0.17. When the crystals are shocked by stresses above 133 kbar, two plastic shocks occur which make the identification of the resistivity associated with each particular shock impossible. The values of the relative resistance, however, are correct for stresses within ± 10% of the stresses given in Table III. A curious result mentioned earlier is that the resistivity behind the second plastic shock is slightly larger than the resistivity behind the first plastic wave. For example, it was noted in Fig. 3(a) that the small inflection in the record at (7) gives a higher relative resistance (0.17) than the value (0.12) which is measured at (6). Remember that the numbers (6) and (7) denote, respectively, the arrival times of the first and second plastic shock waves at the electrode.

We consider the large increase in the relative value, R/R_0, that occurs between 90 and 133 kbar as independent evidence of a transition. The transition occurs at ~133 kbar as measured by free-surface measurements as discussed earlier, and most likely is a polymorphic transition.

The surprise in the data is the low resistance at the elastic stress level. For example, at 59 kbar the relative resistance decreases by > 98%. The corresponding static resistance data for crystalline Si[2,3] show a transition from the semiconductor to a metallic state at stresses ranging from 110 to 200 kbar. The introduction of large shear stresses in the static experiments caused the change to the metallic state to occur at the lower stresses. In our experiments even greater shear forces are present and are very rapidly applied. Therefore, the transition occurs under dynamic compression at significantly lower stress levels and much shorter times, e.g., in the microsecond interval of elastic shock compression near the HEL. The lower dynamic stresses required for conversion to the metallic state are additional evidence that the transition is strongly shear-rate dependent. The resistance data also imply that it was incorrect for Pavlovskii[1] to interpret the discontinuity at ~100 kbar in his dynamic compressibility measurements as a transition to the metallic state.

SUMMARY

In review, the complex effects, e.g., multiple shock-wave structure and polarization, have complicated our experiments to determine the effect of pressure on the resistance of silicon under shock conditions. Despite these complications useful data were obtained. The electrical experiments have clarified the roles of the elastic and plastic waves in the shock polarization behavior of silicon and assisted in the interpretation of its complicated Hugoniot. The resistance measurements imply a transition to the metallic state near the HEL which is shear-rate dependent. The resistance data also imply a polymorphic transition near 133 kbar.

Areas of future work can be recommended. An elastic precursor is likely to be present in most semiconductors under shock compression, and its effect in polarization experiments could contribute to a better understanding of the mechanism of conduction. The effect of variations in the impurity concentration should be studied once an understanding of the cause of the polarization is clearly ascertained. More electrical measurements in the elastic regime are clearly required. Resistivity experiments with the faces of the electrodes parallel to the shock motion (attached to the edges of the crystal) would be free of the polarization signal and allow easier interpretation of the observed resistance changes.

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*Supported by the Naval Ordnance Laboratory Independent Research Fund.

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