J. Phys. Chem. Solids. Pergamon Press 1966. Vol. 27, pp. 1519–1529. Printed in Great Britain.

PHYSICAL BEHAVIOR OF GERMANIUM UNDER SHOCK WAVE COMPRESSION*

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(*Received* 24 *January* 1966)

Abstract—Shock wave compression measurements from 20 to 140 kb and resistivity measurements under shock wave compression to 40 kb are reported for Ge in the [111] orientation. The Hugoniot elastic limit is found to be 44 ± 4 kb and a phase transition in the pressure range from 114 to 122 kb at about 160°C is identified. The transition occurs at a volume between $0{\cdot}870\ V_0$ and $0{\cdot}880\ V_0$. A shock wave velocity measurement in the mixed phase region allows the slope of the phase diagram to be determined as $-3{\cdot}1 \times 10^{-2}$ kb °C^{-1}. The pressure and volume data are in good agreement with the static work; these data, when combined with the slope of the phase diagram, clearly identify the transition as the solid–solid transition to the white tin structure. The observed exponential decrease of resistivity with elastic strain allows an energy gap change computation which agrees with theoretical calculations for silicon to 60%. Unusual features of the band structure of one-dimensionally strained [111] Ge are discussed. The new technique developed is generally applicable for shock compression and resistivity measurements on semiconductors.

INTRODUCTION

PREVIOUS shock wave compression experiments[1] on single crystal germanium have revealed a complex wave structure resulting from a high Hugoniot elastic limit of about 40 kb and a suspected phase transition at about 130 kb. Because of the high elastic limit, large, elastic one-dimensional compressions are uniquely achieved in shock wave experiments below the Hugoniot elastic limit. Since large elastic compressions can be achieved, measurements of the resistivity of germanium under shock loading conditions in the elastic range may provide a measure of the energy gap change induced by one-dimensional strain and a verification of theoretical calculations[2,3] if the germanium samples behave intrinsically. In addition, resistance-time measurements of shock waves produced by symmetrical projectile impacts provide the basis for a method to determine the stress–volume relation for semiconductors. New techniques are required for these measurements because of the complex wave structure of germanium and the necessity of a close coupling between measurements of the stress and electronic properties.

The purpose of this paper is twofold. Both shock wave compression results and measurements of the resistivity of germanium in one-dimensional strain will be presented. The shock compression results give a measure of the Hugoniot elastic limit and give thermodynamic data which permit the transition to be identified as polymorphic. The resistivity measurements are found to provide an approximate verification of the theoretical predictions. A new experimental technique is described which permits a measurement of both shock compression and resistivity from a common experimental record and avoids the wave interaction problem inherent in free-surface velocity measurements. Section 1 includes a description of the experimental arrangement and an analysis of the form of the predicted resistance–time behavior. The results and a discussion of the stress–volume measurements are presented in Section 2. Finally, Section 3 shows the results of and a discussion of the resistivity measurements. The authors are aware that the manuscript contains results which are normally of interest to readers in different

* This work was supported by the United States Atomic Energy Commission.

physical fields. Section 3 is recommended for those readers principally interested in the effects of strain on the band structure of semiconductors; while Sections 1 and 2 are recommended to those readers principally interested in shock wave compression measurements and high pressure phase diagrams.

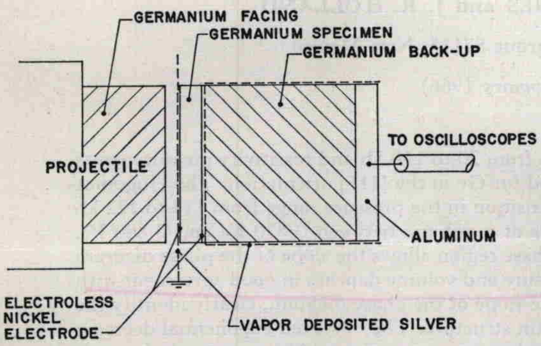

FIG. 1. Schematic drawing of the specimen and impacting projectile.

SECTION I
EXPERIMENTAL CONSIDERATIONS

Experimental arrangement

Shock loading is accomplished by impacting large diameter-to-thickness ratio disks of germanium upon each other in order to ensure a state of uniaxial strain in all but the periphery of the disks for the duration of the experiment. As shown in Fig. 1, one disk, mounted on the face of a projectile, is accelerated to high velocity by means of a compressed gas gun[(4)] and is impacted in vacuum upon the specimen disk mounted on the end of the gun. Angular misalignment between the impacting surfaces is about 5×10^{-4} rad.* Germanium backup disks are carefully mated to the rear of the specimen. The thicknesses of the impact and backup disks are chosen so that the stress waves propagate through and out of the specimen disk without reflection until, finally, the specimen is stressed uniformly to the impact value for a brief interval preceding the arrival of unloading waves.

The disks, 38 mm in dia., are cut from single crystals of high purity, n-type germanium of nominal 50 Ω-cm resistivity and are oriented with their faces parallel to a (111) crystal plane.[(6)] Intrinsic behavior at atmospheric pressure was confirmed by the measured n-type carrier concentration of 10^{14} cm^{-3}, and resistivity–temperature measurements from 20 to 75°C. The dislocation density was measured to be nominally 6×10^3/cm^2. Depending on the particular experiments, the thicknesses of the specimen disks are 3·2, 4·0 and 8·0 mm.

The resistance–time history resulting from stress waves propagating through the specimen is obtained under constant current conditions. Voltage–time measurements across the thickness of the specimen disk are recorded with a Tektronix 545 oscilloscope. The constant current of 1·00 A is applied to the specimen disk about 500 nsec before impact to prevent resistive heating of the disk. The typical signal level prior to impact is 0·4 V.

Both faces of the disk are entirely electroless nickel plated to provide ohmic electrodes.[(7)] The impact surface electrode of the specimen is also coated with vapor deposited silver and maintained at ground potential. The backup disk assembly, entirely vapor coated with silver, serves as the circuit lead to the other electrode. As will be shown in the analysis, the resistance change induced by the stress can be read directly from each record. Thus, contact resistance is effectively canceled out unless this contact resistance changes with stress. Since the electrodes are located at known positions, any change of contact resistance with stress would be shown as a change at the specific time that the stress reaches an electrode. No such changes were observed in the stress region below the elastic limit. It is estimated that the resistivity measurement is accurate to ±10%.

Expected resistance–time behavior

For impact stresses in the range of several hundred kb, multiple waves have previously been observed in germanium which indicate the presence of slope discontinuities, or cusps, in the stress–volume relation.[(1)] To obtain an analytical description of the expected resistance–time behavior, consider a semiconductor disk in which two stress waves of different amplitude and different wave velocity are propagating. As shown in Fig. 2, the disk is divided into zones of different resistivity at any instant of time. The total resistances between the electrodes is then the sum of

* Some of the techniques involved in a gun experiment are discussed in Refs. 4 and 5.