mobility accompanying the electron transfer to a single (111) valley; this represents the classic piezoresistive effect for n-type germanium. Above some critical strain the electrons are completely transferred to a single (111) valley and the conductivity is dominated by the decrease in energy gap with compressive strain. Such a complete transfer of electrons to a single valley has been observed by Schetzina and McKelvey [69S2] in uniaxial stress experiments.

There are two experimental investigations of resistivity of germanium under elastic shock compression. The work of Graham et al. [66G1] interpreted limited measurements on [111] Ge on the basis of intrinsic semiconduction without attempting to account for strain-induced changes in mobilities and effective masses. On that basis, the shear deformation potential was found to be about a factor of two too small. In more recent, heretofore unpublished, work Graham and Julian conducted a very similar but more detailed and carefully executed study of [111] and [100] Ge which was fully integrated with code calculations to both plan and interpret experiments.

An extensive program to characterize conventional electrical properties of the samples at atmospheric pressure was carried out by J.D. Kennedy and R.D. Jacobson of this Laboratory. Since each experiment required three crystals (one sample, one impactor and one impedance-matching disk) it was possible to select sample crystals with the best-behaved electrical properties from among a large group of crystals which were nominally all characterized by the supplier as high-purity, n-type. Preshot characterization included four-probe (Van der Pauwe) conductivity and Hall effect measurements from 220 to 300 K which were used to determine the impurity concentrations. Julian's computer code, "Sparrow", incorporated theory and experimental data from prior germanium studies [64P1] to interpret the low temperature results and arrive at the impurity concentrations. Other preshot characterizations included measurements of photoconductivity and two-probe resistivity measurements at currents from one-fourth to 1 amp. The final sample characterization is performed 500 ns prior to impact loading when the one amp current is pulsed on for the few microseconds of the shock loading.

The [111] orientation samples were found to be n-type with impurity carrier concentrations of from 2.5 to $8 \times 10^{18}\ \mathrm{m}^{-3}$. The [100] samples had carrier concentrations of 14 and $18 \times 10^{18}\ \mathrm{m}^{-3}$. Calculations with the Sante Fe Code indicated that final conductivities would not be significantly influenced by the observed range of carrier concentrations.

The shock-loading experiment of the work above was as described by Graham et al. [66G1] except that crystals 38 mm in diameter by 4 mm thick were used. A single shock-induced emf measurement at a strain of 2.8 per cent showed a signal of 15 mV, which is negligibly small compared to the several volt resistance measurement.

The data obtained from the resistance measurements are shown in fig. 4.9. The assigned values of conductivity are limited in accuracy because the measured resistance was found to be somewhat time dependent. The [100] datum at the lowest strain was particularly so and a definite resistance value cannot be assigned to that point.

The shear deformation potential for the (111) and (100) valley minima determined by fits to the data of fig. 4.9 are shown in table 4.9 and compared to prior theoretical calculations and experimental observations. The deformation potential of the (111) valley has been extensively investigated and the present value compares favorably to prior work. The error assigned recognizes the uncertainty in final resistivity due to observed time dependence. The distinguishing characteristic of the present value is that it is measured at a considerably larger strain than has heretofore been possible. Unfortunately, the present data are too limited to address the question of nonlinearities in the deformation potentials [77T2].

Table 4.9
Shear deformation potentials

Author	Theoretical/Experimental	$\Xi_u(111)$ eV	$\Xi_u(100)$ eV
Goroff and Kleinman [63G1]	Theoretical (Silicon)	17.3	9.6
Saravia and Brust [69S2]	Theoretical	14.0	7.3
Melz [70M3]	Theoretical (Silicon)	—	7.5
Present work	Experimental	19 ± 2	8.3 ± 1
Schetzina and McKelvey [69S2]	Experimental	16.3 ± 0.3	—
Bulthius [68B4]	Experimental	19.5	—
Balslev [66B1]	Experimental	16.2 ± 0.4	9.2 ± 0.3 (Silicon)
Riskaer [66R1]	Experimental	18.0 ± 0.5	8.5 ± 0.5 (Silicon)
Balslev [65B1]	Experimental	—	8.5 ± 0.2 (Silicon)
Dakhovskii [64D1]	Experimental	16.5	—
Schmidt-Tiedemann [62S1]	Experimental	18.9 ± 1.7	11.3 ± 1.3 (Silicon)
Fritzsche [59F1]	Experimental	19.2 ± 0.4	—

Although the [100] data are quite limited, the shear deformation potential determined is the only measurement for this valley in germanium. At atmospheric pressure and small strains the (100) valley minimum is well above the (111) valley minima and not accessible for measurement. In the present uniaxial strain experiment the (100) valley becomes the minimum point on the conduction band. The observed value agrees well with theoretical calculations on silicon.

The data indicate that elastic shock-compression resistance measurements can provide data on the effects of strain on energy gaps and deformation potentials in semiconductors. Drift mobility measurements on holes in germanium and resistivity measurements on samples with different dopings would appear to be of considerable interest.

4.10. Conductivity of metals

Resistance measurements of hydrostatically compressed metals have provided simple and effective means for detecting the onset of polymorphic phase transitions, for studying electronic properties and for gauging hydrostatic pressures. Similar problems are of interest in shock-compression investigations. The first such studies were reported by Fuller and Price [62F1] on iron shortly after similar static-high-pressure measurements by Balchan and Drickamer [61B1]. The shock measurements showed evidence for a resistance change associated with the $\alpha \rightarrow \varepsilon$ phase transition. Since this early demonstration of the capabilities of resistance measurements, progress toward perfecting methods for quantitative study and analysis has been slow. Upon first examination, most metals show well-defined, approximately linear changes of resistance with shock pressure. Nevertheless, closer examination of theory and experiment has invariably revealed considerable underlying complexity. In spite of the difficulties, the capabilities for studying resistivity of shock-compressed metals have now been well demonstrated in a recent detailed investigation of silver by Dick and Styris [75D1].

The literature on resistance changes in shock-loaded metals has been reviewed by Styris and Duvall [70S3], to a lesser extent by Keeler [71K2], and methods and summary of results on a number of metals reviewed by Murri et al. [74M3]. Experimental methods are reviewed by Yakushev [78Y1]. The extensive literature on Manganin has been reviewed by Murri et al. [74M3]