$-4{\cdot}0$ eV/unit strain. Since the energy gap change due to the dilatational component has been evaluated to be $+3{\cdot}7$ eV/unit strain,* the shear strain contribution is $-7{\cdot}7$ eV/unit strain. This is a factor of $1{\cdot}85$ smaller than the theoretical value of $-14{\cdot}29$ eV. Thus, this measurement on Ge agrees with the sign and order of magnitude of the theoretically predicted change for Si.

Although the agreement given above is satisfactory considering the complexity of the problem, somewhat better agreement is achieved by a more detailed examination of the data. The experiment at a strain of $1{\cdot}36\%$ is well below the elastic limit and therefore in a stress region where mechanical relaxation effects are unlikely. The resistance–time record, however, exhibits an increasingly greater downward slope rather than the constant slope expected from the analysis. The curvature is more pronounced early in time and thus is not that expected from the stress unloading behavior from the lateral edge of the sample. Thus, the most likely interpretation of the nonlinear behavior is that equilibrium of carriers is not fully established and that relaxation times are of the order of 10^{-7} sec. The observed resistive behavior tends toward a constant slope late in time; hence, to establish a value for the equilibrium resistivity, the slope of the resistance–time record for late times is extrapolated for full wave transit time.† This yields a resistivity which gives a value of δE_g of $5{\cdot}3$ eV per unit strain. This value of δE_g gives a shear strain contribution for [111] one-dimensional strain of $9{\cdot}0$ eV per unit strain which is a factor of $1{\cdot}6$ smaller than the theoretical value for silicon. Thus, it appears that our best value for the [111] shear strain contribution is 60% lower than that predicted for Si. Considering the uncertain nature of the assumptions concerning the transport properties of the strained Ge and the unknown applicability of the theoretical analysis to Ge, the agreement is considered to be satisfactory. However, further interpretations seem in order.

Results of the extensive work which has been accomplished with hydrostatically strained Ge furnish a comparative background which hopefully might have relevance to the analysis of the current work. However, several major differences exist between the band structure of hydrostatically strained Ge and Ge under [111] one-dimensional strain. As indicated in Fig. 6, the conduction band structure for [111] one-dimensional strain is much simplified. The $L_1(111)$ level is lowered considerably, while the $L_1(1\bar{1}\bar{1})$, $L_1(\bar{1}1\bar{1})$ and $L_1(11\bar{1})$ levels are raised at a rapid rate. Hence, the effect is to change the multivalley semiconductor to a simpler single-valley semiconductor in which all of the electrons are confined to the [111] valley. Further, the nonlinear band gap change indicated for *pressure* greater than 15 kb would not be expected to occur, since detailed analysis[31] of the interband scattering of electrons showed that the effect was caused by the conduction band minima in the [100] direction moving closer in energy to the [111] minima thus causing significant interband scattering. In the one-dimensional strain configuration these two minima are further apart in energy in the strained state than in the unstrained state; thus no intervalley scattering would be expected.

On the other hand, the valence band structure becomes more complex in the one-dimensional strain state than in the hydrostatic state. One-dimensional [111] strain causes the $\Gamma'_{25(j=3/2)}$ edge to be split at a rapid rate. Further, the $\Gamma'_{25(j=1/2)}$ band, originally at the same energy as the $j = 3/2$ level, changes energy with a different coefficient than either of the split $j = 3/2$ levels. Thus, three distinct valence band energy levels exist at the same momentum value for which one level exists in the unstrained and the hydrostatic state.

The band gap for Ge in [111] one-dimensional strain is predicted to be narrowed from $0{\cdot}66$ eV to $0{\cdot}46$ eV at 2% strain. Because of this, deeper lying impurity levels unimportant in the unstrained or hydrostatic state are possibly more important in the uniaxial strain state. Hence, it is clear that because of these several major differences in band structure, results and conclusions concerning conductivity of hydrostatically strained Ge are of marginal applicability to the analysis of [111] one-dimensionally strained Ge.

Noting the simplicity of the one-dimensionally strained conduction band, it is interesting to use the position of the L_1 minimum as a reference and compute the effective energy level of the valence

* A bulk modulus of $7{\cdot}49 \times 10^2$ kb was used to calculate the volume dependence from the measured pressure dependence[30] of the energy gap.

† Wave transit time for this sample is $1{\cdot}42$ μsec.

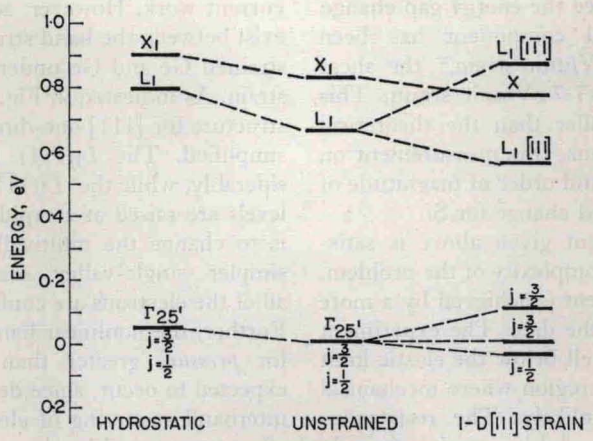

FIG. 6. Diagram of the effect of a 2% hydrostatic compression and a 2% one-dimensional [111] compression on critical points in the band structure. Values shown are calculated from the analysis of GOROFF and KLEINMAN.[3]

band maximum from the calculated energy gap change obtained from our experimental results. This computation suggests that the effective valence band maximum is essentially stationary in energy as if splitting of the valence band edge results in a new distribution of holes among the closely spaced valence band energy levels whose behavior approximates the original unstrained behavior. However, the physical significance of this observation is not clear, since data describing the populations of the various valence band energy levels, hole mobilities and effective masses for Ge in [111] one-dimensional strain are necessary to provide data for a more complete analysis. The large change in the effective mass of holes for Si under uniaxial *stress*[32] suggests that significant changes are to be expected.

The source of the finite time to establish equilibrium resistivity is not apparent from previously measured relaxation times of carriers. Intervalley relaxation times have been measured by high frequency ultrasonic absorption of shear waves[33] and are about 10^{-11} sec at room temperature and for low carrier densities. Similarly, the relaxation time for the repopulation of holes is of the same order of magnitude or shorter. Thus, the observed resistivity relaxation is most likely due to impurity scattering or generation–recombination times.

In summary, the resistivity measurements in elastic one-dimensional strain provide a measure of an effective coefficient of energy gap change with [111] one-dimensional strain if atmospheric pressure values for mobilities and effective masses are assumed for the strained crystal. The coefficient determined gives a shear strain contribution which agrees to 60% with the theoretically predicted value for Si. However, further experiments in one-dimensional strain are required for a more complete physical description of the conduction process. Our results indicate that shock waves in the elastic region provide a convenient deformation for the study of the change in the band gap of Ge by shear strain.

Acknowledgment—The authors are pleased to acknowledge exploratory experiments by W. J. HALPIN and W. B. BENEDICK, the excellent technical assistance of G. E. INGRAM, the copy of Ge data from Dr. JERRY WACKERLE, carrier concentration measurements by Dr. J. KENNEDY, and many useful discussions with Dr. G. E. SEAY and other colleagues at Sandia Laboratory.

REFERENCES

1. McQUEEN R. G., MARSH S. P. and WACKERLE J., *Bull. Am. Phys. Soc.* **7,** 447 (1962).
2. KLEINMAN L., *Phys. Rev.* **128,** 2614 (1962).