Channeling in Zinc-Blende Lattices: Energy-Loss Studies for Hydrogen and Helium Ions in InAs, GaSb, AlSb, and InSb†

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The energy losses of ions channeled in InAs, GaSb, AlSb, and InSb were investigated. The average number of electrons/atom participating in the stopping of channeled particles is about the same for GaSb and InAs. The minimum energy losses along the [111] and [$\bar{1}\bar{1}\bar{1}$] directions were investigated for GaSb and AlSb and were found to be independent of this asymmetry. The lattice parameter has a stronger influence on the minimum energy losses in channeling of zinc-blende compounds than the A or Z of the host-lattice atoms. The Z dependence of incident light ions channeled in a given host lattice is the same as that for normal energy losses. The energy losses of axial channeling were investigated for GaSb and appear to be characterized by the energy losses of the plane having the largest interplanar spacing in the axial intersection.

INTRODUCTION

THIS paper describes a study of the minimum energy losses of hydrogen and helium ions channeled by single-crystal InAs, GaSb, AlSb, and InSb. This paper is the second of a series in a study of channeling in elemental semiconductors and zinc-blende lattices. The first paper,[1] denoted hereafter as I, compared channeling characteristics between Si, Ge, and GaAs, emphasizing the comparison between Ge and GaAs. The study of the covalent elemental semiconductor Ge and the partially ionic compound semiconductor GaAs compared materials having nearly identical crystal structures, lattice parameters, average masses, and electron densities. The minimum energy losses were found to be quite similar for these two materials. Special consideration was given to channeling along the [111] and [$\bar{1}\bar{1}\bar{1}$] directions since permanent damage had been found to be dependent upon that asymmetry for GaAs. It was found in I that for GaAs the minimum energy losses in channeling were not dependent on this asymmetry. In I it was also shown that velocity is the important parameter in the minimum energy losses of channeled protons and deuterons.

The present paper considers many analogous problems. InAs and GaSb are two materials with different physical and electronic properties, but they have nearly the same lattice structure, average mass, and electron density. It is of interest to determine if the minimum energy losses are also similar. In addition, the possible effects on the minimum energy losses of channeling in the [111] and [$\bar{1}\bar{1}\bar{1}$] directions of AlSb and GaSb are of interest. These materials provide a more critical test of the symmetry independence because of the much greater contrast in size between the two atoms of these diatomic zinc-blende lattices.

In this paper the Z dependence of the energy losses in channeling of the incident ion is investigated and shown to be the same as for normal energy losses for a given host lattice (H, D, and He incident). Also, results of channeling for InSb are presented and are compared with those for InAs and GaSb.

In the following order the paper (1) briefly reviews experimental techniques; (2) presents the energy-loss data in tabular form as a function of incident ion energy, crystallographic direction, and type of crystal; (3) compares the minimum energy losses in channeling of InAs and GaSb; (4) compares channeling along the [111] and [$\bar{1}\bar{1}\bar{1}$] directions of AlSb and GaSb; (5) compares the minimum energy losses in channeling for InSb with that for InAs and GaSb; (6) demonstrates the Z dependence of channeling for light ions in a given host lattice; and, finally, (7) gives a rather conclusive demonstration of the orientation dependence of channeling energy losses in a given host lattice GaSb for two channeling directions.

EXPERIMENTAL

The basic experimental arrangement is essentially the same as that presented in I. A thin single-crystal wafer cut normal to the ⟨111⟩-type axis is mounted so that it can be rotated in its own plane around an (azimuthal) axis, by an angle ϕ; and the normal to the plane of the crystal can be tilted away from the beam axis by a polar angle θ. The particles emergent from the crystal are recorded in a junction detector.

The angular positioning apparatus, which was accurate to 0.2°, was mounted in a scattering chamber. The beam of charged particles from the Los Alamos P-9 vertical Van de Graaff accelerator was incident on a thin foil target of gold, and the scattered flux at a forward angle, collimated to 0.2°, was incident on the single crystal. This angular acceptance, while somewhat greater than the angle within which the beam can remain "well channeled" throughout its path in the crystal, is still adequate to obtain very useful data. The channel selects a fraction of incident particles. The

† This work was supported by the U.S. Atomic Energy Commission.

[1] A. R. Sattler and G. Dearnaley, Phys. Rev. **161**, 244 (1967).

TABLE I. Channeling in InAs.

Incident ion energy E_i (MeV)	Energy loss, normal peak ΔE_n (MeV)	Energy loss, channeling peak ΔE_{cp} (MeV)	$\Delta E_{cp}/\Delta E_n$	$G=\bar{B}/AZ^2$ (10^{-3} MeV^2/cm)
	Ions incident along ⟨110⟩-type direction			
6.896 H^+	2.61	0.856	0.327	0.430
5.974 H^+	2.88	0.964	0.334	0.409
4.972 H^+	...	1.022	...	0.354
4.721 H^+	...	1.071	...	0.348
	Ions incident along ⟨111⟩-type direction			
6.976 H^+	2.17	0.846	0.376	0.537
5.974 H^+	2.61	1.06	0.406	0.522
4.972 H^+	2.76	1.13	0.409	0.495
4.476 H^+	...	1.13	...	0.440

spectrum is analyzed effectively using the energy (and angle) dispersion to select the well-collimated particles. For energy-loss measurements, the beam, appropriate crystal axes, and detector were collinear. The energy losses of the channeling peak were measured for the beam incident along the ⟨110⟩-, ⟨112⟩-, and ⟨111⟩-type directions.

The energy calibration was accomplished with the aid of the beam from the accelerator itself, as well as from natural radioactive sources. The thicknesses of the single crystals were obtained from the peaks of normal energy losses by numerically integrating

$$\int_{E_i}^{E_f} \frac{dE}{dE/dx}$$

with the aid of tabulations[2] of dE/dx. The range of crystal thicknesses used was about 0.001 to 0.005 in.

Because of limits on angular resolution, defects in the crystalline samples, etc., the measured most-probable energy of the channeling peak may not be characteristic of the true most-probable energy loss. The true energy loss can be somewhat lower. Ideally, the peak of a Gaussian curve fitted to the high-energy edge of the peak should give the true most-probable energy loss. This point was estimated within a few percent by the high-energy edge of the channeling peak. In instances where the channeling peak is broad, Gaussian curve fitting is quite difficult.

RESULTS AND DISCUSSION

The minimum energy losses of the ions channeled in single-crystal InAs, GaSb, InSb, and AlSb (at one energy) are shown in Tables I, II, III, and IV, respec-

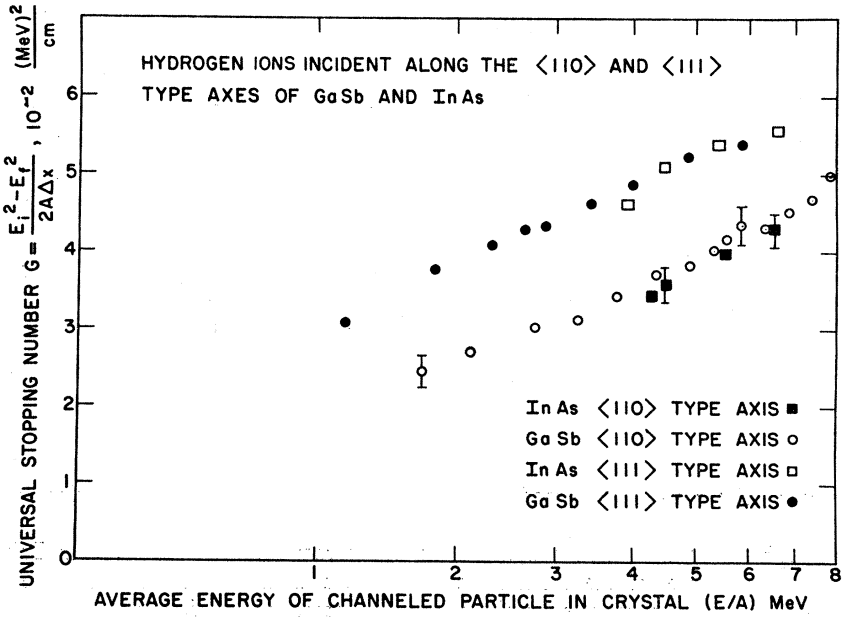

FIG. 1. Effective stopping number for hydrogen ions channeled along ⟨110⟩ and ⟨111⟩ axes of GaSb and InAs.

[2] C. Williamson and J. P. Boujet, Saclay Report No. C.E.A. 2189, 1962 (unpublished).

TABLE II. Channeling in GaSb.

Incident ion energy E_i (MeV)	Energy loss, normal peak ΔE_n (MeV)	Energy loss, channeling peak ΔE_{cp} (MeV)	$\Delta E_{cp}/\Delta E_n$	G (10^{-3} MeV^2/cm)
	Ions incident along ⟨110⟩ direction			
7.978 H^+	0.652	0.258	0.395	0.501
7.477 H^+	0.687	0.256	0.372	0.467
6.976 H^+	0.726	0.276	0.380	0.451
6.425 H^+	0.755	0.285	0.377	0.431
5.974 H^+	0.784	0.307	0.391	0.438
5.473 H^+	0.853	0.313	0.366	0.411
4.972 H^+	0.902	0.332	0.368	0.395
4.470 H^+	0.970	0.350	0.360	0.373
3.968 H^+	1.058	0.368	0.348	0.345
3.465 H^+	1.145	0.385	0.336	0.312
2.962 H^+	1.312	0.442	0.336	0.300
2.459 H^+	1.529	0.489	0.320	0.268
1.953 H^+	•••	0.553	•••	0.222
7.968 D^+	0.989	0.338	0.341	0.227
6.965 D^+	1.095	0.365	0.333	0.307
5.962 D^+	1.212	0.412	0.340	0.295
4.959 D^+	1.359	0.479	0.352	0.285
3.953 D^+	1.613	0.543	0.337	0.249
3.449 D^+	1.799	0.589	0.327	0.231
2.495 D^+	•••	0.655	•••	0.213
	Ions incident along ⟨112⟩ direction			
5.974 H^+	0.851	0.317	0.372	0.434
4.972 H^+	0.951	0.345	0.362	0.340
3.968 H^+	1.130	0.392	0.347	0.347
2.962 H^+	1.397	0.455	0.326	0.295
1.953 H^+	•••	0.598	•••	0.231
5.962 D^+	1.314	0.465	0.354	0.313
4.456 D^+	1.625	0.556	0.342	0.273
2.945 D^+	•••	0.693	•••	0.212
13.884 He^{3+} +	4.164	1.504	0.337	0.410
11.872 He^{3+} +	4.726	1.532	0.324	0.353
9.856 He^{3+} +	5.506	1.526	0.277	0.229
8.848 He^{3+} +	6.288	1.718	0.272	0.285
7.840 He^{3+} +	•••	1.840	•••	0.263
6.828 He^{3+} +	•••	2.068	•••	0.248
5.812 He^{3+} +	•••	2.422	•••	0.237
5.403 He^{3+} +	•••	2.883	•••	0.238
	Ions incident along ⟨111⟩ direction			
5.974 H^+	0.754	0.364	0.482	0.535
4.972 H^+	0.902	0.432	0.478	0.521
3.968 H^+	1.048	0.518	0.494	0.488
2.962 H^+	1.262	0.632	0.502	0.424
6.905 D^+	1.115	0.545	0.490	0.462
5.962 D^+	1.202	0.592	0.492	0.426
4.959 D^+	1.389	0.687	0.495	0.403
3.953 D^+	1.623	0.823	0.505	0.370
2.945 D^+	•••	0.975	•••	0.304
7.840 He^{3+} +	•••	2.94	•••	0.380
6.828 He^{3+} +	•••	3.278	•••	0.369
6.31 He^{3+} +	•••	3.690	•••	0.349

tively. The results are listed as a function of crystal type, incident ion energy, type of ion, and crystallographic direction. The tables also give the ratios of the energy losses of the normal peak to the channeling peak, showing that the smallest energy losses are encountered along the most open axes and planes. The results of the energy losses will be discussed in detail.

A. Presentation of the Data: Effective Stopping Number

The data in Tables I, II, and III are presented as a function of an experimental parameter $\tilde{B}$ called the effective stopping number. The effective stopping number is defined below from Bethe's treatment of energy loss based on the Born approximation applied

TABLE III. Channeling in InSb.

Incident ion energy E_i (MeV)	Energy loss, normal peak ΔE_n (MeV)	Energy loss, channeling peak ΔE_{cp} (MeV)	$\Delta E_{cp}/\Delta E_n$	G (10^{-3} MeV^2/cm)
	Ions incident along ⟨110⟩-type direction			
6.726 H^+	1.556	0.536	0.344	0.405
5.974 H^+	1.669	0.558	0.334	0.366
4.972 H^+	1.952	0.592	0.303	0.324
3.968 H^+	2.348	0.688	0.293	0.276
3.465 H^+	•••	0.755	•••	0.260
	Ions incident along the ⟨111⟩-type direction			
5.974 H^+	1.349	0.624	0.462	0.516
4.972 H^+	1.547	0.697	0.450	0.471
3.968 H^+	2.125	0.843	0.396	0.437

to the collisions between incident heavy particle and atomic electrons.

Use of the Born approximation requires that the amplitude of the wave scattered by the field be small compared to the amplitude of the undisturbed incident wave. The criterion is $Ze^2/hv \ll 1$, where Ze is the charge of the primary particle, h is Planck's constant, and v is the velocity. This condition is fairly well satisfied for MeV protons and deuterons. This approximation also implies that the incident hydrogen beam remains ionized throughout its trajectory. Moreover, the velocity of the incident ions is assumed to be large compared to the orbital velocity of the outer (valence) electrons of the atoms of the host lattice.

Under these conditions, the energy loss can be written as

$$dE/dx = -(C/E)\ \ln bE. \tag{1}$$

Collecting all constants and logarithmic terms so that $B(E) \equiv C \ln bE$,

$$dE/dx = -B(E)/E, \tag{2}$$

$$-\Delta x = -\int_0^{\Delta x} dx = \int_{E_i}^{E_f} \frac{EdE}{B(E)}, \tag{3}$$

where E_i is the ion energy incident on the crystal, E_f is the ion energy emergent from the crystal (characteristic of minimum energy loss of channeled particles), and Δx is the crystal thickness.

The logarithmic dependence upon E, together with all the constants, is contained in B. Since the denominator in Eq. (3) varies much more slowly than the numerator, B is removed from the integral. The value $\bar{B}$ is defined from Eq. (3) by

$$\bar{B} \equiv (\Delta x)^{-1} \int_{E_f}^{E_i} EdE = \frac{E_i^2 - E_f^2}{2\Delta x}. \tag{4}$$

This defines the effective stopping number $\bar{B}$ and it will be used to interpret experimental results. As defined, this quantity is related to the quantities

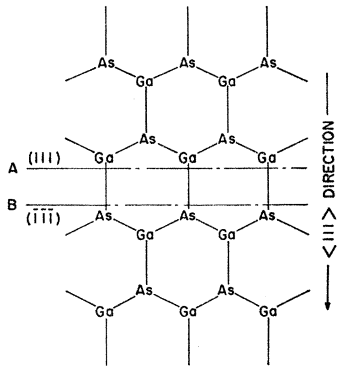

FIG. 2. Model showing [111] and [1̄1̄1̄] asymmetry in zinc-blende lattice; GaAs used as an example.

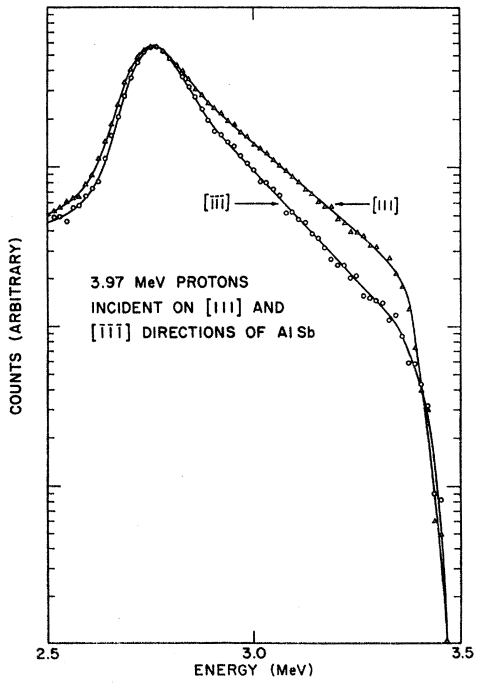

FIG. 3. Spectrum of ions emergent from the [111] and [1̄1̄1̄] directions of AlSb, 3.97-MeV protons incident.

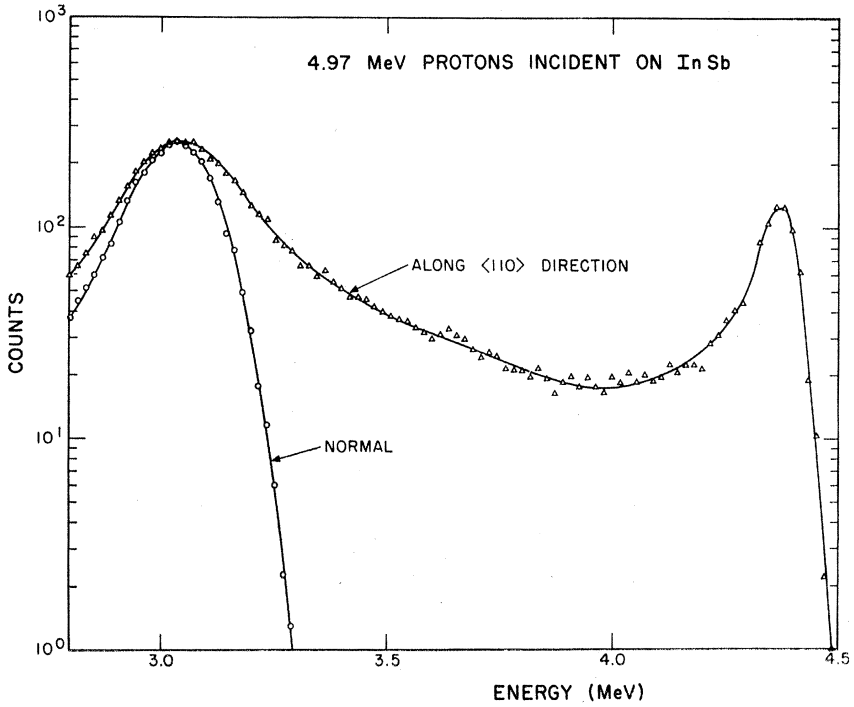

FIG. 4. Spectrum of protons emergent from InSb, 3.97-MeV protons incident. Shown are spectra where the beam is collinear with the ⟨110⟩ direction and where the beam is incident along a random direction.

determined in this experiment, E_i, E_f, and Δx. The quantity $\bar{B}$ is almost independent of crystal thickness for the range of sample thicknesses used in this investigation. The thickness effects will change $\bar{B}$ less than the order of a percent over the range of incident ion energies and crystals used in this investigation. It has been shown in I that the quantity $\bar{B}$ is a highly profitable way to tabulate the data since the fundamental quantities of interest can easily be extracted. The universal stopping number, $G \equiv \bar{B}/AZ^2$, is independent of the A and Z of the incident ions and is used in the tabulations.

B. Comparison of InAs and GaSb

InAs and GaSb are III-V compound semiconductors having different electronic structures and physical properties. The lattice constant, average electron density, and the stopping powers, however, are about the same. The comparison of the minimum energy losses

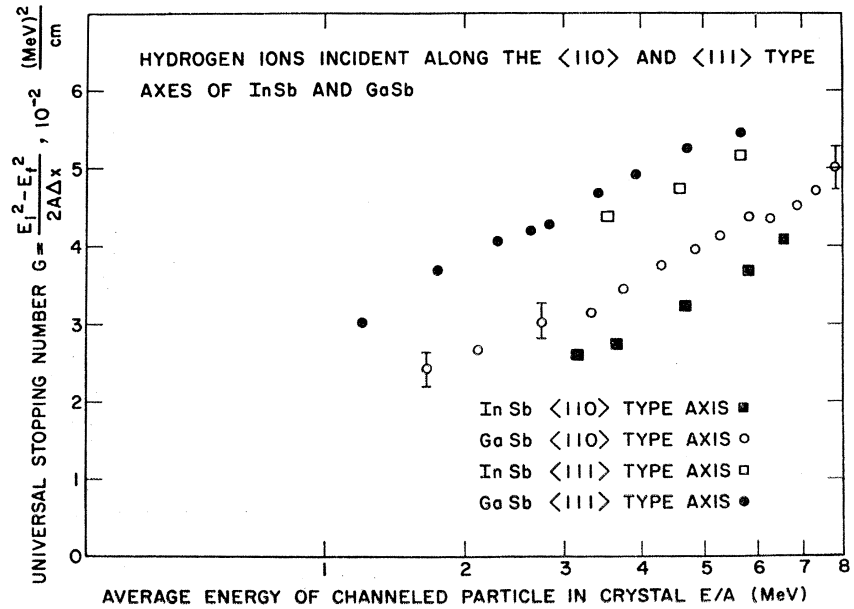

FIG. 5. Effective stopping numbers for hydrogen ions incident along the ⟨110⟩ and ⟨111⟩ axes of InSb and GaSb.

in channeling of these two materials is a further test of whether detailed differences of electronic structure and other physical properties in these materials affect the channeling in the MeV region or whether the minimum energy losses depend only on average effects. The results are shown in Fig. 1. For particles channeled along the ⟨110⟩, the effective stopping numbers in InAs and GaSb are about the same; a similar agreement between the two lattices is also observed along the ⟨111⟩. Thus, as in the case of GaAs and Ge, the minimum energy losses seem to depend upon an average effect rather than detailed differences in electronic or physical properties.

Moreover, the effective stopping numbers are about the same for the ⟨110⟩ and ⟨112⟩ directions of GaSb. These directions have different types of asymmetry for the two types of atoms in the diatomic lattice with respect to the incident beam, but both directions are characterized by the fact that the {111}-type plane is the largest plane in the axial intersection. Therefore, again as in I, in the MeV region it is seen that the largest plane of an axial intersection dominates the minimum energy losses in channeling even when there is a considerable difference in the size of the two types of atoms in the diatomic lattice (Ga versus Sb).

It should be noted that the discussions here are confined to the minimum energy losses in channeling. Some experiments,[3] e.g., Rutherford backscattering, show effects which are more complicated for zinc-blende lattices than for elemental semiconductors. For example, sublattice structures[4] have been picked out in UO_2 using appropriate nuclear reactions and directional effects of incident charged particles. This is easily understood since Rutherford backscattering and nuclear reactions result from close encounters of the incident particle with the lattice atoms, whereas the particles giving minimum energy losses are the "well-channeled" particles that stay near the center of the channels and avoid the lattice sites.

C. Channeling along the [111] and [$\bar{1}\bar{1}\bar{1}$] Directions of AlSb and GaSb

The significant directional displacement effects of some III-V compounds, e.g., InSb[5] and GaAs,[6] seen along the [111] and [$\bar{1}\bar{1}\bar{1}$] directions lead to a reinvestigation of the minimum energy losses in channeling in the III-V compounds in these directions. AlSb has a much larger difference between the two atoms of the diatomic lattice than GaAs (where Ga and As are nearly identical in size) and therefore provides a more critical test than previously obtained for GaAs.[1] The particular symmetry of the zinc-blende lattice is used as an example here and shown in Fig. 2 with GaAs used as an example.

TABLE IV. Channeling in AlSb.

Incident ion energy E_i (MeV)	Energy loss, normal peak ΔE_n (MeV)	Energy loss, channeling peak ΔE_{cp} (MeV)	$\Delta E_{cp}/\Delta E_n$
Ions in [111] and [$\bar{1}\bar{1}\bar{1}$] direction			
3.97	1.25	0.53	0.42

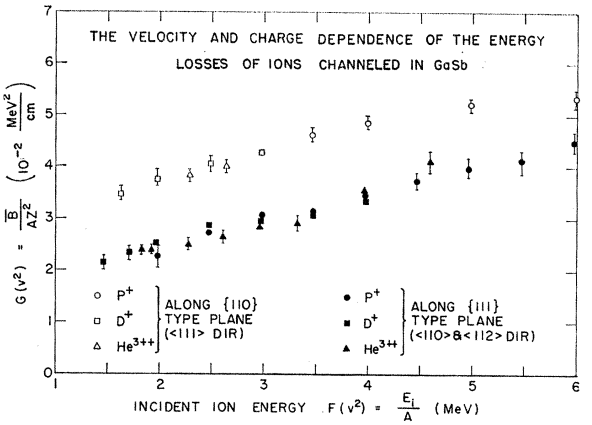

FIG. 6. Plot of universal stopping numbers of p, D, and He^3 ions incident on GaSb showing the A and Z dependence of channeling for light ions.

The results in Fig. 3 show that the minimum energy losses in channeling of even AlSb are in no way affected by the asymmetry of the lattice. The angular resolution was such that no quantitative statements can be made about the different magnitudes of the number of counts for the [111] and the [$\bar{1}\bar{1}\bar{1}$] axes. This is because the number of particles in these regions depends critically on the angular alignment, and the exact angular alignment for each direction was not sufficiently well known. Results for GaSb also show no differences of minimum energy losses along the [111] and [$\bar{1}\bar{1}\bar{1}$] directions.

D. Channeling in InSb

InSb has effectively the largest A and Z of the zinc-blende lattices investigated to date. Also, the lattice constant of InSb is larger than in InAs or GaSb. A spectrum of protons emergent from the InSb single crystal is shown in Fig. 4. In spite of the larger A and Z of the InSb lattice, the effective stopping numbers for InSb shown in Fig. 5 are 20% lower than for InAs and GaSb.

If a very rough assumption is made that it is only the valence electrons that participate in the slowing down of the channeled ions, then the smaller density of valence electrons of InSb and smaller stopping number compared to InAs and GaSb along the ⟨110⟩-type direction could be correlated qualitatively with the differences in the lattice constant of InSb versus AlSb or InAs. Along the ⟨111⟩-type direction the ratios of

[3] S. T. Picraux, J. W. Mayer, J. A. Davies, and L. Eriksson, Bull. Am. Phys. Soc. **13**, 401 (1968).
[4] L. Eriksson and J. A. Davies, Bull. Am. Phys. Soc. **13**, 401 (1968).
[5] F. H. Eisen, Phys. Rev. **135**, A1394 (1964).
[6] G. W. Arnold, in *Radiation Effects in Semiconductors*, edited by F. L. Vook (Plenum Press, Inc., New York, 1968), p. 435.

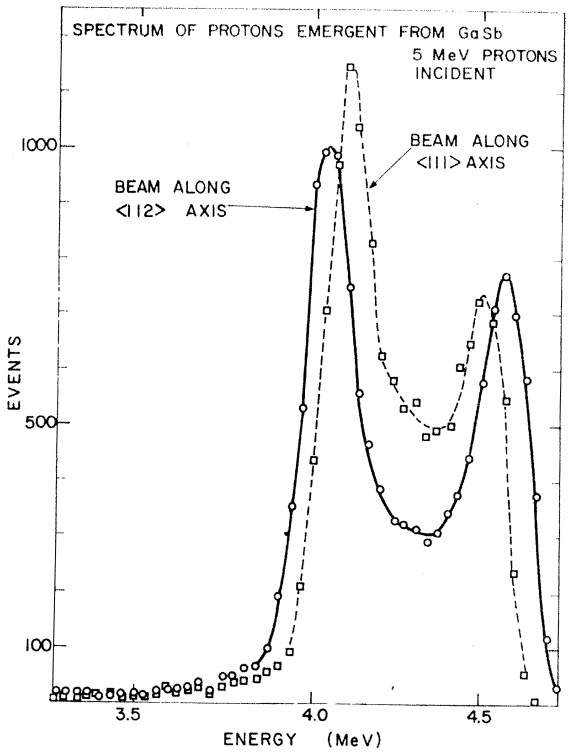

FIG. 7. Spectrum of protons incident from some InSb crystal cut along ⟨111⟩-type axis. Protons incident along the ⟨111⟩ and ⟨112⟩ directions.

the effective stopping numbers of InAs or GaSb relative to InSb seem slightly greater than along the ⟨110⟩ axis (Figs. 1 and 5). Perhaps in this direction nonvalence electrons play a larger role in InAs and GaSb than they do in InSb due to the smaller lattice constants of InAs and GaSb.

E. Z and Directional Dependences of Channeling

As a part of the investigation of channeling, the Z dependence (as well as the velocity dependence) was investigated for the minimum energy losses in channeling for light ions in a given host lattice. Only the velocity dependence was considered in I. It is shown in Fig. 6 for p, D, and He^3 that the Z dependence is the same as that for the stopping of normal particles in GaSb.

As was seen in I for Ge and GaAs, there is a strong dependence of the energy loss of channeled particles upon the particular direction or plane. This effect is shown very clearly in Fig. 7 for GaSb. The crystal was grown along the ⟨111⟩ direction. It is clearly seen that the minimum energy losses along the more open ⟨112⟩ directions or parallel to the {111}-type planes is less than along the ⟨111⟩ direction or parallel to the {110}-type planes. This *reduction* in channeling energy losses occurs in spite of a 7% *increase* of thickness in the crystal which is indicated by the greater energy loss of the normal peak in the ⟨112⟩ direction.

CONCLUSIONS

This investigation has extended the study of the minimum energy losses in channeling to InAs, GaSb, InSb, and, to a limited extent, AlSb. In these crystals there is a substantial difference in the size of the two types of atoms in the zinc-blende lattices. It is found that the channeling properties of particles undergoing minimum energy losses depend upon average effects rather than upon electronic, physical, or symmetry properties. The minimum energy losses of the zinc-blende lattices seem more strongly influenced by the lattice constant than by the A and Z (indicating perhaps the importance of the role of valence electrons). The dependence of permanent displacement effects upon the $[\bar{1}\bar{1}\bar{1}]$ or [111] directions in zinc-blende lattices has no analog in the minimum energy losses in channeling. The Z dependence of the minimum energy losses for light ions in a given host lattice is the same as for normal energy losses, and the minimum energy losses in channeling in a given host lattice are dependent upon the particular axes or planes along which the ions are channeled.

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