

TABLE I. Initial change in *P*-type carrier concentration during neutron bombardment.

Sample (<i>P</i> -type Ge)	Temperature of exposure	Increase in hole concentration per incident neutron
1	0°C	0.61
2	20°C	0.70
3	30°C	0.77

ductivity,

$$\sigma_{\min.} = 2e\mu_e(\kappa/c)^{\frac{1}{2}} \quad (1)$$

(μ_e the electron mobility, c the ratio of electron to hole mobility, and $\kappa = n_e n_h = AT^3 e^{-g/kT}$) that ionizing radiation does not disturb the thermal equilibrium, since the values of μ_e calculated from Eq. (1) at the conductivity minimum were somewhat smaller than the initial values, as was expected.

However, proper interpretation³ of Hall effect measurements in impurity semiconductors leads to lattice mobilities which are far greater than the ones reported previously, and which agree with mobility values from drift experiments.⁴ Using these new mobility values and 1.5 for c , the ratio of mobilities, the value of κ follows from

$$\sigma_{\text{intrinsic}} = n' e \mu_e' (1 + 1/c); \quad n'^2 = \kappa \quad (2)$$

(n' is intrinsic concentration of electrons or holes and μ_e' the electronic lattice mobility.) κ is now 3.6×10^{26} at 300°K as compared with the earlier value of 3.7×10^{27} .

The revised value is considerably smaller than that formerly used, but its correctness can hardly be doubted because of the experimental data which are used for its derivation, and also, since by using these equilibrium values Johnson and Fan⁵ have been able to predict correctly the temperature dependence of the energy gap in Ge. The new value is only about twice the theoretical value obtained by using the electronic rest mass $A = 2^2(2\pi m k T)^3/h^6$ whereas the earlier value was about 20 times larger.

The new value of κ in Eq. (1) leads in all cases to apparent mobilities at the conductivity minimum far greater than the one observed at the beginning of the experiment. Therefore, in high resistance material, measured in the pile, photo-effects due to ionizing radiations do play an important part. These increase the conductivity and must be considered in the theoretical interpretation of the "in pile" conductivity measurements on Ge.

¹ Purdue Progress Report to Signal Corps, May 1, 1948, p. 12 (unpublished).

² J. H. Crawford and K. Lark-Horowitz, *Phys. Rev.* **78**, 815 (1950).

³ V. A. Johnson and K. Lark-Horowitz, *Phys. Rev.* **79**, 176, 409 (1950).

⁴ Pearson, Haynes, and Shockley, *Phys. Rev.* **78**, 295 (1950); Purdue Progress Report to Signal Corps, March 1, 1949, p. 11.

⁵ V. A. Johnson and H. Y. Fan (unpublished).

On the Formation of Dislocations from Vacancies

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CRYSTALS formed from the melt have the property that they contain a relatively high concentration of lattice defects when at the temperature of the melt. Existing measurements¹ indicate that NaCl and KCl have a mole fraction of about 10^{-4} of positive and negative-ion vacancies (Schottky defects). AgCl and AgBr contain² of the order of one percent of imperfections, which may be either interstitial silver ions and silver-ion vacancies (Frenkel defects) or Schottky defects. The latter seem to be most probable. A metal such as copper presumably possesses of the order of 10^{-3} atom percent of vacancies at the melting point, if the energy required to form a vacancy is close to the theoretical value of 1 ev calculated by Huntington.³ The vacancies may disappear in three ways when crystals containing vacancies are

cooled from the melting point: (a) By migration to the surface, an unlikely process; (b) by joining dislocations having Taylor-Orowan character; or (c) by condensing on particular lattice planes to form plates or disks, somewhat like precipitates in alloys. Once disks of this type have a sufficiently large radius, the portions of the crystal on either face of the disk will join to form a general dislocation ring. The Burgers vector associated with the dislocation ring will be determined by the vector distance through which the faces on opposite sides of the disk move in joining. When the crystal contains one atom or molecule per unit cell the dislocation ring automatically will be of the simple type in which the lattice is in registry everywhere except at the periphery of the ring if the plate of vacancies is one monolayer thick. In other cases the lattice may be in disregistry over the ring unless the disk of vacancies is several monolayers thick. The energetically most stable arrangement in the latter type of case would presumably be one in which the disk of vacancies is sufficiently thick to produce registry over most of the area, but tapers to a monolayer of vacancies near the edge, thereby forming a dislocation which is a generalization of the type Heidenreich and Shockley⁴ have termed "extended." It is evident that the aggregates of vacancies will be more stable as general dislocation rings having a high degree of registry than as spheroidal or needle-like aggregates, once the aggregates become sufficiently large.

It is difficult to estimate the relative likelihood of vacancies vanishing during cooling by the possibilities (b) and (c) listed above. Probably the second possibility would be preferred if dislocations were present to the extent of 10^8 or 10^9 lines/cm², since they would be the best nuclei for condensation. On the other hand, it is quite possible that a carefully grown pure crystal contains very few dislocations near the melting point. Frank⁵ has demonstrated very convincingly that dislocations having a component of screw character undoubtedly play an important part in crystal growth by furnishing steps at the surface for adding new layers. However, only a very small number of such dislocations (of the order of one per growing face) are required for this catalytic activity. Griffin's observations⁶ on the prism faces of beryl, presumably grown from solution, also seem to show that only a relatively small density of dislocation lines is required to promote crystal growth under idealized conditions. The density appears to be as small as 10^6 lines/cm² in some areas of his specimens.

The writer would like to propose that the practical, realizable, lower limit to the number of dislocations found in crystals which are carefully grown from the melt is determined by the condensation of vacancies into plates to form general dislocation rings. A density of vacancies of 10^{18} per cc is sufficient to produce 4×10^8 dislocation lines/cm² by forming rings 2.10⁻⁶ cm in diameter, the density of rings being 10^{12} per cc. The general rings formed in this way appear to have all the characteristics required to explain properties of crystals which depend upon the existence of dislocations. More specifically, they can do the following things: (1) Produce all the strain needed⁷ for extensive plastic flow by moving in such a manner that the projected area on the plane normal to the Burgers vector is unaltered. (2) Produce slip bands by the multiplication of the type described by Frank and Read.⁸ Such multiplication can occur most easily after the rings have become elongated during normal plastic flow. (3) Promote prismatic slip⁹ of the material contained within the cylinder generated by lines in the direction of the Burgers vector and passing through the ring. (4) Produce mosaic structure by proper arrangement. (5) Act as sources or sinks for vacancies in any of the numerous processes that require this property.

The foregoing proposal implies that there should be an inherent difference in the behavior of crystals grown carefully from the melt and those grown from aqueous solution or by condensation well below the melting point, in properties which depend upon dislocations. For example, it suggests that a higher degree of perfection should be attainable in crystals grown slowly at temperatures well below the melting point than in those grown from the melt. There is already considerable evidence to support

this point.¹⁰ It also suggests that a crystal of NaCl grown carefully from aqueous solution may have mechanical properties that differ in a marked way from those of a crystal grown from the melt. In this connection it is worth noting that the silver halides, and presumably the thallose halides, have about 100 times as many imperfections as do the alkali halides at the melting point. It would be interesting to know whether crystals of the silver and thallose halides grown from the melt exhibit those properties associated with dislocations more markedly than does an alkali halide crystal prepared under almost identical conditions. It is possible that a high density of such vacancies in the thallose salts promotes the prismatic slip observed by Smakula and Klein.⁹

It is highly unlikely that vacancies are trapped in a non-equilibrium manner during slow growth from the melt. Kelting and Witt¹ have found that Ca, Sr and Ba achieve equilibrium between solid and melt when crystals are grown at the rate of 1.6×10^{-5} cm/sec. We should expect vacancies to achieve equilibrium with the melt at least as easily.

¹ C. Wagner and P. Hantelmann, *J. Chem. Phys.* **18**, 72 (1950); H. Kelting and H. Witt, *Zeits. f. Physik* **126**, 697 (1949); H. Etzel and R. J. Maurer (to be published).

² E. Koch and C. Wagner, *Zeits. f. Physik* **B38**, 295 (1938); F. Seitz, *Phys. Rev.* **56**, 1063 (1939); A. W. Lawson, *Phys. Rev.* **78**, 185 (1950); J. W. Mitchell, *Phil. Mag.* **40**, 249, 667 (1949).

³ H. B. Huntington, *Phys. Rev.* **61**, 315 (1942).

⁴ R. D. Heidenreich and W. Shockley, *Report of Bristol Conference on Strength of Solids* (Phys. Soc. London, 1947), p. 57.

⁵ F. C. Frank, *Crystal Growth* (Discussions of Faraday Society, 1949), p. 48. See also paper by Frank in *Pittsburgh Symposium on Plastic Deformation of Crystalline Solids* (to be published by Naval Research Laboratory). Frank has pointed out that dislocations could be formed by precipitation of vacancies, but has not attempted to develop the idea as a practical topic. See, also, F. R. N. Nabarro, *Bristol Conference* (Phys. Soc. London, 1947), p. 75.

⁶ L. J. Griffin, *Phil. Mag.* **41**, 196 (1950).

⁷ See, for example, a paper by the writer in the *Pittsburgh Symposium* (footnote 5) and a paper by W. T. Read and W. Shockley *Imperfections in Almost Perfect Crystals* (to be published) in which these ideas are developed independently).

⁸ F. C. Frank and W. T. Read, *Phys. Rev.* **79**, 722 (1950).

⁹ A. Smakula and M. W. Klein, *J. Opt. Soc. Am.* **39**, 445 (1949); F. Seitz, *Phys. Rev.* **79**, 723 (1950).

¹⁰ R. W. James, *Optical Principles of the Diffraction of X-rays* (Bell and Sons, Ltd., London, 1949), Chapter VI. It is to be noted that M. Renninger (*Zeits. f. Krist.* **89**, 344 (1934)) has observed regions that are very nearly perfect in sodium chloride grown from the melt; however, the specimens were imperfect as a whole.

The Fierz and Kopfermann-Brix Explanation of the Spectroscopic Odd-Even Isotope Shift Staggering

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THE writer has published a note on "The Schmidt Model and the Odd-Even Staggering of the Isotopic Shift."¹ It has since been pointed out to him that very similar and in some respects identical considerations have been published previously by Fierz² and independently by Kopfermann.³ It is desired to record the fact that the credit of prior publication of the possibility of such a connection belongs to Fierz and Kopfermann. At the time of writing the note the writer was not aware of the existence of the statements by Fierz and by Brix and Kopfermann.

It may be remarked that the connection of odd-even staggering with the Schmidt model, which has been speculatively considered for some time, has become more concrete by 1950, both because of the indication of strong spin-orbit forces⁴ and the existence of calculations⁵ indicating that while the polarization of nuclei by electrons may be an appreciable contributor to the odd-even staggering there is nevertheless room for the existence of contributions from other causes.

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¹ G. Breit, *Phys. Rev.* **78**, 470 (1950).

² M. Fierz, *Göttingen Nach.* **3**, 1 (1947). This paper contains an account of a lecture to the Physical Society of Zürich, February 17, 1947.

³ P. Brix and H. Kopfermann, *Göttingen Nach.*, Heft **2**, 31 (1947).

⁴ M. G. Mayer, *Phys. Rev.* **74**, 235 (1948), **75**, 1969 (1949).

⁵ Breit, Arfken, and Clendenin, *Phys. Rev.* **78**, 390 (1950).

Disintegration of Ru¹⁰³

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THE 42-day activity in Ru has been assigned^{1,2} to Ru¹⁰³. Absorption and coincidence measurements were made by Bohr *et al.*³ and Mandeville *et al.*⁴ Spectroscopic measurements were made by Hole.⁵ In the present investigation metallic Ru was bombarded in the Harwell pile⁶ and was chemically purified by W. Forsling. The pure and fine metallic powder was spread with a thickness of 4 mg/cm² over a 0.15 mg/cm² aluminum foil. Three different samples have been followed for three half-lives each, giving the half-life of Ru¹⁰³ as 39.8 ± 0.4 days.

Ru¹⁰³ has been studied in two spectrographs^{7,8} several times. One of these runs is produced in Fig. 1. The electron peaks at 17

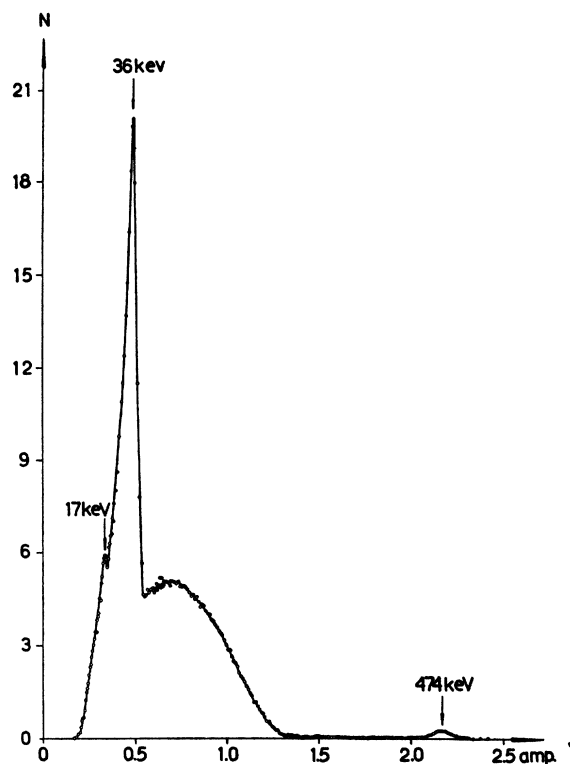


FIG. 1. Beta-ray spectrum of Ru¹⁰³.

and 36 keV are the *K* and *L* lines of 40-keV γ -ray and that at 474 keV is the *K* line of 497-keV γ -ray. The existence of the faint *K* line of 40-keV γ -ray emitted by the metastable level in Rh¹⁰³, which has not been observed before, now makes it certain that the strong β -line is an *L*-line and not a *K*-line, as has been suggested by some investigators.⁹ The photo-spectrum has also been studied in the same spectrographs, which showed two photo-lines identified as the *K* and *L* lines of a 498-keV γ -ray. From the internal conversion lines and photo-lines, the energies of the two γ -rays emitted by Ru¹⁰³ are fixed as 40.0 ± 0.5 keV and 498 ± 2 keV.

The Fermi plot of the β -spectrum shows that it is complex. The maximum energy of the hard component is found to be 698 ± 10 keV. The soft component has a maximum energy of 217 ± 4 keV. The Fermi plots of the two components seem to deviate from straight lines.

No γ - γ coincidences could be found. The β - γ coincidence rate as a function of the thickness of aluminum absorbers placed before the β -tube showed that the 498-keV γ -ray follows the soft β and not the harder one. β , e^- coincidences made in the spectrograph⁸