## Radiation-Induced Expansion of Semiconductors*

D. Kleitman and H. J. Yearian
*Purdue University, Lafayette, Indiana*
(Received August 2, 1957)

GONSER and Okkerse[1,2] recently suggested that deuteron bombardment of GaSb and InSb crystals below −130°C introduced spikes having the higher density liquid configuration, which returned to the normal configuration upon warming to 20°C. Their x-ray measurements[1] seemed to support this hypothesis and indicated a lattice parameter increase accompanied by a dimensional contraction.

We have irradiated 3×3 mm areas of polished GaSb, InSb, and Ge crystals ~1 mm thick with 9-Mev deuterons at temperatures below −130°C. At 20°C, after removing surface contamination,[3] surface contours were determined interferometrically.[4] After a flux ($\phi$) of $3\times10^{16}$ cm$^{-2}$, the bombarded GaSb surface (110) was visible elevated (even to the naked eye). A step surrounding a rounded plateau marked the bombarded region. A similar InSb specimen (110) surface exhibited no step but a hill-like elevation, while a Ge specimen ($\phi=3\times10^{16}$ cm$^{-2}$) showed no comparable elevation.

A GaSb specimen ($\phi=7.5\times10^{16}$ cm$^{-2}$) was examined at 20°C interferometrically and with x-rays. A step ~0.3 micron high follows the bombardment boundary and the maximum elevation of the bombarded region is ~2.0 microns. The unirradiated surface is tilted upward measurably at distances several mm from the boundary; here an abrupt $\frac{1}{8}°$ (maximum) increase in tilt occurs. The total volume increase is of the order of $\frac{1}{2}\%$ of the total irradiated volume. Both lattice-parameter increases and local tilting of the (110) planes were observed using a stationary and a moving film to record the reflected Cu$K\alpha$ beam as the crystal was turned through the fourth-order position. The beam was well collimated in the plane of incidence and divergent at right angles thereto. The inclinations agreed in every respect with the surface contours detected interferometrically, indicating that the elevation must be produced largely by elastic processes rather than by slip. Electron micrographic examination[5] of a similar specimen gave no indication of slip lines or bands but showed characteristically finer etch patterns in the bombarded region. Absence of important plastic deformation was indicated by the sharpness of the diffraction lines. Comparable intensities of diffraction were obtained from bombarded and unbombarded regions. Comparing line widths with $\alpha$-doublet separations, the estimated range of misorientation was not in excess of 3 min of arc and of lattice parameter was less than 1 part in 4000 over distances of ~25 microns, except possibly at the boundary line. Reflection of divergent polychromatic x-rays by the crystal was enhanced in a very narrow region at the boundary, suggesting a more mosaic structure here. Relative to the value just outside the bombarded region a lattice parameter increase (0.12%) was observed at the point of maximum elevation. Most of this increase occurred at or immediately inside the position of maximum tilt. This increase will account for only a fraction of the maximum surface extension, which was ~1% of the deuteron range. Elastic stresses and an undetected lattice parameter change distributed over the unbombarded area might account for part of the difference.

The observed expansion seems near the maximum limit one might estimate from point-defect considerations.[6]

An InSb specimen ($\phi=3\times10^{16}$ cm$^{-2}$) showed similar effects, including a step-like lattice parameter increase, although here the surface contour indicated only general rounding. After two hours anneal at 150°C, the lattice parameter returned to its normal value and residual inhomogeneous microstrains were introduced along the boundary while some surface elevation remained.

* Work supported by U. S. Signal Corps Contract.
1 U. Gonser and B. Okkerse, Phys. Rev. **105**, 757 (1957).
2 U. Gonser and B. Okkerse, Bull. Am. Phys. Soc. Ser. II, **2**, 157 (1957).
3 A surface contamination layer independent of the specimens, of optical density exceeding 1, and probably largely carbon was introduced by bombardment. Interferometric observation suggested by Professor H. Y. Fan, before warming bombarded specimens, indicated an apparent surface depression, but an unknown part of the effect was due to the contamination layer.
4 A versatile interferometer designed by K. W. Meissner [Physik. Z. **30**, 965 (1929)], based on the principal of the Michelson interferometer, was employed.
5 Carried out by Dr. J. F. Radavich. The results appear somewhat similar to those of R. Chang [J. Appl. Phys. **28**, 385 (1957)] who has observed preferential appearance of third-order (0.1–0.5 micron) etch patterns after neutron (but not gamma) irradiations of Ge and Si.
6 See, for example, J. D. Eshelby, in *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic Press, Inc., New York, 1956), Vol. 3, p. 79, on the continuum theory of lattice defects, and F. Seitz and J. S. Koehler, in *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic Press, Inc., New York, 1956), Vol. 2, p. 404, for discussion and reference.

## Reactions $Al^{27}(\alpha,p)Si^{30}$ and $P^{31}(\alpha,p)S^{34}$ at 30.5 Mev*

C. E. Hunting and N. S. Wall
*Department of Physics and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts*
(Received August 9, 1957)

ON the basis of general arguments concerning the nuclear states involved, Butler[1] has recently developed a theory of direct nuclear reactions. The purposes of this letter are to support Butler's general predictions in a reaction that has not previously been studied intensively at moderately high energies and to point out a limitation of his detailed predictions, as summarized in his Eq. (57). Illustrated in Figs. 1 and 2