The microscopic variations of dopant concentrations in crystals pulled either by float zone (FZ) or by Czochralski (CZ) techniques were shown to be the limiting factor of the high-voltage breakdown in thyristor technology. In order to avoid these striations, NTD of high-resistivity silicon as a method to manufacture a well-defined phosphorus-doped silicon was applied in 1973.

The reactions involved are:

$$n + {}^{30}Si \rightarrow {}^{31}Si + \gamma\text{-rays} \rightarrow {}^{31}P + \beta^-\text{-rays}.$$

Typical results in resistivity gradients and tolerances are divided by a factor of two to three in comparison to the standard doping during pulling, but the minority carrier lifetime is reduced by a factor two to ten.

The main markets involved are power thyristors (8 tons year^{-1}), high-power transistors and diodes (30 tons in 1980) and frequency thyristors. Companies suppling NTD silicon are: in the USA (Monsanto), in Europe (Wacker, Topsil) and in Japan (Japan Silicon, Komatsu, Shin Etsu).

The contributions in this volume can be classified in two main categories:

Quality of the material: defects produced by the irradiation, characterization of the defects, annealings, homogeneity of the resistivity.

Industrial requirements: safety aspects, optimization of nuclear parameters, reactor facilities, future applications.

Quality of the material: During irradiation by neutrons, and during radioactive decay, particles with high energy, β^-- or γ-rays and fast neutrons (more than 50 keV) can induce recoil of silicon atoms and generate defects: vacancies or clusters of vacancies, interstitials. One communication shows that a simple cascade model can give a good idea of this recoil. Hundreds of atoms are recoiled for each atom of phosphor created, and this number increases with the proportion of fast neutrons in the flux of thermal neutrons. Annealing is then necessary to restore the quality of the crystal, which is studied in many of the contributed communications.

The quality of the materi l for industrial use is determined by various characterizations: resistivity (four-point probe, spreading resistance, Hall effect), lifetime, device characteristics (leakage currents), and mechanical strength.

But the main effort is directed towards the characterization of defects and their annealing evolution: photoluminescence, photoconductivity, deep-level transient spectroscopy, optical properties (infrared absorption), electron spin resonance, electron paramagnetic resonance, Raman scattering, neutron scattering and transmission electron microscopy are used in these investigations.

The main defects found are two-, four- and five-vacancy, and vacancy–phosphor and vacancy–oxygen centers. For instance, one four-vacancy is created at each cascade as their number is almost identical.

The defects are annealed at various temperatures, the majority of them at under 870 K. It seems that a 1020 K, 30 min thermal treatment restores the quality of the crystal, except for the lifetime which cannot be longer than 0·5 ms. In CZ crystals, such a thermal treatment generates donor states due to the oxygen (with a large role for carbon), and the electrical homogeneity in resistivity is not reached.

Industrial requirements: Safety is an important concern: two products of the irradiation are radioactive with an emission of β^--rays, ^{31}Si and ^{32}P. ^{31}Si has a short half-life (2·6 h), so that each day after the irradiation, the radioactivity due to this isotope is reduced by a factor of 1000. After one week, the radioactivity has cancelled. ^{32}P has a longer half-life (14·3 d). If the doping is large (resistivity less than 20 Ω cm) the radioactivity of silicon is larger than the safety specifications [0·2 pCi g^{-1} (0·074 aBq s^{-1} g^{-1})] and silicon cannot be used until the radioactivity has decreased to this value. Some weeks may be necessary (10 weeks for a 5 Ω cm resistivity).

Various industrial processes of NTD silicon production compared to standard FZ are presented. Many communications study the influence of the design of the reactor (heavy water or water, graphite reflectors, stainless-steel absorbers), flux of neutrons, position of the crystals in the reactor and length (30 to 50 cm) and diameter (8 cm) of the crystals on the characteristics of irradiation: homogeneity of irradiation, proportion of high-energy neutrons, time necessary to reach the doping level. Great attention is given to the measurements of parameters, neutron flux for instance.

Future trends are developed in two communications: NTD silicon can be employed with both FZ and CZ grown extrinsic silicon precisely to compensate residual shallow acceptors present. This material is used in infrared detector technology with gallium or indium doping. Long photocarrier lifetimes and high infrared responsitivities (50 A W^{-1}) have been obtained, with compensations as low as 10^{12} atoms cm^{-3}. NTD was also used for doping GaAs as reactions of neutrons with gallium generates germanium atoms and with arsenic generates selenium.

This book updates the information not only for people involved in neutron transmutation technology, but also for all the scientists working on defects in silicon, especially defects due to the irradiation, and their evolution during annealings.

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Books Received

The following books have been received by the Editor. Brief and generally uncritical notices are given of works of marginal crystallographic interest; occasionally a book of fundamental interest is included under this heading because of difficulty in finding a suitable reviewer without great delay.

J. Appl. Cryst. (1982). **15**, 580

Crystallography: an introduction for earth science (and other solid state) students. By *E. J. W. Whittaker.* Pp. xii + 254. Oxford: Pergamon Press, 1981. Price £8·35, US $19·95 (softback); £13·50, US $32·50 (hardback). A review of this book, by Martin J. Buerger, has been published in the July 1982 issue of *Acta Crystallographica*, Section A, page 560.

Semiconductor technologies, 1982, edited by *J. Nishizawa*, Pp. iv + 348; **Amorphous semiconductor technologies and devices, 1982,** edited by *Y. Hamakawa*, Pp. v + 380; **Optical devices and fibres, 1982,** edited by *Y. Suematsu*, Pp. v + 391; **Computer science and technologies, 1982,** edited by *T. Kitagawa*, Pp. iv + 365: together comprising Vols. 1–4 of an international edition of **Japan Annual Reviews in Electronics, Computers and Telecommunications,** published cooperatively by Ohmsha, Tokyo, and North Holland, Amsterdam, 1982. Price (each volume) Dfl. 310.00, or US $124.00. There is little in any of these four volumes of *direct* relevance to the crystallographer but they do illustrate the present sophistication of this field of applied science. The objective of the two collaborating publishers has been to bring Japanese work to the attention of the West by the production of this special *international* (wholly in English) edition of the *Japan Annual Reviews.* Each of these volumes has about 25 articles and about 50 authors (each carefully profiled at the back), with many references to the original (including Japanese language) literature. The English is mostly good but is just occasionally perplexing. Despite an abject confession, in the preface to Vol. 1, that in Japan 'there has been little original research and development', these volumes are crammed with an impressive variety of examples of solid-state devices, described and illustrated in great detail. For Western scientists in the electronic industries this publication must be a mine of information.