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Semiconductor Measurement Technology:

Technical Impediments to a More Effective Utilization of Neutron Transmutation Doped Silicon for High-Power Device Fabrication

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Neutron transmutation doping (NTD) is a promising technique for the production of uniformly doped silicon needed to optimize power device performance. This report summarizes the problems involved in the neutron transmutation doping process and elaborates the concerns related to damage in transmutation doped silicon resulting from the neutron irradiation. Suggestions for future research are presented.

Key words: Defects; neutron transmutation doping; power device materials; radiation damage; silicon; thyristors.

1. Introduction

The major use of neutron transmutation doped (NTD) silicon at present is for the fabrication of high-voltage thyristors. These devices are used, for example, as elements in systems that convert power from alternating current to direct current and the reverse [1]. Direct-current power transmission systems are being viewed with increasing favor as a potential solution to such problems as grid connections, underwater power transmission, and long-distance overhead power transmission [1]. As the attractiveness of dc power transmission grows, demands on absolute thyristor performance also grow, with an ever-increasing need for higher voltage ratings, higher current-carrying capability, and improved efficiency. Similar demands on thyristor performance are imposed by other applications as well. A major advance in raising the ultimate performance of the thyristor came with the application of the neutron transmutation doping process [2] to silicon thyristor fabrication [3]. The NTD process involves the irradiation of a silicon ingot inside a nuclear reactor, where the capture of a thermal neutron by the naturally occurring isotope ^{30}Si leads to the formation of a ^{31}P atom by radioactive decay. Since the isotope ^{30}Si is uniformly distributed within the crystal, the NTD process has the potential of producing an extremely uniform phosphorus doping concentration. The unprecedented uniformity in doping level possible with the use of transmutation doping holds great promise for significant improvements in yield and also for ultimate device performance [4].

The advantages of NTD silicon for thyristor production were forcefully demonstrated in 1975, when Siemens, which was producing high-power devices fabricated from NTD silicon supplied by Topsil A/S, won a major contract for the Nelson River II hydroelectric plant over bids from U.S. suppliers. Siemens' success was largely attributed to the fact that NTD silicon enabled Siemens to use fewer high-power devices of greater individual performance than could have been produced from conventional float-zoned silicon [4]. Since that event, the use of NTD silicon has grown to where its production exceeded 20 tons per year in 1977 (approximately 20 percent of the world's float-zoned silicon production) [5], a figure which is expected to continue to increase.

The growing importance of NTD silicon can be documented by the interest shown in international conferences on this topic. The Second International Conference on Neutron Transmutation Doping in Semiconductors (April 23-26, 1978, at the University of Missouri at Columbia) was attended by 114 persons, 20 percent of whom came from outside the U.S.A. [6]. Interest in NTD silicon is so great that two more international conferences on neutron transmutation doping are already planned: one in Copenhagen, Denmark (1980), and one in Gaithersburg, Maryland at the National Bureau of Standards (1982). This interest in NTD silicon is not surprising, since the reduced variations in resistivity and improved control of absolute doping level that make NTD silicon so advantageous for thyristor manufacture are also significant for a variety of other semiconductor devices including power transistors [7], infrared imaging arrays [8], and bipolar integrated circuits [9].

The benefits associated with the neutron transmutation doping process do not come without disadvantages, all of which are related to the fact that the production of NTD silicon requires exposing the silicon to a neutron flux inside an atomic reactor. Specifically, these disadvantages are the irradiation costs and procedures, radioactivity safeguard considerations, and the radiation damage produced inside the silicon. Detailed estimates of the cost of neutron doping are not available. However, barring a major change in technology, this cost is expected to follow traditional inflationary trends [5] unless it is influenced by the increased use of NTD silicon for devices other than thyristors. Effective radiation safeguards have been developed and are in use. However, the major technical concerns in the use of NTD silicon are the radiation damage produced in the silicon lattice by the irradiation and the effects that this damage has on device fabrication and on ultimate device performance. In this regard, neutron transmutation doping is very similar to another particle irradiation technology that produces extensive lattice damage in silicon — namely, ion implantation. Many of the difficulties in using implantation have been solved; as a result, ion implantation has become the accepted means of dopant introduction for silicon device fabrication, due to its increased capability over conventional diffusion technology for dopant uniformity and absolute dopant-level control. While differences exist between the types of damage produced by ion implantation and that produced by neutron transmutation doping, the development of effective procedures for annealing of ion-implanted silicon suggests that equally effective techniques can be developed for NTD silicon.

To understand the concerns in applying neutron transmutation doping for thyristor fabrication, it is useful to examine the growth of conventional float-zoned silicon and to compare that with the growth of neutron transmutation doped silicon. The conventional float-zone process begins with the decomposition of a gaseous silicon-bearing compound on a thin rod or wire to form a polysilicon rod [10]. The wire is removed from the rod by drilling, and then the polysilicon rod is refined by passing a molten zone along its length to ultimately produce a dislocation-free single crystal. The conventional float-zoned ingot is doped during the final pass, typically by either inserting a solid dopant into slots cut into the polysilicon rod or through the addition of a dilute concentration of dopant species in an inert gas [11]. Most impurities have thermal-equilibrium distribution coefficients (i.e., the ratio of the density of the impurity in the solid to that in the melt at the liquid-solid interface) much lower than unity. Since crystal growth from the moving melt zone is characterized by a different degree of thermal inequilibrium at each position of the melt-solid interface, the zone-refining process results in a nonuniform impurity distribution [12]. Power devices are typically fabricated from n-type silicon substrates, with phosphorus being the most commonly used n-type dopant species. Unfortunately, phosphorus produces the greatest resistivity fluctuations during conventional float-zoned growth, since it has the lowest segregation coefficient of all n-type dopants. Following the doping, the conventional float-zoned silicon is then sent to the manufacturer for device fabrication.

In contrast to the conventional float-zoned ingot, the NTD silicon is not intentionally doped during the zone-refining process. Instead, the single-crystal ingot is exposed to a neutron flux inside an atomic reactor. Following the neutron irradiation, the NTD material is given a thermal anneal (typically near 1000 K). This process results in material with significantly improved resistivity uniformity. Following the annealing, the NTD silicon is sent to the manufacturer for device fabrication.

The resistivity variations present in conventional float-zoned silicon can strongly affect the performance of power devices. As an example, for a particular silicon-controlled rectifier to sustain a target blocking voltage of 4000 V, a substrate resistivity of 170 $\Omega \cdot cm$ is required. For that design, the $\pm$20-percent variation in substrate doping that can occur for conventional float-zoned silicon leads to variations in maximum blocking voltage from 3400 to 4600 V, while the $\pm$5-percent variation in substrate resistivity common to NTD silicon leads to maximum blocking voltage in the much narrower range from 3900 to 4100 V [13]. Control over parameter variations is especially important for those high-power devices which are to be used as an element of a system and thus must be designed to optimize system performance. However, while NTD silicon produces silicon of greatly improved resistivity uniformity, resistivity is not the only parameter that controls device performance.

Minority-carrier lifetime is another parameter that directly determines electronic device performance, and the concerns for minority-carrier lifetime in NTD silicon due to irradiation-induced defects have not yet been resolved. Thus, while conventionally doped float-zoned silicon contains dopant striations that limit device performance, neutron-doped float-zoned silicon (with its more uniform dopant distribution) may contain residual radiation damage whose effects on device performance are not as easy to predict and, thus, are of great concern.

This report considers the reactor aspects of neutron transmutation doping in section 2. Radiation damage production and annealing are summarized in section 3. Section 4 describes currently known effects of radiation damage on device fabrication and performance. Finally, section 5 summarizes recommendations for further research based on the findings of this review.

2. Reactor-Facility Considerations

One of the goals of neutron transmutation doping is the production of a homogeneous distribution of phosphorus donors throughout the irradiated silicon at a precisely chosen level. The achievement of this goal requires that ^{31}P be produced uniformly throughout the ingot at an acceptable level of residual radioactivity.

Thermal neutron capture by the naturally occurring isotope ^{30}Si (3.09 percent abundant [14]) leads to the formation of ^{31}Si which is unstable and decays to ^{31}P, through β^- emission [14]. The unstable ^{31}Si is an artificially produced nuclide (does not occur normally in nature). In the United States, there is a limit to the allowable level of radioactivity from artificially produced nuclides in material released to individuals without licenses to possess radioactive by-products. The level allowed varies from nuclide to nuclide and is called the "exempt limit."

This exempt limit [15,16] is specified in terms of microcuries per gram (μCi/gm) and depends on the total number of radioactive nuclides of each type produced and also on the amount of time these nuclides have been allowed to decay. Thus the amount of time material must be stored after irradiation depends both on the production rate of the radioactive nuclides and the half-life for their radioactive decay. The desired reaction for neutron transmutation doping is [15]:

$$^{30}Si + n \rightarrow {}^{31}Si$$

$$^{31}Si \rightarrow {}^{31}P + \beta^- \; .$$

Since the half-life for this reaction is 2.6 h [15], were this reaction the only one occurring, residual radioactivity would not be a significant problem. However, as the ^{31}P density increases, the reaction

$$^{31}P + n \rightarrow {}^{32}P$$

$$^{32}P \rightarrow {}^{32}S + \beta^-$$

becomes increasingly likely. This latter reaction has a half-life of slightly longer than two weeks [15]. The production of ^{32}P thus places an upper limit on ^{31}P production for two reasons: first, the increased ^{32}P production leads to excessively long holding times for decay to the exempt limit (for a ^{31}P target density of 9.0 x 10^{14} cm^{-3}, the holding time from a typical irradiation facility is 46 days [15]); and second, ^{32}S-related defects produce energy levels near the middle of the silicon bandgap which can be efficient recombination-generation centers in silicon devices [16]. The exact amount of ^{32}S produced during an irradiation to a given ^{31}P density will depend on the neutron flux available [17]; however, a practical upper limit on NTD phosphorus production is approximately 10^{15} cm^{-3} [15]

(which corresponds to a lower limit of silicon resistivity of approximately 5 $\Omega\cdot$cm). Fortunately, most power devices require substrate resistivities of 50 $\Omega\cdot$cm or greater and the trend for silicon substrates for other devices is for higher resistivity as well.

While semiconductor-grade silicon is one of the purest substances on earth, it does contain significant impurities at or below the part-per-million level. In addition, silicon surfaces can become contaminated by handling, in cutting, or by storage in unclean environments. The presence of these contaminants is of extreme concern for silicon to be doped by the neutron transmutation process, since many contaminants (in particular, the heavy metals) can undergo transformations during neutron bombardment into long-lived radioactive isotopes. Careful cleaning before or after irradiation (typically involving nitric:hydrofluoric acid mixtures [15]) can remove surface contaminants and alleviate related concerns for residual radioactivity from this source [15,17]. However, contaminant impurities grown into the ingot cannot be removed by this procedure. As an example, in irradiation of Czochralski-grown silicon, residual dopants can lead to excessive holding times. Antimony, a common dopant for *n*-type silicon, forms ^{124}Sb, which has a half-life of approximately 8.6 weeks [15].

Many trace impurities (especially the transition metals) form defects which give rise to deep impurity levels in the silicon bandgap. Because the presence of these contaminants at the part-per-million level or below can severely affect device performance, monitoring and control of their presence are of extreme importance. An unexpected benefit of neutron transmutation doping, and one that may not be widely appreciated, is that the neutron irradiation that produces phosphorus doping from thermal neutron capture also produces other unstable nuclides that decay by characteristic emissions. This characteristic decay information can then be used to indicate the type and amount of contaminant impurities present in the original silicon crystal and, in fact, is equivalent to neutron activation analysis. The energy of the particle emitted yields the chemical nature of the initial nuclide. When the number of characteristic particles (gamma rays or beta particles) emitted per decay is known, the count rate of that particle yields the total number of those impurities present in the irradiated material.

The total number of atoms of average volume density n (cm^{-3}) inside a volume V (cm^3) as detected by gamma ray spectroscopy is given by [18]:

$$nV = \frac{A_0}{\varepsilon\Gamma_\gamma \int_0^\infty \sigma(E)\ \phi(E)\ dE} ,$$

where Γ_γ is the number of gamma rays emitted per decay with the characteristic energy, ε represents the detector efficiency at the characteristic energy averaged over the sample volume, $\sigma(E)$ represents the cross section for radionuclide production as a function of energy, $\phi(E)$ represents the energy distribution of neutrons in the reactor environment, and A_0 is the corrected count rate given by:

$$A_0 = \frac{\lambda N e^{\lambda t_1}}{(1-e^{-\lambda\tau})(1-e^{-\lambda\Delta})} \left[\frac{e^{\lambda\delta}-1}{\lambda\delta}\right],$$

where N is the number of characteristic gammas detected and τ is the irradiation time. In the above expression, λ is the decay constant for the nuclear decay (equal to ℓn 2 divided by the half-life for decay), t_1 is the time from the end of the irradiation to the start of counting, Δ is the counting live time of the detection system, and δ is the counting dead time of the detection system. The quantity in square brackets is a correction to account for variable dead time during the counting of an activity of short half-life.

Clearly, the most important decay for neutron transmutation doping is that of ^{31}Si. Except for the gamma abundance Γ_γ (the number of 1266.1-keV gamma rays emitted per ^{31}Si decay), all the parameters in this reaction are well known. Detection efficiency can be established through the use of calibrated gamma ray emitters available both as point sources and as solutions from the National Bureau of Standards.* Irradiation of a standard solution of the element of interest dissolved in a vessel of water with the same volume as the volume of the irradiated silicon then yields $\varepsilon\Gamma_\gamma\int_0^\infty \sigma(E)\ \phi(E)\ dE$, and thus allows numerical determination of the number of atoms present in the irradiated specimen for as long a period as the neutron energy distribution remains constant. Factors affecting the stability of the neutron energy distribution will be discussed later in this section.

There exists only one direct measurement of the gamma abundance of the ^{31}Si decay [19], and this value appears to be an overestimate by 25 percent, as compared with the value determined by Hall-effect measurements of phosphorus donors in annealed, carefully irradiated silicon [20]. Estimation of the gamma abundance from Hall-effect measurements requires assumptions that may not be justified about the effectiveness of damage removal during annealing, namely, that every phosphorus atom produces a single donor, that no phosphorus atom is involved in any damage complexes, and that no compensating centers are present. A reevaluation of the gamma abundance would be desirable not only to provide a direct calibration of phosphorus content of the material (which at present is only measured indirectly), but in addition would yield important information about the effectiveness of damage removal during annealing by comparing the known phosphorus density to the corresponding measured shallow donor density. Knowledge of the gamma abundance for the decay of important contaminant impurities would similarly allow the silicon supplier as well as the device manufacturer to assess both the quality and the suitability of the silicon for device fabrication. It is important to note that this information is present following irradiation regardless of detection and that monitoring these characteristic emissions is an effective means of obtaining an activation analysis of contaminant impurities at levels too low to be detected by other methods. Since neutron activation analysis

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* A list of standard reference materials available from the National Bureau of Standards can be found in NBS Standard Reference Materials Catalog, NBS Special Publication SP 260 (April 1979).

detects the total amount of characteristic radioactive emissions, its sensitivity is determined by the total neutron dose, the cross sections for radionuclide formation, the half-life of the radionuclei, the total number of atoms of each chemical species in the irradiated volume, and the probability of escape of the characteristic radiation. Thus, the larger the irradiated volume, the lower the density of impurity atoms that can be detected (since the sensitivity limit — number of nuclides detected — of this technique is a constant), a relationship which becomes important at the trace impurity levels of concern for silicon devices. The detection of those impurities is most certainly of sufficient importance to merit the additional costs which may be necessary to monitor this characteristic emission.

The reactor operator must also be concerned with the spatial homogeneity and the velocity distribution of the neutron flux. Spatial uniformity of the neutron flux is required to produce the uniform ^{31}P distribution that makes neutron transmutation doping a viable process. Control of the neutron velocity distribution is required for efficient doping and for damage production control.

Since the spatial uniformity of the neutron flux inside a reactor can vary during an irradiation due to movements of the controller or absorber rods, the presence or absence of other experiments or irradiations, or long-term fuel burn-up, a number of procedures have been developed to homogenize the neutron flux over the silicon irradiation volume. In addition to careful placement of the irradiation port [18], these measures include rotation during irradiation [21,22], modification of the flux profile through the use of neutron screens [23], and repositioning of the specimen during irradiation [24,25]. These procedures are satisfactory for achieving good radial uniformity: in well-annealed NTD silicon, radial resistivity variations can be reduced to values lower than ± 5 percent [13]. Uniformity in axial doping along a silicon ingot is determined by the tolerances of the NTD user, since the length of the silicon ingot determines the dimensions of the neutron flux the ingot experiences, so that the length of the ingot to be irradiated depends on the spatial extent of the neutron flux which is uniform to the specified tolerances.

Transmutation doping is accomplished mainly by the capture of low-energy (thermal) neutrons; the major effect of the more energetic neutrons is damage production [26]. Thus, the larger the thermal component of the neutron velocity distribution, the more effective the doping process will be, and the less fast neutron damage will be produced. Unfortunately, the neutron velocity distribution tends to vary with time for the same reasons that the neutron spatial distribution varies with time; furthermore, the determination of the neutron velocity distribution requires procedures that are tedious at best. A reasonable determination of the neutron velocity distribution typically requires the careful irradiation of 20 different foils of well-controlled chemical composition, the determination of the characteristic emission from each irradiated foil, and the unfolding of the experimental data through the use of computer codes [27]. The proportion of thermal-to-fast neutrons can be altered by the use of neutron absorbers or moderators; however, those procedures that increase the ratio of thermal-to-fast neutrons also tend to decrease the total neutron flux. For this reason, a compromise must be made between the amount and type of radiation damage and the duration (and cost) of the irradiation. The optimal irradiation schedule cannot be determined *a priori*, since neither the importance of the neutron velocity distribution for damage production nor the damage recovery process is well understood.

Two different measures of the thermal-to-fast neutron ratio have been proposed. The first [27] involves the commonly used copper-cadmium ratio; the second involves the ratio of two characteristic gamma rays produced in silicon by neutron capture [18].

In the first technique, two separate foils are irradiated, one a bare copper foil, the second a copper foil clad with cadmium. Following the irradiations, the ratio of emission from the bare copper foil to that of the cadmium-clad copper foil is determined. The cadmium acts as a high-pass filter in that it absorbs all neutrons with energies less than approximately 0.5 eV [28]. While this technique is experimentally easy to perform, it only determines the ratio of neutrons with energy below 0.5 eV to those with energy above 0.5 eV. Since the amount of energy a neutron must transfer to a silicon atom to displace that atom from its lattice site is approximately 25 eV [26], it is clear that some neutrons that are recorded as "fast" by the copper-cadmium ratio test do not contribute to the damage produced. Nevertheless, the copper-cadmium ratio is the quantity most often specified by reactor operators as a one-parameter estimate of the proportion of thermal component of the neutron velocity distribution [18,21-24].

An ingenious alternative method for characterization of damage production [18] involves the measurement of characteristic activity produced in silicon by neutron irradiation. While thermal neutrons produce ^{31}P from ^{30}Si, fast neutrons produce ^{29}Al, ^{27}Mg, and ^{28}Al from ^{29}Si, ^{30}Si, and ^{28}Si, respectively. Both the ^{27}Mg and the ^{28}Al activities can also be produced by thermal neutron reactions on aluminum or magnesium that may be present in the crystal from the growth process; however, the ^{29}Al activity can only be produced by irradiation of silicon by neutrons with energies greater than 3.1 MeV [29], well above the 25-eV displacement threshold for silicon. This second technique relies on measuring the relative intensity of the 1273.3-keV gamma ray intensity produced by ^{29}Al decay to that of the 1266.1-keV gamma ray produced by ^{31}Si decay and appears to have a number of advantages over the copper-cadmium ratio test. The ^{31}Si decay not only is a good measure of the thermal neutron component but also is directly related to the ^{31}P production which is the goal of the neutron transmutation process, while the ^{29}Al measures the integrated neutron velocity distribution in a region that is most effective at damage production [26]. This measurement can be performed as a natural extension of trace impurity identification in the ingot by measurement of characteristic activity. Therefore, it can sample the neutron velocity distribution and evaluates damage production for every irradiated specimen for every irradiation, irrespective of changes in reactor conditions. Finally, detector efficiency will not vary significantly from the 1266.1-keV gamma radiation to the 1273.3-keV gamma radiation, and thus the method requires no additional detector calibrations. While damage production studies have been roughly correlated to copper-cadmium ratios (e.g.,

[27]), the comparative advantages of this second technique have yet to be experimentally determined.

Both techniques for reactor characterization share a number of disadvantages in establishing tradeoffs between doping efficiency and damage production. Since point defects (vacancies and self-interstitials) in silicon are unstable at temperatures above approximately 150 K [30], some damage recovery takes place during irradiation. Thus, the question of damage production is directly related to damage recovery, and the extent and stability of defect production depend on ingot temperature during irradiation. Neither the copper-cadmium ratio test nor the ^{29}Al activity test is sensitive to irradiation temperature. In addition, energetic electrons (beta particles) and gamma rays also bombard the silicon and produce damage; however, neither of these damage-producing particles is detected by either technique, and the importance of the damage produced by these particles has not been determined. Finally, it is not clear to what extent the results of a single-parameter measurement can predict the effects produced by a distribution of neutron velocities.

The last aspect of neutron transmutation doping involves control of the time duration of the irradiation to achieve a specified doping level. Both direct and indirect methods have been used to estimate the required irradiation times. The indirect methods rely on the time of irradiation measurement of the ^{31}P density produced in an ingot irradiated for a known period of time typically through post-irradiation annealing in combination with Hall-effect measurements. The irradiation time to achieve the desired doping level is directly scaled from this reference time by the ratio of the ^{31}P sensitivities. The accuracy of these methods is affected by the stability of the neutron distribution inside the reactor.

The direct method [26] involves spiraling a ^{103}Rh (100-percent abundance [14]) wire inside a concentric shield around the material to be transmutation doped. Thermal neutrons captured by the ^{103}Rh induce a nuclear reaction of the type

$$^{103}\mathrm{Rh} + n \rightarrow {}^{104}\mathrm{Rh} + \gamma \rightarrow {}^{104}\mathrm{Pd} + \beta^- \ .$$

The electrons emitted are collected by the concentric shield to produce a current proportional to the thermal neutron flux, which is integrated until a predetermined limit is reached. Since the half-life for the β^- decay is 4.2 s, this method is able to follow any flux variations due to movements of the control rods. This method can also be checked against the indirect methods; under the best conditions, it agrees with the other determinations within 0.5 percent [26].

3. Radiation Damage

3.1 Introduction

The greatest concern among potential users of NTD silicon is the extent to which the damage resulting from neutron irradiation remains after annealing and affects device processing and ultimate device performance. This concern is also felt by device manufacturers who use ion implantation for dopant control. Although implantation also produces extensive radiation damage in silicon, sufficiently effective annealing techniques have been developed to allow implantation to become the accepted means of dopant introduction for integrated circuit manufacturing. The type of damage produced by ion implantation is not exactly identical to that produced by neutron transmutation doping; however, the experience from ion implantation demonstrates that the production of extensive radiation damage in silicon does not necessarily doom a new technology.

The radiation damage and recovery processes in silicon present a truly formidable scientific challenge, since both can vary greatly depending on the silicon ingot to be irradiated and the reactor in which the irradiation is to be performed. The nature of the irradiation damage clearly depends on the number and type of particles present in the reactor environment as well as their velocity distribution. However, damage production and recovery also depend on substrate parameters, as, for example, the extent of trace impurity contamination (such as carbon, hydrogen, or oxygen) in the silicon during irradiation, the density of ionized defects (chemical or structural) in the silicon as reflected in the position of the Fermi level, and the sample temperature during irradiation. Damage is of great concern to device manufacturers since even small numbers of defects (10^{13} or 10^{14} cm^{-3}, or one part in 10^{8}) can strongly influence not only device performance but the device fabrication process; for example, the presence of dislocations can lead to uneven diffusion fronts and procedures, as electron irradiation for lifetime control can cause impurities to be transferred from electrically inactive to electrically active sites. Since so many factors can influence radiation damage and recovery processes, it becomes extremely difficult to examine the relative importance of competing effects. To a large extent, the damage recovery process is not understood for annealing temperatures above approximately 800 K, since the few studies that have been performed above that temperature give conflicting results. This lack of understanding for annealing above 800 K is especially distressing because 1400- to 1700-K temperatures are commonly used for thyristor manufacturing. While understanding the recovery process is a difficult and demanding task, it presents unrivaled possibilities for the development of a comprehensive understanding of the formation and interaction of defects in silicon, due in large part to the chemical identification provided by neutron activation of trace impurities during the irradiation. This section will attempt to summarize the existing understanding of the damage production and recovery processes and to point out areas that need better understanding.

3.2 Damage Production Processes

The radiation damage process begins when a particle (gamma ray, fast neutron, etc.) transfers energy equal to the displacement threshold energy to an atom in the silicon lattice and removes that atom from its equilibrium site, leaving a vacancy in the lattice and an atom in a displaced (interstitial) position. If the energy transferred in the collision is above the displacement threshold energy, then the substrate atom also becomes a projectile (recoil atom), which for sufficiently large energy transfers can repeat the damage process with other substrate atoms. As is typical of radiation damage in silicon, while the concept of the damage process is easy to grasp, detailed understanding is more difficult. Experimental values for the displacement threshold energy for silicon vary from 11 to 21 eV [30], although 24 eV is the most commonly used value [26]! The displacement energy appears to be orientation-dependent for electron irradiation but not for irradiation by heavier particles [26]. Different types of particles lose energy through different processes. Gamma particles lose energy through the Compton effect and through the photoelectric effect [32]; energetic charged particles lose energy through transfer of kinetic energy to the screened substrate nuclei and through excitation of electrons from substrate atoms. Since the cross sections for energy transfer for each particle type are energy-dependent, a detailed prediction of damage production in NTD silicon would require a knowledge not only of the total dose of each of the particle types but also of their velocity distributions. As has been described in the previous section, the determination of the neutron velocity distribution alone requires considerable effort. In addition, both flux and velocity distributions can change because of changes in reactor operating conditions.

There remains considerable controversy over whether the electronic excitation effects which are partly responsible for the energy loss of charged particles directly produce damage by displacing substrate atoms, or whether these effects indirectly create damage through rearrangement of existing defects by changing their charge states or through ionization-enhanced diffusion of impurities [30]. These electronic excitation effects are generally ignored in considerations of damage production for neutron doping, since they can be identified only in studies of low-energy (<100-keV) electron irradiations [30]; therefore, this process should be less effective in damage production than the energy-loss mechanisms of the more energetic particles present in the reactor environment. Gamma irradiation [31] and high-energy (MeV) electron irradiations [32] tend to produce a homogeneous distribution of isolated simple vacancy- or interstitial-related point defects, while neutron-induced damage is more complex. Each radioactive decay produced by thermal neutron capture releases energy which is divided among the reaction products and thus produces damage. A typical recoil energy is approximately 0.5 keV [26] — roughly twenty times the displacement threshold energy. Fast neutrons produce even greater amounts of transferred energy. This energy transfer has been estimated by averaging collision cross sections over a highly idealized neutron velocity distribution; the calculation resulted in a "typical" silicon recoil energy of 50 keV [27]. Considerations of energy available for damage production thus suggest that fast neutrons will dominate neutron damage production until thermal neutrons outnumber fast neutrons by 1000:1 [26] (which does not occur in reactor locations used for neutron transmutation doping). Recoils from fast-neutron damage have energies similar to those used in ion implantation doping of silicon, and thus the damage produced by fast neutrons is similar to that produced by ion implantation [33]. This damage tends to produce high-density defect clusters around the fast-neutron track; these clusters have been observed experimentally in semiconductors bombarded with high-energy neutrons [34].

Since, in some regards, fast-neutron damage on silicon is similar to that produced by ion implantation, it becomes important to examine the possibility of amorphous-zone formation. It has been experimentally determined that amorphous surface layers formed on silicon single crystals by ion bombardment tend to regrow epitaxially from the undamaged substrate [35]. This regrowth leads to better incorporation of the implanted species at lower annealing temperatures. As a result, doping levels are higher and carrier mobilities are larger after annealing in the amorphized implanted layers than in layers of similar implanted dose which had not been driven amorphous [36]. The consideration of energetics that led to the estimates of relative damage production rates between slow and fast neutrons can be extended [26] to show that amorphous-zone formation is highly unlikely for phosphorus doping at levels below 10^{15} cm^{-3} (corresponding to resistivities of 5 Ω·cm or greater).

The majority of the damage produced in silicon would thus be expected to consist of clusters of high-defect density around fast-neutron tracks inside silicon with a homogeneous background distribution of point defects. Unfortunately, this simple picture may not be accurate. Complicating the issue of damage production is the fact that isolated silicon vacancies or self-interstitials in excess of thermal equilibrium densities become highly unstable for irradiation temperatures above 150 K [37]; these simple defects, therefore, are mobile at the approximately room-temperature irradiation temperatures typical of neutron doping. These simple defects diffuse outward from the high-defect-density damage regions along the path of the initial damage-producing particle, thereby increasing the fraction of the crystal that becomes disordered from the irradiation. This process also reduces the energy deposited per unit volume along the damage track, thus making amorphous-zone formation even less likely than previously estimated. While this process also occurs in implanted wafers, implantation damage is produced only in a shallow region near the wafer surface, while neutron damage is produced throughout the NTD material.

Isolated vacancies and interstitials diffuse until they either recombine to annihilate each other or else become trapped by another defect (or chemical impurity) to form a higher order complex that is stable at the irradiation temperature. An example of such a center is the phosphorus-vacancy center [38], which is stable up to temperatures of approximately 420 K. This center is of great importance in as-irradiated NTD silicon, since it is one of the defects in which phosphorus can be trapped to prevent its acting as a shallow donor. The exact types of damage produced are extremely difficult to classify, since simple defects interact so strongly with one another. As an example, for irradiation temperatures similar to those used in neutron doping, the density of the carbon-related defect which is responsible for the 0.97-eV transition in photoluminescence from radiation-damaged silicon depends strongly on the relative density of trace oxygen in the specimen [39]. When defects interact with each other through a coulombic interaction [40], the type of damage produced may be strongly dependent on the electrical state of the specimen [32]; that, in turn, is influenced by the density and energy levels of the existing defects, as well as by specimen temperature. Specimen temperature during neutron doping also determines the type and extent of damage present after irradiation, since different defects remain stable to different temperatures.

As a result of these strong impurity interactions, different silicon specimens irradiated under the same conditions may have vastly different types of damage, depending on the densities and types of trace impurities they contain. Similarly, identical silicon specimens irradiated in different reactor ports to the same phosphorus doping levels could have vastly different types of damage, because there may be differences in the irradiation temperatures, particle densities, and particle velocity distributions. A more important concern is the limits under which the type, stability, and extent of damage present following irradiation control ultimate damage recovery.

3.3 Damage Recovery

Whatever damage is present following irradiation must be removed by annealing to restore the silicon lattice to sufficient quality for electrical devices. As has already been discussed, complications arise because defects with differing thermal stability can be present simultaneously depending upon the trace impurity contamination in the specimen and upon the irradiation conditions. Despite these complications, the basics of the damage recovery process for temperatures below 800 K have been developed as a result of many studies of radiation damage in silicon [e.g., 30,32,37-38].

When an atom becomes displaced from its lattice site, a vacancy is created in the lattice, and the atom is removed to an interstitial position. Point defects present in concentrations exceeding their thermal equilibrium values are highly unstable and become mobile defects. These mobile defects either annihilate each other or become trapped by other impurities or defects to form higher order complexes which remain stable to higher temperatures. As higher temperatures are reached, the secondary complexes become unstable and liberate point defects, which in turn either annihilate each other or form different, more stable defects. Ultimately, these irradiation-induced defects either recombine at a defect sink (such as a free surface) or form a macroscopic defect (such as a dislocation).

In many ways it is useful to consider the damage recovery process to be similar to a precipitation of defects that are initially present in excess of thermal equilibrium values. As an example of this process, annealing of the silicon divacancy (two-vacancy) complex in electron-irradiated silicon at temperatures near 600 K liberates vacancies which then form four- and five-vacancy complexes in sufficient numbers to be identified by electron paramagnetic resonance [41]. Continuing the process, the four- and five-vacancy complexes that were formed by the decomposition of the divacancy themselves become unstable at annealing temperatures of approximately 800 K.

Considerable knowledge has been gained about a few point defects. The isolated vacancy has been identified by electron paramagnetic resonance in silicon that has been electron irradiated at 4 K [37]. The vacancy can exist in one of four charge states (determined by the Fermi-level position), and each charge state has its own characteristic annealing temperature.

In contrast, the self-interstitial in silicon has never been identified, even for electron irradiations performed at 4 K. Indirect evidence suggests the self-interstitial is mobile at 4 K in *p*-type silicon and displaces acceptor impurities from lattice sites, while in *n*-type silicon the self-interstitial appears to be trapped by the divacancy below about 140 K [42]. Since the self-interstitial has never been directly identified, the theoretical pictures of this defect have been generated mainly on the basis of self-diffusion or swirl defect studies [43].

The vacancy itself and many vacancy-related complexes, such as the oxygen-vacancy, divacancy, four-vacancy, and the vacancy group-V-atom complex, have been identified and their annealing characteristics studied (mainly through the use of electron paramagnetic resonance); however, only one silicon self-interstitial-related defect has been identified (the <001> silicon split interstitial [44]). Because of their easier identification, vacancy-related point defects have been examined in great detail; knowledge of their properties has been used to generate descriptions of the radiation-damage recovery process for annealing temperatures below 800 K. Knowledge of even this aspect of the damage recovery process is still far from complete, as many damage-related centers seen in electron paramagnetic resonance studies are still unidentified, even for defects with very large production rates [42], and the lack of certainty and resultant controversy regarding the self-interstitial leaves serious questions about the present understanding of the multiplicity of damage recovery processes, especially for higher temperature annealing.

The fact that point defects have electronic energy levels within the silicon bandgap has important consequences not only for those cases in which damage is intentionally introduced to control device properties (as in electron irradiation for minority carrier lifetime control [45]), but also for recovery of electrical properties when damage is an unintentional by-product of a fabrication process (as in neutron transmutation doping or in ion implantation). The interaction of trace impurities present at 0.01 atomic percent or below with each other in forming defect complexes requires a long-range interaction mechanism, since these impurities are not likely to encounter each other if the reaction between them is controlled only by their densities and their atomic dimensions.

Two common long-range forces that can act in radiation-damaged silicon are strain fields and coulombic effects. Studies of high-energy proton bombardment [40], as well as studies of damage production rates [32,42], directly implicate coulombic interactions as the controlling interactions between defects. The effects of strain fields have not been determined, although their importance is seen in such effects as the precipitation of metallic impurities such as copper in highly strained regions of the silicon crystal (e.g., dislocations and swirls [46]). Because coulombic interactions affect defect interactions, the position of the Fermi level determines not only the characteristic annealing temperatures of simple defects (as was illustrated previously for the isolated vacancy), but also can determine which defects will be formed when simpler defects anneal. Thus, depending upon doping levels and trace impurity contamination, different silicon substrates irradiated under identical conditions could anneal through the formation and dissolution of radically different defect types. In this regard, it may be fortuitous that neutron transmutation doping for high-power silicon devices uses substrates of as low residual dopant and trace impurity levels as possible.

Ultimately, as point defects decompose during annealing, some macroscopic defects, such as dislocations, are formed. Most vacancy-related defects anneal in silicon by approximately 900 K, whereas the <001> silicon split interstitial anneals by approximately 1100 K. In radiation-damaged silicon, streaks and spots are seen by transmission electron microscopy at annealing temperatures above 800 K [26]. For annealing at temperatures above 900 K, these streaks and spots form linear defects as well as dislocation loops [47] that can be clearly resolved by transmission electron microscopy. In float-zoned silicon which has relatively low oxygen concentration, the dislocation lines tend to form loops at approximately 1000 K, and at higher temperatures these loops may anneal out [47-50]. Unfortunately, the temperatures at which dislocation movement and annihilation take place are not assigned the same values by different experimenters, and there are suggestions that these temperatures may be influenced by the type and extent of contaminants present in the ingot prior to irradiation [50]. The damage recovery of Czochralski-grown silicon is more difficult to interpret, since the punch-out of prismatic dislocation loops by silicon dioxide precipitates formed at those temperatures [51] creates new defects as the radiation-induced defects begin to anneal. The formation of new damage by impurity precipitation during annealing may not be unique to oxygen-rich silicon. In the same regard, it has been conjectured [46] that all irradiation-induced damage effects are removed by annealing at 1000 K, and that all defects seen for heat treatments above this temperature are due to contaminant impurities either present in the ingot before irradiation or introduced during thermal treatment, as will be discussed later in this section.

Many aspects of the damage recovery process are the same for neutron-irradiated silicon as for ion-bombarded (ion-implanted) silicon. Streaks and dark spots are seen in transmission electron micrographs of unannealed silicon that has been neutron irradiated near room temperature [50], as well as of silicon that has been ion bombarded near room temperature [47]. Five-vacancy clusters are seen directly following irradiations by fast neutrons [52] or by heavy ions [53]; this is in sharp contrast to electron-irradiated silicon where multiple-vacancy clusters are formed only by the dissociation of divacancies [41]. These identified point defects follow similar annealing characteristics in the neutron-irradiated and the ion-bombarded material until they anneal out near 730 K [41,53]. However, above this temperature, silicon that has been ion implanted at doses below that needed to form an amorphous layer (i.e., that most similar to neutron-irradiated silicon [26,33]) begins to incorporate the implanted ions into the lattice as reflected in the number of free carriers in the implanted layer [47]. It is thought that this incorporation of excess atoms dominates the high-temperature (>900-K) recovery of ion-implanted silicon, as vacancy-related dislocation loops shrink and disappear in implanted silicon above these temperatures; interstitial loops grow due to the excess of interstitials [54]. Since neutron transmutation doping does not introduce additional atoms [26], annealing of neutron-induced damage at high temperatures need not proceed by the same mechanisms.

Most studies of the recovery of radiation damage in silicon consider only annealing temperatures below 1300 K. Since a typical thyristor process uses 1500-K diffusions, the behavior of silicon at these higher temperatures is of extreme importance. In a study of unirradiated float-zoned silicon [48], it was found that the swirl pattern common to float-zoned silicon could be eliminated by 1473-K annealing; however, etching the heat-treated specimen revealed the presence of hillocks attributed to precipitates of a fast-diffusing impurity present in the furnace environment. Even in annealing studies below 1300 K, suggestions of microprecipitate formation have been observed. Measurements of lattice parameters by anomalous x-ray transmission performed on silicon with carbon and oxygen contents intermediate between Czochralski and float-zoned silicon showed a decrease in anomalous x-ray transmission for annealing temperatures up to 1000 K, and then a gradual increase for annealing above 1000 K [55,56]. In this work, just as in the previously discussed study [48], the formation of microprecipitates of uncertain origin was blamed for the formation of new defects at these higher annealing temperatures.

There is also evidence which suggests that trace impurity content influences high-temperature annealing [46]. In addition to oxygen, which affects high-temperature defect formation even in unirradiated silicon [50], evidence exists to show that both hydrogen and carbon influence the high-temperature annealing of neutron-irradiated silicon [46]. In this regard, it is significant that in the past, problems in fabrication of power devices from NTD silicon have been generally attributed to excessive carbon content. In addition, studies have suggested that heterogeneous nucleation of silicon interstitials occurs at carbon nuclei at high temperatures, leading to the formation of interstitial agglomerates, which may convert to dislocation loops [57]. These topics are intimately connected with swirl formation [57] and diffusion [43] which are also of concern at high temperatures. Unfortunately, conflicting theories exist for all of these phenomena, and the situation is far from resolved. In addition, the effects of contamination occurring during annealing are not considered in most high-temperature annealing studies, although contamination by fast-diffusing impurities such as iron [58] is thought to be very likely. Thus a real concern and one that has yet to be resolved in interpreting these effects is that impurities in solution in silicon at these high temperatures may precipitate on cooling and thus lead to defect formation either directly through trapping of intrinsic defects (e.g., silicon interstitials) or indirectly through the stresses thus generated. It is not surprising that it has been conjectured that <u>all</u> defects that seem stable following 1000-K annealing may be impurity related [46]. Alternatively, deep-level transient spectroscopy studies [59] of silicon intentionally deformed at 1053 K showed that defect states associated with dislocations remained despite subsequent thermal anneals at temperatures as high as 1200 K, while control samples given the same thermal treatments showed no detectable defect states. Unfortunately, the relative impurity contents of the various wafers examined in the different studies, which may be of extreme importance, were not known. Although known to be significant, the extent to which impurity content and initial damage influence these defect structures is not well understood. Although the high-temperature recovery of ion-implanted silicon need not occur by the same mechanisms as neutron-irradiated silicon, in silicon implanted with high doses of arsenic through a thin oxide layer (thereby incorporating excess oxygen through recoil implantation [60]), dislocation networks are formed and are stable even until 1500-K annealing. However, these defects are not seen for identical arsenic implants not implanted through an oxide layer — thereby demonstrating not only that trace impurity effects can be important for defect formation, but also that some defect structures can be stable even to very high annealing temperatures. Finally, it should be noted that the electrical activity of dislocations, the degree to which dislocations may be dissociated, and their consequences are highly controversial [59].

Because so many factors influence damage recovery, it is difficult to compare the results of different experiments. To the extent that experiments performed on different ingots irradiated at different reactors can be compared, it appears that the distribution of neutron velocities can influence both low-temperature and high-temperature annealing [33]; that the temperature of irradiation can affect not only low-temperature annealing [52] but high-temperature recovery as well [50]; that the in-diffusion of contaminant impurities from furnace environments can lead to defect formation at high temperatures [48,55,56]; and that the recovery of damaged material can depend on the extent of contaminants present, such as oxygen, carbon, or hydrogen [46], during growth.

While the damage present immediately following irradiation is too extensive to allow even the evaluation of significant material parameters such as dopant density, and thus clearly must be removed for device fabrication, there are indications that some residual damage can improve device performance, probably by gettering heavy metallic impurities [62], a technique commonly used by both integrated circuit [63] and power device manufacturers.

4. Radiation Damage and Electronic Devices

4.1 Introduction

Of all the topics treated in the present report, the material in this section is of the greatest practical concern to potential users of NTD silicon. Unfortunately, this area is also the most difficult in which to get substantive information, since most manufacturers consider problems in device fabrication just as proprietary as the solutions to those problems. As has been described in the previous section, irradiation conditions, annealing temperatures, and impurity interactions determine ultimate defect structures for NTD silicon; no single set of processing temperatures and contamination control conditions characterizes the diverse uses of NTD silicon. As a general rule of thumb, defects in the active regions of devices are "bad," while defects away from device-active regions may, as noted above, actually be beneficial, by gettering unwanted contaminants. The potential benefits of impurity gettering vary greatly among device types, however. Only the first few micrometers away from a wafer surface contain active regions for integrated circuits (and thus most of the wafer is electrically inactive), while the active region of a high-power device such as a thyristor comprises almost the entire wafer volume. The above rule must be tempered by the knowledge that damage is sometimes intentionally introduced into active regions to control excess carrier lifetime [63] and that damage in nonactive device regions can also produce harmful effects by leading to laterally nonuniform diffusion fronts. When damage effects are intentionally introduced, however, most manufacturers prefer to start with material that is as free from damage as possible and then to controllably introduce the desired type and amount of damage required for proper device performance.

Minority carrier lifetime in silicon is a parameter that is strongly degraded by radiation damage [64], and thus the recovery of minority carrier lifetime is thought to provide some measure of damage recovery. As with most other aspects of radiation damage recovery, however, the extent of minority carrier lifetime recovery following neutron irradiation varies from experiment to experiment [33,62,63] and may be dependent on irradiation conditions and trace impurity contamination. In this regard, it is interesting to note that minority carrier lifetimes in NTD silicon in 1978 exceeded those of melt-doped silicon of the same resistivity available three years earlier, and that NTD silicon now available satisfies the rule of thumb that the lifetime in microseconds for "good" float-zoned silicon should be five times the resistivity in ohm-cm [64]. However, good values obtained for lifetimes in NTD silicon may be somewhat misleading, since existing damage sites may be removing lifetime-reducing impurities through the process of gettering [62], as will be considered later in this section.

4.2 Damage Effects on Device Performance and Fabrication

Before developing the discussion of the effects of radiation on device performance, it is useful to consider just the effects of radiation damage on the electrical behavior of phosphorus in silicon. When an isolated phosphorus atom occupies a substitutional lattice site in silicon, it acts as a shallow donor with an energy level approximately 0.045 eV below the conduction band [65]. At temperatures below approximately 500 K, substitutional phosphorus can trap an isolated vacancy. The phosphorus atom then relaxes off its lattice site, producing a defect complex with an energy level approximately 0.4 eV below the conduction band [38]. This defect is so effective at trapping free carriers in electron-irradiated *n*-type silicon that the number of free carriers does not begin to recover to pre-irradiation values until this center has been removed by thermal annealing [38]. Finally, in regions where dislocation loops are seen by transmission electron microscopy of cross sections of ion-implanted silicon after 1223-K annealing, the free carrier density is lower than the phosphorus density [66], suggesting that when phosphorus has interacted with these defects it provides no electrical activity at all. In this example, the presence of radiation damage was seen to affect the shallow-donor density (an important parameter in the determination of device performance). This example also illustrates a number of secondary aspects. Both defects stable at lower temperatures (<800 K) and defects stable at higher temperatures (>800 K) affect device properties, yet they produce different effects. In the above example, the important lower temperature defect was a point defect complex, while the higher temperature defect was a dislocation loop. Point defects are typically not stable at the temperatures common to device fabrication using NTD silicon; however, the effects of point defect complexes on devices have been more extensively studied. In large part, this emphasis on point defects results from the interest of space and military agencies in device degradation in radiation environments whose temperatures do not exceed the temperature range over which point defects are stable (i.e., well below 800 K).

Following high-temperature heat treatment (>1100 K), the major types of defects to be expected in neutron-irradiated silicon are impurity precipitates and decorated and undecorated macroscopic defects such as dislocation lines or loops. Precipitates distort electric field lines in *p-n* junctions and lead to premature reverse breakdown [67]. Dislocations can also act as nucleation sites for precipitate formation, thereby leading to premature reverse breakdown [67]. Dislocations have been associated with the production of energy levels or bands within the forbidden gap of silicon [59] and thus can act as generation-recombination centers, which reduce excess carrier lifetime and increase reverse bias *p-n* junction leakage and forward voltage drop [67]. However, the exact energy levels produced by dislocations and their relation to specific defect structures are still controversial [59].

The effects of neutron-induced damage on devices when temperatures remain below 800 K has been thoroughly summarized by Gregory and Gwyn [68] and will not be repeated here. In general the point defects are responsible for free-carrier removal, reduced mobilities, and the formation of generation-recombination centers.

Metallic impurities, such as gold [69] or platinum [70], are also particularly effective as recombination-generation centers for excess carriers. It has been found empirically that the density of these centers can be reduced in a volume of silicon by the introduction of damage and subsequent thermal treatment, as fast-diffusing contaminants wander to dislocations and decorate (precipitate upon) them. This phenomenon is not completely understood, although it has been hypothesized [63] that dislocations with an $^{a}/2$ <110> Burgers vector are responsible for this effect. When this precipitation occurs away from a space-charge region in a silicon device, it increases excess carrier lifetimes and thus reduces reverse leakage and forward voltage drop in the active region of devices. Thus, in examining NTD silicon it is not surprising that, following irradiation and annealing, some samples actually show an increase in minority carrier lifetime [62,64]. Although it is dangerous to draw parallels between the high-temperature recovery of neutron-irradiated silicon and that of ion-bombarded silicon, it has been seen that an optimum temperature exists for ion-induced-damage gettering. Above that temperature minority carrier lifetime degrades, as though above the optimum temperature these contaminant impurities were being freed from complex damage centers. In (111)-oriented silicon (that commonly used for power-device fabrication), the optimum gettering temperature was found to be 1173 K [71], which is below temperatures commonly encountered during high-power device fabrication. Since subsequent thermal processing may also induce changes in the electrical activity of defects in NTD silicon, it may be important to specify minority carrier lifetime as a parameter for screening NTD silicon only in combination with densities of contaminant impurities. A method for contaminant impurity detection that could provide such analysis is the activation analysis recommended in section 2 of this report.

While dislocations remaining after device fabrication affect device performance in the manner described earlier in this section, dislocation structures can also affect device performance by disturbing processes during device fabrication. As an example, dislocation structures can, by the process of gettering, affect the uniformity of deep-level recombination centers introduced by diffusion (such as gold or platinum) to control device-switching speed. Indeed, the effects of residual neutron damage on post-fabrication lifetime control is an area that has not been investigated in great detail. In a study [72] to determine the impurity dependence of peaks seen by low-temperature photoluminescence from radiation-damaged silicon, silicon wafers were implanted with carbon, oxygen, or both to peak concentrations of 5 x 10^{18} cm^{-3} and then annealed near 1200 K in flowing argon gas. The specimens were then irradiated with 2.5-MeV electrons, and recombination luminescence revealed not only the peaks normally seen from electron-irradiated material but also indicated additional defect centers that had never been previously observed [72]. These new centers indicated a possible interaction between residual damage and the irradiation-induced defects; however, this aspect of the study unfortunately was not further pursued. Similarly, in a study of deep levels following electron irradiation of devices fabricated from NTD silicon, a new, additional defect level, the origin of which has not been identified, has been reported in some specimens [73]. The interaction of any residual neutron-induced damage with damage produced by subsequent particle irradiations may also be of concern as thyristor manufacturers begin to consider proton irradiations for three-dimensional lifetime control to optimize design tradeoffs between switching speed and forward voltage drop, although the fact that electron-induced damage has different characteristics than proton-induced damage (as was described in the previous section) may prove to be an important factor. Since this is an area of active device development, information that may exist appears to be proprietary.

4.3 Parameters for NTD Silicon Specification

Given a complete understanding of radiation-damage production and recovery processes, the parameters needed for reproducible control of device fabrication could be identified and tested to assure an acceptable yield. In our less-than-perfect world, however, a more fruitful procedure may be to ask what parameters are of sufficient import to make screening NTD silicon on the basis of those parameters cost-effective in comparison to the costs of processing devices that fail because of poor control of these parameters. Such information, if it exists, is highly proprietary, since such knowledge could give one company a manufacturing advantage over unenlightened competitors; thus, only a few general guidelines can be suggested. Manufacturers regularly screen silicon intended for power-device fabrication for oxygen content (because of known difficulties with oxygen-donor formation and oxygen-precipitate formation) as well as for shallow-dopant density and uniformity, since these latter parameters determine the maximum reverse-voltage capability of the device. Enough information has been obtained to suggest that carbon content of the wafer should also be specified. These tests should apply whether the starting material has been doped by conventional techniques or by neutron transmutation.

A commonly used parameter to determine material quality in conventionally grown float-zoned silicon is excess carrier lifetime; however, as has been previously described, this parameter by itself may not be relevant to NTD silicon, and perhaps should be specified only in light of total impurity content. Even under the best of circumstances, the measurement of excess carrier lifetime can be a source of confusion and may not measure the parameter actually desired. The confusion about excess carrier lifetime in silicon arises from the fact that deep defect levels in silicon communicate with the conduction and valence bands at different rates under different circumstances. In particular, one defect level will result in different lifetimes for the generation of carriers in a depletion region (generation lifetime), for the recombination of excess carriers when the density of excess carriers is small compared to the density of majority carriers (low-level lifetime), and for the recombination of excess carriers when the density of excess carriers is on the order of or greater than the majority carrier density (high-level lifetime) [74]. The technique most commonly used to measure minority carrier lifetime in NTD silicon is photoconductive decay [38], which produces values which do not always correlate with other measures of minority carrier lifetime as, for example, the lifetime under high-level injection conditions [74], which is typically measured only after device fabrication.

5. Summary and Recommendations

It is clear that power devices will continue to be fabricated from zone-refined silicon due to the problems produced by the complex behavior of oxygen in silicon. Barring a revolution in the doping process during zone refining or the development of a new and effective procedure for homogenizing impurity distributions in silicon after growth, it is also clear that conventional float-zoned silicon will contain typically at least a 20-percent lateral variation in shallow-dopant density. This variation in parameters can result in finished devices achieving less than the design performance. These variations will be most critical in high-power devices in which the device can occupy the entire wafer diameter. Neutron transmutation doping has become a viable technology in spite of the attendant uncertainties about residual radiation effects, because it can produce lateral uniformity of shallow dopants which therefore gives it a significant competitive advantage over other processes for these n-type zone-refined crystals.

It is not clear at present that neutron transmutation doping possesses an overwhelming competitive advantage when applied to Czochralski silicon, both because the contamination from residual dopant species (such as antimony) found in growth crucibles can lead to excessive holding times [15], and since impurities with small segregation coefficients in silicon can be incorporated during melt growth to excellent radial uniformity (such as oxygen [75]). In the case of NTD Czochralski silicon, economic factors rather than material parameters may determine the ultimate utilization of the technique.

Research on NTD silicon needs to focus on assessing ultimate performance and yield limitations, as well as on developing a more complete understanding of the radiation-damage recovery process in silicon.

The procedures for neutron transmutation production of a uniform distribution of ^{31}P are the best controlled and the most completely understood aspects of the entire neutron transmutation doping process; however, a few modifications can be suggested to provide additional useful information to the ultimate device manufacturer.

1. Information is available as a result of exposure of the silicon ingot to a neutron flux during the transmutation doping process and is directly concerned with impurity contamination and defect generation in silicon. Neutron activation of contaminant impurities that could control excess carrier lifetime always occurs regardness of its detection and could be made available both to silicon suppliers and users.

2. Experiments need to be performed to develop a fast, yet effective technique for characterizing the neutron velocity distribution in a reactor that will allow doping efficiency and damage production to be estimated but avoids the limitations of the commonly used copper-cadmium ratio test. It is recommended that measurement of the ratio of ^{29}Al to ^{31}Si activities in NTD silicon [18] be investigated as an alternative measurement of the ratio of irradiation damage to dopant production.

Knowledge of the recovery of radiation-damaged silicon is of extreme importance both scientifically and technologically. Scientifically, this knowledge bears directly on the understanding of the behavior of the solid state of matter, including such topics as point defect interactions, diffusion, and solubility effects. Technologically, this information is necessary for the evaluation and optimization of techniques that rely on particle irradiations as process steps (as, for example, neutron transmutation doping, ion implantation, and electron or proton irradiation for lifetime control).

Since radiation damage production and recovery processes involve such a large number of parameters, both extrinsic and intrinsic to each wafer to be irradiated, the development of an understanding of these physical processes will involve considerable effort. It is recommended that research on damage processes of NTD silicon should be concerned with the following distinct areas:

1. The characterization of the type of damage present following reactor irradiation and the delineation of the parameters (irradiation temperature, neutron velocity distribution, and ingot impurity content) that control this damage.

2. The interaction of trace impurities with each other and with irradiation-induced defects during the annealing process.

3. The defect structures present following annealing at various temperatures above 1000 K and the extent to which trace impurity content and initial irradiation damage influence these high-temperature defect structures.

Such research should be conducted in extremely clean environments and should focus on delineation of the differences between the recovery of neutron-irradiated and that of ion-bombarded silicon.

Correlations between initial damage structures and the irradiation temperature and neutron velocity distribution as sampled by ^{29}Al decay should be attempted to see if a better prediction of initial damage can be obtained in a one-parameter measurement different from the copper-cadmium ratio test.

Finally, the measurement of carrier lifetimes remains an area of uncertainty, and the correlation of minority carrier lifetime to the parameters sampled by commonly applied techniques needs to be developed.

References

1. Hingorani, N., The Reemergence of DC in Modern Power Systems, EPRI Journal, pp. 7-13 (June 1978).

2. Lark-Horovitz, K., Nucleon-Bombarded Semiconductors, *Semiconducting Materials*, H. K. Henisch, Ed., pp. 47-69 (Butterworth, London, 1951).

3. Tanenbaum, M., and Mills, A. D., Preparation of Uniform Resistivity n-Type Silicon by Nuclear Transmutation, *J. Electrochem. Soc.* 108, 171-176 (1961).

4. Snyderman, N., Silicon Neutron Doping Gains Credibility, *Electronics News* (May 1, 1978).

5. Janus, H. M., Application of NTD Silicon for Power Devices, *Neutron Transmutation Doping in Semiconductors*, J. M. Meese, Ed., pp. 37-45 (Plenum, New York, 1979).

6. Meese, J. M., Preface, *Neutron Transmutation Doping in Semiconductors*, J. M. Meese, Ed., pp. v-vi (Plenum, New York, 1979).

7. Denning, R., and White, J., New Technologies Advance Power Semiconductor State-of-the-Art, RCA Technical Communications, Reprint RE-24-5-11 (1979).

8. Hobgood, H. M., Braggins, T. T., Schwartz, J. C., and Thomas, R. N., Role of Neutron Transmutation in the Development of High Sensitivity Extrinsic Silicon IR Detector Material, *Neutron Transmutation Doping in Semiconductors*, J. M. Meese, Ed., pp. 65-90 (Plenum, New York 1979).

9. Caine, E. J., Glairon, P. J., Charlson, E. J., and Charlson, E. M., Transistor Gain Trimming in I^2L Integrated Circuits Using the NTD Process, *Neutron Transmutation Doping in Semiconductors*, J. M. Meese, Ed., pp. 129-141 (Plenum, New York, 1979).

10. Crossman, L. D., and Baker, J. A., Review: Polysilicon Technology, *Semiconductor Silicon 1977*, H. R. Huff and E. Sirtl, Eds., Proceedings Volume 77-2, pp. 18-31 (The Electrochemical Society, Princeton, N.J., 1977).

11. Matlock, J. H., Review: Advances in Single Crystal Growth of Silicon, *Semiconductor Silicon 1977*, H. R. Huff and E. Sirtl, Eds., Proceedings Volume 77-2, pp. 32-51 (The Electrochemical Society, Princeton, N.J., 1977).

12. Janus, H. M., and Malmros, O., Application of Thermal Neutron Irradiation for Large Scale Production of Homogeneous Phosphorus Doping of Floatzone Silicon, *IEEE Trans. Electron Devices* ED-23, 797-802 (1976).

13. Phillips, R. W., NTD Silicon for High Power Semiconductor Devices, *Neutron Transmutation Doping Semiconductors,* J. M. Meese, Ed., pp. 47-52 (Plenum, New York, 1979).

14. See, for example, Enge, H. A., *Nuclear Physics,* pp. 528-568 (Addison-Wesley, Reading, Massachusetts, 1966).

15. Stone, B. D., Hines, D. B., Gunn, S. L., and Mckown, D., Detection and Identification of Potential Impurities Activated by Neutron Irradiation of Czochralski Silicon, *Neutron Transmutation Doping in Semiconductors,* J. M. Meese, Ed., pp. 11-26 (Plenum, New York, 1979).

16. Koyama, R. Y., Phillips, W. E., Myers, D. R., Liu, Y. M., and Dietrich, M. B., The Energy Levels and the Defect Signature of Sulfur-Implanted Silicon by Thermally Stimulated Measurements, *Solid-State Electronics* 21, 953-955 (1979).

17. Haas, E. W., and Martin, J. A., Nuclear Transmutation Doping from the Viewpoint of Radioactivity, *Neutron Transmutation Doping in Semiconductors,* J. M. Meese, Ed., pp. 27-36 (Plenum, New York, 1979).

18. Bickford, N. A., and Fleming, R. F., Silicon Irradiation Facilities at the NBS Reactor, *Neutron Transmutation Doping in Semiconductors,* J. M. Meese, Ed., pp. 165-170 (Plenum, New York, 1979).

19. Lyon, W. S., and Manning J. J., Radioactive Si-31, *Phys. Rev.* 93, 501 (1954).

20. Hart, R. R., Albert, L. D., Skinner, N. G., Young, M. H., Baron, R., and Marsh, O. J., Measurement of ^{31}P Concentrations Produced by Neutron Transmutation Doping of Silicon, *Neutron Transmutation Doping in Semiconductors,* J. M. Meese, Ed., pp. 345-354 (Plenum, New York, 1979).

21. Morrissey, J. E., Tillinghast, T., Ferro, A. P., and Baliga, B. J., General Electric Test Reactor NTD Silicon Development Program, *Neutron Transmutation Doping in Semiconductors,* J. M. Meese, Ed., pp. 171-179 (Plenum, New York, 1979).

22. Bourdon, J. L., and Restelli, G., An Automated Facility for Neutron Doping of Large Silicon Ingots, *Neutron Transmutation Doping in Semiconductors,* J. M. Meese, Ed., pp. 181-195 (Plenum, New York, 1979).

23. Smith, T. G. S., Neutron Doping of Silicon in the Harwell Research Reactor, *Neutron Transmutation Doping in Semiconductors,* J. M. Meese, Ed., pp. 157-163 (Plenum, New York, 1979).

24. Gunn, S. L., Meese, J. M., and Alger, D. M., High Precision Irradiation Techniques for NTD Silicon at the University of Missouri Research Reactor, *Neutron Transmutation Doping in Semiconductors,* J. M. Meese, Ed., pp. 197-214 (Plenum, New York, 1979).

25. Meese, J. M., Silicon Detector Compensation by Nuclear Transmutation, Air Force Materials Laboratory Report AFML-TR-77-178 (February 1978).

26. Stein, H. J., Atomic Displacement Effects in Neutron Transmutation Doping, *Neutron Transmutation Doping in Semiconductors,* J. M. Meese, Ed., pp. 229-248 (Plenum, New York, 1979).

27. Kirk, M. A., and Greenwood, L. R., Determination of the Neutron Flux and Energy Spectrum and Calculation of Primary Recoil and Damage-Energy Distribution for Materials Irradiated in the Low-Temperature Fast Neutron Facility in CP-5, *Neutron Transmutation Doping in Semiconductors,* J. M. Meese, Ed., pp. 143-155 (Plenum, New York, 1979).

28. Evans, R. D., *The Atomic Nucleus* (McGraw-Hill, New York, 1955), p. 443.

29. Rochlin, R. S., Fission-Neutron Cross Sections for Threshold Reactions, *Handbook of Nuclear Technology,* pp. 248-249 (McGraw-Hill, New York, 1960).

30. Cheng, L. J., and Corbett, J. W., Defect Creation in Electronic Materials, *Proc. IEEE* 62, 1208-1214 (1974).

31. Oen, O. S., and Holmes, D. K., Cross Sections for Atomic Displacements in Solids by Gamma Rays, *J. Appl. Phys.* 30, 1289-1295 (1959).

32. Stein, H. J., Defects in Silicon: Concepts and Correlations, *Radiation Effects in Semiconductors, Albany, 1970,* J. W. Corbett and G. D. Watkins, Eds., pp. 125-140 (Gordon and Breach, London, 1971).

33. Young, R. T., Cleland, J. W., Wood, R. F., and Abraham, M. M., Radiation Damage in Neutron Transmutation Doped Silicon: Electronic Properties Studies, *J. Appl. Phys.* 49, 4752-4760 (1978).

34. Bertolotti, M., Papa, T., Sette, D., and Vitali, G., Evidence for Damage Regions in Si, Ga As, and in Sb Semiconductors Bombarded with High-Energy Neutrons, *J. Appl. Phys.* 38, 2645-2647 (1967).

35. Lau, S. S., Mayer, J. W., and Tseng, W. F., Comparison of Laser and Thermal Annealing of Implanted-Amorphous Silicon, *Laser-Solid Interactions and Laser-Processing-1978,* S. D. Ferris, H. J. Leamy, and J. M. Poate, Eds., pp. 84-96 (American Institute of Physics, New York, 1979).

36. Crowder, B. J., The Influence of the Amorphous Phase in Ion Distributions and Annealing Behavior of Group III and Group V Ions Implanted Into Silicon, *J. Electrochem. Soc.* 118, 943-948 (1971).

37. Watkins, G. D., EPR and Optical Absorption Studies in Irradiated Semiconductors, *Radiation Effects in Semiconductors, Santa Fe, New Mexico, October 1967,* F. L. Vook, Ed., pp. 67-81 (New York, Plenum, 1968).

38. Watkins, G. D., Corbett, J. W., and Walker, R. M., Spin Resonance in Electron-Irradiated Silicon, *J. Appl. Phys.* 30, 1198-1203 (1959).

39. Kirkpatrick, C. G., Myers, D. R., and Streetman, B. G., Photoluminescence from Carbon and Oxygen Implanted Silicon, *Radiation Effects* 31, 175-179 (1977).

40. Wiggers, L. W., Channeling Studies of Impurity Defect Interactions in Silicon, Thesis, FOM-Instituut voor Atoom-en Moleculfysica te Amsterdam, 1978.

41. Lee, Y. H., and Corbett, J. W., EPR Studies in Neutron-Irradiated Silicon: A Negative Charge State of a Non Planar Five Vacancy Cluster (V_5^-), *Phys. Rev. B* 8, 2810-2826 (1973).

42. Corbett, J. W., Radiation Damage in Silicon and Germanium, *Radiation Effects* 6, 3-10 (1970).

43. Seeger, A., Frank, W., and Goselle, U., Diffusion in Elemental Semiconductors: New Developments, in Institute of Physics Conference Series Number 46, pp. 148-167 (Institute of Physics, 1979).

44. Brower, K. L., EPR of a <001> Si Interstitial Complex in Irradiated Silicon, *Phys. Rev. B* 14, 872-883 (1976).

45. Tarneja, K. S., and Johnson, J. E., Tailoring of Recovered Change in Power Diodes Using 2 MeV Electron Irradiation, *J. Electrochem. Soc.* 122, 360C (1975).

46. Guldurg, J., Micro-Defects in Float-zone Silicon, thesis, Institute of Applied Physics III and Laboratory of Semiconductor Technology, Technical University of Denmark, February 1978.

47. Bicknell, R. W., and Allen, R. M., Correlation of Electron Microscope Studies with the Electrical Properties of Boron-Implanted Silicon, *Radiation Effects* 6, 45-49 (1970).

48. Secco D'Aragona, F., Annealing Behavior and Etching Phenomena of Microdefects in Dislocation-Free Float-Zone Silicon, *Phys. Stat. Sol. (a)* 7, 577-582 (1971).

49. Shiraki, H., Silicon Wafer Annealing Effect in Loop Defect Generation, *Jap. J. Appl. Phys.* 13, 1514-1523 (1974).

50. Pankratz, J. M., Sprague, J. A., and Rudee, M. L., Investigation of Neutron-Irradiation Damage in Silicon by Transmission Electron Microscopy, *J. Appl. Phys.* 39, 101-106 (1968).

51. Rozgonyi, G. A., and Pearce, C. W., Gettering of Surface and Bulk Impurities in Czochralski Silicon Wafers, *Appl. Phys. Lett.* 32, 747-749 (1978).

52. Hale, G. B., and Katz, L., Electron Spin Resonance in NTD Silicon, *Neutron Transmutation Doping in Semiconductors*, J. M. Meese, Ed., pp. 307-316 (Plenum, New York, 1979).

53. Kirkpatrick, C. G., Noonan, J. R., and Streetman, B. G., Recombination Luminescence from Boron-Implanted Silicon, *Radiation Effects* 21, 225-228 (1974).

54. Seshan, K., and Washburn, J., A Three-Stage Model for the Development of Secondary Defects in Ion-Implanted Silicon, *Radiation Effects* 37, 147-153 (1978).

55. Baldwin, T. O., and Thomas, T. E., Use of Anomalous X-Ray Transmission for the Detection of Defects Produced in Silicon and Germanium by Fast Neutron Irradiation, *J. Appl. Phys.* 39, 4391-4398 (1968).

56. Baldwin, T. O., Thomas, J. E., and Haldeman, J. K., The Effect of Electron Irradiation on the Lattice Parameter and Anomalous X-Ray Transmission of Silicon, *J. Appl. Phys.* 50, 3748-3751 (1979).

57. Foll, M., Gorele, N., and Kolbesen, B. O., Swirl Defects in Silicon, in *Semiconductor Silicon 1977*, H. R. Huff and E. Sirtl, Eds., Proceedings Volume 77-2, pp. 565-574 (The Electrochemical Society, Princeton, N.J., 1977).

58. Weber, E., and Riotte, H. G., Iron as a Thermal Defect in Silicon, *Appl. Phys. Lett.* 33, 433-435 (1978).

59. Kimerling, L. C., and Patel, J. R., Defect States Associated with Dislocations in Silicon, *Appl. Phys. Lett.* 34, 73-75 (1979).

60. Tice, W. K., Tan, T. Y., and Geipel, H. J., The Isochronal Annealing Behavior of Silicon Implanted with Arsenic Ions, *Extended Abstracts*, vol. 76-2, Fall Meeting of the Electrochemical Society, Las Vegas, Nevada, October 17-22, 1976, pp. 863-864 (The Electrochemical Society, Princeton, N.J., 1976).

61. Myers, D. R., and Streetman, B. G., Detection by Low Temperature Photoluminescence of Oxygen Recoils in "Through-Oxide" Arsenic Implanted Silicon, *Solid State Communications* 18, 815-817 (1976).

62. Cleland, J. W., Fleming, P. H., Westbrook, R. D., Wood, R. F., and Young, R. T., Electrical Property Studies of Neutron Transmutation Doped Silicon, *Neutron Transmutation Doping in Semiconductors*, J. M. Meese, Ed., pp. 261-279 (Plenum, New York, 1979).

63. Geipel, H. J., and Tice, W. K., Critical Microstructures for Ion-Implantation Gettering Effects in Silicon, *Appl. Phys. Lett.* 30, 325-327 (1977).

64. Malmros, O., The Minority Carrier Lifetime of Neutron Doped Silicon, *Neutron Transmutation Doping in Semiconductors*, J. M. Meese, Ed., pp. 249-260 (Plenum, New York, 1979).

65. Sze, S. M., and Irvin, J. C., Resistivity, Mobility, and Impurity Levels in GaAs, Ge, and Si at 300 K, *Solid State Electronics* 11, 599-602 (1966).

66. Sadana, D. K., Fletcher, J., and Booker, G. R., Structural and Electrical Profiles for Double Damage Layers in Ion-Implanted Silicon, *Electronics Letters* 13, 632-633 (1977).

67. Ghandi, S. K., *Semiconductor Power Devices,* p. 290 (John Wiley and Sons, New York, 1977).

68. Gregory, B. L., and Gwynn, C. W., Radiation Effects on Semiconductor Devices, *Proc. IEEE* 62, 1264-1273 (1974).

69. Bullis, W. M., Properties of Gold in Silicon, *Solid State Electronics* 9, 143-168 (1966).

70. Lisiak, K. P., and Milnes, A. G., Platinum as a Lifetime Control Deep Impurity in Silicon, *J. Appl. Phys.* 46, 5229-5235 (1975).

71. Ryssell, H., Kranz, H., Bayul, P., and Schmiedt, B., Minority Carrier Lifetime and Backside Measurements of Ion-Gettered Silicon, *Proc. First Conf. on Ion Beam Modification of Materials,* J. Gyulai, T. Lohner, and E. Pasztor, Eds., pp. 461-477 (Central Research Institute for Physics, Budapest, 1979).

72. Myers, D. R., Properties of Silicon Implanted with Arsenic Through Silicon Dioxide, Coordinated Science Laboratory Report R-756, January 1977, pp. 30-37. (Available from the Defense Documentation Center, Alexandria, VA 22314)

73. Evwaraye, A. O., Electron-Induced Defects-Dependence on Prior Heat Treatment, 20th Electronic Materials Conference, June 28-30, 1978, paper E-4 (unpublished).

74. Ghandi, S. K., *Semiconductor Power Devices,* pp. 2-8 (John Wiley and Sons, New York, 1977).

75. Inoue, N., and Oosaka, J., Inhomogeneous Oxygen Precipitation and Stacking Fault Formation in Czochralski Silicon, *Jap. J. Appl. Phys.* 17, 2051-2052 (1978).

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Neutron transmutation doping (NTD) is a promising technique for the production of uniformly doped silicon needed to optimize power device performance. This report summarizes the problems involved in the neutron transmutation doping process and elaborates the concerns related to damage in transmutation doped silicon resulting from the neutron irradiation. Suggestions for future research are presented.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

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