Review of Displacement Damage Effects in Silicon Devices

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***Abstract*—This paper provides a historical review of the literature on the effects of radiation-induced displacement damage in semiconductor materials and devices. Emphasis is placed on effects in technologically important bulk silicon and silicon devices. The primary goals are to provide a guide to displacement damage literature, to offer critical comments regarding that literature in an attempt to identify key findings, to describe how the understanding of displacement damage mechanisms and effects has evolved, and to note current trends. Selected tutorial elements are included as an aid to presenting the review information more clearly and to provide a frame of reference for the terminology used. The primary approach employed is to present information qualitatively while leaving quantitative details to the cited references. A bibliography of key displacement-damage information sources is also provided.**

***Index Terms*—Annealing, damage correlation, defects, displacement damage, nonionizing energy loss, radiation effects, semiconductors, silicon, silicon devices.**

I. INTRODUCTION AND OVERVIEW

THIS PAPER provides a historical review of the literature on the effects of radiation-induced displacement damage in semiconductor materials and devices. Emphasis is placed on effects in technologically important bulk silicon and silicon devices. Displacement damage effects in other materials and devices are noted briefly. Emphasis is also placed on papers that were presented at the annual IEEE Nuclear and Space Radiation Effects Conference (NSREC), and subsequently published in the IEEE TRANSACTIONS ON NUCLEAR SCIENCE, since the present article appears in a Special Issue commemorating the 40th anniversary of that conference. Further, this article focuses on the specific technical literature with which the authors are familiar.

The primary goals of this paper are the following: 1) provide readers with a guide to the rich displacement damage literature; 2) provide critical comments regarding that literature in an attempt to identify key findings; 3) describe how our understanding of displacement damage mechanisms and effects has evolved; and 4) note current trends. Selected tutorial elements are also included as an aid to presenting the review information more clearly and to provide a frame of reference for the terminology used in the displacement damage field. The primary approach employed here is to present information qualitatively while leaving quantitative details to the cited references.

Following a brief summary of the history of displacement damage studies in semiconductors, key displacement damage mechanisms and effects are described qualitatively. The effects of uniform displacement damage in bulk material and Si devices are then considered, followed by a brief consideration of nonuniform displacement damage effects. Damage annealing is then treated, including short-term and long-term thermal annealing and injection annealing. Nonionizing energy loss concepts and damage correlations are then reviewed. This paper concludes with comments on the evolution of displacement damage understanding and on current research and engineering trends. A bibliography of key displacement-damage information sources is also provided in addition to the cited references.

II. BACKGROUND INFORMATION

A. Early Displacement Damage History

Wigner and collaborators performed theoretical and experimental studies of displacement damage in irradiated materials in the early 1940s [1]. Their work initiated considerable interest in radiation effects on materials of technological importance. Lark-Horovitz [2], Seitz [3], and Slater [4] reviewed the investigations of radiation effects in solids conducted in that era. (It is interesting to note that displacement damage work was also performed in the 1800s and early 1900s, as summarized by Billington and Crawford [5].) Scientists at Purdue University and Oak Ridge National Laboratory performed the first studies of radiation-induced displacement damage in semiconducting germanium materials and devices [6]–[8], followed by related Ge work at Bell Telephone Laboratories [9]. Johnson and Lark-Horovitz [8] evidently performed the first study of displacement damage effects in silicon materials and devices. That subject continues to be of interest more than 50 years later.

B. Qualitative Overview of Displacement Damage Mechanisms and Effects

1) Defect Production: Energetic particles incident on a solid lose their energy to ionizing and nonionizing processes as they travel through a given material. The result of this energy loss is the production of electron-hole pairs (ionization) and displaced atoms (displacement damage), with the latter effect being the focus here. The primary lattice defects initially created are vacancies and interstitials. A vacancy is the absence of an atom from its normal lattice position. If that displaced atom moves into a nonlattice position, the resulting defect is called an interstitial. The combination of a vacancy and an adjacent interstitial is known as a close pair or a Frenkel pair. Two adjacent

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vacancies form a defect referred to as the divacancy. In irradiated silicon, larger local groupings of vacancies may also occur. Additional types of defects can form when vacancies and interstitials are adjacent to impurity atoms. The resulting defects are called defect-impurity complexes, with one example being the vacancy-phosphorus pair. This defect is referred to as the E center in irradiated Si.

Now consider the density of defects produced in irradiated materials. At one extreme, radiation-induced defects are relatively far apart and are referred to as point defects or isolated defects. For example, incident electrons and photons with energy on the order of 1 MeV produce such defects. At the other extreme, defects may be produced relatively close together and form a local region of disorder (referred to in the literature as a defect cluster or disordered region). For example, a single incident neutron with energy on the order of 1 MeV gives rise to many defects. The mechanism involved is the initial transfer of a significant amount of energy from that neutron to a single Si atom. The dislodged primary knock-on atom then displaces many other Si atoms locally, thereby creating a disordered region. The defect density in portions of that local damaged region will be much higher than in the example of 1-MeV electron damage. That high-defect-density portion is often referred to as a terminal subcluster or subcascade (discussed in Sections III and VI). In general, incident energetic particles produce a mixture of isolated and clustered defects.

2) Defect Reordering: Once defects are formed by incident radiation, those defects will reorder to form more stable configurations. For example, the vacancy in silicon is an unstable defect and is quite mobile at room temperature. After vacancies are introduced, they move through the lattice and form more stable defects such as divacancies and vacancy-impurity complexes. The effectiveness of defects in altering the properties of bulk semiconductor material and devices (discussed below) depends on the nature of the specific defects and on the time after defect creation at a given temperature. Defect reordering is also temperature dependent (thermal annealing) and dependent on the excess carrier concentration present (injection annealing).

Defect reordering is usually called *annealing*, which typically implies that the amount of damage and its effectiveness are reduced. In general, the reordering of defects with time or increased temperature to more stable configurations can also result in *more* effective defects. This process is often referred to in the literature as *reverse annealing* in contrast to the more typical process of *forward annealing* (i.e., "annealing").

Two examples are given to describe damage reordering further. A short intense burst (i.e., milliseconds or less in duration) of identical incident energetic particles is considered first. The temperature of the bombarded material or device is assumed to be constant at room temperature ($\sim$300 K). Depending on particle type and energy, each particle in this burst may produce several relatively widely spaced defects or a number of more closely spaced defects, as noted above. It is assumed that defects are introduced instantaneously (i.e., in a time comparable to the duration of the burst). Following their creation, defects will migrate and reorder to more stable configurations. If the effectiveness of those locally created defects is monitored as a function of time following creation by, for example, measuring an electrical property such as minority-carrier lifetime in bulk material or dark current in a charge-coupled device (CCD), one generally would observe forward annealing, i.e., a decrease in damage effectiveness. There is a significant short-term thermal annealing process that is essentially complete in seconds to minutes following defect creation, depending on the type and energy of the incident particle. Long-term annealing follows and can continue for years at room temperature. Increasing the temperature will, of course, enhance these annealing processes as will increasing the injection level.

Next, consider steady-state irradiation either of bulk semiconductor material or of a device, which is similar to the environment experienced in space. In this example, defects are introduced continually but defect reordering also proceeds simultaneously. If one were to follow the history of the damage introduced by a *single particle* in this steady-state flux, then the description given above for a burst of radiation applies. That is, short-term and long-term thermal annealing will occur for the damage introduced by that particle. If the rate of steady-state bombardment, i.e., the defect introduction rate, is much lower than the short-term annealing rate for introduced defects, then the effectiveness of the damage produced after a given steady-state irradiation time will be relatively stable. In this situation, when irradiation is stopped one can then observe the relatively slow long-term annealing process.

3) Displacement Damage Effects: The defect reordering discussion given above makes the point that the effectiveness of radiation-induced displacement damage depends on the bombardment conditions and on the time after irradiation. More generally, damage effectiveness depends on many factors, including particle type, particle energy, irradiation temperature, measurement temperature, time after irradiation, thermal history after irradiation, injection level, material type (i.e., n- or p-type), and impurity type and concentration. References to the literature that describe those functional dependences are provided herein. The primary effects of displacement damage that lead to the degradation of material and device properties are now discussed.

In general, any disturbance of lattice periodicity may give rise to energy levels in the bandgap. Radiation-induced defects have such levels associated with them, and it is these defect states, or centers, that have a major impact on the electrical and optical behavior of semiconductor materials and devices. The basic phenomena that cause materials and devices to degrade in a radiation environment that produces displacement damage are: 1) incident particles displace atoms; 2) the resulting defects give rise to new energy levels; and 3) those levels alter material and device electrical and optical properties.

The fundamental effects of defect centers on electrical properties are now described. The first effect is the thermal generation of electron-hole pairs through a level near midgap. This process can be viewed as the thermal excitation of a bound valence-band electron to the defect center and the subsequent excitation of that electron to the conduction band, thereby generating a free electron-hole pair. Alternatively, it can be viewed as hole emission from the center followed by electron emission. Only those centers with energy levels near midgap make a significant contribution to carrier generation; an exponential decrease in generation rate occurs as the energy-level position is moved from midgap. In addition, emission processes dominate over capture processes at a defect level only when the free-carrier concentrations are significantly less than their thermal equilibrium values. Thus, thermal generation of electron-hole pairs through radiation-induced defect centers near midgap is important in device depletion regions. Introduction of such centers increases the thermal generation rate, which is the mechanism for leakage current increases in silicon devices.

The second effect is the recombination of electron-hole pairs. In this process, a free carrier of one sign is first captured at the defect center, followed by capture of a carrier of the opposite sign. Recombination removes electron-hole pairs as opposed to the generation process. In general, the recombination rate depends on the defect-center (or recombination-center) density, the free carrier concentration, the electron and hole capture cross sections, and the energy level position. The mean time a minority carrier spends in its band before recombining is referred to as the recombination lifetime. Radiation-induced recombination centers cause the lifetime to decrease; this is the dominant mechanism for gain degradation due to displacement damage in bipolar transistors.

The third effect is the temporary trapping of carriers at a typically shallow level. In this process, a carrier is captured at a defect center and is later emitted to its band, with no recombination event taking place. In general, trapping of both majority and minority carriers can occur (at separate levels). Radiation-induced traps are responsible for increasing the transfer inefficiency in charge-coupled devices.

The fourth effect is the compensation of donors or acceptors by radiation-induced centers. For example, in n-type material deep-lying radiation-induced acceptors compensate some of the free electrons available from the donor level. The result is a reduction in the equilibrium majority-carrier concentration. This “carrier removal” process will cause an alteration in any device or circuit property that depends on carrier concentration. For example, the resistance of the collector in bipolar transistors will increase due to carrier removal.

A fifth process is the tunneling of carriers through a potential barrier by means of defect levels. This defect-assisted (also called trap-assisted) tunneling process can cause device currents to increase in certain situations. For example, there may be a defect-assisted tunneling component of the reverse current in a pn-junction diode.

In the sixth effect, radiation-induced defects act as scattering centers and cause the carrier mobility to decrease. The mobility decreases with increasing ionized impurity concentration. In a similar manner, the introduction of charged radiation-induced defects also causes the mobility to decrease. This effect should be stronger at temperatures considerably less than 300 K because ionized impurity scattering dominates over lattice scattering in that regime.

A seventh effect is type conversion due to displacement-damage-induced carrier removal. In bulk Ge, introduction of acceptors causes the resistivity of n-type material to increase, which leads to the eventual conversion to p-type material. Type conversion does not occur in bulk Si. Irradiated Si simply becomes compensated intrinsic. However, in Si devices, notably pn-junction devices used for detection of high-energy particles, type conversion does occur in depletion regions. (For example, see [10] and references therein.)

An eighth effect of radiation-induced defects in the bandgap is enhanced effectiveness for thermal generation of carriers. This effect occurs when defects are located in a device region containing a high electric field. One mechanism thought to be responsible for this process is a reduced potential barrier for thermal generation (Poole-Frenkel effect). (For example, see [11]).

In summary, radiation-induced levels in the bandgap can give rise to several processes, including generation, recombination, trapping, compensation, tunneling, scattering, type conversion, and field enhancement of carrier generation effectiveness. In principle, any combination, or all, of these processes can occur through the same level. The role a particular level plays depends on variables such as carrier concentration, temperature, and the device region in which it resides (e.g., in a depletion region).

III. UNIFORM DISPLACEMENT DAMAGE EFFECTS

The typical situation encountered in practical applications and in simulation experiments is the introduction of relatively uniform displacement damage by energetic particles. This section reviews relevant concepts and notes key studies of uniform damage effects. Emphasis is placed on effects in bulk material and in discrete devices, such as solar cells, diodes, and bipolar transistors.

Early studies of displacement damage focused on effects in irradiated Ge and Si bulk material and bipolar transistors. Typically, a specific parameter, such as minority-carrier lifetime or current gain, is measured as a function of particle fluence, and the rate of parameter degradation is determined for specific measurement conditions. That degradation rate has been referred to in the literature alternatively as the damage constant, the damage coefficient, and the damage factor. The first term seems inappropriate since the degradation rate is not a constant; its value depends on the conditions under which it is determined, such as irradiation and measurement temperature, time after irradiation, and particle type and energy. Damage coefficient and damage factor are both more appropriate terms to use for the degradation rate. The term *damage factor* is favored here since it is more concise.

Emphasis was placed in early displacement damage studies on identifying and characterizing the defects responsible for material and device degradation. A key part of that characterization was identifying energy level positions in the bandgap and other defect properties, such as capture cross sections. Curtis reviewed the early work along those lines for isolated defects in irradiated semiconductors [12]. Although workers still pursue the determination of such fundamental information for defects today, measurement and analysis of damage factors for irradiated devices is now a more frequent goal since those factors are directly applicable in practice when designing radiation-tolerant hardware. Using fundamental information to derive more practical information is a very difficult task at best. Consider the seemingly simple example of calculating post-irradiation minority-carrier lifetime based on knowledge of energy levels introduced by radiation. To perform that calculation accurately, one would need to know information such as all the energy levels introduced in the bandgap, the defect concentrations associated with each level, the capture and emission probabilities for electrons and holes for each level, and the temperature dependences of those probabilities. Further, one would need to know all the levels associated with the various charge states for each specific defect.

A key theme that emerged from studies by various early workers is the similarities and differences between the effects on electrical properties of semiconductor materials irradiated with different particles. The primary early example is the comparison of effects produced by fission or 14-MeV neutrons with those produced by 1-MeV electrons or ^{60}Co gamma rays. Until the late 1950s, all radiation effects on semiconductors were interpreted as being due to isolated, or Frenkel, defects. In 1959, several papers demonstrated the importance of impurity type and concentration on observed radiation effects [13]–[15]. These and other studies led to the recognition of the role of defects involving impurities, such as the oxygen-vacancy complex and the phosphorus-vacancy complex. At that same time, Gossick *et al.* [16]–[18] proposed a model to account for differences between effects produced by relatively isolated defects and those produced by more closely spaced, or clustered, defects. Their description is commonly referred to as the Gossick model.

Curtis [19] summarized the differences between the effects of 1-MeV electrons or ^{60}Co gamma rays (i.e., isolated defects) and, for example, fission neutrons (i.e., more closely spaced defects) on recombination lifetime in silicon and germanium. One of those differences is the relative lack of a dependence of the lifetime damage factor on impurity type and oxygen concentration in neutron-irradiated n- and p-type Si [20], but a significant dependence of that damage factor on those parameters in ^{60}Co gamma-irradiated Si [21]–[24]. Another notable difference is the much greater effectiveness, in terms of reducing the recombination lifetime, of a specific number of closely spaced, or clustered, defects as compared to the same number of defects distributed uniformly throughout the lattice structure. Further differences are evident in thermal and injection annealing behavior, as discussed in Section V. Several other early workers observed notable differences between the effects of 1-MeV electrons (or ^{60}Co gamma rays) and neutrons on the electrical properties of silicon. (For example, see [25]–[29].) Curtis [30], [31], and Gregory [32] extended the Gossick model analytically to account for experimental observations on neutron-irradiated silicon.

The qualitative view adopted by many radiation effects workers in the late 1950s through the mid-1980s was the following, which was based on a wide variety of experimental observations and accompanying modeling efforts. Electrons with energy less than about 2 MeV, which includes Compton electrons generated by incident ^{60}Co photons, produce relatively isolated defects. Higher energy electrons (e.g., >5 MeV) and neutrons in the MeV range produce a mixture of isolated defects and clustered defects. The number of defects in a localized cluster may be relatively small. For example, when a single energetic neutron interacts with the lattice and produces a primary knock-on atom (PKA), the resulting damage produced by that PKA may take the form of several subclusters containing relatively few defects, as discussed in more detail in Section VI and in the citations provided therein. Modeling indicates that those terminal subclusters would have a relatively small barrier height associated with them within a modified Gossick interpretation [31].

Clustered defects were invoked to account for the enhanced recombination effectiveness in neutron-irradiated material compared to the situation for isolated defects. In that model, a cluster presents a potential well or sink for minority carriers, which then recombine within the cluster. That recombination enhancement is not present for isolated defects. Another feature of cluster models accounts for the lack of a dependence on impurity type or oxygen concentration noted above for neutron-irradiated Si. In subclusters, the defect density is much greater than the impurity concentration, so the nonimpurity-related defects, such as divacancies, dominate recombination. In the isolated defect case, the radiation-induced defect density and the impurity concentration can be comparable, which leads to the importance of impurity-defect complexes for this situation as compared to closely spaced defects.

The main point is that various experimental observations and comparisons led many early workers to seek a model to account for the differences between effects produced by $\sim$1-MeV electrons and fission neutrons in Si and Ge. The Gossick model and its extensions appeared to be successful in accounting for those differences, at least qualitatively. However, that success does not mean that Gossick-type models provide an accurate description of physical reality. The important point is that any successful model must be able to account for all of the experimental observations. Cluster models appeared attractive in that regard, which was why many early researchers embraced them. It was also noted that it is not necessary to invoke the relatively large clusters originally proposed by Gossick to account for observations. Relatively small terminal subclusters appeared to be sufficient for neutron-irradiated Si [31].

Additional views on displacement damage modeling and on the existence of defect clusters are discussed in [133, Ch. 5]. Also, see [133, Ch. 14] for discussion of hardness assurance considerations for displacement damage effects in devices.

To summarize the above, a successful displacement damage model must account for various experimental observations, some of which are: 1) short-term, thermal, and injection annealing effects and differences, as discussed in Section V; 2) impurity effects, including the lack thereof, on degradation rates; 3) enhanced recombination-lifetime damage effectiveness of particles such as energetic neutrons as compared to 1-MeV electrons, for example; and 4) scaling of degraded parameters with the nonionizing energy loss observed in numerous cases. This aspect of displacement damage phenomena is discussed in some detail in Section VI.

Early displacement damage studies performed on bipolar transistor are summarized briefly here. Many studies of displacement damage mechanisms in bipolar transistors have been conducted, with emphasis placed on examining and predicting neutron effects. For example, see [33]–[41]. A key paper published in 1958 is that by Messenger and Spratt [33] in which an equation is presented for describing gain degradation in transistors. Gain degrades due to the introduction, via displacements, of recombination centers throughout the device. Gregory and Gwyn examined the effects of recombination in various device regions on current gain in irradiated bipolar transistors [38], [40].

Surface recombination can also play an important role in degrading the gain in irradiated bipolar transistors due to the effects of *ionizing* radiation. One mechanism is the change in surface potential produced by charge buildup in surface oxide passivation layers. Alteration of the surface potential can cause the surface recombination velocity to increase, thereby decreasing the gain. Another mechanism is the production of interface traps, which also enhances surface recombination and causes gain degradation.

Displacement damage also gives rise to generation centers, and such centers can play an important role in the reverse-biased base-collector junction. The reverse leakage current at that junction will increase due to the thermal generation of electron-hole pairs at radiation-induced centers. Leakage current can also increase due to generation centers produced at the surface by ionizing radiation. In addition, radiation-induced carrier removal can alter the properties of bipolar transistors. For example, the width of the reverse-biased base-collector junction depletion region will increase, resulting in a decreased punch-through voltage, assuming that the base width is reduced due to carrier removal in the base. Further, carrier removal in the neutral collector will increase the collector resistance.

IV. NONUNIFORM DISPLACEMENT DAMAGE EFFECTS

A very low particle fluence incident on a silicon device can result in nonuniformly distributed displacement damage. Such effects are especially evident in a visible imaging array, such as a CCD, that may contain millions of individual pixels. For that important example, radiation-induced dark current can vary significantly from pixel to pixel. In the extreme case of a single incident particle that produces damage, only one pixel in a dense array will exhibit an increased dark current.

Gereth *et al.* [42] in 1965 evidently made the first report of the effects of displacement damage produced by single particles incident on silicon devices. They explored those effects by irradiating avalanche diodes with fission neutrons and with 2-MeV electrons. Notable differences in device behavior were observed between these two cases. Two decades later, numerous studies of single-particle-induced displacement damage effects were conducted [11], [43]–[49], nearly all of which used visible imaging arrays as test devices. (Researchers during that period were not aware of the earlier work by Gereth *et al.* [42].) Pickel *et al.* [50] review the work conducted during that later era. A review paper by Hopkinson *et al.* [51] provides further information regarding nonuniform displacement damage effects for the interested reader.

V. DISPLACEMENT DAMAGE ANNEALING

The literature on thermal and injection annealing of radiation-induced displacement damage is now discussed. First, the topic of injection annealing is addressed since it is occasionally an integral part of thermal annealing studies. Next, short-term annealing following a short burst of radiation is considered, with emphasis placed on room-temperature studies. Long-term thermal annealing is then discussed.

A. Injection Annealing

Injection annealing is the enhancement of defect reordering by the presence of free charge carriers. That charge may be introduced in several ways, including electrical injection into devices and excitation using ionizing radiation. Note that the same radiation source that introduces displacement damage will also excite electron-hole pairs, which can then enhance the reordering of that damage.

Gregory published the key early paper on injection annealing in irradiated silicon [52]. He demonstrated that point defects produced in p-type Si by ^{60}Co gamma irradiation anneal when electrons are injected into the material. Gregory explained his results in terms of enhanced vacancy motion as a result of altering their charge state from neutral to negative via electron injection. A similar study was also performed for gamma-irradiated n-type Si [53]. Stein [54], [55] and Barnes [56], [57] conducted early studies of injection annealing in neutron-irradiated Si. Gregory and Sander explored the effects of injected carriers on short-term annealing, as described in Section V-B.

Kimerling and co-workers explored the mechanisms responsible for injection annealing [58]–[61]. For specific cases in silicon, a change in defect charge state appears to be the dominant mechanism, with a resulting increase in defect mobility. In other cases, especially in GaAs, the responsible mechanism is recombination enhancement. In this mechanism, nonradiative recombination of electron-hole pairs occurs at a specific defect level, and this local deposition of vibrational energy enhances the annealing rate.

B. Short-Term Annealing

Short-term annealing is the defect reordering process that takes place shortly after a burst of radiation that introduces displacement damage, such as a neutron burst from a pulsed reactor. The manifestation of that process is a time-dependent material or device property, such as current gain in a bipolar transistor. (Short-term annealing is also referred to as *transient* annealing and *rapid* annealing in the literature.)

It is important to distinguish between the time-dependent displacement damage effects occurring after a radiation burst and the permanent effects of such bombardment. Fig. 1 illustrates the events following a neutron burst for bulk silicon and silicon devices at room temperature. The change in carrier lifetime or transistor gain that occurs is shown. Following an abrupt decrease coincident with the radiation pulse, lifetime or gain then exhibits a recovery due to the recombination (i.e., annihilation) and rearrangement of defects. The effectiveness of those defects in degrading lifetime, or gain, decreases with time. The recovery period, referred to as short-term annealing, begins shortly after damage creation and is essentially complete in a time on the order of several minutes to one hour after the burst. The damage remaining at that time is often referred to as “permanent damage.” However, a relatively slow annealing

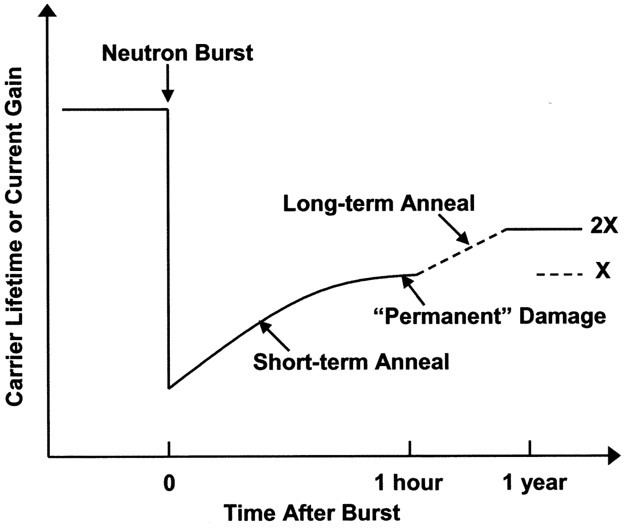

Fig. 1. Conceptual illustration of short-term and long-term thermal annealing at room temperature of displacement damage in bulk silicon and silicon devices following an incident neutron burst.

process, or long-term anneal, will continue after the short-term anneal is completed. For example, recovery by roughly an additional factor-of-two has been observed over a one-year annealing period at room temperature [62], as indicated in Fig. 1.

A short-term annealing factor $AF(t)$ is commonly used in the literature as a measure of the amount of recovery that has occurred at a given time following a burst. For example, the annealing factor for minority-carrier recombination lifetime τ_r is defined as

$$AF(t) = \frac{\left[\tau_r(t)^{-1} - \tau_{r0}{}^{-1}\right]}{\left[\tau_r(\infty)^{-1} - \tau_{r0}{}^{-1}\right]}. \tag{1}$$

The annealing factor is the ratio of the amount of radiation-induced damage at time t to that present at some long time after bombardment (stable damage). Thus, the minimum AF is unity. The amount of *unstable* damage present is then proportional to $AF - 1$. Note that for transistors the AF definition is the same as for lifetime and is obtained by substituting current gain for τ_r in (1).

Early studies of short-term annealing included measurements on Ge and Si devices [63] and bulk Ge material [64] following a neutron burst. Sander evidently made the first detailed report of short-term annealing in silicon devices [65]. Sander and his colleague Gregory subsequently performed significant experiments and analyses on that subject, which are documented in several key publications [66]–[69]. That outstanding body of work by Gregory and Sander constitutes the foundation of our understanding of short-term annealing phenomena in irradiated silicon devices. Other workers also explored various aspects of short-term annealing experimentally and analytically [70]–[87].

Several material and device properties have been measured as a function of time in short-term annealing studies, including minority-carrier lifetime in bulk material [73], [74], [78], [81], [83], conductivity in bulk material [64], [78], diffusion length in solar cells [66]–[68], [75], [82], current gain in bipolar transistors [63], [65], [66], [68], [71], [79], [80], [82], [87], forward voltage drop in diodes [68], [72], junction capacitance in diodes [70], propagation delay time in logic circuits [69], circuit gain in power inverter circuits [69], and dark current [84], [85] and charge transfer inefficiency [85] in CCDs. Various pulsed radiation sources that provided several types of particles were used in those short-term annealing studies, including fission neutrons [63]–[71], [73], [79], [80], [82]–[85], 14-MeV neutrons [73], [82], [83], ~1.4-MeV electrons [66], [68], [74], 10-MeV electrons [72], and 30-MeV electrons [78]. In addition to using pulsed radiation sources, steady-state ^{60}Co gamma irradiations have also been employed to obtain insight regarding short-term annealing mechanisms and phenomena [66], [68].

Key aspects of short-term annealing are summarized below, including irradiation temperature effects, injection-level effects, effects of particle type and energy, and practical application of the results obtained by the various workers. This discussion is based on the body of short-term annealing literature cited above [65]–[87]. The primary references within that group are cited below where appropriate.

Gregory and Sander [67] found that the short-term annealing rate is very sensitive to the carrier injection level present in a device. They also found that the measured annealing factor at a given time correlates well with the electron density present in the active region of a device. This electron density can be either injected or an equilibrium carrier concentration. The injection-level dependence of short-term annealing is an important example of the ionization-enhanced annealing process. Charge state effects, discussed above, appear to play a role in this case. If carrier lifetime in p-type silicon is monitored at a very low minority-carrier injection level (i.e., electron density), then the work of Gregory and Sander [67] suggested that very large annealing factors would be observed. Annealing factors as high as 25–50 indeed were measured later in low-injection-level experiments on such material [75], [82].

The vacancy is quite mobile in silicon at room temperature and hence is referred to as an unstable defect. After vacancy introduction by irradiation, vacancies move through the lattice and form more stable defects, such as divacancies and vacancy-impurity complexes. If electrical properties are monitored during this defect rearrangement (or annealing) process, a decrease in the effectiveness of the damage with increasing time is typically observed. Examples of this are shown in Fig. 2 where the relative amount of damage present in p-type silicon following bombardment with a 40-ns burst of electrons (average energy ~1.4 MeV) and a burst of fission neutrons are plotted versus time following those bursts [74], [82], [83]. To obtain these data, carrier lifetime (which depends on the amount of damage present) was measured as a function of time. For the electron irradiation case, a pronounced recovery stage (i.e., a decrease in the amount of damage present) is observed. A characteristic recovery time can be extracted from the data, since they exhibit a simple exponential decrease in the amount of damage present (i.e., first-order kinetics is followed). Temperature dependence measurements [74] yielded an activation energy (0.32 eV) associated with defect motion. If the data are extrapolated to low temperatures, good agreement with the electron spin resonance data (ESR) of

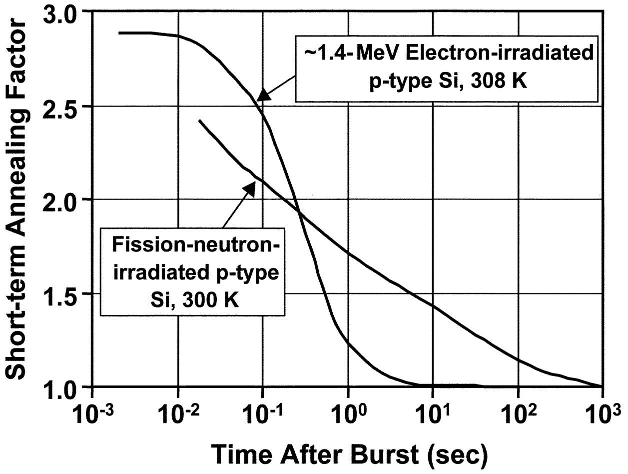

Fig. 2. Annealing factor comparison for p-type Si bombarded with bursts of 1.4-MeV electrons and with fission neutrons [74], [82], [83].

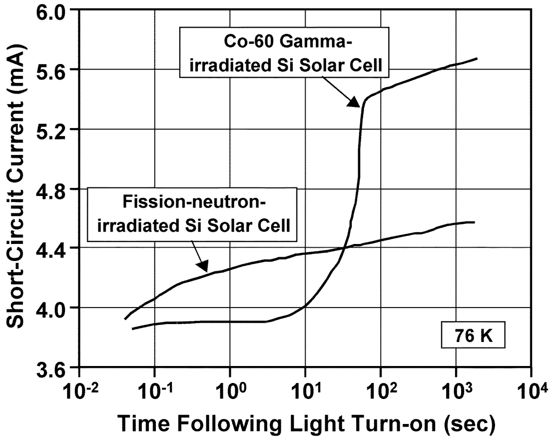

Fig. 3. Comparison of injection annealing at 76 K for solar cells previously irradiated with ^{60}Co gamma rays and with fission neutrons [66].

Watkins [88] was obtained. He attributed his ESR observations to the motion of neutral vacancies. Thus, the transient process exhibited in Fig. 2 for the electron case is consistent with the reordering of radiation-induced isolated vacancies in a neutral charge state. Near room temperature, those findings indicate that stable defects are formed within a few seconds after the radiation burst. In contrast to the electron results, the neutron data in Fig. 2 exhibit relatively complex annealing behavior over several decades in time following the burst.

A related example is shown in Fig. 3 where injection annealing of solar cells at 76 K is shown following bombardment with ^{60}Co gamma rays and with fission neutrons [66]. The isolated defects introduced by gamma rays injection-anneal in a relatively abrupt step, which is in contrast to the more complex annealing in the neutron case. This comparison is comparable to the short-term thermal annealing example in Fig. 2 and again indicates the relative complexity of neutron damage.

Two relevant short-term annealing observations are the following. First, the short-term annealing process for neutron bombardment takes place over several decades in time in contrast to the relatively abrupt annealing stage observed for ~1-MeV electron-irradiated silicon (Fig. 2). This difference may be attributable to the various types of defect interactions that may occur in neutron-produced closely spaced defects as compared to the less complicated situation that evidently prevails for the case of isolated defect production by ~1-MeV electron bombardment. Second, annealing factors at early times are somewhat larger in the case of bombardment with 14-MeV neutrons than for fission neutron bombardment [82], [83]. This difference is possibly due to a slower defect interaction rate in the 14-MeV neutron case as a result of a lower defect density compared to the fission situation.

Sander and Gregory [69] devised a short-term annealing nomograph that aids in determining the appropriate AF for a given situation. That nomograph was developed for reactor neutron irradiations and assumes, for the case of transistors, that recombination in the emitter-base space charge region dominates gain degradation. The electron density (which determines the annealing rate) is the same for npn and pnp devices at the center of that region for a given base-emitter bias. To use their nomograph, one must employ the electron density in the specific region of a device that controls the post-irradiation behavior. As an example, once a bipolar transistor that is off during pulsed bombardment is turned on, recovery occurs rapidly.

C. Long-Term Annealing

Long-term thermal annealing of displacement damage typically is studied experimentally in two ways: isothermal annealing and isochronal annealing. In the former case, properties of the test specimen are monitored as a function of time after irradiation *at a fixed temperature*. In the isochronal annealing case, post-irradiation anneals are performed *for a fixed time duration* at a series of increasing temperatures, and the specimen properties of interest are then measured after each anneal.

In 1970, Gregory and Sander [68] summarized the temperature regimes required to anneal various primary defects and defect complexes in silicon. Consider the vacancy as an example. Relatively isolated vacancies introduced at cryogenic temperatures (e.g., 77 K) by ~1-MeV electrons or by ^{60}Co gamma rays exhibit a characteristic annealing temperature that depends on the charge state of those defects. Neutral vacancies exhibit an annealing stage at 150–180 K [52], whereas negatively charged vacancies, which are more mobile, anneal below 100 K [53], [68]. Additional examples: the divacancy anneals in the 500–550 K range and the E-center anneals at approximately 420 K [58], [68]. For further information regarding long-term thermal annealing of radiation-induced defects in silicon, see, for example, [89] and [90].

VI. NONIONIZING ENERGY LOSS CONCEPTS AND DAMAGE CORRELATIONS

During the last 15 years, it has been shown that the radiation response of many types of devices (e.g., bipolar transistors, solar cells, focal-plane arrays, and other detectors) can be predicted reasonably well based on calculations of the amount of displacement damage energy imparted to the primary knock-on atoms [91]–[94]. Also, since it is not possible to use particle accelerators to simulate fully the radiation environments of practical interest, such as that in space, development of a function to describe the nonionizing energy loss (NIEL) rate in various semiconductors versus incident particle energy has been important. That development permits the use of monoenergetic particle testing to predict on-orbit behavior for space and other applications [95]–[98]. Similarly, simulation testing requirements would be greatly reduced if one could correlate the damage produced by one particle with that produced by another in terms of the impact on device electrical behavior. Thus, considerable effort has been expended in pursuing the goal of displacement damage correlation. Three IEEE NSREC short courses [94], [99], [100] have treated displacement damage effects in semiconductors and have discussed the NIEL concept and its limitations. NIEL studies in semiconductors over the past 15 years are based on early radiation-induced defect studies in which physical models of radiation damage and its impact on semiconductor device behavior were developed. This section reviews key aspects of nonionizing energy loss and damage correlation.

A. Nonionizing Energy Loss Rate Concept

The physics community was very active in the 1950s and 1960s in investigating both elastic and nonelastic ion-solid interactions [101]–[104]. Defects in semiconductors had been studied since the 1940s, as noted in Section II-A, and it was realized that they were key to the operation of solid-state devices. Interest also emerged in correlating the damage produced by various types of radiation and in operating devices in radiation environments, including space, near nuclear power sources, and that produced by weapons.

The nonionizing energy loss rate can be calculated analytically from first principles based on differential cross sections and interaction kinematics. NIEL is that part of the energy introduced via elastic (both Coulombic and nuclear) and nuclear inelastic interactions that produces the initial vacancy-interstitial pairs and phonons (e.g., vibrational energy). NIEL can be calculated for electrons, protons, neutrons, etc., using the following analytic expression that sums the elastic and inelastic contributions:

$$\mathrm{NIEL} = \left(\frac{N}{A}\right)[\sigma_e T_e + \sigma_i T_i] \tag{2}$$

where σ_e and σ_i are total elastic and inelastic cross sections, respectively, T_e and T_i are elastic and inelastic effective average recoil energies corrected for ionization loss, respectively, N is Avogadro's number, and A is the gram atomic weight of the target material. Note that the units for NIEL, typically MeV-cm^2/g, are the same as those for stopping power or linear energy transfer (LET) that describe energy transfer by ionization and excitation per unit length. Many of the early building blocks are used in NIEL calculations today. For example, that fraction of the total energy loss going into ionization is calculated using the 1963 Lindhard theory [105] that was validated by 1965 Si data from Sattler [106]. Also, many models of the nuclear inelastic processes are still followed, such as the Monte Carlo studies of intranuclear cascades performed in the 1950s by Metropolis *et al.* [107].

Analytic calculations of the energy dependence of NIEL for protons incident on Si and Ge appeared in the 1960s [108]–[112], and were revisited in the 1980s [95], [113], [114] once it became clear that experimental damage factors for Si and GaAs solar cells (e.g., [115]–[117]) were not in agreement with earlier NIEL calculations. During the 1960s, the energy dependence of the electron NIEL in silicon was also studied, again using solar cells, and compared to calculations [118]. The energy dependence of neutron damage was also investigated [119], [120]. In each case, NIEL calculations were revisited, refined, and expanded in later years to include other semiconductor materials and to compare with new experimental damage factors.

B. NIEL Correlations to Device Behavior

During the 1960s and 1970s, much effort was expended in attempting to correlate semiconductor device damage from various particle types and energies [119]–[125]. One motive for that work, is, for example, that the significant nuclear weapons effects database could be mined to predict a device response to protons found in a space environment if such a correlation could be established. In 1980, van Lint *et al.* [126] summarized the understanding at that time of displacement damage correlation, including its limitations. They noted the apparent limitation to correlation that arises when one considers the cluster interpretation of neutron damage.

The Gossick cluster model [17], discussed in Section III, essentially involves a disordered volume surrounded by a depletion region. That model appeared to be consistent with many electrical and optical measurements, as indicated in Section III, plus agreed with thermal conductivity studies [127]. In the 1960s, the Gossick model derived timely support from electron microscopy studies [128], which appeared to show evidence of relatively large clusters. However, it was later found that the early microscopy work was compromised by faulty etching techniques [129]. Electrical measurements on irradiated devices performed in the 1980s (e.g., [91], [130]–[132]) appear to be inconsistent with the Gossick model. In fact, some solar cell data originally used to provide support for a cluster model was later employed to support NIEL correlation without modification by cluster theory. It is worthwhile reviewing the studies that led many workers away from cluster models in the 1980s. It is interesting that nearly 25 years later the basic NIEL approach to damage correlation described by van Lint *et al.* [126] is still employed with its limitations.

In the 1980s, bipolar transistor gain measurements for a variety of incident particles (as a function of particle energy) were performed to determine whether the new calculation of the NIEL function [95] could be used both to predict the energy dependence of the device damage factor and to correlate degradation due to different particles [91], [130]. In that work, well-characterized transistors from several diffusion lots were employed for irradiations with neutrons, protons, alpha particles, deuterons, and electrons over a broad energy range. It was demonstrated that by comparing *ratios* of measured damage factor to the calculated NIEL ratios, no scaling parameter is needed to match data with theory. Measurements were also made as a function of collector current, and it was shown that

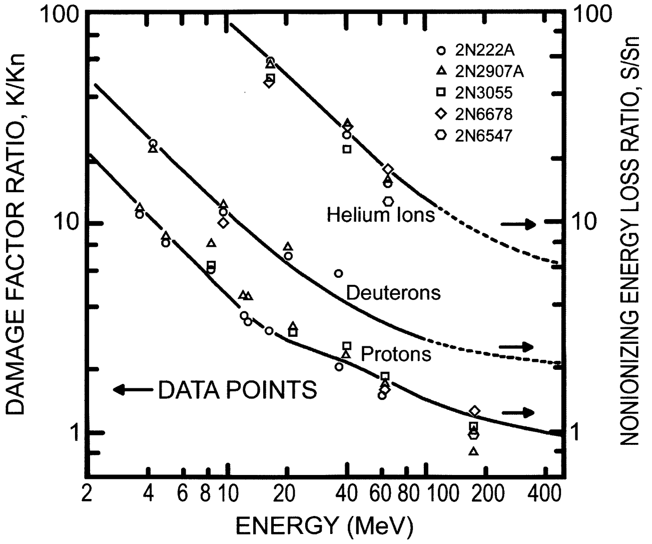

Fig. 4. Transistor damage-factor ratios for a variety of particles compared with fission neutrons are shown along with the corresponding calculations of NIEL ratios. Note that both ordinates are identical (with no fitted parameters), which indicates a direct proportionality between NIEL and the damage factors over a wide energy range (after [91]).

the variation with collector current was identical for all particles tested [91]. In that work, the Messenger-Spratt equation [33] was used to describe the radiation response of the common emitter dc current gain h_{fe} of a bipolar transistor:

$$\frac{1}{h_{fe}} = \frac{1}{h_{fe0}} + K(E)\Phi \tag{3}$$

where the term $1/h_{fe0}$ is the initial reciprocal gain, $K(E)$ is the particle- and energy-dependent displacement damage factor, and Φ is the incident particle fluence. (A detailed description of this equation is given in [133, Ch. 5] and in [33].) The damage factor is determined experimentally by performing device gain measurements (for a particular set of device operating conditions) after incremental exposures at a given particle energy.

Fig. 4 shows the measured damage factors for protons, deuterons, and helium ions normalized to the 1-MeV-equivalent (Si) neutron damage factors as a function of ion energy for a variety of Si bipolar transistors [91]. The importance of this result is that the proportionality between the measured damage factors and calculated NIEL provides the basis for particle-damage-dependent predictions of device degradation.

Research performed during the last 15 years has shown that, to first order, the linear relationship between device degradation from particle-induced displacement damage and NIEL holds for a variety of electrical parameters, incident particles, and device materials [91]–[93], [130]–[132], [134]–[137]. This is a surprising result when one considers that NIEL calculations describe the energy deposited into the formation of Frenkel pairs (over 90% of which recombine) and do not consider the processes by which stable electrically active defects are formed. Since NIEL is a direct measure of the initial number of vacancy-interstitial pairs created, the implications of the NIEL correlation with device degradation are that: 1) the percentage of initial vacancy-interstitial pairs that survive recombination is independent of the primary knock-on atom (PKA) energy, and 2) the resulting stable defects have the same device effect regardless of whether they evolved from a vacancy-interstitial pair originating in a subcascade or as a well-separated pair [130]. This result implies that cluster models are not required to achieve a reasonable correlation methodology. In addition, given that various stable defects have quite different electrical properties, this correlation also implies that the defect inventory produced is independent of PKA spectrum. Nevertheless, the degree to which the NIEL correlation holds is qualitatively consistent with the Monte Carlo calculations that were performed in the 1980s using codes such as MARLOWE that were developed at Oak Ridge National Laboratory [138]. Those simulations showed that a higher energy PKA produces more overall damage but that the microscopic nature of the damage is not drastically different. The branching process simply creates more and more subcascades or subclusters, each separated by a string of relatively isolated defects.

The final configuration of electrically active defects formed by particle irradiation has been a topic of much research but is still not well understood. That topic is central to understanding the use, and limitations, of calculated nonionizing NIEL damage functions to predict the displacement damage response of irradiated devices. Fig. 5 shows the spatial distribution of the *initial* vacancy-interstitial pairs calculated using the MARLOWE code for the example of proton-irradiated Si [140]. As indicated in the plot of the log of the number of interactions (Log N) versus the incident proton energy, most events are Coulomb interactions that produce PKAs with $E_{\text{threshold}} < E <\sim 2$ keV and result in isolated defects. Although there are many fewer of the nuclear elastic and inelastic reaction events that produce cascades, those events are far more damaging and can contribute a significant fraction of the total displacement damage at higher proton energies. As indicated in the figure, recoils with energies between about 2–10 keV produce single subcascades, whereas those with energies in excess of 12–20 keV form a tree-like structure with branches containing multiple subcascades.

Mueller *et al.* [141] also investigated the defect structure near the end of the recoil track in Si and obtained similar results. The term "terminal subcluster or "subcascade" has been used to describe the damaged region where the recoil ion loses the last 5–10 keV of energy and has the highest elastic scattering cross section [140]–[142]. It was found that a single cascade is likely to have two to three terminal subclusters with a characteristic dimension of 5 nm and connected to each other by a string of dilute displacements. (Note that this size is an upper limit since the calculation does not include initial vacancy-interstitial recombination.) This result is consistent with transmission electron microscopy measurements [143], [144] on 1-MeV, 14-MeV, and fission-neutron-irradiated Si that found an average size of 4 nm for the damaged regions. It is clear that the original Gossick cluster model, which was based on heavily damaged regions extending for 200 nm (see [126] and references therein), does not appear to be supported by more recent work. However, as noted in Section III, experimental studies of neutron-irradiated Si [31] were accounted for well using a modified Gossick model that was consistent with relatively small terminal subclusters dominating observed recombination behavior.

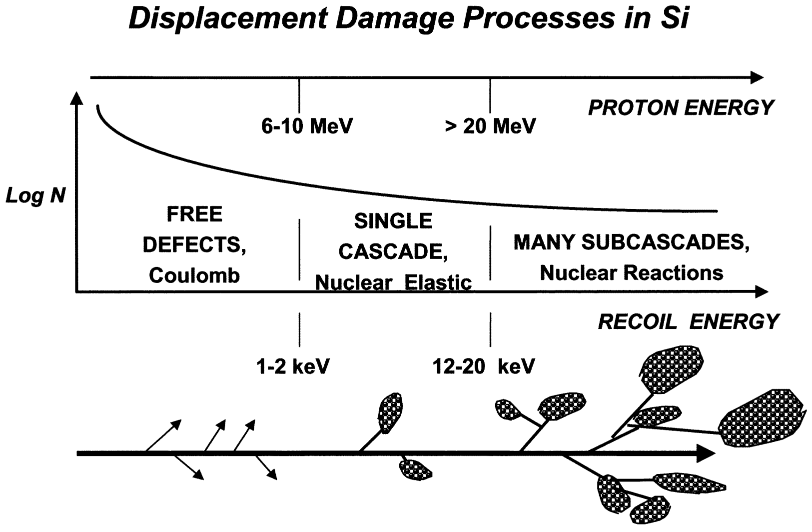

Fig. 5. Pictorial relating the initial defect configuration to the primary knock-on atom energy in Si material. Note from the plot of the number of interactions (N) versus incident proton energy that most interactions are Coulomb events producing isolated defects. For recoil energies above ~2 keV, the overall damage structure is relatively unchanged due to the formation of cascades and subcascades (after [140]).

It is important to keep in mind that, although defects produced from isolated vacancy-interstitial pairs (such as those produced by ^{60}Co gamma rays and 1-MeV electrons) may have similar electrical characteristics to those produced by heavier particles such as protons and neutrons, there *are* important differences, as discussed in Section III. Those differences are not restricted to short-term annealing effects but also manifest themselves in the long-term behavior of device properties. For example, E-centers (vacancy-phosphorus defects) produced by 1-MeV electrons anneal at a significantly lower temperature than those produced by protons [145], [146], a relevant (and unfortunate) fact for charge-coupled device engineers who have considered on-orbit warm-ups to mitigate charge transfer efficiency degradation in CCDs [147]. Differences in the operation of SiGe transistors [148] and AlGaAs–GaAs solar cells [149] have been attributed to differences in the defects produced by neutrons versus protons. Very well controlled deep-level transient spectroscopy studies [150], [151] have unequivocally demonstrated that, although 1-MeV electrons and protons produce some of the same defects in n-type GaAs, there are also different defects produced by each particle. For specific practical applications, the indication is that devices that are highly sensitive to displacement damage should be radiation tested with those particles expected to cause the damage.

C. Further Progress in NIEL Calculations

NIEL has also been calculated by other means, including Monte Carlo programs such as HETC [97], CUPID [152], [153], and SRIM (formerly TRIM) [154]. A comparison between the most recent Burke and CUPID calculations of Si NIEL is discussed in [155]. Although HETC, CUPID, and Burke's calculations of the recoil distributions as a function of incident proton energy show similar trends, they differ in the details [155]. TRIM includes the Coulombic interactions, so it is not appropriate to use it directly for damage calculations for proton energies above the Coulomb threshold at ~8 MeV or so, depending on the target material. It is a very useful code for the analysis of on-orbit solar-cell displacement damage for which low-energy particles are of interest [156], [157]. However, one can also calculate the primary recoil spectrum generated in a material by a given particle by other means, such as MCNP-x (e.g., see [158] and references therein) or GEANT [159] and either directly calculate the nonionizing energy loss for PKAs or utilize the treatments found in the TRIM code in order to calculate NIEL for the PKA spectrum.

D. Limitations on NIEL Usage

NIEL calculations are a useful tool for approximating the expected particle-induced response of a device in a radiation environment, but it is necessary to appreciate the underlying assumptions and limitations in order to use them effectively. Deviations at very low particle energies (approaching the displacement energy thresholds) are expected [100], [130], [160], but they are not generally of concern for *proton* applications in space, for example, because they contribute little to the total displacement damage behind typical shielding. However, silicon solar cell data, while showing a linear correlation with NIEL for n-type material, exhibit a quadratic dependence on NIEL for p-type material (e.g., see [118], [126], and [160]).

Systematic deviations from NIEL correlation for medium to high proton energies have also been observed in Si device measurements (e.g., for several CCDs, a CID, a 2N2907 bipolar transistor [130]), and in GaAs measurements (e.g., LED's [161]–[163], a laser diode [164], solar cells [93], etc.). Depending on how the damage factor measurements were normalized to NIEL, the deviations have been reported either as the damage factors being overestimated by NIEL at higher energies or, equivalently, being underestimated by NIEL at the lower energies.

The choice of a damage function (i.e., the energy dependence given either by the calculated NIEL or by experimental damage factors) has been shown to be significant. For example, one

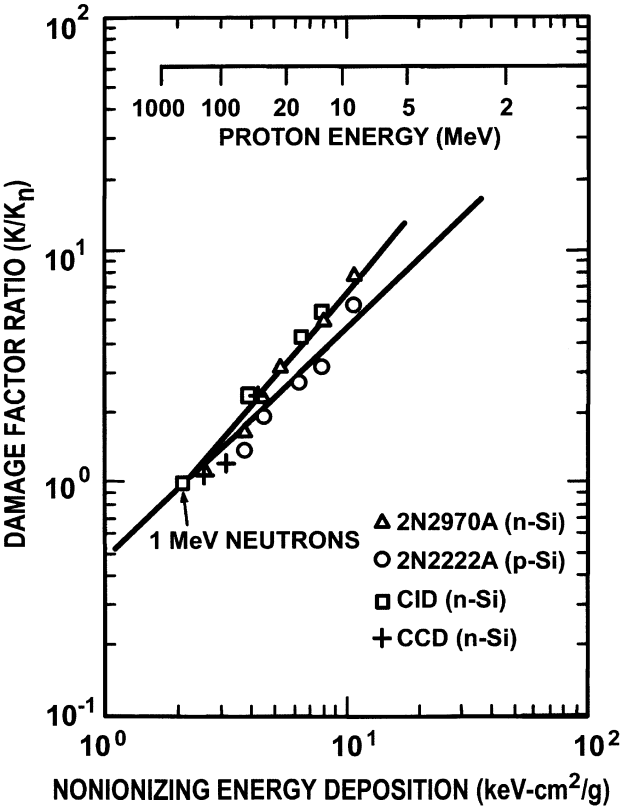

Fig. 6. Transistor damage factors and dark-current damage factors for protons (normalized to fission-neutron damage factors) versus NIEL. Lower line (with unity slope) indicates a linear relationship between the damage factor ratios and NIEL. Deviations from linearity are indicated with the upper line [46]. A similar figure in [130] also shows deviations for transistor damage factors measured for electrons.

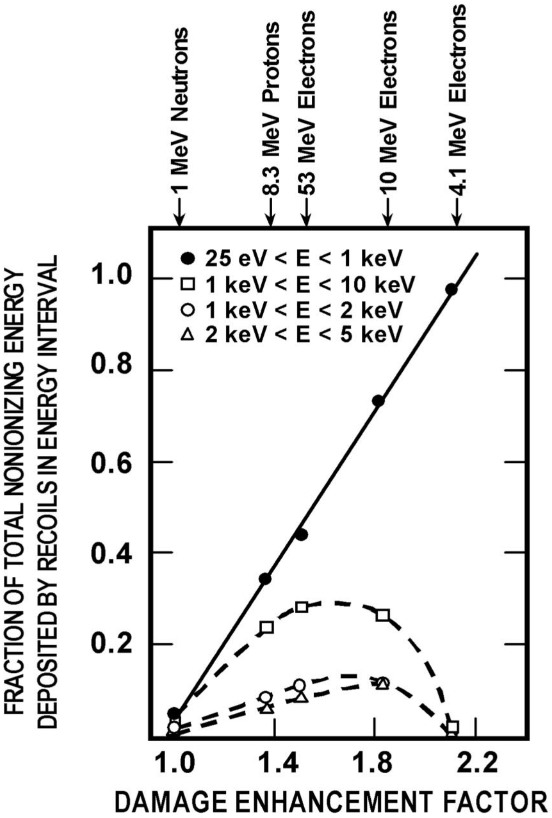

Fig. 7. Correlation between percent NIEL in Si due to recoils in the various energy ranges and the magnitude of the deviation from the ideal linear dependence. Particles associated with a given deviation are labeled at the top of the figure (after [130]).

study found a factor-of-two difference in the on-orbit predictions of the degradation in Si CCD performance depending on which damage function is employed [165]. Deviations from the linear dependence of Si displacement damage factors with the NIEL energy dependence are shown in Fig. 6, which shows proton-to-neutron damage factor ratios for several devices plotted as a function of NIEL [130]. The damage factors represent changes in the recombination rate in the various device regions (minority-carrier lifetime) in the case of the transistor data and the generation lifetime in the case of the CID and CCD dark-current damage factors. A unity slope on the log–log plot indicates a linear relationship, and the observed deviation from linearity is noted by the top curve. A "damage enhancement factor" was defined [130] as the ratio of observed damage factor ratio (upper line) to that expected based on the linearity with NIEL (lower line). In that work, the PKA spectrum produced in Si by the various incoming particles was calculated. Note that the PKA spectrum varies significantly over the range of proton energies of interest in space. It may come as a surprise that the PKA spectrum of a 60-MeV electron is more like that of a 10-MeV proton, than a 10-MeV proton is like a 60-MeV proton. As shown in Fig. 7, the damage enhancement factor is found to correlate with that fraction of the total NIEL due to PKAs with energies less than 1 keV. It is notable that the results hold across the wide range of PKA spectra produced by 4.1-MeV electrons up to 1-MeV-equivalent neutrons, which produce very-high-energy recoils. The observed deviations from linearity would be expected if there were less recombination of initial vacancy-interstitial pairs that are formed by lower energy PKAs (which produce well-separated Frenkel pairs). This result is consistent with the previously described Monte Carlo MARLOWE calculation of collision cascades, which showed that the more dense subcascades do not begin to form until PKAs have energies greater than ~2 keV. Later measurements of the CTE degradation in Si CCDs (from two manufacturers) over a wide range of proton energies also revealed enhanced damage at lower proton energies [92]. However, such deviations were not apparent in a study by Luera *et al.* [166].

Luera *et al.* [166], [167], Barry *et al.* [161], and Reed *et al.* [162] reported evidence that lower energy protons are more effective at producing displacement damage in GaAs as compared to higher energy protons (i.e., more effective than the NIEL correlation would indicate). The studies by Luera *et al.* were based on measurements of carrier removal in Van der Pauw samples and minority-carrier lifetime degradation in LEDs. Once again, the results were explained by variations with PKA energy in the recombination efficiency of the Frenkel pairs. In 1995, Barry *et al.* extended measurement of the minority-carrier lifetime damage factors in GaAs LEDs to proton energies as high as ~500 MeV [161]. Fig. 8 compares those results with the NIEL calculation by Burke [95]. Similar results were obtained by Reed *et al.* [162] for both double- and single-heterojunction AlGaAs LEDs [162], and by Walters *et al.* [168] for InGaAs-GaAs quantum-well LEDs. Other results in the literature also indicate departures of damage factors from the NIEL energy dependence [163], [164]. Although Summers *et al.* [160] demonstrated a general linear correlation between device proton damage coefficients and NIEL for Si, GaAs, and InP, using solar cells as examples, it is important to note that the data they presented do not cover the relevant range of higher proton energies for most space applications, which are more heavily shielded. For example, both the GaAs data (from [169]) and the InP data (from [170]) are for proton energies below 20 MeV and are indeed most relevant to lightly shielded solar-cell applications. It is interesting to note that a paper based on the same solar cell data set [169] shows damage coefficients falling below the calculated GaAs NIEL at higher proton energies [93], consistent with Fig. 8. (The authors in [160] did not discuss this trend, which was not relevant to their solar-cell study.) Clearly, further efforts are required to better understand the nature of these deviations. Recent work by Messenger *et al.* [157] notes that damage efficiency functions, such as those used in the neutron damage studies by Griffin *et al.* [167] and in much earlier work as well, may need to be revisited.

In semiconductor research efforts in the 1950s, it was noticed that NIEL calculations (which compute that portion of the total energy deposited via nonionizing interactions) significantly overestimated defect production. Analytic expressions were developed with *energy-dependent* damage efficiency coefficients that represented the likelihood that the initial Frenkel pairs would survive recombination, and experimental efforts confirmed this behavior in metals [171], [172]. The implication is that if one wants to use *calculated* displacement damage functions to describe the energy dependence of device response for more than rough approximations, then one needs to move beyond NIEL calculations and investigate the time evolution of the initial damage to a variety of electrically active defects. It is not presently clear to what degree the physical processes need to be modeled in order to derive a sufficiently accurate damage function for practical applications, but it is certainly a significant challenge to do so. Kuboyama *et al.* [173] have recently made an attempt to explain NIEL deviations from linearity in silicon by using the MARLOWE code to calculate the recombination efficiency as a function of PKA energy. One point that appears to be missing thus far is the limits of the applicability of codes such as MARLOWE, which is a static code that can only calculate effective recombination efficiencies (either by use of recombination lengths or an effective displacement threshold) with errors that are themselves a function of PKA energy.

As a practical example of the present situation, consider space applications. Designers must typically make on-orbit device performance assessments based on laboratory radiation measurements at one or at most a few proton energies. Thus, they must make an assumption about the energy dependence that the measurements will follow. Several possible approaches are employed, including the use of calculated NIEL curves, experimental displacement damage curves, or combinations of both. All of these approaches have significant uncertainties associated with them that must be reflected in the design margin applied to a given application. Further information concerning the methodology of on-orbit device performance predictions may be found in many papers in the December issues of the IEEE Transactions on Nuclear Science (e.g., see [92], [137], and [162]) as well as in recent NSREC Short Course Notes [94].

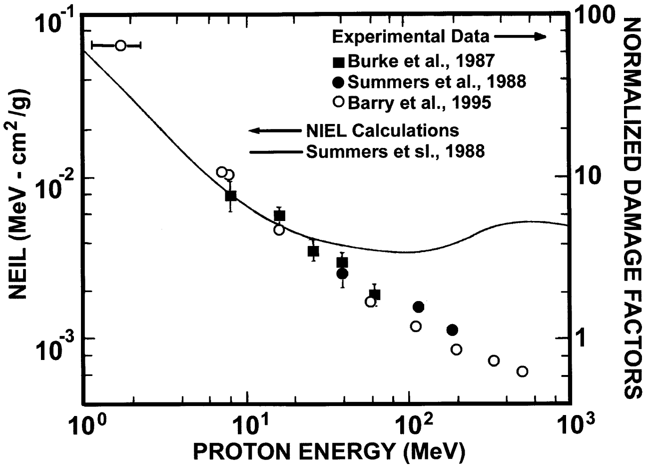

Fig. 8. Experimental damage factor from several studies normalized to the GaAs NIEL calculation at 10 MeV. A significant deviation between the observed damage factors and NIEL is apparent for proton energies above about 40 MeV (adapted from [161]).

In the design of space systems, for example, it is very useful for engineers to be able to predict the end-of-life performance of key electronic elements without performing detailed time-consuming calculations and measurements. The NIEL concept, along with experimentally established damage factors, allows for simple estimates for the degradation of a variety of devices to aid design trades and to efficiently plan any necessary simulation radiation testing. The NIEL methodology has found widespread applicability (e.g., see [174]), but it is nevertheless important to understand its limitations and applicability for specific applications of interest.

VII. Evolution of Displacement Damage Understanding and Current Trends

The understanding of displacement damage mechanisms and effects has evolved in several serial and parallel stages during the last 60 years. A brief overview of those stages is given here, including references to those sections of the present paper that provide more detail.

Modern displacement damage studies started in the 1940s (Section II-A). Changes in semiconductor material and device properties were observed in those early studies, and in many others in the 1950s, including effects on conductivity, mobility, carrier lifetime, and bipolar transistor gain. Those radiation-induced changes were interpreted in terms of Frenkel defects until the late 1950s when the importance of impurity-related defects was established (Section III).

During the period from the late 1950s to the early 1970s, considerable effort was expended in characterizing and modeling displacement damage effects produced by different particle types and energies (Section III). Those studies identified the detailed differences between the effects produced by, for example, fission neutrons and 1-MeV electrons in bulk silicon and germanium. Early observations of those differences led to the development of the Gossick cluster model, which was later extended by Gregory and by Curtis (Section III). That model and its extensions worked well in accounting, at least qualitatively, for detailed measurements of displacement damage effects and related functional dependences.

Correlation of displacement damage with nonionizing energy loss was pursued in parallel with the above efforts during the 1960s and 1970s, and was revisited during the 1980s (Section VI). That subject continues to be of interest today because of its practical importance. A more basic aspect of that interest is the apparent disagreement between the predictions of cluster models and observations of NIEL correlation.

Current trends include: 1) application of NIEL correlation to various devices and device properties as an engineering tool for the prediction of radiation-induced degradation in applications of interest (e.g., space); 2) further characterization and modeling of the similarities and differences between the effects of different particle types and energies on device properties; and 3) exploration of successful and less successful instances of NIEL correlation.

The CERN-RD48 collaboration has performed significant studies of displacement damage mechanisms and effects in irradiated bulk Si and Si devices since 1996 [175]. Their work has emphasized development of radiation-hardened detectors for high-energy physics applications, such as for the Large Hadron Collider (LHC) project at CERN. Recent summaries of the RD48 work are given in [176], [177]. The RD48 collaboration and its successor, RD50 [178], have explored and are continuing to study several of the displacement damage areas where further understanding is needed.

Section III noted several experimental and analytical findings that need to be accounted for in a complete physical model of displacement damage effects in bulk Si and Si devices. Those findings include annealing effects and differences, impurity effects on damage factors, and scaling with nonionizing energy loss. It was also noted that modified cluster models were successful in accounting for numerous experimental observations, but that success does not mean those models are physically correct. What is clear is that *some* model is needed to explain, for example, short- and long-term annealing differences and impurity effects. We also note that, as discussed in Section VI, NIEL correlation works well in many, but not all, cases. It appears, then, that a successful general model of displacement damage effects must not only account for NIEL correlation but also simultaneously explain the various detailed phenomena and comparisons previously described within a modified Gossick framework. Development of such a unified model is a step to be taken in future work.

VIII. BIBLIOGRAPHY

A selected listing of key sources of displacement damage and related radiation effects information is provided here as a supplement to the specific literature references made in the text. Several device physics resources are also included.

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