Universal Damage Factor for Radiation-Induced Dark Current in Silicon Devices

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***Abstract*—A new damage factor formulation is presented for describing radiation-induced dark current in silicon devices. This damage factor, K_{dark}, is the number of carriers thermally generated per unit volume per unit time in a depletion region per unit nonionizing dose deposited in that volume. K_{dark} appears to account successfully for the mean radiation-induced dark current for any silicon device in which thermal generation at bulk centers dominates. This dark-current damage factor applies for devices in all radiation environments except those that produce relatively isolated defects. Evidence is presented which strongly indicates that the defects responsible for dark current increases are not associated with impurities.**

I. Introduction

EXPERIMENTAL and analytical studies of radiation-induced dark current in silicon devices conducted over the past thirty years have led to numerous insights. Successful dark-current modeling efforts have resulted for specific classes of devices, with visible imaging arrays being an important example. Early work (e.g., [1], [2] and references therein) emphasized the determination of damage coefficients for specific cases of interest, i.e., a specific particle type and energy, whereas more recent efforts have focused on developing a modeling approach that is independent of particle type and energy [3]–[6]. In addition, detector specialists within the high-energy physics community have performed significant directly related work on radiation-induced changes in silicon particle detectors (e.g., [7] and references therein). The present work builds on the early investigations and the more recent insights and approaches for the purpose of advancing our understanding of displacement damage phenomena in silicon devices. A further goal is to realize a straightforward approach for determining dark current changes accurately through analysis for any silicon device in any radiation environment. Achieving that goal would reduce the need for radiation-induced dark current measurements.

This paper addresses the mean dark (or leakage) current produced by radiation-induced generation centers in the depletion region bulk. Such centers are the dominant source of dark current in many silicon devices, although surface generation is important in some cases. Emphasis is placed on effects that occur at or near room temperature for a sufficient time after irradiation (e.g., one week) such that the defects introduced are relatively stable. Room-temperature annealing is also addressed. Five damage factors, or coefficients, are considered herein, the first four of which are employed in the literature: 1) K_g, the generation lifetime damage coefficient, which is related to the rate of lifetime degradation for a given fluence of a specific particle [1], [2]; 2) K_p, the particle damage factor, which is the increase in dark current density per unit fluence of a specific particle [3]; 3) α, the damage factor used by the high-energy physics community, which is the increase in dark current per unit damaged volume per unit fluence of a specific particle [8]; 4) K_{de}, a "damage-energy damage factor," which is the increase in dark current density per unit energy deposited in the damaged volume [4], [6]; 5) K_{dark}, the universal dark-current damage factor proposed in this work, which is the increase in thermal generation rate per unit deposited displacement damage dose. Emphasis is placed on K_{dark} here, with consideration given to the other damage factors where appropriate. Expressions are given that relate K_{dark} to the other four factors.

We present arguments and evidence herein in support of the conclusion that K_{dark} is a universal dark-current damage factor that allows accurate analytical determination of the mean radiation-induced dark current in nearly any radiation environment for any silicon device in which bulk thermal generation dominates. The only functional dependencies expected for K_{dark} are temperature and time after irradiation.

II. Dark Current Models

A. Early Modeling Approach

We begin with a summary of the early analytical description of dark current. Radiation-induced dark current density, ΔJ_d, can be expressed as (e.g., [1], [2])

$$\Delta J_d = q n_i \Phi W / K_g, \tag{1}$$

where

- q is the electronic charge,
- n_i is the intrinsic carrier concentration,
- Φ is particle fluence, and
- W is the depletion region width.

This expression assumes a uniform thermal generation rate G in the depletion region, where $G = n_i/\tau_g$. (Shroder [9] clarified the confusion in the literature regarding the definition of G. Some authors (e.g., [1], [2]) have incorrectly assumed that $G = n_i/2\tau_g$. The present work consistently uses the proper expression for G and corrects previous determinations of K_g where needed.) The generation lifetime damage coefficient for a given particle type and energy is defined through the relation

$$K_g \equiv \Phi / [(1/\tau_g) - (1/\tau_{g0})], \tag{2}$$

where τ_{g0} and τ_g are pre- and post-irradiation generation lifetimes, respectively, in the depletion region. Equation (1) applies

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for devices in which bulk thermal generation dominates in producing dark current, which is typically the case for irradiated silicon devices. (Schroder [10] describes the impact of thermal generation at device surfaces on measured generation lifetime.) The physically relevant process is thermal generation of charge in a depleted volume with dimensions specific to a given device and its operating conditions.

Assuming that a single level E_t in the silicon bandgap dominates the thermal generation process, generation lifetime is given by

$$\tau_g = \tau_p \exp[(E_t - E_i)/kT] + \tau_n \exp[-(E_t - E_i)/kT] \quad (3)$$

where E_i is the intrinsic Fermi level (midgap). The prefactors are given by $\tau_p = 1/\sigma_p v_{th} N_g$ and $\tau_n = 1/\sigma_n v_{th} N_g$, where σ_n and σ_p are the electron and hole capture cross sections, respectively, v_{th} is thermal velocity, and N_g is the generation center density. Note that (3) does not distinguish between pre- and post-irradiation lifetimes. It is a general single-level expression for any generation lifetime, i.e., either τ_g or τ_{g0}.

The radiation-induced dark current formulation given by (1)–(3) provides a clear link to the basic mechanisms of dark current introduction, i.e., increased thermal generation of carriers at radiation-induced generation centers. The damage coefficient, K_g, is a quantitative measure of the effectiveness of generation center introduction by particles of a given type and energy. However, the key limitation of that approach [i.e., (1) and (2)] to determining dark current is that a value for K_g is needed for every particle type and energy of interest, which necessitates an experimental determination in each case.

B. More Recent Modeling Approaches

Detector specialists in the high-energy physics community commonly use a radiation-induced leakage current damage factor, α, defined as [8]

$$\alpha \equiv \Delta I_{dv}/\Phi. \quad (4)$$

In this expression, ΔI_{dv} is the radiation-induced increase in dark current per unit volume in a depletion region damaged by a fluence of a specific particle. As in the case of K_g, α also depends on the particle type and energy used in the irradiation.

Burke [11], Summers *et al.* [12], and Dale *et al.* [13] developed a very valuable approach to assessing displacement damage effects in a wide variety of devices. Their method involves using the nonionizing dose deposited in a device as the key factor for determining the degradation of a specific device property. The nonionizing dose, or displacement damage dose (D_d), is given by the product of the particle fluence and the rate of nonionizing energy loss (NIEL). NIEL has been determined for semiconductor materials and particle types and energies of common interest, and a general approach to determining NIEL for any material and particle was described recently [14].

Dale *et al.* [3] studied dark current in irradiated silicon CID (charge injection device) imagers and defined a damage factor as $\Delta J_d/\Phi$. That factor is referred to here as a "particle damage factor," K_p, which gives the increase in dark current density per unit fluence of a specific particle:

$$K_p \equiv \Delta J_d/\Phi. \quad (5)$$

Dale found that K_p scaled linearly with NIEL. This scaling can also be expressed as $\Delta J_d \propto D_d$ since $D_d = (\text{NIEL})(\Phi)$. It is well established experimentally that radiation-induced dark current scales linearly with fluence for irradiation with a given particle. It then follows directly that ΔJ_d will scale linearly with D_d. Also note that K_p and α are related through the depletion width; i.e., K_p is equal to $W\alpha$.

Marshall *et al.* [4], [6] modeled mean radiation-induced dark current and its pixel-to-pixel distribution, or variation, for specific silicon imaging arrays. Their model employed the damage energy (E_d) deposited in a depleted volume, which is that fraction of the available particle energy lost through nonionizing processes. Here we express their work in terms of a "damage-energy damage factor," K_{de}:

$$K_{de} = \Delta J_d/E_d. \quad (6)$$

K_{de} is the mean radiation-induced increase in dark current density per unit amount of damage energy deposited in the depletion region.

The present work builds on that of Marshall and Dale [3]–[6] in that we also relate radiation-induced dark current to the nonionizing dose deposited in the depletion region bulk. We make use of D_d to take advantage of the simplifications offered by that concept. In addition, we incorporate features of the earlier formulation for dark current, as expressed by (1)–(3), so that important functional dependences of damage introduction are included where appropriate. We also employ the numerous experimental and analytical studies of α for particle detectors to broaden the utility of the current work.

Differences between this work and [3]–[6], [8] include: a) expressing the dark current damage factor, termed K_{dark} here, in terms of the radiation-induced increase in *thermal generation rate* per unit displacement damage dose deposited in the depleted volume; b) providing evidence to demonstrate the universality of the K_{dark}-based approach to modeling mean dark current in any silicon device in which bulk thermal generation dominates. The first difference simply reflects reformulation of the damage factors given by (4)–(6). The second difference is more significant in view of the evidence for generality provided herein.

C. Present Model

Dark current is modeled in the present work in terms of the radiation-induced increase in thermal generation rate, ΔG, per unit displacement damage dose deposited in a depleted volume. The dark-current damage factor is defined here as

$$K_{dark} \equiv \Delta G/D_d. \quad (7)$$

This expression is more basic than previous approaches used in the literature (described above) to define a dark-current damage factor. The physical process involved is introduction of generation centers by displacement damage. Those centers cause the generation rate to increase, and the proportionality factor relating that increase to the dose deposited is K_{dark}. Thus, K_{dark} is the number of carriers thermally generated per unit volume per unit time in a depletion region per unit nonionizing dose deposited in that volume.

It is straightforward to determine dark current density once K_{dark} is known. The relationship is

$$\Delta J_d = qWD_dK_{dark}, \tag{8}$$

where D_d is the displacement damage dose deposited during a given irradiation of a specific device having a depletion region width W. Similarly, the dark current per unit depleted *volume* ($\equiv \Delta I_{dv}$) is given by qD_dK_{dark}.

It is also of interest to relate K_{dark} to the other damage factors discussed above (i.e., K_g, α, K_p, and K_{de}):

$$\begin{aligned} K_{dark} &= [n_i/(\mathrm{NIEL})](K_g)^{-1} = [1/\{(q)(\mathrm{NIEL})\}]\alpha \\ &= [1/\{(qW)(\mathrm{NIEL})\}]K_p = [A\rho/q]K_{de}. \end{aligned} \tag{9}$$

In these relationships, ρ is the silicon density and A is the cross-sectional area of a specific depletion region (e.g., that portion of the pixel area in an imager corresponding to the depleted volume for that pixel). Note that the expression in (9) that relates K_{dark} to K_g only applies for a specific type and energy of irradiating particle since K_g is defined in that comparatively restricted manner, as discussed above. A similar statement applies for the relationships in (9) between K_{dark} and both α and K_p, as defined by (4) and (5). (It is straightforward to convert α and K_p to D_d-based damage factors.) The damage factor definitions for K_{dark} and K_{de} are based on the displacement damage dose deposited by irradiation with *any* particle type and energy.

Combining the K_g relationship in (9) with (2) yields

$$K_{dark} = n_i\Delta(1/\tau_g)/D_d, \tag{10}$$

where $\Delta(1/\tau_g) = [(1/\tau_g) - (1/\tau_{g0})]$. This expression is used in the next section to consider the defect(s) responsible for radiation-induced dark current. It is shown there that measurements of $\Delta(1/\tau_g)$ for neutron-irradiated silicon devices yield a linear dependence of that quantity on fluence, and thus degradation of generation lifetime is directly proportional to displacement damage dose. Therefore, $\Delta(1/\tau_g)/D_d$ is a constant for specific measurement conditions. That analysis then suggests that K_{dark} is a constant at a fixed temperature and time after irradiation and is independent of particle type and energy since displacement damage dose is employed.

III. Considerations Regarding the Origin of Radiation-Induced Dark Current

Fig. 1 presents measurements of $\Delta(1/\tau_g)$ for fission-neutron-irradiated MOS capacitors [1]. These data are based on measured capacitance-time transients, followed by Zerbst analysis, which yields bulk generation lifetime. Data in Fig. 1 were obtained for capacitors fabricated on both n-type and p-type bulk silicon, and several processing variations were employed. Even with those significant differences among devices, all data are in excellent agreement and yield a single value for generation lifetime damage coefficient. That finding is interpreted here in a manner we did not previously realize.

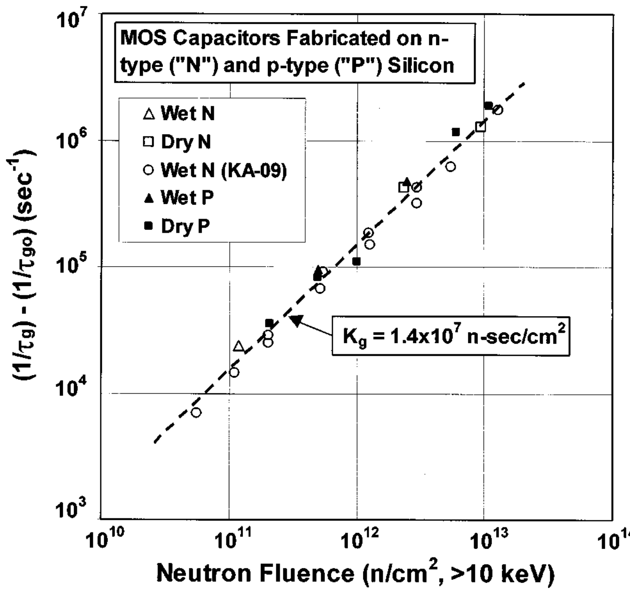

Fig. 1. Generation lifetime degradation in neutron-irradiated MOS capacitors fabricated on n- and p-type silicon using several device processing variations [1]. The unity-slope fit to the data yields a generation lifetime damage coefficient, K_g, that applies for depletion regions in both n- and-p-type material.

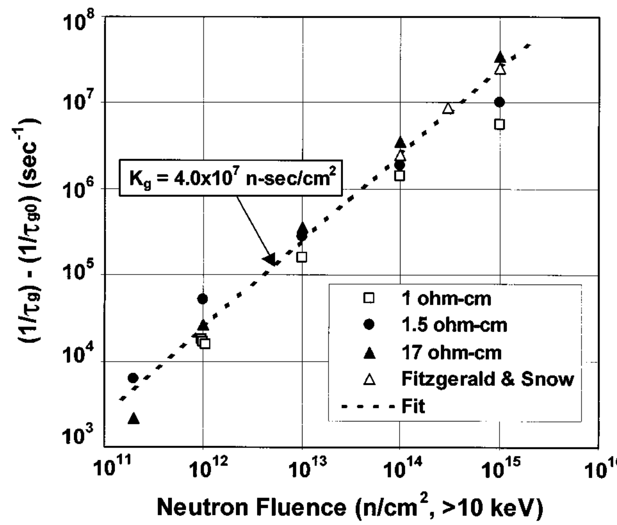

Fig. 2. Generation lifetime degradation in several types of neutron-irradiated p^+n gate-controlled diodes (Kawamoto and Oldham [15]). The unity-slope fit to the data shown here differs slightly from the fit given in [15]. Data of Fitzgerald and Snow [16] are also shown (specifically, the field-induced junction data in [16]).

Fig. 2 shows a similar result for fission-neutron-irradiated p^+n gate-controlled diodes [15], [16]. Agreement is good among several device variations for two different research teams, and yields a single value for K_g. The scatter in the data in Fig. 2 may be due to room-temperature annealing effects and measurement temperature variations. The factor of ~2.9 difference between the damage coefficient values in Figs. 1 and 2 is mostly attributable to differences in measurement temperature and time after irradiation (addressed in Section IV). An approximate application of those corrections reduces this difference to a factor of ~1.8. The remaining discrepancy is most likely due to the lack of detailed information regarding the experimental conditions.

Deposition of nonionizing dose creates generation centers with energy levels in the silicon bandgap, and those centers result in increased thermal generation of charge, i.e., τ_g decreases. K_g is inversely proportional to the introduction rate of generation centers for irradiation with a given particle type at a specific energy (or energy spectrum). From (2), K_g is related to the resulting amount of lifetime reduction at a given fluence. For K_g to agree exactly for n- and p-type silicon (Fig. 1), then it is highly likely that the defect, or defects, that gives rise to the dominant generation center is the same for both material types. This observation strongly suggests that the dominant defect is not impurity related. Clearly, that defect is not related to the dopants (boron and phosphorus). Also, it is most probably not related to some other impurity because it is unlikely that the identical impurity type and concentration would exist in five device lots that were processed differently and used different starting material (Fig. 1).

Recently, Moll *et al.* [17] (see [7] also) demonstrated that the damage factor α associated with the leakage current increase in fast-neutron-irradiated detectors is the same for p^+n and n^+p diodes. Their results covered nearly a four-order-of-magnitude variation in oxygen concentration in the starting material used. A wide variation in the resistivities of p- and n-type silicon material was also covered (a factor of 5 to more than two orders of magnitude, respectively). The carbon concentration also varied by more than a factor of four. For these material conditions, α was shown to be independent of dopant type and concentration and of impurity concentration. (Their results [17] are reminiscent of the early findings by Curtis [18] in which the *recombination* lifetime damage coefficient for neutron-irradiated silicon was shown to be independent of impurity type and concentration. The defects responsible for recombination lifetime degradation are most likely different from those responsible for generation lifetime degradation, although recombination and generation through different energy levels of the same defect is a possibility.)

The experimental results discussed above [1], [15]–[17] span thirty years in device fabrication technology and cover a broad range of starting materials. Those results strongly indicate that the radiation-induced defect (or defects) which gives rise to dark current is not associated with impurities, including the dopants plus oxygen and perhaps carbon, and further suggests that the responsible lattice flaw is a fundamental defect which is intrinsic to silicon. The most basic defects are the vacancy and interstitial, which are quite mobile at room temperature and thus are unstable. The divacancy is a nonimpurity-related defect in silicon that is well established as being stable at room temperature and is abundantly present. Thus, the divacancy (or perhaps a higher-order vacancy) is an obvious candidate for the defect that dominates dark current production at room temperature.

Watts *et al.* [19] identified three defects as being responsible for dark current in neutron-irradiated devices: the divacancy and two other unknown defects, all of which evidently are not impurity related. One of those unspecified defects exhibited a significant annealing stage at ~70°C. Watts noted that the corresponding annealing time constant at room temperature would be on the order of two weeks, which is at least qualitatively consistent with experimental annealing observations discussed below. Thus, one of the unknown defects observed by Watts may account for a significant portion of observed room-temperature annealing in irradiated devices. The suggestion here is that the divacancy does play a significant role in producing dark current, but is not responsible for the spontaneous annealing behavior since it anneals at relatively high temperatures. Clarifying these issues will require further study.

Calculation of K_{dark} requires detailed knowledge of the properties of the dominant defects responsible, which generally is not available. An approach to such calculations is briefly outlined here for reference. Equations (3) and (10) can be combined to express K_{dark} in terms of capture cross sections, energy level position, and the defect introduction rate per unit displacement damage dose. Using the divacancy as an example, relatively broad ranges for defect introduction rate and capture cross sections are given in the literature. There is also some uncertainty in the energy level position. Thus, although in principle one can calculate K_{dark}, in practice the resulting uncertainty is quite large even for the relatively straightforward case of the divacancy.

Under the present model, K_{dark} is predicted to be a constant for all silicon devices at a fixed temperature and time after irradiation. The next section considers the temporal and temperature dependences of K_{dark}. Subsequently, we present our examination of literature data from which K_{dark} is determined, based on measurements on various types of devices, and then examine its generality.

IV. Temporal and Temperature Dependences

Numerous workers have measured the temperature dependence of bulk thermally generated dark current for both unirradiated and irradiated silicon devices. Generally, the measurements are presented as an Arrhenius plot, and an activation energy, ΔE, is determined. Examples are given here for the purpose of selecting a representative temperature dependence to use with the present modeling of mean dark current. Kern and McKenzie [20] obtained $\Delta E = 0.62$ eV before and after irradiation for leakage current measurements on 14.8-MeV neutron-irradiated JFET's. Srour *et al.* [1] obtained $\Delta E = 0.64$ eV before and after irradiation for storage time measurements on MOS capacitors irradiated with fission neutrons. (Storage time is proportional to generation lifetime.) Hopkinson *et al.* [21] noted an activation energy of ~0.64 eV for most of the pixels in an irradiated silicon charge-coupled device (CCD). Hopkinson [22] reported a ΔE of 0.633 eV for 10-MeV proton-irradiated CCD's. Other workers have measured ΔE values in the range from 0.57 to 0.68 eV.

In the present work, we employ an activation energy of 0.63 eV as a reasonable representation of the temperature dependence of dark current associated with thermally generated charge. (The indication by some studies that this activation energy is also appropriate for unirradiated devices suggests that the same defect may be responsible before and after bombardment. However, other explanations are possible, such as a pre-irradiation energy level with nearly the same

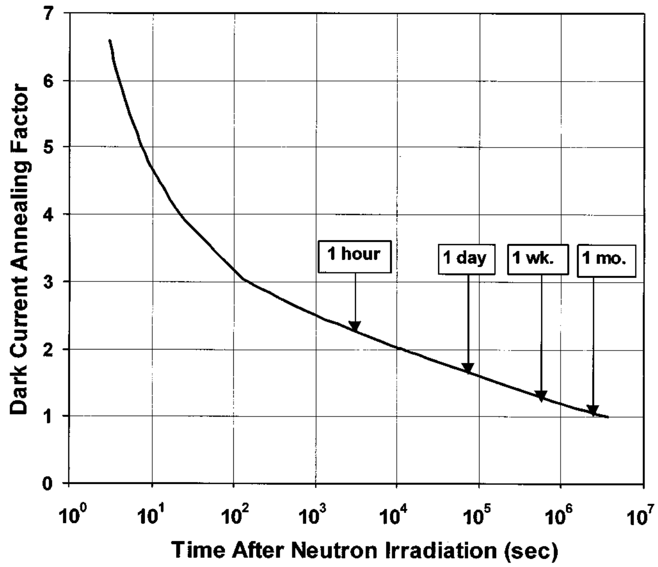

Fig. 3. Dark current annealing factor (AF) versus time following neutron bombardment [25]. AF is arbitrarily normalized to unity at 1000 hours.

characteristics, i.e., location and capture cross sections, but arising from a type of defect different from that dominating after irradiation.) Thus,

$$\Delta J_d,\ K_{dark} \propto \exp(-0.63\ \mathrm{eV/kT}). \tag{11}$$

We now address the temporal dependence of dark current following irradiation. It is well established that significant room-temperature annealing occurs in silicon devices following irradiation, including bombardment with neutrons, protons, electrons, and other particles. Examples for particle detectors are given in [7], [17], and [23]. We use our earlier data for neutron-irradiated devices [2], [24], [25] to estimate the annealing behavior of K_{dark}.

Measurements of dark current in CCD's as a function of time following pulsed fission neutron bombardment [2], [24] exhibited considerable annealing at room temperature over the time regime from 2 sec to 10 000 sec. Subsequent long-term annealing measurements on 14-MeV neutron-irradiated CCD's [25] showed annealing continuing to 1000 hours (3.6×10^6 sec), where the measurements were terminated. CCD's irradiated with 99-MeV protons also exhibited significant annealing continuing to 1000 hours after bombardment [26]. Fig. 3 shows a composite of observed annealing behavior for neutron-irradiated CCD's [25]. Plotted is annealing factor (AF) versus time, where

$$\mathrm{AF} = [J_d(t) - J_d(0)]/[J_d(\infty) - J_d(0)]. \tag{12}$$

In this expression, $J_d(0)$ and $J_d(t)$ are the dark current densities before irradiation and at any time t after irradiation, respectively. $J_d(\infty)$ is the dark current density at some sufficiently long time after bombardment when annealing is essentially complete. In Fig. 3, we arbitrarily use a time of 1000 hours for determining $J_d(\infty)$, although it is evident that annealing is not yet complete at that time.

Fig. 3 can be used to normalize dark current measurements made at different times following irradiation to a specific time. This approach allows measurements made by various workers to be compared more accurately. Not all researchers have observed dark current annealing [3], which appears to be an exception to the many studies in the literature that show spontaneous room-temperature annealing of dark current.

To summarize this section, (11) provides a reasonable assumption for the temperature dependence of ΔJ_d and K_{dark}, and Fig. 3 gives the estimated temporal dependence for those quantities following irradiation at room temperature. This information allows data obtained under varying conditions of time and temperature to be compared.

V. Determination of Universal Dark-Current Damage Factor Using Literature Data

Equations (8) and (9) allow K_{dark} to be determined from literature data. If dark current density and depletion width, or depletion volume, are available in a given reference, (8) is used to determine K_{dark}. That information is commonly found. If K_g, α, K_p, or K_{de} are specified, then (9) leads to K_{dark}. We evaluated literature data for numerous types of silicon devices irradiated with protons, neutrons, electrons, pions, heavy ions, and photons of various energies. For comparison purposes, dark current data were corrected to 300 K when the measurement temperature was specified. If it is not specified, then 300 K is assumed. Regarding temporal differences, many references do not specify the time at which measurements were made following irradiation. In a common case historically, devices were irradiated and then measured at a convenient later time, typically days to several weeks. If no measurement time is specified, we assumed it to be one week post-irradiation. If a measurement time is given, we then corrected the dark current data to one week after bombardment using Fig. 3. (No distinction was made here between annealing *during* a relatively slow irradiation and annealing *following* relatively rapid bombardment.) Also, if a specific reference provided annealing results, that information was used here to correct the data to one week. Clearly, the lack of detailed measurement time and temperature information in a portion of the literature examined introduces error into the determination of K_{dark}.

For all cases in which fission neutrons were used, we employed the NIEL value for 1-MeV neutrons (2.02×10^{-3} MeV cm^2/g) as an approximation in determining K_{dark}. That approximation is good for a TRIGA reactor spectrum where the fluence of neutrons with energy $>$10 keV is approximately equal to the 1-MeV-equivalent neutron fluence for a typical shielding configuration.

Table I lists values for K_{dark} determined from our analyses of literature data. Note that a wide variety of devices were considered, including MOS and bipolar technologies plus devices fabricated on both p-type and n-type silicon, and that the references cited encompass thirty years of device technologies. Fig. 4 presents all data listed in Table I. Plotted is the radiation-induced increase in thermal generation rate per unit fluence, which equals the product of K_{dark} and NIEL, versus the displacement damage dose per unit fluence, which equals NIEL. The slope in the linear regime yields K_{dark}.

TABLE I
VALUES FOR DARK-CURRENT DAMAGE FACTOR DERIVED FROM LITERATURE DATA FOR VARIOUS IRRADIATED SILICON DEVICES. DATA ARE TEMPERATURE-CORRECTED TO 300 K AND TIME-CORRECTED TO 1 WEEK POST-IRRADIATION WHERE APPROPRIATE. THE MEAN DAMAGE FACTOR AND ITS STANDARD DEVIATION, BASED ON ALL LISTED VALUES EXCEPT THOSE FOR LOW-ENERGY ELECTRONS (<2 MeV) AND ^{60}Co IRRADIATION, IS $(1.9 \pm 0.6) \times 10^5$ carriers/cm^{3}sec PER MeV/g

Particle Type	Device Type	Refs.	K_{dark}	Comments
fission neutrons	npn transistor	[27]	1.6×10^5	Assumes 300 K and 1-MeV neutron NIEL
14.8-MeV neutrons	JFET	[20]	2.3×10^5	Measured at 300 K
fission neutrons	p^+n diode	[15]	1.8×10^5	Data shown here in Fig. 2. Assumes 1-MeV neutron NIEL.
fission neutrons	p^+n diode	[16]	1.8×10^5	Data shown in here Fig. 2. Assumes 300 K and 1-MeV neutron NIEL.
fission neutrons	npn transistor	[28]	2.7×10^5	Assumes 300 K and 1-MeV neutron NIEL
fission neutrons	pnp transistor	[28]	1.9×10^5	Assumes 300 K and 1-MeV neutron NIEL
14-MeV neutrons	pn diode array	[29]	2.6×10^5	Assumes 300 K
fission neutrons	MOS capacitor (n-Si)	[1]	3.2×10^5	Data in Fig. 1. K_{dark} corrected from 2 hours post-rad to 1 week post-rad using Fig. 3. Assumes 300 K.
fission neutrons	MOS capacitor (p-Si)	[1]	3.2×10^5	Data in Fig. 1. K_{dark} corrected from 2 hours post-rad to 1 week post-rad using Fig. 3. Assumes 300 K.
fission neutrons	n-channel CCD	[24]	2.9×10^5	Corrections: 298 K to 300 K and from 3 days to 1 week post- rad. Used W = 5.6 μm. Assumes 1-MeV neutron NIEL.
14-MeV neutrons	n-channel CCD	[25]	2.3×10^5	Based on K_g determined from measured average change in dark current density per neutron interaction. Corrected from 303 K to 300 K using (11) and corrected from measurement time to 1 week post-rad.
99-MeV protons	n-channel CCD	[26]	1.3×10^5	Based on K_g determined from measured average change in dark current density per proton interaction. Corrected from 303 K to 300 K using (11) and corrected from measurement time to 1 week post-rad.
147-MeV protons	n-channel CCD	[26]	1.4×10^5	Based on K_g determined from measured average change in dark current density per proton interaction. Corrected from 303 K to 300 K using (11) and corrected from measurement time to 1 week post-rad.
12-MeV protons	CID (n-Si)	[3]	2.1×10^5	Based on K_p value in [3]. Converted K_p to dark current per unit volume using 17 x 17 μm pixel area and depletion region volume given in [5]. Corrected from 291 K to 300 K. No time correction.
22-MeV protons	CID (n-Si)	[3]	2.1×10^5	Same comments as those for CID immediately above
63-MeV protons	CID (n-Si)	[3]	1.8×10^5	Same comments as those for CID immediately above
fission neutrons	CID (n-Si)	[3]	1.5×10^5	Same comments as those for CID immediately above
10-MeV protons	n-channel CCD	[22]	1.8×10^5	Based on K_p calculated in [22] from model fit to data. W = 4 μm. Corrected from 294 to 300 K.
10-MeV protons	n-channel CCD	[21]	1.3×10^5	Based on K_p value in [21]. Used 19 x 19 μm pixel area and an assumed depletion region volume of 19 x 15 x 4 μm. Corrected from 293 K to 300 K.
55-MeV protons	p-channel CCD	[35]	2.1×10^5	Assumes 300 K and W = 4 μm.
18-MeV ^{16}O ions	p^+n diode	[32]	1.3×10^5	No time or temperature corrections made. Assumes 300 K. Uses NIEL values from [32].
41-MeV ^{16}O ions	p^+n diode	[32]	9.9×10^4	No time or temperature corrections made. Assumes 300 K. Uses NIEL values from [32].
93-MeV ^{16}O ions	p^+n diode	[32]	1.9×10^5	No time or temperature corrections made. Assumes 300 K. Uses NIEL values from [32].
150-MeV ^{16}O ions	p^+n diode	[32]	2.1×10^5	No time or temperature corrections made. Assumes 300 K. Uses NIEL values from [32].
20-MeV ^{40}Ar ions	p^+n diode	[32]	1.7×10^5	No time or temperature corrections made. Assumes 300 K. Uses NIEL values from [32].
53-MeV ^{110}Xe ions	p^+n diode	[32]	7.7×10^4	No time or temperature corrections made. Assumes 300 K. Uses NIEL values from [32].
fission neutrons	pin diode	[37]	1.2×10^5	Assumes 300 K and 1-MeV neutron NIEL
24-GeV protons	pin diode	[37]	2.1×10^5	Assumes 300 K and an approximate NIEL value of 8×10^{-4} MeV cm^2/g
800-MeV protons	pin diode	[30]	3.2×10^5	Uses NIEL value of 1.75×10^{-3} MeV cm^2/g. Corrected from 293 K to 300 K.
500-MeV protons	p^+n diode	[31]	1.4×10^5	Uses NIEL value of 1.87×10^{-3} MeV cm^2/g. Corrected from 293 K to 300 K. Corrected to 1 week post-rad.
6.2-MeV neutrons	p^+n and n^+p diodes	[17]	2.4×10^5	Average for 11 device types. Corrected to 1 week post-rad and from 293 to 300 K. Normalized to 1-MeV neutron NIEL.
190-MeV pions	pin diode	[33]	1.2×10^5	Corrected from 298 to 300 K. Corrected to 1 week post-rad. Assumes NIEL of $\sim3.2\times10^{-3}$ MeV cm^2/g [48].
500-MeV electrons	pin diode	[34]	3.0×10^5	Average K_{dark} for 12 devices. Assumed 298 K and corrected to 300 K. Used 40% annealing over 1 week period [34].
5.2-GeV ^{86}Kr ions	p^+n diode	[36]	1.4×10^5	Assumes 300 K. We calculated average NIEL to be ~2.8 MeV cm^2/g.
fission neutrons	p^+n diode	[36]	1.7×10^5	Assumes 300 K and 1-MeV neutron NIEL
1.5-MeV electrons	p^+n diode	[36]	1.5×10^4	Assumes 300 K
1.0-MeV electrons	p^+n diode	[38]	1.3×10^3	300 K measurements
1.0-MeV electrons	n^+p diode	[38]	4.9×10^3	Discrepancy noted in leakage current data in [38]. K_{dark} is possibly a factor of ~4 smaller.
1.8-MeV electrons	diode on n-Si	[39]	4.1×10^3	Assumes 300 K. Corrected from immediately after irradiation to 1 week post-rad using annealing data in [39].
^{60}Co photons	pin diode	[19]	1.4×10^3	Corrected to 300 K. Converted from photons to electrons. Used NIEL value of 1.31×10^{-5} MeV cm^2/g [44].
^{60}Co photons	pn diode	[23]	4.0×10^3	Assumed 293 K; corrected to 300 K. Converted from photons to electrons. Used NIEL value of 1.31×10^{-5} MeV cm^2/g [44].

With the exception of results for relatively low energy electrons (i.e., <2 MeV) and ^{60}Co photons, which are discussed below, K_{dark} values are in reasonable agreement in view of the various assumptions made. The fit to the data spans many orders of magnitude in displacement damage dose, and yields a single value for K_{dark} that accounts well for the data. The mean and standard deviation for all K_{dark} values in Table I, except those for low-energy electrons and ^{60}Co photons, are $(1.9 \pm 0.6) \times 10^5$ carriers/cm^{3}sec per MeV/g. That damage factor applies for the broad variety of devices and irradiation conditions examined, including bombardment with protons, neutrons, pions, and heavy ions. Specific devices included are CID's, n- and p-channel CCD's, npn and pnp bipolar transistors, JFET's, MOS capacitors on n- and p-type Si, and diode detectors fabricated on n- and p-type material with a wide range of dopant and impurity concentrations. As noted above, the primary source of error in the K_{dark} value given here is uncertainties in the experimental conditions for the literature sources used. In spite of those uncertainties, data in Fig. 4 are described well by that value for the linear regime. Well-defined and controlled experiments over a range of NIEL values in principle would remove a significant portion of the error from the present value of K_{dark}.

Heavy-ion data [32], [36] are included in Fig. 4, and are in reasonable agreement with other data in terms of defining a universal damage factor. (A graph similar to Fig. 4 is given in [32]. They correlated their heavy ion results with data for several proton-irradiated detectors by NIEL scaling. Several other groups of detector specialists in the high-energy physics community have also observed NIEL scaling.) To validate the nonionizing dose information given in [32] for heavy ions, we used the methodology recently provided in [14] and obtained agreement within a factor of less than 2. Fig. 4 uses the NIEL values calculated in [32].

Data for bombardment with alpha particles ([40]–[42] and elsewhere) are not included in Fig. 4. Preliminary assessment of those studies indicates that more detailed information is needed about the structure of the irradiated devices and the experimental conditions so that accurate analytical determinations of the average, or effective, displacement damage dose (i.e., NIEL) can be made. Our preliminary analyses of selected alpha-particle data yielded K_{dark} values in reasonable agreement (i.e., within

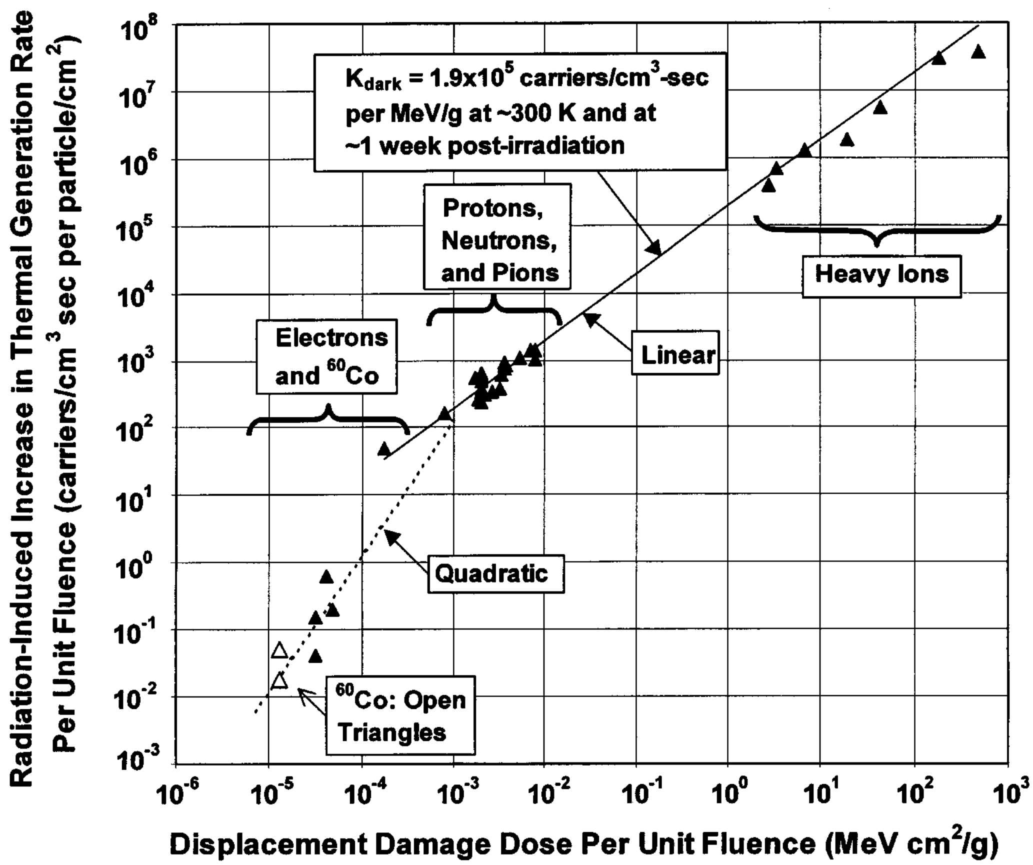

Fig. 4. Radiation-induced increase in thermal generation rate per unit fluence (equals the product of K_{dark} and NIEL) versus the displacement damage dose deposited per unit fluence (equals NIEL). Data points are based on information presented in Table I.

a factor of 2) with the present mean value in some cases, but in other cases yielded disagreement by as much as a factor of 10. Again, those analyses are very approximate due to insufficient experimental information. We expect that dark current increases produced by alpha particle irradiation will agree with the general behavior exhibited in Fig. 4 once accurate analyses are conducted.

Data for devices irradiated with a low-energy electron spectrum from a ^{90}Sr source [34], [43] are also not yet included in Fig. 4. Caution must be exercised because that spectrum produces a nonuniform displacement damage distribution in a depletion region. To determine K_{dark} accurately, one must account for that distribution in determining the radiation-induced increase in dark current. That determination is based on measurements for a depleted volume containing an undamaged region in addition to the nonuniformly damaged zone. Separation of the two components requires detailed knowledge of the damage profile and accurate determination of an effective damaged volume to employ in K_{dark} calculations. We have not performed those detailed analyses, but expect the results will be in agreement with the trend of the data in Fig. 4 for low-energy electron irradiation. These same considerations apply for any particle that produces a nonuniform damage distribution.

Most of the data for low-energy electrons (i.e., $<$2-MeV) shown in Fig. 4 deviate significantly from the linear behavior exhibited in all other cases. (The ^{60}Co data agree with low-energy electron data, which is consistent since the displacement damage produced by ^{60}Co photons is due to Compton electrons with energy less than 1 MeV. Literature damage factors for ^{60}Co bombardment [19], [23] were converted here to an equivalent electron damage factor by converting the photon flux to a secondary electron flux [44]). Summers *et al.* [45] observed a similar deviation from linearity for electron-irradiated solar cells fabricated on p-type silicon, but not for n-type cells. A quadratic dependence on NIEL accounted for their data well. In Fig. 4, a quadratic dependence is illustrated which appears to describe the present low-energy electron and ^{60}Co data reasonably well, although clearly more data are needed. Understanding the detailed physical significance of this apparent dependence will require further study. The nonlinear regime is important in practice for space applications since that environment is often dominated by electrons with energy in the MeV range.

There are several differences between the present findings and those of Summers [45]. First, deviation from linearity is evident here for both p-type *and* n-type devices, whereas Summers observed linearity for n-type and a quadratic dependence for p-type material. Second, *linearity* is also evident here for both p-type and n-type devices. Third, Summers' study involved diffusion length, i.e., *recombination lifetime*, degradation whereas the current work addresses *generation* lifetime changes. Different defects generally dominate recombination compared to generation, so observing identical dependencies on NIEL in both cases for low-energy electrons is not expected.

Additional work is needed to clarify and understand the behavior evident here at low NIEL values.

Regarding differences between the linear behavior in Fig. 4 for all particles except low-energy electrons and the nonlinear behavior in the latter case, one aspect to consider is the significant contrast in defect densities. In the nonlinear regime, the defects are relatively isolated compared to those produced by particles in the linear region. Watts *et al.* [19] and Gill *et al.* [23] addressed the possibility that enhanced thermal generation occurs when defects are closely spaced.

For the linear regime, where a single value of K_{dark} describes the data well, no dependence on impurity type or concentration is evident, as discussed in Section III. However, it remains to be established whether such a dependence exists in the nonlinear regime. For *recombination* lifetime degradation, it is well established that the associated radiation damage does depend on impurity type and concentration for particles that produce relatively isolated defects. For example, Curtis [49] has reviewed such dependencies for electron- and gamma-irradiated silicon. Caution should be used when applying information in the nonlinear regime in Fig. 4 until systematic studies of the impurity dependence of K_{dark} are performed.

Robbins [46] recently modeled dark current distributions for irradiated CCD's. His model includes an expression for the mean bulk dark current that yields a value in good agreement with the mean K_{dark} determined here.

K_{dark} is independent of all variables in all silicon devices except temperature and time after irradiation under the present description, with the exception of low-energy electron irradiation. The value for damage factor determined here applies at 300 K for relatively stable damage, i.e., after approximately one week at room temperature. As discussed above, temperature and time corrections can be made using (11) and Fig. 3, respectively, for other times and temperatures of interest. For example, the dark-current damage factor one hour after irradiation is predicted to be 3.2×10^5 carriers/cm^{3}sec per MeV/g at 300 K.

Using the present damage factor to predict radiation-induced dark current for a specific silicon device is straightforward in many cases, i.e., when the damage distribution in the depletion region is relatively uniform. First, the displacement damage dose deposited in the damaged portion of the depletion region is determined for the radiation environment of interest. Determining D_d for irradiation with penetrating monoenergetic particles requires only the fluence and the NIEL value. Obtaining D_d for an energy spectrum is more involved but relatively straightforward (e.g., see [14], [21], [47]). The next step is to use (8) in conjunction with the universal damage factor and the depletion region width to obtain the dark current density. One can express the dark current density in any manner desired. For example, referencing ΔJ_d to the pixel area is a common practice for imaging arrays. Also, note that the dark current per unit volume, ΔI_{dv}, can be determined directly from K_{dark} and D_d without knowledge of the depletion width. The main caution in using K_{dark} to predict dark current is to be aware of the linear and nonlinear regimes in Fig. 4. The universal value obtained here only applies in the linear regime, e.g., for proton and neutron irradiations. For electrons with energies in the MeV range, i.e., for NIEL values on the order of 10^{-4} MeV cm^2/g or lower, a NIEL-dependent K_{dark} applies.

VI. Conclusion

We have described an approach for determining by analysis the mean radiation-induced dark current in *any* silicon device. This approach appears to be appropriate for any irradiating particle type and energy except for radiation environments that produce relatively isolated defects, such as low energy electrons. No scale factors are involved, other than those for time and temperature, and no measurements are needed. Well-controlled validating experiments and accompanying theoretical analyses would be of value in future efforts. The key to understanding the universality of the damage factor presented here is recognizing that the dominant defects that give rise to radiation-induced dark current are independent of dopant and impurity type and concentration. That realization provides support for the divacancy and/or other intrinsic lattice flaws as the defects responsible for dark current increases.

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