Author(s): Niskanen, Kimmo; Kettunen, Heikki; Lahti, Mikko; Rossi, Mikko; Jaatinen, Jukka; Söderström, Daniel; Javanainen, Arto

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Effect of 20 MeV Electron Radiation on Long Term Reliability of SiC Power MOSFETs

K. Niskanen, *Member, IEEE*, H. Kettunen, *Member, IEEE*, M. Lahti, M. Rossi, *Member, IEEE*, J. Jaatinen, *Member, IEEE*, D. Söderström, *Student Member, IEEE* and A. Javanainen, *Member, IEEE*

***Abstract*—The effect of 20 MeV electron radiation on the lifetime of the silicon carbide power MOSFETs was investigated. Accelerated constant voltage stress (CVS) was applied on the pristine and irradiated devices and time-to-breakdown (T_{BD}) and charge-to-breakdown (Q_{BD}) of gate oxide were extracted and compared. The effect of electron radiation on the device lifetime reduction can be observed at lower stress gate-to-source voltage (V_{GS}) levels. The models of T_{BD} and Q_{BD} dependence on the initial gate current (I_{G0}) are proposed which can be used to describe the device breakdown behaviour.**

***Index Terms*—Electron irradiation, long term reliability, power MOSFET, silicon carbide (SiC), time-dependent dielectric breakdown (TDDB)**

I. Introduction

SILICON carbide (SiC) has gained interest in critical applications due to its superior material properties over silicon. SiC has high critical electric field, high thermal conductivity and high melting point which are favourable properties where high power density is needed [1]. However, it has been found that SiC power devices are sensitive to destructive single event effects due to heavy ion impact in space radiation environment [2]. The majority of studies which reported radiation effects on such devices, indeed focus on catastrophic effects, such as single event burnout (SEB) and single event gate rupture (SEGR). Moreover, the degradation of gate oxide and drain leakage in SiC power devices due to heavy ion and neutron impact has been reported in several studies [3]–[8].

During their operation in the space environment, on top of the radiative stress, electronic devices are exposed to electrical stress, and as for any system, reliable operation of power electronics devices is needed for full desired lifetime of the system. Therefore, on top of the sensitivity to catastrophic failures, it is important to assess if the operation in radiation environments causes a reduction in lifetime of these devices. The effect of electron and gamma irradiation on electrical stress response for silicon-based technologies has been found to be relatively weak below 10 kGy total ionizing dose (TID) levels showing mainly increased leakage current through the gate dielectric [9]–[11].

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K. Niskanen, H. Kettunen, M. Lahti, M. Rossi, J. Jaatinen, D. Söderström and A. Javanainen are with Accelerator Laboratory, Department of Physics, University of Jyvaskyla, P.O. Box 35, FI-40014 University of Jyvaskyla, Finland (e-mail: kimmo.h.niskanen@jyu.fi).

A. Javanainen is also with Electrical and Computer Engineering Department, Vanderbilt University, Nashville, TN 37235, USA

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However, the effect of electron radiation on the SiC power device long term reliability is still unknown. The main degradation mechanism caused by the electrons on SiC MOSFETs is commonly considered to be the total ionizing dose (TID) and a resulting degradation in transfer characteristics [12]–[14]. Fortunately, the effects of TID on the transfer characteristics of SiC power MOSFETs have been found to be moderate, except at high dose levels [15], [16]. However, energetic electrons can interact with the material also through the non-ionizing energy loss (NIEL) resulting in knock-on damage, which refers to displacement of atoms in the target material [17]. Especially, during the space missions reaching beyond the Earth orbit, such as in the Jovian environment, the electron energy can reach hundreds of MeV and thus contribute on the NIEL in the electronic component material.

Regarding the overall reliability of SiC MOSFETs, the gate oxide degradation remains an issue [18], [19]. Even though the intrinsic reliability of the gate SiO_2 has improved over the years, the material defects as well as the radiation impact have a significant effect on the oxide reliability [4]–[6], [20], [21]. The lifetime of the devices at their normal operating voltage conditions is commonly predicted through accelerated time-dependent dielectric breakdown (TDDB) measurements and extrapolation [21], [22].

In this work, we investigate the effect of 20 MeV electron radiation on long term reliability of SiC power MOSFETs through accelerated wear-out experiments by performing TDDB measurements on the pristine and electron-irradiated devices. Moreover, the radiation induced-leakage current (RILC) has been observed and linked to the radiation-induced lifetime degradation. Finally, the models are proposed to describe the stress current dependence on the device lifetime under stress.

II. Experimental details

A. Device under test

The device under test (DUT) is a commercial SiC power MOSFET manufactured by Wolfspeed (part number C3M0280090D). A total of 118 samples were tested of which 53 were irradiated. All the devices were electrically characterized before and after irradiation.

B. Radiation exposure

Electron exposures were performed at RADEF (RADiation Effects Facility) at the University of Jyväskylä, Finland, with a Varian Clinac (Clinical LINear ACcelerator) 2100 CD. The

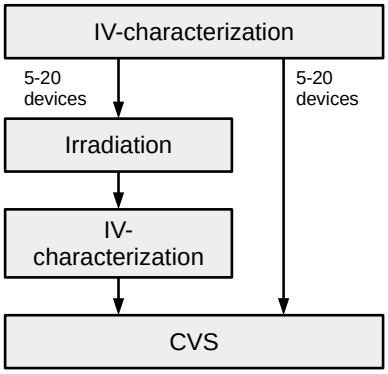

Fig. 1. Flowchart of the test procedure. For each stress voltage configuration, 5 to 20 devices were tested.

electron beam is pulsed and consists of $5\,\mu s$ long pulses every $5\,ms$ (pulse frequency of $200\,Hz$). An electron energy of $20\,MeV$ was used which is the maximum energy of the Clinac. Devices were irradiated in air with an average flux of electrons corresponding to a dose rate of $10\,Gy(H_2O)/min$. The devices were irradiated for $100\,min$, reaching an electron fluence corresponding to the total dose of $1\,kGy(H_2O)$ which corresponds to $0.87\,kGy$ in Si. This was calculated based on stopping powers of electrons in those materials obtained from [23] and also described in [24]. This TID value is approximately representative of $10\,yr$ in low earth orbit (LEO) [25]. During irradiations, $V_{GS} = -4\,V$ and $V_{DS} = 900\,V$ were applied on the devices.

C. Accelerated wear-out experiment

In order to investigate if the electron radiation has an impact on the long term reliability of SiC power MOSFET, an accelerated wear-out procedure was applied on the devices. For each test configuration, two sets of devices (irradiated and pristine) were exposed to a constant voltage stress (CVS) at the gate terminal, while the drain and the source terminals were grounded.

The gate-to-source voltage (V_{GS}) values for CVS were chosen based on the Fowler-Nordheim (FN) curves measured for three randomly picked devices. Four V_{GS} values (V_{GS} = 33 V, 35.5 V, 37 V and 38.3 V) were defined at the points where the gate-to-source currents (I_{GS}) were approximately $1\,\mu A$, $10\,\mu A$, $50\,\mu A$ and $100\,\mu A$ respectively. Such V_{GS} values are well below the instantaneous breakdown voltage of the gate oxide, but at the same time, above the normal operating voltage in order to accelerate the wear-out. The CVS was applied and the I_{GS} was monitored until an abrupt increase in I_{GS} was observed. The time at which that increase occurred, was then defined as the time-to-breakdown (T_{BD}). By integrating the gate current over time until the T_{BD}, we extract the amount of charge (charge-to-breakdown, Q_{BD}) injected through the gate oxide during the CVS. The procedure of the global test approach is illustrated in Fig. 1.

III. Results and discussion

A. Radiation induced degradation and oxide breakdown

It is known that the gate leakage current can be utilized as an indicator of the gate oxide degradation in SiC MOSFETs [18]. In order to assess the effect of radiation on the gate degradation, we first analyze the leakage current through the gate oxide by sweeping the V_{GS} up to the FN tunnelling region before and after the irradiation (Fig. 2). After electron exposure, the gate current exhibits increased leakage behaviour, which can be related to the creation of defects in the gate oxide volume by the electron impact [26]. Similar RILC was originally observed for thin oxides by Scarpa *et al.* [11]. We express the total gate current after irradiation ($I_{GS(post)}$) as the sum of the preirradiation current ($I_{GS(pre)}$) and RILC:

$$I_{GS(post)} = I_{GS(pre)} + I_{RILC}. \quad (1)$$

The RILC component was calculated from (1) and plotted in Fig. 2 for one example case. At V_{GS} values below the FN-region ($V_{GS} \lesssim 22\,V$), the RILC component stays constant. However, at the FN-region, the contribution of RILC in the total I_G increases with applied V_{GS}. Such increase is expected to play a role in the oxide breakdown process, which will be discussed in the next section.

As mentioned in II-C, four V_{GS} values were used in the breakdown measurements. That allows us to compare the effects of not only the electron radiation but also of the stress voltage on the breakdown characteristics. While assuming $50\,nm$ oxide thickness, a resulting E_{ox} of $6.6\,MV/cm$, $7.1\,MV/cm$, $7.4\,MV/cm$ and $7.7\,MV/cm$ respectively were applied across the oxide layer. By choosing such values for E_{ox}, we are able to collect T_{BD} data in an accelerated manner while staying below the critical E_{ox} ($> 10\,MV/cm$) [27] in order to avoid immediate device failure during CVS. Also, the electric field is below the value where the electric field acceleration factor for higher fields plays a role, when performing the lifetime projection based on the TDDB results [21], [28].

The gate current behaviour during the CVS for one device from each category is illustrated in Fig. 3. The breakdown characteristics during CVS is strongly dependent on the applied stress voltage. The initial gate current I_{G_0} plays a role in how the device fails during the CVS. When applying a stress voltage of V_{GS} = 35.5 V, we can see three different phases in the gate current evolution in Fig. 3, also reported in [20]. In the first phase, we observe increasing gate current over time indicating hole trapping process in the gate dielectric layer. In the second phase, the gate current starts to decrease, likely due to increasing electron trapping in the dielectric. In the third phase, the gate current suddenly increases indicating the oxide breakdown. However, when applying higher voltage on the gate terminal during CVS, the gate current keeps increasing until the device breakdown and it never reaches the decreasing phase. At higher V_{GS}, the kinetic energy of the injected charge carriers is high enough to initiate impact ionization which results in a lower injected charge needed for breakdown. On the other hand, for $V_{GS} = 33\,V$ the increasing phase in the gate current does not exist and the gate current keeps on decreasing

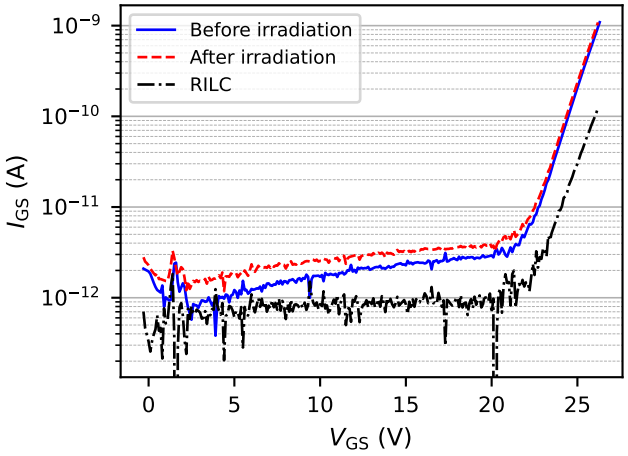

Fig. 2. The Fowler-Nordheim curves for a device before and after electron exposure. Black curve (RILC) represents the calculated difference between the pre- and postirradiation current. In order to minimize the damage induced by the charge injection during the characterization, the V_{GS} sweep was stopped when I_{GS} reached 1 nA.

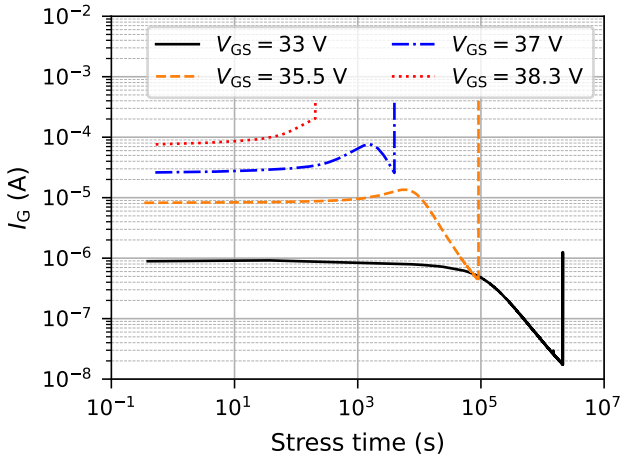

Fig. 3. Gate current of representative devices from each category during CVS as a function of stress time. An abrupt increase in the gate current indicates the oxide breakdown.

until the breakdown occurs. Moreover, the T_{BD} is dependent on the applied V_{GS} and therefore on the gate current as well. It will be discussed in more detail in the following sections.

B. The effect of electron radiation on the wear-out life

In order to extract the lifetime of the devices based on the TDDB results, we applied Weibull statistics on the T_{BD} data. We used the two-parameter Weibull cumulative distribution function (CDF):

$$F(x) = 1 - e^{-(\frac{x}{\eta})^{\beta}}, \tag{2}$$

where β is the shape parameter and η is the scale parameter of the Weibull distribution. The scale parameter η is also known as the characteristic lifetime which refers to the time when 63 % of the population has failed.

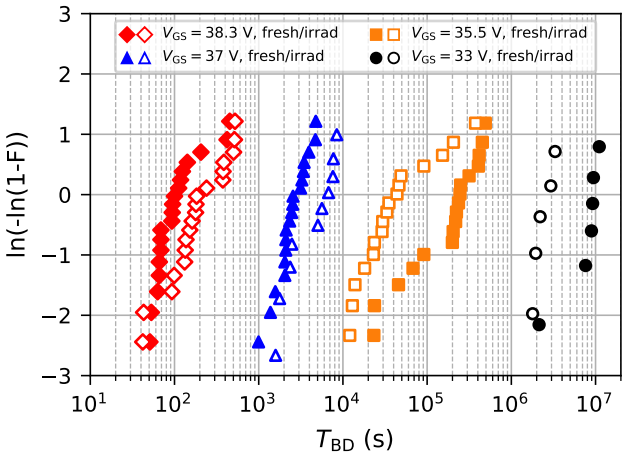

Fig. 4. Weibull plot of the gate oxide breakdown times for non-irradiated and irradiated devices with different V_{GS} values during the CVS.

In order to compare the empirical data with the distribution function, a common way to obtain the y-coordinate for each failure is to apply the Benard approximation (3):

$$F = \frac{i - 0.3}{N + 0.4}, \tag{3}$$

where i is the running number of the failure (first, second etc.) and N is the sample size. Then, rewriting (2) gives:

$$\ln(-\ln(1 - F)) = \beta \ln(x) - \beta \ln(\eta). \tag{4}$$

For each device failure, $\ln(-\ln(1-F))$ was then plotted as a function of elapsed time until corresponding failure (Fig. 4). Equation (2) was then fitted to the T_{BD} data and the β parameter, also known as shape parameter and η parameter representing the characteristic lifetime, were extracted. The parameters were extracted by using a software library [29] and by using maximum likelihood estimation (MLE) for the fitting. The extracted Weibull parameters for different test configurations are presented in Table I.

The characteristic lifetimes of the different sets are presented in Fig. 5. The lifetime of the devices is strongly dependent on the applied V_{GS} during TDDB test. The difference in characteristic lifetimes between V_{GS} = 33 V and V_{GS} = 38.3 V configuration is four orders of magnitude. Similar, strong electric field dependence has been observed for both Si and SiC based technologies [21], [22], [30]. The increasing injected electron energy with increasing electric field in the oxide during the stress will result in faster accumulation of trapped charge which will eventually lead to oxide breakdown [30].

Regarding the irradiation effect, when the applied V_{GS} during CVS is set to 35.5 V, irradiated devices exhibit approximately 70 % lower characteristic lifetime compared to non-irradiated devices. Same trend can be observed also for V_{GS} = 33 V. It indicates clearly that electron irradiation has weakened the gate oxide. Also, it suggests that the radiation-induced defect creation is revealed only at lower stress levels

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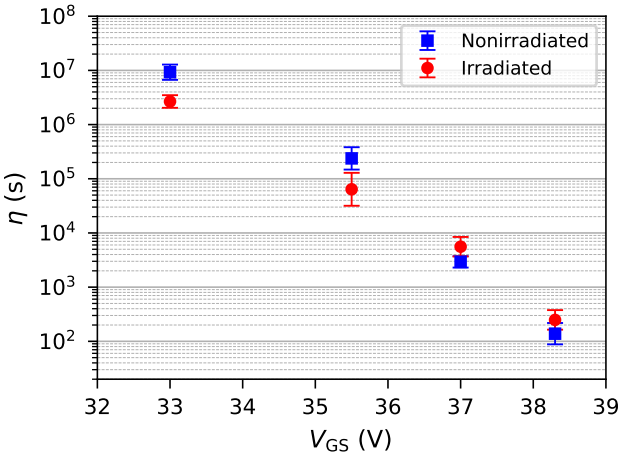

Fig. 5. η parameter of the weibull fits representing characteristic lifetime for different V_{GS} values during CVS. Error bars represent 95 % confidence limits.

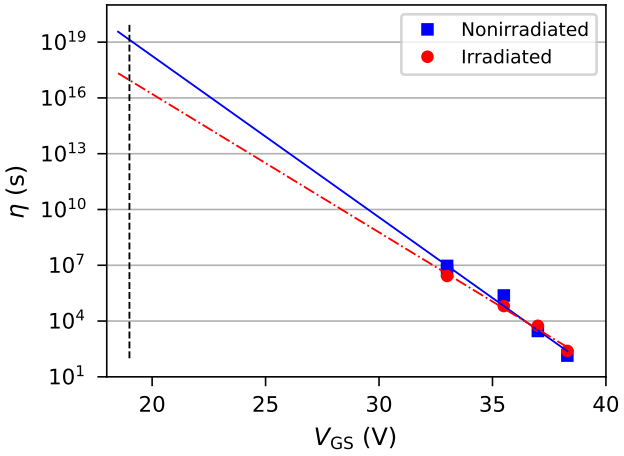

Fig. 6. Lifetime estimation of fresh and irradiated devices as a function of V_{GS}. Dashed vertical line represents the maximum rated gate voltage (V_{GS} = 19 V) given by the manufacturer.

($V_{GS} \leq 35.5$ V). At higher V_{GS} values ($\geq$ 37 V), higher initial stress current and stress-induced defect creation might contribute more on the number of defects in the oxide volume and therefore causing an additional weakening due to the stress test itself.

In order to estimate, how the electron-induced degradation affects on the wear-out life of the components, we have extrapolated the lifetime of the components under the rated voltage condition from the accelerated test results (Fig. 6). The dashed vertical line in Fig. 6 represents the maximum rated V_{GS} = 19 V given by the manufacturer. Based on the extrapolation, the device lifetimes at safe operating V_{GS} for irradiated and non-irradiated devices were found to be 1×10^9 yr and 5×10^{11} yr respectively. However, regarding the effect of the electron radiation on the long term reliability and the lifetime of the device, it should be kept in mind that V_{GS} during CVS should be low enough in order to be able

TABLE I
TEST CONFIGURATIONS AND EXTRACTED WEIBULL PARAMETERS

		T_{BD}		Q_{BD}	
Condition	N	β	η	β	η
V_{GS} = 33 V, no irrad	6	3.50	9.26×10^6	22.07	0.26
V_{GS} = 33 V, irrad	5	4.55	2.67×10^6	23.62	0.23
V_{GS} = 35.5 V, no irrad	17	1.34	2.38×10^5	9.75	0.29
V_{GS} = 35.5 V, irrad	17	0.92	6.39×10^4	6.67	0.25
V_{GS} = 37 V, no irrad	20	2.53	2.92×10^3	3.96	0.16
V_{GS} = 37 V, irrad	10	2.07	5.58×10^3	2.96	0.20
V_{GS} = 38.3 V, no irrad	19	1.35.	1.38×10^2	1.54	0.02
V_{GS} = 38.3 V, irrad	19	1.46	2.48×10^2	1.64	0.03

to conclude on possible lifetime reduction. As discussed in [21] and [22], the lifetime extrapolation should be performed with gate voltages for which the electric field in the oxide is below the impact ionization current threshold. Such threshold value for the E_{ox} is suggested to range from 8.5 MV/cm to 9 MV/cm [21], [22], [28]. Above that threshold value, the field acceleration factor for lifetime extrapolation is approximately double compared to the value when performing the test below the threshold. Therefore, performing the TDDB tests only at high V_{GS}, the lifetime predictions can be strongly overestimated. Moreover, it should be noted that the experiments have been performed at room temperature. Therefore, the lifetime predictions presented here can be optimistic and the lifetime during operation conditions should be significantly reduced due to the temperature stress, as observed in [18], [31], [32].

Here, the electron interaction with the gate oxide material will contribute to the number of defects in the oxide volume. One possible molecular precursor of oxide breakdown is the oxygen vacancy, which is suggested to play a role in low-field TDDB process [33]. Those defects then act as a precursor for a current path through the oxide which results in an increase of the total leakage current through the gate oxide, as shown in Fig. 2. Such increase in leakage current results in shorter T_{BD} for irradiated devices. However, such behaviour is only observed at the lowest used V_{GS} values during CVS, when the defect creation and trapping dominate the breakdown. At higher V_{GS}, the impact ionization current dominates the breakdown current and since it is a fast process, the contribution of irradiation-induced trapping and defect creation in the breakdown characteristics is relatively smaller compared to low V_{GS} settings. When applying higher V_{GS} during CVS, the stress current will cause additional stress to the dielectric material and the radiation-induced defects are masked out.

C. T_{BD} and Q_{BD} dependence on initial gate current

After extracting the T_{BD} for each device from the TDDB data, we pay attention to the initial gate current (I_{G_0}), which is defined as the gate current value at the beginning of the CVS. Fig. 7 shows that the T_{BD} is dependent on I_{G_0} during CVS and follows a power law:

$$T_{BD}(I_{G0}) = k \cdot I_{G0}^{-s}, \tag{5}$$

where k and s are the model parameters. A higher I_{G0} during the CVS results in a shorter breakdown time due to

a faster accumulation of the injected charge. Such behaviour seems to be present for both irradiated and nonirradiated devices. On the other hand, the Q_{BD} has an exponential dependence on the I_{G0}:

$$Q_{\mathrm{BD}}(I_{\mathrm{G0}}) = a \cdot e^{-b \cdot I_{\mathrm{G0}}}, \tag{6}$$

where a and b are the model parameters. It seems that the required injected charge for oxide breakdown saturates below certain I_{G0} level. It indicates that below certain stress voltage level, the T_{BD} could be estimated based on the I_{G0} during CVS. Such saturation is observed also in Fig. 8, where Q_{BD} is plotted as a function of T_{BD}. At lower V_{GS}, the Q_{BD} seems to reach a saturation level around 3×10^{-1} C, also observed in [34]. It seems that below a certain V_{GS}, the breakdown is dominated by the injected charge through the oxide layer.

Also, a simple Q_0 model [34] is shown in Fig. 8, where the Q_{BD} is obtained by multiplying I_{G0} by the T_{BD}. However, especially with longer breakdown times (lower V_{GS}), such model does not well describe the Q_0 behavior. The shape of the stress current curve in Fig. 3 shows decreasing trend over time due to charge trapping and therefore, a simple multiplication does not give correct result for Q_{BD}.

The similar behaviour between fresh and irradiated devices in Fig. 7 suggests that the I_{G0} during CVS may be used as an indicator of the device lifetime, whether the devices have been irradiated or not. Therefore, an electron radiation-induced lifetime reduction of SiC MOSFETs could be estimated based on the RILC at the FN region and thus avoiding the time-consuming TDDB tests.

IV. Conclusion

A long term reliability degradation of the SiC power MOSFET due to electron irradiation was observed. Even though, SiC power technology has been proven to be robust against TID, electron radiation can create defects in the oxide volume and at the oxide-semiconductor interface and therefore result in reliability degradation revealed by the accelerated lifetime test. Even if gate failures were not observed during the irradiation experiment neither during post-irradiation characterizations, stronger stressing through CVS reveals lower T_{BD} of gate oxide for irradiated devices. However, such reliability degradation was observed only at the lower V_{GS} values, when the charge trapping dominates the breakdown characteristics. It is assumed that at higher V_{GS} values, the radiation-induced degradation is masked by the stress-induced defect creation during CVS. Nonetheless, it indicates a degradation of gate dielectric layer due to electron radiation impact and therefore, an radiation-induced reduction in the long-term reliability of the device.

On top of TID effects, the high energy electrons used in this study are able to induce structural damage in the device material. Therefore, in order to extend these results to the other ionizing radiation environments, more investigations should be performed by modifying the energy and fluence of the electrons. However, regarding the TID effect only, the results presented here should represent the worst case for the used accumulated dose.

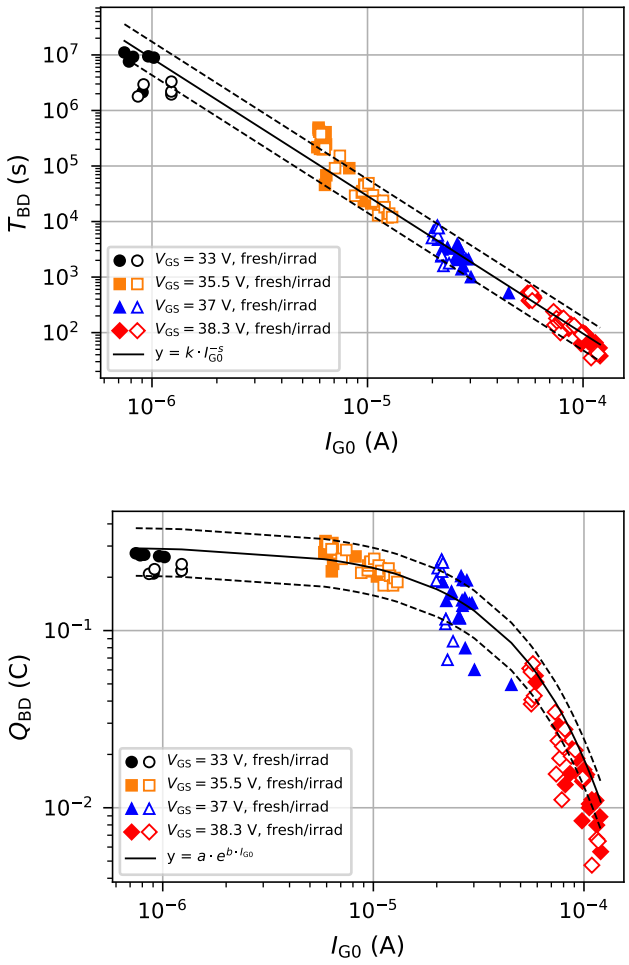

Fig. 7. The dependence of T_{BD} and Q_{BD} on I_{G0}. Fitted models are given in (5) and (6). Dashed lines represent order of two difference.

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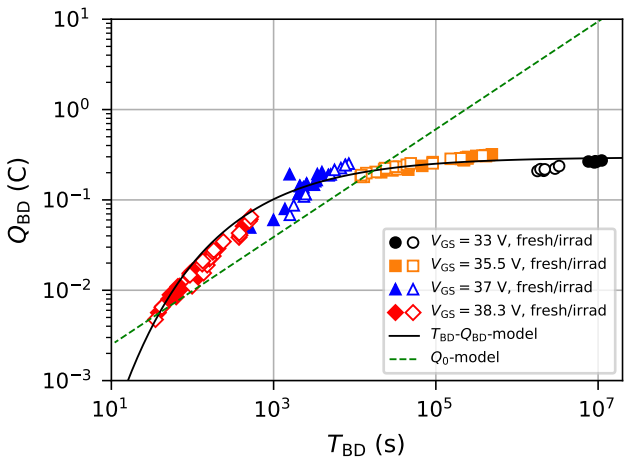

Fig. 8. Q_{BD} as a function of T_{BD}. The black solid line represents the combination of models (5) and (6). The green dashed line represents the Q_0 model. The Q_{BD} saturates around 3×10^{-1} C.

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